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Quality control of acoustic Doppler velocimeter data in the surfzone

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Abstract
Acoustic Doppler velocimeter measurements in the surfzone can be corrupted by bubbles and suspended sediment, lack of submergence during the passage of wave troughs, biofouling, blockage (e.g., from kelp on instrument mounting frames) of the flow field near the current meter or of the path between the sampled fluid volume and the acoustic transducers, and by insufficient distance between an accreting seafloor and the sample volume. Individual bad acoustic Doppler velocity values can be detected (and subsequently replaced) from low along-beam signal-to-noise ratios and from low coherence between successive acoustic returns used to estimate velocity. In addition, corrupted data runs can be identified from ratios of pressure to velocity variance that deviate from linear theory, and from low coherence between time series of collocated pressure and wave-orbital velocities. Unmeasured vertical tilts of a current meter can be estimated from horizontal and vertical velocities, and corrected for numerically.

Keywords: acoustic Doppler velocimeters, data quality, surfzone instrumentation, surfzone waves and currents

1. Introduction

Acoustic Doppler current (ADV) meters perform well in laboratory flumes (Kraus *et al* (1994), Voulgaris and Trowbridge (1998), and references therein), in the deep ocean (Andersen *et al* (1999), Gilboy *et al* (2000) and references therein), and in the surfzone (Elgar *et al* 2001). Although ADVs provide accurate estimates of water velocities, significant post-processing of the acoustic returns may be required to ensure high-quality data. Biofouling or detritus can block the acoustic beam path, and weak scatterers in clear water can reduce the return-signal strength to the level of background noise. The difficulty of quality control of ADV velocity estimates is exacerbated in the surfzone, where bubbles and suspended sediment from breaking waves can corrupt acoustic returns, the transmit and receive transducers can come out of the water at low tide or during the passage of wave troughs, and seafloor accretion can create bottom-proximity effects.

Here, quality control procedures developed during several field experiments, in which more than 75 ADVs were deployed for different periods totalling more than 11 months (almost 80 000 h of current meter data), are described. The criteria used to accept or reject data are a compromise that balances accepting some questionable data with rejecting good data. Thus, for a given velocity time series, some quantities (e.g., mean currents) may be accurate, while estimates of other quantities (e.g., wave directional spreads, which depend on orbital velocities) may be corrupted because portions of the data record are noisy. The criteria presented here have been used to guide automatic quality control of acoustic Doppler velocity data obtained in the swash- and surfzones. Closer inspection to identify good and bad sections of retained data runs may be necessary in some cases.

2. Instrumentation

The data used here were collected nearly continuously at sample rates from 2 to 16 Hz during several field experiments and instrument tests (http://science.whoi.edu/users/elgar/main.html). During XTREE, cabled-to-shore acoustic Doppler, acoustic travel time and electromagnetic current meters were collocated in about $h = 300$ cm water depth for 3 weeks (Elgar *et al* 2001). During SwashX, 11 cabled-to-shore ADVs were deployed for 3 weeks along a cross-shore transect extending from the shoreline to about $h = 300$ cm (Raubenheimer 2002). During BSRIP, four cabled-to-shore ADVs were arranged in a 300 cm long along-shore array at the outer edge of the surfzone ($h = 400$ cm) for 8 months (burial by a migrating sandbar in the middle of the deployment reduced data return to about 4 months, but did not affect post-burial data quality) (Trowbridge and Elgar 2003). During NCEX, 40 cabled-to-shore and 17 stand-alone (battery powered) ADVs were located in the swash- and surfzones ($0 < h < 500$ cm) for 7 weeks. Additional instrument tests included collocated electromagnetic and acoustic Doppler current meters deployed in the swash- and surfzones, and on the inner shelf. Mean currents, wave-orbital velocity frequency spectra, velocity skewness and asymmetry, and mean wave direction and directional spread estimated with the collocated current meters were compared with each other, and with linear theory.

A wide range of wave and current conditions was observed during these deployments. Offshore incident significant wave heights ranged from 20 to 300 cm, with peak periods from 5 to 20 s. Wave heights in the swash- and surfzones often were limited by breaking. Maximum 3072 s mean cross-shore, along-shore and vertical currents were approximately 75, 150 and 5 cm s^{-1}, respectively, and instantaneous horizontal velocities exceeded 300 cm s^{-1}.

