CHAPTER 315

REYNOLDS STRESS AND SMALL-SCALE MORPHOLOGY MEASUREMENTS DURING DUCK94

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Abstract

A recently developed Coherent Acoustic Sediment Probe (CASP) was deployed from an instrumented sled during the Duck94 nearshore experiment at Duck, North Carolina, in October 1994. The CASP measured acoustic backscatter profiles and three component velocity vectors in an O(1 cm^3) volume 25cm in front of the downward-looking instrument package. The CASP was remotely positioned to selected heights to form profiles of velocity and sediment concentration through the bottom boundary layer. A vertical stack of 8, two-axis electromagnetic current meters extended the horizontal measurements to the surface. A co-located scanning pencil-beam sonar and tilt sensors were used to map the small-scale morphology across a 1m by 4m area centered on the CASP measurements, quantitifying the local roughness and slope elements down to 4cm scales under low acoustic clutter conditions. It is shown that the stress measured near the bed in a gravity oriented vertical reference system is associated with both the turbulent Reynolds' stresses and a wave stress due the vertical velocity induced by the horizontal wave velocity acting on the sloping bottom being correlated with the horizontal velocity. The wave stress is largest at the bed and decreases towards the surface and can be larger than the turbulent Reynolds' stresses.

DUCK94 Experiment

The data presented herein were obtained during the comprehensive nearshore DUCK94 experiment conducted in October 1994 at the U. S. Army Corps of Engineers Field Research Facility (FRF), Duck, North Carolina. The FRF beach usually is a two-bar system composed of a dynamic inner bar (30-120 m offshore) and a secondary bar of lower amplitude (300-400 m offshore). The mean foreshore slope of the beach is approximately 0.08 (1:12) and the mean slope offshore of the bars is approximately 0.006 (1:170) (Lippmann et al., 1993). Sediments have a wide range of coarse sediment size on the beach and foreshore and fine, well sorted sand within the trough and seaward (mean grain diameter ~ 0.2 mm) (Stauble, 1992). The mean tidal range is approximately 1 m.

Boundary layer stress and velocity profile measurements from 11 October have been chosen to show the structure of the bottom boundary layer under strong wave forcing conditions. Storm waves with significant wave heights of 2m approaching at 16° (in 8m depth) produced mean longshore currents of 1 ms^{-1} in the surf zone. The resulting bottom boundary layer was composed of both the steady longshore flow and O(1 ms^{-1}) magnitude cross shore oscillatory flow due to the incoming waves.

Wave, velocity and sediment flux data were acquired using an instrumented sled. A Coherent Acoustic Sediment Probe (CASP) was mounted on a moveable boom (with elevation controlled from shore) deployed from the sled. The CASP measured acoustic backscatter profiles and three-component velocity vectors in an O(1 cm^3) volume 25cm in front of the downward-looking instrument package, as it was remotely positioned to selected heights to form profiles of velocity and sediment concentration through the bottom boundary layer. A co-located scanning pencil-beam sonar and tilt sensors were used to map the small-scale morphology across a 1m by 4m area centered on the CASP measurements, quantitifying the local roughness and slope elements down to 4cm scales under low acoustic clutter conditions

Additional instrumentation on the sled included a vertical stack of eight Marsh-McBirney two-component electromagnetic current meters mounted on a 2.5 m mast to measure vertical profiles of longshore and cross-shore currents. The sled was oriented with the vertical stack of current meters placed on the up-current side to prevent the sled structure from contaminating flow measurements. Surface elevations were measured using an array of five pressure sensors configured in a 3 m square with sensors at the corners and one at the center. For data collection, the sled was towed by the CRAB to its furthest position offshore, dependent upon wave conditions, for the first data run. The sled was tethered to the shore with a chain. A forklift on the beach pulled the sled shoreward approximately 10 to 30 m for each subsequent run. Data were acquired at each location for approximately one hour at four to eight locations. Data were digitized on the sled and transmitted to shore via an armored fibre optic cable married to the chain tether.

Additionally, directional wave spectra were acquired using a linear array of 10 pressure sensors in 8 m depth offshore of the survey area. A fixed current meter in the trough at line 820 m was used to measure longshore currents continuously.

Vertical profiles of the mean longshore currents at various cross-shore location superposed on the bottom profile measured on 11 October are shown in Figure 1. The longshore currents were relatively strong on this day with mean currents exceeding 1 m/s. The bottom profile is barred. The small-scale morphology is near planar on the seaward side and atop the bar and on the foreshore, with well-developed mega-ripples within the trough.

