SYSTEMATIC DEVIATION IN

ANEMOMETER CALIBRATION DUE

TO GEOMETRICAL INTERFERENCE

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Version 2.1

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1 Introduction

A general requirement of the *ISO Guide to the expression of uncertainty in measurement* [1] is that corrections in calibrations must be applied for every perceived systematic effect. As anemometers are calibrated in wind tunnels whose dimensions, due to economical and practical reasons, are much smaller than the environment in which the anemometers operate, systematic deviations take place and therefore must be taken into account.

The presence of an anemometer affects the flow field in the wind tunnel. During calibration the flow around the anemometer will be affected to some extent by wind tunnel blockage effects and mounting effects such as length and diameter of mounting pole and missing base closure in the wind tunnel.

In this report, results from measurements regarding this problem performed at the Deutsche WindGuard wind tunnel, in the 2005 – 2010 period are presented.
The purpose of this measurements was to reduce the total uncertainty in anemometer calibration down to 0.05 m/s (coverage factor k=2) in the range of 4 m/s to 16 m/s. This was confirmed by the ***Physikalisch Technische Bundesanstalt (PTB)*** in August 2009. PTB is the national metrology institute (NMI) or Bureau of Standards of Germany.

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Deutsche WindGuard
Wind Tunnel Services GmbH

Varel, 18.04.2011

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Deutsche WindGuard Wind Tunnel Services GmbH accredited according to DIN EN ISO/IEC 17025: 2005 by Deutsche Kalibrierdienst (DKD) of Physikalisch-Technische Bundesanstalt (PTB) for calibrations of anemometers.

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2 The WindGuard Wind Tunnels

Since 2009 Wind Guard Wind Tunnel Services is operating a second calibration wind tunnel in addition to its first wind tunnel. Both wind tunnels are identical with respect to geometry. Wind tunnel II has the capability to reach higher flow speeds through the use of a stronger fan unit with higher installed power.

As of July 2010 the Physikalisch-Technische Bundesanstalt, PTB (the national metrology institute of Germany) is using the wind tunnel II as a facility to embody the German national standard for the flow speed of air enabling to perform research and calibrations on larger test items. The national standard of flow speed is hence realized through a permanently installed, PTB owned and calibrated, Laser Doppler Anemometer (LDA) within our test section of Wind tunnel II.

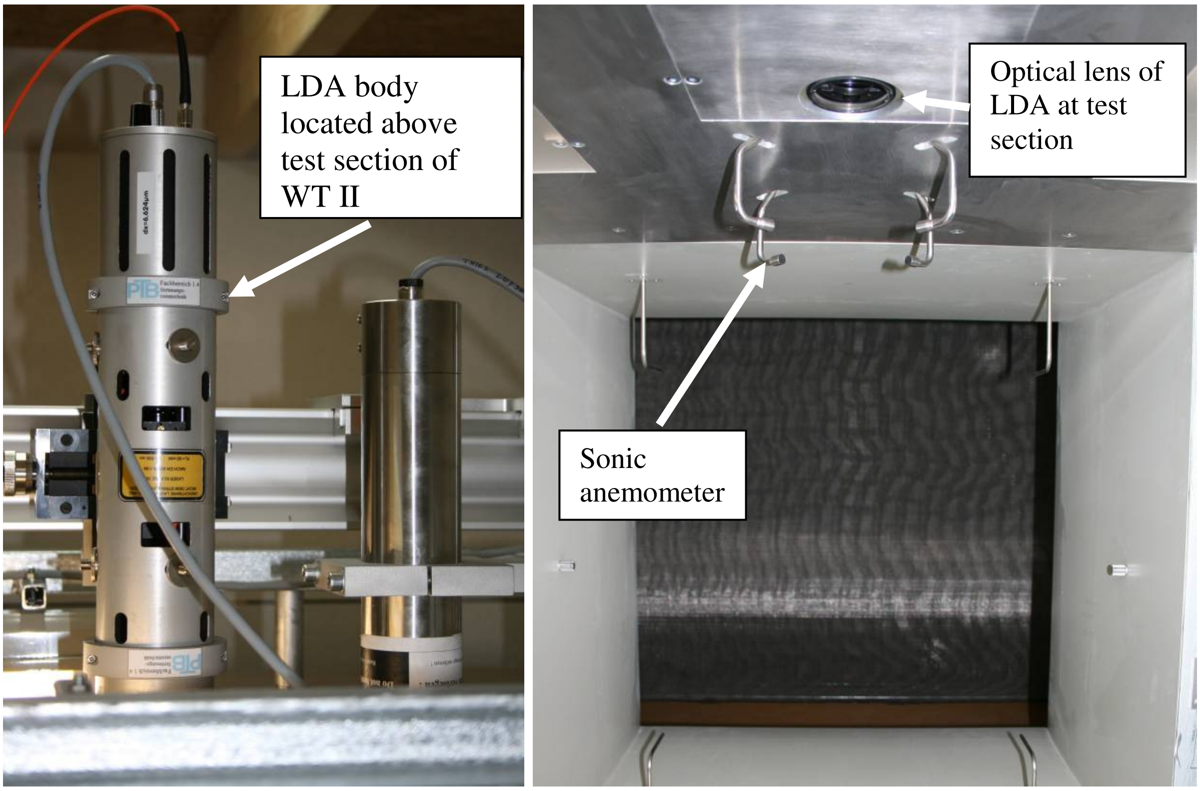

Figure 1: Permanently installed Laser Doppler anemometer (PTB owned) installed above the test section of Wind Tunnel II

Wind tunnel I and II of Deutsche WindGuard GmbH are characterized by a particularly homogeneous flow with low turbulence. They feature active turbulence elements, as well as the possibility of producing very small flow rates (<0.1m/s). Additionally, they allow investigating the behaviour of flow sensors at different tilt and yaw angles.

The wind tunnels were conceived mainly for the calibration and scientific investigation of anemometers and other wind sensors. On this basis, the following design criteria were laid:

- Flow speed in the empty test section up to 20 m/s for wind tunnel I
- Flow speed in the empty test section up to 38 m/s for wind tunnel II
- Excellent flow quality in space and time
- Displacement relationship (Blockage ratio) for conventional anemometers < 3%
- Dynamic tests capability
- Tilting tests capability
- Yawing tests capability
- Ease of anemometers mounting
- Good accessibility to test section

Based on these criteria and constraints, the preferred tunnel design is the closed-circuit configuration tunnel. It offers better control of the flow conditions such as pressure, temperature, noise and it also reduces the necessary power to operate the wind tunnel at a given speed in comparison to an open circuit tunnel. A 1.8 m long test section with a cross sectional area of 1m x 1m was chosen. This gave ample room for mobility and provided an acceptable blockage ratio for anemometer testing. In order to conduct angle of attack tests on the sensors, a tilting device was attached to the frame of the working section, allowing for a ± 31 deg forward and backward movement. Space provisions to install a turntable with a step motor to gradually rotate sensors in the test section were also taken into consideration. To achieve a high-quality flow, the settling chamber consists of a special honeycomb/screen arrangement of five screens and one honeycomb. Calculations were performed in order to determine the size of individual wind-tunnel components, the pressure variation and flow speed in different sections of the tunnel. These calculations were based on well proven values of diffuser angles, contraction ratios and pressure drop coefficients**.** Consequently a fan unit was chosen to compensate the pressure loss and produce the desired wind speed at the test section at low noise levels. *Figure 2* shows the wind tunnel I at the Deutsche WindGuard headquarters.

Figure 2: Wind tunnel I of Deutsche WindGuard Wind Tunnel Services GmbH used for anemometer calibration and testing (picture dated 2005)

The wind speed perceived by an anemometer during calibration cannot be measured directly, thus the wind tunnel must be 'calibrated'. This involves correlating conditions at a reference position with those at the position to be occupied by the anemometer rotor during anemometer calibration. The wind tunnel calibration factor, which indicates the relation between the reference measurement position and the anemometer position, was determined by using pitot-static tubes. Using six pitot-static tubes, four at the permanent reference position and two at the location to be occupied by the anemometer to be calibrated, the wind tunnel calibration was carried out. Due to the high pressure region in front of the anemometer to be calibrated the reference pitot-static tubes can be influenced by the presence of the anemometer. As shown by Dahlberg [15] this can have a significant Influence in calibration results. *Figure 3* represents the influence in the reference measurements due to a large-size anemometer found on the market today. For distances of more than 60 cm downstream from the nozzle outlet of the wind tunnel no significant influence in the indicated pressure of the pitot-static tubes can be seen.

