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Traceability of CM-11 pyranometer calibrations at KNMI

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Abstract

KNMI has used Kipp&Zonen CM-11 pyranometers for operational radiation measurements since 1989. The pyranometers are calibrated regularly following WMO recommendations in the KNMI calibration laboratory against a KNMI reference CM-11 pyranometer. Operational calibrations show no degradation of sensors, and no drift in mean sensitivity, during the more than 25 years they have been in use. Variations of the calibration sensitivity are found to feature a standard deviation of 0.6%.

The KNMI reference pyranometers were calibrated in an unconditioned manner (i.e. neither ventilated, nor heated) on an irregular basis at PMOD-WRC in Davos, but roughly every two years. The sensitivities found in Davos with outdoor calibrations against a ventilated reference CM-22 showed sensitivities consistently lower than the nominal value from 2002 onwards, up to 2%. The uncertainty of these calibrations is typically 1.3%. A bias error thus seemed to be present in these calibrations. Two KNMI reference pyranometers were also calibrated at the calibration site of the Deutsche Wetter Dienst. These calibrations showed a sensitivity of the reference pyranometers close to the nominal value. The bias in the sensitivity during the calibration at PMOD-WRC is attributed to zero-offset A, which can be reduced by ventilating the KNMI reference pyranometers during calibration at PMOD-WRC, to be compliant with the specified uncertainty.

Also the laboratory calibration procedure at KNMI has been investigated by Kipp&Zonen, and apart from minor issues, is considered to be accurate. Differences up to 0.5% has been identified, which are well within the uncertainty of the calibration procedure. An adaptation of the waiting time for the measurement of the dark current from 2 minutes to 1 minute is advised.

Other advises following from this study are that it is not necessary to correct operational global radiation measurements of the KNMI network, as the bias error had not been forwarded from the KNMI reference pyranometers to the KNMI network sensors. Furthermore, calibrations using method (b) from the CIMO guide cancel zero-offset A, and are thus preferred over method (a), which are currently used at PMOD-WRC. It should be investigated if such measurements can be done routinely for the calibration of KNMI reference pyranometers.

Introduction

KNMI has measured several radiation components from as early as January 1954 in a number of locations, that are part of the national observational network. The earliest measurements were most probably taken with a Moll-Gorczynski type pyranometer developed at the University of Utrecht. Instruments of different make were used, like Funk, Suomu, or Bellani. Later Kipp&Zonen CM-2 and CM-5 pyranometers were used. Starting from august 1989 the network was equipped with Kipp&Zonen CM-11 pyranometers. Those are still in use.

In 2005 KNMI also put a radiation station in use at the Cabauw research site in the Netherlands, that is part of the GCOS global Baseline Surface Radiation Network (BSRN). Many radiation components are measured here with high accuracy sensors and data collection devices. [9]

The CM-11 pyranometers of the national observational network are calibrated by comparison with one of three CM-11 reference pyranometers in the KNMI radiation calibration laboratory in De Bilt. From 1998, the reference pyranometers were calibrated at the Physikalisch-Meteorologisches Observatorium Davos (PMOD), which is the World Radiation Centre (WRC) in Davos during field comparisons against a secondary standard pyranometer. Even though the calibrations were performed on an irregular basis, roughly every two years a calibration has been performed. PMOD-WRC used a shaded Eppley PSP pyranometer until 2003, and a heated and ventilated shaded Kipp&Zonen CM-22 after that date.

The calibrations of the KNMI network CM-11 pyranometers in the radiation laboratory in De Bilt appear to be very stable over the years. However, unconditioned (i.e. neither ventilated, nor heated) outdoor calibrations at PMOD-WRC showed a consistently lower sensitivity after 2002 than the nominal value, which is given after production. This bias was as large as 2% of the nominal sensitivity, while an uncertainty of 1.3% is typical for these calibrations. Because the laboratory calibrations consistently showed a stable value of the network pyranometers, KNMI hesitated to use the sensitivities of the calibrations at PMOD-WRC for their reference pyranometers without a thorough knowledge of the nature of the differences.

To study the cause of this bias, a study is made on calibration methods, possible uncertainties during calibrations, and a closer look is taken at the archived results of calibrations performed on KNMI pyranometers. This includes the calibrations done at PMOD-WRC, Deutsche Wetter Dienst (DWD), and the KNMI calibration laboratory. This report addresses the results of this study and is structured in the following way. Chapter 1 describes the operating principles of the CM-11 pyranometer used at KNMI. The requirements that are put to pyranometer calibrations are reported in chapter 2. The errors and uncertainties that are involved with such calibrations are reported in chapter 3. Chapter 4 shows the current calibration methods used for the KNMI pyranometers. Historical values from the calibrations of the reference sensors and the operationals sensors are presented in chapter 5. Chapter 6 describes the mutual calibration laboratory visit, which was organised with Kipp&Zonen. Finally, some conclusions and recommendations are presented in chapter 7 and 8 respectively.

Chapter 1

CM-11 pyranometer

KNMI uses the Kipp&Zonen CM-11 pyranometer as the standard operational device for the measurement of global radiation in the operational network. A picture of such instrument is given in figure 1.1, and a schematic drawing in figure 1.2. CM-11 pyranometers are passive sensors that convert solar energy into electrical energy, that can be measured with data acquisition equipment. The sensing element consists of a thermopile of 100 thermocouples imprinted on a corundum (Al_2O_3) substrate. The hot junctions are located in the centre of the round shaped substrate disc, while the cold junctions are at the edge of the non-illuminated side of the disc. Sunlight illuminates the black painted disc, and causes a temperature rise of the surface. The temperature difference between the hot junctions at the surface and the non-illuminated cold junctions at the backside causes a thermo-electric voltage that is a measure for the received radiation energy. A thermistor measures the temperature of the element [6]. The thermistor is included in a simple resistor network to compensate for the temperature dependant sensitivity of the thermopile (Figure 1.3). The sensing element is protected to wind, rain, snow and dust by two glass domes. The glass transmits radiation in the visible and near IR spectrum, limited to 3000 nm. Longwave radiation (> 3000 nm) is almost completely absorbed.

CM-11 pyranometers come with a sensitivity in the order of nominally 5 $\mu\mathrm{V\,W^{-1}m^2}$, that can range from 4.2-5.7 $\mu\mathrm{V\,W^{-1}m^2}$. To facilitate interchangeability of sensors, the sensitivity is adjusted by KNMI to a standardized value of 4.00 $\mu\mathrm{V\,W^{-1}m^2}$ by adding resistance R_p, see figure 1.3. Also resistance R_v is increased to compensate the decrease of the overall internal impedance and avoid affection of the temperature compensation.

