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Article

Cup Anemometers' Loss of Performance Due to Ageing Processes, and Its Effect on Annual Energy Production (AEP) Estimates

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Abstract: The deviation of calibration coefficients from five cup anemometer models over time was analyzed. The analysis was based on a series of laboratory calibrations between January 2001 and August 2010. The analysis was performed on two different groups of anemometers: (1) anemometers not used for any industrial purpose (that is, just stored); and (2) anemometers used in different industrial applications (mainly in the field—or outside—applications like wind farms). Results indicate a loss of performance of the studied anemometers over time. In the case of the unused anemometers the degradation shows a clear pattern. In the case of the anemometers used in the field, the data analyzed also suggest a loss of performance, yet the degradation does not show a clear trend. A recalibration schedule is proposed based on the observed performances variations.

Keywords: anemometer calibration; cup anemometer; MEASNET; Annual Energy Production (AEP); recalibration schedule; anemometer wear and tear; anemometer loss of performance

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1. Introduction

Today, there is a massive use of wind speed anemometers by industry. The growth experienced by the wind energy sector has increased and spread their use, but leaving aside the applications related to wind energy it should be said that they are being increasingly used in other fields potentially affected by wind (bridges, big cranes). The accuracy of the measurements is extremely important for the wind energy industry as the extractable wind power is proportional to the third power of the wind speed [1,2]. In order to ensure the accuracy of an anemometer it should be recalibrated after being in use some time. The calibration method consists of placing it in an incoming flow with a known speed, uniformity and turbulence level, and measuring its output signal at various given wind speeds. It is thereby possible to obtain a relationship between the velocity of the wind flow and the anemometer's output signal (the control parameter of the output signal normally being its frequency). It is widely accepted that the relationship between the measured wind speed and the anemometer's output frequency is linear [3], that is:

$$V = \mathrm{A} \times f + \mathrm{B} \tag{1}$$

where V is the velocity of the flow (wind speed), f is the anemometer's rotation frequency output, and A (slope) and B (offset) are the calibration coefficients corresponding to the tested anemometer. However, it must also be said that this behavior is not exactly linear, although as mentioned, for most purposes the linear approximation is sufficiently accurate [3,4].

The aim of the present paper is to analyze the variations of the calibration constants A and B over time. This particular study has been proposed to the IDR/UPM Institute many times by enterprises in the wind energy sector, interested in anemometers' potential loss of performance due to wear and tear. At present, the ageing of the anemometers is addressed through frequent recalibration [5]. Some effort has also been done with regard to the anemometers' recalibration in the field [6,7]. However, as far as the authors know there seems to be a lack of results and research in the available literature concerning anemometers' loss of performance.

It is reasonable to assume that once an anemometer is in service, the loss of performance, if it happens, should modify both calibration constants, A and B. On the one hand, this degradation could affect the anemometers' rotational speed, that is, the anemometers' capacity to transform energy from wind into rotation of the shaft should be reduced if energy losses increase (friction, for example), or the rotor's moment of inertia or its aerodynamics are changed by the mass addition of dirt. The reduction in the rotational speed can be translated into an increase of the constant A value. On the other hand, the degradation could also affect the starting speed of the anemometer, that is, as it is longer in service the wind speed necessary to start its rotation could be higher if the friction has increased, and that effect can be translated into an increase of the constant B. Together with the aforementioned considerations, it should also be mentioned that, as common in complex mechanisms, the anemometer's rotor could have a transitional period of time at the beginning of its service life before reaching its stable working condition.

Two different anemometers' degradation cases have been studied. The first one is the degradation of anemometers not used in field and just stored. This case was studied with the data from many calibrations performed on three different single individual anemometers. These calibrations are periodically carried out as part of the internal quality procedures at the IDR/UPM Institute. Each one of these three anemometers is stored in its own box between calibrations, the average seasonal variation of the climatic conditions in the calibration lab being around 20–30 °C, 928–955 hPa, and 18–44% relative humidity. No maintenance program was performed on these anemometers. The second case is related to the degradation of anemometers used in the field. The data from calibrations performed on the same anemometers, sent several times to the IDR/UPM Institute, were collected and analyzed in order to study the degradation of five different models of anemometers. In order to obtain statistically more significant results, the calibrations period covered in a previous study [4] (January 2003 to August 2007) has been extended to January 2001 and January 2011.

Five enterprises of the wind energy sector (Barlovento, Cener, Dekra Ambio, Ecosem, and Ges-Siemsa) collaborated with the IDR/UPM Institute in order to complete the information and strengthen the study with regard to the anemometers' behavior once in service. Thanks to the information provided by the aforementioned enterprises, the maintenance work on several individual anemometers was traced. Some of these anemometers were subjected to high level maintenance, normally consisting of changing the bearings (sometimes together with the change of the anemometer's electronics and the cups' rotor, if damaged).

2. Testing Configuration and Anemometers Studied

The anemometer calibrations analyzed in the present paper were performed by strictly following the MEASNET recommendations [8,9], that is, over 13 points, from 4 to 16 $m{\cdot}s^{-1}$. More details concerning the facility and the calibration process are included in reference [4].

Six different cup anemometers were studied: Risø P2546 (WindSensor, Risø DTU: Roskilde, Denmark); Thies Clima 4.3350 and 4.3303 (Thies Clima: Göttingen, Germany); Climatronics 100075 (Climatronics Corp: Bohemia, NY, USA); Vector Instruments A100 L2 and LK (Windspeed Limited, trading as Vector Instruments: Rhyl, UK).

As stated in the introduction, two different analyses were carried out, the first one was based on calibrations performed on three anemometers used for internal procedures at the IDR/UPM Institute (Climatronics 100075, Vector Instruments A100 L2, and Thies 4.3350), the last two of them being first class anemometers in accordance with IEC-61400-12-1 [10]. These anemometers were calibrated periodically in order to test the quality of the calibration process (more information of the requirements fulfilled by the IDR/UPM Institute in order to ensure a high level of accuracy can be found in reference [4]). The second analysis was based on the data available concerning anemometers sent several times to the IDR/UPM Institute for periodic calibrations. Those anemometers have mostly been used in the field (e.g., installed on wind turbines), and each one under different climatic conditions.

3. Results and Discussion

3.1. Variations in Calibration Constants from Stored Anemometers (not Used in the Field)

In Figure 1 the values of the calibration coefficients corresponding to the IDR/UPM Institute anemometers (Climatronics 100075, Vector Instruments A100 L2, and Thies Clima 4.3350 –from now on these anemometers will be referred to as Cl-100075, A100 L2, and Th-4.3350 in the text), are shown as a function of the number of days after their first calibration. A linear fitting to the data has been included in all graphs. The average values for every 300 days, together with the standard deviation bars, have also been included in the graphs (see Table 1). As said, these three anemometers were used just for IDR/UPM Institute internal procedures and apart from their periodic calibrations, they were not used at all. Despite the scattering of the data shown in Figure 1, some trends can be observed by analyzing the 300-day average results. In some cases the variation of the coefficients seem to clearly fit a linear behavior (Cl-100075 and Th-4.3350 A coefficients, and A100 L2 B coefficient), whereas in others (Cl-100075 and Th-4.3350 B coefficients, and A100 L2 A coefficient) the correlation with the linear fit is worse (see in Figure 1 that the coefficients of determination, R^2, are in these cases significantly lower, from 7.47×10^{-3} to 1.56×10^{-2}, than the ones previously mentioned, from 3.53×10^{-1} to 6.93×10^{-1}).

In Figure 2 the output frequency at 7 m·s^{-1} wind speed of the studied anemometers is plotted as a function of the number of days after their first calibration. There seems to be a transitional period after the starting of life, where the anemometers were more and more efficient in terms of translating the wind speed into rotation (although the practical differences are negligible, around 0.1–0.2 Hz). After this transitional period, the anemometers tend to be less efficient, their output frequency at constant wind speed being decreased with the use. The transitional period observed is around 450 days after the first calibration, for the studied anemometers. The number of calibrations performed on each anemometer within this period was respectively 9 (Cl-100075), 18 (A100 L2) and 30 (Th-4.3350).

If a linear behavior over time after the first calibration, Δt, is considered, both calibration coefficients, A and B, can be expressed as:

$$\mathrm{A} = \mathrm{A}_0 + \frac{d\mathrm{A}}{dt}\Delta t \pm \sigma_{\mathrm{A}} \tag{2}$$

$$\mathrm{B} = \mathrm{B}_0 + \frac{d\mathrm{B}}{dt}\Delta t \pm \sigma_{\mathrm{B}} \tag{3}$$

where (A_0, dA/dt) and (B_0, dB/dt) are respectively the linear fit of both coefficients, and the terms σ_{A} and σ_{B} are a measure of the scattering of the data (as known, the interval $\pm\sigma$ indicates a 68.2% confidence error limits in a Gaussian process).

