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Pyranometer intercomparison at the BSRN site in Cabauw, the Netherlands

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Abstract

A pyranometer intercomparison study has been performed with the objective of assessing the suitability for the KNMI observation network and the impact of replacement of the Kipp & Zonen CM-11 pyranometer by the Kipp & Zonen SMP-11. The intercomparison has been executed at the Cabauw BSRN site, where quality controlled, high-end instruments are available as reference for the measurement of global radiation. Other instruments from other manufacturers have been placed at the site in order to enable comparison with other instruments that are commercially available. Values for global radiation and the derived quantity of sunshine duration have been studied in this work.

A key finding of this study is that an overestimation of 1% of the currently operational KNMI reference could be determined. Previous studies were inconclusive on this overestimation, but through the intercomparison the presence and degree of overestimation could be confirmed. With the introduction of a new instrument, a new reference pyranometer will also be introduced at KNMI, which will not contain the 1% overestimation of its sensitivity. An overestimation of sensitivity results in an underestimation of global radiation. Therefore, with the introduction of the new pyranometers, it is expected that global radiation measurements will increase approximately 1% ± 1%.

Requirements as set by the WMO can only be fully met by the proposed Kipp & Zonen SMP-11 if the instrument is conditioned such that the impact of dew and rime events is minimized.

The change in estimated sunshine duration was found to be proportional to the difference in measured global radiation. Therefore also a 1% ± 1% increase in sunshine duration is expected. On the basis of the study it was concluded that the Kipp & Zonen SMP-11 is a suitable pyranometer instrument for the KNMI network .

Chapter 1

Introduction

Global radiation is measured on a routine basis at KNMI in its measurement network throughout the Netherlands using Kipp & Zonen CM-11 pyranometers. These instruments have been operational since 1989 and are at the end of their lifetime. The Kipp & Zonen SMP-11 is the designated replacement of the currently operational sensor. Given the use in climatic records of the measurement data, the impact of such instrument replacement is to be studied before introduction into the measurement network.

This document describes the intercomparison campaign that aimed to assess the impact of the replacement of the Kipp & Zonen CM-11 pyranometer by a digital Kipp & Zonen SMP-11. To investigate the impact of the digitalisation, the analog counterpart of the Kipp & Zonen SMP-11 is also investigated, which is the Kipp & Zonen CMP-11. Furthermore, a Hukseflux SR-20, SR-25 and prototype version of SR-30 are also placed at the test location in order to compare the instruments to others on the market. Pyranometers must adhere to specifications from the World Meteorological Organisation (WMO), described in the Guide to Instruments and Methods of Observation [1]. A table listing the required characteristics of pyranometers from this guide is displayed in figure 1.1.

The Baseline Surface Radiation Network (BSRN) site at the Cabauw measurement location is chosen as test location. Here the several radiation components are measured with the purpose to detect changes in the earth's radiation field, that may be related to climate change [2]. Many radiation components are measured with state of the art equipment and procedures. The basic radiation components measured are direct and diffuse shortwave radiation, and downward and upward global shortwave and longwave radiation.

The intercomparison campaign is executed between the 19th of February 2016 and the 14th of June 2017. The impact of the proposed instrument replacement on the global radiation measurements at KNMI is investigated. The sunshine duration is calculated from the global radiation measurements. This study also investigates the impact of the instrument replacement on the calculated sunshine duration.

Pyranometers can show large measurement errors during dew or rime conditions. This phenomenon occurs generally in unconditioned (neither heated, nor ventilated) instruments [3], and is also observed in the currently operational unconditioned Kipp & Zonen CM-11. The dataset that is created in this pyranometer intercomparison, is suitable to study the effect of instrument conditioning, but a detailed study is not presented in this document.

Chapter 2 describes the experimental equipment used during the measurement campaign. The uncertainties involved with such measurements are detailed in Chapter 3. The results of the tests are explained and analysed in Chapter 4. Finally, conclusions are drawn in Chapter 5.

Characteristic	*High quality*[a]	*Good quality*[b]	*Moderate quality*[c]
Response time (95% response)	< 15 s	< 30 s	< 60 s
Zero offset:			
(a) Response to 200 W m^{-2} net thermal radiation (ventilated)	7 W m^{-2}	15 W m^{-2}	30 W m^{-2}
(b) Response to 5 K h^{-1} change in ambient temperature	2 W m^{-2}	4 W m^{-2}	8 W m^{-2}
Resolution (smallest detectable change)	1 W m^{-2}	5 W m^{-2}	10 W m^{-2}
Stability (change per year, percentage of full scale)	0.8	1.5	3.0
Directional response for beam radiation (the range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring, from any direction, a beam radiation whose normal incidence irradiance is 1 000 W m^{-2})	10 W m^{-2}	20 W m^{-2}	30 W m^{-2}
Temperature response (percentage maximum error due to any change of ambient temperature within an interval of 50 K)	2	4	8
Non-linearity (percentage deviation from the responsivity at 500 W m^{-2} due to any change of irradiance within the range 100 to 1 000 W m^{-2})	0.5	1	3
Spectral sensitivity (percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within the range 300 to 3 000 nm)	2	5	10
Tilt response (percentage deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1 000 W m^{-2})	0.5	2	5
Achievable uncertainty (95% confidence level):			
Hourly totals	3%	8%	20%
Daily totals	2%	5%	10%

Notes:

a Near state of the art; suitable for use as a working standard; maintainable only at stations with special facilities and staff.

b Acceptable for network operations.

c Suitable for low-cost networks where moderate to low performance is acceptable.

Figure 1.1: Fragment from the WMO Guide to Instruments and Methods of Observation (CIMO guide) [1] on the characteristics of operational pyranometers. For the KNMI network pyranometers, the column for good quality would apply.

Chapter 2

Experimental setup

This chapter describes the experimental setup and equipment in the measurement campaign. It starts with a short description of the measurement site in Cabauw, i.e. the BSRN Site, in Section 2.1. In this Section also the applied maintenance procedure is described. Then the installed pyranometers are described in Section 2.2. The data acquisition equipment is finally described in Section 2.3.

2.1 BSRN Site Cabauw

The Ruysdael Observatory is a collaboration of several research institutes and universities, e.g. TNO, Delft University of Technology, European Space Agency. The Cabauw site is used for a variety of atmospheric research topics, and features a 213 m high tower, see figure 2.1. It is located 51.971° N and 4.927° E at an elevation of -0.7 meter above mean sea level. Solar radiation is also measured at the observatory at the radiation site, which is part of the BSRN network since 2005. A variety of radiation parameters is collected at the BSRN site. The key parameters are:

- Direct, diffuse and global irradiance
- Downward longwave irradiance
- Upward shortwave and longwave irradiance
- Narrowband direct irradiance (for Aerosol Optical Depth, AOD)
- Sky temperature (Nubiscope)
- Total sky images
- Sunshine duration

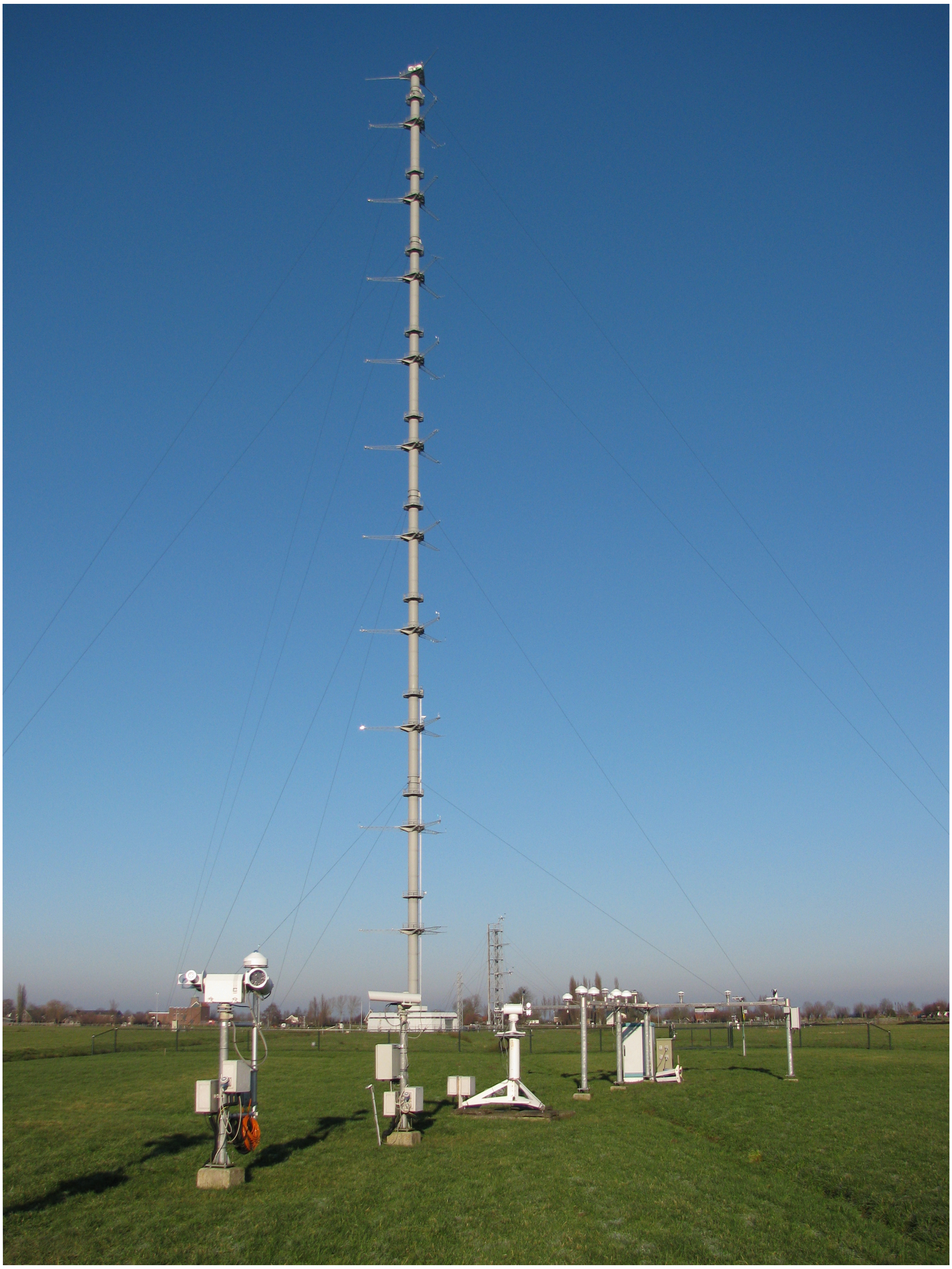

Figure 2.1: 213 m high tower at the Cabauw experimental site for atmospheric research. In front of the tower, the BSRN instruments are visible in north-south alignment. Photo: Wouter Knap, May 2015.

The instruments are placed on a lawn, of which the grass is kept short. Maintenance to the instruments is carried out on site on a semi-daily basis. During the maintenance, the domes of the pyranometers are cleaned, and the level positions are checked. The visit is also useful as a general check for any irregularities. The generated data is quality checked and sent to the World Radiation Monitoring Center (WRMC) [2].

2.2 Instrumentation

A total of 7 pyranometers are placed for the intercomparison, next to the instruments that are already present, see table 2.1. An overview of the test location is found in figure 2.2. Global radiation is measured using two different methods at the BSRN site. One method is direct measurement of global radiation by using an unshaded and conditioned, i.e. heated and ventilated, Kipp & Zonen CM-22, placed at position S-03. The other method is by measuring direct radiation and diffuse radiation separately, using a conditioned CH-1 pyrheliometer, and a shaded and conditioned Kipp & Zonen CM-22 pyranometer respectively. These instruments are both placed on a Kipp & Zonen Solys 2 suntracker, which is located at position S-04. The measurement of global radiation by the unshaded Kipp & Zonen CM-22 pyranometer is chosen as reference for the intercomparison presented here. The reason for this choice is the fact that global radiation is measured with a single instrument, employing the same physical background as the pyranometers under test. This results in a similar type of measurement response between devices under test and the reference. Other options as reference would have been possible, such as the combination of the measurement of direct and diffuse radiation. While arguably more accurate, it involves two instruments, of which one is a pyrheliometer. Moreover, both instruments are placed on a suntracker, such that the orientation of the instruments is always the same towards the sun. Consequently, there is no variation in the directional response in azimuth direction. Particularly at high solar zenith angles (SZA), the directional error can be a significant source of measurement error.

