

Correction of the Heat and Momentum Flux Measurements with the Ultrasonic Anemometers at the FINO I Offshore Meteorological Mast for Flow Distortion and Mounting Effects

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Summary

Three ultrasonic anemometers, were investigated in the Oldenburg wind tunnel, prior to installation on the measurement platform FINO I. The calibration was found to be insufficient for flux measurements and was corrected and enhanced. A method depending only on few measurements was developed for this. The correction was tested with wind tunnel and field data. Additionally, the method of planar fit was applied for tilt correction and a trend removal was conducted for the measured values. Improvements of the measurements and in the calculation of fluxes could be shown.

1 Introduction

The structure of the atmospheric boundary layer is largely determined by the vertical fluxes of momentum, heat and moisture between the surface and the free atmosphere. They are directly connected to the vertical profiles of wind speed, temperature and humidity. For offshore wind power utilisation, the vertical wind speed profile is of paramount importance, since it determines the wind conditions at a site.

Accurate measurements of momentum and heat flux are commonly derived from sonic anemometer measurements with the eddy-correlation method. Calibration of these instruments for flow distortion and mounting errors is of crucial importance when highly accurate flux measurements are needed.

Three Gill 1210R3 ultrasonic anemometers are installed at different heights at the offshore measurement platform FINO I, 45 km north of Borkum in the North Sea.

Prior to installation, the response of the three sonic anemometers was tested in the wind tunnel of the University of Oldenburg. A correction method for an azimuth and tilt angle dependent calibration has been developed, which employs a limited number of wind tunnel measurements. With this method, the calibration for horizontal flow, which is supplied by the manufacturer, can be improved and extended to a three-dimensional correction.

2 Wind Tunnel Investigation

The aim of the wind tunnel investigation was to check the factory installed calibration for validity, especially accounting for the uncorrected vertical component. For a detailed description see Tautz (2004), Lange and Tautz (2004).

2.1 Measurement Instruments and Experimental Setup

The ultrasonic anemometers used in this work are from Gill Instruments Ltd., model 1210R3-50, serial numbers #255, #273 and #274. Their overall height is 0.75 m. The probe head is symmetrical, the three supporting struts are located at 0°, 120° and 240°. Specifications are given in Table 1.

Table 1: Specifications of the Gill R3-50, from Gill (2001).

Sonic Model	Gill 1210R3-50
Ultrasonic Sampling Rate	50 Hz
Wind Speed Range and Resolution	0-45 m/s, 0.01 m/s
Wind Speed Accuracy	$< \pm 1\%$ RMS
Wind Direction and Resolution	0-360°, 1°
Wind Direction Accuracy	$< \pm 1^\circ$
Temperature Range	-40° bis +60° C
Accuracy Range	< 32 m/s



Figure 1: Experimental setup in the Oldenburg wind tunnel

The measurements were done in the wind tunnel at the University of Oldenburg. The wind tunnel has an open measurement volume of $1.8 \times 1.0 \times 0.8$ m³ and a closed circulatory system. For more detailed information about the wind tunnel see Stabe and Langner (1997).

The experimental setup is shown in Fig. 1. The ultrasonic anemometer is mounted on a swivel arm in the open measurement volume, with its north direction pointing in the direction of the wind. The mounting allows a full rotation (360°) in the horizontal plane to change the wind direction. Variation of the tilt angle is possible with the swivel arm, allowing angles from -35° to 35° . Four pitot tubes, used for obtaining the reference wind speed, are mounted at the opening of the wind tunnel.

2.2 Measurement Results

Dependencies on wind direction, wind speed and tilt angle were investigated. Systematic errors were found for all ultrasonic anemometers.

Additionally two of the instruments showed a specific overall deviation of 1-1.5 % of the reference wind speed, throughout every spatial configuration (see Fig. 2).

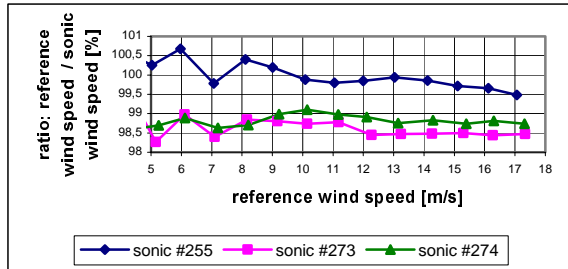


Figure 2: Ratio of reference wind speed and measured wind speed for all three ultrasonic anemometers.