Bearing in mind what was mentioned in the Introduction with regard to the anemometers' performance degradation (that is, coefficients A and B—one of them or both—tend to increase if degradation is produced), and the data from Figure 1, the behavior of the three considered anemometers has been estimated as follows:

Figure 1. Calibration coefficients' variation with regard to IDR/UPM Institute anemometers: Climatronics 100075 (top), Vector Instruments A100 L2 (middle), and Thies Clima 4.3350 (bottom) cup anemometers. These coefficients were measured in different calibrations from January 2001 to June 2006 (Climatronics 100075), from September 2003 to September 2007 (A100 L2), and from November 2006 to August 2010 (Thies Clima 4.3350). The 300-day average value has been included, together with the standard deviation bars. The linear fitting to the data has been also included.

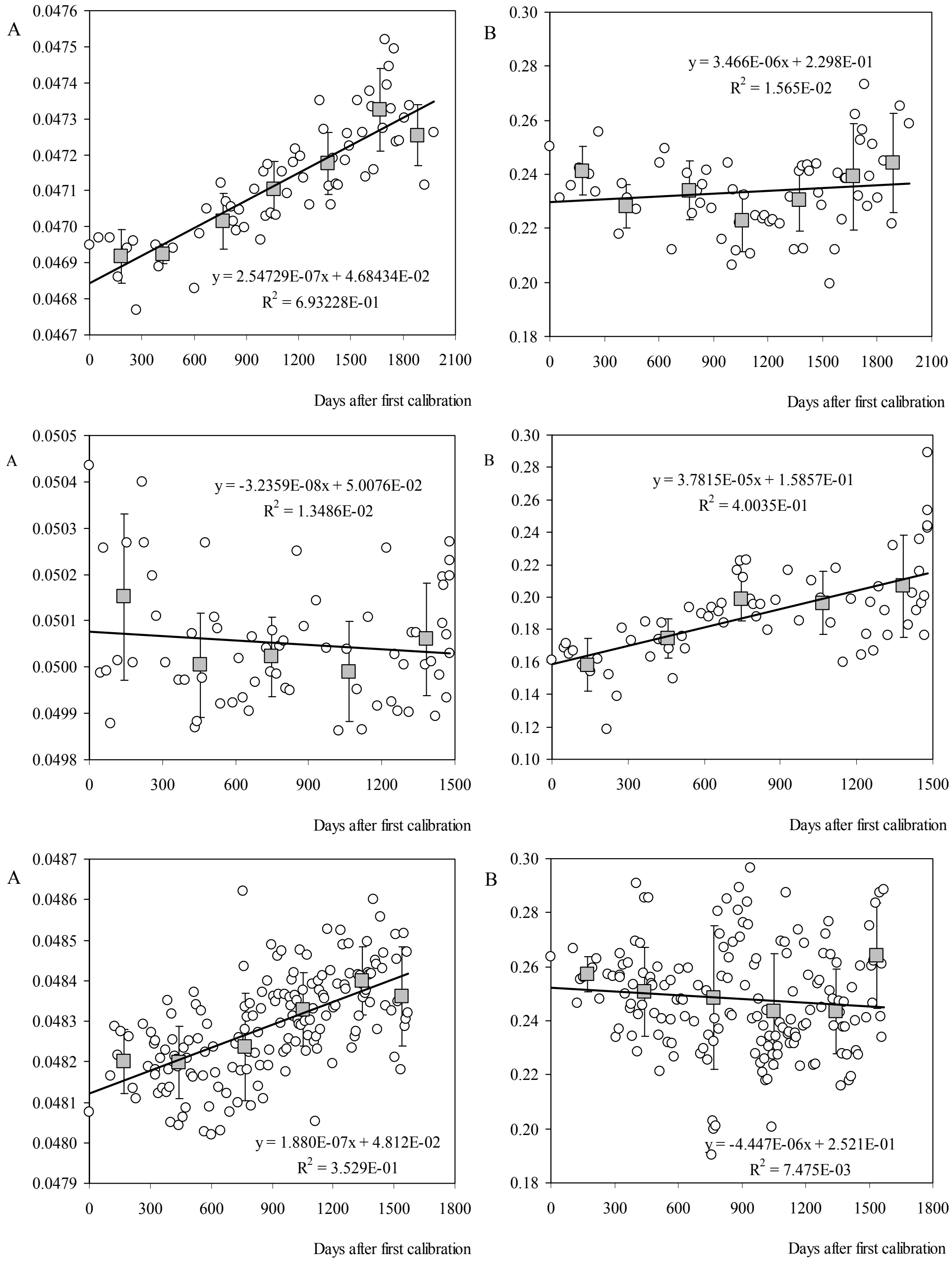
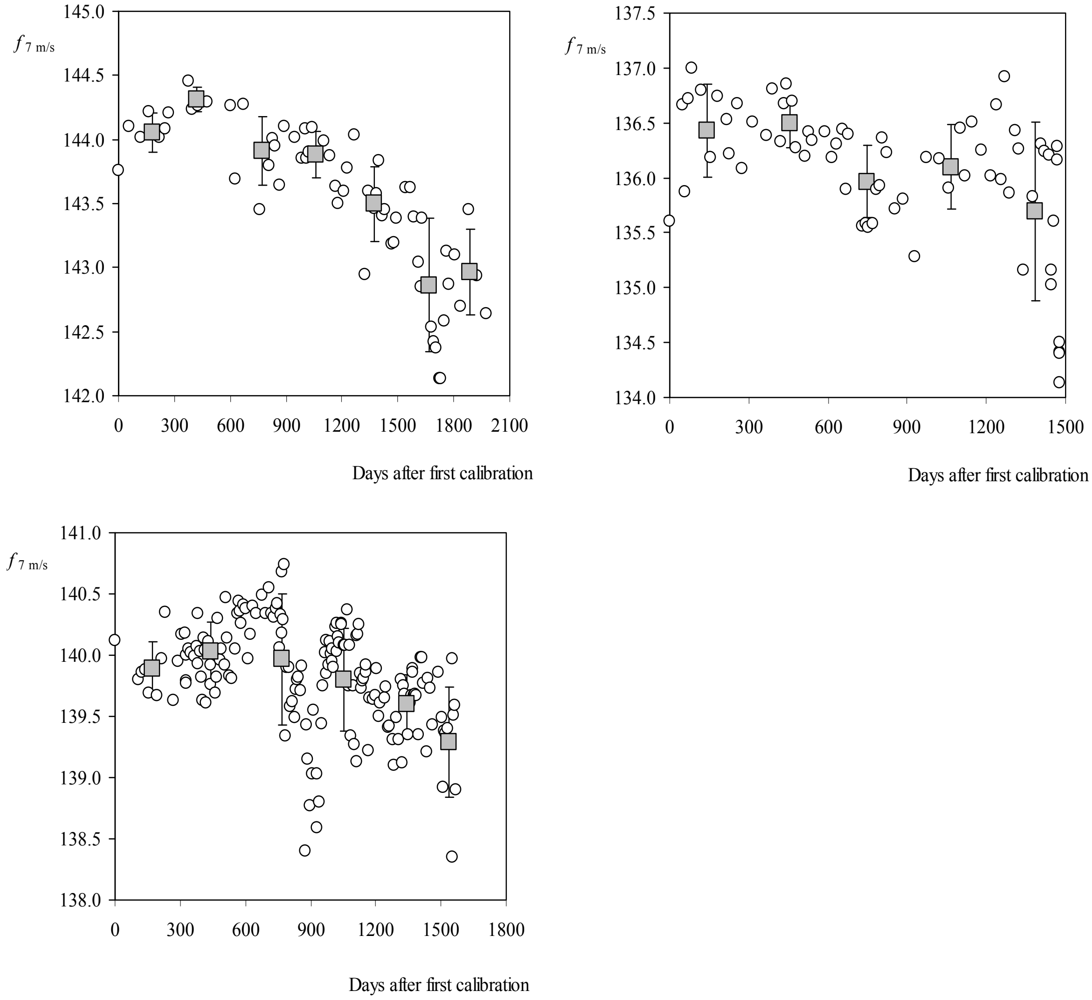


Table 1. Mean and standard deviation values of calibration coefficients A and B every 300 days, corresponding to the IDR/UPM Institute Climatronics 100075, Vector Instruments A100 L2 and Thies Clima 4.3350 anemometers.