The Kipp & Zonen CM11 that is present at the T-frame position T-20 is a pyranometer from the KNMI national network. This pyranometer is equipped with wires for the prevention of birds sitting on the glass dome, see figure 2.4, as in the rest of the network. The other pyranometers for the intercomparison are not equipped with such wires. The pyranometers that were placed specifically for the intercomparison presented here, are placed on the T-frame at positions T-01 to T-07, see figure 2.3. The largest distance between instruments is the distance between the BSRN instruments on the suntracker at position S-04 and the pyranometer at position T-01, and measures less than 25m.

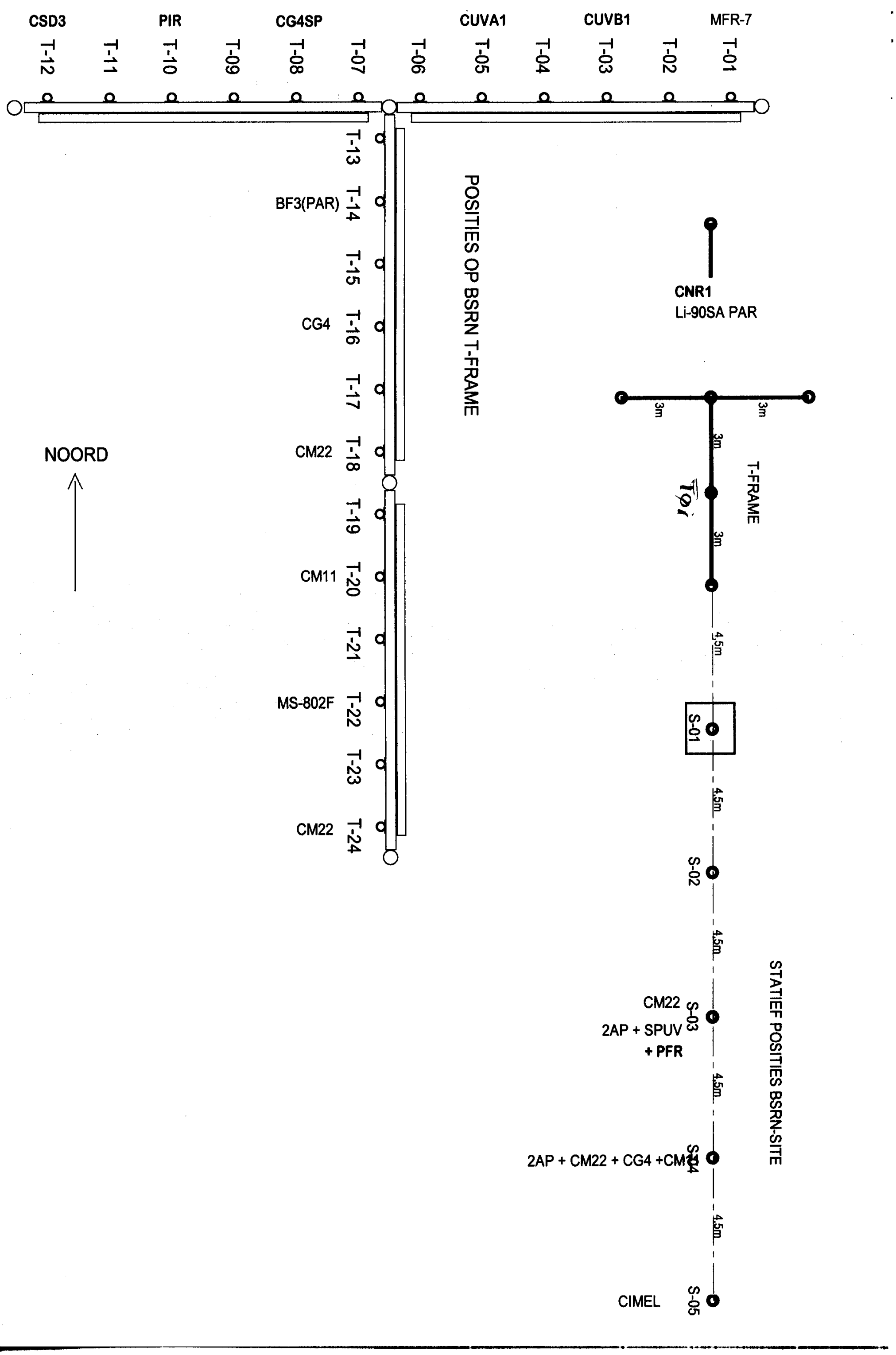

Figure 2.2: Overview of the BSRN site.

Figure 2.3: Pyranometers placed on the experimental setup. Photo: Tiemo Mathijssen, February 2016.

2.3 Data acquisition

Data from the instruments is acquired using different methods depending on the output of the instrument. All instruments are sampled with a 1 Hz frequency. With exception of one instrument, all data acquisition is done using a so-called SIAM (Sensor Intelligent Adaptation Module). The SIAM provides communication to the sensor and converts the output into a standardised KNMI-specific format. Moreover, a basic quality control is performed by the SIAM.

The analog signals from the Kipp & Zonen CM-22, CH-1, CM-11 and CMP-11 sensors are collected using a BSRN-Q SIAM [4]. The Kipp & Zonen SMP-11 instruments include their own A/D converter and feature a digital RS-485 output. These are collected via a BSRN-Q2 SIAM [5]. The Hukseflux instruments also feature a RS-485 output, but a different modbus register structure is used. Their output is collected via a modified version of the BSRN-Q2 SIAM, specifically designed for this purpose, which is named BSRN-Q3 SIAM [6]. The Hukseflux SR-20 and SR-25 are connected to this BSRN-Q3 SIAM. The Hukseflux prototype instead is connected directly to a Moxa NPORT 5630-16 to allow data transport via the network. The SIAMs and Moxa are placed in a cabinet next to the measurement site, see figure 2.5, protecting the electronics from weather influences. The cabinet allows the distance to the sensors to be kept short, which is of particular importance for the analog signals. An embedded linux system puts the timestamp for all instruments and stores the data in a netCDF file, which is further transported within the KNMI network.

position	type	conditioning type	shaded	BSRN instrument	code
S-03	Kipp & Zonen CM-22	Kipp & Zonen CVF-4	no	yes	CM22V
S-04	Kipp & Zonen CH-1	self-made ventilation	no	yes	CH1
S-04	Kipp & Zonen CM-22	Kipp & Zonen CVF-4	yes	yes	CM22V
T-01	Hukseflux prototype	internal ventilation	no	no	SRPR
T-02	Hukseflux SR-25	heated	no	no	SR25
T-03	Hukseflux SR-20	-	no	no	SR20
T-04	Kipp & Zonen SMP-11	Kipp & Zonen CVF-4	no	no	SMP11V
T-05	Kipp & Zonen SMP-11	-	no	no	SMP11
T-06	Kipp & Zonen CMP-11	Kipp & Zonen CVF-4	no	no	CMP11V
T-07	Kipp & Zonen CMP-11	-	no	no	CMP11
T-20	Kipp & Zonen CM-11	-	no	no	CM11

Table 2.1: Instruments that took part in the pyranometer intercomparison.

Figure 2.4: Kipp & Zonen CM-11 pyranometer as currently used in the KNMI network.

Figure 2.5: Cabinet with electronics. Inside the cabinet, four racks with SIAMs are visible, that provide the data acquisition for the entire BSRN site.

Chapter 3

Measurement Uncertainties

This chapter describes known uncertainties from the measurements this intercomparison. An overview of the uncertainty estimation is documented by Henzing and Knap [7]. They are subdivided into instrument uncertainties, here described in section 3.2, uncertainties in the data acquisition in section 3.2 and in field uncertainties, such as influence of dew and rime, in section 3.4.

3.1 Working principle of a pyranometer

Pyranometers are sensors that convert solar radiation into an electric energy. A drawing of such an instrument is displayed in figure 3.1. A thermopile is used as detector, consisting of a number of thermocouples. The hot junctions are covered by a black paint, and exposed to the sun. The cold junctions are connected to a thermal reservoir, that keeps a stable temperature. Practically all solar radiation is absorbed by the black paint, which heats up the hot junction. The resulting thermo-electric voltage in the thermopile is a measure for the amount of solar radiation. High-end pyranometers record the housing temperature with an additional sensor to compensate for temperature dependence. A dome protects the sensing element from the weather. The dome transmits shortwave visible radiation, but absorbs longwave infrared radiation. However, the transmitting spectrum varies depending on the dome material.

3.2 Instrument uncertainties

3.2.1 Zero Offset

Two types of bias errors due to temperature differences are identified: zero offset A and zero offset B.

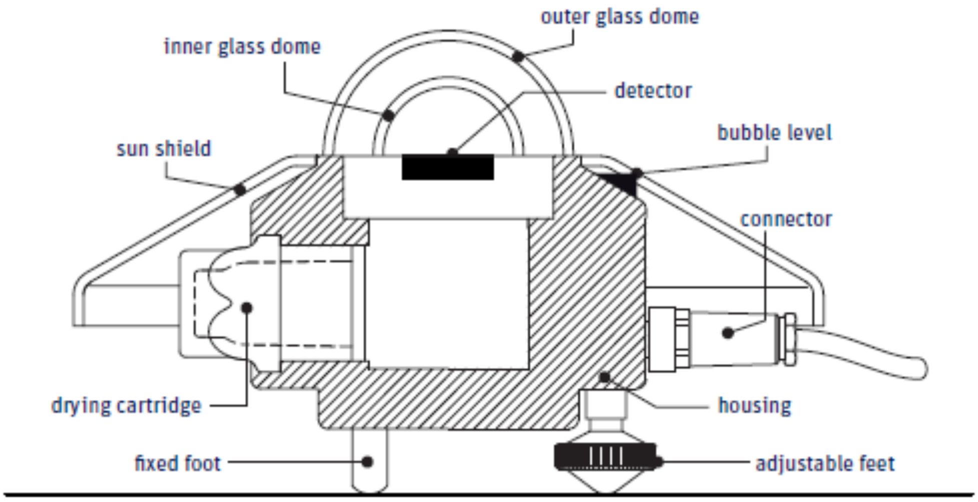

Figure 3.1: Drawing of pyranometer components. Image taken from the Kipp & Zonen manual [8]

Zero offset A is caused by radiative cooling of the hot junction. Both the hot junction and the dome emit infrared radiation. The amount of emitted energy depends on the temperature. The dome cools down due to cold sky temperature, making its temperature lower than the thermopile. Consequently the amount of emitted infrared radiation by the dome decreases, and in turn also the thermopile hot junction. This cools down the hot junction, showing up as a negative offset in the output. During nights, the offset is identified because of the absence of solar light, but it is also present during the day. This offset can be reduced by ventilation of the dome. When it is ventilated with heated air, this offset can be removed or even reversed.

Zero offset B is introduced by temperature differences across the thermopile caused by ambient temperature fluctuations. Since the temperature variation of the thermopile is not uniform, a bias error is introduced.

3.2.2 Directional response

The measured radiation intensity is ideally exactly the same the cosine of the incidence angle with respect to the zenith. Due to manufacturing process of the dome and the detector, a deviation from this so-called cosine law can be present.

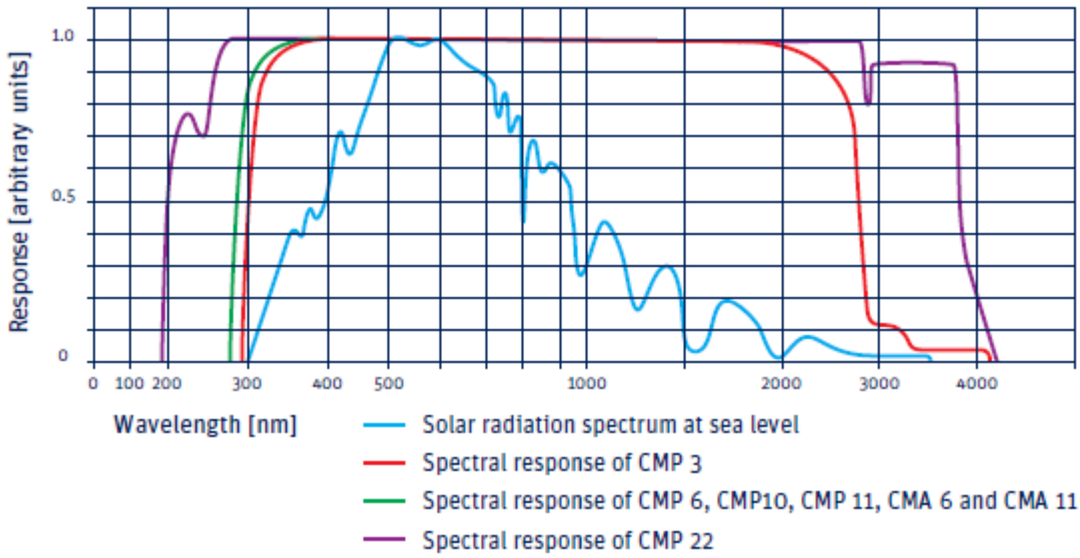

Figure 3.2: Example of spectral transmission of Kipp & Zonen pyranometers. Image taken from the Kipp & Zonen manual [8]

3.2.3 Nonlinearity

The thermal equilibrium in the detector is not entirely linear due to a varying convective and radiative heat loss. This introduces the nonlinearity error.

