# Observations of Waves and Currents Near the Surf Zone

Jerome A. Smith
Scripps Institution of Oceanography
La Jolla, CA 93093-0213
http://jerry.ucsd.edu

***Abstract*- A major challenge in understanding nearshore wave/current systems lies in obtaining measurements that resolve both the waves and currents over appropriate spatial and temporal scales. In SandyDuck (1997), two "Phased-Array Doppler Sonars" (PADS) were deployed looking shoreward from sites 300 m apart. Each provides radial velocities over an area roughly 400 m radius by 90 degrees. Horizontal vector currents are estimated over the intersecting area. The result is analogous to CODAR, but on a finer scale: resolution of 5 to 20 m up to 400 m away, sampled every second. Deployments of current meters by collaborators at SandyDuck help in assessment of the usefulness and limitations of this approach. Correlations with these independent current measurements are very high, and the amplitude of the sonar response is consistent with a simple acoustic model for the bubble/bottom competition. Two limitations are: (1) severe breaking can fill the water column with bubbles, so the sound attenuates quickly, limiting the useful range. (2) In light conditions, there is competition between backscatter from within the water column versus the bottom. On very calm days the response can be dominated by bottom backscatter for depths less than 3 or 4 meters. In general, however, the measurements are usable over a wide range of conditions. Several compelling advantages derive from quasi-continuous coverage in both space and time, including the ability to estimate vorticity fields associated with the circulation, to locate nodes associated with edge waves and reflected waves as functions of frequency, and to estimate gradients of wave quantities. Such concurrent observation of waves and currents is ideal for wave/current interaction studies. Many applications for this technique can be envisioned, including (for example) the interaction of waves and currents in tidal inlets or between islands.**

## I. INTRODUCTION

Flows near shore are forced by a combination of wave breaking, winds, and topographic effects. Exchanges of materials, mass, heat, and momentum between the surf-zone and water farther offshore are thought to occur mainly via horizontal flow patterns [1]. The narrow offshore-directed portions of this flow pattern are often referred to as "rip currents." People who swim at oceanic beaches are usually familiar with both alongshore flow and the occasional occurrence of "rip currents." The former is seen as a nuisance, carrying children and toys down the beach; but the latter can be frightening. These phenomena are also thought to influence the movement and sculpting of sand near shore [2, 3], and could be important in the offshore transport of sand and other materials [4].

When do rip currents occur, and what drives them? Two hypotheses are that (1) rip current activity is associated with cuts or channels in the nearshore sandbar, and (2) they are associated with nearly normal incidence of the waves. In addition, it is (newly) hypothesized that conditions of swell-driven flow opposing the wind-driven flow leads to stronger variability and hence more rip currents.

Rip currents generally vary irregularly in strength and location, making it difficult to formulate a sampling strategy. Thus, at a practical level, the challenge is to make horizontal velocity measurements over an area of sufficient size to resolve the time-space variability of these phenomena. The velocity observations must also be coordinated with measurements of the bottom topography, incident wave field, and wind. Finally, the measurements must extend over a length of time sufficient to experience a variety of conditions.

In general, it is thought that several factors are important in determining the form and dynamics of near shore flows in general:

1) The incident angle of the waves,
2) Along-shore variability in wave height & direction,
3) Bottom topography (sandbars, cuts, etc.),
4) Wind,
5) Edge waves,
6) Instabilities of the alongshore flow (e.g., shear waves).

All these factors were monitored in "SandyDuck," a major field experiment that took place near Duck, North Carolina, in 1997 at the USACE's "Field Research Facility" (FRF). With this data, we hope to come to understand the form and dynamics of the flows and exchanges near shore. Such understanding could lead to predictions of the features such as instabilities and rip currents, the net effects on horizontal mixing and diffusion, and the feedback on morphological evolution and beach erosion.