Period considered	**Number of calibrations**	**A mean**	σ_A	**B mean**	σ_B
Climatronics 100075					
First 300 days	7	4.6917×10^{-2}	7.5214×10^{-5}	2.4124×10^{-1}	8.9279×10^{-3}
Between 300 and 600 days	4	4.6925×10^{-2}	2.6458×10^{-5}	2.2824×10^{-1}	7.9439×10^{-3}
Between 600 and 900 days	10	4.7015×10^{-2}	7.7683×10^{-5}	2.3398×10^{-1}	1.0886×10^{-2}
Between 900 and 1200 days	11	4.7103×10^{-2}	7.8608×10^{-5}	2.2276×10^{-1}	1.1274×10^{-2}
Between 1200 and 1500 days	13	4.7175×10^{-2}	8.5312×10^{-5}	2.3057×10^{-1}	1.1498×10^{-2}
Between 1500 and 1800 days	14	4.7325×10^{-2}	1.1543×10^{-4}	2.3905×10^{-1}	1.9730×10^{-2}
Between 1800 and 2100 days	5	4.7254×10^{-2}	8.4135×10^{-5}	2.4437×10^{-1}	1.8364×10^{-2}
Vector Instruments A100 L2					
Period considered	**Number of calibrations**	**A mean**	σ_A	**B mean**	σ_B
First 300 days	12	5.0151×10^{-2}	1.7868×10^{-4}	1.5813×10^{-1}	1.6276×10^{-2}
Between 300 and 600 days	12	5.0005×10^{-2}	1.1291×10^{-4}	1.7469×10^{-1}	1.2122×10^{-2}
Between 600 and 900 days	15	5.0022×10^{-2}	8.4847×10^{-5}	1.9887×10^{-1}	1.3416×10^{-2}
Between 900 and 1200 days	8	4.9991×10^{-2}	1.0809×10^{-4}	1.9644×10^{-1}	1.9603×10^{-2}
Between 1200 and 1500 days	21	5.0060×10^{-2}	1.2157×10^{-4}	2.0680×10^{-1}	3.1423×10^{-2}
Thies Clima 4.3350					
Period considered	**Number of calibrations**	**A mean**	σ_A	**B mean**	σ_B
First 300 days	10	4.8200×10^{-2}	7.8535×10^{-5}	2.5722×10^{-1}	6.4219×10^{-3}
Between 300 and 600 days	36	4.8198×10^{-2}	8.8757×10^{-5}	2.5058×10^{-1}	1.6461×10^{-2}
Between 600 and 900 days	33	4.8237×10^{-2}	1.3275×10^{-4}	2.4841×10^{-1}	2.6559×10^{-2}
Between 900 and 1200 days	45	4.8329×10^{-2}	9.0911×10^{-5}	2.4362×10^{-1}	2.1235×10^{-2}
Between 1200 and 1500 days	33	4.8398×10^{-2}	8.4043×10^{-5}	2.4344×10^{-1}	1.5727×10^{-2}
Between 1500 and 1800 days	10	4.8361×10^{-2}	1.2206×10^{-4}	2.6393×10^{-1}	1.9459×10^{-2}

- Cl-100075. This anemometer seems to degrade decreasing the rotation speed, but no clear effect can be observed on the offset speed, so only degradation due to the loss of rotation speed was considered ($A_0 = 4.684 \times 10^{-2}$, and $dA/dt = 2.547 \times 10^{-7}$: both the linear fit from Figure 1; $B_0 = 0.2505$: value from the initial calibration in 2001, and $dB/dt = 0$; $\sigma_A = 7.7548 \times 10^{-5}$, and $\sigma_B = 1.26607 \times 10^{-2}$: average values of the scattering from Table 1).
- A100 L2. Only degradation due to the increase of the offset speed was considered for this anemometer ($A_0 = 5.044 \times 10^{-2}$: value from the initial calibration in 2003, and $dA/dt = 0$; $B_0 = 1.5857 \times 10^{-1}$, and $dB/dt = 3.7815 \times 10^{-5}$: both the linear fit from Figure 1; $\sigma_A = 1.21218 \times 10^{-4}$, and $\sigma_B = 1.85679 \times 10^{-2}$: average values of the scattering from Table 1).
- Th-4.3350. As in the case of the Cl-100075 anemometer, only degradation due to the loss of rotation speed was considered ($A_0 = 4.8120 \times 10^{-2}$, and $dA/dt = 1.880 \times 10^{-7}$: both the linear fit from Figure 1; $B_0 = 0.26358$: value from the initial calibration in 2006, and $dB/dt = 0$; $\sigma_A = 9.9509 \times 10^{-5}$, and $\sigma_B = 1.7644 \times 10^{-2}$: average values of the scattering from Table 1).

Figure 2. Variation of the output frequency at 7 m·s^{-1} wind speed, $f_{7m/s}$, as a function of the number of days after the first calibration, for the IDR/UPM Institute's anemometers, Cl-100075 (top left side), A100 L2 (top right side), and Th-4.3350 (bottom). The 300-day average value has been included, together with the standard deviation bars.



Taking into account the Equations (1) to (3), the variation in the measured wind speed as a function of the time (days) after the first calibration can be estimated as:

$$\Delta V = \left(\frac{1}{\mathrm{A}_0} \frac{d\mathrm{A}}{dt} V + \left(\frac{d\mathrm{B}}{dt} - \frac{\mathrm{B}_0}{\mathrm{A}_0} \frac{d\mathrm{A}}{dt} \right) \right) \Delta t \pm \left| \frac{V - \mathrm{B}_0}{\mathrm{A}_0} \sigma_{\mathrm{A}} + \sigma_{\mathrm{B}} \right|, \tag{4}$$

where the second term is the 68.2% confidence error limits (obviously, this confidence level can be extended by increasing the respective confidence levels of A and B, that is, σ_A and σ_B).

Once the variation of the measured wind speed regarding an individual anemometer has been defined as a function of the time from its first calibration, it is possible to establish some criteria in order to decide when it should be necessary to recalibrate it. The first criterion could be based solely on the deviation of the measured speed. In this case, the recalibration should be programmed when, at a certain wind speed, V, the difference between that velocity and the measured wind speed, ΔV, has reached a certain level. Let us suppose that the limit is established at X% of the reference wind speed, V. Then, the recalibration of the anemometer should be scheduled at:

$$\Delta t = \frac{\frac{X}{100}V + \left|\frac{V - \mathrm{B}_0}{\mathrm{A}_0}\sigma_\mathrm{A} + \sigma_\mathrm{B}\right|}{\frac{1}{\mathrm{A}_0}\frac{d\mathrm{A}}{dt}V + \left(\frac{d\mathrm{B}}{dt} - \frac{\mathrm{B}_0}{\mathrm{A}_0}\frac{d\mathrm{A}}{dt}\right)}, \qquad (5)$$

where Δt is the number of days after the initial calibration. At that time, the measured wind speed has X% deviation with respect to the wind speed, with 84.1% confidence (supposing a Gaussian process). Obviously, if it is decided to increase the confidence level to 97.7% the values of σ_A and σ_B would have to be increased by a factor of 2. On the other hand, if a 50% confidence level is considered the term related to σ_A and σ_B must be ignored in Equation (5).

In Tables 2–4, the proposed recalibration schedules of the Cl-100075, A100 L2, and Th-4.3350 IDR/UPM anemometers, for reference wind speeds V = 4, 10, 16 and 22 m·s^{-1}, have been respectively included as a function of the accepted difference between the measured and the reference wind speeds, and the confidence level. See also in the Figure 3, the recalibration diagrams corresponding to the reference wind speed V = 10 m·s^{-1} as a function of the confidence level, for 1, 0.5, 0.3 and 0.1% error with respect to the reference wind speed.

Table 2. Recalibration schedule (days after the initial calibration) of the IDR/UPM Institute Cl-100075 anemometer for reference wind speeds 4, 10, 16 and 22 m·s^{-1} as a function of the accepted deviation from the reference wind speeds, and the confidence level.

1% deviation from reference wind speed					**0.5% deviation from reference wind speed**				
Confidence	**Reference wind speed**				**Confidence**	**Reference wind speed**			
level	4	10	16	22	**level**	4	10	16	22
50.0%	1962	1886	1868	1860	50.0%	981	943	934	930
84.1%	2887	2430	2321	2272	84.1%	1906	1486	1386	1342
97.7%	3813	2973	2773	2683	97.7%	2832	2030	1839	1753
99.9%	4738	3516	3225	3095	99.9%	3757	2573	2291	2165
0.3% deviation from reference wind speed					**0.1% deviation from reference wind speed**				
Confidence	**Reference wind speed**				**Confidence**	**Reference wind speed**			
level	4	10	16	22	**level**	4	10	16	22
50.0%	589	566	560	558	50.0%	196	189	187	186
84.1%	1514	1109	1013	970	84.1%	1122	732	639	598
97.7%	2439	1652	1465	1381	97.7%	2047	1275	1091	1009
99.9%	3365	2196	1917	1793	99.9%	2972	1818	1544	1421

The second criterion suggested to recalibrate the anemometers can be based on the variations of the Annual Energy Production (AEP) estimations due to the error in the wind speed measurements caused by the anemometer's loss of performance. In Figure 4 the variations of the AEP due to the Cl-100075, A100 L2 and Th-4.3350 anemometers' degradation (with 84.1% confidence level) are shown for 4, 7 and 10 m·s^{-1} hub height annual average wind speed (see also Table 5). These AEP calculations have been made by following the procedure recommended by the International Electrotechnical Commission (IEC) [10], using the General Electric GE2.5 wind turbines power curve as a reference (see [4]). The recalibration of the anemometer should then be ordered when the underestimation of the AEP reaches a certain critical level.

Table 3. Recalibration schedule (days after the initial calibration) of the IDR/UPM Institute A100 L2 anemometer for reference wind speeds 4, 10, 16 and 22 m·s^{-1} as a function of the accepted deviation from the reference wind speeds, and the confidence level.