The cabled-to-shore acoustic Doppler current meters were mounted on frames held in place with pipes inserted (using a water jet) into the sandy seafloor. In the surfzone, three-dimensional (3D, three components of velocity are estimated) SonTek Ocean probes were mounted looking up or down (vertical), and in the swashzone 3D SonTek Field probes were mounted looking down and 2D (two velocity components) SonTek Cable probes were mounted looking sideways (horizontal, so horizontal velocities are measured) (figure 1). The current meters were fixed to telescoping shafts to allow vertical adjustments by SCUBA divers to keep the sample volumes as close as possible to a specified distance above the evolving seafloor (usually 50 cm for downward looking sensors in the surfzone, and 2–10 cm for sensors in the swashzone). A ParoScientific pressure gauge was deployed at each frame, usually buried under approximately 10 cm of sand to prevent flow noise (Raubenheimer *et al* 1998). The frame-mounted ADVs do not contain a tilt sensor, but the ADV data can be used to detect (and correct for) cross-shore tilts (see the appendix). The stand-alone ADVs (SonTek Tritons and NorTek Vectors, both with built-in pressure gauges, compasses and tilt sensors) were mounted on single pipes (upward looking for ADVs deployed seawards or within the surfzone) or on cantilevers attached to single pipes (downward or sideways looking in the swash- and inner-surfzones).

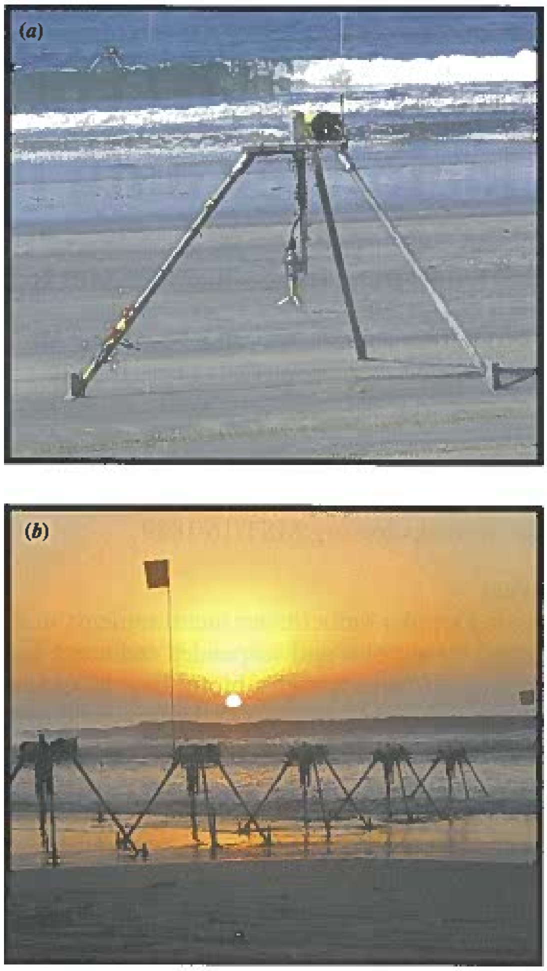

Figure 1. Photographs of (*a*) a SonTek Ocean ADV mounted looking downward on a tripod at low tide (the top of a second tripod can be seen beyond the breaking wave) and (*b*) a cross-shore transect of five tripods, each with a vertical stack of three sideways-looking SonTek Cable probes. Electronics are housed in the cylinders on top of the tripods to reduce flow blockage, with cables routed along a tripod leg (to be connected to cables from shore-based data acquisition systems).

3. Quality control criteria

Acoustic Doppler current meters transmit short acoustic pulses that are backscattered by reflectors within the fluid sample volume, and subsequently are received by the instrument. For the parameters used here, the 3D and 2D acoustic Doppler current meters measure the velocity within an approximately 1 to 2 cm long, 1 cm diameter cylindrical sample volume centred from 5 to 20 cm (depending on the sensor pulse frequency and configuration) from the (collocated) transmit and receive transducers. Using information about the instrument orientation and measurements along acoustic beams, the average phase differences between successive returns are converted into cross-shore, along-shore and vertical velocities (Lhermitte and Serafin (1984), Cabrera *et al* (1987), Brumley *et al* (1991), Lhermitte and Lemmin (1994), Zedel *et al* (1996), Voulgaris and Trowbridge (1998) and references therein). To avoid ambiguities associated with phase differences greater than 2π, the ADVs used a velocity range of $\pm$ 500 cm s^{-1}, which is greater than the expected maximum velocities of less than 400 cm s^{-1}.

