Field calibration of cup anemometers

Schmidt Paulsen, Uwe; Mortensen, Niels Gylling; Hansen, Jens Carsten; Said, U.S.; Moussa, A. E.-S.

Published in:
Conference proceedings (online)

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Schmidt Paulsen, U., Mortensen, N. G., Hansen, J. C., Said, U. S., & Moussa, A. E-S. (2007). Field calibration of cup anemometers. In Conference proceedings (online) Brussels: European Wind Energy Association (EWEA).

FIELD CALIBRATION OF CUP ANEMOMETERS

Uwe S. Paulsen, Niels G. Mortensen and J. Carsten Hansen
Risø National Laboratory, Technical University of Denmark, Roskilde, Denmark

Usama Said Said and Ashour Abd El-Salam Moussa
New and Renewable Energy Authority, Cairo, Egypt

ABSTRACT

A field calibration method and results are described along with the experience gained with the method. The cup anemometers to be calibrated are mounted in a row on a 10-m high rig and calibrated in the free wind against a reference cup anemometer. The method has been reported [1] to improve the statistical bias on the data relative to calibrations carried out in a wind tunnel. The methodology is sufficiently accurate for calibration of cup anemometers used for wind resource assessments and provides a simple, reliable and cost-effective solution to cup anemometer calibration, especially suited for recalibration in places with limited access to high-quality wind tunnels.

INTRODUCTION

Cup anemometers are usually calibrated in a wind tunnel for reasons of precise calibration of the instrument and documentation of the uncertainty. A comparison of calibrations of anemometers carried out in different wind tunnel draws attention to the different sources of uncertainties [2]. Various sources of error apply in the wind tunnel calibration; noticeably solid (wind tunnel dimensions) and effective (turbulent rotor wake) blockage [2]. Other disturbing influences are flow inhomogeneities (settling time and temperature constraints related to fan performance) and contrasts in sensing by the instrument in the natural wind [3]. A European harmonisation effort has been developed within MEASNET [4], in order to improve calibration of cup anemometers in wind tunnels and to pinpoint uncertainties. However, even with a substantial technical effort, including time-consuming and costly procedures, the statistical scatter is between 0.2-0.6% [5].

For a large number of wind instruments to be calibrated at regular intervals, cup calibration in the field has been proposed and developed from a method for a collocated transfer test for wind instrument auditing suggested in 1989 [6]. A row of audited cup anemometers were calibrated against one or two reference cup anemometers and an improved statistical bias was found. The methodology has been re-evaluated and the first production facility implemented at the Wind Energy Technology Center in Hurghada at the Red Sea Coast of Egypt – in a joint project between the New and Renewable Energy Authority in Cairo (NREA) and Risø. NREA uses the facility for re-habilitation and -calibration of series of cup anemometers for wind resource measurements in Egypt. The wind climate in Hurghada facilitates field calibration because the wind is fairly strong and mostly occurs within certain sectors and the site for the field calibration facility is more than 5 km flat and homogeneous fetch. In 2003, the first batch of 10 anemometers was calibrated with this method. In 2004 and 2005, another 18 and 12 calibrations were carried out.

THE CALIBRATION FACILITY

Regular maintenance and calibration of the anemometers are necessary prerequisites for obtaining accurate and reliable measurements of mean wind speed, turbulence intensity, gust wind speed and lull wind speed – not the least when the measurements are used for wind resource assessment or power performance verification. NREA alone has almost 50 cup anemometers that need rehabilitation and recalibration at regular intervals, say, every 2-3 years.

A cup anemometer rehabilitation and recalibration facility was therefore established at the Hurghada Wind Energy Technology Center (WETC) as part of the Wind Atlas for Egypt project [7]. The purpose of this facility is to enable NREA to rehabilitate and recalibrate their cup anemometers, i.e. to establish an accurate relation between the ambient wind speed and the anemometer output.

Figure 1. Cup anemometer calibration facility at Hurghada WETC: upwind fetch to the NW (left) and details of the cup anemometer set-up (right).