3.2.4 Temperature Dependence

The temperature dependence of the instrument depends on the thermo-dynamics of the construction. To limit this error, a pyranometer is compensated for the temperature dependence. High-end pyranometers feature a temperature sensor to measure the temperature of the housing to compensate the temperature dependence.

3.2.5 Spectral Selectivity

The variation of the dome transmissivity and detector absorption with respect to wavelength is called spectral selectivity. The spectrum for Kipp & Zonen pyranometers is displayed in figure 3.2.

3.2.6 Calibration

The calibration of the instrument introduces a significant uncertainty in the measurement. It depends on many factors, such as sensor accuracy, calibration method, used equipment and lab facilities, etc. For the Kipp & Zonen CM-11 pyranometers currently used in the KNMI network, the uncertainty due to calibration is evaluated by Mathijssen et al. [9] to be approximately 1%. The Kipp & Zonen pyranometers used for intercomparison presented here are calibrated in the KNMI radiation laboratory. The Hukseflux instruments are calibrated in the calibration lab of the manufacturer, because the KNMI calibration laboratory could not accomodate these instruments. For both the KNMI and Hukseflux calibrations, the pyranometer under test is compared to a reference pyranometer, which in turn is traceable to the World Radiometric Reference (WRR). The BSRN instruments for global and diffuse radiation, as well as the pyrheliometer for the direct solar radiation are all calibrated at the World Radiation Centre (WRC) at the Physical Meteorological Observatory in Davos (PMOD), directly against the WRR.

3.3 Data acquisition

The data acquisition error is subdivided into the three parts. The resolution of the instrument output, which is only applicable to the digital sensors, the resolution of the SIAM, and the resolution of the data storage.

For the BSRN instruments and the Kipp & Zonen CMP-11 pyranometers, the output is analog, so no error is made in the resolution of the instrument output. Any error in the signal transfer from the sensor to the A/D converter is discarded. The accuracy of the SIAM is 1 μV plus a maximum reading error due to the SIAM resolution, which is also 1 μV [4]. The data storage resolution is kept the same value of 1 μV by limiting the range from -1045 μV to 15535 μV. The sensitivity of the analog instruments varies between 8.94 $\mu V\,W^{-1}m^2$ and 10.42 $\mu V\,W^{-1}m^2$ respectively, leading to an uncertainty due to the data acquisition between 0.19 W/m^2 and 0.22 W/m^2. The exception is the Kipp & Zonen CM-11, which has a sensitivity of 4.0 $\mu V\,W^{-1}m^2$ leading to an uncertainty due to the data acquisition of 0.5 W/m^2.

The digital Kipp & Zonen instruments were set to a resolution of 1 W/m^2 and are rounded to the closest integer. The minimum value that is registered by the Q2-SIAM is -40 W/m^2 and the maximum is 1500 W/m^2, leading to a total range of 1540 m^2. The storage of this data is done in 16 bit integers, leading to a maximum error of 0.02 W/m^2. In total the data acquisition error is thus 0.5 W/m^2 plus 0.02 W/m^2.

The Hukseflux instruments are all digital, and feature an output resolution of 0.01 W/m^2. For the acquisition, a Q3-SIAM is used, which is an adapted version of the Q2-SIAM. The resolution of the Q2-SIAM and Q3-SIAM output is only 1 W/m2, such that the higher output resolution of the pyranometer is rounded off to an integer value in the SIAM.

Data storage is done using the same method as the digital Kipp & Zonen instruments. Consequently, the same accuracy is obtained, i.e. 0.5 W/m2 plus 0.02 W/m^2.

3.4 Field uncertainties

A variety of environmental influences impact the accuracy of the measurements. Examples are blockage from objects on the horizon at low solar angles, birds that occasionally sit on top of a pyranometer, raindrops on the pyranometer dome, contamination of the dome, and dew or rime on the dome. These often lead to unrepresentative measurements. This is minimalized in the current intercomparison by cleaning of the dome during the semi-daily maintenance. By comparing the measurements to physical limits [10], and applying quality flags [11], many of such cases can be identified. Nevertheless, observations in field conditions lead to a higher uncertainty than only instrument and data acquisition uncertainty. Estimation of the total field measurement uncertainty is up to 4% [12, 13].

Chapter 4

Results

4.1 Data reduction

Data for all instruments are sampled on a 1 Hz basis. In order to reduce the amount of data and to mimic the sampling frequency in the measurement network, this is downsampled to 1/12 Hz, corresponding to the network SIAM measurement frequency. Subsequently, a few events have been removed from the data, because of obviously incorrect data, and are specified in table 4.1. Please note that the cleaning events have not been removed from the data set, and thus remain part of the used data. The time duration of the cleaning event per instrument is small, such that the impact on the statistics of the measurements is negligible.

A minimum, maximum and average over the last 10 minutes is calculated from the data, that is downsampled to 1/12 Hz. The 10 minute average value of global irradiance is used in the analysis. This is exactly the same procedure as is employed in the KNMI measurement network.

date	start time	end time	affected sensors	reason
25/04/2016	09:08:30	10:10:30	CM-22V	instrument exchange
02/06/2016	09:35:23	09:40:48	CM-22V	bird on instrument
05/06/2016	12:13:00	12:24:00	CM-22V	bird on instrument
07/12/2016	08:58:30	09:36:30	CM-22V	instrument exchange
17/05/2017	09:46:24	09:52:48	CM-22V	bird on instrument
18/05/2017	06:19:00	06:30:00	CM-22V, CM-11, CH1+CM22V	SIAM issue

Table 4.1: Events for which data is removed.

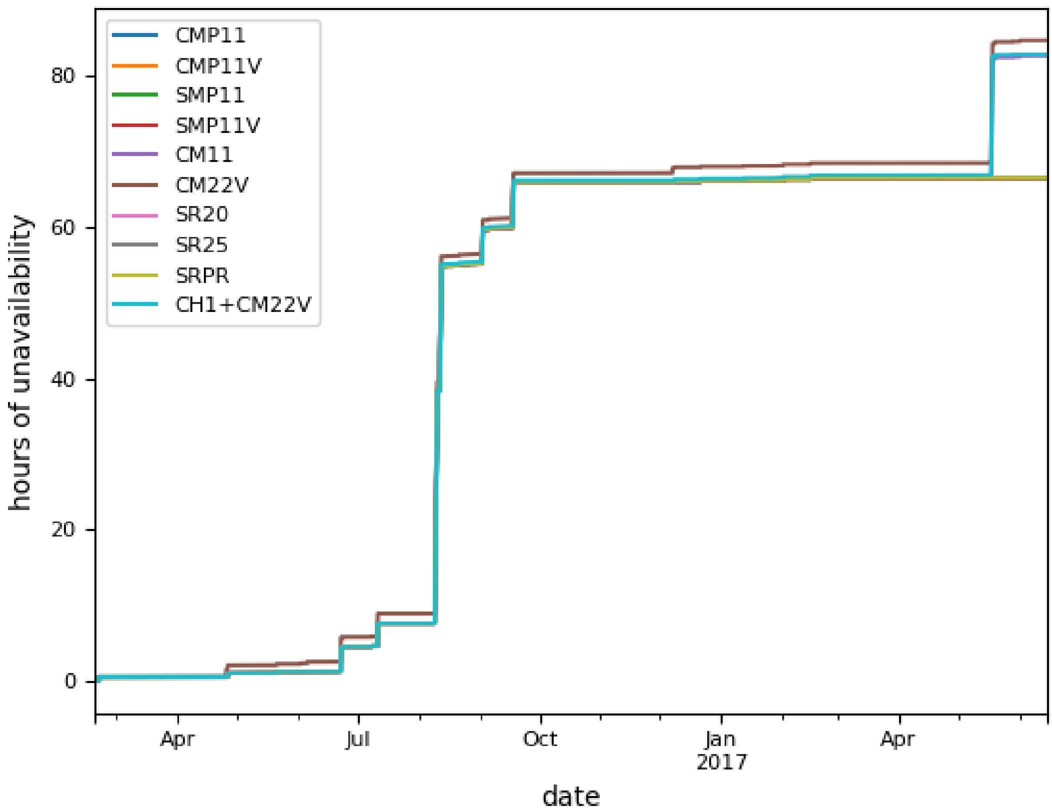

Figure 4.1: Cumulative missing data as a function of time. All instruments have very similar amount of missing data of approximately 66.50 hours, except the Kipp & Zonen CM-11, CM-22V, and the sum of Kipp & Zonen CH-1 and CM-22V, that have 82.69, 84.72 and 82.85 hours of missing data.

4.2 Data availability

The dataset is taken from the 19th of February 2016 to the 14th of June 2017, making up for a total of 482 days. During the intercomparison, less than 1% of the time duration was missing for all sensors, see table 4.1 and figure 4.1. The reason for the most missing data was due to a power outage. The missing data comprises the same time frame for all instruments, with one notable exception. From 15th of May 2017 15:00 UTC until 16th of May 09:40 UTC, no data was recorded only for the Kipp & Zonen CM-11, CH-1 and CM-22 instruments, due to failure of data acquisition equipment that was shared for these instruments. This period was mostly during the night, and therefore has little effect on the intercomparison.

instrument	missing data [h]	missing data [%]
CMP-11	66.48	0.57
CMP-11V	66.48	0.57
SMP-11	66.51	0.57
SMP-11V	66.51	0.57
CM-11	82.69	0.71
CM-22V	84.72	0.73
SR20	66.55	0.58
SR25	66.55	0.58
SRPR	66.55	0.58
CH1 + CM-22V	82.85	0.72

Table 4.2: Amount of missing data per sensor. The Kipp & Zonen SMP-11 is the proposed instrument to be introduced into the KNMI operational network. The Kipp & Zonen CM-11 is the currently operational instrument on the BSRN site. CH1 + CM-22V is the sum of BSRN measurements of the direct radiation as measured with the Kipp & Zonen CH-1 and the diffuse radiation as measured with the shaded conditioned Kipp & Zonen CM-22.

4.3 Statistics

An example of the daily global irradiance curves is shown in figure 4.2. This day, the 26th of May 2017, is chosen because it is a clear-sky day. A small dip in radiation at midday is visible. The cause of this dip can be identified when the original data with sampling frequency of 1/12 Hz is visualised, see figure 4.3. The cleaning event shows a very short blockage of nearly all radiation for all instruments consecutively.

All pyranometers give a similar response throughout the day, except the Kipp & Zonen CM-11. This instrument records lower radiation levels than the other instruments, which is more prominent before the maximum sun elevation than after, which is visualised in figure 4.4. This is caused by two effects. The first effect is a significant bias in its calibration, creating an offset with the other instruments. This is discussed in more detail in section 4.4. The other effect is that the leveling of the instrument seemed to be sub optimal, which is discussed in more detail in section 4.5. A normalization is performed in order to compare instruments with each other. The normalization is done using the pyranometer from the BSRN site that measures global radiation. The reason for the choice of this conditioned Kipp & Zonen CM-22 instrument is described in section 2.2.

