A new methodology for recalibrating cup anemometers based on field measurements and statistical analysis

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Abstract. This paper presents a novel methodology for calibrating cup anemometers, addressing a critical need in the wind energy sector for accurate and reliable wind speed measurement. Ensuring measurement accuracy through calibration remains a major challenge. In response, a cost-effective alternative methodology is presented that takes advantage of statistical analysis techniques. York linear regression is applied for the estimation of calibration coefficients, a novelty in the context of cup anemometer calibration. The approach overcomes the limitations of traditional procedures reliant on wind tunnel facilities. Experimental validation of the proposed methodology, carried out with wind turbines placed at a height of 10 meters, demonstrates that a reliable calibration can be achieved even in sites with a low wind regime. **Keywords:** Cup anemometer; Calibration; York regression; Wind speed; Statistics.

1 Introduction

Wind speed anemometers are widely used in various sectors, including meteorology, civil structures, and wind energy [1]. Accurate quantification of wind speed is crucial for the planning and development of several civil engineering projects, as well as for the advancement of renewable energy technologies [2,3]. Cup anemometers (CAs) stand out as prominent sensors in the wind energy sector due to their characteristics such as robustness again the natural environment, low power consumption, low cost, and minimal maintenance requirements [4].

Cup anemometers (CA) shows a linear response in the normal wind speed range [5,6], making these instruments the preferred choice for wind resource assessment. Periodic (re-calibration) is, however, of the essence in order to ensure reliable and comparable measurements over time. Various calibration methods, including those relying on wind tunnel experiments (WTE), have been explored to ensure the linear correlation between wind speed and rotational speed [2] and determine the parameters of the calibration line. One of the most commonly used methodologies for calibrating cup anemometers is the MEASNET standard [7]. While being a generally accepted procedure, MEASNET calibration requires a

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large wind tunnel with specific characteristics which puts a significant price tag on the procedure and limits frequent recalibrations.

Field-based calibration methodologies may not only potentially represent a cost-effective alternative where adequate wind tunnels and instruments are not available but also enable frequent recalibrations contributing to a consistent timeline of measurements. In this paper we present such an approach for the calibration of CA based on statistical analysis. Processing stages include the analysis of the wind direction regime at the site to avoid wake effects due to tower shadows, the selection of an adequate regression schemes accounting for errors in both the reference and the independent variable sensitivity analyses to ascertain that the wind resource is adequate for the reliable determination of the calibration parameters. The York linear regression was found to be the most adequate method for recalibration, marking this work the first application of this method in the context of CA calibration, to the best of the knowledge of the authors.

The remainder of this manuscript is organized as follows: Section 2 provides an overview of the methodology, detailing pre-processing steps and regression techniques employed. Section 3 presents and discusses the results. Finally, Section 4 provides a summary and the conclusions of the study.

2 Methodology

2.1 Objective

An analogous instrument or sensor provides an output, e.g., pulses or a continuous voltage signal, that is later adjusted to generate an output signal which is to be interpreted as the value of the variable of interest. Frequently, these conversions are affine transformations characterized by a slope C and an offset D as shown on Eq. 1, where S_p is the processed signal and S is the analogous output or signal provided by the instrument.

$$S_p = CS + D. \tag{1}$$

In this study, the analogous signal is a pulse frequency f provided by an anemometer and the processed signal is the speed v measured by the device, as seen in Eq. 2

$$v = Cf + D. \tag{2}$$

The parameters of interest, called calibration coefficients, are the device slope and offset coefficients that convert the frequency to speed. As mentioned on the introduction, this study proposes an on-site methodology using wind speed measurements provided by a reference anemometer A_R, and a used anemometer A_U that has previously been deployed in wind measurement campaigns and whose calibration certificate is no longer valid. We then have the following equations:

$$v_R = C_R f + D_R \tag{3}$$
$$v_U = C_U f + D_U \tag{4}$$

The objective is to install both sensors on the same site and height and to measure the same wind resource. On an ideal world where both anemometers are exposed to the same wind, the wind speed measured by both sensors would be the same, $v_R = v_U$. However, after years of use in the field the original coefficients C_U y D_U are generally no longer accurate.