At the calibration facility, up to 10 test cup anemometers are mounted on a horizontal boom, with a reliable reference anemometer in the centre position, see *Figure 1*. The reference instrument is calibrated in a certified wind tunnel, so for this anemometer the relation between flow speed and anemometer output is well known. By comparing the 10 test anemometers with the reference anemometer, similar relations can be established for the test anemometers. These relations can subsequently be used in the calibration software that is set up for each meteorological station operated by NREA.

This methodology has two important requirements in order to provide reliable calibration expressions for the cup anemometers:

- The comparisons should be made over such a long period of time – and range of wind speeds – that the calibrations are statistically stable and reliable. This period is dependent on the wind climate (i.e. location and season), and range from a few weeks to more than a month.
- The anemometers must experience the same wind conditions in each of the 10-min data-collecting intervals. Therefore, only a narrow range of wind directions can be used and the up-wind terrain (fetch) in this sector must be completely flat and uniform. At Hurghada WETC a 30°-degree sector is used.

In the siting of the anemometer calibration facility, the following additional requirements were taken into account:

- The boom is mounted perpendicular to the prevailing wind direction, in this case perpendicular to the direction of the mean wind vector.
- The upwind fetch should be as flat and uniform as possible, i.e. have the same land-use and terrain surface roughness length. If we require that the wind at the height of the anemometers (10 m above ground level) should be in equilibrium with the upstream terrain surface, there should be no changes of roughness within at least 100 times this height. Adding a safety margin of 50%, the upwind surface should then be uniform within at least 1500 m from the calibration facility.
- There should be no sheltering obstacles close to the calibration facility, especially in the upwind sector.
- The facility should be easily accessible for operation and maintenance.

- The facility should preferably be fenced in and/or guarded, to protect the instruments and accurate set-up from any changes caused by human activity.
- Any fence in the upwind direction must interfere as little as possible with the wind flow.

The data acquisition hardware in Hurghada is based on the 10-bit Anderaa 3660 data logger system. Data are exchanged via memory modules and can be retrieved with Aanderaa Data Reading Program 5059. Post processing is carried out by sharable DOS programs and license free plotting software for PCs. Results obtained so far from this in-situ calibration facility indicate that the calibration expressions are sufficiently reliable and accurate for wind resource assessment.

REHABILITATION AND RECALIBRATION PROCEDURES

The steps for rehabilitation of cup anemometers are:

1. Visual inspection and dismantling of cup anemometers
2. Installation of the cup anemometers on the Cup Calibration Rig
3. Collection of data
4. Post processing of data
5. Refurbishment of bad proven cups(bearings, cups etc)
6. Re-run of cups with new bearings/cups
7. Post-calibration in the Cup Calibration Rig and re-analysis

The calibration procedure consists briefly of the following steps:

1. to provide a time series of the raw data of individual cups
2. selection of flaw-less cup anemometers based on analysis of time series(from 1)
3. to post process files invoking wind direction range selection and regression
4. to post process fits and provide graph result (Figure 2)
5. assessment of result and acceptance criterion (results within bands)/rejection of data(results past bands)
6. result plot and summary

DATA MATERIAL

Table 1 represents a schematic of the Cup Calibration Rig setup, i.e. the relative position of each of the anemometers seen in the direction of the mean wind – from WD 338° towards 158°. Left in the table is therefore approximately towards NE and right is towards SW. The data-logger channel number and position key(M:-) (P:+) is given in the head of the table.

Table 1. Overview of anemometer calibrations carried out at the Wind Energy Technology Center at Hurghada.

Channel	2	3	4	5	6	7	8	9	10	11	12	13	14
Position	M05	M04	M03	M02	M01	M00	P01	P02	P03	P04	P05	WD	WS
Batch #1	351	392	374	375	373	1386	391	330	377	329	371		
Batch #2	353	354	393	333	378	1386	352	376	372	384	383		
Batch #3	336	334	331	337	332	1386	339	338	335	---	---		
Batch #4	---	---	379	380	390	1386	10	15	72	---	---		
Batch #5	---	---	494	492	458	1386	332	303	351	---	---		
Batch #6													
Bearing*	068° ← the direction of the cup anemometer boom → 248°											008°	

* All directions are relative to true North (magnetic declination 2004: +3° East).

Batch #1-5: cup anemometer calibration runs – after post-calibration and rehabilitation. Anemometers listed in red colour need re-analysis, rehabilitation and/or re-calibration.

