Measuring Air Temperature by using an Ultrasonic Anemometer

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Abstract

This paper describes the basics for using a standard ultrasonic anemometer for measuring the air temperature. Under zero-wind conditions an uncertainty of measurement of < 0.1 K was achieved in the temperature range from -25°C to +25°C. At wind speeds up to 14 m/s the measurement accuracy is better than 0.2 K. Future potential of acoustic temperature measurements and necessary improvements are presented.

Introduction

Measurement of air temperature by using contact thermometers in weather screens of various designs is state of the art in meteorological measurements. However many screen intercomparisons have identified numerous sources of measurement errors that are inherent in all these systems, e.g. radiative heating, unsufficient ventilation, psychrometric cooling, ageing effects and time constants.

To quantify these errors there is a need for a reference sensor, capable of measuring the true ambient air temperature with high accuracy. Measurement of the temperature dependant sound propagation has the potential for building such an "ideal" sensor as it offers a contactless temperature measurement and hence avoids most of the above mentioned error sources.

Moreover the accuracy of acoustic temperature measurements is best at low absolute air humidity conditions, e.g. at mountain sites. Therefore some ultrasonic anemometers that have already proven to perform well even under severe icing conditions [3] could be a future option for temperature measurements at automatic weather stations.

Theory

The temperature dependence of the speed of sound c in humid air is given by [1]

$$c = \sqrt{\gamma_d R_d T \cdot \left(1 + \left(\frac{\gamma_v}{\gamma_d} - \frac{M_v}{M_d} \right) \cdot \frac{e}{p - \left(1 - \frac{M_v}{M_d} \right) \cdot e} \right)} \qquad (1)$$

where γ_d and γ_v are the ratios of specific heats for dry air and water vapour, R_d is the gas constant of dry air, T is the air temperature, M_v and M_d are the molar masses for water vapour and dry air, e is the partial water vapour pressure and p the total air pressure.

It is important to note that the acoustic virtual temperature

$$T_{av} = T \cdot \left(1 + \left(\frac{\gamma_v}{\gamma_d} - \frac{M_v}{M_d} \right) \cdot \frac{e}{p - \left(1 - \frac{M_v}{M_d} \right) \cdot e} \right) \qquad (2)$$

measured by an ultrasonic anemometer is not equal to the virtual temperature T_v used in meteorology [1], where the ratio of specific heats γ_v / γ_d in equation (2) has to be replaced by 1.

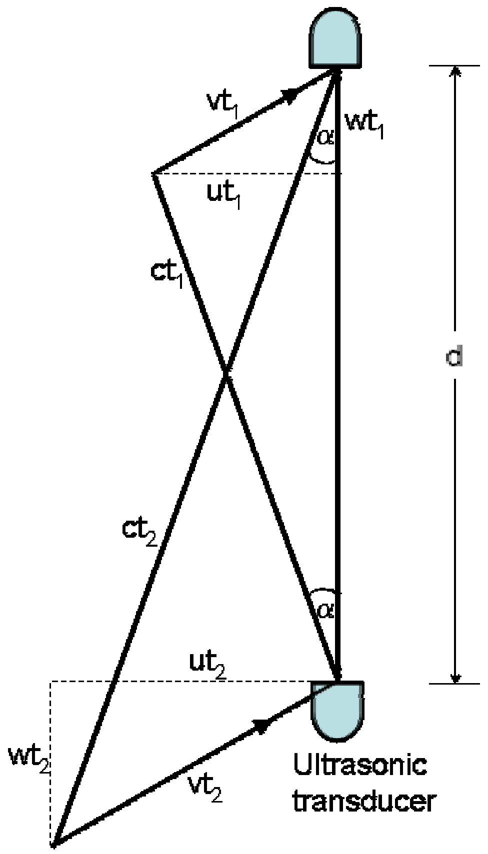

Figure 0: Schematic function principle of an Ultrasonic Anemometer (after Coppin and Taylor [4])

Unlike the wind measurement which is based on a differential measurement sonic thermometry uses an absolute measurement of the transit times

$$t_1 = \frac{d}{c \cdot \cos(\alpha) + w} \quad \text{and} \quad t_2 = \frac{d}{c \cdot \cos(\alpha) - w} . \qquad (3)$$