Figure 1.1: KNMI pyranometers are equipped with bird wires to prevent shading by birds.

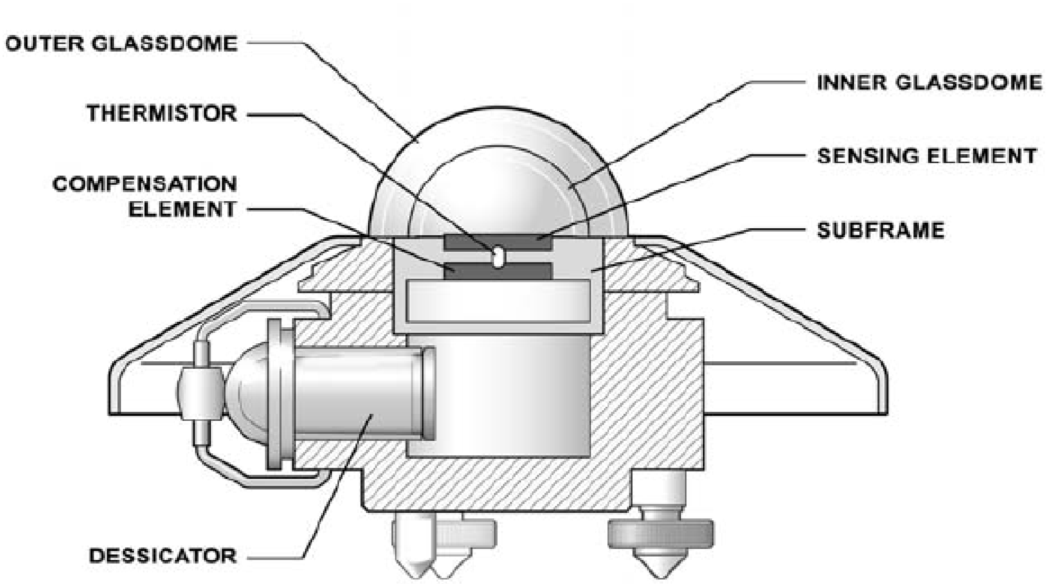

Figure 1.2: Drawing of Kipp&Zonen CM-11 pyranometer.

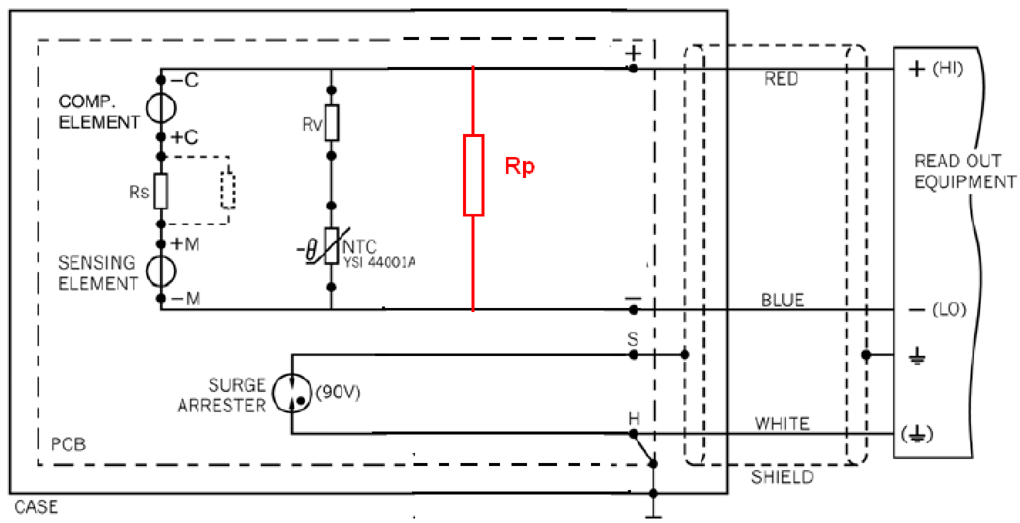

Figure 1.3: Schematics of the Kipp&Zonen CM-11 pyranometer. R_p is not present in a standard CM-11, but is added to provide a standardized sensitivity of 4.00 µV W^{-1}m^2. To avoid affecting of the temperature compensation, R_v is increased to make sure that the decrease of the overall internal impedance of the sensor is compensated.

Chapter 2

Calibration requirements

2.1 WMO requirements

The synoptic and climatological stations in the operational observations network in The Netherlands all use Kipp&Zonen CM-11 pyranometers. Those observations are subject to standards prescribed by the WMO in the WMO GUIDE TO METEOROLOGICAL INSTRUMENTS AND METHODS OF OBSERVATION, better known as the CIMO-guide [10], maintained by the Commission for Instruments and Methods of Observations. Radiation measurements are covered by chapter 7 in the CIMO-guide issue 2014.

KNMI calibrates all instruments using the recommendations found in the latest issue of the CIMO guide (2010). CIMO distinguishes three different instrument classes: high, good and moderate quality. The highest class is used for state of the art techniques, but requires the availability of maintenance staff and special facilities, as for example is present at the BSRN site at Cabauw. The second class is considered as sufficient for network observations, as is the case for the KNMI network. The achievable 95% confidence uncertainty for this class is 5% for daily totals (8% for hourly totals).

In Annex 7.C of the CIMO chapter on radiation the specifications are given for typical reference centers, distinguished as World, Regional and National Centers. World Radiation Centers are located in St Petersburg (Russia) and Davos (Switzerland). Regional Centers close to the Netherlands are in Uccle (Belgium) and Lindenberg (Germany). A National Center is not available in The Netherlands.

In chapter 1 of the CIMO-guide the requirements for all meteorological observations are specified. Radiation is not specified for all components, but only as a general requirement for daily amounts, see table 2.1.