2.2 Estimation of calibration coefficients and validation

The basic assumption in this work, as in most calibration procedures, is that a linear relationship exists between the wind speed v_R measured by a calibrated reference sensor and the value v_U measured by the used sensor.

$$v_R = mv_U + b \tag{5}$$

The slope m and offset b parameters from the linear regression become essential for estimating the new calibration coefficients. Substituting Eq. 5 with Eq. 3 and 4 the relation between the calibration coefficients of the reference and used sensors can be shown.

$$C_R f + D_R = m(C_U f + D_U) + b \tag{6}$$

The following identities are obtained easily from the previous equation:

$$C_R = mC_U \tag{7}$$
$$D_R = mD_U + b \tag{8}$$

allowing to solve for the designed new calibrations coefficients.

$$C_U = C_R/m \tag{9}$$
$$D_U = (D_R - b)/m \tag{10}$$

In the context of a wind tunnel measurement, wind flow can generally be assumed to be laminar and blockage effects are negligible (if the projected area of the anemometer is very small compared to the effective flow area), leading to a very clean relationship between variables v_U and v_R. In the setting of a field measurements, on the other hand, tower shadow (or “wake”) effects must be carefully avoided, as well as distortions of the wind flow from nearby obstacles. But even in the absence of such effects readings on both anemometers will reflect the statistical nature of the wind flow in the presence of ambient turbulence, which is why the linear relationship of Eq. 5 will only hold in a statistical sense. It seems straightforward to estimate the slope and offset of Eq. 5 by a (simple) linear regression (SLR). This approach has some an important drawback, however, as can be seen if the SLR between and independent variable x and a dependent variable y is written in the following form [8]:

$$\hat{y} = \mu_y + \rho_{xy}\frac{\sigma_y}{\sigma_x}(x - \mu_x) \tag{11}$$

It can be readily seen the slope of the regression is given by $m = \rho_{xy}\,\sigma_y/\sigma_x$, whereas the offset is $b = \mu_y - m\mu_x$. Therefore, for a given value for the ratio of the standard deviations (expected to be $\sigma_y/\sigma_x \sim 1$ in a calibration setting) the value of the correlation coefficient ρ_{xy} has an important impact on the fit parameters m and b, and, consequently on the calibration parameters C_U and D_U. The lower the correlation, the lower the slope and the higher the offset. The specific conditions at the site will then directly reflect the results of the calibration.

Fortunately, this downside of the field calibration setup can be avoided by using a suitable regression approach. One option is to use a symmetrized fitting scheme, where the parameters resulting from a fit of y vs x are averaged against those obtained from a fit of x vs y. Another, more consistent, approach is to use a regression model allowing for errors in both the independent and the dependent variable, first introduced by Deming [9] and later extended to correlated errors by York [10], which is relevant to the current context. While less common than simple linear regression, codifications of the Deming-York approach are available for common programming platforms like Matlab [11] and R [12]. For the final results presented in this work, an implementation with Matlab and validation with R was used.

Another important issue is the range of wind speeds required for reliable outcomes of the calibration study. Though cup anemometers have a linear response over a very large wind speed range, making it possible to estimate the calibration parameters from a relatively small speed range, the reliability of the regression parameters, given the statistical nature of wind resource in the field, must be assessed carefully. To do so, a sensitivity analysis has been conducted in all cases, where the upper wind speed value used in the regression analysis has been reduced artificially and the effect on the fit results has been recorded. By plotting the evolution of the fit results as a function of the upper wind speed it can then be established if the results converge to their final values withing the wind speed range available during the measurements.

To validate the calibration coefficients obtained with the procedure described the York method was also applied to the recalibrated wind speed readings to ascertain that the new slope was close to one and the offset close to zero, as one would expect from two calibrated sensors measuring a very similar wind resource.

2.3 Experimental arrangement and data acquisition

This arrangement considers two heights where two sensors are installed, a reference, calibrated anemometer, and the anemometer under study (yet to be calibrated) at a height of 10m above ground level. This arrangement is replicated at a height of 8m. The second height level was added to allow for extending the measurement period of each sensor, while being able to start calibrating the following sensor. All cup anemometers used in this work are THIES first class advanced wind transmitters [13]. A wind direction sensor (or vane) was installed at a height of 9m with its boom pointing in a direction approximately perpendicular to the anemometer booms to avoid interference. Fig. 1. a) shows the tower with the experimental setup of the sensors used in this work. Fig. 1. b) shows the installation diagram indicating the heights at which the different sensors were placed.