For a variation of the wind direction, a 120° symmetry consistent with the 120° symmetry of the probe head was found in the deviations of the measured wind speed compared to the reference wind speed (see Figure 3). This was found for the horizontal and the vertical components. Around the supporting struts, strong deviations of up to 4% of the reference wind speed were found.

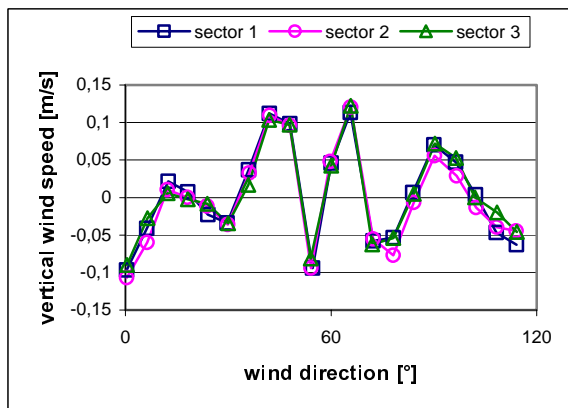


Figure 3: Vertical component versus wind direction, for a wind speed of 10 m/s, all three sectors.

The dependence on tilt angles with different algebraic signs is not symmetric, as can be seen in Figure 4.

For a positive tilt angle the measured values fall off in comparison to the reference wind speed. Two small peaks around the strut can be found. For a negative tilt angle a strong peak is found in front of the strut. The deviations around the struts increase with increasing tilt angle for both algebraic signs. For tilt angles with different magnitude and identical algebraic signs, the response of the ultrasonic anemometer is linear in between.

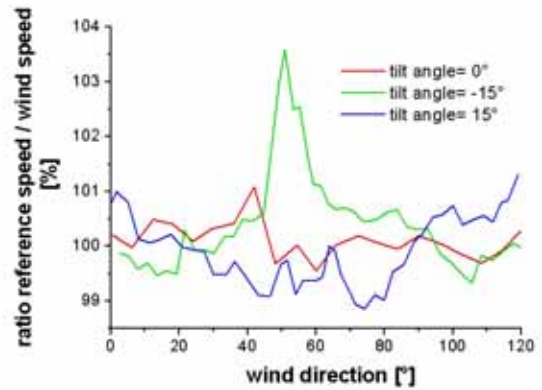


Figure 4: Ratio of reference wind speed and sonic wind speed versus wind direction, different tilt angles.

The vertical component showed deviations of about 0.15 m/s for a tilt angle of 0° at a wind speed of 10 m/s (see Figure 3). Around the struts the deviations were strongest as well.

The influence of the wind speed was found to be linear, as can be seen in Figure 5.

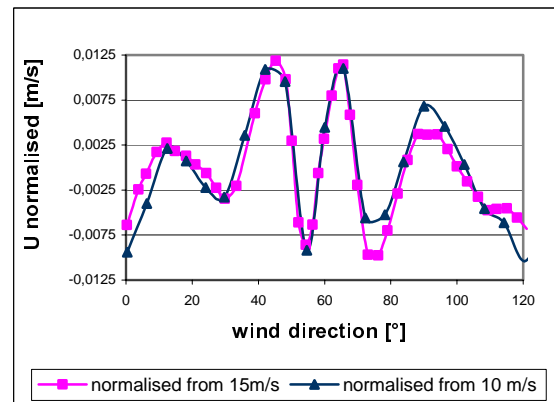


Figure 5: Normalised wind speed, previously 10m/s (squares) and 15m/s (triangles).

3 Derivation of Fluxes

3.1 Correction Method for Flow Distortion

An empirical correction method was developed, using the data acquired in the wind tunnel measurements. This correction makes use of the symmetries found for wind direction and the dependence on the tilt angle. Additionally the linear dependence on the wind speed was utilized. Thus the correction is in need of very few measurements. Of these measurement values lookup tables are build, in which correction values appropriate for each spatial configuration are listed. The measured wind speed is normalized before the correction value is applied.