Theory and Analysis

Linear wave theory over a horizontal bed predicts that the horizontal and vertical wave induced velocities are in quadrature, and therefore do not contribute to the Reynolds' stresses. However, for a sloping bottom in a gravity oriented vertical reference system, a vertical velocity is induced at the bed by the horizontal velocity acting on the sloping bottom

$$w = u \tan\beta \qquad (1)$$

where u,w are the horizontal and vertical velocities and tan B is the bottom slope. The vertical

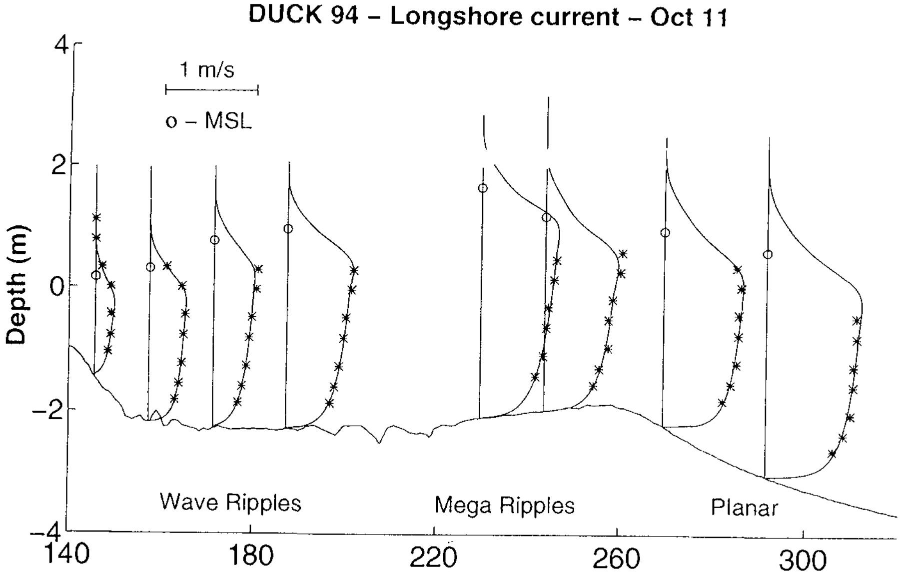

Figure 1. Measured longshore current vertical profiles (*) at various cross-shore locations compared with logarithmic profile (solid line) superposed on the bottom profile.

velocity near the bed will be in-phase with the horizontal velocity, resulting in a contribution to the co-spectrum, <uw>, which is proportional to the Reynolds' stress. The total stress is composed of an induced wave stress plus the stress due to the friction velocity defined as

$$\frac{\tau}{\rho} = u_{*T}^2 = <\vec{u}w> = u_{*Friction}^2 + u_{*Wave}^2 \tag{2}$$

It is hypothesized that the appropriate coordinates to measure the Reynold's stresses near the bed are oriented normal to the bottom. However, the bed has a broad range of scales in the near shore (Thornton, et al 1997) ranging from the general bottom profile with horizontal scales O(10m) to mega-ripples and ripples with horizontal scales O(1m). A question then arises as to what is the corresponding scale over which to measure the bottom slope? Instead of trying to measure the appropriate bottom slope, we will use hydrodynamic measures to establish the coordinate system. Hydrodynamically, the velocity normal to the bed goes to zero at the bed. Therefore, the bottom slope in (1) is determined three different ways by minimizing the measured near-bed quantities of covariance between horizontal and vertical velocity, <uw>, mean vertical velocity, W, and vertical velocity variance, $<w^2>$.