The data acquisition arrangement includes two CR10X Campbell Scientific dataloggers. The loggers were configured to extract the wind speed every two seconds and perform a two-minute average where the standard deviation and maximum values were also registered. Data were acquired during period of two weeks for each sensor, one week at the 10m height level and a consecutive week at 8m. For data acquisition the reference calibration coefficients C and D were used for both anemometers

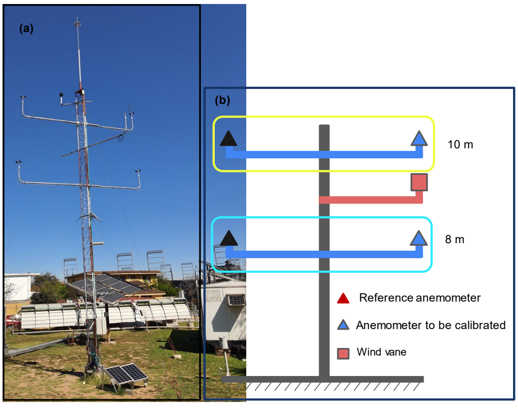

Fig. 1. Experimental arrangement. a) Tower installed at the facilities of Tecnológico de Monterrey – Mexico. b) Schematic of the experimental arrangement.

2.4 Data processing, statistics, and estimation of coefficients

2.4.1 Data pre-processing

Data pre-processing involved clearing the dataset of any inconsistent or atypical values potentially caused by voltage variations or logger registry errors. Subsequently, the datasets were filtered to remove any trailing effects that may have developed during data acquisition.

The booms carrying the anemometers were positioned at geographic orientations of 120° and 300°, respectively, at both heights. Using this information and the two-minute average wind direction, wind speed values falling within angles prone to developing wake effects were filtered out. as the exclusion zones were taken as ranges of -15° to +15° around the boom directions of 120° and 300°, respectively. Fig. 2 presents the wind direction histogram for the heights of 10 m and 8 m. In this figure, the ranges for the wake effects are shown as the dotted black lines.

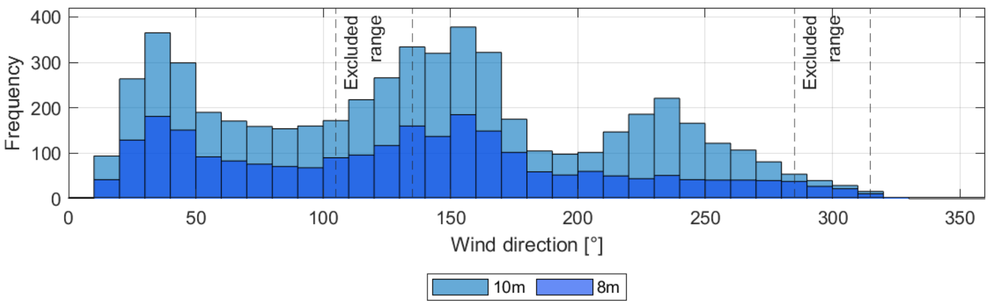

Fig. 2. Wind direction histogram for the 10m and 8m heights and a wind speed ratio between the reference and study anemometer as well as the proportion and mean proportion between the reference and study wind speed.

After this pre-processing is performed the final dataset for both heights is achieved.

2.4.2 Symmetrical linear regression - sensitivity analysis

As mentioned above, it was important to validate if the wind speed range available at the measurement site, located at cleared obstacle-free location but surrounded by the built-up environment of the city limiting the available wind resource, was sufficient to obtain reliable results. To do so, the upper value of the wind speed range considered in the study was reduced artificially, and all fit parameters were retained and plotted for each upper value.

In the case of the symmetrized simple linear analysis two standard linear regressions were performed: one using the reference wind speed as the X-values and the study wind speed as the Y-values, referred to as the 'Reference-Study Analysis,' and another using the study wind speed as the X-values and reference wind speed as the Y-values, referred to as the 'Study-Reference Analysis.' The results of this analysis for the heights of 10 m and 8 m are presented in Fig. 3 and Fig. 4., respectively.

