Measuring-Network of Wind Energy Institutes

Anemometer Calibration Procedure

Version 3, December 2020

1. INTRODUCTION

The MEASNET Anemometer Calibration Procedure is the measurement procedure agreed upon by the MEASNET members to be mutually used and accepted. The procedure provides the basis for a common interpretation and understanding in accordance with the MEASNET Quality Evaluation Program whose main objective is the continuous improvement of the measurement quality.

The Procedure originally developed within MEASNET (Cup anemometer calibration procedure, Version 1, September 1997 and Version 2, October 2009) has been the basis of Annex F of IEC 61400-12-1 (Edition 1, 2005 and Edition 2, 2017).

Version 3 of the MEASNET Anemometer Calibration Procedure applies Annex F of IEC 61400-12-1 (Edition 2, 2017).

The MEASNET Expert Group -Anemometer Calibration has agreed to compile the present document which provides the common understanding and implementation of the Reference Standard among the MEASNET organization. The procedure includes -where required- interpretations of specific technical issues, guidance for implementation of flow quality tests and specific additional requirements such as a methodology for quantifying the Proficiency Test results. The document will also be utilised in the assessment of MEASNET applicants.

2. REFERENCE MEASUREMENT PROCEDURE

The Reference Measurement Procedure on which the present MEASNET Anemometer Calibration Procedure is based is:

> *IEC 61400-12-1, Edition 2, 2017-03: Wind energy generation systems- Part 12-1: Power performance measurements of electricity producing wind turbines (Annex F- Wind tunnel calibration procedure for anemometers).*

3. MEASNET IMPLEMENTATION OF THE REFERENCE MEASUREMENT PROCEDURE

The following sections are numbered according to the relevant clauses of IEC 61400-12-1, Ed.2 – Annex F. The IEC standard sets a list of requirements which are interpreted below when required

F.1 General Requirements

Quality control anemometer:

The *quality control anemometer* is used to assess and verify the flow quality on a given day of calibrations and ensure that calibration consistency and quality is obtained.

The "daily comparative calibrations of the facility's *quality control anemometer*" are interpreted to refer to calibrations performed each day on which calibration services are performed.

The calibration of the *quality control anemometer* will reveal if changes in wind tunnel setup of measurement techniques -which has been applied either intentional or unintentional- has caused changes in the flow quality. Thus, the quality control anemometer might reveal a need to update the flow measurements documentation according to F.2.

F.2 Requirements to the wind tunnel

The below requirements shall be assessed through suitable tests and the results shall be considered in the uncertainty evaluation if necessary.

All tests in Section F.2 shall be performed during the initial set up of the wind tunnel, after a change of the wind tunnel, or the measuring technique that could affect the flow condition.

The air velocity during the flow quality tests should be kept within ± 5 % of the nominal speed.

a. **Blockage ratio.** A maximum permitted value of 0.05 is set for the blockage area ratio BR. This limit value is not linked to the test section configuration. When applying blockage corrections, the test section configuration (e.g. open/ closed/ base and top plate only) must be taken into account.
b. **Flow uniformity.**
   The grid resolution of the flow uniformity tests shall not exceed 15 cm in each direction within the area covered by the anemometer b x h (Fig. F.1). The grid resolution outside the "anemometer b x h" area may be increased.

   It is essential to always perform (grid) measurements in relation to a stationary reference measuring element. Therefore, a variation in flow speed over time will influence both measurement values at the location of the reference position and any grid position in an identical magnitude and thus compensating the effects of long-term instability of flow speed.