A histogram of all the normalized data per sensor is displayed in figure 4.5, together with the mean value and standard deviation. This includes all the solar zenith angle (SZA) values and also night values. At high solar zenith angles, the measured values of solar radiation are very low, while the instrument error is large due to the directional

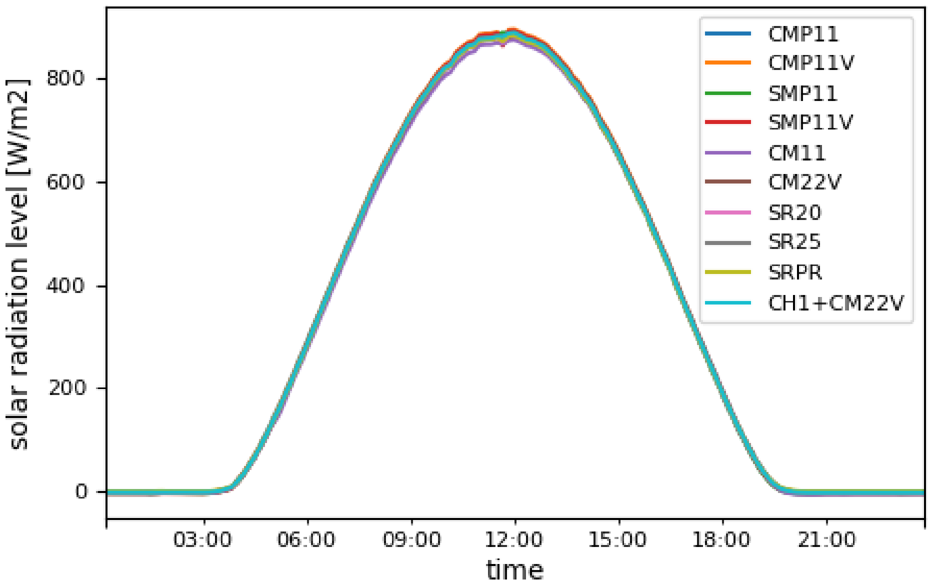

Figure 4.2: Global radiation during the clear-sky day of 26th of May 2017. In this image the 10-minute averaged data is displayed.

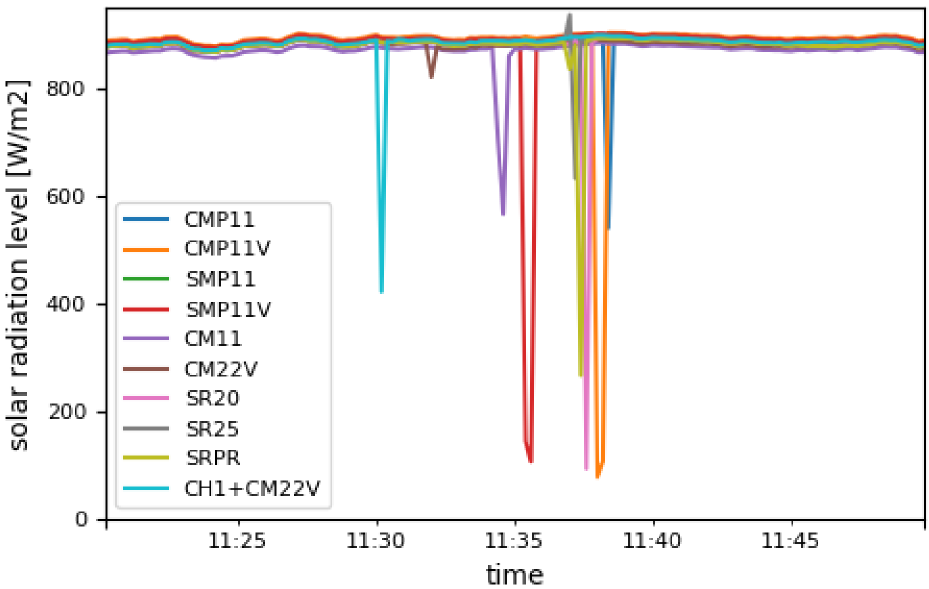

Figure 4.3: Detail of the clear sky radiation level around mid day of the 26th of May 2017. In this image the 1/12 Hz data is displayed.

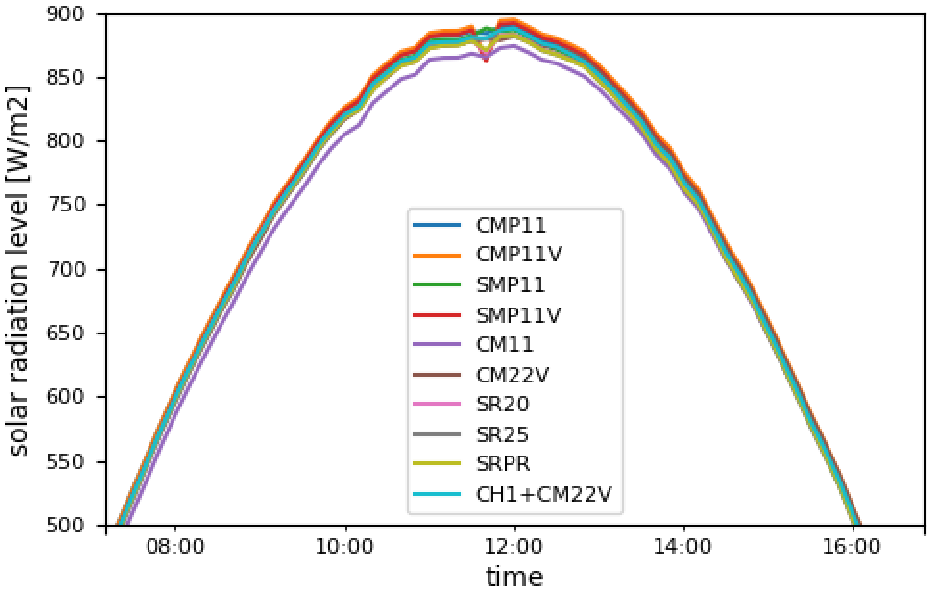

Figure 4.4: Detail of the clear sky radiation level around mid day of the 26th of May 2017.

response. This results in very large relative differences between instruments, while in absolute terms the difference is small. Therefore, it is not a normal distribution, and the standard deviation is very high, while the mean value is far from 1. Evaluation of the relative differences is performed in the current study, to evaluate the quality of instantaneous measurements under various levels of irradiance. However, it is necessary to create a subset of the data with thresholds in solar zenith angle and radiation level in order to compare statistics of the instruments. Figure 4.6 displays the normalized data is displayed as a function of the solar zenith angle. From this diagram can be derived that a threshold of a minimum solar elevation of 15°, equivalent to a SZA below 75°, removes the largest uncertainties from the dataset. This is similar to Long and Dutton [11], who describe quality control tests for BSRN, in which a thresholds are defined for SZA below 75° and global radiation above 50 W/m^2. A data subset is created with only data points for which the solar zenith angle is below 75° and global radiation is above 50 W/m^2.

The mean value of the normalized data of this subset is displayed in table 4.3, and the histogram in figure 4.7. The uncertainty resulting from the calibration of the pyranometer in the KNMI laboratory is estimated to be 1% [9]. All pyranometers, except the currently operational Kipp & Zonen CM-11, show mean global radiation levels that are within 1% of the conditioned BSRN Kipp & Zonen CM-22, which acts as a reference. The Kipp & Zonen CM-11 shows global radiation levels that are on average 1.5% lower

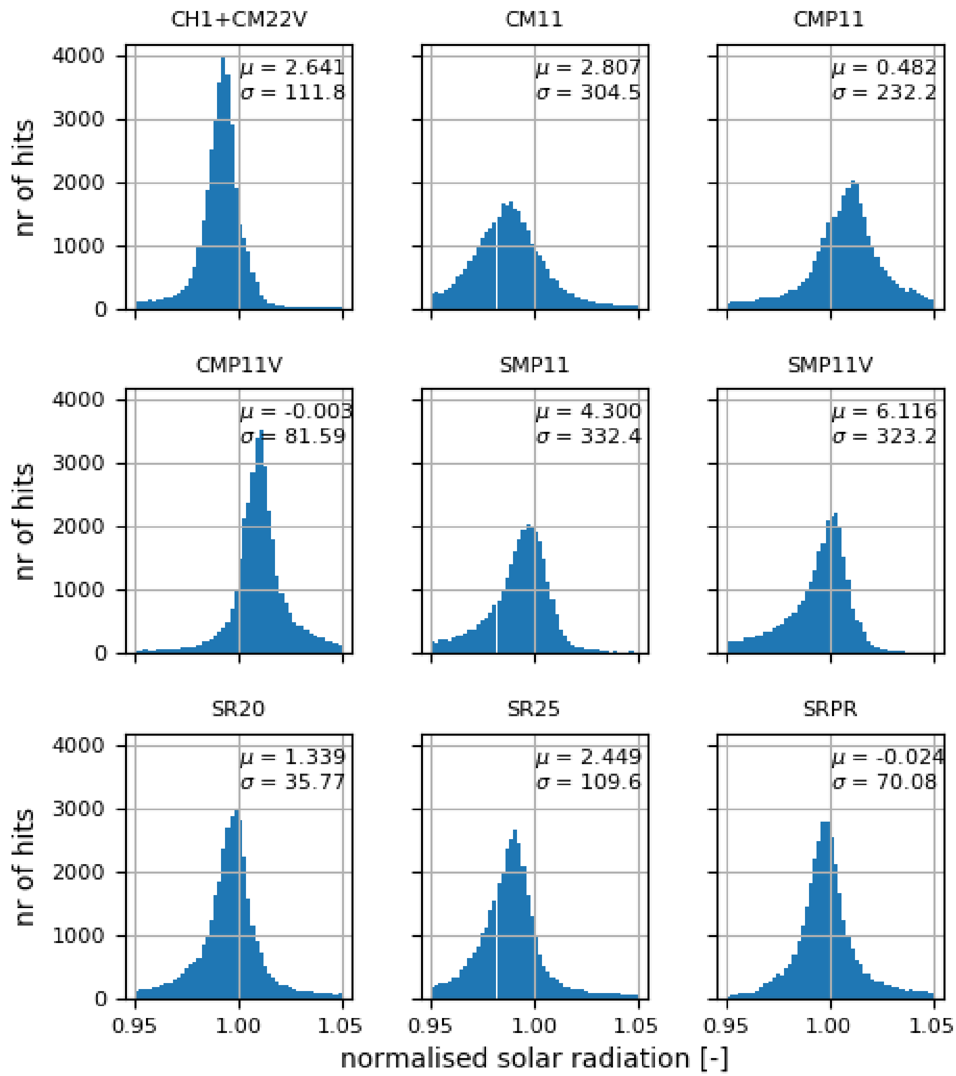

Figure 4.5: Histogram of relative radiation intensity compared to the measurement of the conditioned Kipp & Zonen CM-22. CH1+CM22V represents the sum of the BSRN measurements of direct and diffuse radiation. CM11 is a Kipp & Zonen CM-11 pyranometer as currently implemented in the KNMI network. The proposed pyranometer to be implemented in the KNMI network is the Kipp & Zonen SMP-11. The addition of the letter V indicates that the pyranometer is conditioned. The histogram is created using the entire dataset of 10-minute averages, which includes all solar zenith angles and global radiation values. The night values, that are included in this dataset, lead to a large number of outliers, and consequently inaccurate estimation of the mean value and standard deviation.

