Sonic anemometers in Aeolian sediment transport research

van Boxel, J.H.; Sterk, G.; Arens, S.M.

Published in:
ICASALS Publication

In : Lee, Jeffrey A. and Zobeck, Ted M., 2002, Proceedings of ICAR5/GCTE-SEN Joint Conference, International Center for Arid and Semiarid Lands Studies, Texas Tech University, Lubbock, Texas, USA Publication 02-2 p. 132

Sonic anemometers in aeolian sediment transport research

J.H. van Boxel: Institute for Biodiversity and Ecosystem Dynamics (IBED), Universiteit van Amsterdam, Nieuwe Achtergracht 166, 1018 WV Amsterdam, The Netherlands (Email: J.H.Boxel@science.uva.nl)

G. Sterk: Erosion, Soil and Water Conservation, Wageningen University, Nieuwe Kanaal 11, 6709 PA Wageningen, The Netherlands (Email: Geert.Sterk@users.tct.wau.nl)

S.M. Arens: Bureau for Beach and Dune Research, Iwan Kantemanplein 30, 1060 RM Amsterdam, The Netherlands (E-mail: Arens@duinonderzoek.nl)

Fast response wind and turbulence instruments, including sonic anemometers are used more and more in the research of aeolian sediment transport. These instruments provide data on mean wind, but also on friction velocity, wind speed fluctuations and turbulence statistics, such as the U-W and W-T covariance (C_{UW} and C_{WT}), which are a measure for the momentum flux and the sensible heat flux.
This short paper will examine two problems that may arise when using sonic anemometers, namely the low/high frequency losses and the interpretation of the sonic anemometer measurements over sloping or non-homogeneous terrain.

The sonic anemometer

The sonic anemometer uses the speed of sound to measure temperature and wind speed. The wind speed is measured in three orthogonal directions, so the complete three-dimensional wind vector is known. Since the instrument has no moving parts the measurement is almost instantaneous. Many sonic anemometers have a path length of 15-20 cm and an output frequency of around 20 Hz. They can be used to obtain high frequency wind measurements, mean wind speeds and standard deviations of wind speed in the stream-wise or longitudinal (U), lateral (V) and vertical (W) direction. The C_{UW} covariance, multiplied with the density of the air yields the vertical flux of momentum and the square root of $-C_{UW}$ is the friction velocity ($U_* \equiv \sqrt{-C_{UW}}$). Generally a good estimate of the heat flux can be obtained by multiplying the C_{WT} covariance with the density and heat capacity of the air. Since the Obukhov length is mainly a function of friction velocity, heat flux and temperature, which are all measured by the sonic anemometer, a sonic anemometer will also provide the Obukhov length, which is a measure for atmospheric stability.

In : Lee, Jeffrey A. and Zobeck, Ted M., 2002, Proceedings of ICAR5/GCTE-SEN Joint Conference, International Center for Arid and Semiarid Lands Studies, Texas Tech University, Lubbock, Texas, USA Publication 02-2 p. 133

The turbulence spectrum

Let us picture turbulence as a collection of vortices, big and small, superimposed on the mean wind and on each other. These vortices transport air with its characteristics (e.g. momentum, temperature, humidity) up and down and will thereby create the fluxes of momentum, heat, water vapor, carbon dioxide, etc.

Large vortices transport momentum over large distances, but are rare. There are many small vortices, but these are inefficient in transporting momentum. Most of the transport is done by intermediate vortices (compare with frequency-magnitude principle). The shaded area in Figure 1 indicates the frequencies that cause 90% of the total momentum transport.

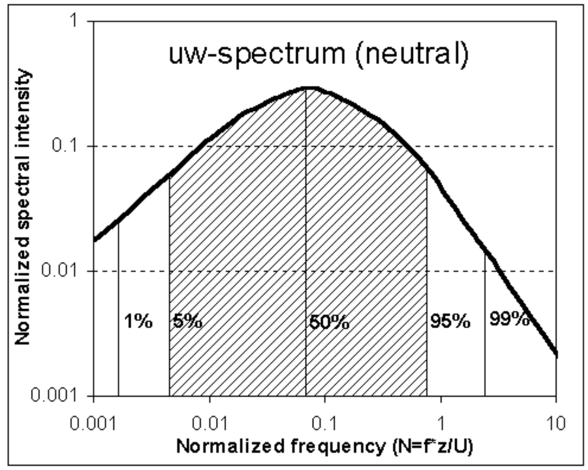

Figure 1: **The uw-cospectrum (after Busch 1972). Vertical lines indicate 1, 5,**

Low frequency losses of more than 1% occur when normalized frequencies (N=f*z/U) of more than 0.0016 are not resolved any more (table 1). When using for example a measuring height (z) of 2 m and a wind speed (U) of 5 m/s, under neutral conditions, that would mean that we would have to resolve frequencies (f=N*U/z) down to 0.004 Hz, requiring our period of measurement to be at least 250 s. To be on the safe side, we want to have at least a few of these large eddies, so 750 s would be a good measurement period.