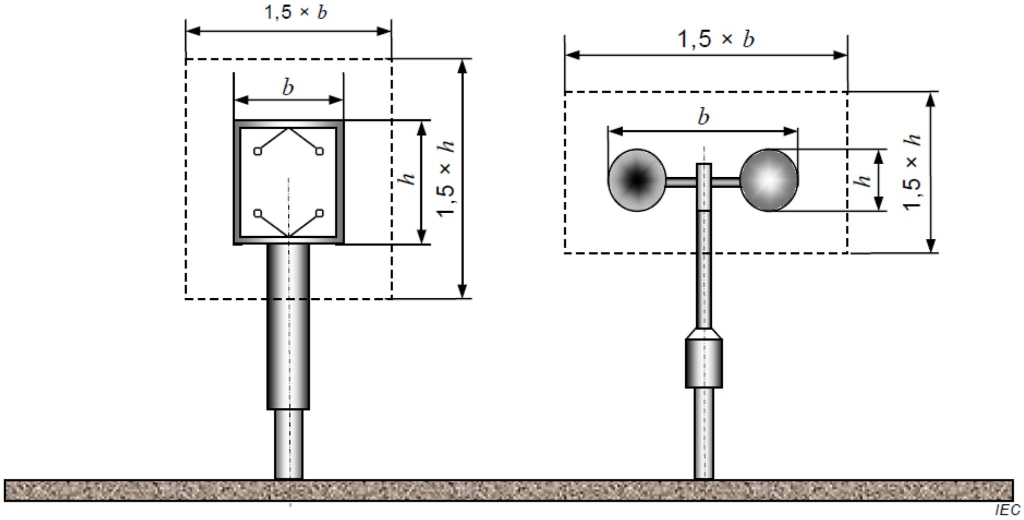

Figure 1: Definition of volume for flow uniformity test - The volume will also extend 1.5 x b in depth (along the flow) [Source: IEC 61400-12-1:2017, Figure F.1].

c. **Flow stability with respect to time.** The flow stability measurements shall be conducted at the flow speeds of 4 m/s, 8 m/s, 12 m/s and 16 m/s.

d. **Horizontal wind gradients.** The horizontal wind speed gradient shall be determined at the flow speeds of 4 m/s, 8 m/s, 12 m/s and 16 m/s.

   Furthermore, since different horizontal wind gradients can be caused by pollution of nets and smoothing devices, it is recommended to regularly monitor and document the measuring results.

   The variation of the horizontal gradient could be checked using quality control anemometers of similar type that rotate CW or CCW. There is no apparent change in horizontal wind speed gradient if the ratio of the calibration results of both sensors (CW/CCW) is within the expected scatter.

e. **Influence of the anemometer under test.** The influence of the anemometer on the reference flow speed measurement shall be assessed by using a test item with a high blockage ratio. The measurement should be performed at least for a wind speed of 8 m/s.
   The test can be done by comparing the measurements taken with the anemometer at least at two positions, while the wind tunnel fan is set to a constant rpm setting:
   1. at a position considered to not disturb the reference flow speed measurement (as far as possible away from the reference measurement system)
   2. at the normal calibration position

   The difference in the measured reference flow speed between those two measurements shall be evaluated.
   Further positions can be analyzed to define a minimum distance, at which no influence on the reference measurement system can be seen.

f. **Axial/Longitudinal turbulence intensity.** As specified in the standard.

g. **Wind tunnel calibration factor.** The standard specifies that the calibration factor shall be appraised using pitot tubes for a speed range of 4 m/s to 16 m/s. MEASNET considers that other appropriate measurement devices (i.e. LDA) are also acceptable provided the associated uncertainty shall be less than or equal to that of pressure based (pitot-tube) measurements. The wind tunnel calibration factor can be calculated in terms of wind speed or differential pressure as long as it is correctly accounted for in the equation defining the reference wind speed. Furthermore, since different calibration factors can be caused by pollution of nets and smoothing devices, it is recommended to regularly monitor and document the measuring results.

h. **Reproducibility of anemometer calibrations.** The long-term stability of the calibration facility shall be tested using a quality test anemometer. The test shall be based on a statistically significant number (at least 50) of calibrations gathered during a period of at least 3 months that form the **reference** average values.

Note: The use of the word repeatability in the IEC is misleading when referring to long-term stability. The correct term is reproducibility [VIM 2.25].

F.3 Instrumentation and calibration set-up requirements

Mounting arrangements in the calibration set-up must be of the same dimensions as the mounting arrangements of which the anemometer will be mounted in service in the free atmosphere. The tolerance of mounting tube diameter should be +/- 1 mm, following the conclusion in the *MEASNET Statement: Influence mounting pipe diameter, June 2019* [included as Annex C).

Mounting arrangement alternative to tubes may be used in the calibration set-up if instructed by the client and must be reported within the calibration certificate.

