CHAPTER 267

TURBULENT STRESSES IN THE SURF–ZONE: WHICH WAY IS UP?

John W. Haines[1] and Guy Gelfenbaum[1]

Abstract

Velocity observations from a vertical stack of three-component Acoustic Doppler Velocimeters (ADVs) within the energetic surf-zone are presented. Rapid temporal sampling and small sampling volume provide observations suitable for investigation of the role of turbulent fluctuations in surf–zone dynamics. While sensor performance was good, failure to recover reliable measures of tilt from the vertical compromise the data value.

We will present some cursory observations supporting the ADV performance, and examine the sensitivity of stress estimates to uncertainty in the sensor orientation. It is well known that turbulent stress estimates are highly sensitive to orientation relative to vertical when wave motions are dominant. Analyses presented examine the potential to use observed flow-field characteristics to constrain sensor orientation. Results show that such an approach may provide a consistent orientation to a fraction of a degree, but the inherent sensitivity of stress estimates requires a still more restrictive constraint. Regardless, the observations indicate the degree to which stress estimates are dependent on orientation, and provide some indication of the temporal variability in time-averaged stress estimates.

Introduction

Few observations of turbulent stresses in energetic surf–zone conditions exist. This observational void is in marked contrast to modeling efforts describing surf–zone circulation. Published models include details of the stress distribution which have yet to be constrained by field observations (*Svendsen et al.*, 1987, *Deigaard et al.*, 1991). Moreover, investigations of nearshore circulation have suggested that simpler (constant eddy viscosity) models of the stress distribution may be inconsistent with field observations of the mean flow field (*Haines and Sallenger,* 1994).

[1]U.S. Geological Survey, Center for Coastal Geology, 600 4th St. South, St. Petersburg, FL, 33701

In an attempt to better constrain modeling efforts, a field program was designed to collect data on the vertical and temporal distribution of turbulent stresses within the surf-zone. As part of the Duck94 field program a vertical array of SonTek Acoustic Doppler Velocimeters (ADVs) was deployed and 24 days of nearly continuous data collected (Figure 1). The principle aim of the deployment was to return observations of the high-frequency intermittent phenomena associated with bottom and surface boundar–layer processes. The objective was to accurately describe the turbulent statistics of the flow-field adjacent to both boundaries under breaking and non-breaking wave conditions.

A critical requirement for the calculation of stress estimates is the precise definition of an appropriate coordinate system. Because of the relatively large horizontal flows associated with shallow–water incident waves, stress estimates are inherently sensitive to the choice of a vertical coordinate. Previous work has suggested that, under representative incident wave conditions, a precision of 0.03 degrees is required in definition of the tilt angle to assure stress estimates are correct within $1 cm^2 s^{-2}$ (*Lohrmann et al.*, 1995). The appropriate coordinate system may depend on the modeling approach taken. For example, a gravitational coordinate system may produce results significantly different than a coordinate system aligned with the local bed slope. In the absence of field observations of the magnitude and variability of the stresses, the precision required for array design is speculative. Observed variability also provides an indication of the sensitivity of results to the choice of coordinate frame.

The ADV array deployed was instrumented with a continuously recording tilt-meter. Subsequent analyses suggest that the tilt–meter lacked the required accuracy for definition of a reliable coordinate system. Given the shortcomings of the tilt measurements, and the sensitivity of stress estimates to tilt, we are investigating the potential for using the flow data itself to determine an appropriate coordinate system. Regardless of the success of this effort, the data also provides a means for investigating the sensitivity of field observations to deviations from the vertical. The observations will also provide some indication of the magnitude of the temporal and spatial variability of surf-zone stresses.

Data

As part of the Duck94 experimental program, a vertical stack of Sontek ADVs was deployed at the US Army Corps of Engineers (ACOE) Field Research Facility (FRF) in Duck, NC. The deployment consisted of 7 ADV sensors in a vertical array, with supplementary observations of water level, optical backscatterance, array tilt and rotation, and bed elevation from a sonic altimeter (Figure 1). All sensor outputs were digitized *in situ*, synchronized via GPS clock, and written to shore-based storage via a fiber optic cable. The ADVs were sampled at 25 Hz. All other sensors were sampled continuously at $64 Hz$. The ADV distribution was intended to span the bulk of the water column and return observations of near-bed and near-surface turbulent fluctuations.

