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Contents

Samenvatting

De onnauwkeurigheden in pyranometer (Kipp & Zonen CM11) en pyrheliometer (Kipp & Zonen CH1) metingen van globale (GLOB), directe (DIF) en diffuse (DIF) irradiantie op het KNMI in De Bilt zijn onderzocht. De onnauwkeurigheden in GLOB (19 Wm^{-2}), DIR (10 Wm^{-2}) en DIF (7 Wm^{-2}) zijn vergelijkbaar met de onnauwkeurigheden van het Baseline Surface Radiation Network (BSRN) in 1990. In het ideale geval is GLOB gelijk aan de som van DIR en DIF. Deze gelijkheid is als uitgangspunt genomen voor de analyse van instrumentele en operationele onnauwkeurigheden. Rekening houdend met de instrumentele eigenschappen schatten we de nauwkeurigheid van de term GLOB – (DIR + DIF) op -2 ± 20 Wm^{-2}. Uit een meetperiode van drie jaar selecteerden we 22 wolkenloze dagen en vonden we GLOB – (DIR + DIF) = 12 ± 7 Wm^{-2} (metingen op het middaguur). De verdeling van de operationele metingen ligt dus binnen het verwachte instrumentele bereik. Desondanks laten we zien dat verscheidene verbeteringen van de stralingsopstelling van het KNMI mogelijk zijn. Een correctie voor de *zero-offset I* (veroorzaakt door langgolvige afkoeling van de pyranometers), die 10 Wm^{-2} kan bedragen, is zowel effectief als eenvoudig uit te voeren. Voor deze correctie is het essentieel dat het nachtelijke signaal van de pyranometers opgeslagen wordt. Met betrekking tot het meten van de globale straling benadrukken we dat nauwkeurige metingen van deze grootheid gedaan dienen te worden met een pyrheliometer (voor het meten van de directe component) en een geschaduwde pyranometer (voor het meten van de diffuse component). Het optellen van beide componenten leidt tot een nauwkeuriger resultaat dan een afzonderlijke meting met een ongeschaduwde pyranometer. De *component summation technique* verhoogt de nauwkeurigheid van metingen van globale straling met gemiddeld 7 Wm^{-2}.

Abstract

The uncertainties of pyranometer (Kipp & Zonen CM11) and pyrheliometer (Kipp & Zonen CH1) measurements of global (GLOB), direct (DIR), and diffuse (DIF) irradiance at KNMI in De Bilt are investigated. The uncertainties in GLOB (19 Wm^{-2}), DIR (10 Wm^{-2}), and DIF (7 Wm^{-2}) are comparable to the uncertainties of the Baseline Surface Radiation Network (BSRN) in 1990. Ideally, GLOB equals DIR + DIF, which is used as starting point for the analysis of instrumental and operational accuracies. Taking into account the instrument characteristics, the required accuracy of the term GLOB - (DIR + DIF) is estimated to be -2 ± 20 Wm^{-2}. For a three year period, 22 clear-sky days were selected, and it is found that GLOB - (DIR + DIF) = 12 ± 7 Wm^{-2} (noon measurements). So the distribution of operational measurements is within the expected instrumental range. Nevertheless, it is shown that several improvements of the KNMI radiation set-up are possible. The correction for the so-called zero-offset I (caused by long-wave cooling of the pyranometers), which can amount to 10 Wm^{-2}, is both effectively and simple to accomplish. For this correction it is essential that the night-time signal of the pyranometers is stored. With respect to the measurement of global radiation it is emphasized that accurate measurements of this quantity should be made with a pyrheliometer (measuring the direct component) and a shaded pyranometer (measuring the diffuse component), instead of with an unshaded pyranometer only. This so-called component summation technique increases the accuracy of global irradiance measurements by 7 Wm^{-2} on average.

1. Introduction

The central aim of CLOSAER, a scientific project between KNMI, ECN, and RIVM, is to study the effect of aerosols on shortwave radiation. To pursue this goal, a detailed comparison is made between model calculations and measurements of clear-sky direct and diffuse solar irradiance. Recently, Kato et al. (1997) and Halthore et al. (1998) reported that radiative transfer models consistently overestimate surface diffuse downward irradiances in cloud free atmospheres by 6 to 28 Wm^{-2}. Consequently, uncertainties of irradiance measurements should be less than 5 to 10 Wm^{-2} in order to successfully perform the CLOSAER study. Since the pyrheliometers and pyranometers at KNMI are so-called “first class” and “secondary standard” instruments, respectively (WMO, 1983), solar irradiance measurements made at KNMI should in principle be suitable for CLOSAER.