## II. EXPERIMENTAL SETUP

To study these flows, a pair of Phased-Array Doppler Sonars (PADS) was deployed as part of the SandyDuck experiment (figure 1). The essential method is to project short encoded sequences ("pings") of sound in a 90°-wide horizontal fan (filling the water column in shallow water). The sound scatters off both the near-surface bubble layer and the bottom (and anything else in the water). Some backscattered sound returns to the sonar, where the signal is received on an array, beamformed into returns from discrete directions, and analyzed for the mean Doppler shift versus elapsed time since transmission. For direct-path transmission and return, the time-delay since transmission simply translates into distance from the sonar. As operated at SandyDuck, the spatial resolution is about 7.5 m in range by 6 degrees, so (for example) at 200m range the sample area is about 8 by 20 meters. The sonars transmitted a 13-bit "repeat sequence code" [5] every 0.75s, simultaneously sampling over all angles. Each PADS produces a field of estimates of the radial component of velocity over a pie-shaped region about 400 m radius by 90° in azimuth from every ping. Over the intersecting region the radial velocities are combined into horizontal vector currents. Sequences of these combined estimates produce movies of the 2-dimensional flow field, along with the associated fields of acoustic backscatter intensity (bubble cloud density). Two-ping averages were

0-7803-6551-8/00/$10.00 ©2000 IEEE

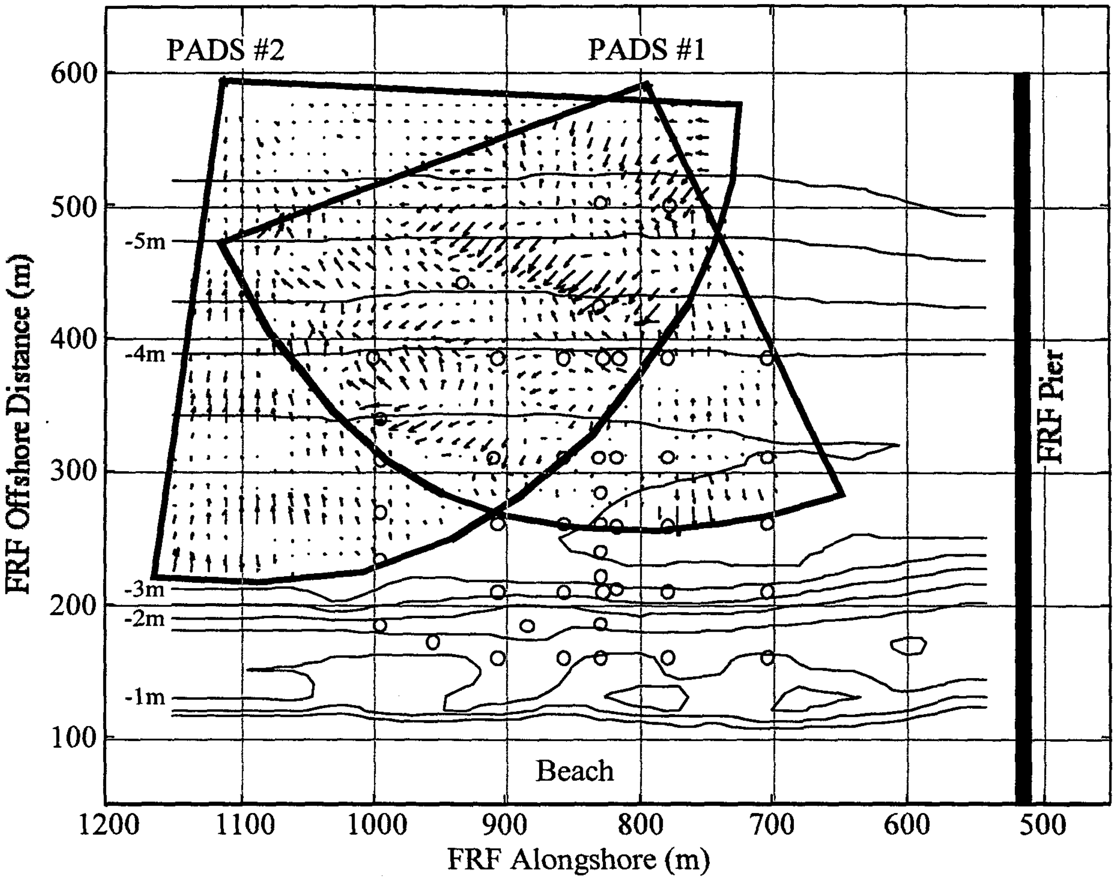

Fig. 1. SandyDuck experimental site, showing the area covered by the two "Phased Array Doppler Sonars" (PADS). The arrows indicate velocity estimates from a single "snapshot," dominated by swell from the upper right (SE); the longer arrows correspond to velocities approaching 1 m/s. Both horizontal components are estimated in the overlap region, but only one in the corners covered by a single sonar. The circles show locations of frames with current meters (etc.). North is about 20° clockwise of left. The location is the Field Research Facility of the US Army Corps of Engineers, near Duck, North Carolina.

recorded, providing estimates every 1.5 seconds with about 7 cm/s RMS velocity error in each range-angle bin. The data resolve both surface-wave motion and lower frequency motions, with longer time averages achieving sub-cm/s velocity accuracy. The latter include infragravity waves, shear waves, and rip currents.