The uncertainty on the daily amount of solar radiation (in MJ m^{-2}) cannot be simply converted into an uncertainty for the specific solar power (in Wm^{-2}) by dividing the daily amount by the total number of seconds in a day, because solar radiation is not

0.4 MJ m^{-2}	for $\leq$ 8 MJ m^{-2}
5 %	for > 8 MJ m^{-2}

Table 2.1: Accuracy requirement according to the CIMO-guide

Field calibrations: a By comparison with a standard pyrheliometer for the direct solar irradiance and a calibrated shaded pyranometer for the diffuse sky irradiance; b By comparison with a standard pyrheliometer using the sun as a source, with a removable shading disc for the pyranometer; c With a standard pyrheliometer using the sun as a source and two pyranometers to be calibrated alternately measuring global and diffuse irradiance; d By comparison with a standard pyranometer using the sun as a source, under other natural conditions of exposure (for example, a uniform cloudy sky and direct solar irradiance not statistically different from zero);
Laboratory calibrations: e By comparison with a standard pyrheliometer for the direct solar irradiance and a calibrated shaded pyranometer for the diffuse sky irradiance; f In the laboratory, with the aid of an integrating chamber simulating diffuse sky radiation, by comparison with a similar type of pyranometer previously calibrated outdoors.

Table 2.2: Methods of calibration, taken from the CIMO-guide

present during the full 24 hours. KNMI estimates the uncertainty on the measurement of instantaneous global radiation measurements to -9 $\pm$ 19 Wm^{-2} in clear-sky conditions and -3 $\pm$ 19 Wm^{-2} in cloudy conditions [5].

2.2 Calibration methods

The CIMO-guide names various methods of calibration, as listed in table 2.1. For field calibrations, method (a) is commonly used, e.g. by PMOD-WRC. Laboratory calibrations require a reference pyranometer, calibrated outdoors. Method (e) is the most commonly used method in laboratory conditions. These methods are also described in ISO-standards:

- ISO-9846 (comparison to a pyrheliometer) [3]
- ISO-9847 (comparison to a reference pyranometer) [2]

Both CIMO and ISO require that calibration results must be traceable to a primary reference. The primary reference for global radiation is the world radiometric reference (WRR) as measured by the world standard group (WSG): a set of pyrheliometers kept at the World Radiation Center (WRC) in Davos, Switzerland.

Chapter 3

Calibration considerations

All KNMI network pyranometers are used in a standard non-heated non-ventilated setup. Only during laboratory calibrations the devices are ventilated, in a thermally stable environment. This guarantees reproducible calibrations. However, in field situations (or field calibrations), pyranometers may suffer from a number of errors due to unstable conditions.

3.1 Snow, rain, dew and rime

In field situations the dome of the pyranometer may be covered with snow, raindrops, dew or rime. This affects the transmissivity of the dome, which can affect the measured radiation both in a positive and negative offset.

3.2 Temperature dependency

The pyranometer sensitivity is temperature dependent, so ambient temperature influences calibrations. The CM-11 pyranometer is equipped with a thermistor to compensate for the non-linearity of the thermopile. The manufacturer specifies a maximum of 1% deviation.

3.3 Zero offset

The output of a pyranometer is proportional to the temperature difference between the lower and the higher surface of the black thermopile. Under stable conditions, this is also proportional to the incoming radiation energy. The energy is converted to heat, that causes a temperature difference between the hot and cold junction of the thermopile, which in turn induces a thermovoltage. However, temperature differences may also be caused by other undesired sources, and are classified as zero-offset type A and type B respectively.

The outer dome, just as any object, emits longwave radiation. Because the radiative temperature of the sky is much colder than the outer dome, there is a net radiative heat transfer from the dome to the ambient. As a result the dome cools down below the ambient air temperature. This in turn cools the inner dome and the hot junction of the thermopile, showing up as a negative offset, called zero-offset type A. Sun elevation, ambient temperature, humidity, wind speed and cloudiness have an influence on the offset. Note that in daytime conditions the offset is not visible, but nevertheless present, especially in clear sky conditions. Ventilation of the outer dome enhances the heat transfer from the ambient air to the outer dome, limiting the temperature difference between the ambient and the outer dome, which effectively decreases the zero offset A. Kipp&Zonen claims a type A offset less than -7 Wm^{-2} in a ventilated setup, and less than -12 Wm^{-2} in a non-ventilated setup for the CM-11 pyranometer.

During laboratory calibrations, the dome may be heated due to irradiation by the hot filament lamp, causing a positive offset. This offset is repeatable in the calibration and is canceled out since indoor calibrations should be performed using the same type of instrument. In that case, the zero-offset A is equal for both instruments and is cancelled out in the calibration.

When the temperature of the housing changes, there is also a heat flow from the sensing element to the housing or vice versa. This heat flow causes an error voltage that is called zero-offset type B. As the offset is caused by temperature changes of the housing, it is mainly present when the ambient temperature is fluctuating, like during sunrise and sunset, during a shower and with fluctuating cloudiness. To minimize this effect the housing is shielded by a white plastic cover. To compensate for type B offset, there is a second element below the sensing element in the CM-11 sensor. As this element is not illuminated, it only measures the temperature gradient due to the flow of thermal energy to the housing, thus compensating for this effect in the sensing element. The resulting error is limited to < 2 Wm^{-2} at a temperature gradient of 5 K/h.

3.4 Dome

A directional inaccuracy is induced by the dome of the instrument. This is caused by material impurities and manufacturing processes, making it a sensor specific error, which is directional in nature, depending both on the solar azimuth and the elevation angle. The uncertainty due to the dome is specified to be <10 $\mathrm{W/m}^{-2}$ at 1000 $\mathrm{W/m}^{-2}$ irradiance for the CM-11.

During laboratory calibrations, the light source is positioned at the zenith of the dome. Typically, the directional error is the lowest at this point. Furthermore, the light source angle does not change during such a lab calibration and is thus fully repeatable. On the other hand, the sun continuously changes the azimuth and elevation angle during field calibrations, which are taken over the course of multiple weeks, depending on the weather conditions. Consequently also the directional error varies during these calibration.

3.5 Non-linearity

The response of a pyranometer is not an entirely linear function of incoming radiation. The deviation from linearity is limited to $< 0.6\%$ of the measured value.

3.6 Unstable conditions

During field calibration, results may fluctuate with changing weather conditions. If the calibration is performed with a different type of pyranometer as a reference, the outcome may vary with cloudiness and time of day (due to changing spectrum at lower sun angles). The main source for unstable results is changing water vapour content in the atmosphere, since water vapour is a long wave radiation source. Furthermore, unventilated pyranometers may be affected by difference in wind speed, as this has an impact on the heat transfer between the ambient air and the outer dome, impacting type A offset.

Chapter 4

KNMI calibration facilities

4.1 Calibration methods

For operational use KNMI uses method (e) from table 2.2, that compares the device under calibration with a reference pyranometer of the same type under laboratory conditions.