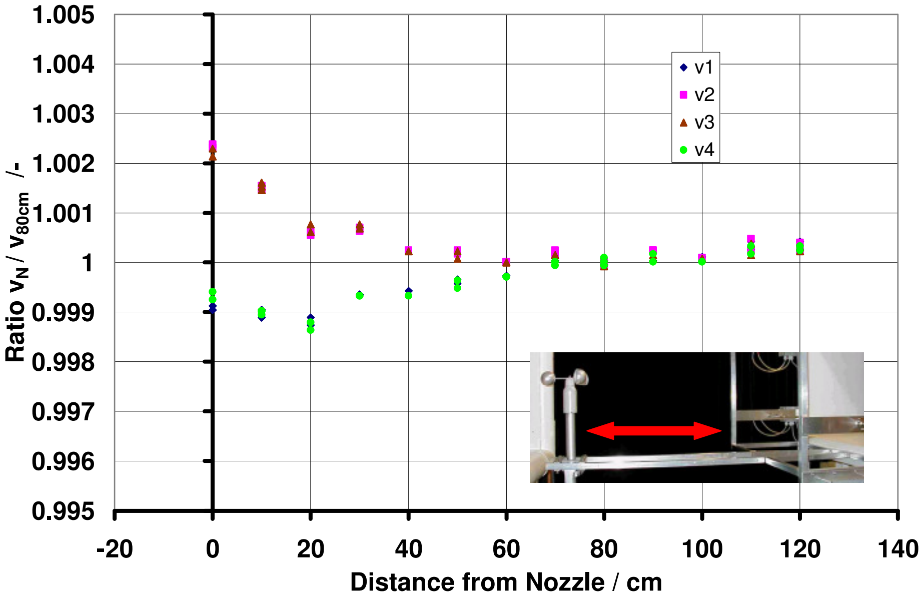

Figure 3: Anemometer influence on reference measurements. For distances of more then 60 cm downstream no significant influence in the indicated pressure of the pitot-static tubes can be seen.

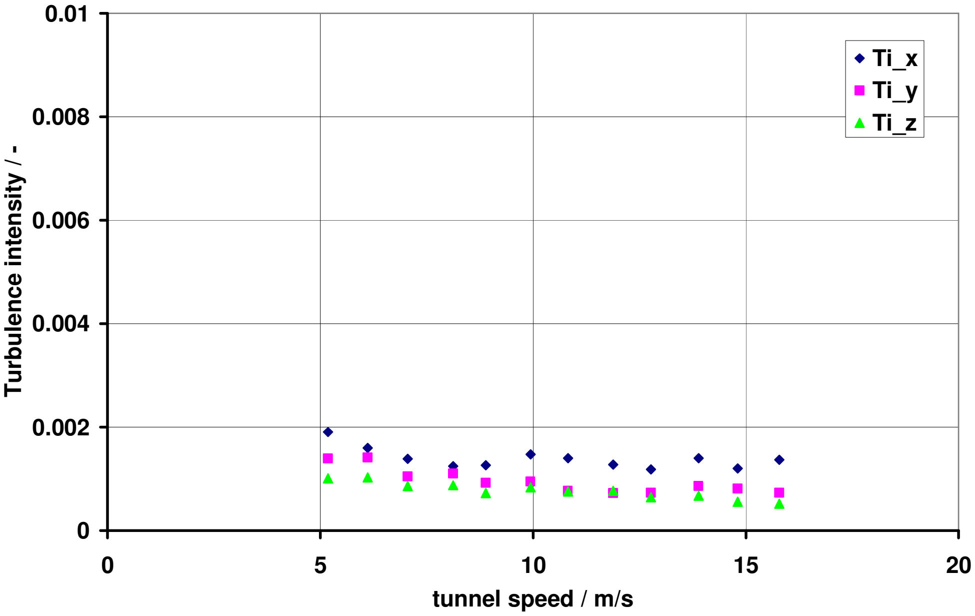

Figure 4: Turbulence intensity in the test section measured with a Gill-3D ultra sonic anemometer (sampling 4 Hertz).

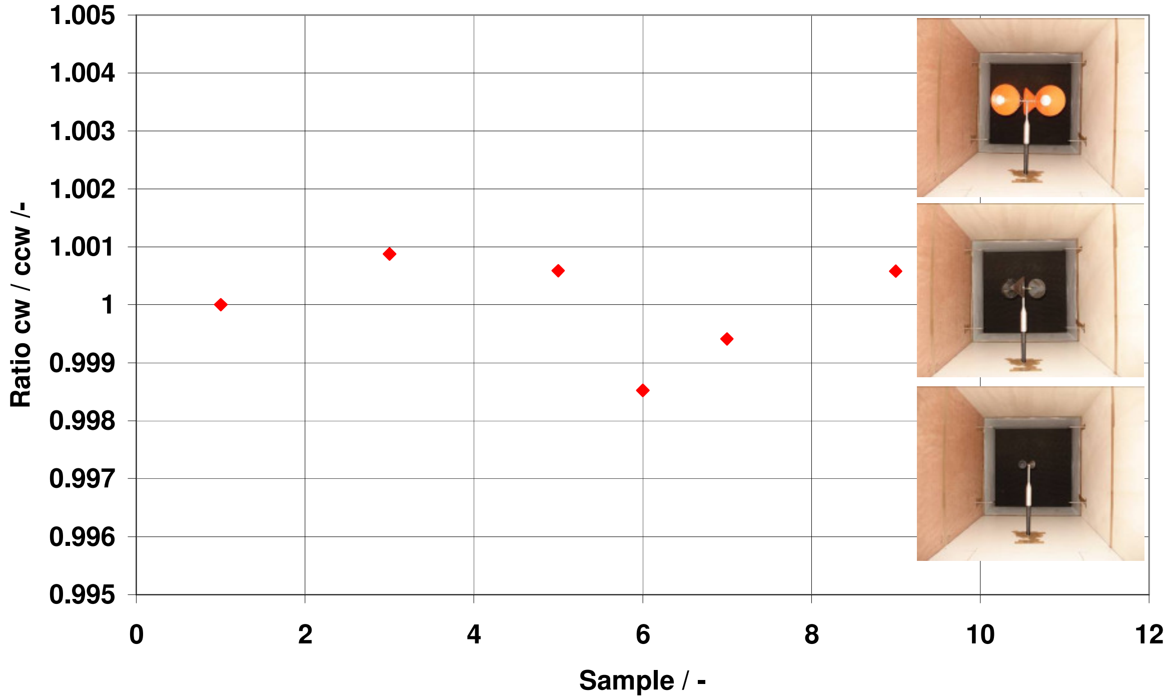

Figure 5: Horizontal wind profile measurements with 3 different cups running clockwise and counter clockwise.

3 Blockage

3.1 Disk measurements

An important problem that – because of a limited test section size – affects all wind tunnel tests is the influence that the test section boundaries have upon the test object. This also applies to the apparently nonexistent boundaries of an open test section. The flow around a body in a closed test section will be accelerated because of compressing effect of the walls. In an open test section, the flow lines are allowed to deviate around the object because of the lack of flow outside the test section. The consequence of this is that for open test sections the flow speed at the test-object's location will be reduced in comparison to a free air flow. The main question to answer when determining forces acting upon an object within the flow is what undisturbed flow is required in a wind tunnel for it to exhibit the same physical reaction as in an undisturbed free air flow. The influences upon the object (blockage) because of the constraining test section boundaries are mainly dependant on the following factors:

- Test section type (open, closed, other configurations)
- Ratio of the model projected area (S) normal to the flow to the test section cross sectional area (C) (S/C=Blockage Ratio)
- Model drag (C_D)
- Wake size

Several experimental investigations have been performed in closed test section wind tunnels [14,19] but the open test section case has not been thoroughly investigated. We have systematically investigated this case in our wind tunnel, in which the wind tunnel was operated with open, closed and partial closed test section [16]. The results obtained from the closed test section tests agree with the results from known measurements [14,19], but the results from open and half-open configurations show important deviations from the regularly accepted theories [13]. This phenomenon has also been demonstrated by other authors [18]. *Figure 6* shows results from a flat circular disk drag test, in which the blockage ratio was varied by using different sized disks for several test section configurations. It is clearly evident that the configuration consisting of a base and top plate shows the smallest blockage effects when the blockage parameter lies under 0.15.

