

# MEASUREMENT AND CORRECTION OF ULTRASONIC ANEMOMETER ERRORS AND IMPACT ON TURBULENCE MEASUREMENTS

Detlev Heinemann, Dirk Langner, Ulf Stabe, Hans-Peter Waldl

Energy and Semiconductor Research, Department of Physics,  
Carl von Ossietzky Universität Oldenburg, D-26111 Oldenburg, Germany  
Fax: + 49 441 798-3206, email: office@ehf.uni-oldenburg.de  
http://www.physik.uni-oldenburg.de/ehf

Ultrasonic anemometers commonly show systematic errors depending on wind speed due to inaccurate ultrasonic transducer mounting, transducer shadowing and distortion caused by the mounting struts. In windtunnel measurements of several Solent sonics we have systematically investigated their performance. Based on this data a model of the errors including a geometric transformation model and a transducer shadowing model has been derived. Also a correction procedure has been established. The influence on statistical values is examined using synthesized three-dimensional wind speed time series. Results for the variance and power spectra are shown.

## 1 INTRODUCTION

Ultrasonic anemometers have become the number one choice for many applications in the field of outdoor measurements of the wind velocity vector. Sonics have no moving parts and therefore do not show the response problems of mechanical anemometers and in general need no maintenance. This is an important aspect in long term measuring campaigns.

On the other hand there are two main problems in measuring wind speeds with ultrasonic anemometers: The measured flow is distorted by the probe head and the measurement depends on the geometric arrangement of the ultrasonic transducers. This arrangement can be inaccurate by manufacturing or can be altered by external influences, i.e. during the installation. Although these effects are in general taken into account by calibration procedures, they still can lead to measuring errors in practice.

In our study we investigated six Solent Standard and two Solent Windmaster anemometer in a wind tunnel experiment. All of them showed a transformation error that occurs if the alignment of the sensor arrangement deviates from the nominal values. To quantify the possible errors, we applied a model for the transformation of the wind vectors simulating the behaviour of a sonic with altered geometry. It incorporates a transducer shadowing model based on the linear velocity attenuation model of /Kaimal,1994/. Finally the model was applied to synthesized wind speed time series to investigate the effect of the transformation error on statistical quantities.

## 2 THE SOLENT SONIC ANEMOMETER

Ultrasonic anemometers measure the flight time of a sound impulse travelling forth and back on the path between two transducers. Using the flight time differences, it calculates velocity components along this direction using the nominal path length. In an internal procedure these components are transformed into cartesian components of the standard orthogonal u-v-w-coordinate system. Thus the geometry of the array alignment enters basically in the measuring process of the sonic.

The anemometer under investigation has an omnidirectional sensor array (figure 1). The transducer pairs are orientated at 120° azimuth intervals and at an inclination of 47° for the horizontal. The path length between the transducers is 148 mm and the transducer diameter is 12 mm.

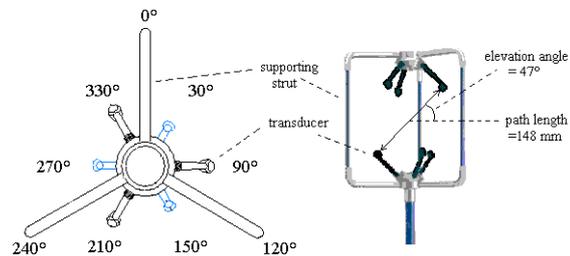


Figure 1: The Solent Standard 1012/s, top and side view.

Object to a detailed investigation in the wind tunnel was a Solent Standard 1012/S anemometer (#086). This anemometer type comes with a generic calibration table for an online correction of the distortion of the measuring volume by the mounting struts. Table 1 shows the nominal and the measured set of angles and path lengths that describe the transducer arrangement of the investigated sonic. We assume an accuracy of  $\pm 2^\circ$  for angle and 0.5 mm for length determinations.

	pair 1	pair 2	pair 3
azimuth (nom/meas)	30°/29°	150°/148°	270°/268°
elevation (nom/meas)	47°/51°	47°/53°	47°/46°
path length (nom/meas)	148mm/ 148.5mm	148mm/ 147mm	148mm/ 146.5mm

Table 1: Measured and nominal values describing the position of the transducer pairs (see figure 1). The azimuth angle is given for the bottom transducer.