At KNMI in De Bilt, direct (DIR), diffuse (DIF), and global (GLOB) irradiances are measured on a routine basis with a Kipp & Zonen CH1 pyrheliometer, a shaded Kipp & Zonen CM11 pyranometer, and an unshaded Kipp & Zonen CM11 pyranometer, respectively. These instruments constitute the operational radiation set-up in De Bilt. In this report we give a complete overview of the most common and dominant uncertainties in pyranometer and pyrheliometer measurements. We distinguish between *instrumental* and *operational* measurement uncertainty. The instrumental uncertainty is the result of a combination of isolated error sources, which are reported by the instrument manufacturer, in calibration reports, and in literature. Examples of such error sources are calibration uncertainty and non-linear instrument response. The operational uncertainty, which refers to the overall uncertainty when the instruments are placed in the field, does not simply follow from the instrumental error sources because the precise measurement conditions are often unknown. Moreover, the operational uncertainty is determined by additional factors, which are related to the instrumental set up (levelling, dirtiness of instruments, etc). In this report we investigate the performance of the KNMI radiation set-up. To do this, we compare instrumental (i.e. expected) and operational (i.e. measured) values of the quantity GLOB - (DIR + DIF). Furthermore, we discuss the most important instrument maintenance factors and we suggest how to improve the KNMI radiation measurements.

2. Instrumental uncertainty

It is convenient to make a distinction between the words *accurate* and *precise* in the context of errors. A result is said to be accurate if it is relatively free of systematic error, and precise if the random error is small. Instrumental random errors may be detected by repeating the measurements under equal conditions. Furthermore, by taking more and more readings we obtain from the arithmetic mean a value, which approaches more and more the true value (Squires, 1991).

It is practically impossible to repeat outdoor irradiance measurements due to rapid fluctuations in the incoming radiation. However, repetitive measurements have been made indoors during the so-called "reproducibility test" of the calibration procedure. This test reveals that instrumental random variations are within 0.25%. This is equal to the noise of the used lamp. We may therefore conclude that pyranometer and pyrheliometer measurements are precise.

2.1 Pyranometer (shaded)

In terms of the ISO 9060 standard, which has been accepted by WMO, the Kipp & Zonen CM11 is a "secondary standard" pyranometer. We assumed a diffuse irradiance level of 400 Wm^{-2} to translate relative errors, reported in the Kipp & Zonen pyranometer manual (K&Z, 1996b), into absolute errors. In Table 1 shaded pyranometer measurement uncertainties are listed per source of error, and details are given in the following.

Zero offset

A radiation instrument reads a zero offset if it gives a signal that is not caused by absorption of solar radiation at wavelengths in the spectral range of the instrument. Pyranometer zero offset is the result of lack of thermal equilibrium in the instrument. Two types of offset are distinguished: zero offset I and zero offset II.

Zero offset I

Zero offset I is caused by the low effective clear-sky temperature. Net upward longwave radiation cools the glass domes of a pyranometer below air temperature. The domes in turn attract heat from the sensor by net infrared radiation. Since the housing remains close to air temperature, a heat flow opposite to the heat flow from absorbed solar radiation must be present from the housing to the sensor. The heat flow causes the well-known negative pyranometer readings at night.

Wardle et al. (1996) applied statistical analysis to 20 months of night-time zero offset data, obtained from unventilated Kipp & Zonen CM10[1] measurements. Prior to the analysis, data points were rejected that possibly suffered from other inaccuracies. Unfortunately one of the rejection criteria was: reject all readings deviating more than 3 Wm^{-2} from the mean. This criterion probably rejected all clear-sky nights.

Bush et al. (2000) showed that measured offset values depend completely on the difference in the fourth power of the temperatures of pyranometer outer dome and sensor, which is not surprising when considering the blackbody power law, $\sigma_B T^4$, where σ_B is the Stefan-Bolzmann constant. Temperatures are normally higher during daytime than at night. The longwave effect is therefore stronger during the day than at night. Wardle et al. (1996) indeed concluded that both the mean daytime offset I and the variability of offset I, are about 30% greater than night-time values.

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[1] Although CM10 is the forerunner of CM11, all aspects influencing zero offset I are equal according to Los (Product Manager Atmospheric Science, Kipp & Zonen)

In Table 1 estimates for mean and standard deviation of daytime zero offset I, corrected with the 30% estimate, are given. The estimates for cloudy skies are from Wardle et al. (1996), clear sky estimates are based on personal communication with Van Wely (K&Z).