High frequency losses can occur due to the limited measurement frequency of the sonic anemometer or due to the measurement volume of the instrument. In order to keep the high frequency loss below 1% we should be able to resolve normalized frequencies (N) up to 2.37 (table 1). In the above example (z=2m, U=5m/s) that corresponds to a frequency (f=N*U/z) of 6 Hz, so that the sampling frequency of the sonic should be at least 12 Hz.

If the highest frequency that must be resolved is 6 Hz and the wind speed is 5 m/s, that means that vortices as small as 0.8 m (λ=U/f) should be measurable. Kaimal & Finnigan (1994) state that vortices can measured down to a size of $\lambda=2\pi d$. So our sonic with a path length (d) of 15 cm should be able to resolve vortices of 0.94 m. In the above example we would have a high frequency loss of slightly more than 1%.

Loss	1%	2%	5%	10%
Low freq.	0.0016	0.0023	0.0045	0.0087
High freq.	2.37	1.53	0.77	0.45

Table 1: Normalized frequencies (N=f*z/U) that must be resolved in order to keep high or low frequency

Measurements over sloping terrain

Sonic anemometer measurements are easiest to interpret if they are performed over flat and homogeneous terrain, preferably under neutral conditions. However often our objects of study often are neither flat nor homogeneous. Measuring on a slope or near a roughness transition will cause the streamlines to slope.

When the streamlines are sloping part of the stream-wise fluctuations will be measured as vertical fluctuations. If the slope is upward this will give a positive contribution to C_{UW} (the U-W covariance). Since C_{UW} is negative this will decrease the measured friction velocity. Therefore the sonic coordinate system has to be rotated according to the streamlines, which are not necessarily parallel to the surface.

Kaimal and Finnigan (1994) already discussed the three rotations required, which we will refer to as yaw, pitch and roll. The yaw rotation (along a vertical axis) is required to orientate the longitudinal velocity U along the streamlines, so that the mean of V becomes zero. The second rotation (pitch) will orient the Z-axis perpendicular to the streamlines (mean W = 0). The roll rotation will set C_{VW} to zero. Wilczak et al. (2001) applied these rotations to sonic tilt errors and derived equations for simplified cases. If both yaw and roll can be ignored, they argue that the pitch-error in C_{UW} is approximately 6.4% per degree of tilt.

To test their theory we used 293 runs of 15 minutes each of sonic anemometer measurements, taken on a beach near Faro (Portugal) on 17 days between 14 January 1999 and 21 March 1999. Part of the beach was steeply sloping (about 8°). During the measurements almost all wind directions occurred and wind speeds varied from 1 to 10 m/s. The sonic anemometer was placed at different locations on the beach, usually at an elevation of approximately 0.9 m. The high frequency loss in C_{UW} resulting from the sonic path length (15 cm) was estimated to be circa 4% under near neutral conditions and less during unstable conditions. For wind speeds below 10 m/s the high frequency cut off resulting from the sample frequency (21 Hz) will be at a higher frequency than that resulting from the sonic path length. So in our case the path length is the factor determining the high frequency losses in C_{UW}.

We have calculated the error resulting from the sloping streamlines, by correcting individual data points as well as by using turbulence statistics and the equations suggested by Wilczak et al. The results were almost identical, except for two runs in which there was a strong change in wind direction.

From figure 2 it can be seen that the error in the C_{UW} covariance can be considerable when the slope corrections are not applied. In three cases the uncorrected C_{UW} was positive, meaning that the friction velocity was not defined anymore. Our data suggest that the error is 9.5% per degree, which is larger than the 6.4% per degree predicted by Wilczak et al. (2001) for neutral cases. If the regression line is not forced through the origin, there is an offset (-1% error for zero slopes).