The reference anemometer #1386 was calibrated in a low turbulence wind tunnel following MEASNET standards and procedures[4].

POST PROCESSING

A graphical plot for visual quality inspection of the individual anemometers M05..M01, M00, P01..P05 raw data are carried out, see *Figure 2* for a subset. For satisfactory sensor output, further analysis within the 30 deg sector with accepted cup anemometers is carried out.

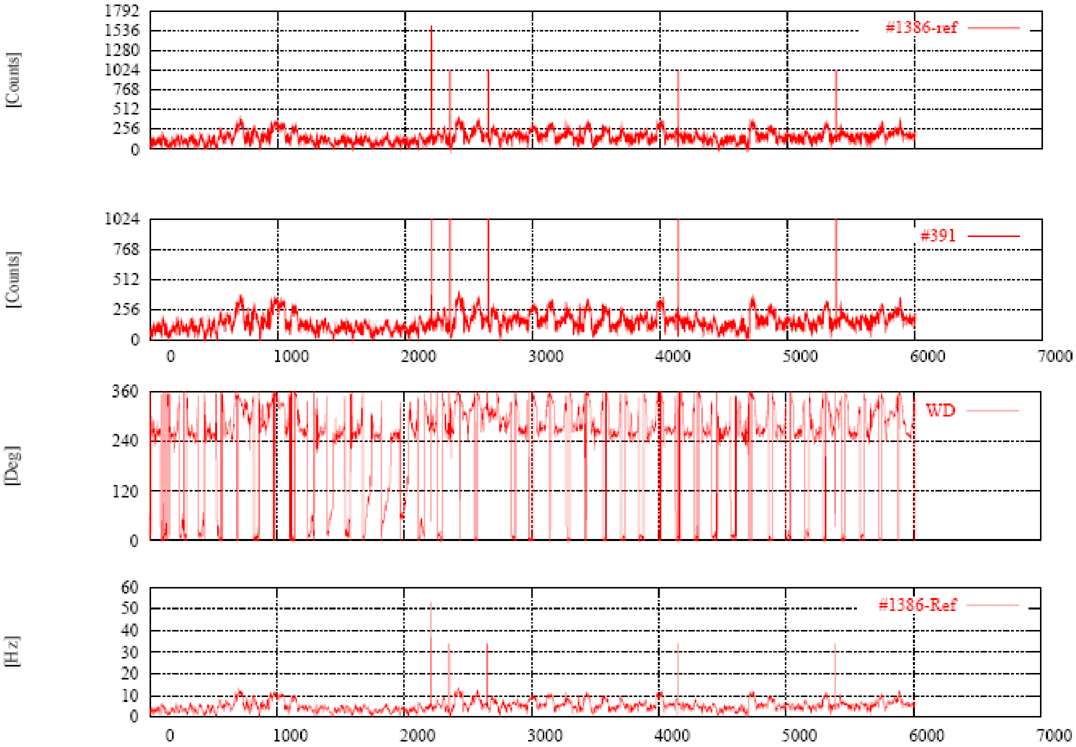

Figure 2. Subset of time traces of raw cup anemometer signals, wind direction and reference wind speed.

The filtered data are regressed on a frequency to frequency basis with the orthogonal fitting technique, which is minimizing the perpendicular distance d from the individual points (x_i,y_i) to the line i.e. by minimizing the function $\Phi=(N^{-1})\Sigma d_i^2$[1]. Following [1] and introducing $\delta=½\ \ln(Var(x)/Var(y))$ and $\varepsilon=½\ln(Var(x)/Var(y)/Var(xy))$, which is equal to $-\ln(|\rho|)$ (ρ| being the sample correlation coefficient), the slope can be derived as $\tan(\alpha)=sign(Mean(xy)\ (\sqrt{}(1+(e^{\varepsilon}\sinh(\delta)^2)-e^{\varepsilon}\sinh(\delta))$. The intercept b is calculated by means of $y_0=\tan(\alpha)x_0+b$. Standard error on slope is estimated as $Var(\tan(\alpha))=2N^{-1}\ (1-\rho)$ and on intercept $Var(b)=N^{-1}(Var(x)+Var(y)-2Mean(xy))$. From the analysis [1] it is further shown that slope and offset are uncorrelated.