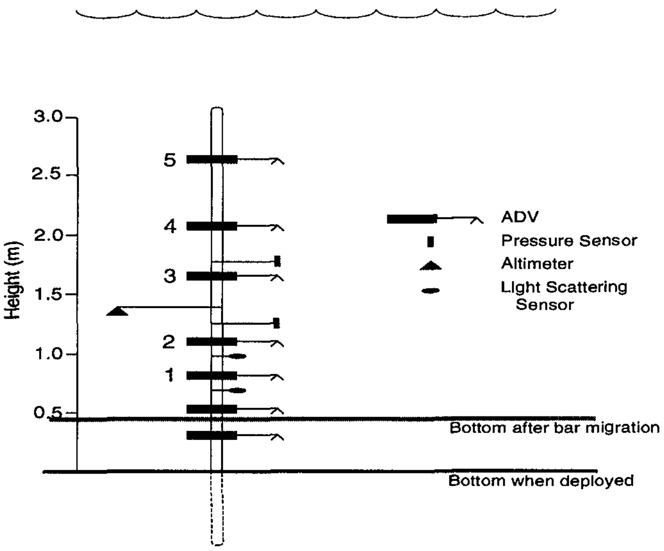

Figure 1: Array configuration. Bed height determined from altimeter is approximately $1m$ from ADV position. ADV sensing volumes are $15cm$ below the sensor heads shown.

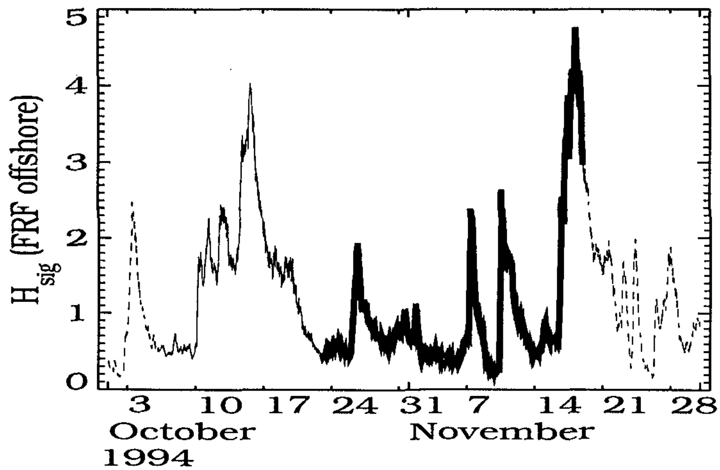

Figure 2: Offshore significant wave heights from the Field Research Facility pressure array in $8m$ water depth. Solid lines indicate period of sensor deployment, thick solid line shows period of data recovery.

The array was initially deployed in approximately 4.5m water depth, outside the primary bar normally present at the Duck site. Subsequent to deployment, an energetic storm event (October 16-18th, Figure 2) resulted in substantial bar migration, burying the lowermost ADV and obscuring the sampling volume of the next highest sensor. The following weeks saw a slow erosion of the bar, and the upper impacted sensor eventually began to return data. Figure 2 shows the offshore wave conditions present throughout the deployment. The deployment spans 3 substantial storm events, and only data from these events, where the array was within the surf zone, are discussed in the following. Discussion is further limited to those 5 sensors which were continuously operational. The deployment was violently terminated by surf-zone debris associated with the passage of Hurricane Gordon.

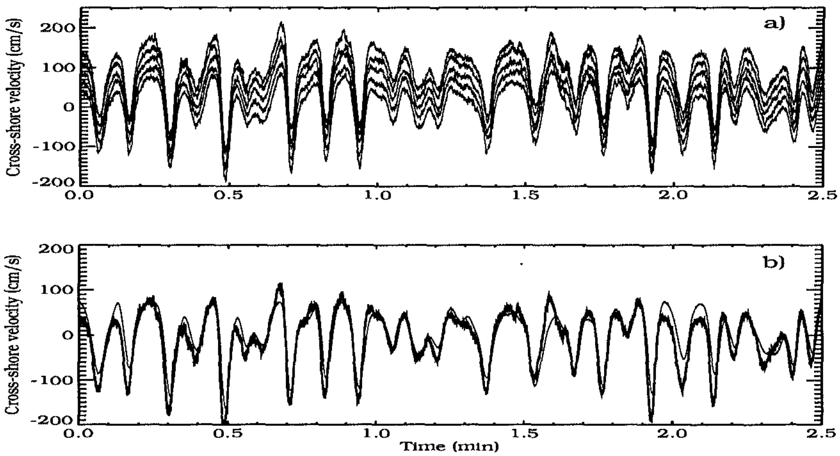

Figure 3: a) Time series from ADV sensors, offset to indicate increasing height above the bed. b) Time series from uppermost ADV and pressure sensor (normalized by velocity variance).