These are the times a sound wave needs to propagate from the lower transducer in Figure 0 to the upper one and back. Adding their reciprocals [2] we get

$$\frac{1}{t_1} + \frac{1}{t_2} = \frac{2 \cdot c \cdot \cos(\alpha)}{d} = \frac{2}{d} \sqrt{c^2 - u^2} . \qquad (4)$$

In this equation u is the wind component perpendicular to the measuring section between the transducers. Using eq. 3 and eq. 2 leads to

$$T_{av} = \frac{1}{\gamma_d R_d} \cdot \left[\left(\frac{d}{2} \right)^2 \cdot \left(\frac{1}{t_1} + \frac{1}{t_2} \right)^2 + u^2 \right] \qquad (5)$$

In ultrasonic anemometers the measurement of transit times t_1 and t_2 is done by counting the numbers n_1 and n_2 of clock cycles with duration t_0 between the transmission and the reception of a sound signal. Due to processing times in the electronics some offset cycle counts n_0 have to be added so that e.g. $t_1 = (n_1+n_0) \cdot t_0$. Replacing these terms in eq. 5 leads to a final equation which has been used in these experiments to calculate T_{av} from the anemometers "raw data" n_1 and n_2:

$$T_{av} = \frac{1}{\gamma_d R_d} \cdot \left[\left(\frac{d}{2} \right)^2 \cdot \left(\frac{1}{(n_1 + n_0) \cdot t_0} + \frac{1}{(n_2 + n_0) \cdot t_0} \right)^2 + u^2 \right]. \qquad (6)$$

Because it is an absolute measurement the geometric distance d of the sonic transducers has to be known very precisely if a precise temperature measurement is required. A deviation of 0.1 mm will result in a temperature deviation of about 0.3 K. Eq. 6 is used for calibration of d where T_{av} has to be determined by eq. 2 using precise reference measurements of T, e and p.

Experiment

In the following experiments two 2D ultrasonic anemometers (Thies Model 4.3810.20.340, Germany) have been investigated. Before using them for temperature measurements it is necessary to determine their actual measuring sections d_{NS} and d_{WE} of both sonic paths in a temperature controlled chamber.

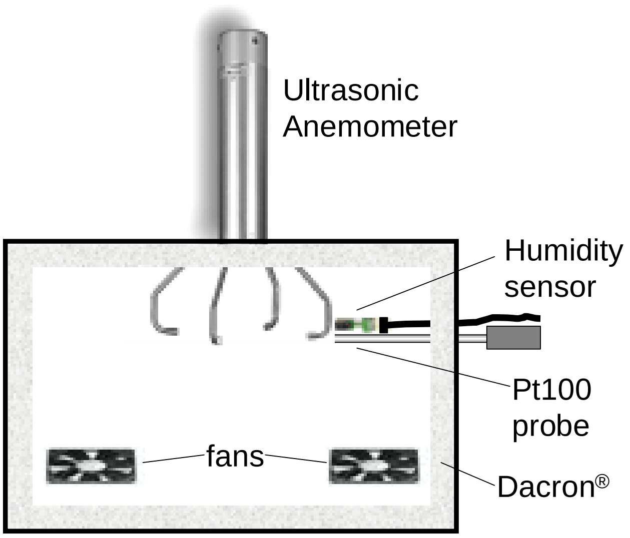

Figure 0: Temperature calibration box with ultrasonic anemometer mounted upside down, reference sensors for temperature and humidity and two fans providing vertical air circulation.

To avoid echoes of the sonic signals we placed the anemometer inside a wooden calibration box lined with a 5 cm layer of Dacron wadding. The reference thermometer (Pt100, 1/5 DIN class B, manufacturer: Heraeus) and a digital humidity sensor (Sensirion SHT75) were also mounted inside this box and at the same height as the ultrasonic transducers in order to avoid temperature differences by possible thermal layering. In a later experiment two small fans have been added to reduce this effect by circulating the air vertically. Air pressure was measured by a separate barometer.

The calibration box was placed inside a two-level controlled temperature chamber. Because of different time constants of the used sensors it was necessary to measure in stationary conditions, i.e. various fixed temperature levels of T=-25°C, -15°C, -5°C,…,+25°C. The insulated and closed box itself had a time constant of about 25 minutes which allowed the temperature inside to stabilise to a final temperature with an accuracy of <±0.02 K after about 4 hrs.