For calibration of a directional sensitive anemometer with respect to horizontal flow, a reference orientation shall be defined. The mounting setup and anemometer orientation during calibration shall be documented and referred to in the calibration report.

The maximum misalignment allowed for the pitot static tube used as reference speed measurement equipment is 0.5°, in any direction.

F.4.1 General procedure cup and sonic anemometers

Anemometer types: Annex F, in its introductory section F.1, refers to the calibration of anemometers. Subsequently, it focuses on cup anemometers and gives some initial guidance for ultrasonic anemometers which are the acceptable sensors for the power performance test of wind turbines. In this respect, MEASNET considers that anemometers of different measuring principles may also be calibrated according to procedure F4. When anemometers other than cup are to be calibrated, then any specific conditions or configurations that affect the calibration shall be reported where appropriate.

Configurable anemometers: If an anemometer is able to be configured, the setup parameters must be documented and reported in the calibration certificate, if applicable.

Pre-calibration run-in: The standard dictates that the anemometer shall run in for minimum 5 min at about 10 m/s before the calibration procedure begins.

Calibration speed range: The strict wind speed range 4-16 m/s may be extended. Note: The wind energy community uses calibrated anemometers for applications beyond power performance purposes; other fields of operation may require calibrated anemometers according to Annex F in a speed range outside the 4-16 m/s specification as well. Therefore, the same procedure can be applied to calibrate anemometers outside the 4-16 m/s range; accordingly the flow quality tests should be extended to ensure that adequate flow conditions apply to the extended wind speed range and the uncertainty calculations should be properly adjusted.

Note: The linear regression must be calculated exclusively for the speed range 4-16 m/s. For the extended range, the linear regression shall not be stated in the calibration certificate, but provided in a separate document.

F.4.3 Determination of wind speed at the anemometer position

In the case that the reference wind speed is measured through a Laser Doppler Anemometer (LDA), equation F.3 is replaced by

$$v = f\left(k_b, k_i, k_p, v_p, \dots\right) k_c \frac{1}{n} \sum_{i=1}^{n} v_{p,i}$$

and k_p is meant to be the correction factor due to interference caused by the anemometer (including its mounting tube) on the velocity measured (v_p) by the LDA. Equations F.1 and F.2 are still applied to calculate the air density reported in the calibration report (reference to environmental conditions during calibration).

F.5 Data analysis

According to Annex F of IEC 61400-12-1 (Edition 2, 2017).

F.6 Uncertainty analysis

The list of uncertainty items to be considered in the Reference Measurement Procedure includes point h: *uncertainty due to the difference between the result of the wind tunnel performing the calibration and the average result of other wind tunnels as determined through proficiency testing to the extent not covered by other uncertainty components.*

The participation in the regular MEASNET Proficiency Tests (PTs) is compulsory for MEASNET members. The success of each member is based on a quantitative criterion which is determined by (a) the scatter of the results with regard to the consensus level (average among participants, excluding outliers) and (b) a set uncertainty value. The latter reflects the state-of-the-art regarding the Anemometer Calibration procedure (methodology, instrumentation and analysis) and shall be adjusted following the technological and procedural improvements.

Any laboratory not succeeding to comply with the PT "pass criterion" shall investigate and recognise the cause of its deviation and apply the appropriate measures/ improvements. The effectiveness of these actions shall be re-evaluated by the MEASNET group. It is emphasized that any deviating laboratory is not allowed to increase its stated uncertainty or apply correction factors to restore convergence to the consensus level. Therefore, the uncertainty item h) as defined above will be zero by default for a MEASNET member as long as it shall be required to fulfil the following two conditions:

a) The Compliance Factor as defined in Annex A of the present document is less than or equal to 1%.
b) The Compatibility Index E as defined in Annex B of the present document is less than or equal to 1.

The measurement uncertainty of the test sensor shall be included in the calculations.

F.7 Reporting format

The calibration facility report shall have been prepared by any calibration laboratory upon the commissioning of the wind tunnel for anemometer calibration. It shall be updated whenever modifications affecting any flow quality characteristic or the measurement and/or analysis procedures are implemented.