Table 1 Pyranometer (shaded) measurement uncertainties. Level of irradiance 400 Wm^{-2}. The mean represents the mean error incurred if the source of error, mentioned in column 1, is ignored. The standard deviation, σ, represents the 67% level of confidence, if the mean is used for correction.

Source of error	Uncertainty Mean ± σ	Reference
Zero offset I (cloudy)	-3.3 ± 1.3 Wm^{-2}	Wardle et al., 1996
Zero offset I (clear-sky)	-9 ± 3 Wm^{-2}	Van Wely, 2000
Zero offset II (5 K/hr)	± 2.2 Wm^{-2}	Wardle et al., 1996
Non linearity (0.5%)	± 2 Wm^{-2}	K&Z, 1992b
Temperature sensitivity (1%)	± 4 Wm^{-2}	K&Z, 1992b
Non stability (0.5%)	± 2 Wm^{-2}	K&Z, 1992b
Instrument calibration (1%)	± 4 Wm^{-2}	KNMI calibration lab.
Total Uncertainty (cloudy)	**-3 ± 7 Wm^{-2}**	
Total Uncertainty (clear-sky)	**-9 ± 7 Wm^{-2}**	

Zero offset II.

The heat capacity of a pyranometer sensor is greater than the heat capacity of a pyranometer dome. A pyranometer sensor, therefore, responds much slower to ambient temperature changes than a pyranometer dome. During atmospheric temperature changes a gradient across the detector is therefore present. The detected gradient caused by a 5 Kelvin per hour change in ambient temperature is stated under "zero offset II" in Table 1. This value is estimated from various laboratory experiments and the statistical analysis of several outdoor experiments (see Wardle et al. (1996), chapter 6; Bush et al. (2000)).

Non linearity

Ideally, the output signal of the pyranometer is doubled when the level of irradiance is doubled. In practice the output signal is not exactly linearly proportional to the level of irradiance. The maximum deviation, for uncorrected diffuse irradiance measurements, based on the relative sensitivity variation with irradiance given in the pyranometer manual (K&Z, 1992b), is given in Table 1.

Temperature sensitivity

Ideally, the output signal of the pyrheliometer is always the same for a fixed level of irradiance. In practice the output signal is sensitive to temperature, as the thermocouple material is temperature-dependent. CM11 pyranometers incorporate internal temperature compensation, which is accomplished by adding a temperature-dependent attenuator circuit between the thermopile output and the pyranometer output connections. The compensation is, however, not perfect and varies from instrument to instrument. At KNMI temperature characteristics of individual pyranometers are not known and further correction is therefore not possible. The maximum deviation, relative to the +20°C output signal, over the range [-10°C, +40°C] (K&Z, 1992b) is given under temperature sensitivity in Table 1.

The uncertainties due to spectral selectivity are believed to be negligible compared to other uncertainties (K&Z, 1992b). The individual uncertainty estimates in Table 1 are valid throughout the calibration period and over the mentioned temperature range. Since the uncertainties mentioned above depend on the precise conditions during a measurement, it is difficult to estimate the overall instrument accuracy. We believe that the best estimate of the standard deviation of shaded pyranometer measurements is the rms of the individual standard deviations. For shaded pyranometer measurements we find as total uncertainty: -3 ± 7 Wm^{-2} for cloudy situations and -9 ± 7 Wm^{-2} for clear-sky situations.

2.2 Pyranometer (unshaded)

Unshaded pyranometers partly have the same errors as the shaded pyranometers. We assumed an irradiance level of 1000 Wm^{-2} to translate relative errors into absolute errors. In Table 2, shaded pyranometer measurement uncertainties are listed per source of error.

Directional response

Unlike the shaded pyranometer measurements an unshaded pyranometer measurement is sensitive to the directional response, which is an individual feature of a pyranometer depending on imperfections of the glass domes and angular reflection properties of the black paint. On average the combined error of the cosine and azimuth reponse deviates 1% from the ideal and is proportional to the cosine of the solar zenith angle (K&Z, 1992b).

For unshaded pyranometer measurements we find for the total uncertainty: -3 ± 19 Wm^{-2} for cloudy situations and -9 ± 19 Wm^{-2} for clear-sky situations.

Table 2 Pyranometer (unshaded) measurement uncertainties. Level of irradiance 1000 Wm^{-2}. The mean represents the mean error incurred if the source of error, mentioned in column 1, is ignored. Standard deviation, σ, represents the 67% level of confidence, if the mean is used for correction.