The references are calibrated at PMOD-WRC in Davos, Switzerland, using method (a) from table 2.2. Method (a) uses the sun as a radiation source. The device under calibration is compared to PMO2, one of the instruments of the world standard group for the direct solar radiation component, together with a ventilated shaded pyranometer for the diffuse solar radiation component. The measurement of the device under calibration is then compared to the sum of the pyrheliometer and the shaded pyranometer.

For research applications also method (b) from table 2.2 can be used. The device under calibration is compared with an absolute pyrheliometer. The device under calibration is alternating shaded and unshaded to obtain the diffuse and global solar radiation respectively. The difference between these two measurements is the direct component of the global radiation, and must be the same as the radiation as measured by the absolute pyrheliometer. This method is currently not used by KNMI for operational pyranometers. PMOD-WRC does not offer such calibrations due to the labour-intensive process involved.

4.2 Reference pyranometers

KNMI uses three reference CM-11 pyranometers (denoted by REF1, REF2 and REF3) as WMO and ISO specify that a sensor can only be calibrated with a reference sensor with the same characteristics, like spectral, time, and directional response. The reference instruments are listed in table 4.1. The nominal sensitivity is defined as the

REF number	KNMI number	Serial number	Year of production	Initial sensitivity	Adjusted sensitivity
REF1	01.23.010-002	820272	1989	5.478	4.01
REF2	01.23.010-031	861327	1990	4.77	-
REF3	01.23.010-004	820291	1989	5.43	-

Table 4.1: overview of reference pyranometers

initial sensitivity, except for reference pyranometer REF1, for which it is the adjusted sensitivity.

All standard pyranometers for the Netherlands observational network are standardized to a sensitivity of 4.00 ± 0.01 µV $W^{-1}m^2$, to facilitate exchange of instruments without changing sensitivity parameters. For this purpose the temperature compensation network of the instrument was changed by KNMI by introducing a voltage divider, while maintaining the compensation resistance value. Pyranometer REF1 has been standardized, such that its sensitivity has been adjusted to 4.00 µV $W^{-1}m^2$. Pyranometers REF2 and REF3 have not been standardized by introducing a voltage divider, such that its sensitivity is still the original one. The reason is that REF1 has been previously operated in the field as standard operational sensor, while REF2 and REF3 have always remained in the calibration laboratory.

All reference pyranometers have been calibrated at WRC in Davos, therefore the calibrations in the KNMI laboratories are traceable to the WRC primary standard.

It should be noted here that PMOD-WRC calibrates pyranometers as delivered by the customer. Since KNMI normally sends its reference pyranometers without ventilation unit, most calibrations presented in this report were performed unconditioned, i.e. unventilated and unheated. Only in 2015, KNMI included a ventilation unit and two conditioned calibrations were carried out (see section 5.1). For BSRN, pyranometer calibrations are always performed conditioned.

4.3 Calibration procedure

The standard calibration at KNMI is performed in a dimmed room, using a halogen filament lamp. The reference pyranometer and the device under calibration are placed in a horizontal plane on a turntable at equal distances from the nadir point 110 cm below the lamp, see figure 4.1. A ventilator is used to cool the instruments while they are exposed to the lamp. Because the spectrum of the lamp contains much more infrared (IR) radiance than the sun, a glass filterplate is used right below the lamp to block most of the IR radiance. The plate is ventilated to remove absorbed energy. The nominal radiation intensity at the instrument is 500 Wm^{-2}. The output of both pyranometers is measured using an Agilent 34970A acquisition-switch unit in an automated setup. The

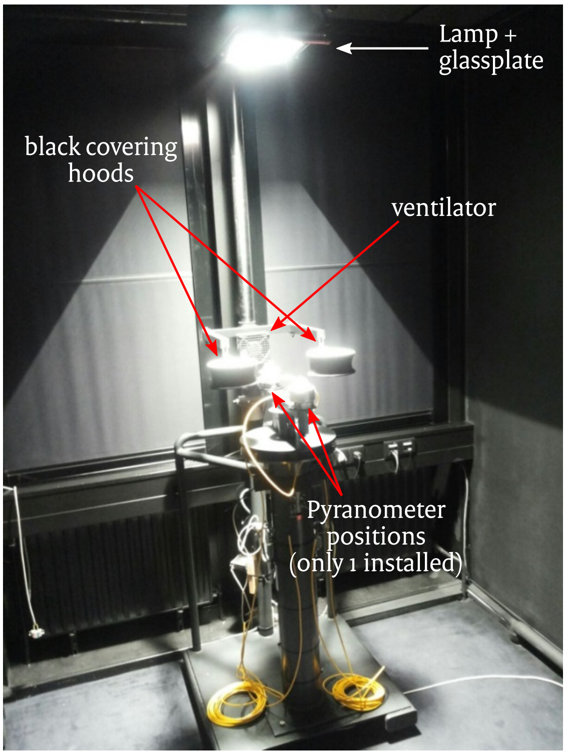

Figure 4.1: KNMI radiation calibration laboratory setup

acquisition-switch is calibrated yearly.

After switching on the lamp, a stabilization phase of 300 s is applied. Ten samples from both pyranometers are taken at a frequency of 1 Hz and averaged, providing $\bar{U}_{\mathrm{s}}$ (device under calibration) and $\bar{U}_{\mathrm{r}}$ (REF). As the spatial intensity of the lamp is not uniform, the turntable is turned 180°, so the devices exchanged their position. Another stabilization phase of 300 s is follows and subsequently another measurement of 10 s at the same acquisition frequency. Then the turntable is again turned over 90°. In this position both pyranometers are covered by a black hood. After 5 minutes the output under dark circumstances are measured. This results in three values for both sensors: U_1,U_2 and U_d.

The sensitivity F_s of the device under calibration is then calculated using equations 4.1 to 4.3:

$$U_r = 0.5\,(\bar{U}_{r_1} + \bar{U}_{r_2}) - \bar{U}_{r_d} \tag{4.1}$$

$$U_s = 0.5\,(\bar{U}_{s_1} + \bar{U}_{s_2}) - \bar{U}_{s_d} \tag{4.2}$$

$$F_s = F_r \frac{U_s}{U_r} \tag{4.3}$$

The dark output voltage U$_d$ is measured to compensate for the Type A offset. When the radiation source is taken away, by covering with a black hood, both the sensing element and the inner dome will cool down to ambient temperature. The time constant for the cooling curve of the sensing element is approximately 4 seconds, while the time constant for the cooling of the dome is much higher, up to several minutes. Thus after 1 minute the energy at the sensing element is discharged for more than 99.999%, the energy at the dome is discharged for only 10-20%. Kipp&Zonen recommends a cooling time of 1 minute, which is sufficient with respect to the time constant of the sensing element. The KNMI procedure uses a cooling period of 5 minutes. The extended cooling time may cause an underestimation of the offset of approximately 20%.