## 3 WIND TUNNEL MEASUREMENTS AND TRANSFORMATION MODEL

### 3.1 Equipment

The measurements with the Solent sonics were carried out in the wind tunnel of the University of Oldenburg which has a cross-section of 1.0m x 0.8m. The free flow of this wind tunnel is extremely homogeneous, the mean flow speed differs less than  $\pm 0.2\%$  across the stream. The reference speed was measured with a Laser-Doppler anemometer with an accuracy of 0.01 m/s. To generate different flow directions the sonic was mounted on a turn table and

systematically rotated 360° in azimuth angle for different elevation angles from 0° to 40°. The horizontal flow was investigated for seven mean velocities from 3.4 m/s to 30.4 m/s. For measurements with the tilted anemometer, a flow speed of 7.65 m/s was chosen.

### 3.2 Measuring results for horizontal flow

Figure 2 shows the result of the wind tunnel measurements for the horizontally mounted anemometer for seven horizontal flow speeds. The sonic mean wind speed normalized to the value of the flow measured with the Laser-Doppler anemometer is plotted versus the mean azimuth angle which refers to the wind direction. It can be seen that the measuring error is independent of wind speed. A variation of the measured wind speed of up to 5% can be seen over the wind direction range. Furthermore, the mean wind speed averaged over all directions is about 3% lower than the reference value.

Measurement results for the vertical component are shown in figure 3. The relative deviation is up to 2% of the horizontal reference flow speed, although the wind tunnel induced vertical component is negligible.

The general behaviour of the wind speed measurements is typical for this kind of ultrasonic anemometer and is due to deviations of the real from the nominal angles of the transducer arrangement (see below).

The results shown for a specific sonic are representative for the complete set of sonics investigated.

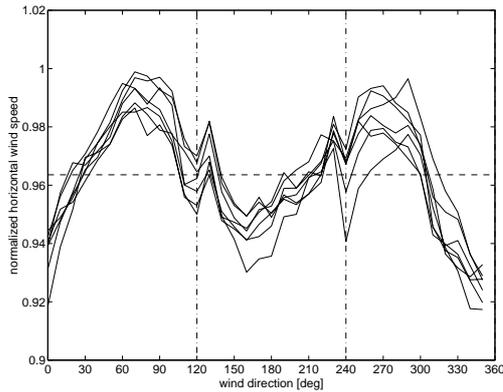


Figure 2: Sonic horizontal wind speed  $u$  normalized to the reference speed at seven wind speeds. The solid horizontal line indicates the mean sonic response over all wind directions. The vertical lines show the position of the struts.

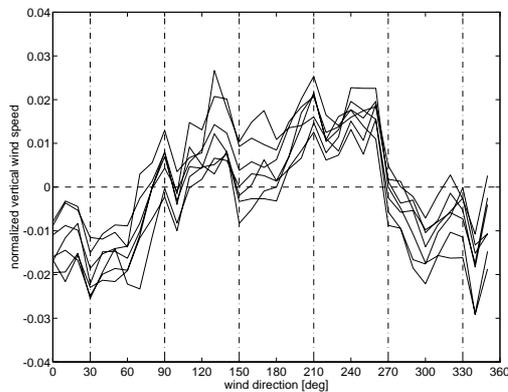


Figure 3: As figure 2, for vertical wind speed  $w$ .

### 3.3 Model of the Solent transformation error

Because of the non-orthogonal array of the probe head a transformation of the measured wind components into e.g. a cartesian coordinate system is required. The set of nominal angles and lengths that is used in the internal transformation of the sonic may differ from the real geometry of the transducer array. This deviation leads typically to a systematic error which varies with wind direction as seen in figure 2.