Source of error	Uncertainty Mean $\pm\sigma$	Reference
Zero offset I (cloudy)	-3.3 ± 1.3 Wm^{-2}	Wardle et al., 1996
Zero offset I (clear-sky)	-9 ± 3 Wm^{-2}	Van Wely, 2000
Zero offset II (5 K/hr)	± 2.2 Wm^{-2}	Wardle et al., 1996
Non linearity (0.5%)	± 5 Wm^{-2}	K&Z, 1992b
Temperature sensitivity (1%)	± 10 Wm^{-2}	K&Z, 1992b
Non stability (0.5%)	± 5 Wm^{-2}	K&Z, 1992b
Directional response	± 10 Wm^{-2}	K&Z, 1992b
Instrument calibration (1%)	± 10 Wm^{-2}	KNMI calibration
Total Uncertainty (cloudy)	**-3 ± 19 Wm^{-2}**	
Total Uncertainty (clear-sky)	**-9 ± 19 Wm^{-2}**	

2.3 Pyrheliometer

In terms of the ISO 9060 standard, which has been accepted by WMO (1983), the CH1 is a "first class" pyrheliometer. We assumed a direct irradiance level of 800 Wm^{-2} to calculate absolute errors from relative errors. In Table 3 the pyrheliometer measurement uncertainties are listed per source of error.

Zero offset

The principle of zero offset I is equal for pyrheliometers and pyranometers. The pyrheliometer glass window cools below air temperature. However, for a pyrheliometer the net longwave cooling of the sensor is hampered, as the opening angle from the sensor to the glass window is much smaller. The effective longwave emission is therefore much smaller, so zero offset I is negligible for pyrheliometers. Zero offset II for a pyrheliometer is similar to that of a pyranometer.

Table 3 CH1 Pyrheliometer measurement uncertainties. Level of irradiance 800 Wm^{-2}. The mean represents the mean error incurred if the source of error, mentioned in column 1, is ignored. Standard deviation, σ, represents the 67% level of confidence, if the mean is used for correction.

Source of error	Uncertainty Mean ± σ	Reference
Zero offset II	± 3 Wm^{-2}	K&Z, 1992a
Non linearity (0.2%)	± 2 Wm^{-2}	K&Z, 1992a
Temperature sensitivity (1%)	± 8 Wm^{-2}	K&Z, 1992a
Instrument calibration (0.5%)	± 4 Wm^{-2}	KNMI calibration
Suntracker alignment	- 2 ± 2 Wm^{-2}	Fröhlich and Quenzel, 1974
Total Uncertainty	**- 2 ± 10 Wm^{-2}**	

Alignment

Suntracker alignment should be within 0.75° of the solar direction in order to have the sun entirely within the slope angle of the pyrheliometer (K&Z, 1992a). Aureole intensity is strongest in the direction of the sun and can be quite substantial as shown by Fröhlich and Quenzel (1974). However, not the intensity itself but the intensity distribution as a function of viewing angle close to the sun is of importance. Especially in high optical depth situations, changes in pointing accuracy affect the uncertainty in the direct solar + aureole signal centred on the sun. From the work of Fröhlich and Quenzel (1974), an evaluated estimate is made for the maximum irradiance measurement error due to the suntracker alignment error. The estimate, -2 ± 2 Wm^{-2}, is based on highly turbid atmospheres (Stammes and Henzing, 2000).

Temperature sensitivity and non-linearity are similar for pyrheliometers and pyranometers. The temperature sensitivity is now valid over the temperature range [-20°C, +50°C].

Uncertainties due to non-stability and degradation of the pyrheliometer window are believed to be negligible compared to other uncertainties, provided that the pyrheliometer is regularly calibrated.

2.4 Summary and conclusions

Table 4 summarizes the KNMI instrumental uncertainties described above. For comparison, the Baseline Surface Radiation Network (BSRN) instrumental uncertainties valid for 1990 and 1995 (Ohmura et. al., 1998) are also listed in Table 4. The BSRN uncertainties are based on uncertainty estimates for the best-known practices in calibration and quality control at BSRN sites, and corrected for known systematic errors (non-linearity and temperature response). From Table 4 it is concluded that the KNMI instrumental uncertainties are in broad agreement with the BSRN values as reported in 1990. The table also shows that the current set of KNMI instruments is not accurate enough to obtain the accuracies achieved by BSRN in 1995.

Table 4 Instrumental uncertainties. Standard deviation, σ, represents the 67% level of confidence, if the mean is used for correction.