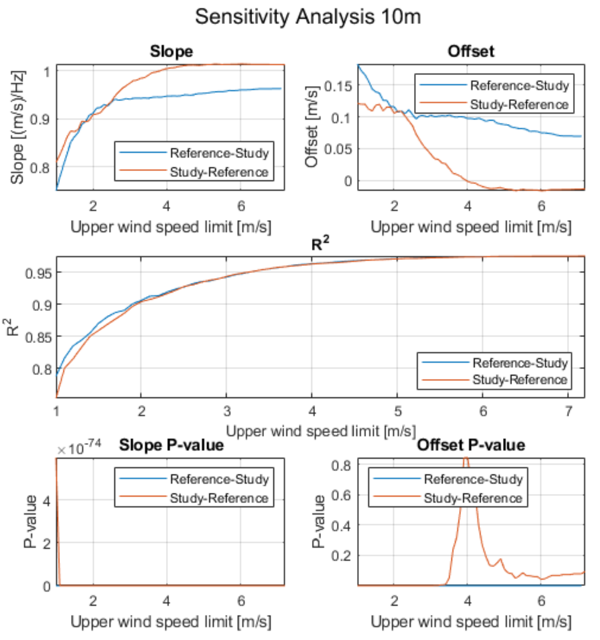

Fig. 3. Sensitivity analysis performed with linear regression on the Reference-Study case and Study-Reference case for 10m. P-value of the reference-Study is P<0.05 which means its statistically significative with a 95% confidence interval.

As seen in Fig. 3 and Fig. 4, the R^2 value achieves 95% starting at 3.3 m/s at 10m height, while achieving around 93% with the same upper wind limit at 8m. This indicates that even only considering the data with windspeeds below 3.3 m/s, the linear regression can explain up to 95% of the variance for the 10 m height case. More importantly, the R^2 curve can be seen to converge around to 4 to 5 m/s, indicating that no changes to the results occur upon considering higher wind speed values. Similarly, the fit parameters (slope and offset) can be seen to level out in the same wind speed interval.

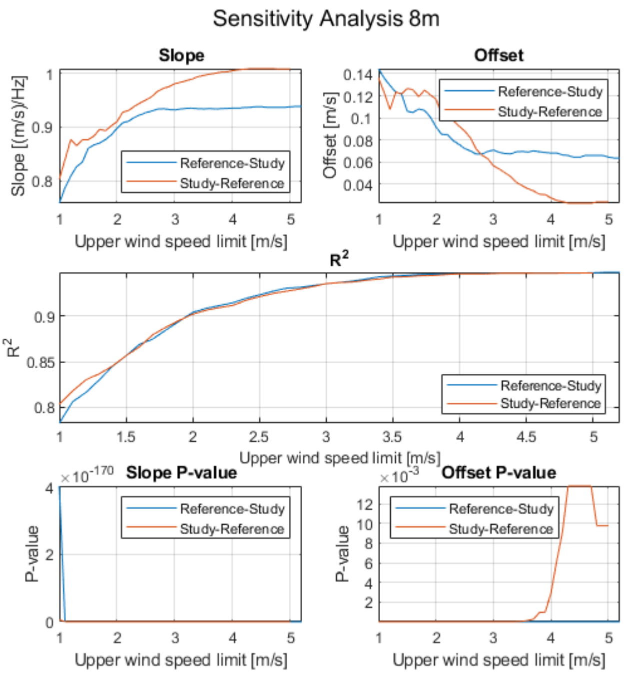

Fig. 4. Sensitivity analysis performed with linear regression on the Reference-Study case and Study-Reference case for 8m. P-value of the reference-Study is P<0.05 which means its statistically significative with a 95% confidence interval.

The results of the symmetrized standard linear regression were used only to ascertain than the wind speed range available at the site is sufficient for consistent results. The actual calibration values were determined with the York linear regression method, mentioned above and described in more detail below.

2.4.3 Linear regression with uncertainties in both X and Y-Values

To obtain the slope m and offset b parameters for recalibration, a weighted linear regression with uncertainties in X and Y values is performed, following the method described by York et al. [10]. This York linear regression method utilizes the two-minute average wind speed from the reference anemometer as its X-value, with the standard deviation of this average serving as its uncertainty. Similarly, the two-minute average wind speed from the use anemometer is used as the Y-value, with its corresponding standard deviation as its uncertainty [11].

The results of this linear regression can be seen in Fig. 5 for the measurement heights of 10m and 8m, respectively. The two curves exhibit an expected feature, the higher wind resource at 10m. The fit lines can be seen, however, to produce very similar results, as also shown below.