The requirement for the calibration facility report may be also met through references to relevant quality records of the laboratory provided that these collectively cover the requirements of Annex F as further clarified in the present document

F.8 Example uncertainty calculation

The section provides an example calculation for a nominal wind speed of 10 m/s. The quantification values and associated reasoning are indicative. Each MEASNET member shall apply elaborate uncertainty calculations considering all the involved components.

Annex A

MEASNET Anemometer Calibration Proficiency Test rules

1. Responsibilities

The MEASNET Proficiency test on anemometer calibration is organized under the responsibility of the MEASNET Expert Group on Anemometer Calibration. The MEASNET Expert Group on Anemometer Calibration nominates the coordinator for each PT.

2. PT plan

A PT plan should be agreed upon and shall be documented before commencement of the scheme, and should include the following information:

a) The name and address of the PT provider,
b) the name and address of the coordinator and other personnel involved in the design and operation of the scheme,
c) the nature and purpose of the scheme,
d) the reference procedures,
e) the expected participants (Names and addresses)

Additionally to the above, the PT plan should include information on the following

- Identification of anemometers to be calibrated. This should include at least the following:
  - Anemometer type and manufacturer
  - Anemometer individual identification (serial number, equipment code etc.)
  - Mounting method and main dimensions. It is recommended that a common mounting boom is supplied for each anemometer and were possible is used by all institutions. Where the wind tunnel layout of an individual institution does not allow for the use of the provided common mounting boom, a different boom may be used, provided that at least the part of the boom immersed in the wind tunnel flow is identical to the “common mounting boom” provided for the RR.
  - Information about electrical connections and operating principles for each anemometer (preferably copies of the respective manufacturers manuals)
- A time schedule including the expected initial and target dates or deadlines of the scheme, and, where appropriate, the dates on which testing is to be carried out by participants;
- Outline of the statistical analysis to be used, including the determination of assigned values and any outlier detection techniques;
- A description of the data or information to be returned to participants;
- A description of the extent to which the PT results and conclusions are to be made public.

Special issues:

-Two or more institutions using the same wind tunnel but with different instrumentation are counted as different participants.

-One institution with two or more wind tunnels will decide which wind tunnel will be used for defining the “MEASNET reference value”. The other wind tunnel(s) of the same institution will be assessed for compliance if requested, but will not be included in the estimation of the reference MEASNET value.

3. Statistical analysis of PT Results

The following steps are followed:

Step 1: Assessment of anemometers integrity.

After the end of the measurement campaign by all participants, the physical condition of the anemometers used will be assessed, on the responsibility of the laboratory providing the initial and final calibration (usually the sensors’ provider). In case any sign of damage, degradation, or irregular operation that could possibly have effect on the PT results, is identified on any of the anemometers used in the PT, then this anemometer must be discarded from the PT and the result obtained must not be used in the compilation of the PT results.

Step 2: For each anemometer three output values are determined, corresponding to wind speeds of about 7, 10 and 13 m/s.

Step 3: For each anemometer and for each of the three values the wind speeds according to the calibration results of the RR participants are calculated. Each wind speed is assumed to have a standard uncertainty of 1%.

Step 4: As a first estimate of the MEASNET -reference wind speed the results per anemometer and per output frequency of all institutes recognized by MEASNET for anemometer calibration are averaged. The standard uncertainty of this reference wind speed is $(\frac{1}{\sqrt{N}}\%)$ in which N is the number of MEASNET institutes that calibrated the regarded anemometer.

Step 5. Per anemometer and per output value the results of the calibration of a MEASNET recognized institute is discarded when the deviation with respect to the estimated reference wind speed is one standard uncertainty of the difference or more. The standard uncertainty of the difference is equal to $\sqrt{1^2+(\frac{1}{\sqrt{N}})^2}$ % where N is the number of non-discarded results per anemometer and output value). This step is carried out several times until no more data are discarded. The measurements are discarded in the order of their deviation, the biggest deviation first.

Step 6. For each anemometer and for each output value the MEASNET -reference wind speed **is defined** as the average value of the non-discarded values.

Step 7. For each anemometer and for each of the three output values the difference between the wind speeds obtained with the various calibration results of the participating institutes and the MEASNET -reference wind speed is determined.