Results and Conclusions

Direct estimates of the Reynolds stress components <uw,vw> and mean velocity <U,V> were formed at each measurement height with averaging times between 4 and 10 minutes. As a vertical profile of these quantities is formed over approximately 1 hour, measurement stations were selected where the mean currents and wave conditions were relatively constant during this time. Profiles of (U,V) vectors, orbital displacement standard deviations in the x,y directions, the friction velocity vector (u*,v*), and the friction velocity magnitude for station 1 (see Figure 1) are shown in Figure 2. The instrument coordinate velocity vector time series was rotated into a vertically orientated coordinate system to a precision of $\pm$ 0.2° before the mean velocity and stress estimates were made. Therefore the true vertical (rather than bed normal) stresses are shown here. Height above the bed was determined to $\pm$1.6 cm by using the acoustic backscatter profiles. The velocity coordinate system in these plots is v+ offshore and u+ toward the south, and w+ upwards. At both sites, the U/V profiles, which span the lower 0.5m of the bottom boundary layer, show strong offshore and long-shore mean currents decaying toward the bed. The upper CASP-measured mean velocities matched the em-current meter profiles, which extend to the surface (not shown). In the absence of an oscillatory flow component, the stress vectors would be expected to be aligned with the mean current direction within the inner "wall" boundary layer established by the mean flow. However, the mean vertical stress vector has a strong cross-shore wave stress component, increasing toward the bed, which rotates the stress vectors toward the offshore direction (Figure 2). This cross-shore stress is attributed to the wave stress component arising from the shoaling waves interacting with the bottom slope, producing a linearly decreasing wave stress toward the surface (Rivero and Arcilla, 1995). The slight increase in stress in the first 20cm above the bed seen in most of the profiles is likely due to the rotational stress components of the wave boundary layer arising from the strong oscillatory flow and the local bed roughness elements.

An example of the co- and quadrature spectra measured in gravity oriented coordinates at an elevation of 27 cm above the bed is shown in Figure 3. In the gravity oriented vertical reference coordinates, there is a large contribution to both the co- and quadrature spectra (vw, uw) at the wind-wave band of frequencies (0.1 - 0.5 Hz). The co-spectrum is minimized by rotating the coordinates about the x,y axis in 0.1° increments (Figure 4). A definite minimum is found, indicating a mean cross-shore slope of 4.3° and an alongshore slope of 1.6°. The minimized cross-spectra are shown in Figure 5. The co-spectra are greatly reduced, whereas the quadrature spectra are virtually the same, indicating the co-spectral contributions are bottom slope induced, and should not be attributed to turbulent Reynold's stress contributions.

The mean and vertical velocities variance were similarly minimized and the corresponding calculated bottom slopes were essentially the same as calculated from the minimization of the co-spectra. Therefore, the coordinate rotations are based on the minimization of the co-spectra.

The friction velocities calculated at various elevations over the vertical before and after rotations of the coordinates and the cross-shore tilt calculated from the minimization of the co-spectra indicative of the bottom slope are shown for locations offshore the bar and within the trough (Figures 6 and 7). The measured cross-shore bottom slope (averaged over 5m) is also indicated. On the near planar, smooth slope on the seaward side of the bar the calculated slope from the co-spectral minimization corresponds to the bottom slope (averaged over 5m) as the bottom is approached; this indicates that the additional stress is associated with the sloping