All data are coordinated via GPS time-stamping with other measurements of waves, currents, bottom topography, etc., carried out by other participants at SandyDuck. This enables detailed comparisons between the quasi-continuous coverage from the PADS and the currents measured at a variety of points in or near the PADS area (section III; see figure 1, circles). In addition to current and wave measurements, there are winds and directional wave spectra provided by C. Long (FRF staff, USACE), and bottom topography was measured each day (weather permitting) by M. Leffler and crew (also at the FRF/USACE).

Both systems were operational by September 7th, and were operated until November 1st with numerous interruptions for modifications and repairs. There were 42 days with both systems working part of the time, including over 27 days of continuous (around-the-clock) dual-PADS data collection. Software to combine the data from the two PADS (collected on separate systems) was operational by mid-October 1997 (implemented during the field experiment). The approach is based on "objective analysis" [6], incorporating dynamic estimates of the signal-to-noise levels. This permits the viewed area to vary in time as the good data retrieved varies. The data are well behaved, so spatial derivatives can be taken; e.g., sensible-looking vorticity maps. "External data" such as the wind speed and direction, wave height and direction, tidal elevation, and bottom contours are time-coordinated and incorporated into the analysis. The synchronized elevation and bottom contours permit calculation of the "transport divergence" and potential vorticity from the estimated 2D velocity fields (for example).

The main factors affecting nearshore flow (listed in the introduction) were monitored at SandyDuck over a period long enough to experience a variety of conditions. We experienced incident wave fields with a variety of incident angles, heights, and directional spreads, and at different angles to the wind. From these observations, we are developing objective measures of the flow; for example, bulk momentum budgets can be used to put bounds on the bottom

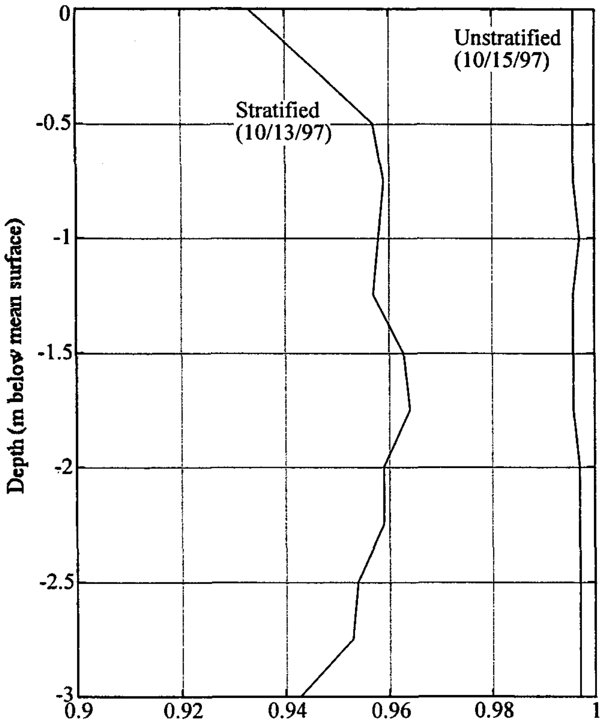

Fig. 2. Correlations between near-bottom currents and nearby PADS velocities (~15 m away). The line to the left (smaller correlations) is from stratified conditions; on the right from well mixed. Maximum correlation for the stratified case occurs near 1.5 m depth.

friction and wave driving terms [7]. We can examine whether the evolution of the vorticity field is consistent with the same frictional estimates. Kinetic energy estimates (mean square velocity perturbations) over 1 to 10 minute periods can indicate the strength of flow perturbations, including rip currents, shear waves, and other infragravity motions. Further analysis via time-space Fourier transforms will permit separation of motions via appropriate dispersion relations.