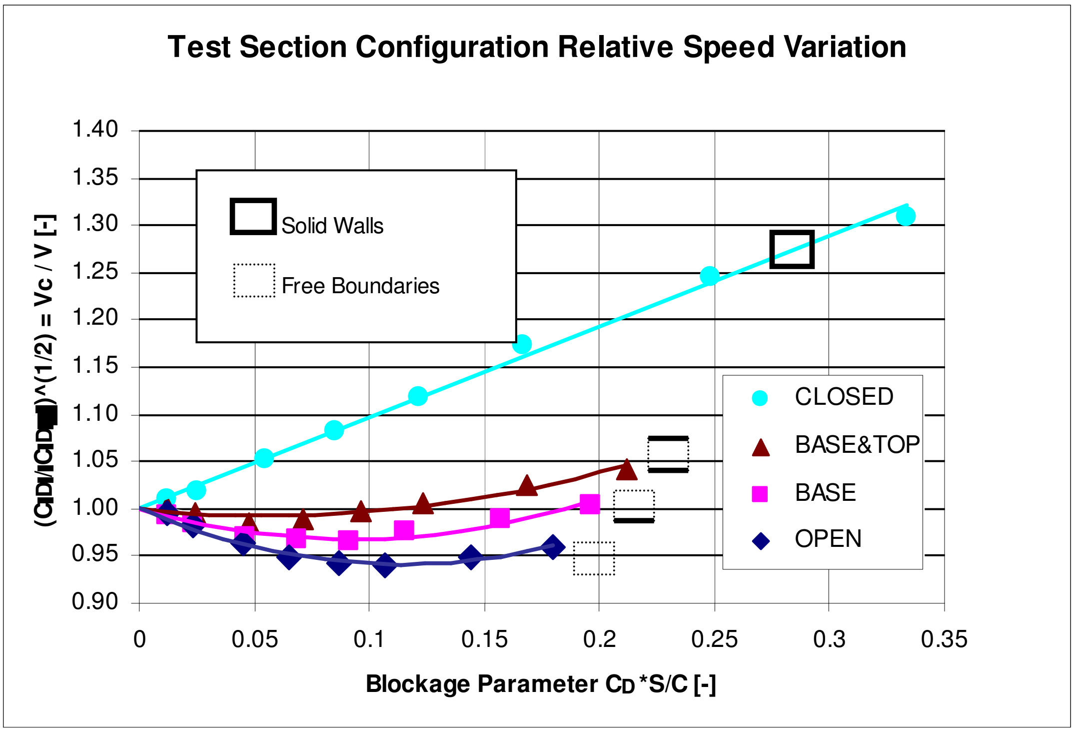

Figure 6: Relative speed variation as a function of blockage

3.2 Anemometer measurements

As it is not possible to scale anemometers directly, several tests were performed with 3 different sized commercially available anemometers and a set of 3 specially constructed different sized cup sets, used previously by Dahlberg [15]. Even though the magnitude of the speed increase was different to what was experienced in disk drag tests, results agree with the blockage trends shown by the disks, and again, the test section configuration consisting of a base and top plate exhibited the smallest blockage effects.

Based on the assumption that blockage effects are negligible for the base and top plate configuration for low blockage ratios, frequency outputs were normalized with the results from the test with base and top plate, and are displayed on *Figure 7*.

This graph is the most important one of all concerning anemometer blockage. It allows a direct correction for the different types of tested anemometers. As the frequency an anemometer displays is proportional to the wind speed, the ratio is as well, and the wind speed correction can be extracted directly from this graphic. It is important to note that these are wind tunnel / test section specific measurements, and are not necessarily valid for wind tunnels other than WindGuard wind tunnel.

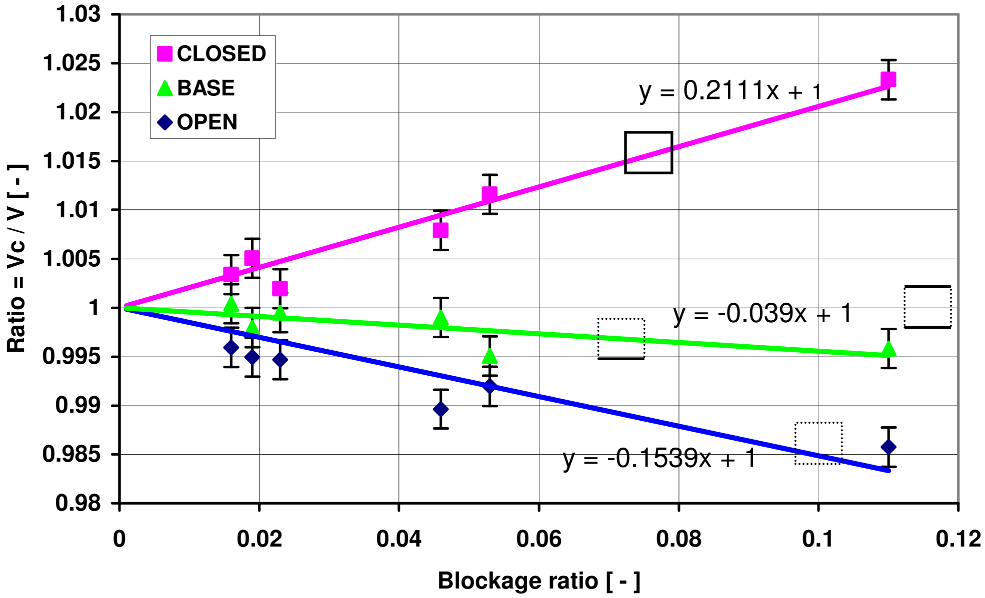

Figure 7:Deutsche WindGuard anemometer measurements normalized to measurements performed with a base and top plate only

An experimental method to investigate the blockage effects may also be achieved by calibrating anemometers of varying sizes (blockage ratios) in a substantially larger test section [15]. The results measured at the "large" wind tunnel can be used to normalize the findings of the investigation obtained in wind tunnel I.
These investigations were performed in the "large" wind tunnel of Deutsche WindGuard located in Bremerhaven. The dimension of the test section is 2.9 X 1.9 m. This equates to a cross sectional area which is 5.5 times larger than that of wind tunnel I and II in Varel (note *Figure 8*). The blockage effect for the "large" wind tunnel is negligible for common anemometer (sizes) and therefore justifying the relative comparison of the calibration results. No noticeable blockage induced effect can be noted in the results as depicted in *Figure 9* within the general uncertainties for such measurements.

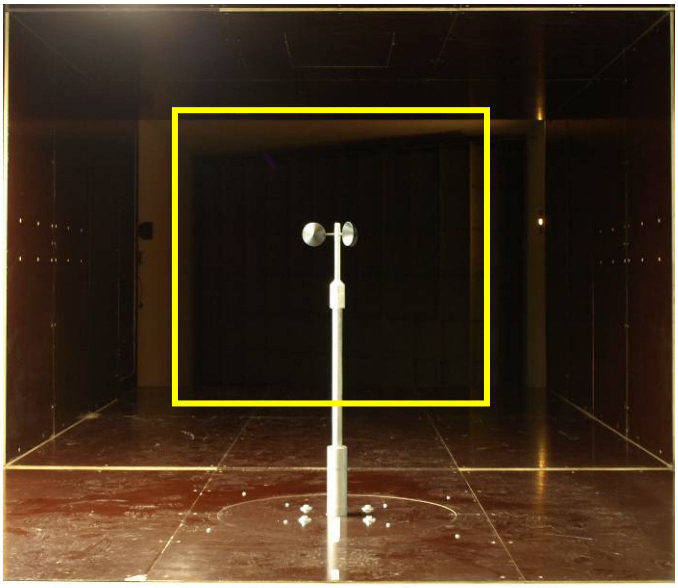

Figure 8: anemometer mounted in the „large" wind tunnel of Deutsche WindGuard. The yellow square resembles the dimensions for the test section of wind tunnel I

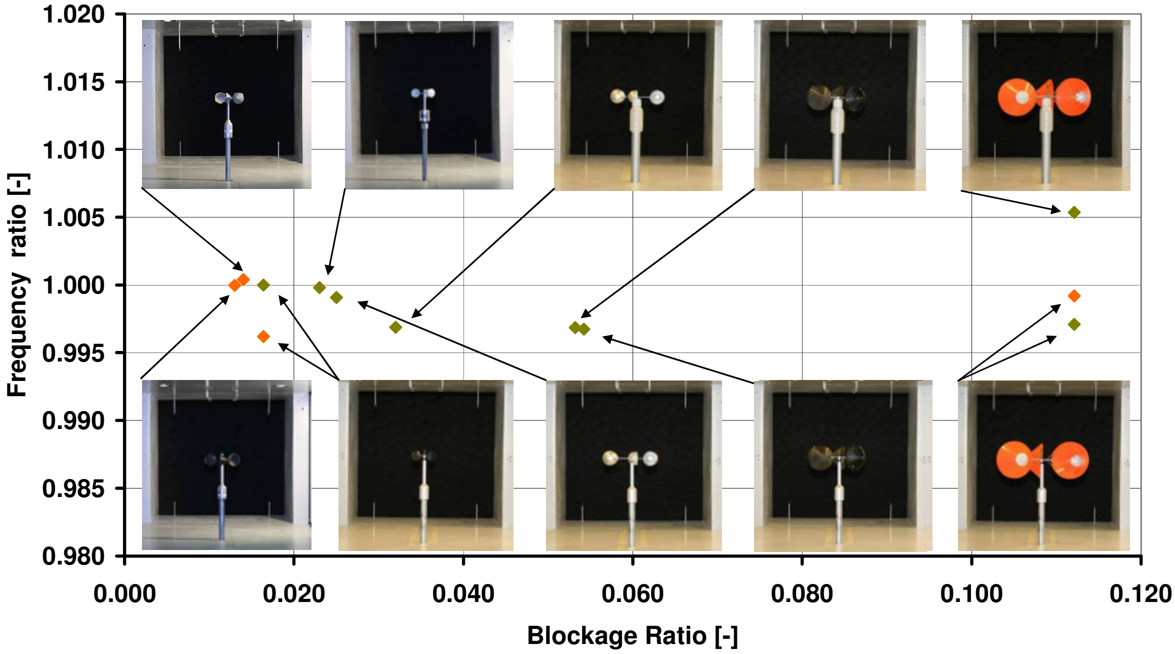

Figure 9 Shows the frequency ratios ($f_{WT\,I}$ / $f_{largeWT}$) for different blockage ratios (for WT I with boundary plates at the top and bottom). The orange marks denote results from previous measurements. The green marks denote results from measurements performed in 2009