3.1. Low return-signal strength

Accurate ADV estimates require that the strength of the received backscattered signal exceeds the system noise. The backscattered signal amplitude or the signal-to-noise ratio (SNR), reported for each ADV beam, is used for quality control. Although usually there are sufficient scatterers (e.g., bubbles, suspended sediment) in the surfzone to ensure strong reflections, low SNRs will result if the sensor is not submerged during low tide or the passage of wave troughs, or if the acoustic beam is blocked (e.g., by transducer biofouling, kelp or flotsam). In addition, bubbles can absorb or scatter the acoustic signals. However, the data suggest that SNR reductions caused by bubbles are small, at least for the relatively high power, cabled-to-shore sensors. To reject inaccurate data from sensors expected to be submerged, runs are discarded if more than 0.81% of the values (25 times the sample frequency for the 3072 s long (approximately 1 h) records used here) have low signal-to-noise ratios. This empirical criterion is a compromise that retains time series that appear to be high quality except for a few low SNRs, while rejecting time series that may have corrupted sections. Alternatively, for sensors expected to be submerged intermittently (e.g., in the swash or above wave troughs), velocities can be set to zero for data points with low SNR. In these cases, additional quality control may be required to detect low SNR caused by blockage of the acoustic path. The thresholds used here (signal amplitude < 100 for SonTek Ocean probes, SNR < 4 for SonTek Tritons, and SNR < 8 for NorTek Vectors) are based on manufacturer's recommendations and on comparisons with collocated pressure sensors, which can be used to determine water depth at the current meter, providing an independent estimate of time periods when the ADV sample volume is not submerged.

3.2. Low along-beam correlations

Inaccurate velocity estimates can result if there are returns from different scatterers within the pairs of acoustic pulses used to estimate the Doppler shift (Cabrera *et al* 1987), if excessive scatterers near the sample volume reflect acoustic side-lobe energy (Voulgaris and Trowbridge 1998), or if the sample volume of downward looking sensors is too close (less than about 10 cm for 3D SonTek Ocean probes) to the seafloor. In these situations, correlations between successive returns are low, and the along-beam correlation averaged over the sample period (reported by the ADVs) can be used to identify and subsequently replace potentially inaccurate data points. The size of statistical fluctuations is approximately inversely proportional to the square root of the number of pulses per sample (i.e., proportional to the square root of the sample frequency s_f) (Jenkins and Watts 1968). The correlation threshold used here for swash- and surfzone data (see Elgar *et al* (2001) for additional details) is $0.3 + 0.4\sqrt{s_f/25}$, which decreases as $\sqrt{s_f}$ from the recommended (SonTek 1995) values of 0.7 for $s_f = 25$ Hz. Sequences of samples less than 1 s duration that fall below the threshold are replaced with values linearly interpolated between velocities before and after the incoherent sequence. Although individual returns may be noisy, they are unbiased, and thus sequences of incoherent values longer than 1 s duration are replaced with a 1 s running mean of the values (figure 2). The 1 s window duration was determined empirically from comparisons with other types of current meters collocated with the ADVs (Elgar *et al* 2001).

The number of points with low correlations is not used as a criterion for rejecting data runs, because of the variable quality of time series with similar numbers of replaced (low correlation) points. Although time series rejected using other criteria (described below) often have many (replaced) points with low correlations, some accepted time series also have many replaced points. Of approximately 20 000, 2 Hz, 3072 s long time series obtained with 3D ADVs in roughly 1.0 and 2.5 m depths in NCEX that passed all quality control criteria, 72% had fewer than 1% low correlations, 84% had fewer than 5% low correlations, and 99% had fewer than 50% low correlations. Retained records with the highest number of low correlations were from the inner surfzone. A section of velocity time series from the mid surfzone for a 3072 s data run with 2% low correlations that passed the quality control criteria is shown in figure 2(*a*), and time series from an inner surfzone data run with 68% low correlations that was rejected are shown in figures 2(*b*) and (*c*). The rejected data run barely fell below quality control thresholds, and thus is not dissimilar from some accepted time series. For data runs passing the quality control criteria, additional inspection may be required to identify noisy subsections of the time series that may not be suitable for some purposes.