## III. COMPARISONS WITH OTHER DATA

A technical necessity is verification and calibration of these PADS measurements. Considerations include partial backscatter from the bottom, loud reflections from artificial structures, and the net effects of surface waves (e.g., sheltering, extreme slopes, and displacements). Bottom reflections are generally weaker than the volume scatter from bubbles, but are roughly independent of the wind/wave conditions, and can become significant when the wind and waves are so weak that too few bubbles are generated. Data from discrete locations within the PADS viewing area are used for direct comparisons. Near-bottom currents were provided for many locations by Elgar (WHOI), Herbers (NPG), O'Reilly (UC Berkeley), and Guza (SIO), henceforth "EHOG," and at a few other locations by Hay and Bowen (Dalhousie U.); current profiles in 25-cm vertical bins were provided for one location by P. Howd (U.S.FL).

For lower frequency motions, such as shear-waves and eddies associated with the alongshore shear, the correspondence between near-surface and near-bottom measurements can vary depending on the stratification. The profile data (from P. Howd) are used to evaluate the depth of the strongest correlation with the PADS data, and the correlation with various depth-weighted averages (figure 2). Where there is strong vertical mixing, currents near the bottom correlate well with the near-surface currents. In contrast, when there is stratification the correlation is smaller, with mean angles exceeding 45° between the top and bottom. The stratified case appears to support the hypothesis that the PADS signal is dominated by scatterers with about 1.5 m depth scale.

Wave motions, which penetrate in a predictable way to the bottom in finite-depth water, can be compared at all the available sensor locations (wave-frequency data are from EHOG). As seen in Table 1, the wave-frequency correlations are comparable to the "test case" correlating two current meter records at a similar spatial separation (15 m; see last column of Table 1). However, there is a "scale factor" between the magnitudes of the currents measured by PADS versus in-situ current meters. The magnitudes of the PADS estimates are always smaller than the in-situ data (hence they require a "scale factor" greater than 1.0). The explanation is that mixing the volume backscatter signal with bottom backscatter always reduces the magnitude, since the bottom yields zero Doppler shift.

## IV. DIRECTIONAL SURFACE WAVE SPECTRA

Incident waves, edge-waves, and "leaky-mode" waves or "surf-beat" propagate faster than the eddies and shear waves associated with vorticity. The various modes of motion in the nearshore can be distinguished on the basis of their unique dispersion characteristics. Previous analyses have described and separated the observed motions on the basis of a 2D "fountain plot" [8], in which the spectral density is displayed versus frequency and alongshore wavenumber. Here we exploit the full 3D (2 space and time) views of horizontal velocity in the region sampled by the dual-PADS setup, looking at both the alongshore and cross-shore characteristics.

TABLE I
Wave-Frequency Correlations

| | PADS/SPUV72<br>FRF x, y=500, 829 | | PADS/SPUV62<br>385, 828 | | SPUV62/SPUV63<br>385, 828 vs 815 | |
|---|---|---|---|---|---|---|
| Run Time | corr. | scale | corr. | scale | corr. | scale |
| 09/10 1900 | 0.939 | 1.13 | 0.925 | 1.46 | 0.907 | 0.976 |
| 10/14 0100 | 0.873 | 1.65 | 0.725 | 3.73 | 0.890 | 0.935 |
| 10/18 0800 | 0.936 | 1.59 | 0.855 | 1.75 | 0.865 | 0.943 |