4 Base Plate

4.1 Base Plate

The mounting tube causes a positive pressure region in the upwind direction that is dependant on the tube's diameter. If the tube is seen in a two dimensional way, the result is a uniform pressure distribution below the anemometer. If the test section has no bottom closure, the flow caused by the positive pressure can unrestrictedly divert downwards. This causes a considerable momentum loss that an anemometer at a close distance can detect. With a base plate or alternatively a long mounting tube in a big wind tunnel this effect is negligible. In the DWG wind tunnel, the distance is only 50 cm. This causes, as can be seen in *Figure 10*, an evident speed reduction that depends on the tube's diameter. This effect cannot take place when a closed base is in place; hence calibrations are performed with a base plate in the test section.

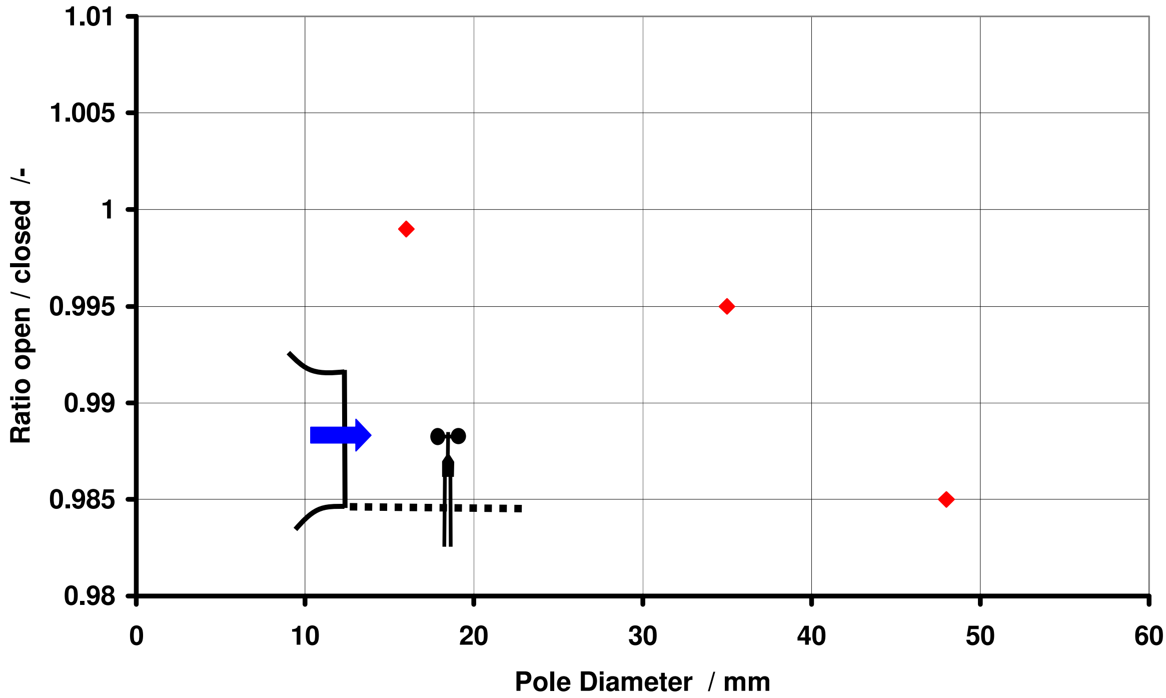

Figure 10 Relative speed variation (closed – open bottom) as a function of pole diameter

5 Anemometer position in test section

5.1 Ideal Position

Intuitively one would adopt the middle of the air jet as the optimal location for a calibration in a wind tunnel. Although this assumption is apparently correct for symmetrical objects, it is not valid for anemometers that are mounted on a tube. *Figure 11* shows an anemometer's response (Risoe P2546A) for different installation heights and constant speed. It is clearly noticeable that anemometers rotate faster by increasing tube length. Not until a height of 60 – 70 cm above the lower edge of the nozzle does the anemometer's rotational speed evidence hardly any measurable variation.

Note: Such an effect could also be caused by an inappropriate profile in the wind tunnel. This effect had been until then not taken into account in calibrations, and the results where so impressing that further investigations were performed, to be sure, that it actually is a support tube-length effect and not of the wind tunnel. In *Figure 12* the tube length was gradually increased from below, and additionally the same procedure was performed from above. The effect is clearly noticeable.