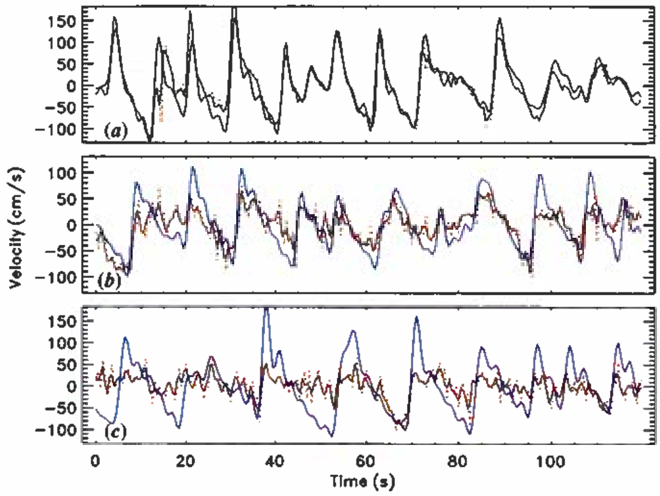

Figure 2. Cross-shore velocity before (red dotted curves) and after (black curves) individual points with low correlations were replaced, and pressure converted (using linear finite-depth theory) to equivalent velocity (blue curves) versus time. (*a*) Data from 1.5 m water depth that passed the quality control criteria. (*b*), (*c*) Data from 1.0 m water depth (directly onshore of those shown in (*a*)) that failed (barely) the quality control criteria. There are fewer points with low correlations in (*b*) than in (*c*). Pressure (blue) and cross-shore velocity (black) are coherent in (*a*), and more coherent in (*b*) than in (*c*). The three 120 s time series were observed within about 30 min of each other.

3.3. Deviations from linear finite-depth theory

The variance of wave-induced pressure (p) and cross- (u) and along-shore (v) velocities at radian frequency ω are related in linear theory by

$$z^2 = \frac{p^2}{\left(\frac{\omega}{gk}\right)^2 \frac{\cosh^2(kd_p)}{\cosh^2(kd_u)}(u^2+v^2)} = 1, \qquad (1)$$

where g is the gravitational acceleration, k is the magnitude of the wavenumber given by $\omega^2 = gk\tanh(kh)$, h is the water depth, and d_p and d_u are the distances above the seafloor of the pressure gauge and current meter, respectively. If the pressure gauge is buried, then $d_p < 0$ and the $\cosh(kd_p)$ term is replaced

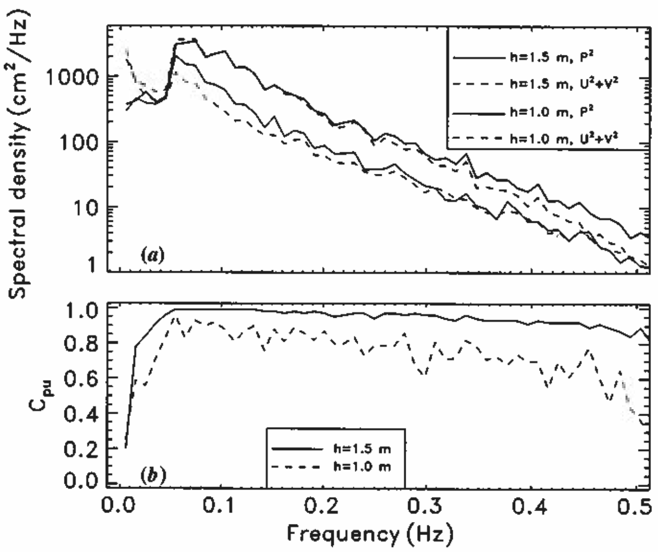

Figure 3. (*a*) Spectral density of collocated pressure and horizontal velocity and (*b*) coherence (C_{pu}) between pressure and cross-shore velocity observed in 1.0 and 1.5 m water depths versus frequency. Linear theory (equation (1)) predicts that the sum of cross- and along-shore velocity variance ($u^2 + v^2$) converted to equivalent pressure (denominator of equation (1)) (dashed curves in (*a*)) equals the pressure variance (solid curves) (i.e., $z^2 = 1$). For the (accepted) data observed in 1.5 m depth (thick black curves in (*a*), solid curve in (*b*)), there were 139 low along-beam correlations (i.e., replaced points), $z^2 = 0.96$, and $C_{pu} = 0.99$ (where both z^2 and C_{pu} are estimated over the frequency band $0.05 < f < 0.20$ Hz). In contrast, for the (rejected) data observed directly onshore in 1.0 m depth (thin blue curves in (*a*), dashed curve in (*b*)), there were 4204 low along-beam correlations, $z^2 = 1.68$ (owing primarily to low velocity variance near the spectral peak), and $C_{pu} = 0.89$ (barely below the retention threshold of $C_{pu} = 0.90$). Estimates are from 3072 s long time series sampled at 2 Hz, and have approximately 60 degrees of freedom.