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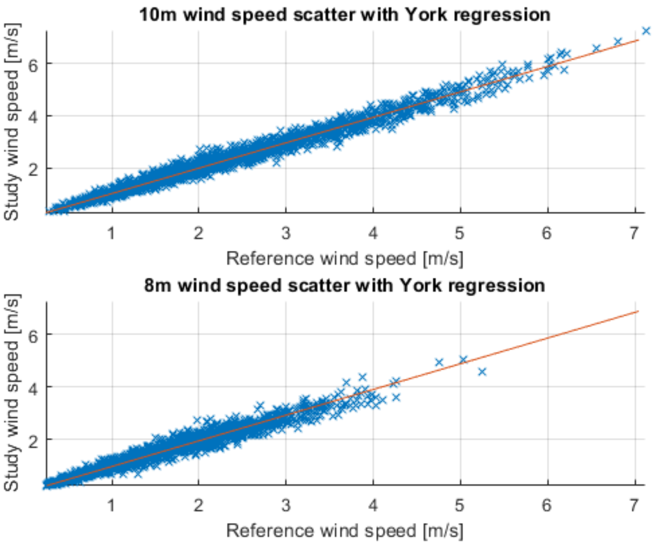

Fig. 5. Linear regression with uncertainties in both X and Y values for both 10m and 8m.

The regression analysis parameters obtained from the 10m dataset are:
Slope: 0.9747 ± 0.0020 Offset: 0.0331 ± 0.0031
The regression analysis parameters obtained from the 8m dataset are:
Slope: 0.978 ± 0.0028 Offset: -0.0035 ± 0.0027
While being close to one, the slope of the York regression can be seen to deviate from the expected value of one a statistically significant way, given the error bounds provided by the method, indicating a need for recalibration. Similarly, the offset, at least in the case of the results for 10m, can be seen to differ significantly from zero.

2.4.4 Calibration coefficient estimation

After obtaining the slope and offset parameters of the linear regression and its standard deviations as error, a substitution is performed using the known certified calibrated coefficients of the reference cup anemometer. The calibration coefficients C_R and D_R for the reference cup anemometer at 10 m are 0.04580 (m/s)/Hz and 0.2362 m/s, respectively, while the calibration coefficients C_R and D_R for the reference cup anemometer at 8 m are 0.04577 (m/s)/Hz and 0.2425 m/s, respectively.

Using these calibration coefficients and substituting on Eq. 9 and 10 the new calibration coefficients can be achieved to obtain a recalibrated C_U and D_U for each height.

3 Results and discussion

3.1 Recalibration coefficient estimates for both heights

After performing the methodology and regression analysis and substituting the linear regression parameters of slope m and offset b using Eq. 9 and 10, the recalibration coefficients for C_U and D_U for each height can be estimated. These will now be referred as C_{10m}, D_{10m}, C_{8m}, D_{8m} according to each height.

For the 10m height the recalibration coefficients are:

C_{10m} = 0.04699 (m/s)/Hz
D_{10m} = 0.21483 m/s
For the 8m height the recalibration coefficients are:
C_{8m} = 0.0468 (m/s)/Hz
D_{8m} = 0.25158 m/s

Once the wind speed values gathered with the used cup anemometer have been recalibrated, a comparison between the non-recalibrated and recalibrated is performed. This is achieved by performing a sensibility analysis similar to the one explained in the methodology section, but using the York linear regression and obtaining the slope and offset parameters such as the values shown on Fig. 6.

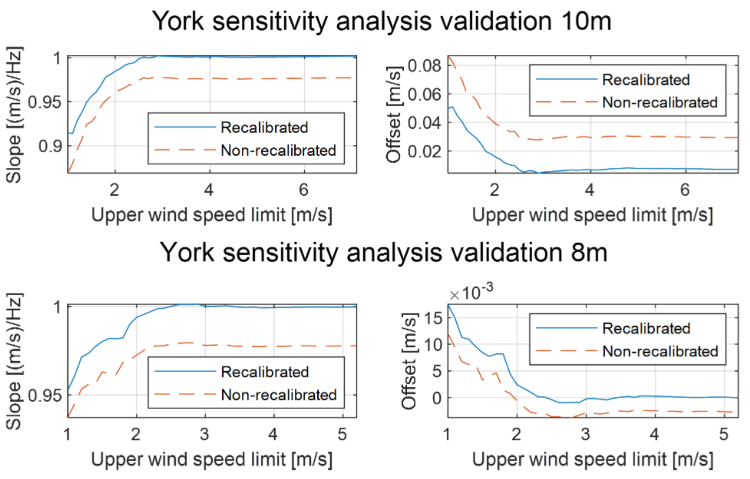

Fig. 6. York sensibility analysis validation with dataset at 10m and 8m.