Step 8. At each approximate wind speed (7, 10 and 13 m/s) the differences obtained from each institute for all anemometers result in a series of values with an averaged value and a standard deviation. Both values should be close to zero. The sum of the absolute value of the average and the standard deviation (|AV| + stdevp) is used as a quantity that characterizes the compliance of the calibration institute with the MEASNET –reference wind speeds. (stdevp = standard deviation of the population)

Step 9. The values (|AV|+stdevp) are averaged for the approximate wind speeds (7, 10 and 13 m/s).

PASS / FAIL Criterion: The institutes with an average value of the Compliance Factor ≤ 1% comply with the MEASNET requirement for anemometer calibration uncertainty.

It is recommended to perform an in-depth comparison of interlaboratory calibrations taking into account air temperature, pressure and indirectly air density or other relevant parameters (e.g. turbulence) for explaining/investigating deviations. The motivation should be to reduce the differences of calibration results between different calibration facilities for the benefit of the industry.

Annex B
Compatibility Index E

Compatibility index E measures the ratio between the deviation of the measurements of the laboratory and the declared uncertainty. It is defined as:

$$E = \frac{|V_L - V_{PT}|}{\sqrt{U_L^2 + U_{PT}^2}}$$

where V_L is the velocity according to the laboratory calibration, V_{PT} is the proficiency test reference wind speed and U_L and U_{PT} are the expanded uncertainties (k=2) of the laboratory's measurement and of the proficiency test reference wind speed, respectively (see equation B.5 of ISO/IEC 17043, Ed.1 (2010)). The test reference wind speed uncertainty is estimated as:

$$U_{PT} = \frac{\sigma}{\sqrt{N}}$$

where σ is the standard deviation of the speeds declared by the laboratories and N is the number of laboratories that have been used to calculate the proficiency test reference wind speeds.

The compatibility index E, which is based on the participants' reported estimates of measurement uncertainty, are only meaningful if the uncertainty estimates are determined in a consistent manner by all participants; this requirement is fulfilled in the present application.

A compatibility index bigger than 1 indicates that the deviation of the laboratory from the PT reference value is not compliant with the laboratory's declared uncertainty.

Annex C

Influence of mounting tube diameter on anemometer output

Introduction

Sections *G2: Single top-mounted anemometer* and *G4: Side mounted instruments* of IEC 61400-12-1, Ed.2, Annex G specify that

> “*The anemometer shall be mounted on a round vertical tube of the same (± 0,1 mm) outer diameter as used during calibration (and classification), but of no larger diameter than the body of the anemometer*.”

The ± 0.1 mm diameter specification requires a disproportional increase in complexity in design, procurement and stock-keeping of meteorological masts and their calibrated instrumentation.

Deutsche WindGuard Wind Tunnel Services GmbH which is a member of the MEASNET expert group for anemometer calibration has performed a parameter study in the beginning of 2018 to assess the influence of varying mounting pipe diameters upon wind tunnel calibration results for three commonly used cup anemometer types [2]; Note detailed information: REPORT: Influence of mounting tube diameter on anemometer output.

Test procedure

Each combination of anemometer model and mounting pipe diameter was tested for five consecutive calibration runs following MEASNET / IEC 61400-12-1 standard in the specified speed range of 4 m/s – 16 m/s. The installation of different mounting pipe sizes was performed in an alternating manner (e.g. 24.0, 26.9, 25.0 …).

The selected pipe diameters in this study are located in a range well below and above the 0.1mm specification in relation to the recommended mounting pipe diameter. Tests with the actual manufacturer's recommended mounting pipe diameter have also been performed.

In additional surveys an enlarged pipe size was also selected that corresponds to the outer diameter of the anemometer body.

1.1. Setup

Table 1 shows the selection of different mounting pipes manufactured for this survey in combination with the associated test specimen. The rotor plane for all tests was always located in the centre of the test section (1000 mm x1000 mm) at a height of 500 mm above the test section base plate.

Table 1 Tested anemometer types and corresponding mounting pipe diameters.