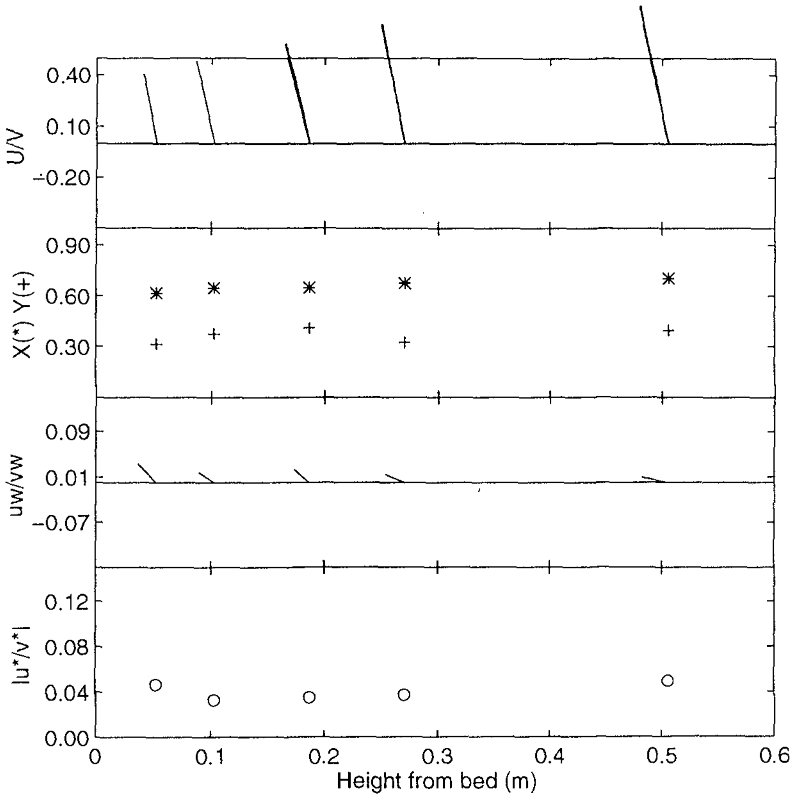

Figure 2. (U,V) mean velocity, orbital displacement magnitudes for x,y components, u*,v* friction velocity vector and friction velocity magnitude profiles from 0 to 0.5m above the bed for the offshore station 1 on October 11.

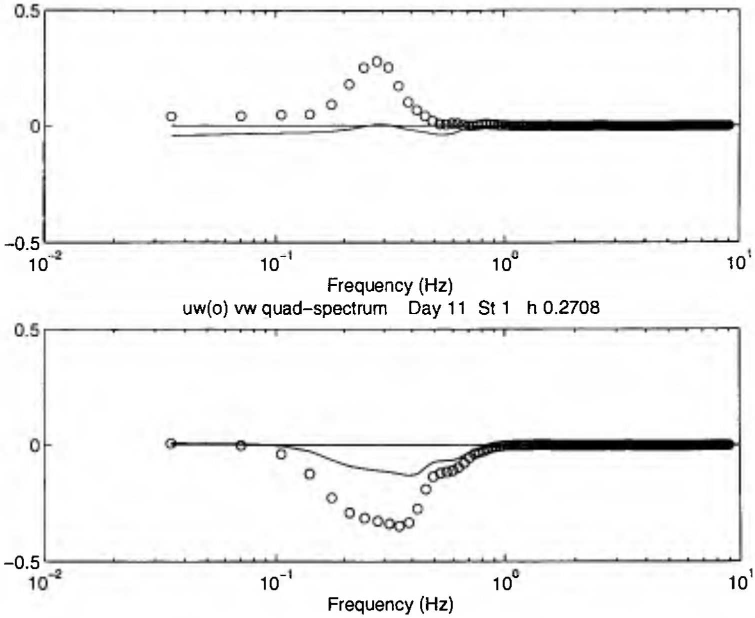

Figure 3. Co-spectra (upper panel) and Quadrature-spectra (lower panel) of uw (o) and vw (-) (m^2-sec) in gravity vertical coordinates, Station 1 at elevation 27cm off the bottom.

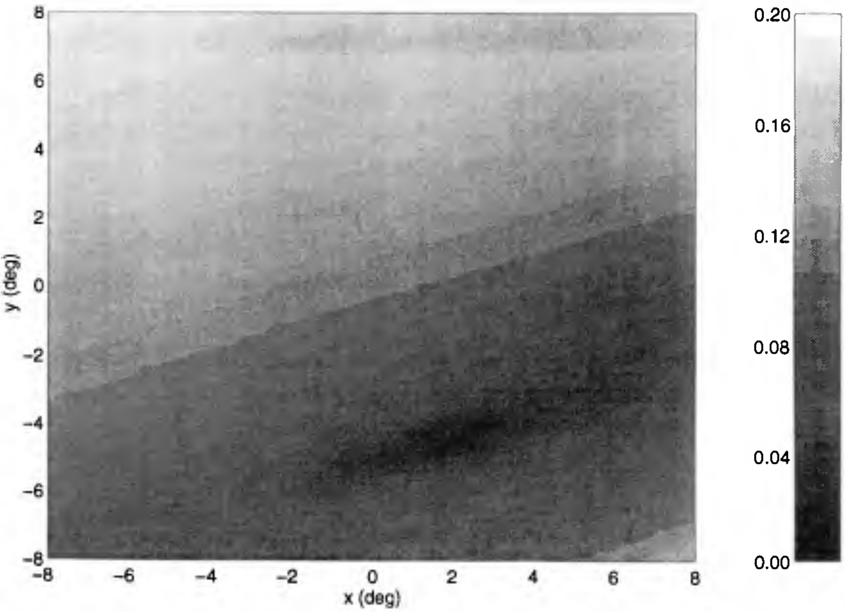

Figure 4. Co-spectra calculated at 0.1 degree rotations in x,y showing minimum, Station 1.