RESULTS

A calibration result example is shown in *Figure* 3 for the test cup anemometer # 377 as a plot with basic user information on the fit: gain and offset of the reference cup anemometer #1386(0.6205 and 0.1928, respectively) together with gain and intercept constants for line of the orthogonal regression, derived from the inter-calibration (1.01017 and -0.06704, respectively). Additionally the difference between the indicated wind speed of #377 and the reference cup #1386 is presented in the second part of the figure along with the chosen ±0.1 m/s band criteria. Standard error on the slope and the offset, variance and cross-variance of abscissa and ordinate, and coefficient of correlation are also provided to the user for quality measures. The secondary part of the plot clearly shows the 10 bit resolution capability.

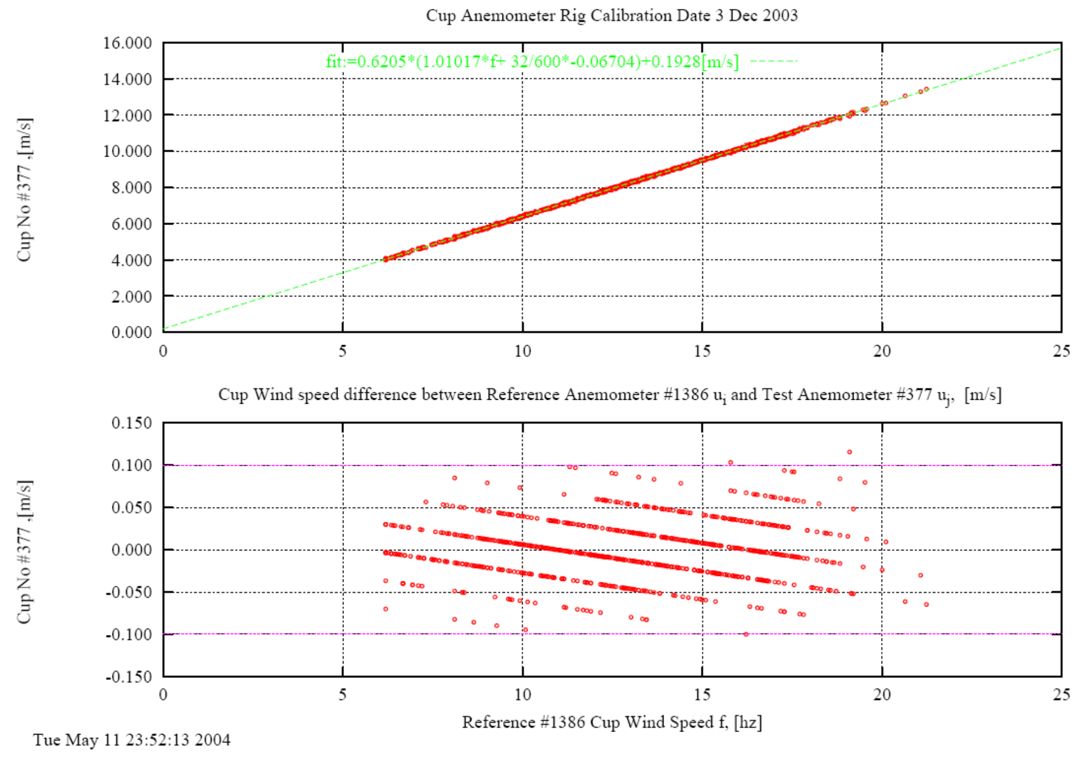

Figure *3*. Calibration result sheet for cup anemometer #377, plotted using the software package *gnuplot*, see http://www.gnuplot.info/.

The field calibration results of 37 cup anemometers are summarized in *Figure 4* , resembling statistically a Gaussian Bell N[μ,σ,N] random process of realisation on deviations between the data point and the fit. The broadness and height of the bell shaped curve depends on the rejection criteria of ±0.1 ms^{-1}. A discussion on sharpening the rejection criteria to ±0.05 ms^{-1} would change the bell curve without loosing a lot of data in the range 4-16 ms^{-1}, but likely increases the measurement time with a noticeable amount due to rare occurrences of very high wind speeds from this sector. The wind climate details according to the Wind Atlas [7, 9] at the rig at 10 m a.g.l. is estimated to A=6.8 ms^{-1}, k=3.45, the frequency of occurrence for northerly winds is 16.1%.