with $\exp(kd_p)$ (Raubenheimer *et al* 1998). Although waves in the surfzone are nonlinear, deviations in the wavenumber from that given by the linear dispersion relationship are small in the wind–wave frequency band ($0.05 < f < 0.20$ Hz, where f is frequency) (Freilich and Guza 1984, Herbers *et al* 2002). In the mid and outer surfzones, electromagnetic current meter estimates of wind–wave $z^2 \pm$ two standard deviations range between about 0.5 and 2.0 (Herbers *et al* 1999).

Values of $z^2 > 1$ can occur if flow around the sensor is obstructed, if the sensor is within the wave bottom boundary layer, or if the sample volume intersects the bed, whereas $z^2 < 1$ if the velocity time series is noisy. The high-frequency cut-off for evaluating z^2 must be adjusted depending on h, d_u and d_p to ensure sufficient wave signal at both the pressure and velocity sensors. Here, mid-water-column, surfzone data from the ADVs (corrected for low along-beam correlations) are rejected unless $0.5 < z^2 < 2.0$, where z^2 is integrated over the wind–wave frequency band (figure 3).

3.4. Comparisons with collocated pressure observations

For unidirectional waves, the coherence (C_{pu}, the magnitude of the normalized cross-spectrum) between collocated p and u is 1.0. The directional spread S (in radians) of nearly normally incident waves or waves that are symmetric about normal incidence is (Kuik *et al* 1988)

$$S \approx \sqrt{2 - 2C_{pu}}. \qquad (2)$$

As the directional spread of the wave field increases, C_{pu} decreases. Noise in the velocity signal also decreases C_{pu}.

Although wave breaking, nonlinear effects and wave–current interactions in shallow water can lead to wind–wave directional distributions that are broader than the narrow distributions predicted by Snell's law (Herbers *et al* 1999, Hendersen *et al* 2005), surfzone directional spreads usually are less than 25°, corresponding to $C_{pu} < 0.9$. Here, 3072 s long ADV data runs are discarded if $C_{pu} < 0.9$, where C_{pu} is calculated over the wind–wave frequency band (figure 3).

The empirically determined C_{pu} and z^2 thresholds are a compromise between accepting data that are corrupted for some purposes (e.g., estimating wave directional spreads) and rejecting data suitable for other purposes (e.g., estimating mean currents). Data are rejected if they fail either threshold. Data from sensors in depths less than 50 cm (e.g., the swashzone) are not discarded on the basis of z^2 or C_{pu} values, because plausible ranges are not known (Raubenheimer 2002).

4. Conclusions

Criteria to identify inaccurate acoustic Doppler velocimeter estimates of wave-induced velocities in the swash- and surfzones were determined from thousands of 1 h long data records obtained in a wide range of conditions. Individual bad data points can be identified (and subsequently replaced) from low signal-to-noise ratios of reflected acoustic beams and from low correlations between sequential acoustic pulses. Bad 1 h data runs can be identified (and rejected) by large deviations from linear theory of the ratio of pressure (observed with an accurate collocated pressure gauge) to horizontal velocity variance, and from low values of the coherence between pressure and cross-shore velocity. These criteria can be used for any type of current meter collocated with a pressure gauge.