Two general findings can be observed from Fig. 6: (1) The slope of the calibration curve between the reference anemometer and the anemometer under study is consistent with the value of one after recalibration and the offset is consistent with zero. (2) Results converge to their final values at around 3 m/s, confirming that consistent results can be obtained at a site with a relatively low wind resource.

Specifically, in the case of the 10m analysis the slope improves from *0.9747* with the non-recalibrated coefficients to *0.9990* with the recalibrated coefficients. The same happens with the offset parameter, improving from *0.0331* with the non-recalibrated data to *0.0117* with the recalibrated data. Similarly, in the 8m case, the slope improves from *0.9780* with the non-recalibrated coefficients to *1.0001* with the recalibrated coefficients. The same happens with the offset parameter, improving from *-0.0035* with the non-recalibrated data to *-0.0012* with the recalibrated data.

3.2 Final recalibration coefficients

This study proposes two different heights to increase the size of the data acquired and to benefit from momentary increases in wind. However, this creates the situation where there are two sets of recalibration coefficients.

Since a single pair of recalibration coefficients needs to be reported a weighted mean is proposed to obtain the final value of C_V and D_V, which are both the slope and offset final recalibrated coefficients.

The estimation of the weights for the weighted mean is done by considering the Root-mean-square error RMSE between the reference anemometer wind speed and the used anemometer wind speed measured for each height, so that the pair of coefficients that belong to the height dataset with less RMSE has a greater significance on the final coefficients, the weights are estimated as shown on Eq. 12 and 13 for the 10m and 8m datasets.

$$w_{10\mathrm{m}} = 1 - \mathrm{RMSE}_{10\mathrm{m}}/(\mathrm{RMSE}_{10\mathrm{m}} + \mathrm{RMSE}_{8\mathrm{m}}) \tag{12}$$
$$w_{8\mathrm{m}} = 1 - \mathrm{RMSE}_{8\mathrm{m}}/(\mathrm{RMSE}_{10\mathrm{m}} + \mathrm{RMSE}_{8\mathrm{m}}) \tag{13}$$

The final recalibration coefficients can then be calculated as follows.

$$C_V = w_{10m}C_{10m} + w_{8m}C_{8m} \tag{14}$$
$$D_V = w_{10m}D_{10m} + w_{8m}D_{8m} \tag{15}$$

In this case the 10m dataset has a lesser RMSE than the 8m dataset. Performing this final estimation allows for the final recalibration coefficients to be estimated.

C_V = 0.04693 (m/s)/Hz
D_V = 0.22671 m/s

As to validate the data a final RMSE and York regression estimation is performed by appending the 10m and 8m use and reference measurements and using the non-recalibrated and recalibrated C and D coefficients. By using these coefficients for the whole dataset on both heights, the RMSE is reduced from 1.7746 m/s for the non-recalibrated dataset to 0.3692 m/s to the recalibrated dataset using the recalibration coefficients C_V and D_V. Obtaining a reduction of 79.20% of the RMSE. Likewise performing the York regression using the recalibration coefficients achieves the following parameters, using the same notation as before:

Slope: 1.0051 ± 0.0014 Offset: -0.0059 ± 0.0017

4 Summary and conclusions

This paper introduces a novel approach for the calibration of cup anemometers (CAs) for the wind energy sector, allowing for cost-effective recalibration without the need of a large wind tunnel required for conventional calibration methods. The proposed methodology is based on a statistical approach, using the York linear regression and sensitivity analyses with respect to the wind speed range used, to achieve accurate calibration. The proposed method was validated experimentally and results for a study case have been reported. The method is believed to be useful for frequent recalibration of anemometers previously used in the field, allowing their useful life to be extended significantly, while maintaining a consistent timeline of measurements. While projects may still rely on new or wind tunnel-calibrated sensors for their main anemometer set, field-calibrated anemometers may be good enough to serve as secondary or “redundant” anemometers, or for additional measurement locations at existing development sites.

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