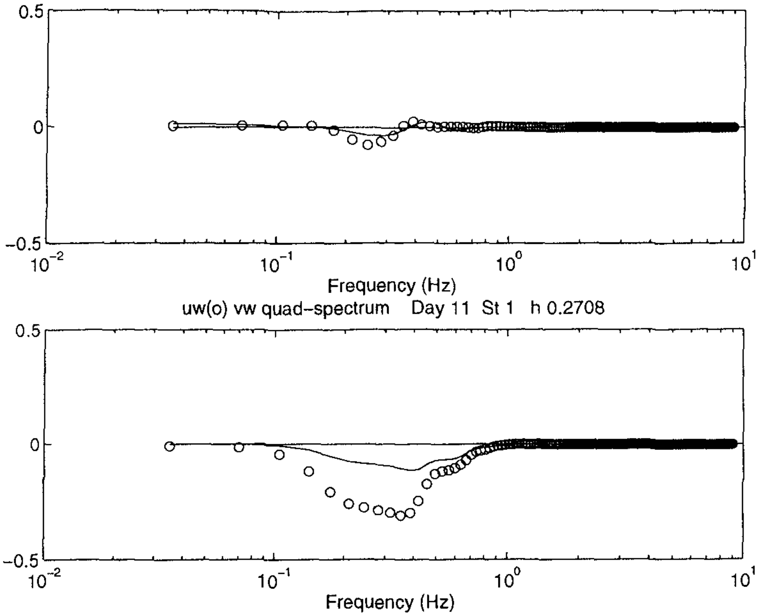

Figure 5. Co-spectra (upper panel) and Quadrature-spectra (lower panel) of uw (o) and vw (-) in rotated coordinates minimizing the co-spectra, Station 1.

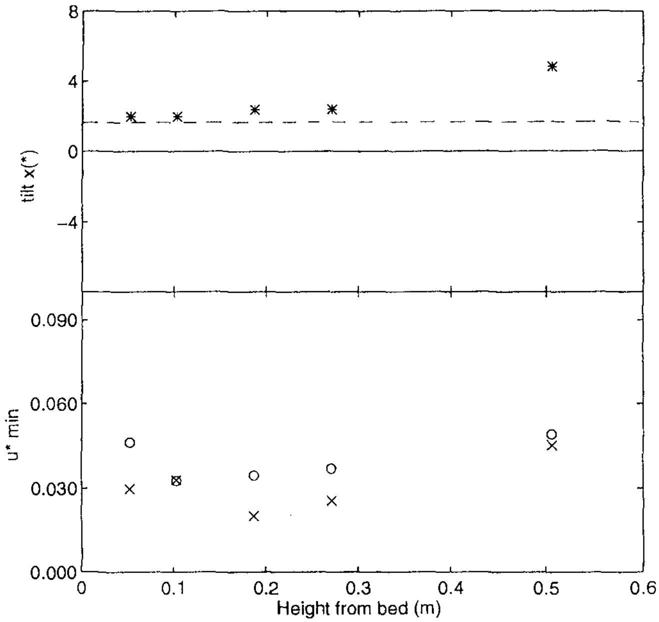

Figure 6. Vertical profiles of cross-shore (x) rotation angles to minimize co-spectra (*) compared with average slope over 5m (-) (upper panel), and total friction velocity (o) and friction velocity in bed normal coordinates (lower panel), Station 1.

bottom. However, within the trough where mega-ripples are prevalent, just the opposite effect is seen where the calculated slope from the minimization of the co-spectra and the bottom slope measure over 5m do not converge until almost 40cm off the bed. The total near bed shear velocities are large. After subtracting u^2_{*Wave} from the total shear velocity, the residual friction velocities are essential constant over the vertical. The detailed bottom profile at station 5 shows the bottom is composed of mega-ripples with heights of approximately 15cm and wave lengths of about 1m (Figure 7). The location of the CASP is at the vertical dotted line and unfortunately information right beneath the CASP is not available. The mean slope is indicated and it can be seen that is can be quite different that the local slope near the bed as indicated by the tilt values calculated in Figure 6.