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Appendix. Detecting vertical tilts

Although many stand-alone ADVs have a built-in tilt sensor (as well as a compass) so that along-beam velocity estimates can be converted to vertical and horizontal velocity components, cabled-to-shore instruments often do not have tilt or direction sensors. The horizontal orientation of current meters can be determined by aligning the instrument with its mounting frame, and measuring the frame orientation after deployment with an external compass. Although frames held in place with pipes jetted into the sand rarely rotate horizontally, vertical

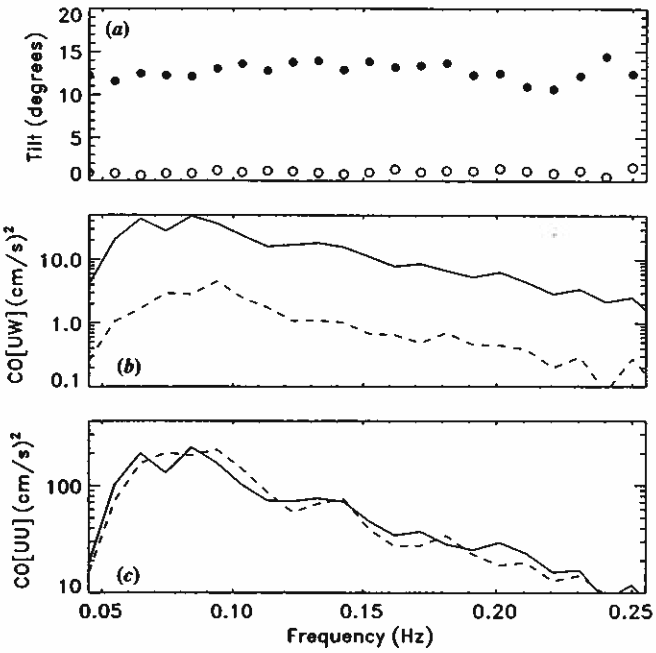

Figure A1. (*a*) Vertical tilt in the cross-shore direction, (*b*) co-spectrum $CO[u_{obs}w_{obs}]$ between cross-shore (u_{obs}) and vertical (w_{obs}) velocity, and (*c*) co-spectrum $CO[u_{obs}u_{obs}]$ between u_{obs} and u_{obs} (i.e., the autospectrum of cross-shore velocity) versus frequency. Observations were made in $h = 2.0$ m depth before (full circles in (*a*), solid curves in (*b*) and (*c*)) and after (open circles in (*a*), dashed curves in (*b*) and (*c*)) the tripod was adjusted vertically to remove the cross-shore tilt. There is a 1 h gap between the time series when the tripod was straightened. These data were obtained in the same location, but between 5 and 7 h earlier (higher tide), as those obtained in $h = 1.0$ m depth shown in figures 2 and 3. Processing is the same as described in figure 3.

tilts can occur when cross-shore wave forces are increased by fouling (e.g., by kelp), and when erosion removes the sediment overlying the anchors on the mounting pipes. If cross-shore tilts are not accounted for, then cross-shore velocity 'leaks' into estimates of the vertical velocity, and vice versa. The observed vertical (w_{obs}) and cross-shore (u_{obs}) velocities at any frequency are related to the true velocities (w_{true}, u_{true}) by

$$w_{obs} = w_{true}\cos(\theta) + u_{true}\sin(\theta) \qquad (A.1)$$

$$u_{obs} = u_{true}\cos(\theta) + w_{true}\sin(\theta), \qquad (A.2)$$

where θ is the amount of cross-shore tilt relative to the vertical (radians). If the sensor is vertical and sufficiently far above a gently sloping seafloor, then according to linear theory the co-spectrum (the real part of the cross-spectrum) between u and w is $CO[uw] = 0$ (Chu and Mei 1970, Elgar *et al* 2001). Multiplying w_{obs} by u_{obs}, and assuming shallow water waves ($u \gg w$) and small θ,

$$CO[u_{obs}w_{obs}] = u_{true}^2\cos(\theta)\sin(\theta). \qquad (A.3)$$

Similarly,

$$CO[u_{obs}u_{obs}] = u_{true}^2\cos^2(\theta), \qquad (A.4)$$

and thus,

$$\tan(\theta) = CO[u_{obs}w_{obs}]/CO[u_{obs}u_{obs}]. \qquad (A.5)$$

An example of data collected after strong wave forces, extreme fouling by kelp and sediment erosion resulted in significant (estimated visually by SCUBA divers to be about 15°) shoreward tilting of a tripod deployed in the surfzone is shown in figure A1. The tilt estimated from the co-spectrum of velocities observed with an ADV (equation (7)) was about 13°. After straightening the tripod, divers estimated the tilt to be 0°, whereas the ADV observations yielded 1° (figure A1). Post-processing can be used to correct the velocity estimates for vertical tilts using equations (3) and (4).

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