Irradiance	Instrumental uncertainty Mean ± σ (Wm^{-2})		BSRN uncertainty (Wm^{-2}) 1990	1995
Global (1000 Wm^{-2})	-3 ± 19 -9 ± 19	(cloudy) (clear)	± 15	± 5
Direct (800 Wm^{-2})	-2 ± 10		± 3	± 2
Diffuse (400 Wm^{-2})	-3 ± 7 -9 ± 7	(cloudy) (clear)	± 10	± 5

The uncertainty in direct irradiance measurements is largely determined by the temperature sensitivity of the pyrheliometer, which could be obtained in a laboratory. A complete correction for temperature sensitivity would decrease the standard deviation in direct irradiance measured at KNMI by more than 4 Wm^{-2}.

In this chapter the zero offset values do not give information on errors for partly cloudy situations. It is therefore impossible to use the values in Table 4 to correct arbitrary pyranometer measurements.

Flowers and Maxwell (1985), Ohmura et al. (1998), Wardle et al. (1996) and Michalsky et al. (1999) state that accurate global irradiances should be measured with two instruments, one measuring direct irradiance (cavityradiometer or pyrheliometer) and one measuring diffuse irradiance (shaded pyranometer), instead of one instrument measuring both (unshaded pyranometer). Measuring global irradiance in this way is called the *component summation technique*. The argument for using this technique is that the directional response of unshaded pyranometers is very poor. Indeed, if we compare the combined uncertainty estimate of the independent shaded pyranometer and pyrheliometer measurements (rms: 12 Wm^{-2}) with the unshaded pyranometer uncertainty estimate (19 Wm^{-2}), it is clear that the two-instrument measurement is more accurate than the unshaded pyranometer measurement. Unshaded pyranometer measurements, however, provide a valuable possibility for quality check.

3. Operational uncertainty

As argued in the introduction of this report, the operational uncertainty comprises more than just the sum of the uncertainties related to the instrumental error sources. Although it is virtually impossible to obtain a reliable estimate of the operational accuracy of the irradiance measurements at KNMI, it is possible to perform a quality check using the different components of solar irradiance. The procedure, the measurements and the discussion are presented in Section 3.1. The most important aspects concerning the maintenance of the instruments are discussed in Section 3.2. Furthermore, possible improvements for the KNMI radiation set-up are given.

3.1 Quality check of KNMI measurements

Procedure

The quality check is based on the fact that we have two independent and simultaneous measurements of global irradiance: a single-instrument measurement with the unshaded pyranometer (GLOB) and a two-instrument measurement which is composed of a diffuse measurement with the shaded pyranometer (DIF) and a direct measurement with the pyrheliometer (DIR) (component summation). For convenience, we define

$$\Delta \equiv \mathrm{GLOB} - (\mathrm{DIR} + \mathrm{DIF}),$$

which should equal 0 in an ideal situation. For a comparison between instrumental and operational values of Δ, we introduce mean values $\langle\Delta_i\rangle$ and corresponding standard deviations of a sample σ_i. So we write:

$$\Delta_i = \langle\Delta_i\rangle \pm \sigma_i,$$

where the index i = oper for operational values and i = instr for instrumental values. Note that we have taken the standard deviation of a sample and not the standard deviation of the mean.

In order to obtain a set of measurements of Δ_{oper} we selected clear-sky hourly-mean values of the irradiances around solar noon (i.e. one hourly mean for each clear-sky day).

In order to estimate $\langle\Delta_{instr}\rangle$, we have to take into account that zero offsets in the global and diffuse irradiance measurements partly depend on each other. The zero offset depends on clearness of the atmosphere. Pyranometers of the same type thus experience the same zero offsets; we therefore expect the zero offsets to cancel in Δ.

To estimate σ_{instr} we took the rms of the independent standard deviations. The absolute error in the radiation components depends on the level of irradiance. According to Wardle et al. (1996), the absolute uncertainties at lower intensities are less, usually following approximately a square root dependence on the signal. For example, the uncertainty at one quarter of full scale would be approximately half its uncertainty value at full-scale and, expressed as a percentage, it would be twice as great. So, we will use the factor [(mean operational global irradiance) / 1000]$^{1/2}$ to scale σ_{instr}.