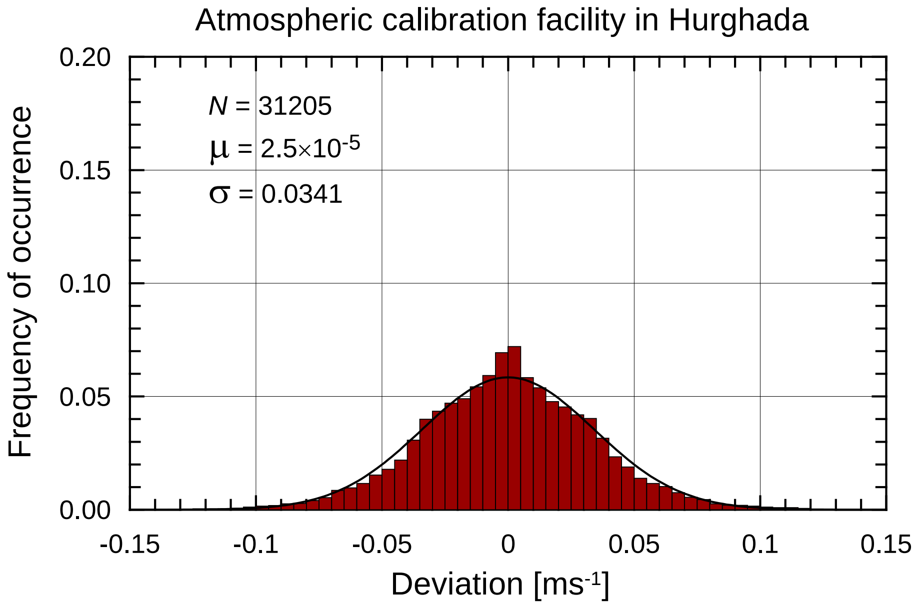

Figure 4. Distribution of deviations between test anemometers and the reference anemometer.

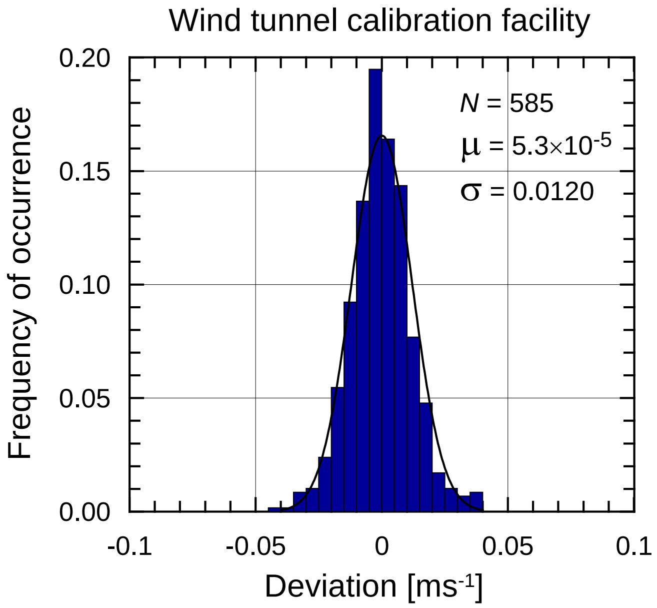

Figure 5. Distribution of deviation from the fit for wind tunnel calibrations performed on cup anemometers according to Measnet standards and procedures. The anemometers are similar to the anemometers analysed in the field study, i.e. Risø P2546A.

The wind tunnel calibration results for 45 cup anemometer calibrations are summarized in Figure 4, revealing approximately a 3 times smaller standard deviation than for the field calibration results.

Figure 6 shows the correlation coefficients R^2 from batch 1-5 with a decreasing trend with position relative to the reference position, influenced by sector width, distance between the cups [1] and likely the rotational sense of the cups. However for the present application it demonstrates the value for potential use of more rigorous rejection criterion than ±0.1 ms^{-1}.