Conclusions

The total near-bed friction velocity is viewed as the sum of the friction velocity associated with the turbulent Reynolds' stress and a wave friction velocity induced by the sloping bed. The friction velocity is calculated by minimizing the co-spectra to eliminate the contribution by the horizontal wave velocity acting on the bed to induce an in-phase vertical velocity which contributes to the co-spectrum. The horizontal scale of the bed slope which induces the near-bed vertical velocity due to the waves appears to be related to the distance from the bed. Where a multitude of scales exist very close to the bed, such as when mega-ripples are present, the local bed slope (horizontal scale < 1m) appears to dominate, whereas away from the bed the corresponding bed slope can be much larger. For a smooth, near-planar bed, all horizontal scales have essentially the same slope.

The wave-induced friction velocity is largest near the bed and decreases toward the surface, which agrees with the theoretical work of Rivero and Arcilla (1995). The wave-induced velocity near the bed can be much larger than the turbulent Reynolds' stresses.

Acknowledgments

This work was funded by the Office of Naval Research, Coastal Sciences Branch under contract N00114-95-AF-002. The authors wish to express their appreciation to all those who participated in DUCK94 experiment, particularly the staff of the U.S. Arm Field Research Facility under the direction of B. Birkemeier. In addition, special appreciation is expressed to R. Wyland and J. Stockel for their roles in the acquisition and analysis of the data.

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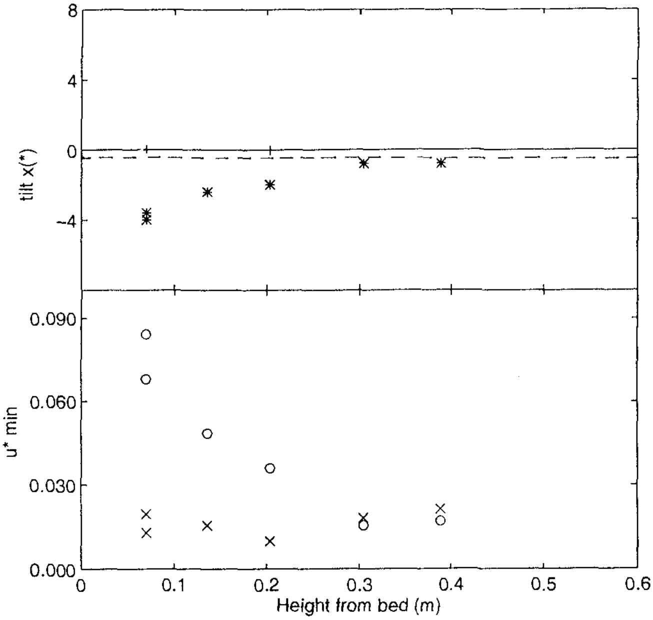

Figure 7. Vertical profiles of cross-shore (x) rotation angles to minimize co-spectra (*) compared with average slope over 5m (-) (upper panel), and total friction velocity (o) and friction velocity in bed normal coordinates (lower panel), Station 5.

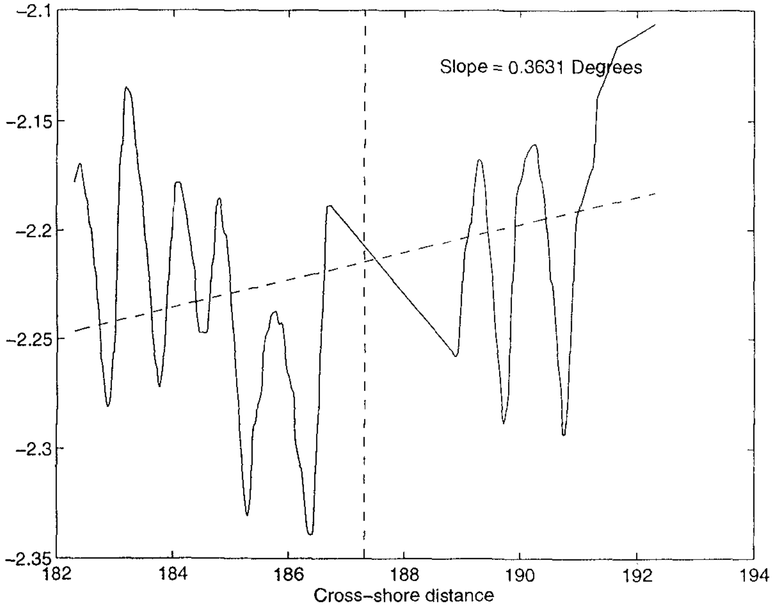

Figure 8. Bottom profile showing mega-ripples superposed on a mean slope (averaged over 5m) of 0.36 degrees.