The data quality from the ADV sensors appears to be uniformly good. Figure 3a shows representative data from the 5 operational ADV's, demonstrating extremely high coherence between sensors across the incident wave band. Independent verification of sensor performance is given by comparison to the water level data (as shown in Figure 3b.) Depth decay of the incident-band velocities are consistent with linear theory, supporting the overall data quality. Visual inspection of the data suggests that high-frequency variance "events" occur with greater frequency high in the water column. This may be suggestive of breaking–produced turbulence, and is an area for further investigation.

The data are further described in Figure 4a, showing cross-shore, u, and vertical, w, velocity spectra (Figure 4a). Above incident–band frequencies the

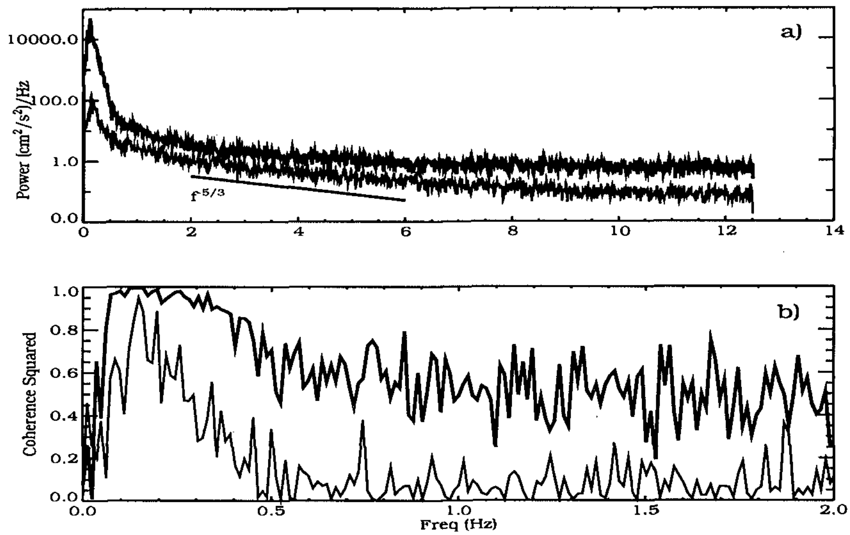

Figure 4: a) u (higher energy) and w spectra. b) pu (thick line) and pw squared coherences. Frequency scales are not equivalent for the two panels. Data shown are post–rotation as determined by the analysis described herein.

spectra show an $f^{-5/3}$ decay. The horizontal velocities generally show enhanced energy levels relative to the vertical velocities at all frequencies. The leveling of spectral energy at high frequencies for the horizontal velocity is due to the noise-floor of the sensor, which is substantially reduced for the vertical component. Coherences between pressure observations, p, and horizontal velocities are high across the incident band and uniformly higher than pw coherences.

Analysis

While the data appear reliable, calculation of the turbulent stresses requires accurate constraint of the coordinate frame. In the following we will attempt to determine the sensor orientation from the observed flow characteristics. In order to maximize the signal-to-noise ratio of the data, further analysis is restricted to high-energy conditions. Selected one–hour data segments, described in Table 1, were analyzed.

The underlying assumption for the following analysis is that the flow field, as described by the observations, contains information about the sensor orientation. A plausible first assumption might be that, following linear wave theory over a horizontal bed, within the incident-wave band, vertical and horizontal velocities are in quadrature. It follows that the time-averaged stress, $\langle uw \rangle$, should be zero. We might then choose to rotate the observations into a coordinate frame where this criteria is met. For a sloping bed, the result is rotation into a bed-normal