It was also important to avoid any heat source inside the calibration box. In our first experiments the ultrasonic anemometer was mounted completely inside the calibration box and its consumption power of 3 W induced a permanent temperature drift. In an improved setup we therefore mounted the sensor body outside the calibration box (see Figure 0), leaving only the sensor arms inside. The sensor's built-in heating was also switched off during calibration.

After calibration the influence of wind speed and direction on the acoustic temperature measurement has been investigated. In the wind tunnel of DWD in Hamburg the ultrasonic anemometer was slowly turned from 135° to 315° while applying stepwise wind speeds of 5 m/s to 45 m/s.

Results

When determining the measuring sections *d* in the calibration box, we soon could see that *d* seems to be temperature dependent (see Figure 1) and apparently the arms of the anemometer bend slightly inward at low temperatures making the transducers coming closer. We measured a change of $\Delta d \approx 0.4$ mm/50K corresponding to a temperature error of about 1.2 K if it would not be corrected. All sensors of this type we have calibrated so far show the same general behaviour but with different parameters. This means, every sensor has to be calibrated individually. To plot the temperature characteristic in Figure 1 the data for both measuring sections (North-South and East-West) were fitted by 4th order polynomials. It turned out that the data at T≈+25°C could not be used for the fit because the temperature had not stabilised enough inside the calibration box.

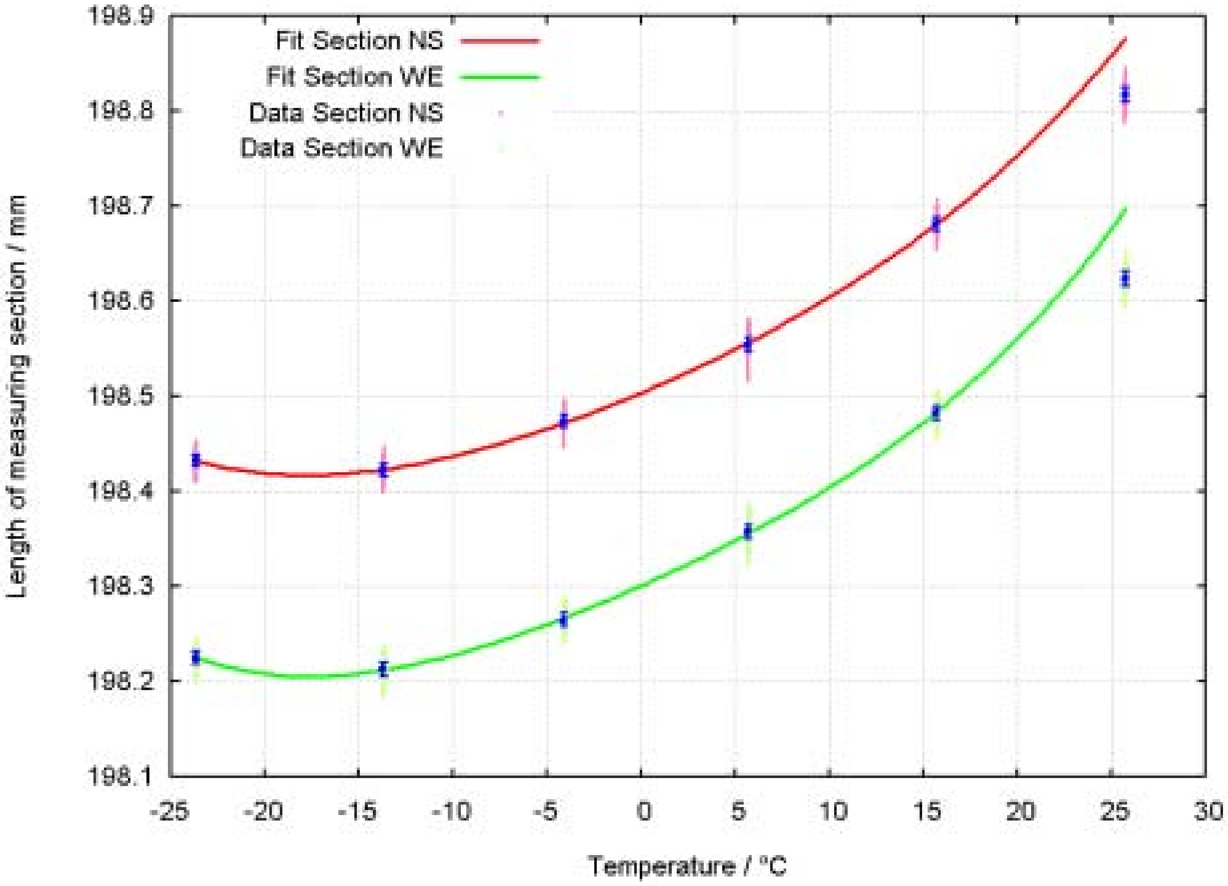

Figure 1: Calibration of both measuring section (NS and WE) of the ultrasonic anemometer. A 4th order polynomial was fitted to measured data. Each calibration point contains at least 1500 data whose vertical spread, mean values and standard deviation are indicated in the graph.