After 2 minutes the residual voltage is probably mainly due to offset in the data acquisition unit, and is normally in the order of 2 µV (0.5 W/m^2), which corresponds to 0.1% of the nominal value. The Agilent 34790 acquisition-switch unit is specified to have a long term maximum offset of 0.004% of full scale (one year). The measurements are taken on a 100 mV scale, so the acquisition offset may be as high as 4 µV, excluding thermal offset. Thermal offset is however negligible since the unit is operated in a temperature controlled environment.

Chapter 5

Calibration results

5.1 PMOD-WRC calibrations

The reference pyranometers are calibrated at PMOD-WRC in Davos. Although this has been done on an irregular basis, a reference sensor has been calibrated roughly every two years. Calibration method (a) from table 2.2 is used for these calibrations, in which the device under calibration is compared to the sum of the direct solar radiation measured with an instrument of the WSG, multiplied by the cosine of the solar zenith angle, and the diffuse solar radiation as measured with a shaded pyranometer. PMOD-WRC calibrates the pyranometer unconditioned or conditioned, as the customer supplies the instrument. KNMI always supplied their instruments without ventilation unit, such that it is calibrated in an unconditioned manner. Only in 2015 two pyranometers were calibrated both in an unconditioned and in a conditioned way. In figure 5.1 the results of the calibrations of the KNMI reference pyranometers at PMOD-WRC from 1998 are shown.

The measured sensitivities are always lower than the nominal value, up to 2%, particularly from 2004 onwards. This means a bias error towards lower sensitivity is present apart from the statistical variation due to the calibration process. Because the cause of the bias was not clear, KNMI did not use the new values as a new reference sensitivity after 2004, since there was no reason to believe that the reference instruments suddenly degraded. Moreover, in case the reference instrument would have degraded, this would affect all the calibrations of the pool of operational pyranometers, which was not the case.

PMOD-WRC used a non-ventilated Eppley PSP pyranometer until 2002, and a ventilated and heated Kipp&Zonen CM-22 after that. The WRC sent a letter dated 27th of October 2003, explaining that due to the fact that their diffuse pyranometer had been unconditioned “led to an underestimation of the diffuse irradiance it measured and consequently to an overestimation of the sensitivities of the instruments calibrated” [1].

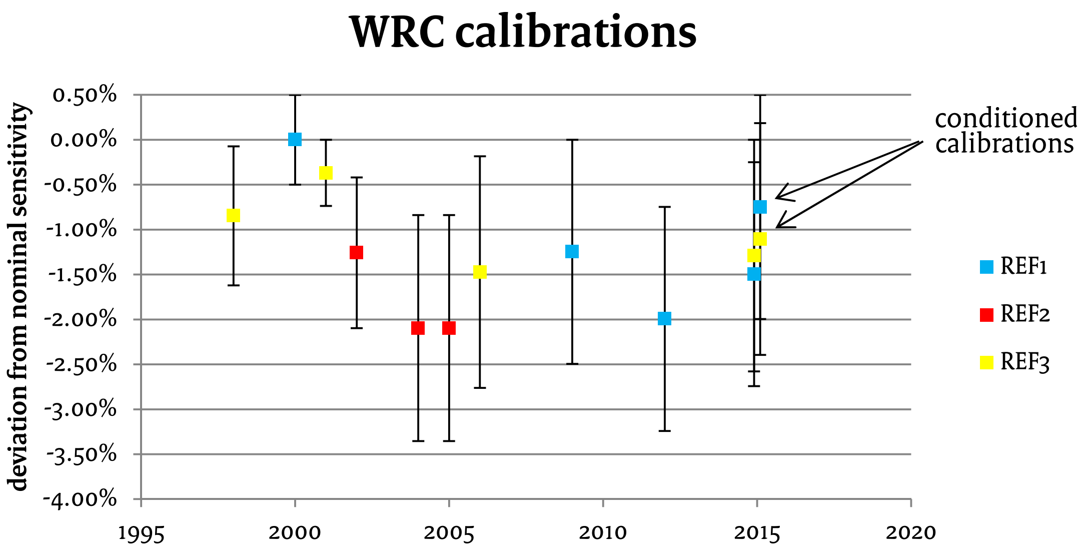

Figure 5.1: Deviation from original nominal sensitivity of the KNMI reference pyranometers found by PMOD-WRC in Davos for the period 1998-2015. All calibrations have been performed with unconditioned KNMI pyranometers, except in 2015, when REF1 and REF3 were each calibrated both conditioned and unconditioned.

This was of the order of 1%. More details are given by Philipona [8].

As was mentioned in Section 3.3, zero offset A influences the irradiance level of a pyranometer and therefore affects the calibration. The thermal offset of a ventilated Eppley PSP pyranometer is characterized to be between -5 and -15 W/m^2 for the diffuse solar radiation [4], while the Kipp&Zonen CM-22 has a lower maximum thermal offset of -3 W/m^2 [7]. The Kipp&Zonen CM-11 features a zero offzet A of -7 W/m^2 in case it is conditioned and -12 W/m^2 for unconditioned instruments [6]. Because the zero offset of a Kipp&Zonen CM-11 and Eppley PSP is comparable, this offset had been largely cancelled out until 2002. Since the conditioned Kipp&Zonen CM-22 features a much lower zero offset A, the difference ended up in the calibrations after 2002.

In order to confirm this effect on the calibration of the reference pyranometers of KNMI, a special series of calibrations has been performed by PMOD-WRC in 2015 on request of KNMI. Two reference sensors (REF1 and REF3) have been calibrated twice: once using a Kipp&Zonen CVF4 ventilation unit, which also heats the ventilated air, and the other time unconditioned. The purpose was to identify the influence of the ventilation. Reference sensor REF1 had a deviation of -1.5% unconditioned, which was only -0.75% when it was conditioned. Reference sensor REF3 had a deviation of -1.3% unconditioned and -1.1% conditioned. This confirms that the zero-offset is the cause of the deviation from the nominal sensitivity as shown in figure 5.1.