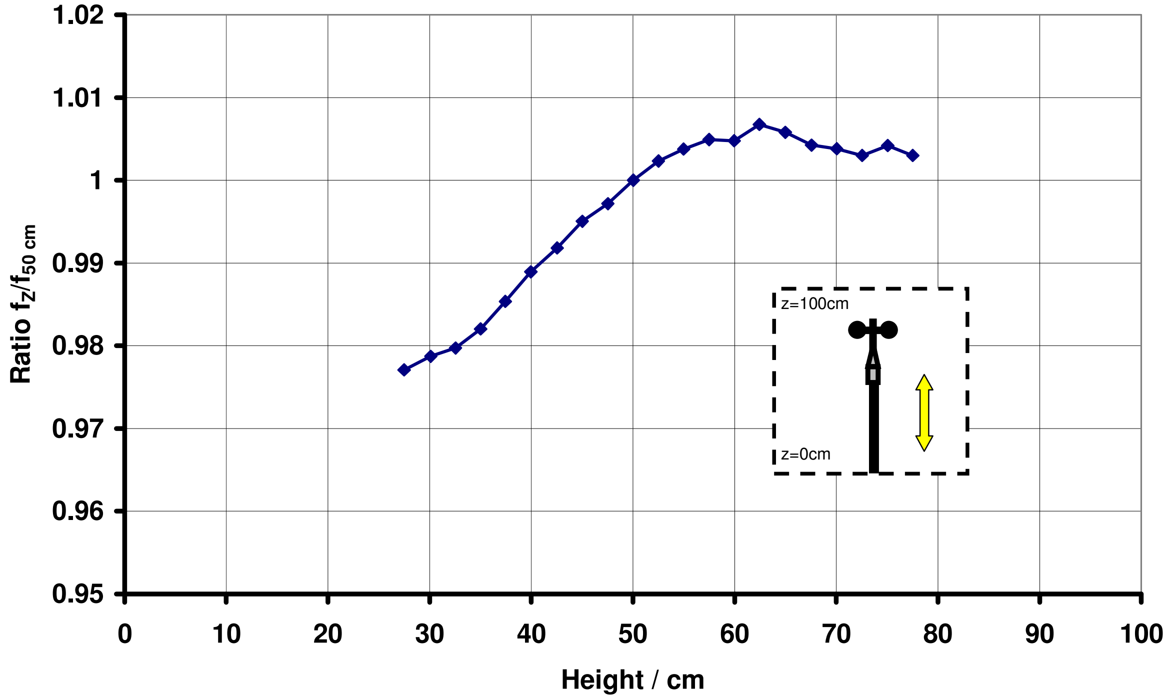

Figure 11 Relative speed variation as a function of pole length

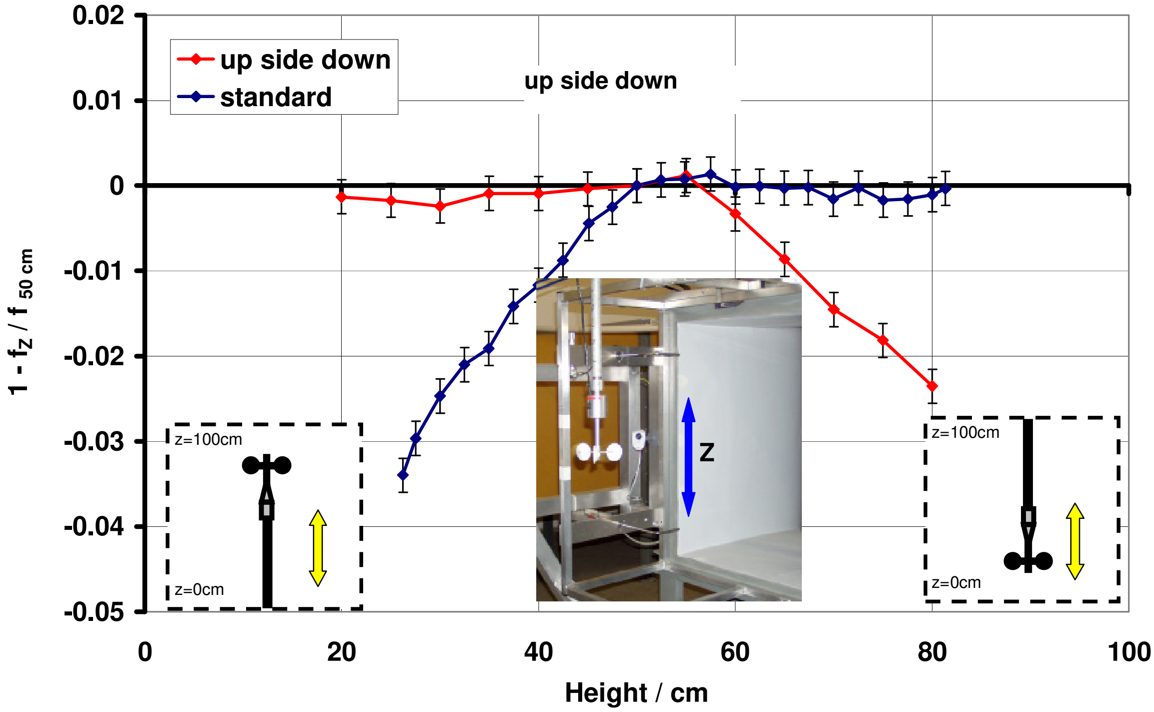

Figure 12 shows the investigation performed with an anemometer (Vector A 100 L2), which was once mounted as usual (standard, blue line) and then in an inverted manner while the height respectively varied. Both characteristic curves exhibit the same trend and that the anemometer does not reach a stable output value until it has 50 cm free tube length.

5.2 Mounting Position

Normally wind speed measuring anemometers are mounted upon a measuring mast of considerable length. The mast length is several times longer than the tubular strut used for wind tunnel calibrations. Because of this length reduction, two effects arise in wind tunnels with open test sections, which cause systematic deviations. One effect is that the flow can divert downwards because of the lack of flow under the test section's lower boundary, causing a reduction of the flow that effectively acts upon the cups. The other effect is that the drag of a mounting tube (cylinder) is highly dependant from the diameter (D) to length (L) ratio. With increasing D/L ratio the drag is increased asymptotically until it reaches an extreme value of 0.6 by no less than a D/L ratio of 50. This means that the support tube length must be at least 20D. From *Figure 13* and *Figure 14* it is notably visible, that the threshold is 50 cm in the test section with a base closure and 70 cm in a wind tunnel with an open test section.

Results from tests in two different wind tunnels (80 cm height and 100 cm height respectively) show in an evident way, that depending on size and diameter of the mounting tube, at least 60 to 70 cm above the lower boundary of an open test section and approximately 50 cm above the base closure are required in order to be independent from the length of the mounting tube.

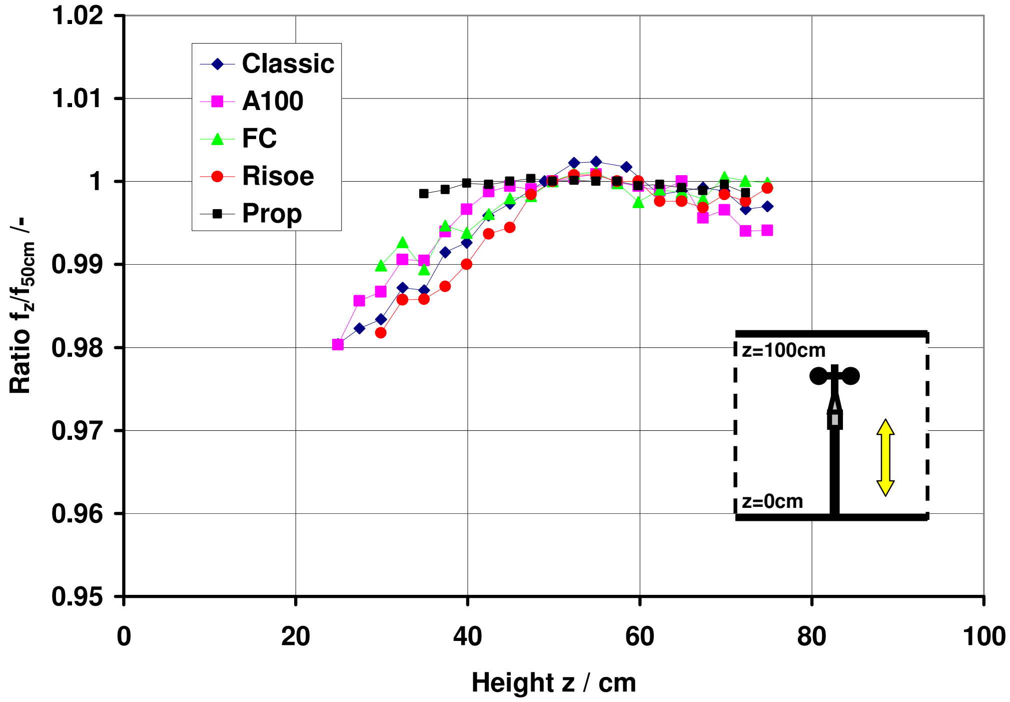

Figure 13 Relative speed variation as a function of pole length for different anemometers (base closure)

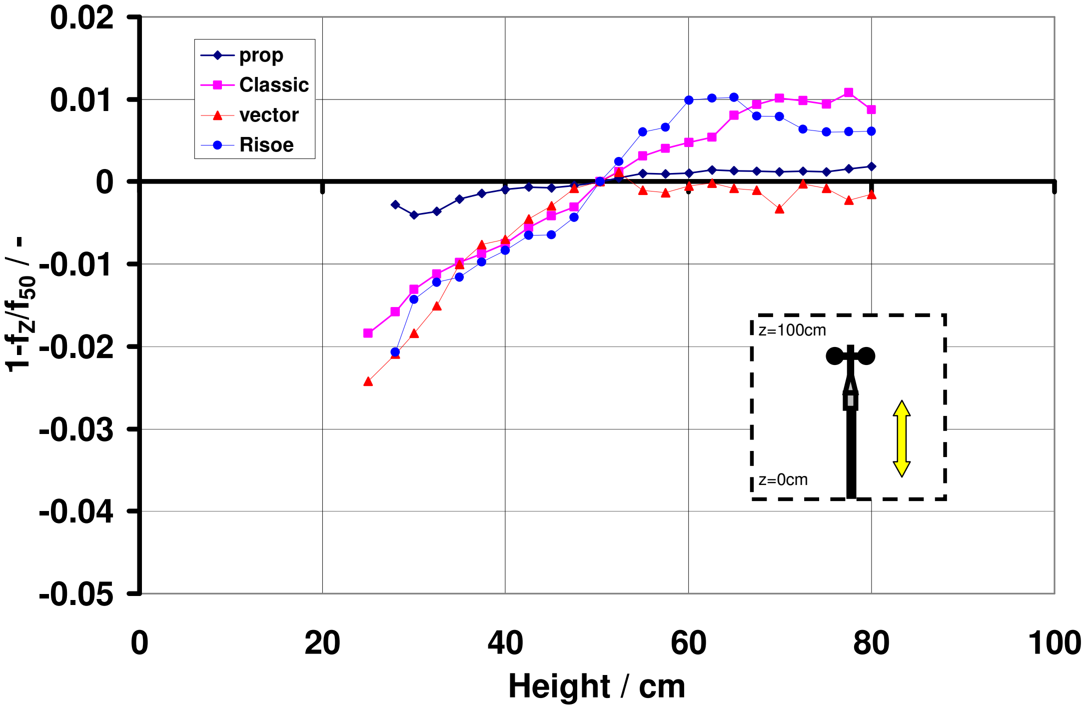

Figure 14 Relative speed variation as a function of pole length for different anemometers (no base closure)

6 Anemometer Tilting

The determination of the anemometer's response to statically inclined air flow is done with the help of an automatic tilt angle device installed in the wind tunnel.

During the measurements, the anemometer is slowly tilted back and forth with a sweep rate of about 0.03°/sec to approx ±30° (±8°) for approx. 60 Minutes. Any influence on the results due to this rotational speed can be neglected. If the anemometer signal has a rather low resolution a stepwise tilting is applied. No tilting is performed during the first 300 seconds to ensure that sufficient data fall into the zero bin (±1°; ±0.1°). This data can be used for normalization.

As the behaviour of an anemometer is strongly influenced by the free space around and especially underneath the anemometer, it is important that during the variation of tilt angle the anemometer rotor should remain within the pivot axis of the tilt device. This will avoid additional uncertainties from changes due to a possible wind profile in the test section. The tilt angle, the output of the anemometer and all other relevant signals are sampled with 10 Hertz.