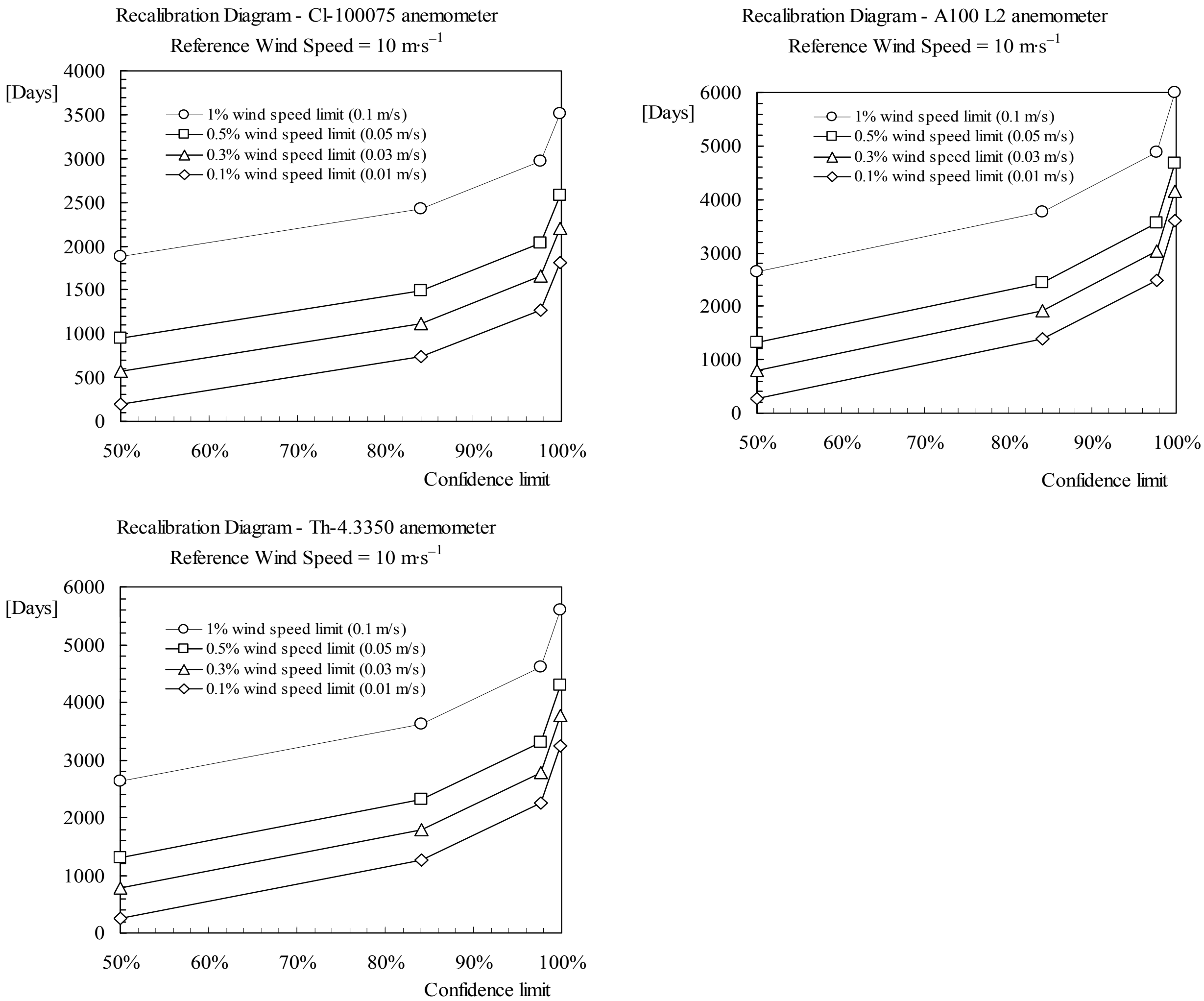
1% deviation from reference wind speed					**0.5% deviation from reference wind speed**				
Confidence level	**Reference wind speed**				**Confidence level**	**Reference wind speed**			
	4	10	16	22		4	10	16	22
50.0%	1058	2644	4231	5818	50.0%	529	1322	2116	2909
84.1%	1793	3761	5729	7697	84.1%	1264	2439	3613	4788
97.7%	2528	4877	7227	9576	97.7%	1999	3555	5111	6667
99.9%	3263	5994	8724	11455	99.9%	2734	4672	6609	8546
0.3% deviation from reference wind speed					**0.1% deviation from reference wind speed**				
Confidence level	**Reference wind speed**				**Confidence level**	**Reference wind speed**			
	4	10	16	22		4	10	16	22
50.0%	106	264	423	582	50.0%	106	264	423	582
84.1%	841	1381	1921	2461	84.1%	841	1381	1921	2461
97.7%	1576	2497	3419	4340	97.7%	1576	2497	3419	4340
99.9%	2311	3614	4916	6219	99.9%	2311	3614	4916	6219

Table 4. Recalibration schedule (days after the initial calibration) of the IDR/UPM Institute Th-4.3350 anemometer for reference wind speeds 4, 10, 16 and 22 m·s^{-1} as a function of the accepted deviation from the reference wind speeds, and the confidence level.

1% deviation from reference wind speed					**0.5% deviation from reference wind speed**				
Confidence level	**Reference wind speed**				**Confidence level**	**Reference wind speed**			
	4	10	16	22		4	10	16	22
50.0%	2740	2629	2602	2591	50.0%	1370	1314	1301	1295
84.1%	4478	3622	3419	3328	84.1%	3108	2308	2118	2032
97.7%	6216	4615	4235	4065	97.7%	4846	3301	2934	2769
99.9%	7954	5608	5051	4802	99.9%	6584	4294	3750	3506
0.3% deviation from reference wind speed					**0.1% deviation from reference wind speed**				
Confidence level	**Reference wind speed**				**Confidence level**	**Reference wind speed**			
	4	10	16	22		4	10	16	22
50.0%	822	789	781	777	50.0%	274	263	260	259
84.1%	2560	1782	1597	1514	84.1%	2012	1256	1077	996
97.7%	4298	2775	2413	2251	97.7%	3750	2249	1893	1733
99.9%	6036	3768	3230	2988	99.9%	5488	3242	2709	2470

There seems to be some discrepancy with regard to the recalibration based on the deviation of the measured speed at 10 m·s^{-1} reference wind speed (Figure 3), and the recalibration based on the underestimation of the AEP (Figure 4).

Figure 3. Recalibration diagram proposed for the IDR/UPM Institute's Cl-100075 (top left side), A100 L2 (top right side), and Th-4.3350 (bottom) cup anemometers.



Based on the loss of performance at 10 m·s^{-1} wind speed, the Cl-100075 anemometer should be recalibrated before the A100 L2 anemometer, however, for 4 m·s^{-1} hub height annual average wind speed the underestimation of the AEP is higher in the case of the A100 L2 anemometer than in the case of the Cl-100075 anemometer, no matter the time elapsed since the first calibration. This can be explained as both anemometers degrade differently, according to the data in Figure 1. The Cl-100075 anemometer loses performance by decreasing the rotation speed for a given wind speed, whereas the A100 L2 anemometer does it by increasing the offset speed. This represents a different degradation of the anemometers' performances at different reference wind speeds. In Figure 5 the underestimation of the measured wind speed, ΔV, is plotted as a function of the reference wind speed for the three anemometers considered 300, 900 and 1800 days after the first calibration. As can be observed in the aforementioned figure, for low wind speeds the loss of performance of the A100 L2 anemometer is greater than the one from the Cl-100075 anemometer, whereas the situation is different for higher wind speeds.

Figure 4. Variation of the Annual Energy Production (AEP) underestimation caused by the error in the wind speed measurement due to the loss of performance of the IDR/UPM Institute's Cl-100075 (top left side), A100 L2 (top right side), and Th-4.3350 (bottom) cup anemometers. AEP related to General Electric GE2.5. Underestimation calculated with 84.1% confidence level.