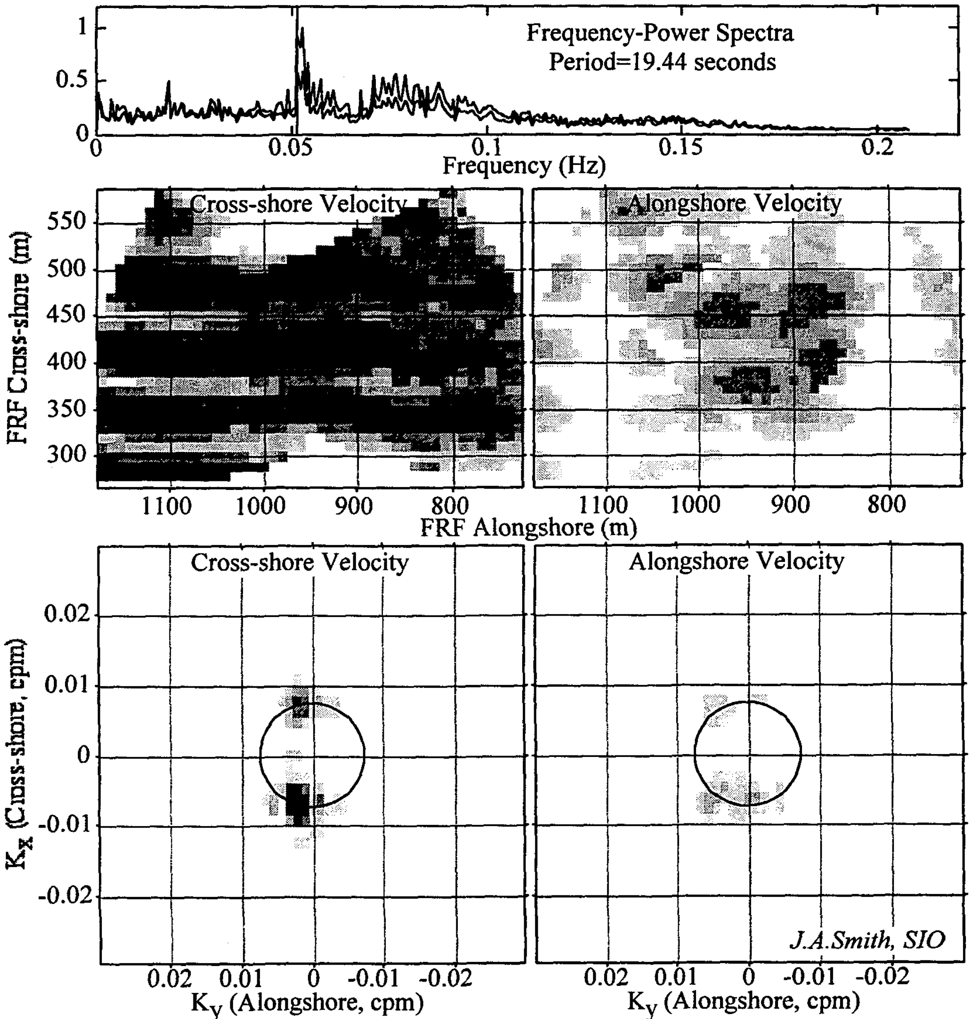

**Figure 4.** (Uppermost plot) Linear frequency-power-spectrum, with vertical line at frequency shown in remaining plots (black line: shore-normal velocity component; grey line: alongshore component). Note swell peak near 19 second period. (Middle) Spatial distributions of variance at 19.44 s period for (left) shore-normal and (right) alongshore velocity. Nodes and antinodes are visible, indicating significant reflection. (Lowermost) Wavenumber spectra at 19.44 s period for (left) shore-normal and (right) alongshore velocity. Grey ring is linear dispersion computed for the mean depth.

Insight can be gained from spatial maps of the variance at each frequency. For example, maps of variance near 19 s periods show distinct nodes and antinodes, indicating reflection of these very long waves off the beach (figure 4, middle panels). The locations of these nodes (as functions of frequency) are sensitive to the bottom topography shoreward of the viewed area. This is true not only of the long incident surf, as shown here, but also of edge wave modes. There is hope that such information can be "inverted" to deduce the bathymetry and (perhaps) current structure shoreward of the viewed area [9, 10].

The 3D views are conducive to analysis via 3D Fourier analysis. Since the sample region spans only a modest depth range (typically 3.5 to 5.5 m depth), and since gravity wave dispersion depends on depth only as the square-root (or weaker), approximate 3D spectra can be calculated without explicit corrections for non-uniformity within the sample-area (figure 4, lowest panels). For periods less than about 100 seconds, variance in the 3D spectra lies near the dispersion circle, as seen in figure 4 for T = 19.44 seconds.

In general, the wave-mode data can be used to examine the spatial distribution of wave variance, to assess the wave's mass transport, and to assess wave refraction and reflection through the outer shear-zone of the alongshore flow. Additionally, edge waves, which are essentially shore-trapped gravity waves, appear in the 3D spectra as similar to pairs of incident and reflected waves.

## V. DISCUSSION

Time-averaging velocities over a couple minutes or more reduces gravity-mode variance sufficiently to examine the underlying flow, where vorticity dynamics dominate. There are times with meandering alongshore flow, and other times where the flow is straight and uniform. Some periods exhibit clear indications of rip currents, others do not. A feature suggestive of a "vortex pair" propagating South along an isobath was observed on one occasion, persisting with about a 20 minute time scale (the interested reader can view a color movie at http://jerry.ucsd.edu/vort1014.MOOV). Such isolated "vortex pairs" appear to be rare, and (we surmise) are more likely to occur during low winds and low to medium waves. This example occurred during the unusual conditions of alongshore flow opposing the driving by both wind and waves. Features resembling rip currents appear more frequently, but generally fade quickly as well.