1) recommended pipe size; 2) same pipe diameter as anemometer body

Sensor	Pipe diameter / mm
WindSensor P2546A-OPR	24.0
	25.01)
	25.4
	26.0
	26.9
	46.02)
Windspeed A100L2	24.0
	25.0
	25.41)
	26.0
	26.9
	37.62)
Thies First Class Advanced 4.3351.00.000	33.0
	33.5
	33.71)
	34.0
	35.0
	50.02)

Results

2.1. WindSensor P2546A-OPR

The calibration results for diameters between 24.0 mm and 26.9 mm show a maximum variation ranging -0.04 % through +0.03 %. The results seem to have an arbitrary dis-tribution, which is not related to the tube diameter (Figure 1).

Only the results for an enlarged diameter of 46.0 mm, shows an influence due to the increased tube diameter. The deviation compared to the mean value of the recom-mended diameter (Ø 25.4 mm) size is about 1.1 %.

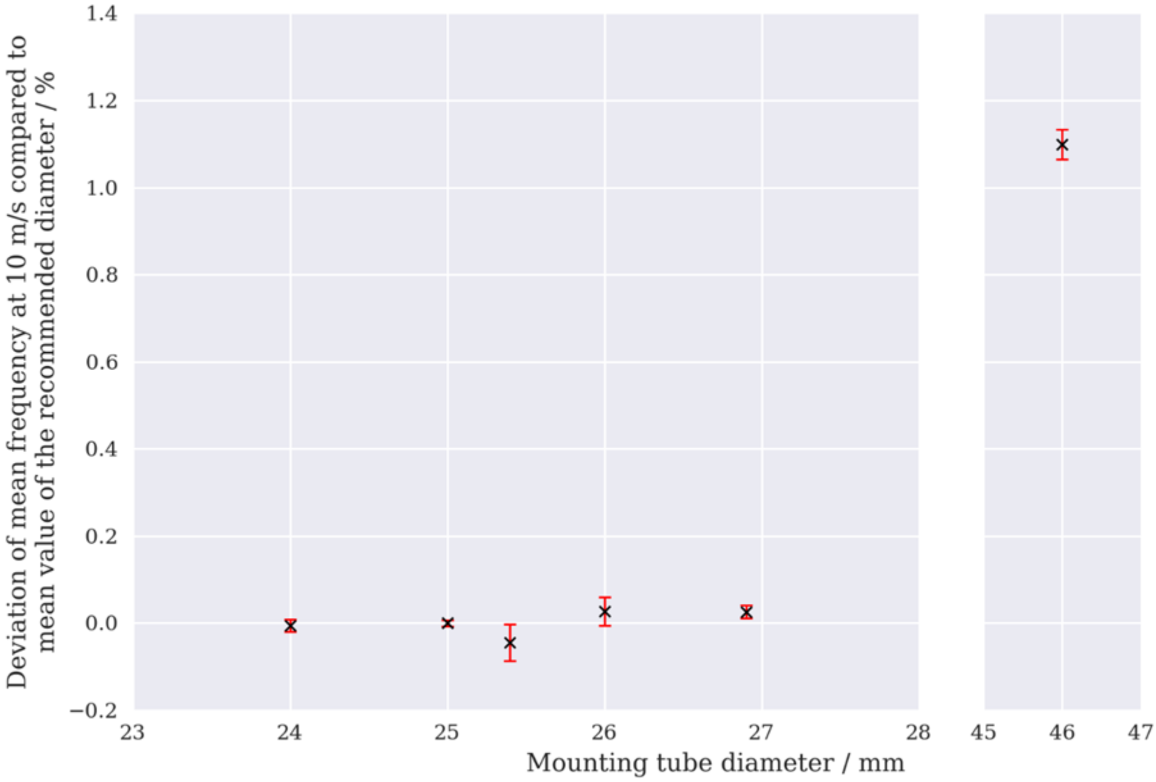

Figure 2: Deviation of the mean frequency at 10 m/s compared to the mean value at the recommended diameter for the WindSensor P2546A-OPR anemometer. The error bars indicate the standard deviation for each of the 5 measurements.

2.2. WindSpeed A100L2

The calibration results for diameters between 24.0 mm and 26.9 mm show a maximum variation of 0.22%. The results seem to have an arbitrary distribution, which is not related to the tube diameter (Figure 3).