REF number	Calibration type	Nominal sensitivity [µV $W^{-1}m^2$]	Calibrated sensitivity [µV $W^{-1}m^2$]	Calibration date	Deviation
REF1	lab	4.01	4.01	Nov 2012	+ 0.0%
REF3	lab	5.43	5.47	Jun 2013	+ 0.7%
REF3	outdoor	5.43	5.46	Jun 2013	+ 0.6%

Table 5.1: calibrations of KNMI reference pyranometers at DWD

5.2 DWD calibrations

In order to obtain an independent check of our reference pyranometer sensitivitiy, KNMI also had REF1 and REF3 calibrated at the calibration facilities of the Meteorologisches Observatorium Lindenberg of the Deutsche Wetterdienst (DWD). DWD uses the same calibration method as KNMI, using a filament lamp as a light source in the laboratory. The KNMI reference pyranometers were calibrated against a DWD reference pyranometer of the same type (CM-11) and were not conditioned.

The DWD reference pyranometer has not been calibrated at PMOD-WRC for its traceability to the WRR, like the KNMI references. Instead DWD calibrates their reference pyranometer against a cavity radiometer using method (b): the alternating sun-and-shade method. The cavity radiometer is calibrated every five years at the International Pyrheliometer Comparison (IPC) campaign at WRC in Davos, and is therefore traceable to the WRR. The results of the KNMI reference calibrations are listed in the table below:

REF3 was also calibrated in an outdoor calibration at DWD against their cavity radiometer. This gave nearly the same sensitivity value: 5.46 µV $W^{-1}m^2$. During this outdoor calibration, method (b) is used, in which REF3 has been shaded and unshaded at regular intervals. Because no shaded reference pyranometer has been used, the zero offzet A is similar during shaded and unshaded periods, and thus cancels out. This is significantly different than the calibration procedure used at PMOD-WRC, where calibration method (a) is used, in which a shaded Kipp&Zonen CM-22 is used to provide a value for the diffuse radiation.

5.3 Operational calibrations at KNMI

Figure 5.2 shows the deviation from the nominal sensitivity of all 905 calibrations of the operational network CM-11 pyranometers, since May 1999, as determined by indoor calibrations in the radiation laboratory at KNMI. For these calibrations, the method described in section 4.3 is used.

Over the years, several switches of reference pyranometer have been used. Initially, REF3

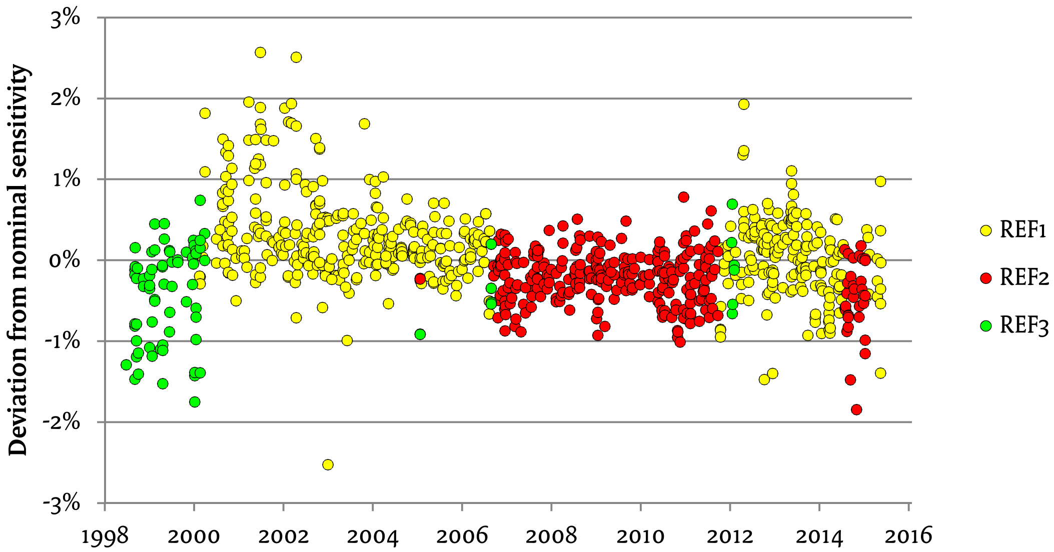

Figure 5.2: Calibration results of the KNMI network CM-11 pyranometers. The colour is determined by the reference sensor used in the calibration.

(see table 4.1) was used as reference pyranometer. It had been calibrated at PMOD-WRC in 1998, which returned a slightly lower sensitivity than its nominal value. This new value was used. Because the new lower sensitivity of the reference pyranometer was used, all network pyranometers were found to have a lower sensitivity too. This explains the negative deviations from the nominal sensitivity from 1998 to 2000. These network sensors were adjusted, and used in the field for two years.

In 2000, REF1 was calibrated at PMOD-WRC in Davos, and exactly the nominal value was found. REF1 was then used as reference pyranometer, and consequently all network pyranometers were found to have a higher sensitivity. This explains the high values of deviation from the nominal sensitivity from 2000 to 2002. Again, the network pyranometers were adjusted. After 2002, the reference pyranometers were no longer adjusted, despite the variation in calibration value found at PMOD-WRC. In 2007, a switch in reference instrument was made to REF2. In 2012, a switch was made back to REF1. Since then REF1 has been reference instrument, except for brief periods when this sensor was at PMOD-WRC for calibration. During these times, REF2 has been used.

By performing a statistical analysis, more insight in the calibrations can be obtained; see table 5.2. The mean value of all operational calibrations, shown in figure 5.2, is very close to the nominal value of 4.00 $\mu V\, W^{-1}m^2$, and the calculated standard deviation is 0.57% of the nominal value. A histogram of the operational calibrations is displayed in figure 5.3 with a bin size of 0.005 $\mu V\, W^{-1}m^2$. When comparing the histogram of the operational calibrations with the curve of a normal distribution using the mean value and

	absolute [$\mu V\,W^{-1}m^2$]	relative [%]
Mean sensitivity	3.999	-0.02 %
Standard deviation	0.023	0.57 %

Table 5.2: Statistical parameters found from the dataset of operational calibrations.