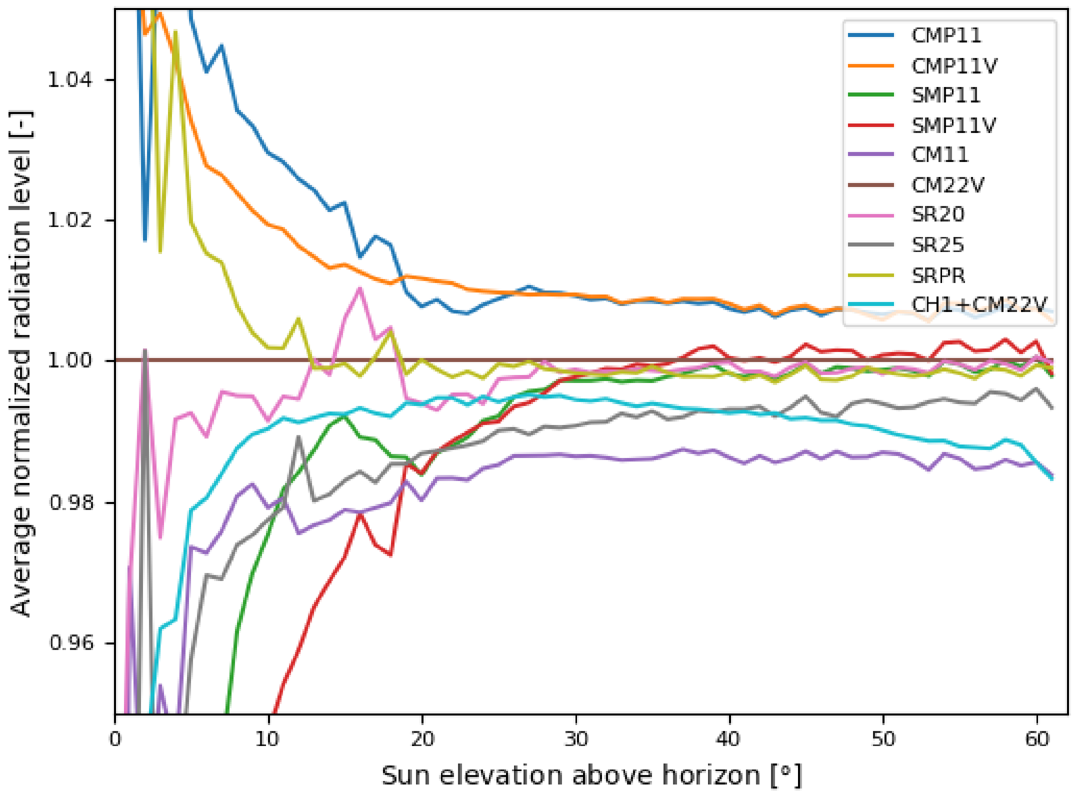

Figure 4.6: Normalized data vs. solar elevation angle using a 1-degree binsize.

than the reference. This difference stems from the calibration of the pyranometer that is used as a reference pyranometer in the KNMI laboratory, and is further explained in section 4.4. The Kipp & Zonen CM-11 also shows an optically broader Gaussian curve than the other instruments in the histogram, even though this is not always reflected in the standard deviation. The broader histogram can be explained by the lower response time of this instrument compared to the others. It can be noted that the conditioned instruments show a more narrow Gaussian curve and lower standard deviation than the unconditioned version of the instrument. Also the standard deviation of the conditioned instruments is significantly lower than the unconditioned version.

A regression analysis is performed as addition to comparison of the mean value of the normalized measurements. An orthogonal regression is selected as the most suitable method to analyse the data of each instruments with respect to the reference Kipp & Zonen CM-22V. Results are presented in table 4.4 and figure 4.8. The slope found in the regression analysis is comparable to the normalized values of global radiation,

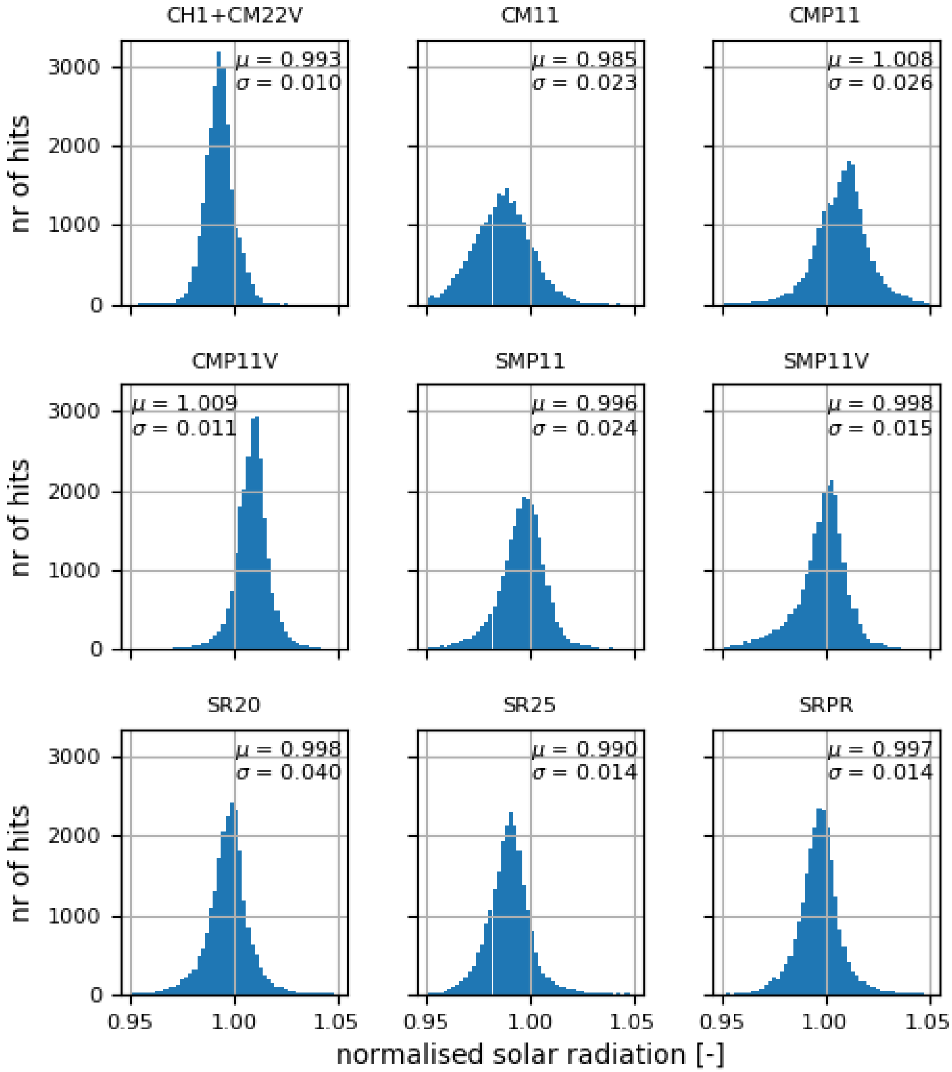

Figure 4.7: As figure 4.5, but using a subset of the dataset, containing only values of global radiation greater than 50 W/m^2 and solar zenith angles less than 75°.

instrument	normalized value [-]	deviation [%]
CMP11	1.008	0.82
CMP11V	1.009	0.89
SMP11	0.997	-0.35
SMP11V	0.998	-0.20
CM11	0.985	-1.47
CM22V	1.000	0.00
SR20	0.998	-0.17
SR25	0.990	-0.95
SRPR	0.997	-0.28
CH1+CM22V	0.993	-0.71

Table 4.3: Mean radiation level normalized by the mean radiation level of the CM-22V instrument and the difference to the reference Kipp & Zonen CM-22V.

instrument	Slope [-]	Deviation [%]	Intercept [W/m2]
CMP11	1.002	0.23	1.25
CMP11V	1.005	0.48	1.03
SMP11	1.001	0.09	-1.09
SMP11V	1.008	0.79	-2.16
CM11	0.987	-1.29	-0.63
CM22V	1.000	-0.00	0.00
SR20	0.995	-0.53	0.67
SR25	0.992	-0.76	-0.59
SRPR	0.993	-0.71	0.85
CH1+CM22V	0.994	-0.60	-0.35

Table 4.4: Results of the orthogonal regression of each instrument with respect to the reference Kipp & Zonen CM-22V.

presented in table 4.3. Also in the regression analysis, all pyranometers show mean global radiation levels that are within 1% of the conditioned BSRN Kipp & Zonen CM-22, except the currently operational Kipp & Zonen CM-11. Only the slope of the regression and the mean normalized value differs slightly for the Kipp & Zonen SMP-11 instruments. Morevover, also a relatively large negative intercept is found for these instruments, which is consistent with a relatively large negative offset, which is observed during the night. The cause is investigated and further explained in section 4.6.

4.4 Kipp & Zonen CM-11 Calibration

The average deviation of all instruments are all within 1% of the reference BSRN Kipp & Zonen CM-22 pyranometer, except the Kipp & Zonen CM-11 pyranometer. The estimated calibration uncertainty is 1% for all pyranometers, and the higher deviation of the Kipp & Zonen CM-11 pyranometer requires further investigation. The reason for this deviation is the applied sensitivity of the KNMI reference pyranometers of the Kipp & Zonen CM-11 type. The reference instruments themself are calibrated on a regular basis at the WRR at PMOD/WRC in Davos. All field pyranometers of the Kipp & Zonen CM-11 type are calibrated in the KNMI laboratory against one of these reference pyranometers, including the one used in this intercomparison. A previous investigation found a difference in sensitivity between the KNMI reference CM-11 and the WRR [9], see figure 4.9. This difference was partly attributed to the fact that the KNMI instrument had not been conditioned during calibrations against the WRR at PMOD/WRC in Davos. Conditioning the instrument during the calibrations against the WRR resulted in a deviation of the sensitivity within the uncertainty of the calibration, thus no conclusion of the offset could be drawn. Therefore, no correction on the sensitivity of the KNMI reference pyranometer was performed.

With the data from the current intercomparison, the conclusion on the calibrations described by Mathijssen et al. [9] needs to be re-evaluated. In 2002, the shaded reference pyranometer in the international standard at PMOD-WRC in Davos had been replaced. The unconditioned Eppley PSP was replaced by a conditioned Kipp & Zonen CM-22 for the measurement of diffuse radiation. The unconditioned Eppley PSP featured a higher zero offset A bias error. The sensitivities of calibrated instruments were overestimated by approximately 1% before the introduction of the conditioned Kipp & Zonen CM-22, as communicated by PMOD/WRC [14]. KNMI never corrected for this overestimation, due to uncertainty about the accuracy of the various calibration methods [15]. Instead it has kept the original calibration of its reference pyranometers.

The CM-11 is thus traceable to the WRR before 2002, including the 1% overestimation in sensitivity. All other instruments in the current pyranometer intercomparison are traceable to the current WRR without such bias error, because their reference pyranometer employs a sensitivity that was determined after introduction of the new shaded pyranometer at PMOD-WRC. In case the sensitivity of the CM-11 is corrected for this

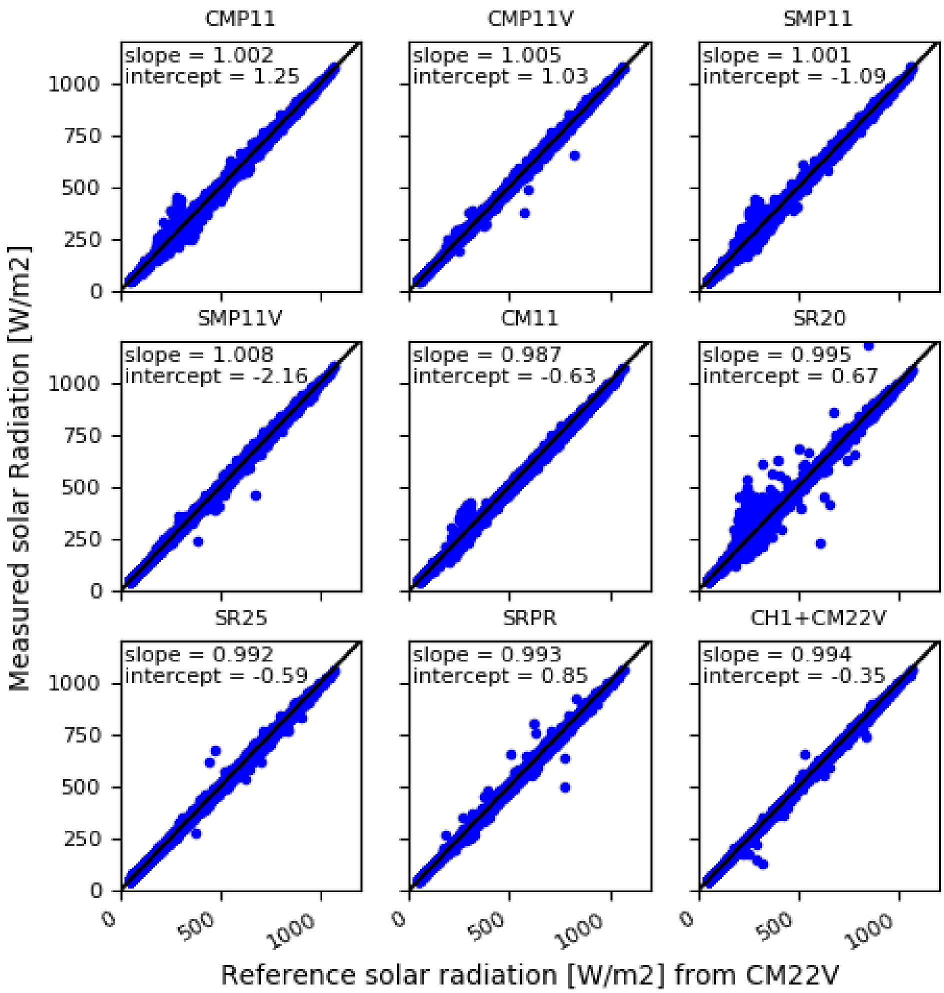

Figure 4.8: Visual results of the orthogonal regression of each instrument with respect to the reference Kipp & Zonen CM-22V.