In order to allow for a sufficient movement of the mounting pipe during its tilting action it is necessary to slot the bottom boundary plate. This slot would unfortunately permit a secondary flow affecting the primary flow within the test section. This adverse effect is avoided through the installation of a sliding cover designed to be flush with the bottom boundary plate of the test section.

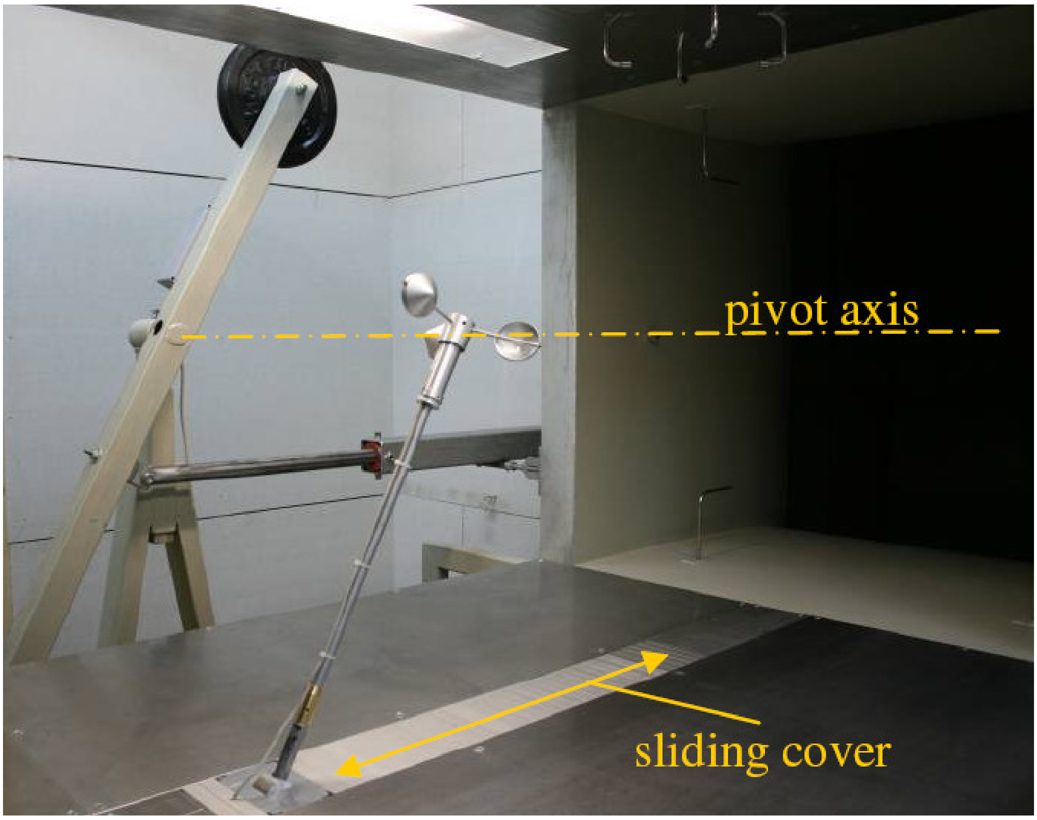

Figure 15 Tilting meachanism of WT II with sliding cover

Most cup anemometers show a response to inclined flows that noticeably deviates from the cosine of the angle of incidence. *Figure 16* shows the relation of some cup anemometers by small incidence angles. The IEC tolerated deviation from the reference line should be 2° at the most. During wind tunnel calibrations the maximum allowed deviation is 1° (MEASNET). In simple terms this can lead to a 1% (0.5%) systematic deviation caused only by the tilted installation of an anemometer in the wind tunnel.

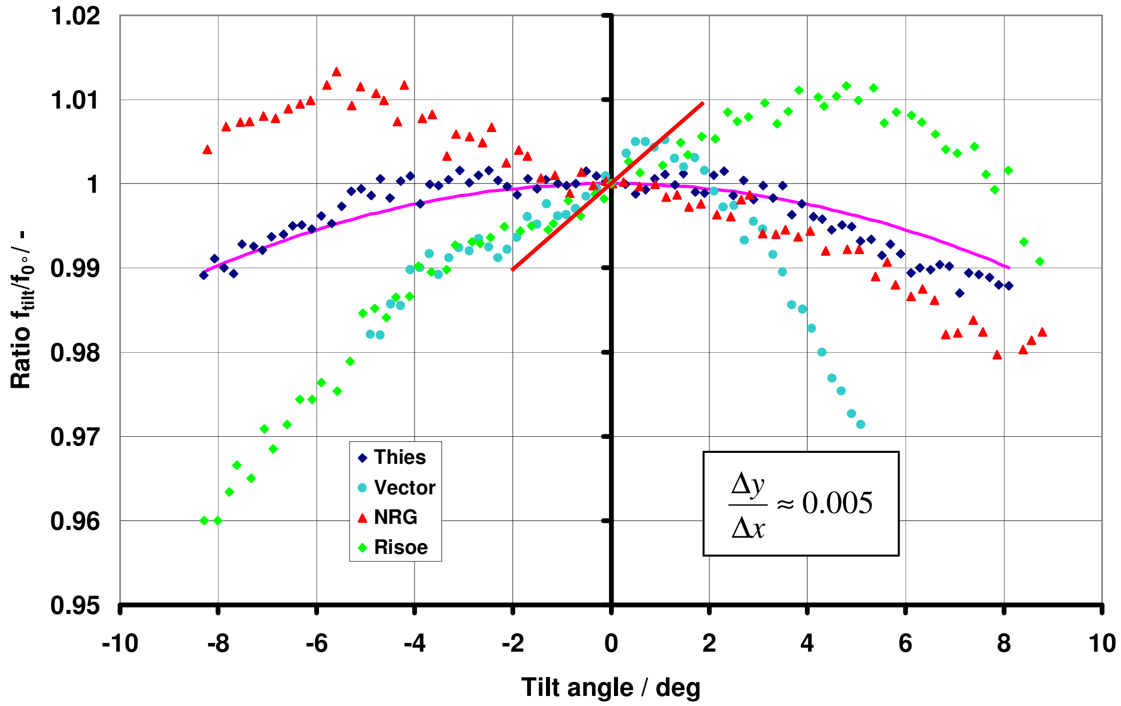

Figure 16 Relative speed variation as a function of tilt angle

7 Anemometer Mounting Pipe Diameter

It is known that the mounting arrangement with respect to pipe diameter will influence the wind speed “seen” by the anemometer. Wind tunnel tests have been performed to assess this effect. The results are depicted in *Figure 17*.

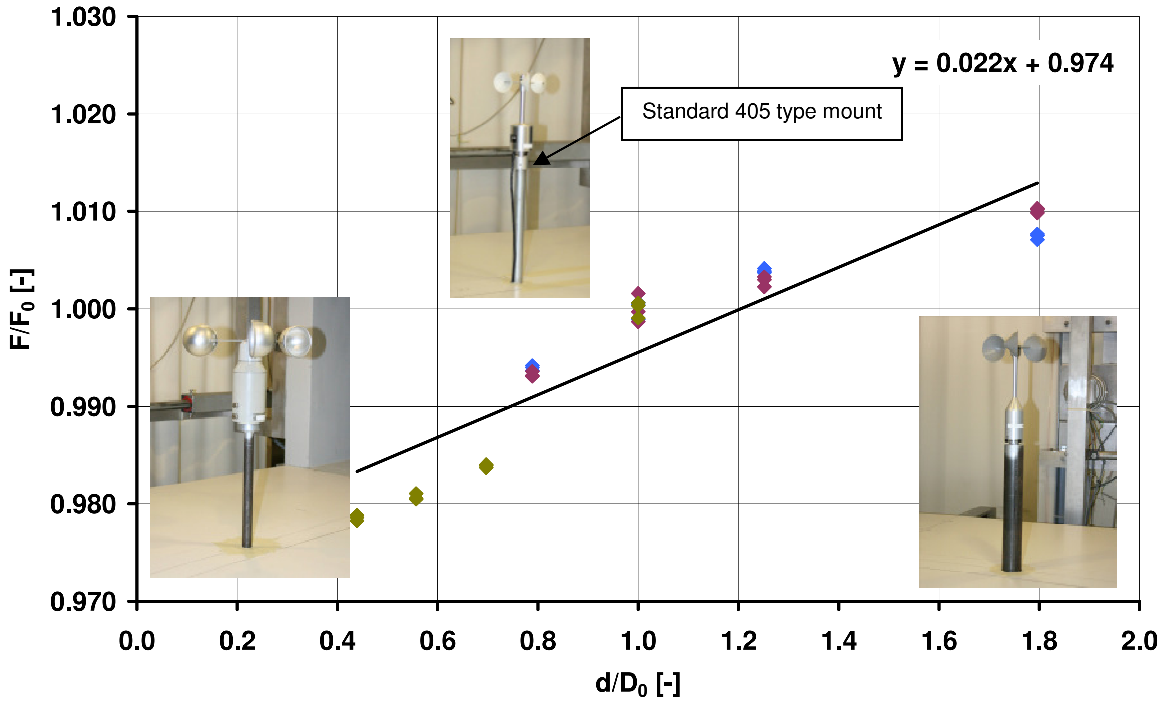

Figure 17 Influence of the anemometer frequency for varying mounting pipe diameters. D_0 and F_0 =1 denote values for the manufacturers standard pipe diameters. Green marks identify values for the Thies Classic anemometer. Blue marks identify values for the Risoe anemometer. Magenta marks identify values for the A100 type anemometer.