3.2 Planar Fit

For field measurements, additional effects have to be considered. Inaccuracies in the exact vertical

orientation of the instrument are difficult to avoid in the field. They can have an important effect on the result of the flux measurements. The planar fit method (see Wilczak 2001) has been used to correct for any tilt in the mounting of the instrument. This method transforms the measured values in a mean streamline coordinate system, hence putting the mean vertical component orthogonal to the streamlines.

3.3 Trend Removal

Other effects influencing the measurements are data trends. An increase in wind speed leads to a deviation from the mean value of a measurement interval, which is not produced by turbulence. Thus these parts of the deviation from the mean have to be avoided. Therefore, a trend is calculated for each 10 min time interval via linear regression and subtracted from the measurement values, before the fluxes are calculated with the eddy-covariance method.

3.4 Fluxes

After these corrections, the fluxes can be calculated. Of further importance are the sensible heat flux and the momentum flux, which are defined in the following. With the covariance of temperature and vertical wind speed $\overline{w'T'}$, the sensible heat flux can be calculated:

$$H = \rho c_p \overline{w'T'}$$

where ρ is the air density and c_p the specific temperature for moist air at a constant pressure. From the covariance of the horizontal and vertical wind speed components $\overline{u'w'}$ and $\overline{v'w'}$ the momentum flux τ can be derived:

$$\tau = -\rho \sqrt{\overline{u'w'}^2 + \overline{v'w'}^2}$$

4 Flux Measurements of FINO I

The correction method for the flow distortion is used with data from the FINO I offshore meteorological mast to investigate the importance of the flow distortion correction. Data from November 2003 for the measurement heights of 40 m and 60 m has been used.

At first, the developed correction for flow distortion itself was tested. A ratio of the uncorrected and the corrected wind speed plotted against the wind direction shows the expected 120° periodicity of the correction (see Figure 6), which was already found in the wind tunnel measurements. Deviations from the 120° periodicity are due to the corrections from planar fit and detrending.

Comparisons of fluxes calculated with uncorrected and corrected data show the effect of the calibration on the flux calculation.

Table 2 shows the change of the mean values of one month of data.

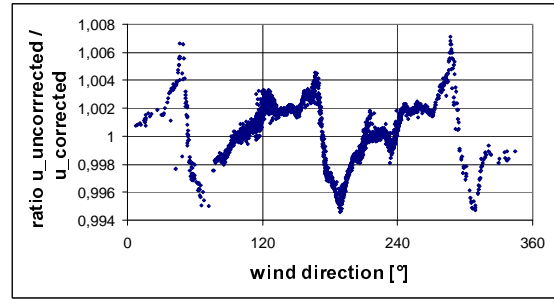


Figure 6: Ratio of the uncorrected and the corrected measured wind speed versus the wind direction. The 120° periodicity of the correction can be seen.

Table 2: Corrected and uncorrected measurements from FINO I, November 2003.

	40m change [%]	60m change [%]
U	-1.2	1.6
u*	-0.5	-1.2
H	-6.4	-6.8
z/L (z=height)	-10.4	-1.5

The changes for the sensible heat flux H show a relatively large magnitude caused by the influencing vertical component. Because the applied correction results in the largest relative changes for the vertical component, this large change is not surprising. The changes for u^* are smaller, including also the corrections for the horizontal components, in addition to the vertical component.

Wind speed U changes differently for each height, increasing the wind speed at 40m and decreasing it at 60m. This is an effect of the different overall deviation of the wind speed. The changes of the stability parameters 40/L and 60/L reflect the change of H and u^* from which it is calculated.

As a measure of the correction quality the parameter Δ is introduced.

$$\left| \frac{U_{reference}}{U_{sonic,uncorrected}} - 1 \right| - \left| \frac{U_{reference}}{U_{sonic,corrected}} - 1 \right| = \Delta$$

Δ basically consists of the ratios of reference and measured wind speed. These ratios show how well the wind speeds agree. A ratio of one is reached for two identical wind speeds. Therefore the magnitude of the difference between the wind speed ratios and one should decrease after a correction is applied, because the wind speed should be closer to the reference wind speed after that. Thus the difference between the magnitudes for an uncorrected measurement and a corrected measurement should be positive, resulting from the decreased deviation from the optimal ratio one.