Run #	Date	Time UTC	Depth m	H_{rms} m	T_p s	bed ht. m
0	10/26	13:00	4.49	.81	4.9	.25
1	10/26	15:00	4.78	.92	5.3	.26
2	10/26	19:00	4.54	1.21	6.1	.27
3	10/26	21:00	4.20	1.21	6.4	.26
4	11/7	08:00	3.50	.55	12.8	.35
5	11/7	09:00	3.65	.68	11.6	.36
6	11/7	10:00	3.77	.79	11.6	.37
7	11/7	11:00	4.18	1.14	11.6	.38
8	11/7	12:00	4.52	1.29	11.6	.39
9	11/7	13:00	4.80	1.38	6.4	.41
10	11/7	16:00	4.90	1.60	7.5	.42
11	11/7	17:00	4.69	1.35	7.5	.37
12	11/7	22:00	3.80	.99	11.6	.38
13	11/8	14:00	4.73	.62	11.6	.48

Table 1: Summary statistics for analyzed runs. All quantities are from array observations of surface water level and bed elevation. Bed height is distance beneath lowermost operational sensor. Sensor height for remaining sensors are, relative to lowermost sensor, 20.8 cm, 86.4 cm, 130.1 cm, 189.4 cm.

coordinate system, or more correctly, rotation into a wave-defined coordinate system. Alternative criteria for determination of the coordinate system might include rotation to zero mean vertical velocity, $\langle w \rangle = 0$, or minimization of the vertical variance, $\langle ww \rangle$. The $\langle w \rangle$ criteria would follow on assuming that mean flows were constrained to be bed–parallel. The validity of this assumption may vary with distance from the bed. In all cases the resulting coordinate frame may be expected to reflect the influence of a sloping bed. It is of interest to examine whether variations on the order of the bed slope significantly change the estimated stress quantities.

The rather simplified view outlined supports a variety of approaches for determining a best rotation. The assumption that relevant information is contained in the wave–driven flow requires application of any methodology across some subset of the entire frequency range sampled. Any of the above criteria might be applied, singularly or in a weighted combination. The assumption of uw–quadrature further supports minimization of a number of co–spectral quantities across the frequency band of interest. In fact, any of the variance properties $(\langle uw \rangle, \langle ww \rangle)$ may be minimized as band-averaged quantities, or minimized frequency band–by–band in a least–squares sense across the entire frequency range of interest.

A number of candidate criteria were tested. The "best" criteria were determined by the consistency of the resulting coordinate system. This is based on the necessary assumption that the array was stationary throughout the data examined. Here the deposition of approximately 50cm of sand associated with the bar migration may be viewed as a benefit. This deposition, we presume, further stabilized the array, reinforcing the stability properties provided by a deep central jetted pipe and three anchored guy wires. A further assumption is that the coordinate frame, as defined by the flow, is stationary. This assumption is invalidated by any significant change in the underlying bed topography.

Among all the criteria tested the most consistent results were achieved by constraining the mean vertical velocity to be zero ($\langle w \rangle = 0$) and minimizing the vertical variance subject to this constraint. The minimization requires selection of a frequency band of interest, and it is the band–averaged variance which is ultimately minimized. Variations arising from this selection will be discussed in the following.

The constraint of $\langle w \rangle = 0$ defines a functional relationship between the two tilt angles given by $\gamma = f(\beta)$, where γ is the tilt angle in the alongshore/vertical (yz) plane, and β is the tilt angle in the cross-shore/vertical (xz) plane. The search for $\langle ww \rangle = \min$ may then be restricted to the line in $\gamma\beta$ space defined by the $\langle w \rangle$ constraint.

The shore–normal horizontal coordinate frame chosen approaches, for the nearly shore–normal wave conditions examined here, a frame oriented with the principle component of the wave velocities. As a result, as will be shown, the tilt angle, β, in the shore–normal direction is strongly constrained by the energetic wave motions, while the γ solution, subject to less energetic wave motions, is less well defined. Conversely, small variations in β have a large (relative to γ) impact on the estimated stresses. The alongshore component of the system is dominated by the strong alongshore currents present during most of the runs analyzed. The mean currents influence the rotation through the $\langle w \rangle = 0$ constraint.

This approach to determining a coordinate frame implies a further, less obvious constraint. The minimization procedure ($\langle w \rangle = 0, \langle uw \rangle = \min$) is equivalent to constraining the stress terms, $\langle uw \rangle$, to be zero. We do not expect this constraint to be strictly valid, due to system noise and the influence of "non–wave" motions. Nonetheless, the results provide the greatest consistency in determination of sensor tilt. While it might be hoped that averaging the results over several data segments might reduce the effects of such contamination, it is equally (or more) likely that this procedure has a systematic bias in the tilts determined.