8 Summary

The total uncertainty budged that has to be considered during anemometer calibration is made up of multiple factors. It could be demonstrated within this report that a geometric interference through an interaction of the anemometer under test and the flow within the wind tunnel may be substantial. It is therefore important to know each one of these contributions in detail so a meaningful assessment of the total uncertainty can be accomplished.

An overview of the general parameters contributing to the total uncertainty budged for anemometer calibrations is depicted in *Figure 18*.

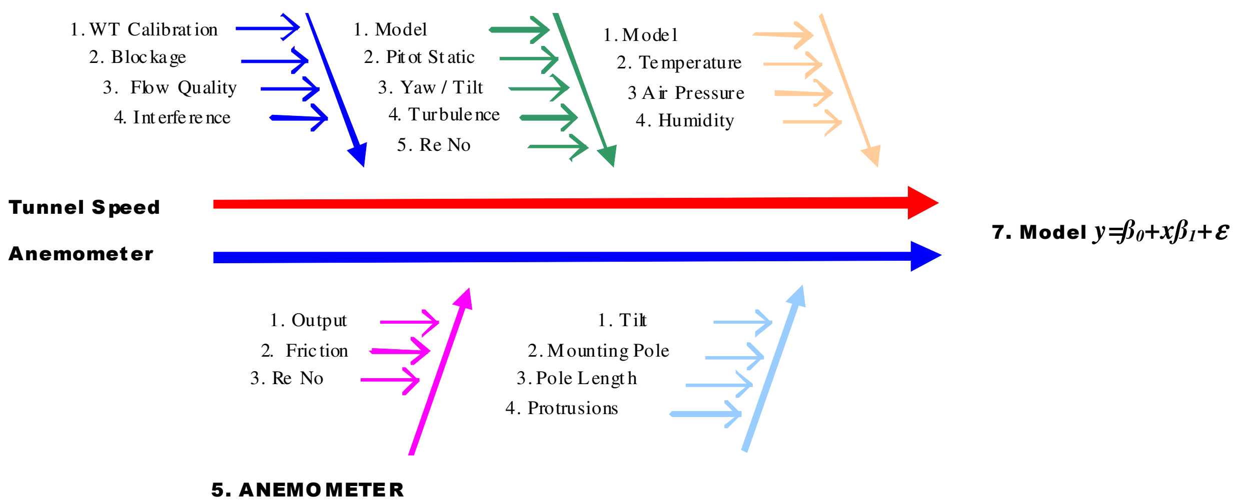

Figure 18 General uncertainties influencing the performance during anemometer calibrations

A more detailed graph describing the magnitude of each uncertainty parameter is presented in *Figure 19*. The results presented here are for a typical anemometer and a typical calibration setup/ wind tunnel.

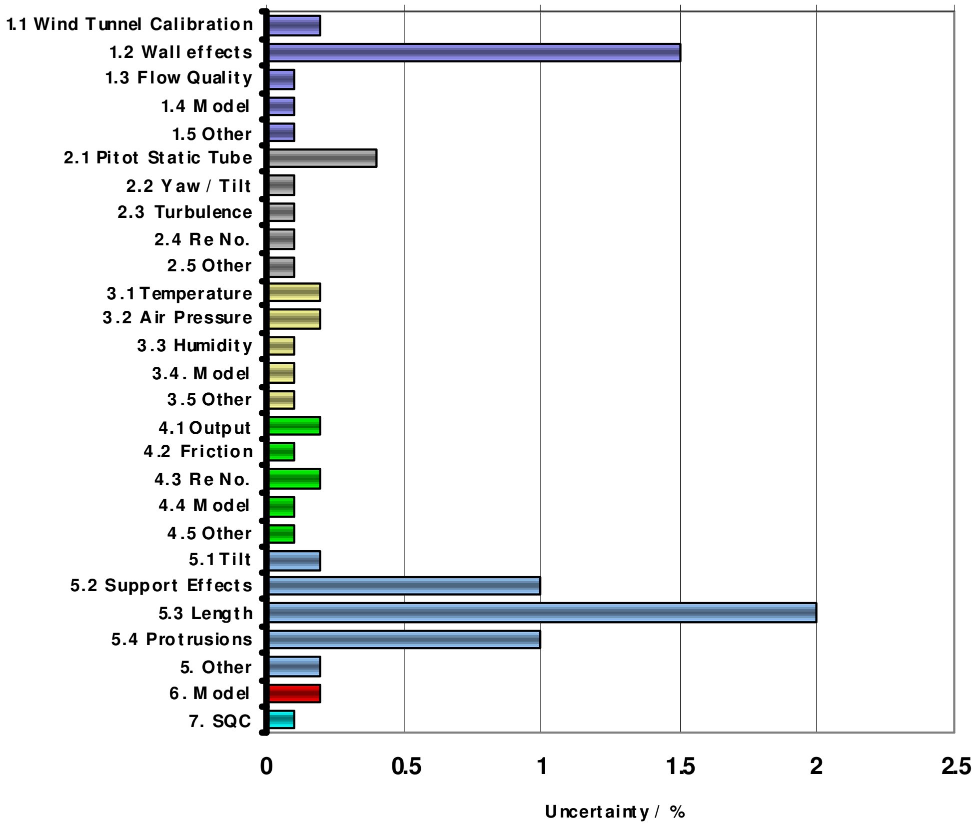

Figure 19 Overview of the individual factors contributing to the general uncertainty budged.

A more in-depth diagram of the uncertainty parameters for wind tunnel I and II are presented in *Figure 20*. The individual uncertainty factors are also a function of wind speed. Therefore the distribution of the individual uncertainties for each wind speed range is presented below. The values for the total uncertainty pictured thereafter are determined for a coverage factor of K=1. That means that about 68% of the uncertainties for the measured values lie within a Gaussian normal distribution curve. The green bar with uncertainties due to geometry is comprised of wind tunnel wall effects, support effects, length of mounting pole and uncertainties due to protrusions within the mounting setup.

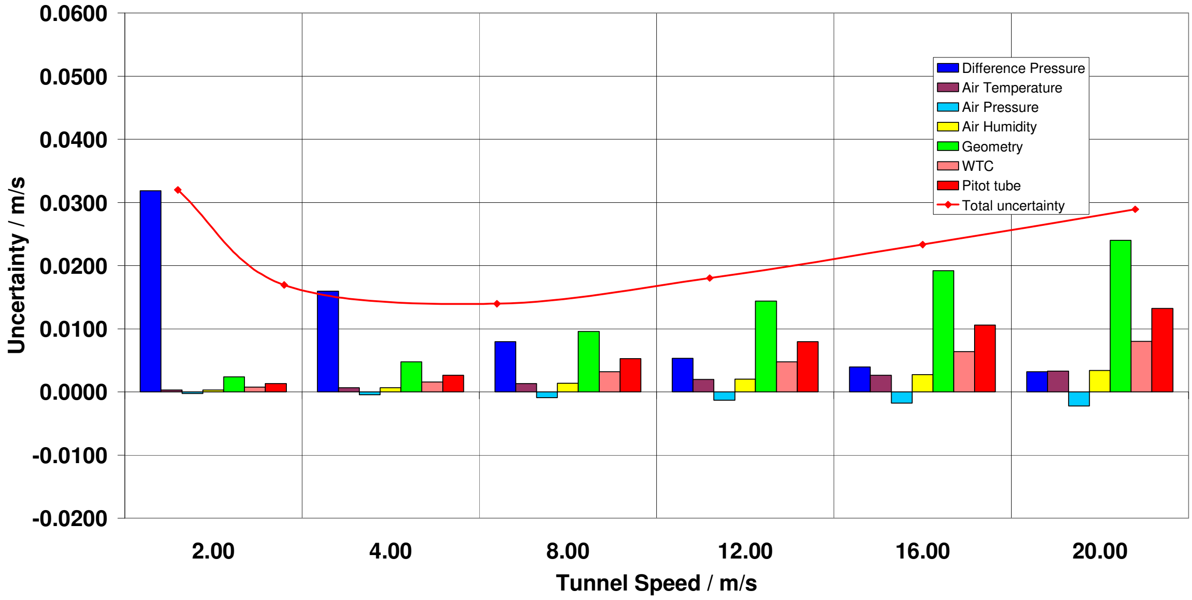

Figure 20. Detailed description of the individual uncertainties as a function of wind speed. The parameters depicted above are only valid for the uncertainty calculation applied to WT I and II of Deutsche WindGuard Wind Tunnel Services GmbH and may not be applicable for other wind tunnel facilities or calibration laboratories. Note: WTC stands for Wind tunnel calibration factor. Total uncertainty depicted is for a coverage factor of K=1 (68% of the uncertainties for the measured values are within a Gaussian normal distribution curve.