Results

In order to obtain a set of measurements for the verification of the equality $\Delta_{oper} = 0$, we selected 22 clear-sky days during the period 1998-2000. Fig. 1 shows the daily variation in Δ_{oper} and Fig. 2 shows the corresponding noon values. Following the procedure described above we find $\Delta_{oper} = 12 \pm 7$ Wm^{-2} and $\Delta_{instr} = -2 \pm 20$ Wm^{-2}. On the basis of these numbers we conclude that the measured distribution lies completely within the expected instrumental range. This implies that the quality check as described before does not give reason for mistrusting one of the instruments. Nevertheless, the large difference between $<\Delta_{oper}>$ and $<\Delta_{instr}>$ (14 Wm^{-2}) needs further discussion and explanation, which is given below. With respect to the standard errors it is striking that σ_{oper} is much smaller than σ_{instr}. Most probably this is caused by the fact that the conditions during the different measurement days are rather similar; there is relative little variation in the noon temperature and solar zenith angle.

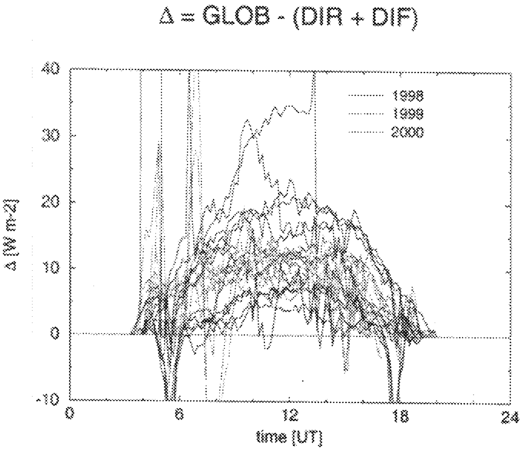

Fig. 1 The daily variation of Δ [Wm^{-2}] as a function of the time [UT], for 22 clear sky days from 14 May 1998 to 20 June 2000. At noon we find $\Delta_{oper} = 12 \pm 7$ Wm^{-2}.

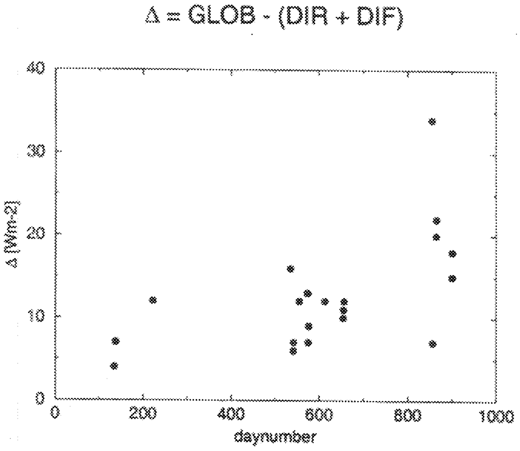

Fig. 2 Noon Δ values [Wm^{-2}] as a function of the daynumber, for 22 clear sky days from 14 May 1998 to 20 June 2000. Daynumber 1 corresponds to 1 January 1998.

Discussion

Standard pyranometers are calibrated to a windowless pyrheliometer or cavityradiometer with the sun as source. This means that, although the pyranometer does not see solar radiation beyond the cut-off of the glass dome (2800 nm), this part is "calibrated in" by reference to the reading of a windowless pyrheliometer. The amount of the direct solar irradiance at wavelengths above 2800 nm, relative to the irradiance integrated over the entire solar spectrum, depends on the water vapour content along the path through the atmosphere. Since in Davos, where the pyranometers are calibrated, the water vapour content is low compared to the situation in De Bilt, the pyranometer measurements in De Bilt are systematically overestimated. Using the radiative transfer model MODTRAN4.1 with a standard midlatitude summer atmospheric profile we find an overestimation of 2.2 Wm^{-2} for a clear sky day without aerosols. The overestimation is about 0.5 Wm^{-2} smaller if aerosols are included (aerosols absorb more in the visible). For extreme atmospheric conditions Fröhlich et al. (1995) found about 4 Wm^{-2}. The calibrated-in value is a multiplication factor; its effect is much stronger for global irradiance than for diffuse irradiance. The error, introduced by the calibrated-in value is therefore almost completely passed on to Δ. Using MODTRAN4.1 we estimate $<\Delta_{oper}>$ is overestimated by about +2 Wm^{-2}.

For the analyses of Δ presented in this report, pyranometer measurements are not corrected for non-linearity. Instead errors due to non-linearity are treated as if they are randomly varying. In practice pyranometers are more sensitive to high irradiances than to small irradiances. The mean global irradiance for our operational set was 772 Wm^{-2}, it is thus likely that the global irradiance was overestimated. On the other hand, diffuse irradiance was underestimated. The result is an overestimation of the operational mean Δ value. We combined the mean level of irradiance (610 Wm^{-2}) from the calibration certificate of the latest standard pyranometer calibration and the relative sensitivity variation with irradiance from the Kipp & Zonen manual (K&Z, 1992b) and we found that $<\Delta_{oper}>$ is overestimated by +2 Wm^{-2}.