To confirm our suspicion that a mechanical deformation is the source of the temperature dependence we plan to carry out a direct distance measurement (e.g. interferometric), but generally any component in the signal path (transducers, protection caps) could cause this temperature effect.

Air temperatures can now be determined by an iterative calculation using eq. 2 resolved for *T*:

$$T = \frac{T_{av}}{\left(1 + \left(\frac{\gamma_v}{\gamma_d} - \frac{M_v}{M_d}\right) \cdot \frac{e}{p - \left(1 - \frac{M_v}{M_d}\right) \cdot e}\right)} \qquad (7)$$

in which $T=f(T_{av}, e, p)$. The acoustic virtual temperature is derived by eq. 6 where $T_{av}=f(d, n_1, n_2, u)$, and in turn $d=f(T)$. In the first step of the iteration a fixed value for d was chosen, e.g. d at T=20°C, resulting in a first guess for the air temperature which is used in $d=f(T)$ for the next iteration step. After the third iteration the results converged and are shown in Figure 2.

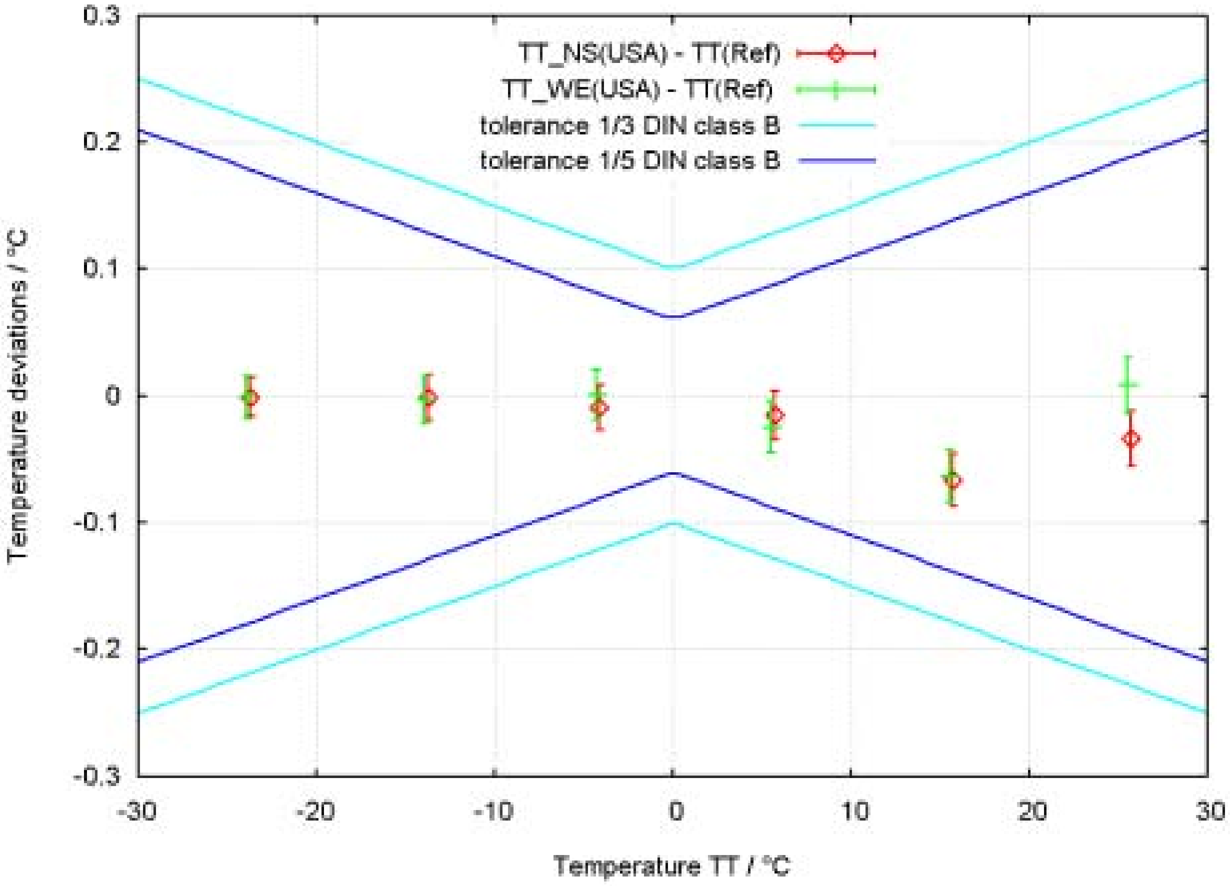

Figure 2: Plot of Mean values and standard deviations of the sonic thermometer comparison with a reference Pt100 sensor (1/5 DIN class B). The air temperatures derived from the sonic thermometer are within the specifications of a good Pt100 sensor (under laboratory conditions).

The mean values and standard deviations of all measurements are well inside the 1/5 DIN tolerance over the whole temperature range from -25°C to +25°C . The 1/3 DIN specification for operational pt100 thermometers is easily fulfilled.