Only the results for an enlarged diameter of 37.6 mm, shows an influence due to the increased tube diameter. The deviation compared to the mean value of the recommended diameter (Ø 25.4 mm) size is about 1.24 %.

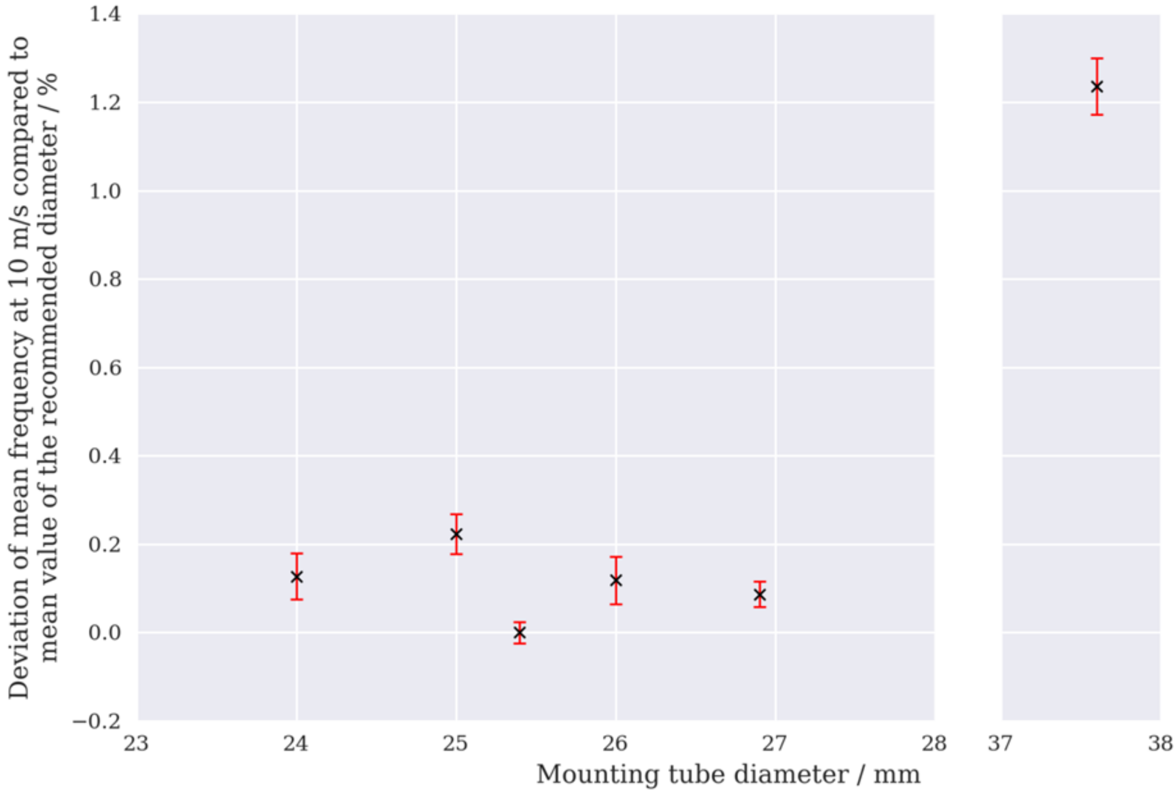

Figure 3: Deviation of the mean frequency at 10 m/s compared to the mean value of the recommended diameter size for the Windspeed A100L2 anemometer. The error bars indicate the standard deviation for each of the 5 measurements.

2.3. Thies First Class Advanced

The calibration results for diameters between 33.0 mm and 35.0 mm show a maximum variation of 0.04%. The results seem to have an arbitrary distribution, which is not related to the tube diameter (Figure 4).

Only results for an enlarged diameter of 50.0 mm show a slight influence due to the increased tube diameter. The deviation compared to the mean value of the recommended diameter (Ø 33.7 mm) size is about 0.15 %.