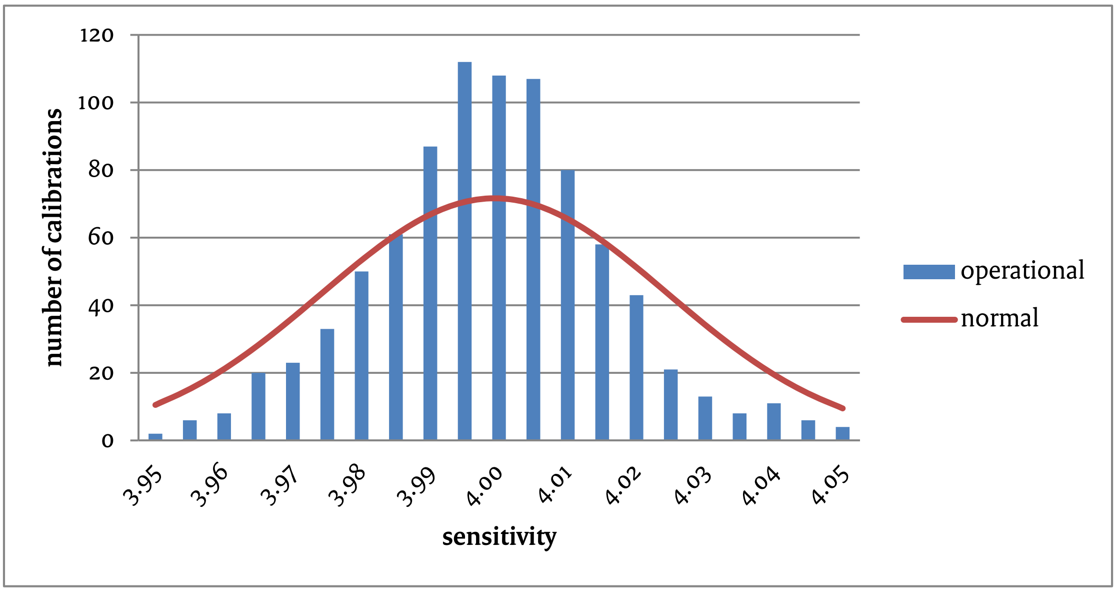

Figure 5.3: Histogram of operational calibrations compared to the normal distribution.

standard deviation from table 5.2, it is clear that the histogram is not well represented by a normal distribution with the found standard deviation. The number of calibration results with a sensitivity between 3.99 $\mu V\,W^{-1}m^2$ and 4.01 $\mu V\,W^{-1}m^2$ is higher than expected, and the number of calibrations with a higher deviation is lower. This is due to the presence of outliers, which are not caused by statistical variation.

A check can be made to see if the calibrations can be represented by a normal distribution by removing the outliers from the dataset. All calibrations with a deviation more than 1% from the mean value are removed from the dataset, and the statistical analysis is repeated on this dataset without outliers, see table 5.3 and figure 5.4. On this dataset, the histogram fits well with the normal distribution. From this analysis, it is clear that the pyranometers are very stable over the years, generally within 1%, which is the estimated uncertainty from the indoor calibrations.

	absolute [µV W^{-1}m^2]	relative [%]
Mean sensitivity	3.998	-0.04 %
Standard deviation	0.015	0.38 %

Table 5.3: Statistical parameters found from the dataset of operational calibrations when outliers are removed.

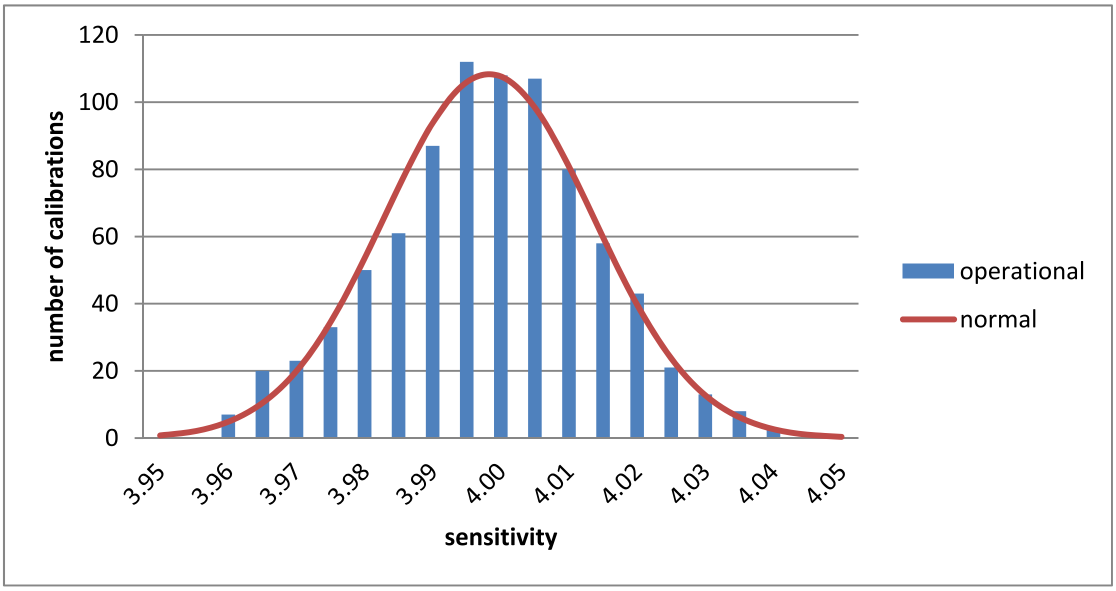

Figure 5.4: Histogram of operational calibrations without outliers compared to the normal distribution.

Chapter 6

Audit calibration laboratory

In order to confirm the belief that the laboratory calibrations are done in an appropriate manner, a visit to the KNMI calibration laboratory by Kipp&Zonen is organized in 2015, together with a return visit. During this visit several calibrations have been performed using the KNMI CMP-11 pyranometers and Kipp&Zonen CMP-21 pyranometers.

Some differences in the calibration procedures came to light. At KNMI, a first measurement is taken 300 seconds after the lamp is switched on. Then the position of the pyranometers are changed and subsequently a second measurement is performed after another 300 second stabilization phase. Finally the lamp switches off. 300 seconds later a dark current measurement is conducted. The measurements themselves take 10 seconds to conduct, in which 10 samples are collected at a measurement frequency of 1 Hz.

At Kipp&Zonen, a first light measurement is taken after a 60 second stabilization phase. The measurement itself takes in total 30 seconds. Subsequently a dark current measurement is conducted after a 60 second stabilization phase. Then the positions of the pyranometers are transposed. The procedure is repeated with a 60 second stabilization phase, with a 30 second measurement in the light, a 60 second stabilization phase and a 30 second measurement in the dark.

The stabilization duration is significantly different between the two procedures. A further test in the KNMI laboratory is conducted by changing the stabilization duration from 300 to 60 seconds. This resulted in a maximum difference of 0.1% in sensitivity, from which can be concluded that a 300 second stabilization duration is unnecessary. A stabilization time of 60 seconds is sufficient.