To simulate the influence of the transformation on the measured wind vector, a constant cartesian reference vector is transformed into a coordinate system described by the measured set of angles. The non-orthogonal velocity components are transformed into flight-time differences using the measured path length. These simulated differences correspond to the measured ones. The internal transformation was simulated by calculating the cartesian output vector using the nominal set of angles and lengths. The described transformation process sums up in the following equation:

$$\vec{v}^*|_{cart} = C|_{nom}^{cart} \cdot C_L \cdot C|_{cart}^{dev} \cdot \vec{v}|_{cart} \quad (1)$$

with

$\vec{v}$  cartesian reference vector

$\vec{v}^*$  simulated cartesian velocity components including the transformation error

$C|_{cart}^{dev}$  Transformation matrix based on the deviating set of angles

$C|_{nom}^{cart}$  Transformation matrix based on the nominal set of angles

$C_L$  Diagonalized matrix of the ratios of nominal and deviating path length

### 3.4 Model of transducer shadowing

The transducer shadowing is a well-known error in sonic anemometry. /Kaimal,1994/ gives an estimation of the velocity deficits in the wake of the transducers. A linear relationship between velocity attenuation along the path length and the angle between the flow and the path length is assumed. The maximum velocity attenuation is a function of the path length to transducer diameter ratio ( $L/a=12$  for the Solent Standard). Within the limited range of the results for non-horizontal flow we give an estimation of the parameters for the Kaimal model applied to a probe head with a Solent geometry. These results have to be considered preliminary because they are based on the measurement with only one Solent sonic. A value of  $L/a=12$  indicates a maximum velocity attenuation of 22% for the Solent transducer types. The measurements indicate that the influence angle of the transducer shadowing is 57°. This is less than the influence angle of 75° in the Kaimal model. These results lead to the following approximation:

$$(V_d)_m = \begin{cases} V_d(0.78 + 0.22 \cdot \beta / 57) & 0^\circ \leq \beta \leq 57^\circ \\ V_d & 57^\circ < \beta \leq 90^\circ \end{cases} \quad (2)$$

with

$(V_d)_m$  measured velocity component along path length

$V_d$  real velocity component along path length

$\beta$  angle between main flow  $V$  and  $V_d$

This model has been incorporated into the transformation error model.

### 3.5 Comparison of simulation and measurements

Figure 4 and 5 show the results of the measurements and the simulation for horizontal flows for  $u$  and  $w$ . The behaviour of the horizontal component (figure 4) is primarily dominated by the transformation error. A maximum error of -7% occurs at a wind direction of 330°. Note that the inter-

nal correction of the strut distortion is applied in the measurements and is very small.

For the vertical component (figure 5), the transformation error creates an offset that systematically varies with wind direction. This leads to errors from up to 30% for  $w$  if the elevation angle of the flow is small ( $<5^\circ$ ). Contrary to the horizontal component the vertical component is influenced also by the transducer shadowing effect. Note the flow distortions at wind directions  $30^\circ$ ,  $90^\circ$ ,  $150^\circ$ ,  $210^\circ$ ,  $270^\circ$  and  $330^\circ$ . These are the azimuth positions of the transducers. The quality of the simulation indicates that the combination of the transformation and transducer shadowing errors are the main reasons for the observed deviations. Since the wind direction is calculated from the distorted cartesian velocity components, it also shows transformation errors which we don't present here.

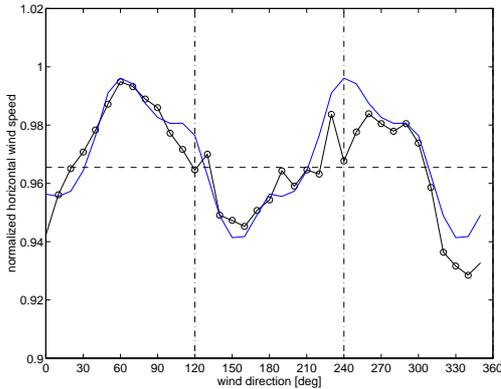


Figure 4: Measured (points) and simulated (solid line) sonic normalized horizontal wind speed  $u$ . Reference speed is 7.65m/s.

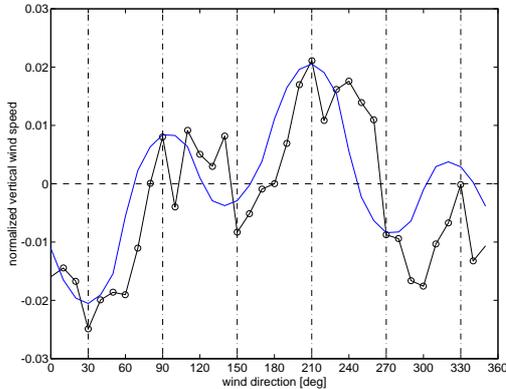


Figure 5: Measured (points) and simulated (solid line) sonic vertical speed  $w$ . Reference speed is 7.65 m/s.