The numeric results of this comparison are summarised in Table 1. The achieved accuracy is thus better than 0.1 K for the used temperature range.

It must be stated that this test has been performed under favourable conditions, i.e. stationary conditions, medium (indoor) humdity and no wind. As soon as the temperatures are drifting, larger differences between the sonic and the reference thermometer can be observed.

The measurement displayed in Figure 3 was also performed in the calibration box but a rapid temperature drop was applied. The lag free sonic thermometer (green curve) reacts immediately to the temperature change whereas the reference Pt100 (red curve) follows with a time constant of about 80s.

Table 1: Results from the laboratory comparison of the sonic thermometer with a reference Pt100 sensor (see Figure 3).

Reference temperature	Mean of $TT_{USA} - TT_{Re}$ $(NS)_f$	Standard deviation	Mean of $TT_{USA} - TT_{Ref}$ (WE)	Standard deviation
-23.70	-0.001	0.016	-0.002	0.017
-13.72	-0.002	0.017	-0.004	0.019
-4.16	-0.009	0.018	0.000	0.020
5.66	-0.015	0.019	-0.025	0.020
15.66	-0.066	0.021	-0.064	0.021
25.68	-0.034	0.022	0.008	0.022

The differences (orange curve) add up to -1.5 K. If the sonic data are post processed (blue curve) with the same time constant as the reference (about 80 s) the deviations (light green curve) become less than 0.3 K. The remaining differences observed might be due to imperfect ventilation during the cooling process leading to real temperature differences on a cm scale inside the calibration box.