The accreditation of Deutsche WindGuard Wind Tunnel Services for anemometer calibrations was revised in 2009. The accreditation now allows for a reduction of measurement uncertainties down to 0.05 m/s in the range of 4 m/s to 16 m/s. The stated uncertainty of 0.05 m/s does include a coverage factor of K=2. That means that 95% of the stated uncertainties for the measured values lie within a Gaussian normal distribution curve. (for K=1 this uncertainty value would be reduced to 0.025 m/s, note also *Figure 20*).
Deutsche WindGuard Wind Tunnel Services is accredited by:

- Measnet:
  The international Measuring Network of Wind Energy Institutes (MEASNET) is a co-operation of institutes which are engaged in the field of wind energy and want to ensure high quality measurements, uniform interpretation of standards and recommendations as well as interchangeability of results

- DKD
  Within the system of Deutscher Kalibrierdienst (DKD) calibration laboratories of industrial firms, research institutes, technical authorities, inspection and testing institutes carry out calibrations. These laboratories are accredited and supervised by the Accreditation Body of Deutscher Kalibrierdienst. The traceability of all calibration measurements is embodied through the Physikalisch Technische Bundesanstalt (PTB). PTB is the National Metrology Institute (NMI) or Bureau of Standards of Germany.

Physikalisch-Technische Bundesanstalt

Braunschweig und Berlin

Bericht

Report

Validation of the traceability of the enhanced WindGuard calibration wind tunnel "Varel 2"

According to the cooperation agreement between the Deutsche WindGuard Wind Tunnel Services GmbH and the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, the WindGuard wind tunnel facilities are used to provide well defined reference wind speed conditions for the investigation of anemometer calibration procedures in order to ensure a high degree of equivalence for future calibration results of different anemometer types. Especially the enhanced WindGuard calibration wind tunnel "Varel 2", which has additionally been equipped with a PTB-LDA (Laser-Doppler-Anemometer) as reference standard, will serve as reference wind tunnel for PTB investigations.

For this purpose the traceability of the enhanced WindGuard calibration wind tunnel "Varel 2" located at the Deutsche WindGuard site, Oldenburgerstr. 65 in Varel, has been evaluated by performing comparison measurements with a non-contact transfer standard, serving as best available meter according to the BIPM recommendations.

As non-contact transfer standard a PTB-LDA traceable to the primary velocity standard had been applied. This transfer standard features an expanded uncertainty U < 0,3 % (coverage factor k = 2); it was recently used for laser based EURAMET comparison measurements and has been recommended for the implementation of future comparisons.

Based on the evaluation of the laser based comparison measurement the smallest uncertainty of measurement for the measurand wind speed in the enhanced wind tunnel "Varel 2" was assessed to be 0,05 m/s (k = 2) in the measuring range from 2 m/s up to over 18 m/s.

A short description of the comparison measurements, the instrumentation and the measuring results is given on page 2 of this report.

Im Auftrag:
By order:

Dr. Harald Müller

Braunschweig, 20.09.2010

Siegel
Seal

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT 41

393 008 k

Physikalisch-Technische Bundesanstalt

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Comparison measurements, instrumentation and measuring results

In the wind tunnel "Varel 2" an installed PTB-LDA reference standard is used to ensure the traceability of the wind speed measurements based on four installed Pitot static tubes of the NPL-type with ellipsoidal nose according to the standard BS ISO 3966 (see fig. 1).

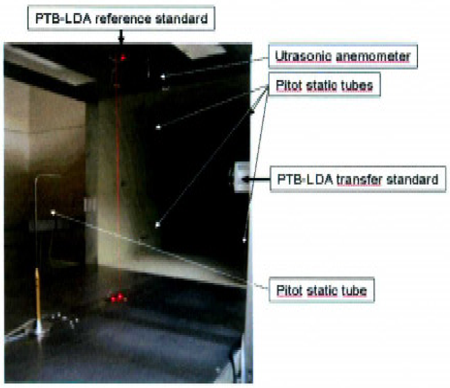

Figure 1: Measurement set-up in the wind tunnel "Varel 2"

The reference wind speed $v_{reference}$ determined by the four Pitot static tubes was directly compared with simultaneous velocity measurements at the measurement position 800 mm behind the nozzle outlet by the LDA reference standard and at a position 500 mm behind the nozzle outlet of the wind tunnel by the LDA transfer standard. The result is shown in figure 2.

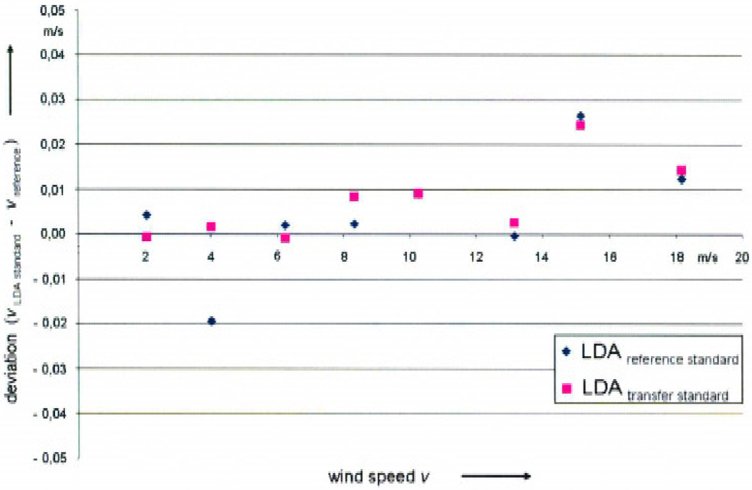

Figure 2: deviation of the velocities measured by LDA standards to the tunnel reference velocity

<u>Result:</u> The deviation between the wind tunnel reference velocities given by the four Pitot static tubes and the velocity values measured by the two LDA standards are within the uncertainties of the LDA measurements as well as the velocity variations between the two measurement positions with a local distance of 300 mm in the wind tunnel test section. The measurement uncertainty of both LDA standards was scaled up to 0,3 %.

Physikalisch-Technische Bundesanstalt

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Die Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig und Berlin ist das nationale Metrologieinstitut und die technische Oberbehörde der Bundesrepublik Deutschland für das Messwesen und Teile der Sicherheitstechnik. Die PTB gehört zum Dienstbereich des Bundesministeriums für Wirtschaft und Technologie. Sie erfüllt die Anforderungen an Kalibrier- und Prüflaboratorien auf der Grundlage der DIN EN ISO/IEC 17025.

Zentrale Aufgabe der PTB ist es, die gesetzlichen Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI) darzustellen, zu bewahren und – insbesondere im Rahmen des gesetzlichen und industriellen Messwesens – weiterzugeben. Die PTB steht damit an oberster Stelle der metrologischen Hierarchie in Deutschland. Kalibrierscheine der PTB dokumentieren die Rückführung des Kalibriergegenstandes auf nationale Normale.

Dieser Ergebnisbericht ist in Übereinstimmung mit den Kalibrier- und Messmöglichkeiten (CMCs), wie sie im Anhang C des gegenseitigen Abkommens (MRA) des Internationalen Komitees für Maße und Gewichte enthalten sind. Im Rahmen des MRA wird die Gültigkeit der Ergebnisberichte von allen teilnehmenden Instituten für die im Anhang C spezifizierten Messgrößen, Messbereiche und Messunsicherheiten gegenseitig anerkannt (nähere Informationen unter http://www.bipm.org).

CIPM MRA

***The Physikalisch-Technische Bundesanstalt** (PTB) in Braunschweig and Berlin is the National Metrology Institute and the highest technical authority of the Federal Republic of Germany for the field of metrology and certain sectors of safety engineering. The PTB comes under the auspices of the Federal Ministry of Economics and Technology. It meets the requirements for calibration and testing laboratories as defined in the EN ISO/IE 17025.*

It is fundamental task of the PTB to realize and maintain the legal units in compliance with the International System of Units (SI) and to disseminate them, above all within the framework of legal and industrial metrology. The PTB thus is on top of the metrological hierarchy in Germany. Calibration certificates issued by it document that the object calibrated is traceable to national standards.

This certificate is consistent with Calibration and Measurement Capabilities (CMCs) that are included in Appendix C of the Mutual Recognition Arrangement (MRA) drawn up by the International Committee for Weights and Measures (CIPM). Under the MRA, all participating institutes recognize the validity of each other's calibration and measurement certificates for the quantities, ranges and measurements uncertainties specified in Appendix C (for details see http://www.bipm.org).

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