Figure 7 shows the mean relative wind speed statistical error of the inter-calibration at about 8 ms^{-1}.

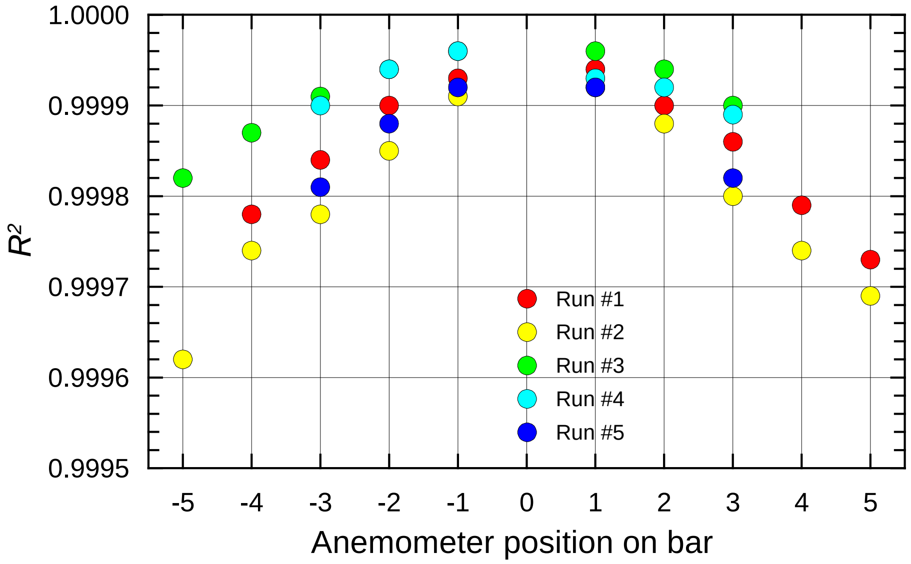

Figure 6. Correlation coefficient between test and reference anemometers for batch 1-5. The x-axis indicates the test anemometer position relative to the reference anemometer (position '0').

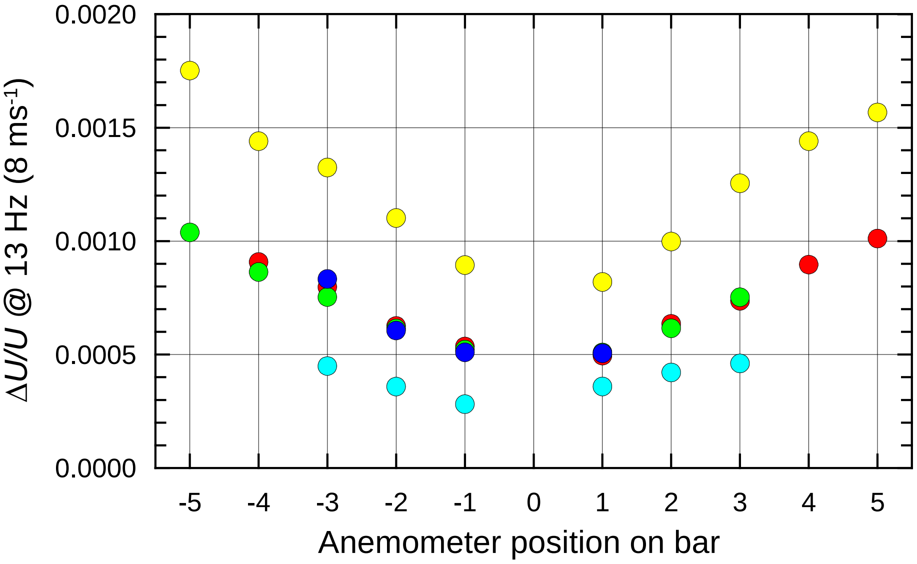

Figure 7. Mean relative wind speed error at 13 Hz, corresponding to approximately 8 ms-1. The x-axis indicates the test anemometer position relative to the reference anemometer (position '0')

The uncertainty of the reference cup anemometer is not included in the expression for deriving *Figure 7*. To incorporate a 1% uncertainty of the reference cup anemometer would add an increased uncertainty by an equal amount. Another clear trend pinpoints batch 2 as a run with less accuracy relative to other runs, is demonstrating the potential for more detailed analysis in pursuing lack of performance. The last two figures indicate that the mutual interaction from the individual cup anemometer in the calibration results is deterministic and that it can be accounted for by a relative correction procedure(on R^2 fitting).