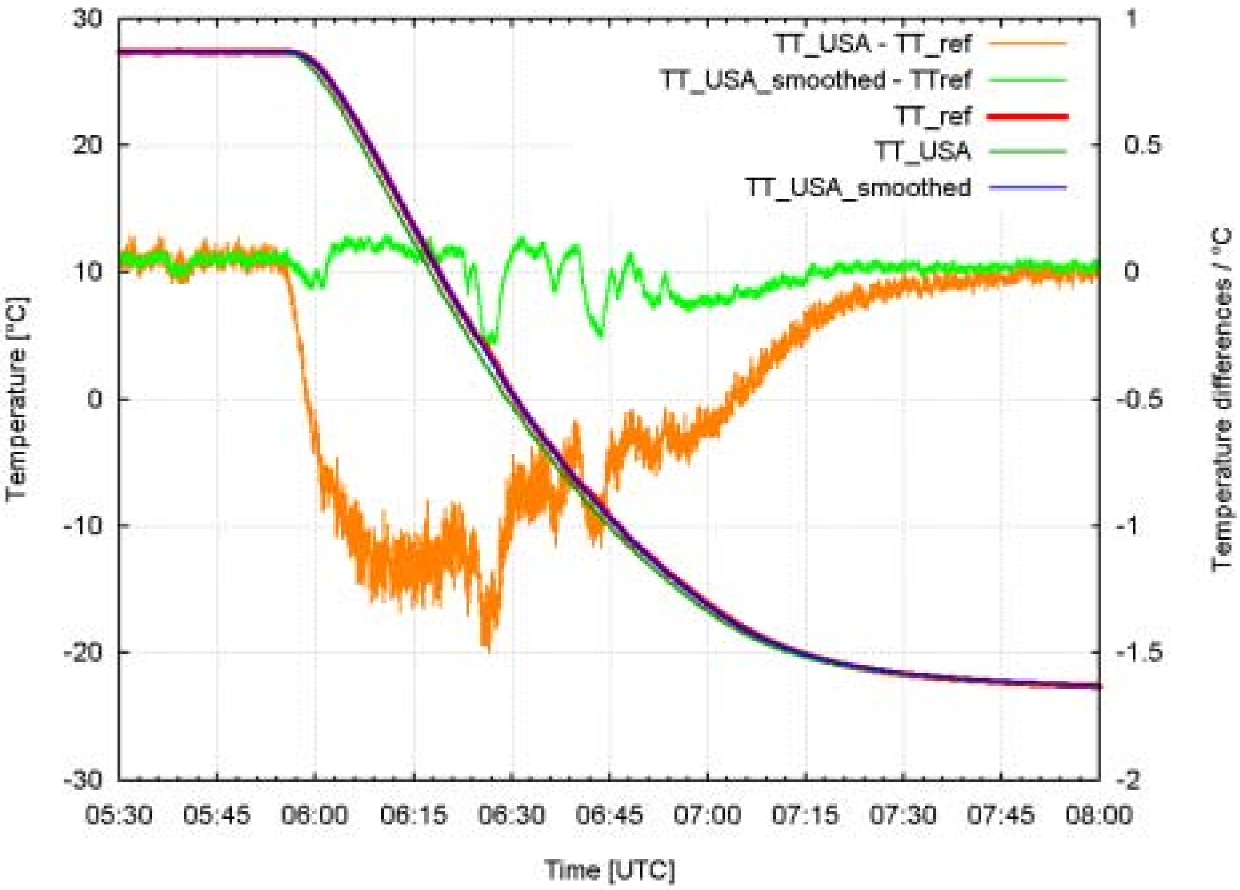

Figure 3: Comparison of the sonic thermometer and the reference during a rapid cooling process from +27°C to -22°C (left axis) within 1.5 hrs. Obviously the sonic thermometer (green curve) reacts faster and the reference thermometer (red curve) follows with delay. For the blue curves the sonic data have been smoothed with a time constant *Tc*=80s , resulting in much smaller differences (light green curve).

In order to examine the influence of the crosswind component, perpendicular to a respective measuring section, the ultrasonic anemometer was exposed to various wind speeds in a wind tunnel.