The minimization procedure was applied to the data subsets described in Table 1. Stable estimates resulted only when conditions were energetic, suggesting the wave signal must exceed some "noise" level in the data (where noise may include a variety of non–wave motions as well as system or random noise). Further examination indicated that the stability of the estimates was enhanced when the incident wave field was narrow–banded in direction. The stability of the tilt estimates was determined from the variance of the estimates from segmented runs. While variability in the results increased with decreasing wave height,

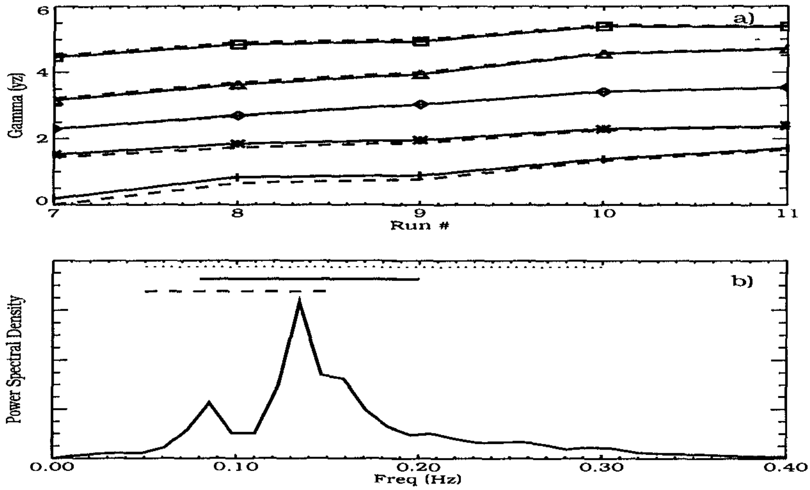

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Figure 5: a) Resulting best γ (tilt in yz plane) values for 1 hour data runs. Values offset to indicate sensor location. Line types indicate the frequency range of the solution. b) Representative cross-shore velocity spectrum and frequency range of solutions (shown by horizontal lines).

there was no significant change in the mean values determined. The final values determined are consistent with the data from the tilt sensor, though this provides constraint within only a few degrees.

Determination of the best rotation in the following is restricted to data Runs $7 - 11$ (Table 1) which are relatively continuous in time and subject to energetic incident wave conditions. In fact, all runs listed are well within the surf–zone. Only beneath breaking waves were conditions energetic enough to result in stable estimates. The impact of breaking wave conditions on the approach can not be assessed as non–breaking conditions with large waves were not observed.

Results

Results for the γ (yz plane) tilt determination are shown in Figure 5a. The minimization was applied over three separate frequency bands as shown in Figure 5b. For determination of γ the results are insensitive to the frequency band chosen. The best γ values resulting show significant variance and a marked trend with time. While the variance in γ is large, the relatively modest amounts of incident wave energy in the along-shore direction results in little effect on calculated stress quantities.

Determination of β, in the plane of maximum wave orbital motions, has a far greater impact on stress calculations. Figure 6 shows that while the overall variance in the estimated orientation is reduced relative to γ, the sensitivity to

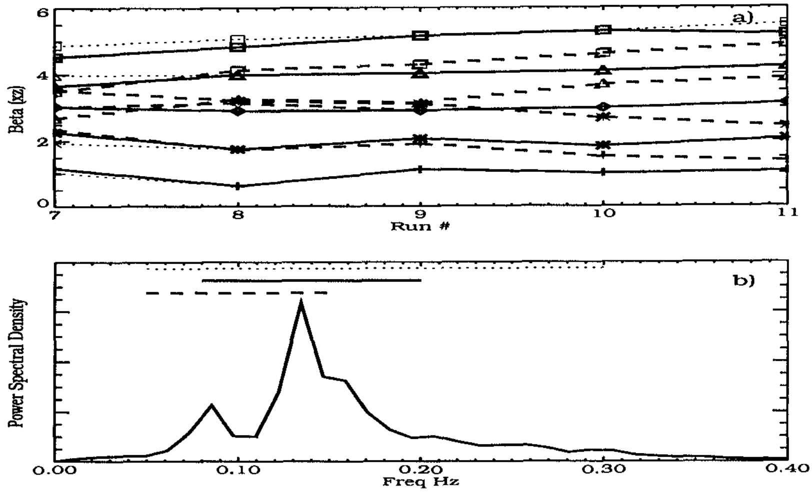

Figure 6: a) Resulting best β (tilt in xz plane) values for 1 hour data runs. Values offset to indicate sensor location. Line types indicate frequency range of solution. b) Representative cross-shore velocity spectrum and frequency range of solutions (shown by horizontal line).