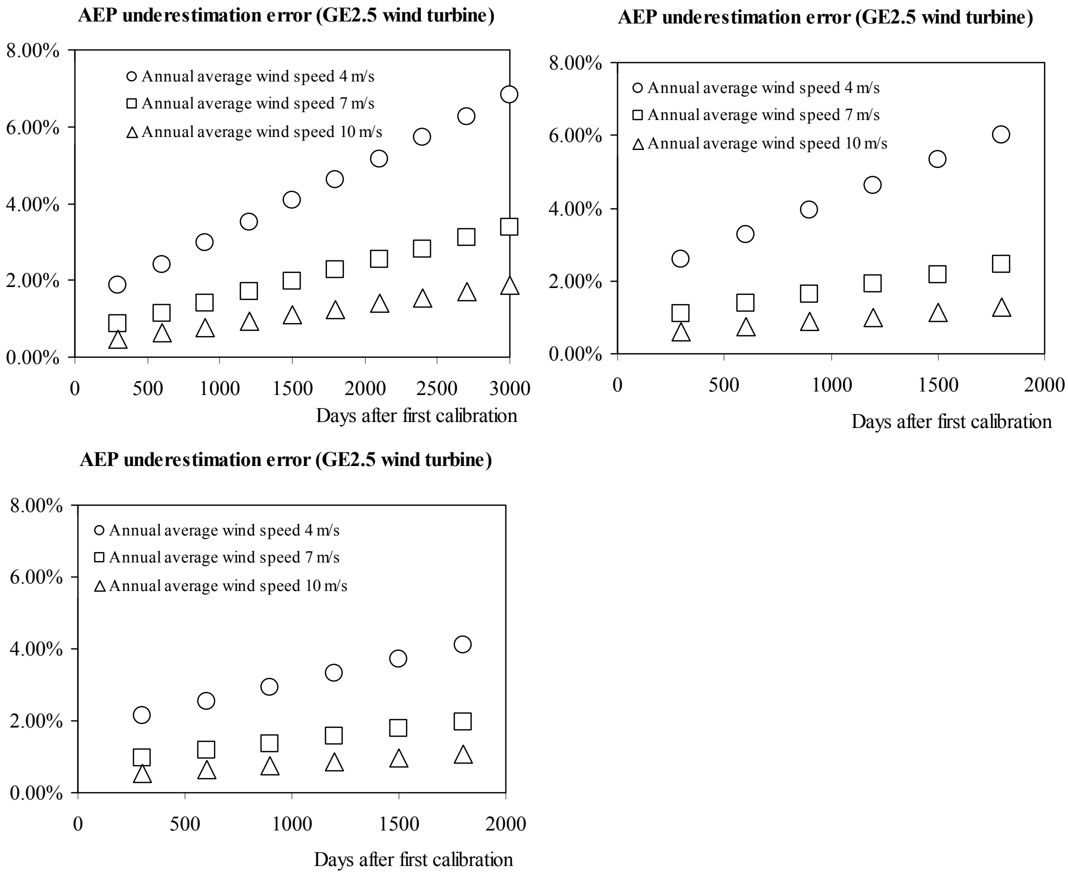
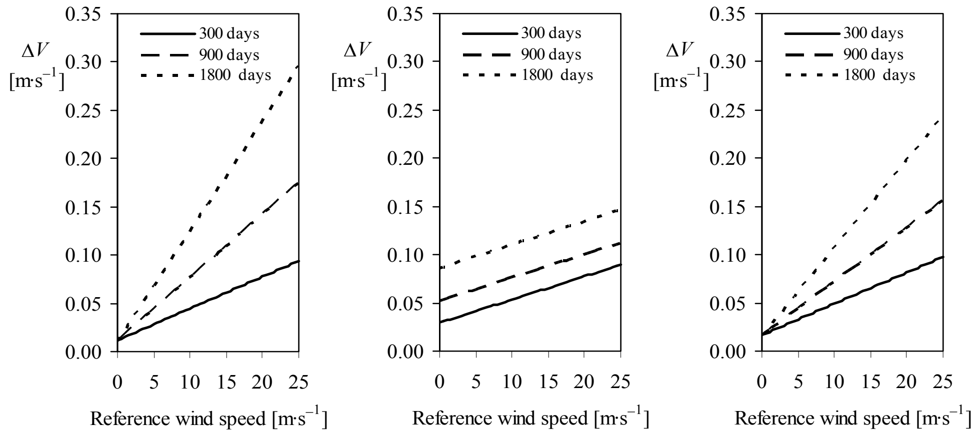


Figure 5. Underestimation of the measured wind speed, ΔV, as a function of the reference wind speed for the three anemometers considered (left: Cl-100075; middle: A100 L2; right: Th-4.3350) 300, 900 and 1,800 days after the first calibration of the anemometer. Confidence level: 84.1%.



3.2. Variations in Calibration Constants from Anemometers Used in Field

As mentioned previously, the behavior of five different anemometers (Risø P2546, Thies Clima 4.3303 and 4.3350, Climatronics 100075, and Vector Instruments A100 LK), has been studied using the data from individual anemometers calibrated at least two times at the IDR/UPM Institute. The number of anemometers analyzed with regard to the number of calibrations performed is as follows, Risø P2546: 29 anemometers calibrated 2-times, 18 anemometers calibrated 3-times, 11 anemometers calibrated 4-times, four anemometers calibrated 5-times, and one anemometer calibrated 6-times; Climatronics 100075: five anemometers calibrated 2-times, and three anemometers calibrated 3-times; Vector Instruments A100 LK: 90 anemometers calibrated 2-times, 45 anemometers calibrated 3-times, and seven anemometers calibrated 4-times; Thies Clima 4.3303: 33 anemometers calibrated 2-times, 11 anemometers calibrated 3-times, three anemometers calibrated 4-times, and one anemometer calibrated 5-times; Clima 4.3350: 227 anemometers calibrated 2-times, 54 anemometers calibrated 3-times, and four anemometers calibrated 4-times.

Table 5. Underestimation of the Annual Energy Production (AEP) caused by the deviation in the wind speed measurement due to the loss of performance of the IDR/UPM Climatronics100075, Vector Instruments A100 L2 and Thies Clima 4.3350 anemometers. AEP related to General Electric GE2.5. Underestimation calculated with 84.1% confidence level.

	Climatronics100075		
Days after first calibration	**Hub height annual average wind speed**		
	4 m·s^{-1}	7 m·s^{-1}	10 m·s^{-1}
300	1.87%	0.86%	0.47%
600	2.42%	1.14%	0.62%
900	2.97%	1.42%	0.78%
1200	3.52%	1.70%	0.93%
1500	4.07%	1.98%	1.09%
1800	4.62%	2.26%	1.24%
2100	5.17%	2.54%	1.40%
2400	5.72%	2.82%	1.55%
2700	6.27%	3.10%	1.71%
3000	6.82%	3.38%	1.87%

	Vector Instruments A100 L2			**Thies Clima 4.3350**		
Days after first calibration	**Hub height annual average wind speed**			**Hub height annual average wind speed**		
	4 m·s^{-1}	7 m·s^{-1}	10 m·s^{-1}	4 m·s^{-1}	7 m·s^{-1}	10 m·s^{-1}
300	2.61%	1.12%	0.60%	2.14%	0.97%	0.52%
600	3.29%	1.38%	0.73%	2.54%	1.17%	0.63%
900	3.96%	1.65%	0.87%	2.93%	1.37%	0.75%
1200	4.64%	1.92%	1.01%	3.33%	1.57%	0.86%
1500	5.32%	2.18%	1.15%	3.72%	1.77%	0.97%
1800	5.99%	2.45%	1.29%	4.12%	1.97%	1.08%

All anemometers studied were used in the field under different climatic conditions during different time periods. The elapsed time between calibrations is not exactly equal to the periods of service due to transportation, installation and disassembly times, but it seems reasonable to assume that this time is minimal when compared to the period of service. The percentage variation of the calibration constants A and B of the studied anemometers is shown in Figures 6 and 7 as a function of the time elapsed from the first calibration.

Figure 6. Percentage variation of calibration constants A and B from the initial values with regard to Risø P2546 (top), Thies Clima 4.3303 (middle), and Thies Clima 4.3350 (bottom) anemometers calibrated several times at the IDR/UPM Institute. The 300-day average value has been included, together with the standard deviation bars.