The principle of zero offset is equal for shaded and unshaded pyranometers. During clear sky conditions a shaded pyranometer, however, operates in a different thermal state than an unshaded pyranometer, as it receives direct sunlight. Bush et al. (2000) show that, for an Eppley PSP pyranometer, the glass-dome temperature decreases significantly more than the sensor temperature when a unshaded pyranometer is suddenly blocked with a disk. Apparently the outer dome is significantly warmed by direct irradiance with wavelengths > 2800 nm. The zero offset is thus smaller (more negative) for shaded pyranometer measurements. Bush et al. (2000) on average found 8.2 Wm^{-2} smaller shaded pyranometer offsets than unshaded pyranometer offsets. The average they found is not representative for De Bilt, mainly because of differences in atmospheric composition. However, the effect is illustrative since Eppley PSPs and Kipp & Zonen CM11s both have Schott optical glass domes. At this moment correction is not possible, as we do not know the effect of direct sunlight falling on CM11's.

Since the operational set mainly consists of early summer days with strong (global) irradiances, calibrated-in and non-linearity very likely biased our mean ($<\Delta_{oper}>$). The magnitude of the significant bias caused by zero offset, is a matter of further research. It is however clear that the three effects we described, all resulted in an overestimation of $<\Delta_{oper}>$. The joint effect of the calibrated-in factor and non-linearity is estimated to be 4 Wm^{-2}. Correcting $<\Delta_{oper}>$ with 4 Wm^{-2}, we find an even better agreement between our operational set and the instrumental uncertainty estimate.

3.2 Maintenance and improvements

For a well-working radiation set-up it is necessary that Δ_{oper} is within the limits of uncertainty in Δ_{instr}. Although in Section 3.1 we have shown that this is true, this condition is not sufficient to conclude that the instruments operate at their highest possible skill. In this section we emphasize the importance of cleaning the instruments and discuss possibilities for improving the measurements at KNMI.

Maintenance

The instruction manuals of the Kipp & Zonen instruments (K&Z, 1992a, 1992b) suggest inspection of alignment, window (pyrheliometer) and domes (pyranometers), and drying cartridge as part of a daily routine. According to Phillipona (1998), the gradually increasing dirtiness of pyrheliometer windows can lead to 10 Wm^{-2} reduction of measured direct irradiances. It is thus very important that the window of a pyrheliometer is cleaned (and not only inspected!) on a regular basis. Dirtiness of the pyranometer domes does not significantly influence global and diffuse irradiances (Kuik, 1997). The reason for this is twofold: the dirtiness of the pyranometer glass domes does not increase above a certain value, and the major part of the direct irradiance scattered by dirtiness at pyranometer domes, is still received as a diffuse irradiance. The reduction of the irradiance is in the order of 1 Wm^{-2} (Kuik, 1997).

The manuals also suggest inspection of leads and connections and replacement of the drying cartridge as part of a monthly routine. Not working drying cartridges can lead to serious errors, especially on clear-sky mornings.

Improvements

Pyranometers

Ideally, the output signal of the pyranometer is doubled when the level of irradiance is doubled. In practice the output signal is not exactly linearly proportional to the level of irradiance. Standard pyranometers are calibrated outdoors in Davos, at the World Radiation Centre. The mean level of irradiance in the calibration period is given in the "calibration certificate". Since the relative sensitivity variation with irradiance is given in the pyranometer manual (K&Z, 1992b), a correction for non-linearity is in principal possible.

For improving the accuracy of irradiance measurements at KNMI it is necessary to correct pyranometer irradiance measurements for zero offset I. The simplest correction is to measure the dark signal instantaneously, by covering the pyranometer with a "black box" (Bush et al., 2000), and subtract it from the daytime measurements.

A procedure suitable for continuous monitoring is to determine the mean dark signal every night and to use linear interpolation between the preceding and following night values to compute the offset through the day. At KNMI this procedure is not possible since negative night-time pyranometer measurement values are set to zero by the SIAM. A SIAM is a standardized instrument; i.e. it is designed to be used with almost any KNMI instrument. Storing the negative output implies changing the SIAM, which is recommended.