frequency band selection is increased. Stable estimates require a choice which encompasses the entire incident band, and stability is further enhanced by inclusion of the higher harmonics. This is a somewhat problematic finding. Ideally we would like to determine orientation using an approach independent of information in the higher turbulent frequencies.

The standard deviations of the β values found for the 5 runs are shown in Table 2. The variance reduction with increasing frequency range is clear. There is also an indication that the upper and lower sensors are less well constrained. This is consistent with enhanced turbulence generation at the boundaries (reducing the wave signal relative to other motions) or may suggest some deviation from linear-wave behavior near the free-surface and bed. Overall, consistent tilt estimates are found to within half a degree (2 standard deviations) for all sensors.

Discussion

The mean tilt values from the 5 runs described were applied to correct all the data. The resulting vertical velocity spectra and uw coherences are shown in Figure 4. Vertical velocity variances are substantially reduced relative to the unrotated data, as are uw coherences; suggesting a removal of wave fluctuations from the vertical component. The data still show marked spectral and coherence peaks in the incident wave band. The method applied minimizes the w-variance across the entire band. Peak removal is somewhat enhanced if the variance mini-

Std. deviation β (degrees)			
Sensor #	Low Freq.	Incident	Broad band
5	.53	.32	.23
4	.47	.29	.10
3	.10	.09	.09
2	.44	.20	.14
1	.38	.22	.20

Table 2: Standard deviation of β values determined over 5 runs analyzed. Values are shown (in degrees) for frequency ranges indicated in Figure 5b.

mization is applied in a least–squares sense, band–by–band, across the frequency range selected. Results from this approach are comparable, though somewhat more variable.

The approach followed here is based on some general assumptions about the frequency contribution to the stress. Figure 7 describes this contribution, and the effect of rotation. The figure shows the cumulative stress as higher frequencies are included in the stress calculation. Shown are the results for the best orientation determined previously (averaged over 5 runs), and rotations representive of ± 0.2 and ± 0.4 degrees in γ and β. The solid horizontal line shows the frequency range for which the tilt angles are determined. The best rotation for this run (as opposed to the best average rotation) would result in the intersection of the cumulative stress curve and the high–frequency end of the frequency range. The case shown is a worst case result, serving to illustrate the sensitivity of the stress to relatively small changes in tilt.

The total stress is given by the high–frequency end of the cumulative stress curve (flat beyond the limits shown). It is clear that the resulting estimates are highly sensitive to the tilt. Furthermore, the stress is completely specified to a high degree by frequencies lower than $0.5Hz$. This result is independent of uncertainties in the orientation. Also of note, the resultant stresses change in a near–linear fashion with orientation, with the rate of change fairly constant for all sensors. This implies that, though absolute values of the stress may be highly sensitive to orientation, temporal and spatial trends (between-sensor variability) may be more amenable to observation.

For the sensor and data run shown the "best" average rotation results in a flattening of the cumulative stress curve across the incident band. In contrast, the best solution specific to this run and sensor (approximated by the lowermost cumulative stress curve) shows stress contributions which cancel within the incident band. This cancellation of regions (in frequency) of opposing stress is common to all the runs examined. A more rigorous approach will require a more complete consideration of this structure and the indicated physics of incident–band motions.