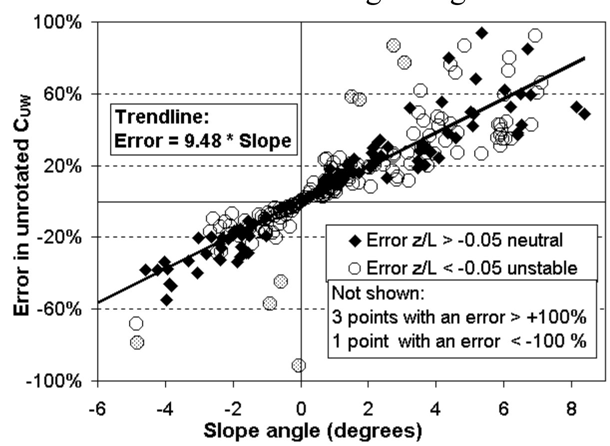

Figure 2: **Error when the C_{UW} covariance is not corrected for the**

Wilczak et al. predict a stronger response at unstable conditions. Although the worst outliers in figure 2 (in gray) are very unstable (z/L< -0.1), the majority of the unstable points do not show a trend that differs very much from the measurements during near neutral conditions.

Since stability is not the only source of the difference between theory and the results in figure 2 we will examine the high frequency cut off as a possible cause. At first approximation the relative error in $-C_{UW}$ is given by: $RE_{UW} = 100\% * \frac{\sigma_U^2 - \sigma_W^2}{U_*^2} * \sin(slope)$, where σ_U and σ_W denote the standard deviation of the wind speed component in the X- (stream-wise) and Z-direction (near vertical, but perpendicular to the streamlines) (for a more accurate formula see Wilczak et al.). Since σ_U exceeds σ_W the relative error is positive for positive slope angles.
The W-spectrum peaks at higher frequencies than the UW-cospectrum and the U-spectrum peaks at lower frequencies. Therefore the high frequency losses in σ_U^2 become small, but those in σ_W^2 will be considerably larger than 4%. Panofsky et al. (1977) argue that at near neutral conditions σ_W/U_* should be near 1.25. In our measurements the ratio was 1.09 for near neutral conditions. The high frequency loss in C_{UW} was estimated 4%, so that our U_* is underestimated by 2% and the ratio of σ_W/U_* becomes 1.07. If we compare this with the value of 1.25 suggested by Panofsky et al. we conclude that our σ_W values are about 15% to low, probably because of high frequency losses. If we correct all our σ_W values for this high frequency loss and recalculate the slope error, the –1% offset disappears, but the slope error still is 9.0% per degree, which is yet considerably higher than the slope error proposed by Wilczak et al. 2001. So although the high frequency losses for σ_W are considerable this does not seem to affect the correction very much. For σ_U/U_* Wilczak et al. suggest a value of 2.29 for near neutral conditions. Our data show a large scatter for σ_U/U_*, but the mean value in our measurements at near neutral conditions was about 2.65, which is 16% larger than the value suggested by Wilczak et al. If we take this value into account and consider the high frequency loss in σ_W/U_* that explains the difference in slope sensitivity between our measurements and the theoretical calculations by Wilczak et al. According to our estimates only 2% of the difference between our σU/U* and the value proposed by Wilczak et al. can be attributed to high frequency losses in our U*. The reason for the rest of the difference is not known. It is very well possible that the general relations for σU/U* and σW/U* that Wilczak et al. derived from Panofsky et al. (1977) do not hold for sloping or non-homogeneous terrain.

Conclusions

- Sonic anemometers can provide very useful information for aeolian research.
- High and low frequency losses can be estimated using the turbulence spectra.
- When measuring over sloping or non-homogeneous terrain the measurements must be corrected for the slope of the streamlines.
- Our best estimate from the measurements on a Portuguese beach is that the slope error in C_{UW} is 9.0% per degree of slope, which is considerably more that the 6.4% suggested by Wilczak et al. (2001) on the basis of theoretical considerations.

References

Kaimal, J.C. & J.J. Finnigin, 1994: Atmospheric boundary layer flows. Oxford University Press, New York, Oxford, 289 pp.

Busch, N.E., 1972. On the mechanics of atmospheric turbulence. In: D.A. Haugen, (ed.), Workshop on micrometeorology. American Meteorological Society, Boston, 392 pp.

Panofsky, H.A., J. Tennekes, D.H. Lenschow & J.C. Wyngaard, 1977. The characteristics of turbulent velocity components in the surface layer under convective conditions. Bound. Layer Meteor. 11: 355-361.

Wilczak, J.M., S.P. Oncley & S.A. Stage, 2001: Sonic anemometer tilt correction algorithms. Bound. Layer Meteor. 99: 127-150.