If SIAMs are to be adapted, ventilation of pyranometers is recommended. Ventilation reduces the zero offset I variability by 30% (Wardle et al. 1996). Zero offset II would also benefit from ventilation as the time lag in the sensor temperature is decreased.

A very accurate procedure for zero offset correction is based on real-time pyrgeometer measurements in combination with adabted SIAMs. At night the longwave emission measured with the pyrgeometer can be linked to the negative SIAM output. The daytime pyrgeometer measurement can then be used to estimate the zero offset I. Again ventilation results in a better estimate of the zero offset[2] of the pyranometer.

The best estimate of zero offset I is probably obtained when a pyranometer is equipped with precision thermistors that measure temperature difference between outer dome and detector. Bush et. al. (2000) show how the relation between temperature difference and zero offset can be obtained in the laboratory.

Kuik (1997) showed that for automated operational KNMI stations unventilated pyranometers give better results than ventilated pyranometers, because ventilated domes suffer from 'ring' shaped pollution after a few months. Furthermore, ventilation stimulates the heat transfer between receiver and domes. Wardle et al. (1996) showed that the mean night-time zero offset I of pyranometers therefore becomes more negative and changes from -2.5 Wm^{-2} to -3.4 Wm^{-2}. As long as correction for zero offset at the present (automated) KNMI radiation set-up is impossible, ventilation is undesirable because it increases pollution.

A better estimate of zero offset is possible for ventilated pyranometers in combination with adabted SIAMs. Pollution however possibly cancels the advantage. Instruments should therefore be cleaned every week, a job that can be fulfilled during intensive measurement campaigns but is hard to fulfil on a routine basis.

Pyrheliometers

The accuracy of pyrheliometer measurements is predominantly determined by temperature sensitivity. Temperature sensitivity functions can, however, be obtained in laboratories. Temperature sensitivity correction is then possible if the sensor temperature is known. An exact measurement of the sensor temperature, without influencing the

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[2] Ventilation changes zero offset. Pyranometer and pyrgeometer of one type, i.e. shaded or unshaded, should be both ventilated or both not ventilated.

temperature of the sensor, is difficult. Measuring the ambient air temperature is sufficient when the instrument is ventilated; i.e. ventilation narrows the gap between sensor and ambient temperature. We are not aware of studies discussing the influence of pyrheliometer ventilation.

4. Conclusions and recommendations

On the basis of the analysis of the Kipp & Zonen pyranometers (CM11) and pyrheliometers (CH1) presented here, we can conclude that the instrumental uncertainties in global, direct and diffuse irradiance measurements are quite considerable (Table 4). For proper validation of radiative transfer calculations and of radiation schemes in climate/weather models, for which a few Wm^{-2} can be of decisive importance, the uncertainties are even too large. However, by comparing the uncertainties with the ones reported by BSRN for 1990 and 1995, we can conclude that the situation at KNMI is comparable to the BSRN standards of 1990. Between 1990 and 1995, BSRN has raised its standards, and these are now beyond the possibilities of the present radiation set-up at KNMI.

The comparison of instrumental (i.e. expected) and operational (i.e. measured) values of the quantity GLOB - (DIR + DIF) gave no unexpected results; the operational values were always within the instrumental range of uncertainty. Nevertheless, the analysis of the measurements together with a study of literature learned that several improvements of the existing KNMI radiation set up are in principle possible. Each improvement has its own degree of complexity and whether or not it is carried out should be weighted against the required accuracy. Since a correction for zero-offset I (caused by long-wave cooling) is both simple and effective, we feel that it is waste of accuracy not to correct for this error, which can amount to more than 10 Wm^{-2}. An effective correction is possible if the (negative) night-time signal of the pyranometers is stored. For the current situation at KNMI this requires an adaptation of the SIAM.

With respect to the measurement of global radiation we associate ourselves with what is said in the literature: accurate measurement of this quantity should be performed on the basis of the component summation technique, i.e. global radiation should be measured with a pyrheliometer (measuring the direct component) and a shaded pyranometer (measuring the diffuse component). As compared to measurements with an unshaded pyranometer, the component summation technique increases the accuracy of global irradiance measurements by 7 Wm^{-2} on average.

We emphasize the importance of proper, regular, and well-documented calibration of the radiation instruments and its standards. Since calibration uncertainty itself can be up to 10 Wm^{-2}, it is essential to obtain the highest possible accuracy by means of careful and in-time calibration. Finally, we stress the importance of instrument maintenance, in particular cleaning of the pyrheliometer windows. Not doing this on a regular basis may lead to reductions of 10 Wm^{-2} in irradiance.

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