Overall the message from Figure 7 is rather disheartening. The suggestion

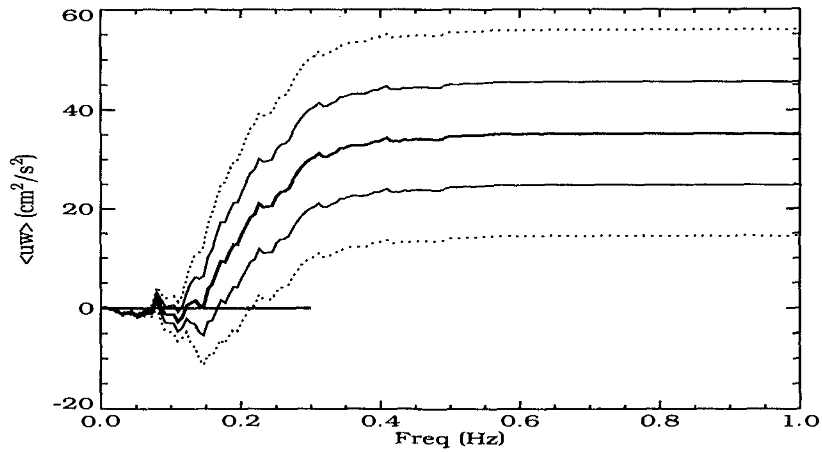

Figure 7: Cumulative stress plots for representative time series. Results from best rotation (thick line), plus (minus) 0.2 degrees in γ and β are given by upper (lower) solid lines, plus (minus) 0.4 degrees in γ and β are given by upper (lower) dotted lines.

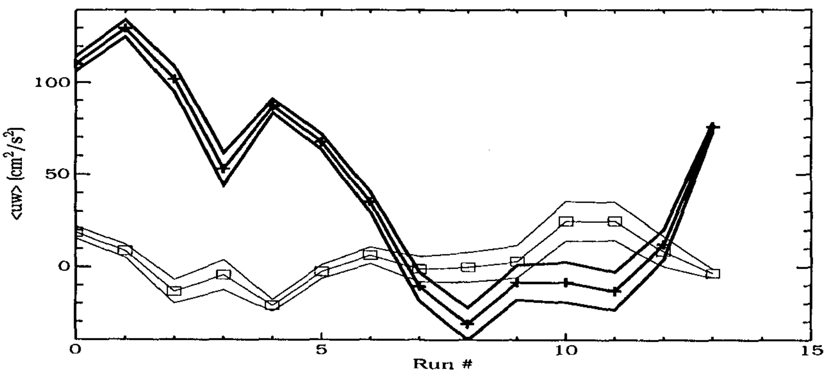

Figure 8: Stress estimates for all runs for uppermost (thin) and lowermost (thick) sensors. Error bounds indicated represent $\pm$ 2 standard deviations in γ and β.

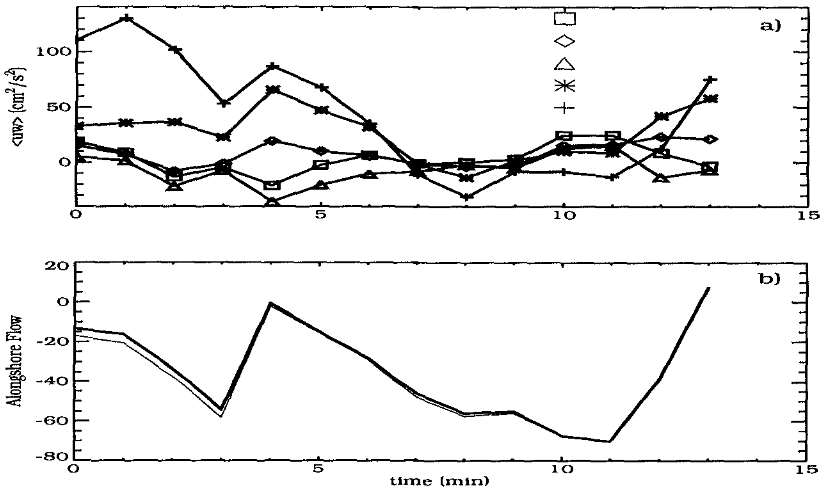

Figure 9: a) Estimated stresses for all sensors. Sensor location indicated by symbols. b) Variation in alongshore mean current for uppermost (thin line) and lowermost (thick line) sensors.

is that the most consistent results require utilization of flow information across the entire frequency band responsible for the observed stresses. There is no clear indication that the wave band is, in fact, independent of some turbulence band which contributes significantly to the stress.

The stresses resulting from the top and bottom sensors are shown in Figure 8. Calculations have been extended to incorporate all the data from Table 1, applying the best rotation as found for the 5 runs (7 – 11) previously discussed. While we believe the array was stationary across the entire period, we can not demonstrate this to the level required and the data must be viewed with some skepticism. Indications are that the near surface stress is much less variable than that near the bed. The effects of significant changes in bed elevation may be contributory. Estimates show changes in sign for both sensors, and changes in relative sign between sensors. The degree of temporal variability is large near the bed and suggests that observational efforts, with orientation precision of order 0.2 degrees are feasible. Some credibility is added to these results as both the bottom two sensors show marked temporal variability relative to the uppermost sensors (Figure 9a).