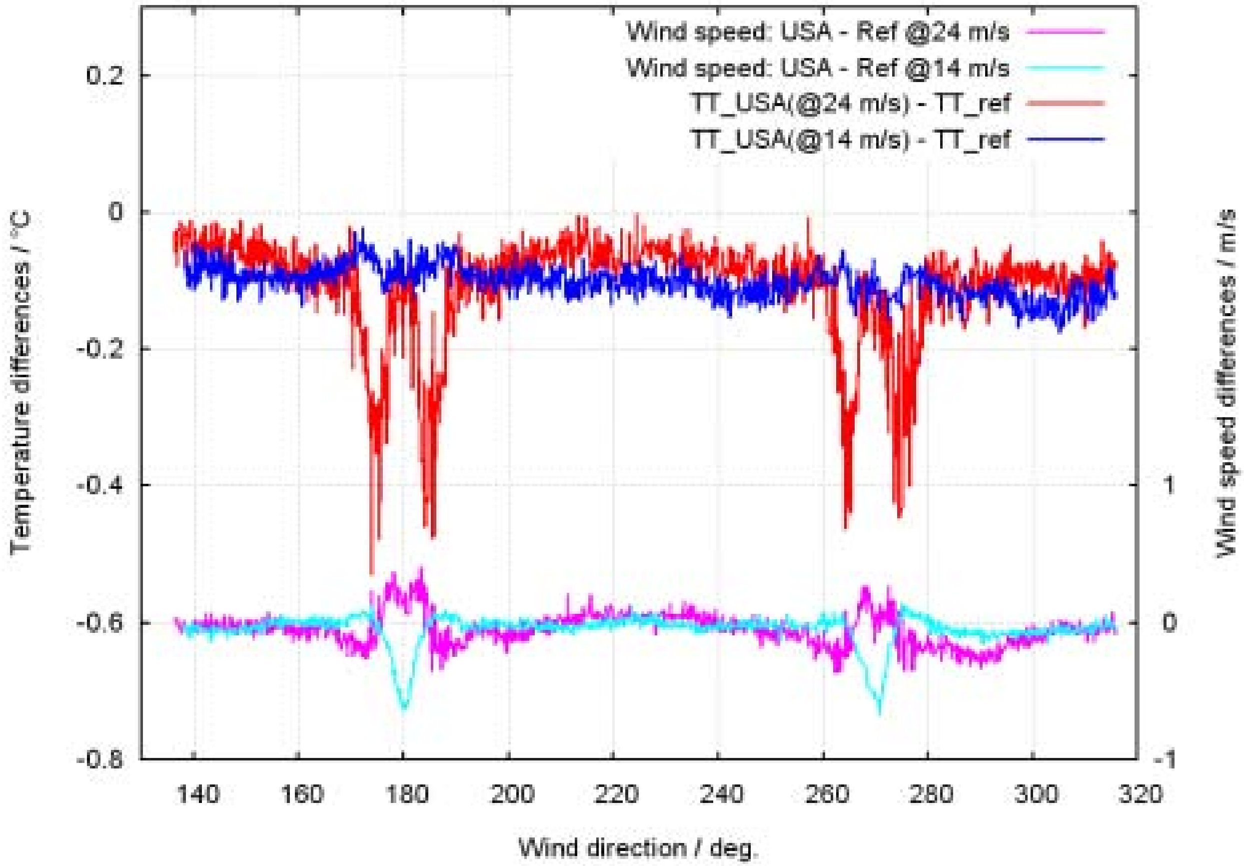

Figure 4: Temperature differences between the ultrasonic anemometer and the Pt100 reference at 20°C and wind speeds of 14 m/s and 24 m/s (upper curves) plotted against wind direction. The lower curves show the corresponding wind speed deviations of the ultrasonic anemometer.

According to equation 6 the crosswind component causes a temperature deviation of $u^2/(\gamma_d R_d)$, which amounts e.g. to 0.5 K at 14 m/s and 1.4 K at 24 m/s. In the plot in Figure 4 this correction has been applied and it is shown that the compensation generally works well. The sonic temperatures deviate only by - 0.1 K from the reference which is partly due to imperfect calibration of the measuring sections at temperatures around 20°C (see Figure 2). Figure 4 shows that the largest deviations in acoustic temperature (approx. 0.5 K at 24 m/s) and wind speed coincide at wind directions of 180° and 270° where the ultrasonic transducers are mounted. Thus these deviations originate from the transducers disturbing the wind field at higher wind speeds. For precise sonic temperature measurements it is therefore essential to correct these wind speed errors.

Conclusions

For precise sonic temperature measurements the measuring sections of a sonic anemometer have to be calibrated with respect to its temperature dependance inside a zero-wind calibration box. By means of the resulting temperature characteristic an accuracy of less than 0.1 K can be achieved in zero wind speed conditions. The source of the observed temperature dependence of the Thies anemometer has to be further investigated and sonic anemometers of other manufacturers should be tested as well.

It has been shown that the influence of the crosswind component can be compensated very well for wind speeds up to 14 m/s. At higher wind speeds turbulences originating from the ultrasonic transducers disturb the measurements of wind speed and acoustic temperature. A sophisticated correction algorithm for the wind speed as a function of wind direction and speed has to be developed to provide precise temperature measurements under all conditions. Further comprehensive wind tunnel experiments are necessary to establish an effective method.

The results encourage us to use a temperature calibrated ultrasonic anemometer as a temperature reference for an analysis of the measurement errors caused by a weather screen. Knowing the time lag of a thermometer-screen system as a function of wind speed it is possible to apply the respective time constants to the sonic temperature data that are virtually free of any time lag. Thereby it should be possible to separate the intrinsic lag effects from "real" screen errors like radiative heating, psychrometric cooling and others.

Application of ultrasonic anemometers for measuring temperature at mountain sites benefits from lower temperatures resulting in a reduced influence of water vapour on the acoustic temperature. On the other hand an accurate wind correction is indispensable and the influence of the automatic heating for deicing the sensor on the temperature has to be investigated.

Acknowledgements

The authors wish to thank Manfred Theel from DWD in Hamburg for his valuable contributions to these measurements and also for assisting the evaluation by fruitful discussions. Special thanks go to Horst Niemand for building the calibration box in a very short time.

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