During these measurements also fluctuations of the signals in time have been recorded. These fluctuations are of the order of 1.0%, which are attributed to lamp instability. In principle the irradiance fluctuates for both sensors at the same time, and has no consequences for the resulting sensitivity. On the other hand, a voltage regulator for

Calibration facility	Reference pyranometer	Pyranometer	Calibration sensitivity [µV $W^{-1}m^2$]	Reverse calibration [µV $W^{-1}m^2$]	Average sensitivity [µV $W^{-1}m^2$]
KNMI	CMP-21 140297	Reversal test 1	8.13	8.17	8.15
Kipp&Zonen	CMP-21 140297	Reversal test 1	8.149	8.136	8.143
Kipp&Zonen	CMP-21 070115	Reversal test 1	-	-	8.24
Kipp&Zonen	CMP-21 070115	Reversal test 1	8.232	8.217	8.225
Kipp&Zonen	CMP-21 140297	CMP-21	-	-	8.67
Kipp&Zonen	CMP-21 140297	CMP-21	-	-	8.70
Kipp&Zonen	CMP-21 140297	CMP-21	-	-	8.73
Kipp&Zonen	CMP-21 140297	CMP-21	-	-	8.73
Kipp&Zonen	CMP-21 140297	CMP-11 113490	8.71	8.71	8.71
KNMI	CMP-11 113490	CMP-11 113491	8.65	8.68	8.67

Table 6.1: Overview of calibrations and reversal tests.

the lamp power supply could reduce these fluctuations and remove this effect to a large extent.

The KNMI lamp is of the halogen type, which is different from the Kipp&Zonen metal-halide lamp. The spectrum coming from the halogen lamp is very different than from the sun, mostly because the infrared regime contains much more energy. KNMI has already taken measures to correct this by installing a glass plate, which is ventilated. The spectrum from the Kipp&Zonen metal-halide lamp is much more similar to the solar spectrum.

To confirm a correct calibration procedure and good quality calibration facility, a reversal test is conducted. In this test a standard calibration is performed and subsequently the same calibration, with as only difference that the connection of the pyranometers is reversed. In case the facility produces a bias error, it should show up in this test. For the KNMI facility, the error was approximately 0.5%.

All in all, despite these minor differences, the resulting sensitivities of the pyranometers were very similar in reversal tests and in both the Kipp&Zonen and KNMI facility. All were within 0.5% from each other, see table 6.1. This is well below the expected uncertainty of 1% and below the standard deviation of 0.57% found in the statistical analysis described in section 5.3.

Chapter 7

Conclusions

Calibrations in the KNMI laboratory show stable results for almost 20 years. Based on the calibration results, the CM-11 network pyranometers show no sign of degradation at all. The uncertainty related to these calibrations is less than 1%.

Outdoor calibrations of our unconditioned reference pyranometers performed at PMOD-WRC in Davos show sensitivities that are up to 2% lower than the nominal value, which is larger than the 1.3% uncertainty typical for these calibrations. This bias appeared after the introduction of a new conditioned Kipp&Zonen CM-22 pyranometer at PMOD-WRC for the measurement of diffuse radiation. This instrument replaced the unconditioned Eppley PSP. It is likely that this bias is due to the difference in zero-offset A between these two instruments. PMOD-WRC uses calibration method (a) from the CIMO guide. With this calibration method, zero-offset A cancels out only if the zero-offset of the device under calibration and the reference shaded pyranometer are the same. While the Eppley PSP and the Kipp&Zonen CM-11 had a similar zero-offset A, the new conditioned Kipp&Zonen CM-22 shaded pyranometer features a much lower zero-offset A. By conditioning of the KNMI CM-11 during these calibrations, the error due to zero-offset A is minimized, such that it is compliant with the specified calibration uncertainty. The reduction of the bias is confirmed by the calibration test, that is performed using a pyranometer in both conditioned and unconditioned setup. Two KNMI reference pyranometers were calibrated in 2015 in a conditioned way at PMOD-WRC, and their sensitivity showed an offset of -0.75% and -1.1% of the nominal value, contrary to -1.5% and -1.29% when unconditioned. The conditioned calibrations are within the given uncertainty of approximately 1.3%.

The cause of this bias value is further confirmed in an outdoor calibration performed at the DWD, in which calibration method (b) from the CIMO guide is used. In this calibration, the device under calibration is alternately shaded and unshaded. The difference between these is then compared to the direct solar radiation measured with a cavity radiometer. Because only a single pyranometer is used, the zero-offset shows up in both the shaded as the unshaded period, the error is canceled out and gives a similar sensitivity as the nominal one. This measurement using the more accurate calibration method (b) confirms that the used nominal sensitivity of the KNMI reference pyranometers for calibrations is accurate. Consequently, the measured values of global radiation do not have to be corrected.

During laboratory calibrations, zero-offset A does not pose any problems. The dome does not view the clear sky, but the walls of the room, such that the net longwave radiation energy is much smaller. Furthermore, the device under calibration and reference pyranometer are of the same type, such that they have a similar zero-offset, which cancels out in the calibrated sensitivity. This is reflected in the lab calibrations, which remain within the estimated $\pm 1\%$ uncertainty. Laboratory calibrations at the DWD and at Kipp&Zonen show very similar results.

Chapter 8

Recommendations

1. The sensitivity of the KNMI reference pyranometers, used for calibrations of the network pyranometers, is accurate. Global radiation data of the KNMI network does not have to be corrected.
2. Calibrations of KNMI pyranometers at PMOD-WRC should be done with a ventilated pyranometer in order to minimize the effect of zero-offset A in the pyranometer calibration.
3. It is not necessary to have three reference pyranometers. Two is sufficient. One should be used as reference pyranometer for KNMI laboratory calibrations. This sensor remains in the laboratory. The other reference is used as traveling standard, which is calibrated externally to monitor the traceability of our reference pyranometers.
4. The traveling standard should be calibrated on a regular basis. Since degradation of the sensors has not been observed, a calibration interval of 2 years is sufficient.
5. Calibrations at PMOD-WRC using method (a) from the CIMO guide are sufficient to guarantee the specified calibration accuracy. However, calibration method (b) is more accurate, making it a preferred option. It is advised to experiment with this method by KNMI under local weather conditions, and to investigate the feasibility of such calibration method for its traveling standard.
6. The dark-current of the pyranometers are currently measured 2 minutes after covering with a hood. This is unnecessary long. A cooling time of 1 minute is sufficient, and gives a more accurate figure for the type A offset.

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