The temporal variability noted may be related to both changes in bed elevation and changes in the fluid forcing. The mean alongshore flow was highly variable across the runs examined. Figure 11b shows this variability, which is qualitatively similar to that observed for the stress estimates in the lower water column. The temporal trend in γ previously shown (Figure 5) is strongly correlated with the

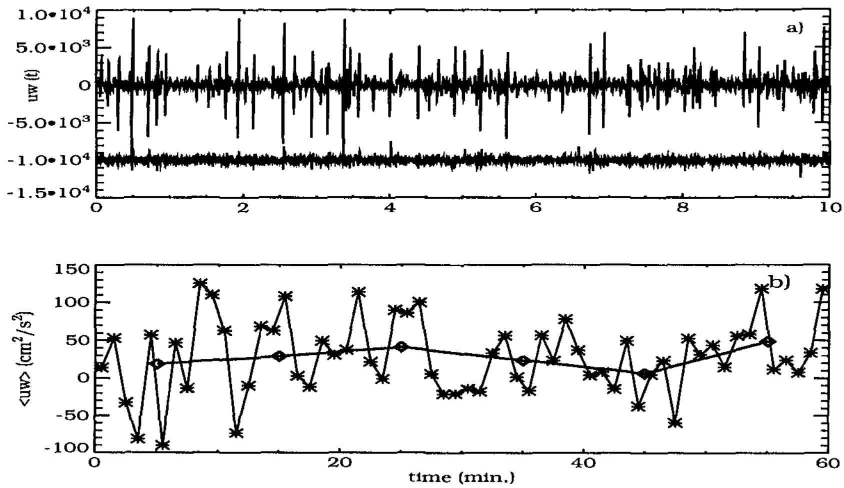

Figure 10: a) Instantaneous stress (uw) for uppermost and lowermost (offset by -10^{-4}. b) One and ten minute averages of stress from uppermost sensor.

variability in the alongshore current.

As a final note we leave the rotation problem behind to examine the variability of the stress estimates on short time scales. Figure 10a shows time series of stress from the uppermost and lowermost (offset by -10^{-4}) sensors. The degree of variability in the instantaneous stresses is elevated near the free surface, in constrast to the behaviour previously shown for time-averaged values. Averaged values (1 and 10 minute averages, Figure 10c) from the uppermost sensor clearly show that, over 10 minute periods, the stress estimates display substantial temporal variation.

Conclusions

First and foremost, precise sensor orientation is critical to estimating the absolute magnitude of turbulent stresses. Observed sensitivity to variations in tilt suggests that a precision of order 0.1 degrees in the vertical is required. Flow derived orientations are consistent to roughly 0.4 degrees. This level of precision appears to be sufficient for investigations of the temporal and spatial variability in stress estimates in at least some cases. The lack of a clear physical underpinning for the resulting coordinate frame limits further application of the results. The sensitivity of the results to orientation further suggests that consideration of bed slope effects may be required.

The observations demonstrate that stress estimates are highly variable across a variety of temporal scales. The bulk of the stress is generated by motions at frequencies approaching the incident band fundamental and harmonic frequencies.

The separation of motions into turbulent and wave–driven components is dubious when based solely on the frequency characteristics of the data.

Acknowledgements

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References

Deigaard, R., P. Justesen, and J. Fredsoe, Modelling of undertow by a one-equation turbulence model, *Coastal Eng.*, 11, 565–602, 1987.

Haines, J. and A. H. Sallenger, Vertical structure of mean cross-shore currents across a barred surf zone, *J. Geophys. Res.*, 99, 14,223–14,342, 1994.

Lohrman, A., R. Cabrera, G. Gelfenbaum, and J. Haines, Direct measurements of Reynolds stress with an acoustic doppler velocimeter, *Proceedings IEEE Fifth Workshop on Current Measurements*, 205–210, 1995.

Svendsen, I., A. Hemming, and J. Buhr Hansen, The interaction between the undertow and the boundary layer flow on a beach, *J. Geophys. Res.*, 93, 11,845–11,856, 1987.