SUMMARY AND CONCLUSIONS

37 cup anemometers have been calibrated so far in production mode. The calibration results are obtained with a modest effort and correlation coefficients are better than 0.999895 (median value) for well-operating cup anemometers. The σ on gain values is 0.003 ms^{-1}. The σ on offset values is 0.01 ms^{-1}. At 8 ms^{-1} the average wind speed error ΔU/U is less than 0.1%.

The methodology is sufficiently accurate for calibration of cup anemometers used for wind resource assessment and it provides a simple, reliable and cost-effective approach to cup anemometer calibration in locations with limited access to high-quality wind tunnels.

The method quickly indicates the technical condition of the cup anemometers, a process which might be useful for identification of the need for overhaul of the instrument. The calibration results are obtained with a modest effort and demonstrate correlation coefficients better than 0.999895 (median value) for well-operating cup anemometers; the standard deviation in the linear calibration expressions is typically about 0.06%. The paper describes the calibration facility, the test and calibration procedures and provides a summary of the results obtained so far. The paper suggests improving the calibration results of the individual cup anemometer results by a deterministic correction procedure on the individual results on R^2 fitting.

ACKNOWLEDGEMENTS

The Wind Atlas for Egypt is a result of the Egyptian-Danish project *Wind Atlas for Egypt*, sponsored by the governments of Egypt and Denmark. The Danish contribution to the project and the publication of the atlas are funded by the Danish Ministry of Foreign Affairs through Danida.

REFERENCES

1. Kristensen, L. et al.: Field Calibration of Cup Anemometers, Risø-R-1218(EN), 2001.
2. T. Lockhart: Uncertainty in Anemometer Calibration Methods, Proceedings *European Wind Energy Conference*. Dublin Ireland Oct 5-9, 1997.
3. K.H. Papadoupulus et al.: Effects of Turbulence and Flow inclination on the performance of cup anemometers in the field. *Boundary-Layer Meteorol*. **101**, 2001, 77-107.
4. J.P. Molly et al.: 'MEASNET: Network of European Measuring Institutes, Proceedings *European Wind Energy Conference*. Dublin, Ireland, Oct 5-9, 1997, 290-293.
5. P. Eecen et al.: 'Uncertainties in Cup Anemometer Calibrations, Type A and Type B uncertainties'. ECN-C-05-066, June 2005.
6. T. Lockhart: Accuracy of the collocated transfer standard method for wind instrument auditing, *Amer. Meteo. Soc. J. Atmos. and Technol*. **6**, 1989, 715-723.
7. Mortensen, N.G., J.C. Hansen, J. Badger, B.H. Jørgensen, C.B. Hasager, L. Georgy Youssef, U. Said Said, A. Abd El-Salam Moussa, M. Akmal Mahmoud, A. El Sayed Yousef, A. Mahmoud Awad, M. Abd-El Raheem Ahmed, M. A.M. Sayed, M. Hussein Korany, M. Abd-El Baky Tarad (2005). *Wind Atlas for Egypt, Measurements and Modelling 1991-2005*. New and Renewable Energy Authority, Egyptian Meteorological Authority and Risø National Laboratory. ISBN 87-550-3493-4. 258 pp.
8. Mortensen, N.G., D.N. Heathfield, L. Myllerup, L. Landberg and O. Rathmann (2005). Wind Atlas Analysis and Application Program: *WAsP 8 Help Facility and On-line Documentation*. Risø National Laboratory, Roskilde, Denmark. 335 topics. ISBN 87-550-3457-8.
9. Niels G. Mortensen, Usama Said Said, Helmut P. Frank, Laila Georgy, Charlotte B. Hasager, Mohamad Akmal, J. Carsten Hansen and Ashour Abdel Salam (2003). *Wind Atlas for the Gulf of Suez. Measurements and Modelling 1991-2001*. New and Renewable Energy Authority, Cairo, and Risø National Laboratory, Roskilde. ISBN 87-550-3195-1. 196 pp.