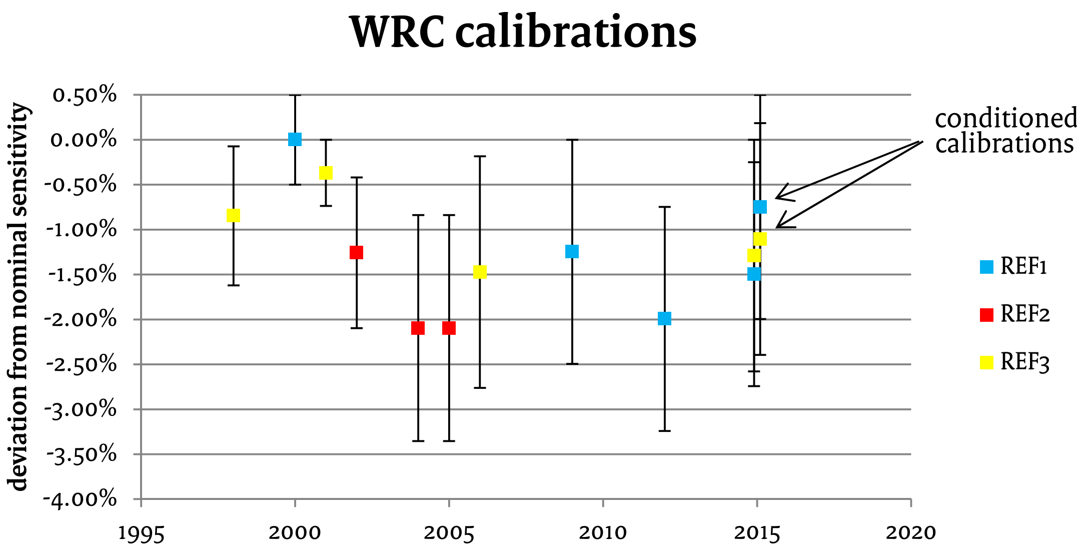

Figure 4.9: Differences in sensitivity of KNMI reference CM-11 pyranometers in calibrations at PMOD-WRC with respect to the initial sensitivity.

bias, the deviation would only be -0.47% with respect to the conditioned CM-22, and thus also falls within the 1% range of the estimated uncertainty from calibration.

The introduction of a new pyranometer type in the KNMI network requires a new reference pyranometer. The new reference pyranometer will be traceable to the current WRR, and thus not feature this 1% overestimation in sensitivity compared to the WRR. Note that an overestimation of sensitivity in pyranometers leads to an underestimation of measured global radiation. Measured global radiation levels are thus expected to increase by approximately 1% with the introduction of a new pyranometer type into the KNMI network.

4.5 Instrument leveling

From the nearly clear sky graph shown in figure 4.2, the global irradiance appears to be lower in the morning and higher in the afternoon for the Kipp & Zonen CM-11 compared to the other instruments. This is probably caused by inaccurate leveling of this instrument. In order to assess the impact on the statistics, a closer look is taken at the data of the Kipp & Zonen CM-11 on an overcast day, see figure 4.10. In overcast conditions, there is no significant difference between the morning and afternoon. It confirms that the effect is due to instrument leveling, since mainly direct radiation exhibits an angular dependency and to a lesser degree diffuse radiation, because diffuse

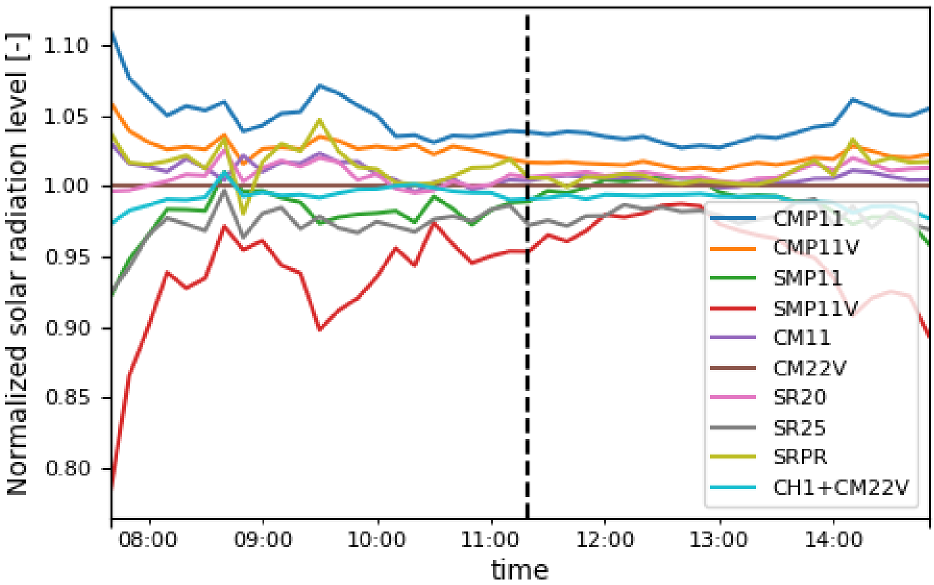

Figure 4.10: Solar irradiance normalized by the CM-22V instrument of 9th of November 2016. The dashed line indicates the maximum solar elevation that day. No significant difference between the morning and afternoon radiation is visible.

radiation comes from all directions.

In order to objectively evaluate the impact of the leveling of the instrument, the mean normalized radiation value for the complete period of the intercomparison is determined before solar noon, and after solar noon, see table 4.5, using the reduced dataset in which solar zenith angles above 75° and global radiation below 50 W/m^2 is filtered out. From this data is deduced that the difference between the measured normalized solar irradiance in the morning and in the afternoon for the Kipp & Zonen CM-11 is 0.86%. The underestimation of the solar irradiance in the morning is largely compensated by the overestimation of the solar irradiance in the afternoon. Therefore, the impact on the total amount of global irradiance from inaccurate leveling is much smaller than 0.86%. It can thus be concluded that the instrument leveling did not influence the conclusion of the calibration of the Kipp & Zonen CM-11, as given in section 4.4.

4.6 Nighttime offset

Typical for pyranometers is that the measured value during night times are slightly negative. This is the result of a zero offset type A, described in section 3.2.1. An example of a clear sky night is given in figure 4.11. The large negative nighttime values

instrument	before solar noon[-]	after solar noon[-]	difference [%]
CMP11	1.012	1.005	0.66
CMP11V	1.011	1.007	0.36
SMP11	0.998	0.995	0.34
SMP11V	0.998	0.998	0.03
CM11	0.981	0.990	-0.86
CM22V	1.000	1.000	0.00
SR20	1.000	0.997	0.30
SR25	0.991	0.990	0.12
SRPR	0.998	0.997	0.08
CH1+CM22V	0.995	0.991	0.39

Table 4.5: Mean radiation level normalized by the mean radiation level of the CM-22V instrument before the solar noon, and after the solar noon. The last column shows the difference between them in %.

are expected from the CM-11 instrument, because of its large zero offset A. Despite the same indicated zero offset A of the Kipp & Zonen CMP-11 pyranometers, these show smaller negative nighttime values than the Kipp & Zonen CM-11. The negative offset by the Kipp & Zonen SMP-11 instruments was expected to be similar to the Kipp & zonen CMP-11 pyranometer, because they employ the same type of detector, but is found to be larger. This is attributed to heat production in the A/D converter of the Kipp & Zonen SMP-11, which causes an additional offset of approximately 2 W/m^2, that can be compensated by the internal software. As a test, one instrument was modified by Kipp & Zonen to include such software compensation for this effect, and a short one-month measurement campaign is performed, in which an unconditioned SMP-11 with compensation is compared to an uncompensated unconditioned SMP-11, an unconditioned CMP-11, an unconditioned CM-11 and the BSRN conditioned CM-22V and CH1+CM22V take part. A clear night sky example of offsets is displayed in figure 4.12. Clearly visible is that the night time offset of the compensated instrument matches the night time offset of the CMP-11 instrument, and thus effectively compensates for the A/D converter heat production. Such compensation is necessary and will be applied to all Kipp & Zonen SMP-11 instruments that will be used in the KNMI network.

4.7 Dew & Rime conditions

An investigation into the response of the Kipp & Zonen CMP-11 and SMP-11 under dew or rime conditions is performed in order to check substantial differences with respect to the operational Kipp & Zonen CM-11 pyranometer. An example of a severe rime event, which happened before this intercomparison, is presented in figure 4.14. It is well-known that dew and rime can create large measurement errors. Global radiation

instrument	zero offset A (W/m^2 response to 200 W/m^2 thermal radiance)
CMP11	12
CMP11V	7
SMP11	12
SMP11V	7
CM11	12
CM22V	3
SR20	5
SR25	1
SRPR	2

Table 4.6: Zero offset A according to manufacturer's specification.

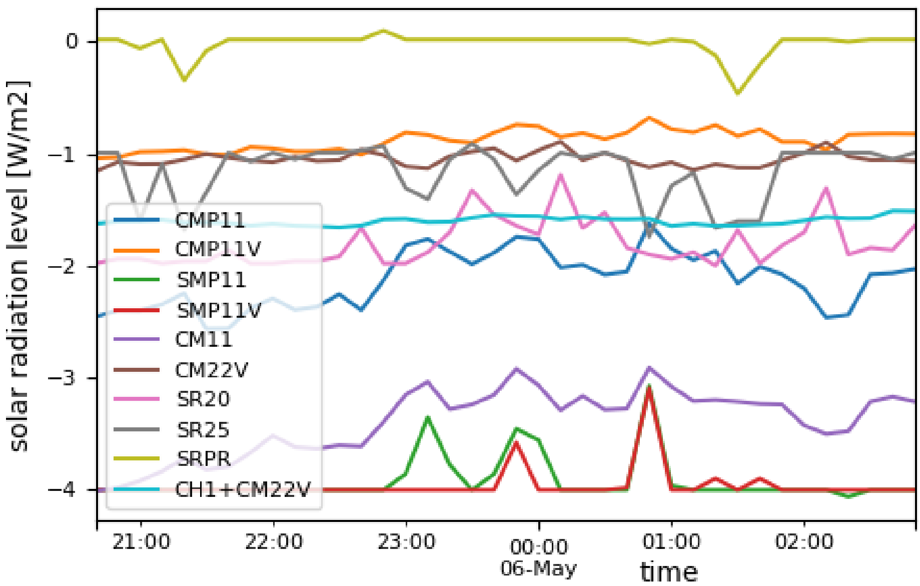

Figure 4.11: Radiation level during the clear night of the 5th and 6th of May 2016.

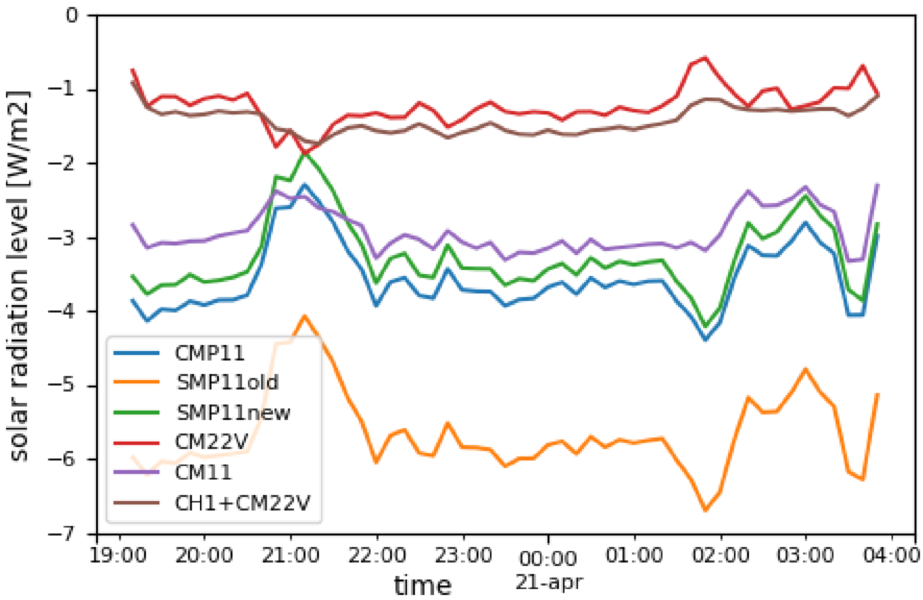

Figure 4.12: Radiation level during the clear night of the 20th and 21st of April 2019.

instrument	normalized value [-]	deviation [%]
CMP11	1.001	0.09
SMP11old	0.999	-0.12
SMP11new	1.005	0.54
CM22V	1.000	0.00
CM11	0.974	-2.58
CH1+CM22V	0.994	-0.63

Figure 4.13: Normalized radiation and the difference to the reference Kipp & Zonen CM-22V for the data subset of the 2019 campaign, which lasted one month.

measurements of a typical dew or rime event is displayed in figure 4.15, measured on the 4th of December 2016. The temperature was between −2°C and 4°C and relative humidity was measured to be close to saturation level in the morning, see figure 4.16. The unconditioned pyranometers show very large offsets, up to 130%, and these errors remain until 12am. 6The Kipp & Zonen CM-11 shows large errors for almost the entire day. The conditioned pyranometers show hardly any effect on rime. Only the conditioned Kipp & Zonen CMP-11V deviates significantly from the reference Kipp & Zonen CM-22V, up to 25%. This is a much smaller deviation than the unconditioned version, and the duration of the error is also much shorter.