We hypothesize that the dissipation of vorticity is larger inside or near the surfzone (due to wave breaking induced turbulence), and smaller further offshore. To make a first-cut examination of this, the measurement area was subdivided into two parts, inshore and offshore of the 4 m depth contour. The notion that the nearshore vorticity dissipates more rapidly than that offshore is born out in this calculation. In one example, an offshore feature resembling a "vortex pair" propagates through along the 5 m contour, leaving behind a "tail" of negative vorticity; this remnant tail persists after the feature exits the other boundary, and decays with about a 20 minute time-scale. In contrast, the occasional offshore "squirts" seen in the shallower sub-region decay too rapidly to measure well, lasting only a few minutes.

## VI. CONCLUSIONS

The means by which we have viewed the velocity and vorticity fields in this study is novel. Patterns suggestive of vortex dynamics (e.g., self-propagating vortex pairs) have been observed in the nearshore environment for the first time. The PADS measurements are a natural complement to the discrete arrays of high-precision current meters, pressure sensors, (etc.) deployed within and near the surf-zone. The combined data set spans an area from the shoreline out to some 500 to 700 m, with a similar extent alongshore. As the data are analyzed, much will be learned about the dynamics and form of the currents near shore.

Comparisons between PADS and other current measurements is encouraging, with correlations typically in the range of 0.90 to over 0.99 (depending on the measurements being near-surface or near-bottom, and on the existence of stratification). The depth of measurement most tightly correlated with the PADS estimates is near 1.2 m below the surface (mean with respect to waves, moving with the tide). At surface wave frequencies, cross-spectra show high correlations up to frequencies of about 0.2 Hz. Higher frequency waves have wavelengths comparable to the 20 m averaging scale of the measurements (i.e. less than 40 m).

One day it should be possible to predict the nonlinear regime of the flow: Will there be rip currents today? How much on/offshore mixing may we expect? Are the conditions conducive to sediment transport? To build this ability, we need a database covering a variety of conditions, both in forcing and response, with sufficient time-space coverage to provide the needed measures of the flow.

## VII. REFERENCES

[1] F. P. Shepard and D. L. Inman, "Nearshore water circulation related to bottom topography and wave refraction," *Trans. Am. Geophys. Union*, vol. 31, pp. 196-212, 1950.

[2] R. Holman, "Nearshore Processes," *Reviews Of Geophysics*, vol. 33, pp. 1237-1247, 1995.

[3] R. A. Holman and A. J. Bowen, "Bars, bumps, and Holes: models for the generation of complex beach topography.," *J. Geophys. Res.*, vol. 87, pp. 457-468, 1982.

[4] J. A. Smith and J. L. Largier, "Observations Of Nearshore Circulation - Rip Currents," *Journal Of Geophysical Research-Oceans*, vol. 100, pp. 10967-10975, 1995.

[5] R. Pinkel and J. A. Smith, "Repeat-sequence coding for improved precision of Doppler sonar and sodar," *J. Atmos. Oceanic Technol.*, vol. 9, pp. 149-163, 1992.

[6] F. P. Bretherton, R. E. Davis, and C. B. Fandry, "A technique for objective analysis and design of oceanographic experiments applied to Mode-73," *Deep Sea Res.*, vol. 23, pp. 559-582, 1976.

[7] F. Feddersen, R. T. Guza, S. Elgar, and T. H. C. Herbers, "Alongshore momentum balances in the nearshore," *Journal of Geophysical Research-Oceans*, vol. 103, pp. 15667-15676, 1998.

[8] J. Oltman-Shay, P. A. Howd, and W. A. Birkemeier, "Shear Instabilities Of The Mean Longshore Current. 2. Field Observations," *Journal Of Geophysical Research-Oceans*, vol. 94, pp. 18031-18042, 1989.

[9] U. Putrevu, J. R. Booker, J. Oltman-Shay, and M. J. Pruis, "Inverting edge-wave measurements to determine nearshore bathymetry and longshore currents. Part I - Theory and tests.," *J. Geophys. Res.*, vol. (submitted), 2000.

[10] A. B. Kennedy, Q. Chen, J. T. Kirby, and R. A. Dalrymple, "Boussinesq modeling of wave transformation, breaking, end runup. I: 1D," *Journal of Waterway Port Coastal and Ocean Engineering-Asce*, vol. 126, pp. 39-47, 2000.