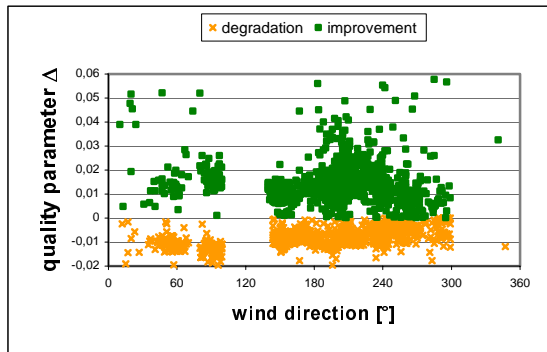


Figure 7: Correction quality parameter Δ versus wind direction. Orange indicates degradations, green improvements.

A positive value for Δ therefore indicates an improvement because of the correction, while a negative value for Δ would indicate a degradation resulting from the correction. Figure 7 shows the calculated quality parameter Δ versus the wind direction. The range in which the mast shadowing influences has been taken out of consideration. Although also degradations are found, these are smaller than the improvements, which especially occur for the position of a strut at approximately 200° (The instruments are not north aligned on the platform). Overall the measurement quality increases.

Also the standard deviation could be decreased with the application of the correction function, leading to less scatter, especially around the struts. This is shown in Figure 8 for the standard deviation of the friction velocity. This figure shows the difference of the standard deviation of the friction velocity for uncorrected and corrected measurements plotted versus the wind direction. Only wind direction intervals with more than 100 measurement values were accounted for. A peak can be seen for wind directions for which a strut is interfering. It is therefore likely that the deviations in each sector result not only from different meteorological situations but also from the disturbing influence of the strut.

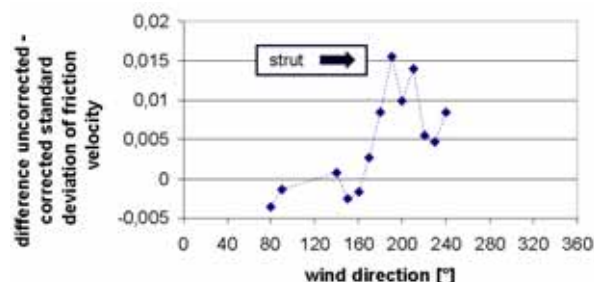


Figure 8: Difference of corrected and uncorrected standard deviation of the friction velocity versus wind direction.

5 Conclusions

The factory-installed calibration of the ultrasonic anemometers were tested in the wind tunnel of the

University of Oldenburg. Systematic errors similar for all three ultrasonic anemometers as well as errors which are specific for each individual instrument were found. Around the struts, the measured wind speed can deviate up to 4 % from the reference wind speed. Additionally, the uncorrected vertical component proves to be problematic, erroneous vertical wind speeds of up to 0.1 m/s for a reference speed of around 10 m/s were found.

For flux calculations, an improvement of the calibration is needed. This applies not only to the instruments used, but shows that the factory-installed calibration for the ultrasonic anemometers should generally be treated with care, if used for flux measurements.

A correction method for the calibration of the ultrasonic anemometers has been developed, based on the wind tunnel measurements. The correction is dependent on wind direction and tilt angle and makes use of symmetries and linearities found in the behaviour of the instrument in the flow. Therefore the correction employs only a limited number of wind tunnel measurements.

The correction was applied to measurement data from the FINO I offshore measurement platform. Additionally the method of planar fit has been used to account for misalignment of the instrument in the field. Data trends have been removed from the measured values, to assure that only turbulent parts were used for the flux calculations.

Effects of the correction of the mean monthly values are for example a change of wind speed of over 1%, while the change of the heat flux is even higher than 6%.

Improvements in the calculation of fluxes could be shown. The scatter of the fluxes decreased and improvements in the measurements of the wind speed are shown.

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