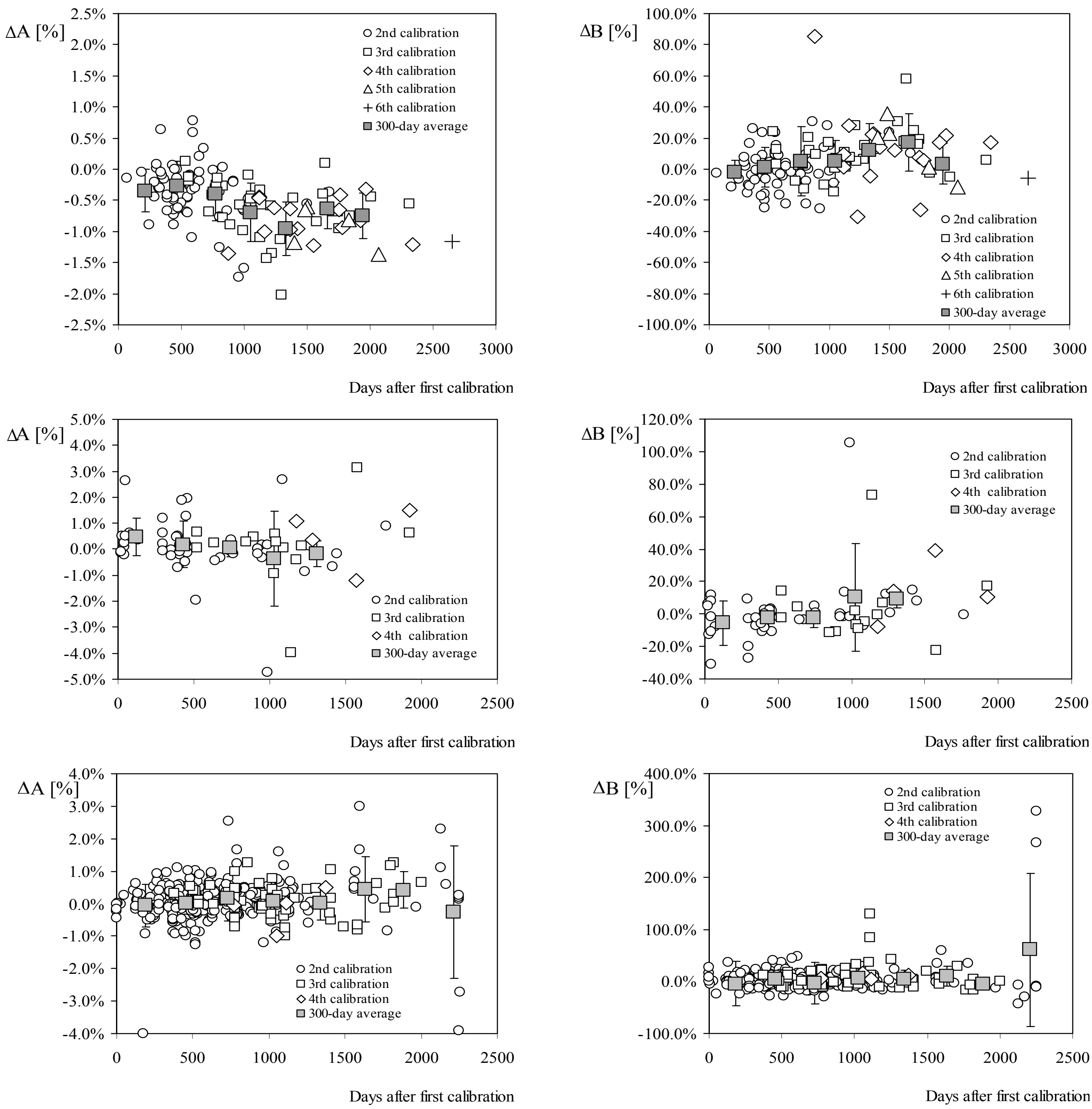
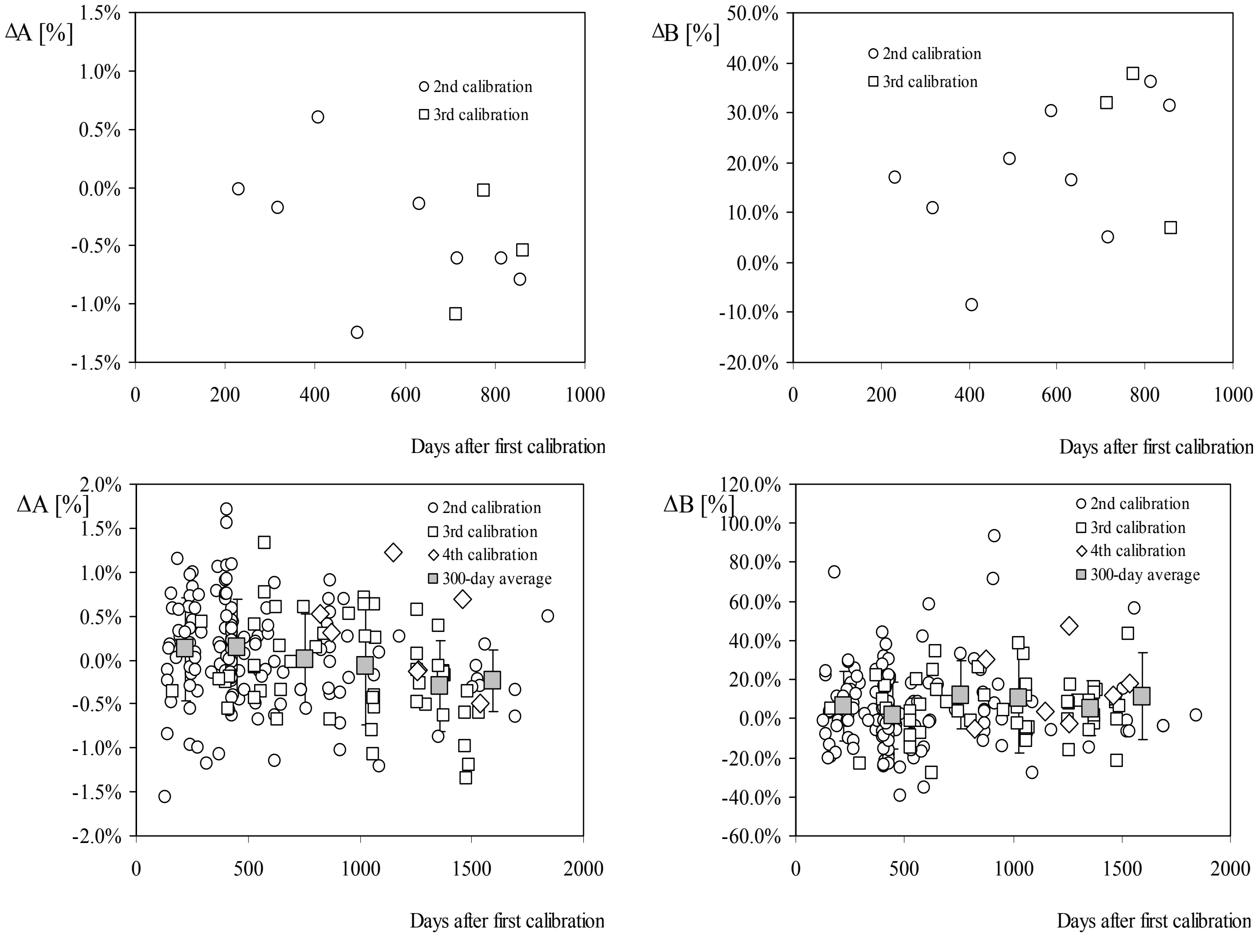


Figure 7. Percentage variation of calibration constants A and B from the initial values with regard to Climatronics 100075 (top), and Vector Instruments A100 LK (bottom) cup anemometers calibrated several times at the IDR/UPM Institute. The 300-day average value, together with the standard deviation bars, have been included for the second model (the data corresponding to the Climatronics 100075 model is clearly not sufficient for an equivalent statistic).



In these figures, the 300-day average variation and the standard deviation bars have also been included as a way to filter the great scattering from the data (see also in Table 6 the mentioned average and standard deviation values of each anemometer model, with the exception of the Climatronics 100075, as not enough data is available with regard to this model—only 11 calibrations were carried out in the studied period, see Figure 7). Taking into account this 300-day average evolution, there seems to be a similar behavior between all anemometers, the value of constant A decreasing over time since the first calibration, and the value of constant B increasing. The only exception to this rule is the Thies Clima 4.3350 anemometer, whose 300-day average variation seems to increase slightly with regard to both coefficients (see Figure 6).

Table 6. Percentage variation of coefficients A and B from the initial calibration each 300 days, corresponding to Risø P2546, Thies Clima 4.3303, Thies Clima 4.3350, and Vector Instruments A100 LK anemometers respectively calibrated at the IDR/UPM from June 2003 to January 2011, from September 2003 to September 2010, from November 2003 to January 2011, and March 2005 to January 2011. Average and standard deviation values (see also Figures 6 and 7).

Risø P2546					
Period considered after the first calibration	**Number of calibrations in the considered period**	**ΔA mean [%]**	$\sigma_{\Delta A}$ **[%]**	**ΔB mean [%]**	$\sigma_{\Delta B}$ **[%]**
First 300 days	5	0.34%	0.34%	1.62%	7.61%
Between 300 and 600 days	39	0.27%	0.40%	1.21%	12.79%
Between 600 and 900 days	21	0.40%	0.44%	5.06%	22.26%
Between 900 and 1200 days	20	0.70%	0.47%	4.83%	13.42%
Between 1200 and 1500 days	12	0.96%	0.43%	12.31%	17.27%
Between 1500 and 1800 days	13	0.63%	0.33%	17.05%	18.50%
Between 1800 and 2100 days	6	0.75%	0.37%	3.35%	13.03%
Between 2100 and 2700 days	3	0.98%	0.36%	5.62%	11.42%
Thies Clima 4.3303					
Period considered after the first calibration	**Number of calibrations in the considered period**	**ΔA mean [%]**	$\sigma_{\Delta A}$ **[%]**	**ΔB mean [%]**	$\sigma_{\Delta B}$ **[%]**
First 300 days	14	0.46%	0.73%	5.58%	13.57%
Between 300 and 600 days	19	0.19%	0.88%	2.00%	5.92%
Between 600 and 900 days	8	0.04%	0.34%	2.43%	6.10%
Between 900 and 1200 days	15	0.36%	1.82%	10.21%	33.20%
Between 1200 and 1500 days	6	0.17%	0.48%	9.51%	5.45%
Between 1500 and 2100 days	6	1.02%	1.41%	7.86%	20.17%
Thies Clima 4.3350					
Period considered after the first calibration	**Number of calibrations in the considered period**	**ΔA mean [%]**	$\sigma_{\Delta A}$ **[%]**	**ΔB mean [%]**	$\sigma_{\Delta B}$ **[%]**
First 300 days	52	0.06%	0.66%	4.26%	42.73%
Between 300 and 600 days	112	0.03%	0.48%	3.91%	13.08%
Between 600 and 900 days	84	0.16%	0.71%	3.10%	39.46%
Between 900 and 1200 days	58	0.07%	0.52%	6.76%	22.86%
Between 1200 and 1500 days	12	0.03%	0.53%	5.20%	16.38%
Between 1500 and 1800 days	16	0.43%	1.01%	10.22%	19.39%
Between 1800 and 2100 days	5	0.42%	0.55%	5.62%	9.04%
Between 2100 and 2400 days	8	0.25%	2.04%	60.81%	147.46%
Vector Instruments A100 LK					
Period considered after the first calibration	**Number of calibrations in the considered period**	**ΔA mean [%]**	$\sigma_{\Delta A}$ **[%]**	**ΔB mean [%]**	$\sigma_{\Delta B}$ **[%]**
First 300 days	41	0.13%	0.59%	6.47%	17.59%
Between 300 and 600 days	77	0.15%	0.55%	1.55%	17.22%
Between 600 and 900 days	29	0.01%	0.52%	12.15%	17.38%
Between 900 and 1200 days	22	0.06%	0.67%	10.36%	27.80%
Between 1200 and 1500 days	22	0.30%	0.51%	5.34%	14.16%
Between 1500 and 2100 days	10	0.31%	0.26%	12.37%	23.29%