Statistically the effect of dew and rime is noticed in the width of the histograms displayed in figure 4.7 and the corresponding standard deviation. The conditioned pyranometers feature a narrower histogram and a lower standard deviation. While the standard deviation of the Kipp & Zonen CMP-11, SMP-11 and CM-11 are 0.026, 0.024 and 0.023 respectively, the standard deviation of the conditioned Kipp & Zonen CMP-11V and SMP-11V is evaluated to be 0.011 and 0.015 respectively. This shows that the impact of dew and rime events on these three instruments are approximately similar. Conditioning of the instrument significantly reduces the impact of such events.

4.8 WMO criteria

It is checked whether the WMO criteria on hourly and daily sum, as described in the CIMO guide [1], are met. This is done by calculating the hourly and daily sums for all instruments, and comparing them to the conditoned Kipp & Zonen CM-22 reference pyranometer. Network operations such as the KNMI network, would be in the classification of "good quality networks", and achievable accuracy would be 8% for hourly totals and 5% for daily totals, with a 95% confidence interval. An issue in the evaluation is the negative nighttime values and the very low values at sunrise and sunset. The negative values can have a significant influence on hourly and daily sums, even though the global radiation during the night is known to be zero. Negative values are therefore set to 0 for the calculation of the daily sum. For calculation of the hourly sum, the nighttime values are irrelevant, and the low radiation values at sunrise and sunset lead to very large offsets in which it can not be expected that the WMO criteria are met. Therefore, the filtered dataset is used for calculation of the hourly sums, in which only hours are selected in which the SZA was below 75° and all 10-min average values of global radiation were above 50 W/m^2.

An overview of the normalized mean value, standard deviation, and accuracy at 95% confidence interval is presented in table 4.17 for the hourly sums, and in table 4.18 for the daily sums. In the table also the 95% confidence interval is presented, which is 2 times the standard deviation. These numbers for the hourly sums are very similar to the values calculated for the 10-minute interval in section 4.3, and, on the basis of the 95%

Figure 4.14: Heavy rime on a Kipp & Zonen CM-11. The photo was not taken during the intercomparison.

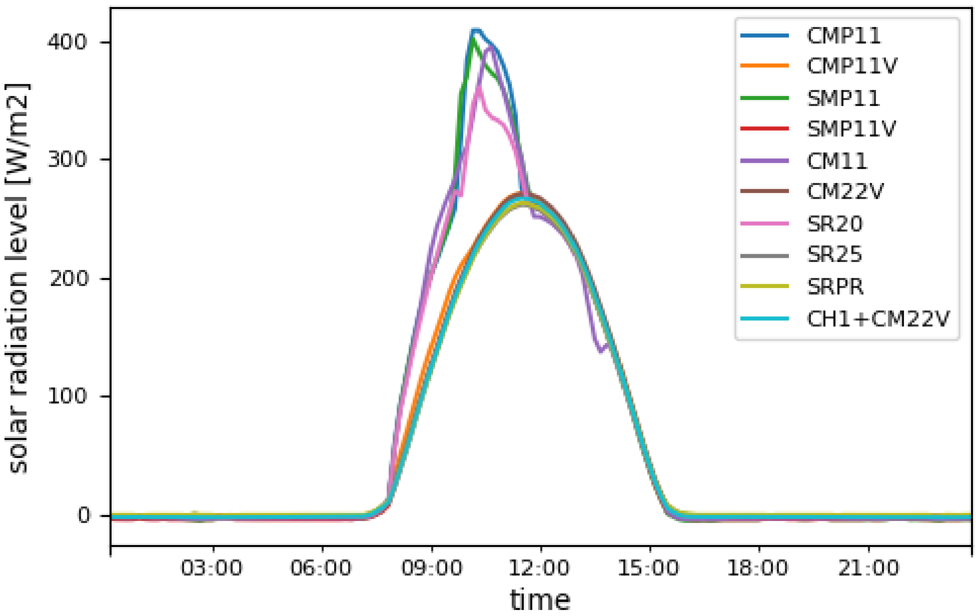

Figure 4.15: Radiation level on the 4th of December 2016.

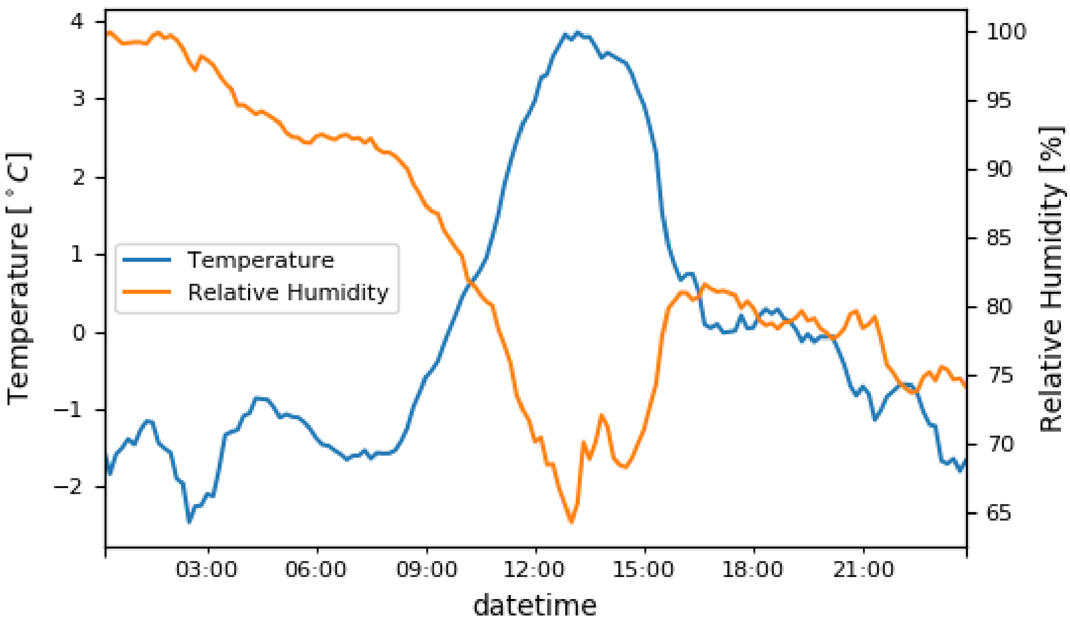

Figure 4.16: Temperature and relative humidity during the 4th of December 2016.

instrument	Mean value [-]	Standard deviation [-]	95% Confidence interval [%]
CMP11	1.008	0.026	5.20
CMP11V	1.009	0.011	2.23
SMP11	0.998	0.026	5.23
SMP11V	0.999	0.019	3.77
CM11	0.986	0.026	5.10
CM22V	1.000	0.000	0.00
SR20	0.998	0.038	7.53
SR25	0.989	0.015	3.00
SRPR	0.996	0.014	2.80
CH1+CM22V	0.994	0.012	2.33

Figure 4.17: Mean level of hourly radiation normalized by the mean daily radiation of the CM-22V instrument, the standard deviation and the 95% confidence interval.

confidence interval, all pyranometers appear to lie within the 8% WMO requirement. The daily sum includes also measurements at high SZA angles. Only the pyranometers that are conditioned are meeting the WMO norm for network operations of 5% accuracy on the 95% confidence interval. Days in which this requirement is exceeded are only found from November to March, see figure 4.20. Two causes are found for exceeding of the threshold. The occurrence of dew or rime results in strong deviations of unconditioned pyranometers. Such events are described in section 4.7, and an example of a day with rime is presented in figure 4.15.The other reason for not meeting the WMO requirements is the extremely low irradiance level on dark winter days without sunshine. For these days measurement errors become disproportionately important. An example of such a day is presented in figure 4.21. The maximum global radiation does not exceed 40 W/m^2 on that day. In order to meet the WMO requirement on such a day, the maximum measurement error should be below 2 W/m^2. This is unrealistic, in particular because of the directional response of pyranometers in combination with the high SZA under consideration. The Kipp & Zonen SMP-11 pyranometers, that were used in the intercomparison, suffer from an offset, caused by heating from the A/D converter. This offset is too high to meet the WMO requirement on such days, and leads to a relatively high standard deviation. Note that the SMP11 pyranometers that will be used in the KNMI network are compensated for this effect, see section 4.6.

It is interesting to know the achievable performance for the Kipp & Zonen SMP-11, in case compensation is applied for the offset from the A/D converter heat production. This is investigated by adding a constant offset to the measured data. Note that this is not a full correction of zero offset A, but just a numerical experiment to demonstrate the effect of an offset on the WMO norm of 5%. An optimum value for the offset is determined by evaluating the lowest standard deviation for a range of offsets. The same

instrument	Mean value [-]	Standard deviation [-]	95% Confidence interval [%]
CMP11	1.016	0.034	6.80
CMP11V	1.011	0.011	2.29
SMP11	0.995	0.031	6.26
SMP11V	0.989	0.023	4.66
CM11	0.987	0.028	5.63
CM22V	1.000	0.000	0.00
SR20	0.997	0.028	5.61
SR25	0.986	0.010	1.95
SRPR	0.997	0.010	1.92
CH1+CM22V	0.992	0.005	1.09

Figure 4.18: Mean level of daily radiation normalized by the mean daily radiation of the CM-22V instrument and the standard deviation.

procedure is applied to all pyranometers. The optimum offset is presented in table 4.19, together with the resulting mean value, standard deviation and 95% confidence interval uncertainty. Despite the significant reduction of the standard deviation of the conditioned Kipp & Zonen SMP-11, the WMO norm of 5% uncertainty is still not met for the Kipp & Zonen CMP-11, SMP-11, CM-11, and the Hukseflux SR-20. This numerical experiment indicates that removal of offsets is particularly important for low irradiance levels and that the only possibility to meet the WMO requirements year-round using the Kipp & Zonen SMP-11, is by conditioning the instrument.

4.9 Sunshine duration

Sunshine duration is defined as the duration at which the direct radiation exceeds 120 W/m^2 [1]. At the Royal Netherlands Meteorological Institute, it is estimated from global radiation measurements using a KNMI-specific algorithm [16]. Implementation a new instrument for the measurement of global radiation thus also impacts the estimated amount of sunshine duration.

In order to assess this impact, the data of the intercomparison is used to estimate the sunshine duration using the same algorithm. The BSRN site features a Kipp & Zonen CH-1 pyrheliometer, that measures direct radiation. The sunshine duration can readily be calculated from this instrument, and is used as a reference. For the estimation of sunshine duration from the pyranometers, the exact same procedure is applied as currently operational at KNMI. This means that a fraction of sunshine duration is calculated per 10-minute interval using the mean, minimum and maximum value and the SZA.

instrument	correction offset [W/m^2]	Mean value [-]	Standard deviation [-]	95% Confidence interval [%]
CMP11	-1.41	1.003	0.028	5.63
CMP11V	-0.57	1.006	0.009	1.82
SMP11	1.05	1.003	0.030	6.02
SMP11V	2.57	1.008	0.007	1.46
CM11	-0.66	0.982	0.027	5.46
CM22V	0.00	1.000	0.000	0.00
SR20	0.05	0.998	0.028	5.61
SR25	0.86	0.993	0.006	1.25
SRPR	-0.47	0.993	0.008	1.62
CH1+CM22V	0.23	0.993	0.005	1.02

Figure 4.19: Same as table 4.18, but with an offset applied to all instruments.