### 3.6 Measuring results for non-horizontal flows

The measured distortion for non-horizontal flow is shown in figure 6. It shows how the sonic reproduces the reference flow speed. The transducer shadowing error becomes dominant for increasing elevation angles ( $>5^\circ$ ) of the flow (three uprising ridges for increasing elevation angle).

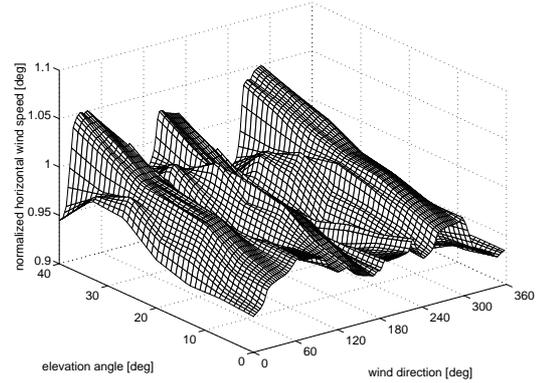


Figure 6: Ratio of measured absolute flow speed  $(u^2+w^2)^{1/2}$  and reference speed (7.65 m/s) for azimuth angle  $0^\circ$  to  $360^\circ$  and elevation angle  $0^\circ$  to  $40^\circ$ .

## 4 STATISTICAL QUANTITIES

To assess the influence of the transformation and transducer error on statistic quantities characterizing the turbulent flow simulated measurements have been performed. An algorithm for the synthesis of stochastic time series /Shinozuka,1972/ was applied to produce time series of three-dimensional wind vectors /Degner,1997/. Using known characterizations of the power spectral density and the correlations between the wind speed components, this method simulates 'real' time series for given parameters like mean wind speed  $\bar{u}$ , height over ground  $z$ , turbulence intensity  $\hat{\sigma}_u$ , length of time series  $N$  and time step  $t$ . The synthesized time series was used to simulate the outdoor measurement with the investigated Solent Standard sonic. To create a time series that incorporates the systematic error, the transformation was used to derive simulated correction tables. The error was added to the time series by applying the correction backwards. Table 2 shows the deviation of the simulated statistical values from the values of the original time series.

Mean wind direction	$\frac{\bar{u}_{sim}}{\bar{u}_{org}}$	$\frac{\sigma_{u,sim}^2}{\sigma_{u,org}^2}$	$\frac{\sigma_{v,sim}^2}{\sigma_{v,org}^2}$	$\frac{\sigma_{w,sim}^2}{\sigma_{w,org}^2}$
$0^\circ$	0.95	0.94	0.96	0.92
$30^\circ$	0.97	1.03	0.98	0.93
$60^\circ$	0.99	0.98	0.86	0.88
$90^\circ$	0.98	0.9	0.92	0.87
$120^\circ$	0.97	0.96	0.9	0.88
$150^\circ$	0.94	0.96	1.02	0.9
$180^\circ$	0.94	0.91	0.96	0.88
$210^\circ$	0.98	0.89	0.98	0.87
$240^\circ$	0.99	1.02	0.86	0.87
$270^\circ$	0.98	1.06	0.93	0.90
$300^\circ$	0.97	0.97	0.9	0.89
$330^\circ$	0.94	0.84	1.01	0.9

Table 2: Ratios of simulated and original values for mean wind speed  $\bar{u}$  and variances  $\sigma_u^2$ ,  $\sigma_v^2$ ,  $\sigma_w^2$ , calculated for 12 mean wind directions. The parameters to synthesize the original time series are:  $\bar{u}=7.5\text{m/s}$ ,  $z=50\text{m}$ ,  $N=1\text{h}$ ,  $t=1\text{s}$ ,  $\hat{\sigma}_u=0.2$ .

The mean wind speed varies with mean wind direction in a range of -6% to -1%. When calculating the variances from

erroneous time series, the deviation lies in a range of -16% to 6% varying with mean wind direction. Figures 7 and 8 show the influence of the investigated errors on the power spectra.