Table 7. 68.2% confidence limits (ΔA_{lower}, ΔA_{upper}, ΔB_{lower}, and ΔB_{upper}) for the variation of the constants A and B in the intervals 0–300, 300–600 and 600–1000 days from the initial calibration, with regard the anemometers studied (Risø P2546, Thies Clima 4.3303 and 4.3350, and Vector Instruments A100 LK).

Risø P2546				
Interval [days after first calibration]	**ΔA_{lower} [%]**	**ΔA_{upper} [%]**	**ΔB_{lower} [%]**	**ΔB_{upper} [%]**
0–300	−0.45%	0.03%	−17.40%	32.36%
300–600	−0.67%	0.14%	−12.84%	18.30%
600–1000	−0.73%	0.19%	−16.93%	22.17%
Thies Clima 4.3303				
Interval [days after first calibration]	**ΔA_{lower} [%]**	**ΔA_{upper} [%]**	**ΔB_{lower} [%]**	**ΔB_{upper} [%]**
0–300	−1.18%	1.51%	−25.01%	24.77%
300–600	−0.68%	1.07%	−7.55%	1.89%
600–1000	−1.29%	0.85%	−17.05%	32.12%
Thies Clima 4.3350				
Interval [days after first calibration]	**ΔA_{lower} [%]**	**ΔA_{upper} [%]**	**ΔB_{lower} [%]**	**ΔB_{upper} [%]**
0–300	−0.74%	0.60%	−44.85%	36.07%
300–600	−0.45%	0.52%	−12.18%	20.61%
600–1000	−0.25%	0.69%	−11.94%	13.13%
Vector Instruments A100 LK				
Interval [days after first calibration]	**ΔA_{lower} [%]**	**ΔA_{upper} [%]**	**ΔB_{lower} [%]**	**ΔB_{upper} [%]**
0–300	−0.75%	0.65%	−10.95%	29.08%
300–600	−0.40%	0.74%	−15.53%	18.97%
600–1000	−0.64%	0.39%	−14.30%	36.10%

In Table 7 the 68.2% confidence limits (assuming a Gaussian process), for the variation of constants A and B in the intervals 0–300, 300–600 and 600–1000 days from the initial calibration are included. With these variations of the constants A and B it is possible to estimate the same confidence limits for the measured wind speed deviation, V_{lower} and V_{upper}, at any wind speed, V:

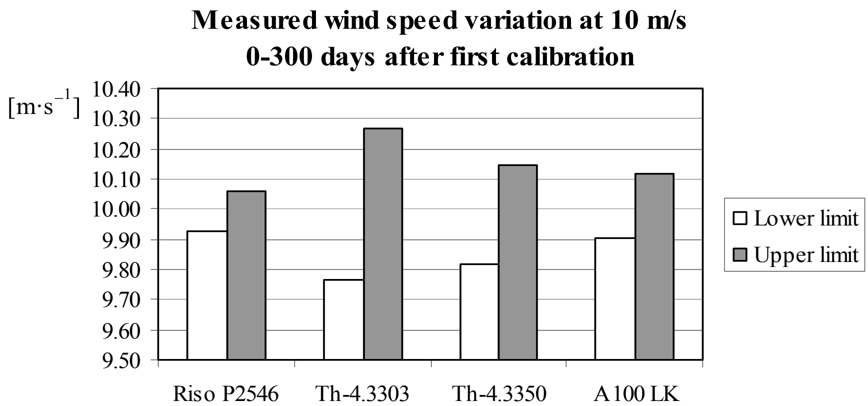
$$V_{\text{lower, upper}} = \left(1 + \Delta A_{\text{lower, upper}}\right) A_0 f + \left(1 + \Delta B_{\text{lower, upper}}\right) B_0 \quad (6)$$

where ΔA_{lower}, ΔA_{upper}, ΔB_{lower}, and ΔB_{upper} are respectively the variation limits of calibration coefficients from Table 7, A_0 and B_0 are the calibration constants corresponding to each anemometer (from reference [4]: $A_0 = 0.627$ and $B_0 = 0.179$ for the Risø P2546; $A_0 = 0.047$ and $B_0 = 0.499$ for the Thies Clima 4.330; $A_0 = 0.0483$ and $B_0 = 0.248$ for the Thies Clima 4.3350; $A_0 = 0.0505$ and $B_0 = 0.195$ for the Vector Instruments A100 LK), and f is the frequency output, which can be obviously expressed as a function of the reference wind, V, speed as:

$$f = \frac{V - B_0}{A_0} \quad (7)$$

In Figure 8 the 68.2% confidence limits for the variation of the measured wind speed at 10 m·s^{-1} reference wind speed, and for the selected anemometers are shown. The results included in Table 7 show that the loss of performance is greater for the Thies Clima 4.3303, Thies Clima 4.3350, and Vector Instruments A100 LK in the first period considered (0–300 days after the initial calibration) than in the second (300–600 days after the initial calibration). This suggests the existence of a transitional period after installation where the anemometer is adjusting before reach a stable working point. In the case of Thies Clima 4.3303 and Vector Instruments A100 LK, the deviation from the initial calibration in the third period studied (600–1000 days after the initial calibration) returns to the level of the first period. This indicates that the aforementioned adjusting period is over. In the case of the Thies Clima 4.3350 anemometer it seems that the adjustment period is extended to the third period studied. With regard to the Risø P2546, it also seems that there is a transitional period. However, this effect is less clear in this case as only calibration coefficient B seems to increase in the third period its deviation from the first calibration.

Figure 8. 68.2% confidence limits for the variation in the interval between 0 and 300 days after the first calibration, of the measured wind speed at 10 m·s^{-1} with regard to the anemometers studied.