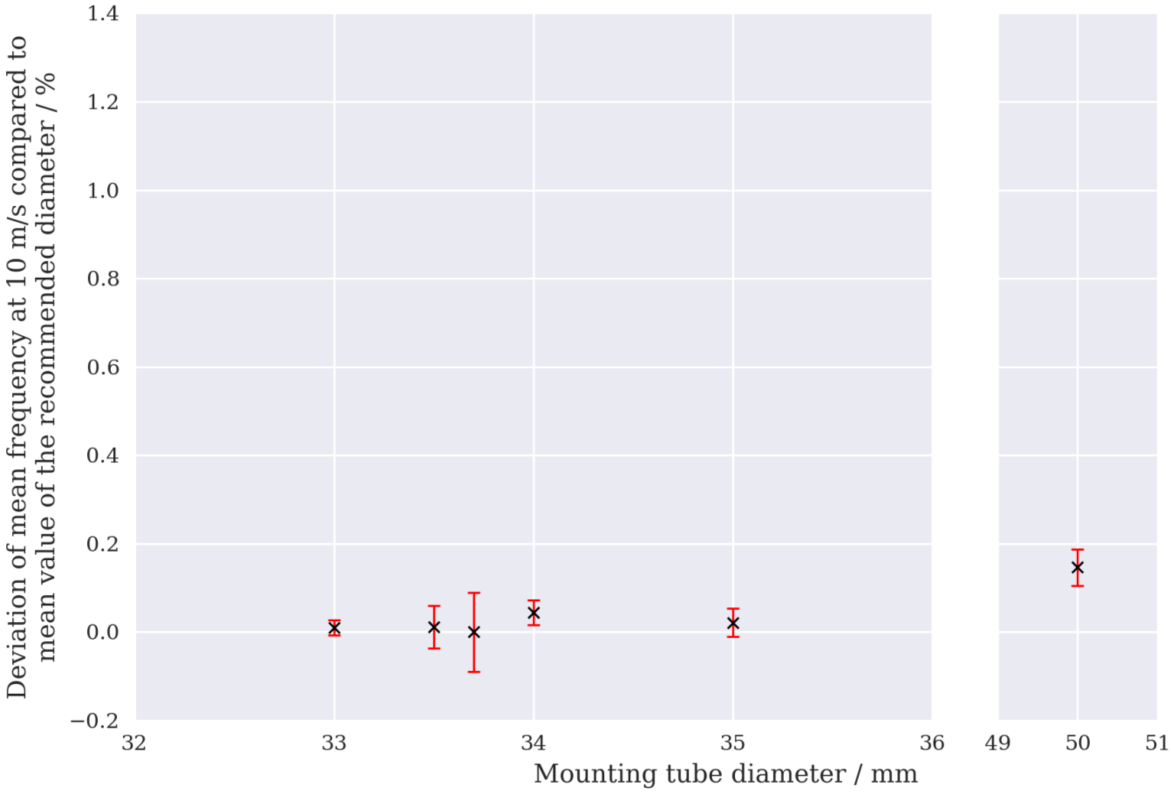

Figure 4: Deviation of the mean frequency at 10 m/s compared to the mean value of the recommended diameter size for the Thies First Class Advanced anemometer. The error bars indicate the standard deviation of the 5 measurements.

Concluding Statement

Based on the detailed tests performed by the MEASNET expert group member *Deutsche WindGuard Wind Tunnel Services GmbH* for a representative sample of widely used cup anemometer models, the MEASNET Expert Group for Anemometer Calibration states that there is no evidence that a variation of mounting pipe diameters by up to ± 1 mm will lead to a bias in wind tunnel calibration results outside the normal scatter.

Consequently, the strict requirement for a maximum permitted tolerance of ± 0.1 mm (Annex G, IEC 61400-12-1, Ed.2) for the mounting tube diameter during calibration/classification/field application does not seem to improve the uncertainty related to open field wind speed measurements.

References

[1] IEC 61400-12-1, Edition 2.0, WIND TURBINE GENERATOR SYSTEMS, Power performance measurements of electricity producing wind turbines, March 2017

[2] A. Roß, VT180177_01_Rev0, Influence of mounting tube diameter on anemometer output, April 2018, REPORT: Influence of mounting tube diameter on anemometer output

[3] MEASNET, ANEMOMETER CALIBRATION PROCEDURE Version 2, October 2009