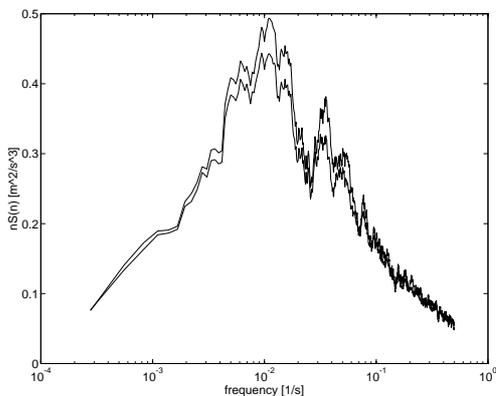


Figure 7: Original (lower line) and simulated (upper line) one-sided power spectral density of  $u$ . The original time series was used to simulate the measurement of the investigated Solent Standard for a mean wind direction of  $270^\circ$ .

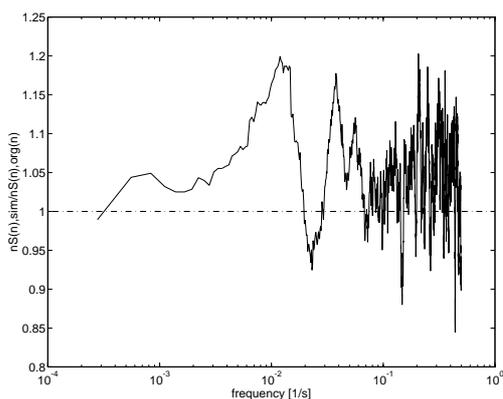


Figure 8: As figure 7 with simulated values normalized to the original spectrum

## 5 CORRECTION

From our results two different correction procedures for the wind speed values measured with the Solent anemometer have been derived, either using the measured or simulated data. Both methods apply a correction of wind direction, elevation angle and absolute wind speed. Application of measured calibration tables leads to an error range of  $\pm 1\%$  for all wind directions. The simulated calibration tables leave an error of  $\pm 2\%$ , a value which can be further improved when a correct strut distortion model is included in the simulation (figure 9). Since windtunnel measurements for the derivation of three-dimensional calibration are quite costly, simulated calibration tables which are based on one horizontal flow measurement for all wind directions are a reasonable alternative.

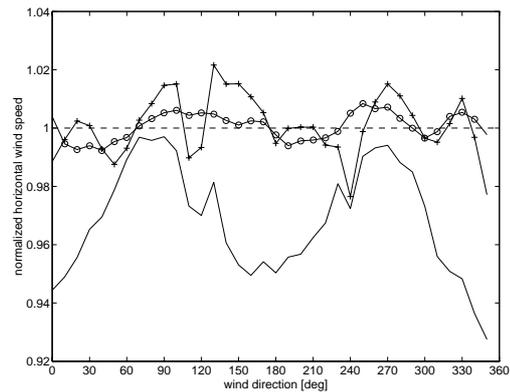


Figure 9: Correction of the horizontal velocity component  $u$  (solid) with measured (crosses) and simulated (points) calibration tables. The reference wind speed is 19.85 m/s.

## 6 CONCLUSIONS

The observed systematic errors are caused by a combination of transformation and transducer shadowing error. The impact of the deviations on turbulent statistics can not be neglected. The calculation of statistical values from time series measured with the investigated sonic thus strongly depends on the mean wind direction of the flow. Both errors are accounted for in the introduced transformation model, which can be used in a correction procedure. From a simulation model three dimensional calibration tables are produced, which consider the varying influence of transformation error and transducer shadowing for increasing elevation angles of the flow. The parameters used in the transducer shadowing model have to be further verified in wind tunnel measurements.

## 7 REFERENCES

- /T. Degner, 1997/, Synthese von Zeitreihen der u,v,w-Komponenten eines Windvektors, Internal report, Dept. of Physics C.v.O. University Oldenburg
- /J.C.Kaimal, J. J. Finnigan, 1994/, Atmospheric Boundary Layer Flows, Oxford University Press
- /N.Mortensen, J.Høstrup, 1995/, The Solent sonic, response and associated errors, Proc. 9<sup>th</sup> Symp. on Meteorological Observation and Instruments.
- /Shinozuka, C.M. Jan, 1972/, Digital simulation of random processes and its application, Journal of Sound and Vibration, 25(1).