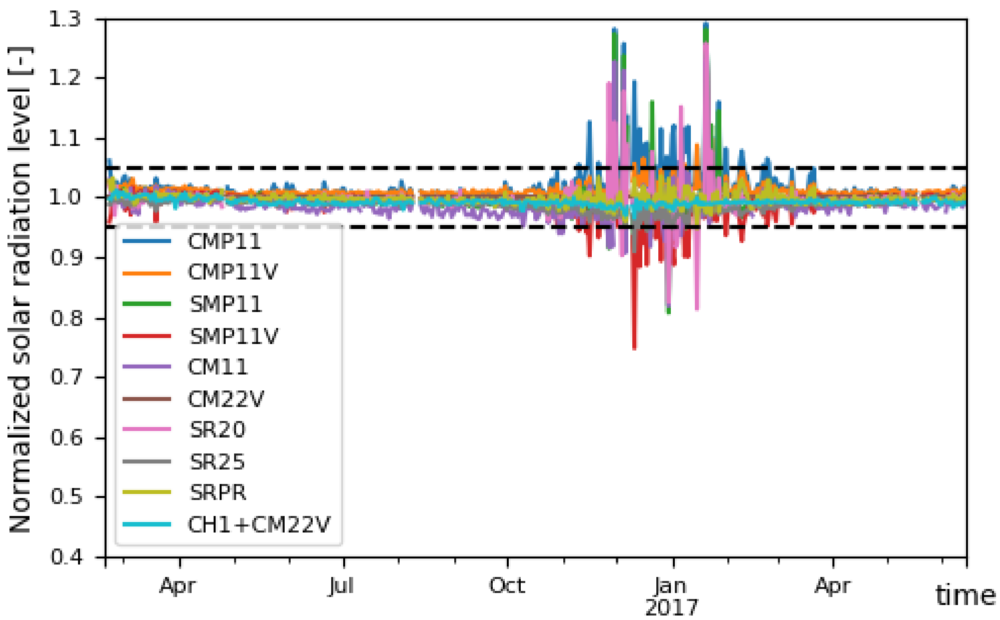

Figure 4.20: Normalized value of the daily global radiation sum throughout the year. The dashed lines indicate the WMO norm of 5% deviation from the reference Kipp & Zonen CM-22.

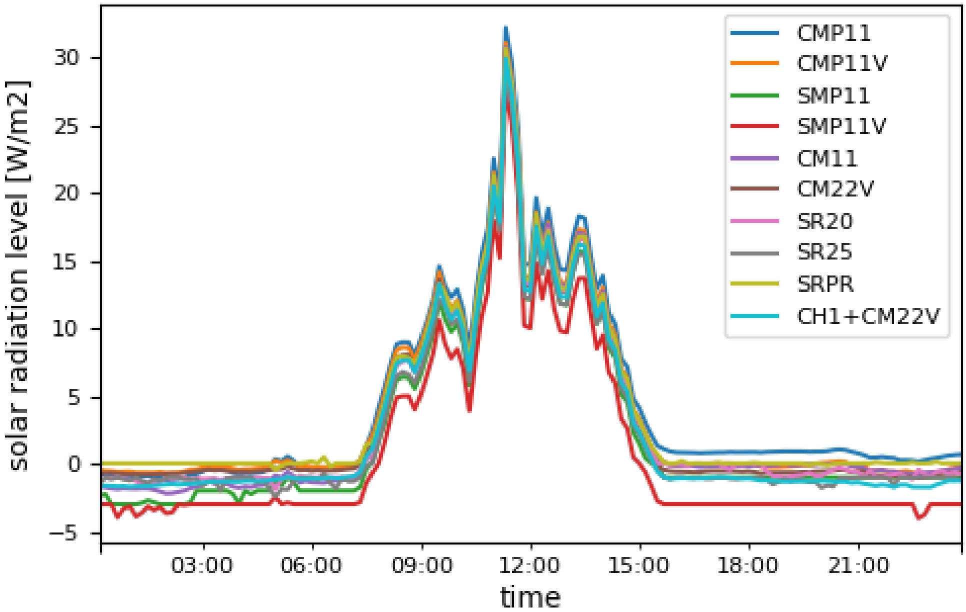

Figure 4.21: Solar radiation on the 10th of December 2016.

The results are presented together with the deviation with respect to the reference instrument in table 4.22. Intervals in which at least one of the instruments did not supply data were removed from the dataset, in order to compare the sum of sunshine duration. It is known that the algorithm produces a large bias error, as it is tuned to the sunshine duration reported by a Campbell Stokes instead of the 120 W/m^2 criterion for direct radiation. The overestimation was estimated to be 191 hours for the period of March 2005 to February 2006 [17]. In this intercomparison, which lasted approximately 1 year and 4 months, a bias error of approximately 250 hours can be expected. All the pyranometers show a bias of that order of magnitude. The variation in sunshine duration between the pyranometers types is maximum 90 hours, or 3.8%.

Not surprisingly, the deviation correlates with the total amount of measured global radiation, as displayed in table 4.3. The variation of sunshine duration among pyranometers is partly explained by the variation in global radiation. To assess the impact independent of variation of global radiation, an artificial dataset is created by multiplying the measured global radiation with the same factor as displayed in table 4.3. Also the minimum and maximum value are then multiplied with the same factor. From this dataset, the sunshine duration is then calculated again using the same algorithm. The results are shown in table 4.23. The variation among pyranometers is reduced to 42 hours, or 1.8%. Moreover, the value of the proposed Kipp & Zonen SMP-11 only differs 6.5 hours to the current operational Kipp & Zonen CM-11.

instrument	sunshine duration [hr]	sunshine deviation [hr]	deviation [%]
CMP11	2658	259.4	10.82
CMP11V	2661	263.0	10.96
SMP11	2609	210.8	8.79
SMP11V	2619	220.9	9.21
CM11	2571	172.4	7.19
CM22V	2643	244.9	10.21
SR20	2597	198.5	8.28
SR25	2604	206.0	8.59
SRPR	2629	230.5	9.61
CH1	2398	0.0	0.00

Figure 4.22: Total sunshine duration per pyranometer, the deviation with respect to the measurement by the Kipp & Zonen CH1 pyrheliometer, and the relative deviation.

The relative correction for the global radiation is compared to the relative variation of sunshine duration for the original data and the data that is corrected for the calibration factor. The results are shown in table 4.24. The sunshine duration is approximately proportional to the variation in global radiation. Therefore, it is expected that the introduction of the Kipp & Zonen SMP-11 will result in an increase in sunshine duration of approximately 1%.

instrument	sunshine duration [hr]	sunshine deviation [hr]	deviation [%]
CMP11	2637	238.8	9.96
CMP11V	2644	245.6	10.24
SMP11	2617	218.9	9.13
SMP11V	2624	225.2	9.39
CM11	2611	212.4	8.86
CM22V	2643	244.9	10.21
SR20	2602	203.3	8.48
SR25	2628	229.6	9.57
SRPR	2635	237.0	9.88
CH1	2398	0.0	0.00

Figure 4.23: Total sunshine duration per pyranometer, the deviation with respect to the measurement by the Kipp & Zonen CH1 pyrheliometer, and the relative deviation, for the artificial case for which the global radiation is corrected for its calibration factor.

instrument	correction global radiation [%]	variation sunshine duration [%]	difference [%]
CMP11	0.82	0.78	0.04
CMP11V	0.89	0.66	0.23
SMP11	-0.35	-0.31	-0.04
SMP11V	-0.20	-0.16	-0.04
CM11	-1.47	-1.53	0.06
CM22V	0.00	0.00	0.00
SR20	-0.17	-0.18	0.01
SR25	-0.95	-0.90	-0.05
SRPR	-0.28	-0.24	-0.04

Figure 4.24: Correction on global radiation compared to the resulting variation on the calculated sunshine duration.

Chapter 5

Conclusion

An pyranometer intercomparison is performed with the aim of identifying the impact of the replacement of the Kipp & Zonen CM-11 pyranometer by a Kipp & Zonen SMP-11. The campaign is executed at the Cabauw BSRN site, where quality controlled, high-end instruments are available as reference for the measurement of global radiation. Also other instruments from other manufacturers are placed to be able to compare the instruments with other instruments in the market.

Calibration of pyranometers at the KNMI calibration lab is estimated to cause an uncertainty of 1% in the measurements. All instruments measure within this 1% interval of the reference instrument, except the Kipp & Zonen CM-11 pyranometer, which measured on average 1.5% less solar radiation. This type of instrument is currently used operationally in the KNMI measurement network.

The reason for the deviation of the Kipp & Zonen CM-11 instrument can be attributed to the calibration of the reference pyranometer, which in turn is calibrated against the world radiometric reference at PMOD/WRC. PMOD/WRC introduced a new shaded pyranometer into their calibration setup in 2002, and communicated that the sensitivity of instruments calibrated before had been overestimated previously by approximately 1%. Note that an overestimation of sensitivity in pyranometers leads to an underestimation of measured solar radiation. This effect is seen in the regular calibrations of the KNMI reference instruments at PMOD/WRC, but the corrections for this effect were never implemented. A previous study did not show sufficient evidence to apply this correction [9], but data from the current pyranometer intercomparison confirms the sensitivity of the Kipp & Zonen CM-11 that KNMI uses as reference pyranometer in the calibration laboratory is overestimated. Correction for this overestimation in the presented intercomparison, would lead to global radiation values of the Kipp & Zonen CM-11 within the 1% calibration uncertainty interval.

With the introduction of a new type of pyranometer in the measurement network, a new reference pyranometer will be used. While the Kipp & Zonen CM-11 reference pyranometer still includes a 1% offset in sensitivity, a new type of reference pyranometer will not include this offset. Hence, an increase of approximately 1% ± 1% in solar radiation is expected by the introduction of a new instrument.

A small but noticable bias error of a constant 2 W/m^2 is found in the digital pyranometers of Kipp & Zonen This was found to be due to the A/D conversion, causing a small thermal effect on the instrument. In modern versions of this pyranometer, this effect is compensated. A short 1-month test, that included an older version and a modern version of the Kipp & Zonen SMP-11 and the analog version of the pyranometer CMP-11 confirmed that the bias is succesfully removed in the modern version, without impact on the accuracy of the instrument. The pyranometers that are to be introduced in the KNMI network include the compensation for the heat production of the A/D converter.

The adherence to the WMO requirements on global radiation is investigated. The accuracy requirement for network pyranometers of 5% on daily total global radiation is not met by the current Kipp & Zonen CM-11, nor by the proposed Kipp & Zonen SMP-11, when unconditioned. On the basis of the 95% confidence interval, the accuracy on the daily sums has been determined to be 5.6% and 6.3% for the Kipp & Zonen CM-11 and SMP-11 respectively. Exceeding of the WMO requirements occurred only in the period from late October to February. During this time, the global radiation is very low, leading to larger relative errors, while the high SZA leads to large directional errors due to dome effects. Furthermore dew and rime events lead to large errors in unconditioned pyranometers, causing exceeding of the WMO requirements. The WMO requirements can only be met year-round for the Kipp & Zonen SMP-11 in case the instrument is conditioned.

KNMI estimates sunshine duration from global radiation measurements using a KNMI-developed algorithm. The impact of the introduction of a new pyranometer on the estimation of sunshine duration is studied. The sunshine duration estimated from global radiation all feature a large bias error, compliant with the known bias error of the algorithm of approximately 191 hours evaluated in the period of March 2005 to February 2006. Variation among pyranometers were 90 hours, or 3.8%. The sunshine duration is correlated with the measured value of global radiation. Therefore part of the variation between pyranometers can be attributed to calibration of the reference instrument. After correcting for the measured mean global radiation level, the variation between pyranometers reduces to maximum 1.8%. The difference between the Kipp & Zonen CM-11 and Kipp & Zonen SMP-11 is only 0.3%. The change in estimated sunshine duration is proportional to the difference in measured global radiation. Therefore, the introduction of the Kipp & Zonen SMP-11 is expected to increase estimated annual sunshine duration by 1% ± 1%.

This concludes that the Kipp & Zonen SMP-11 pyranometer is a suitable candidate to replace the Kipp & Zonen CM-11 in the KNMI measurement network. Conditioning of the instrument will result in a significant improvement in data quality, particularly in wintertime. With the introduction of the new pyranometers, it is expected that measured global radiation and estimated sunshine duration is increased by approximately 1% $\pm$ 1%.

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