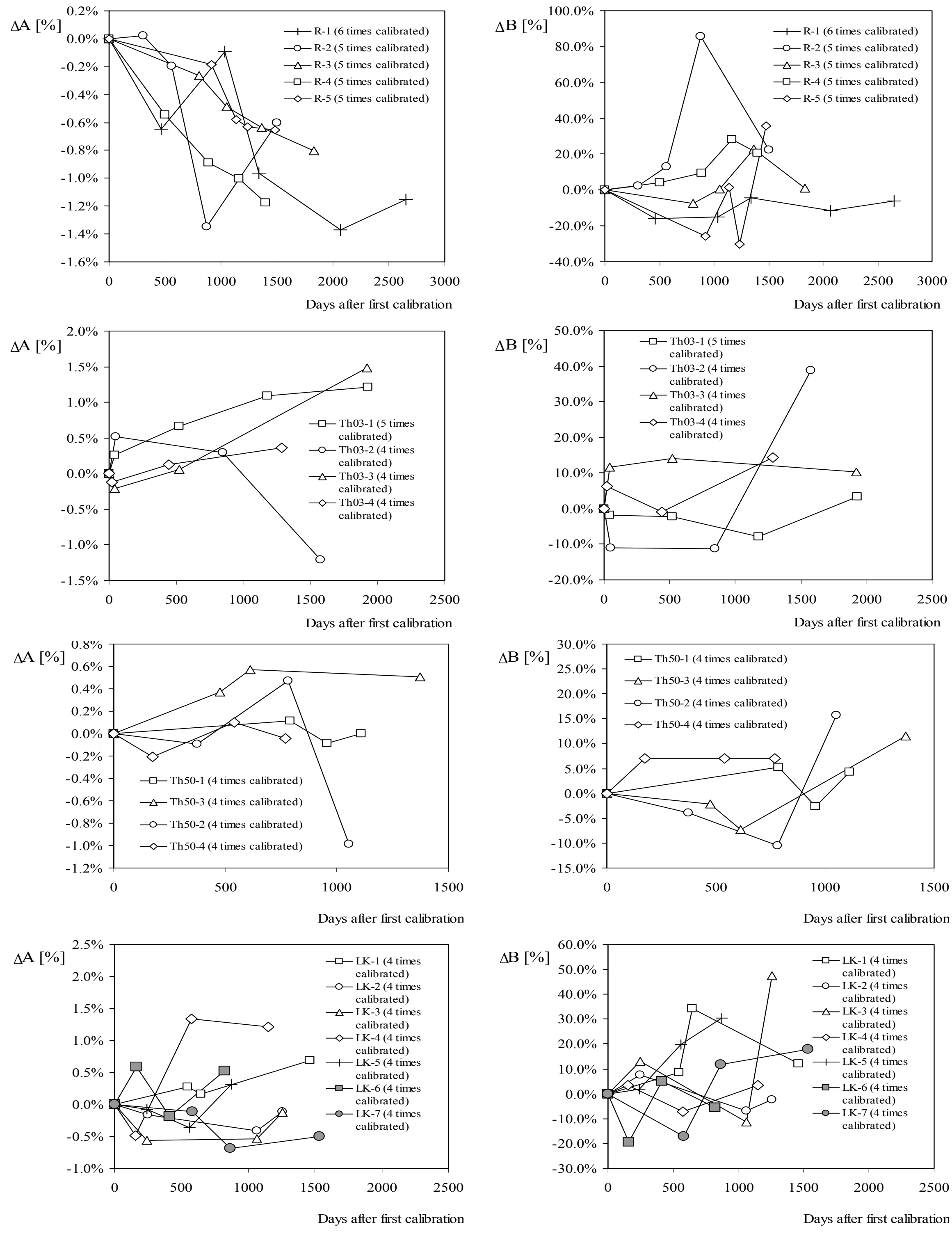
However, these tendencies that could be applied to a large number of anemometers may not describe the behavior of a single individual anemometer. In Figure 9 the behavior of the anemometers that were calibrated more times at the IDR/UP Institute during the studied period of time is shown. No clear pattern for the loss of performance of an anemometer can be extrapolated from these graphs, that is, with the available information it is not possible to estimate, with the procedure described previously for the stored anemometers, the variations of the measured wind speed over time since the first calibration. It should also be said that together with the different conditions in which each anemometer was in service, these anemometers were subjected to different maintenance processes before their calibrations. The maintenance performed on each anemometer referred to in Figure 9 has been included in Table 8, according to the available information. No clear effect of the maintenance on the calibration constants variation with the time elapsed from the initial calibration can be observed. Some anemometers that were not subjected to any maintenance before their calibration showed a change in the A constant variation pattern that, as far as the authors know, could only be attributed to a change in the service conditions (see in Figure 9 variations of A constants with regard to R-1—3rd calibration, and R-2—5th calibration; or in Figure 10 with regard to Th50-1—3rd calibration, and Th50-4—3rd calibration).

Table 8. Maintenance works performed on the more times calibrated anemometers at the IDR/UPM Institute in the studied period of time.

Risø P2546					
Anemometer	**Maintenance before calibration**				
	2nd	3rd	4th	5th	6th
R-1	No	No	No	Yes [0]	No
R-2	No	No	No	No	-
R-3	Yes [0]	No	No	No	-
R-4	No	No	No	No	-
R-5	Yes [0]	No	No	No	-
Thies Clima 4.3303					
Anemometer	**Maintenance before calibration**				
	2nd	3rd	4th	5th	6th
Th03-1	Yes [1]	Yes [1]	(*)	Yes [1]	-
Th03-2	Yes [1]	(*)	Yes [1]	-	-
Th03-3	Yes [1, 2]	Yes [1]	Yes [1,2]	-	-
Th03-4	Yes [1]	No	Yes [1]	-	-
Thies Clima 4.3350					
Anemometer	**Maintenance before calibration**				
	2nd	3rd	4th	5th	6th
Th50-1	No	No	No	-	-
Th50-2	No	Yes [1]	(*)	-	-
Th50-3	(*)	(*)	(*)	-	-
Th50-4	No	No	No	-	-
Anemometer	**Maintenance before calibration**				
	2nd	3rd	4th	5th	6th
LK-1	No	Yes [1]	Yes [1]	-	-
LK-2	No	Yes [1]	No	-	-
LK-3	No	Yes [1]	No	-	-
LK-4	No	Yes [0]	No	-	-
LK-5	No	No	No	-	-
LK-6	No	No	No	-	-
LK-7	No	Yes [1]	Yes	-	-

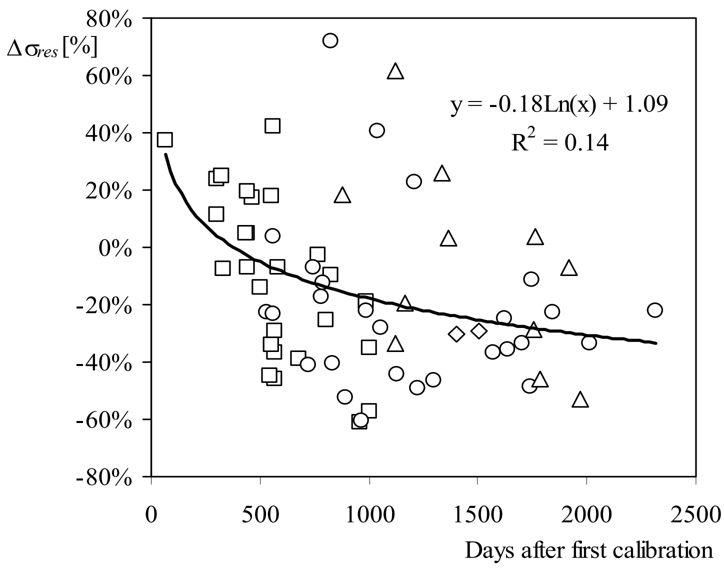
* No information is available with regard to any possible maintenance before the calibration; [0] No information is available with regard to the maintenance performed to the anemometer, but probably change of bearings; [1] Change of bearings; [2] Change of the cups' rotor.

Figure 9. Percentage variation of calibration constants A and B from the initial values with regard to (from top to bottom): five specific Risø P2546 anemometers (R-1 to R-5) calibrated more than four times; four specific Thies Clima 4.3303 anemometers (Th03-1 to Th03-4) calibrated more than three times; four specific Thies Clima 4.3350 anemometers (Th50-1 to Th50-4) calibrated more than three times; and seven specific Vector Instruments A100 LK anemometers (LK-1 to LK-7) calibrated more than three times. All anemometers calibrated at the IDR/UPM Institute.



Going one step further, the residuals concerning the calibrations performed on the single individual anemometers whose maintenance was traced were analyzed. The residuals of a calibration are calculated as the difference between the reference wind speed and the transfer function at all the calibration points. No conclusion that could lead to foreseeing the maintenance requirements for an anemometer can be derived from this particular analysis. In Figure 10, the percentage deviation of the residuals' standard deviation, σ_{res}, from the initial calibration has been plotted for the traced Risø P2546 anemometers as a function of the time elapsed since the initial calibration. In order to have consistent data, only calibrations performed on anemometers never subjected to any maintenance are included in this graph. Although in the figure it seems that the residuals tend to stabilize some time after the initial calibration, no clear conclusion with regard to the loss of performance can be extrapolated from the data.

Figure 10. Variation of the standard deviation of the residuals, σ_{res}, as a function of the time elapsed from the initial calibration, with regard to calibrations performed to 27 Risø P2546 anemometers that were not subjected to maintenance. These anemometers were calibrated several times at the IDR/UPM Institute (16 anemometers calibrated 3-times, nine anemometers calibrated 4-times, and two anemometers calibrated 5-times). The symbols indicate second calibration (squares), third calibration (circles), fourth calibration (triangles), and fifth calibration (rhombi). A natural logarithm line has been fitted to the data.



4. Conclusions

In this study, the variation of the calibration coefficients over time has been analyzed for six anemometer models (Climatronics 100075, Vector Instruments A100 L2, Vector Instruments A100 LK, Risø P2546, Thies Clima 4.3303, and Thies Clima 4.3350). Two kind of analyses have been carried out, the first one being with anemometers unused in the field, that is, just stored (Climatronics 100075, Vector Instruments A100 L2, Thies Clima 4.3350), and the second one being with anemometers used in the field (Climatronics 100075, Vector Instruments A100 LK, Risø P2546, Thies Clima 4.3303, and Thies Clima 4.3350). The major conclusions resulting from this work are:

- The stored anemometers showed clear degradation trends, affecting both calibration coefficients, A and B. This degradation of the anemometer's behavior is translated into a loss of rotation speed (increase of coefficient A), and/or an increase of the offset speed (increase of coefficient B). Depending on the anemometer the degradation can affect both calibration constants differently, thus changing the degradation pattern. The stored anemometers analyzed seemed to have a 450 days transitional period in which the anemometer's behavior is adjusted.
- The loss of performance of anemometers used in the field is affected by a great level of scatter. The data analyzed suggest that, in general, the studied anemometers tend to accelerate the rotation speed and increase the offset speed. However, based on the data from anemometers calibrated more than three times over a large period of time (more than 600 days), this conclusion can not be applied to predict the behavior of an individual anemometer. In terms of the data with regard to variation between two consecutive calibrations, the level of scattering was higher for the calibrations done within 300 days than the one for the period between 300 and 600 days. This suggests that as far as normal climatic conditions are concerned, the anemometer has a transitional period after the first calibration before reaching the stable performance range.

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