Pyrgeometer Calibration Procedure at the PMOD/WRC-IRS

J. Gröbner and S. Wacker
(Switzerland)

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Chairperson, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 8403
Fax: +41 (0) 22 730 8040
E-mail: Publications@wmo.int

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Foreword

The last 25 years have seen significant improvement in the measurement of longwave, terrestrial based irradiance. Prior the establishment of the Baseline Surface Radiation Network a typical estimate of the uncertainty of downward terrestrial irradiance was of the order of 5-15% (20-60 Wm-2) depending on the methodology of measurement. That uncertainty in consistency with a reference has been reduced to significantly less that 5% in the last two decades.

The Physikalisch-Meteorologisches Observatorium Davos (PMOD), which is now an institute member of Committee International des Poids et Mesures CCPR/CIPM, has been at the forefront of development the processes of a traceable measurement of terrestrial irradiance, with the work of Rolf Philipona and his team at PMOD in the 1990s including a re-examination of the measureand, the construction of some reference blackbody sources, the development of the Absolute Sky Scanning Radiometer (ASR) and the construction of the group of pyrgeometers that make up the World Infrared Standard Group (WISG).

This report demonstrates that the processes of terrestrial irradiance measurement at PMOD, now under the leadership of Julian Groebner, continues its excellent and methodical work on defining both the measureand and refining the definition of the reference and its uncertainty. It also demonstrates the value in diversity in the processes of measurement to achieve better traceable measurements of terrestrial irradiance with multiple measurement methods referenced including the IRIS radiometer.

In addition, as the title indicates, it provides the methodology used at PMOD for referencing pyrgeometers as well as highlighting areas where further investigation is required, and the questions further investigations will need to try and provide answers to.

It also assists providing foundation evidence to establishing the framework to ensure future instrument calibrations, intercomparisons, and establishment of traceability to recognised units of the SI as required by BIPM, and ultimately will lead to Calibration and Measurement Capabilities documents for terrestrial irradiance.

I recommend this paper to all interested in the future of terrestrial irradiance measurement.

(Prof. B. Calpini)
President
Commission for Instruments and Methods of Observation

Introduction

Pyrgeometers measure longwave radiation, defined as radiation emitted by the atmosphere (downwelling) or the Earth surface (upwelling) in the wavelength range between 3 and 100 ìm [WMO, 2008]. At the Infrared Radiometry Section of the World Radiation Center, Pyrgeometers are calibrated for downwelling longwave irradiance relative to the World Infrared Standard Group (WISG) of pyrgeometers. The WISG consists of four pyrgeometers, two modified Eppley PIRs 31463F3 and 31464F3, and two Kipp&Zonen CG4 FT004 and CG4 010535. A fifth Pyrgeometer, Kipp&Zonen CG4 030669, is running continuously besides the WISG since February 2008 but is not used for the calibration of test pyrgeometers.

Currently, the calibration coefficients of the WISG are those retrieved during the IPASRC-I measurement campaign [Philipona et al., 2001b], relative to the Absolute Sky Scanning Radiometer (ASR) [Philipona, 2001a] and have not been changed since. Recently, a new transfer standard radiometer, the Infrared Integrating Sphere (IRIS) Radiometer, has been developed to allow traceability of longwave radiation to reference blackbody cavities [Gröbner, 2012].

While it is the goal to eventually calibrate the WISG relative to a group of transfer standard radiometers, comprised of IRIS radiometers and possibly additional radiometers, the aim of this report is to describe the current pyrgeometer calibration procedure adopted at the WRC-IRS and to propose suitable changes to improve the reproducibility and uncertainty in the pyrgeometer calibrations in view of recent findings.

Pyrgeometer Calibration Procedure at WRC-IRS

Test Pyrgeometers are calibrated at the WRC-IRS based on the following radiometric equation, first proposed by Albrecht et al., 1974 and endorsed by the BSRN [see BSRN Manual V2.1, McArthur, 2004]:

$$E = \frac{U}{C}\left(1 + k_1 \sigma T_B^3\right) + k_2 \sigma T_B^4 - k_3 \sigma\left(T_D^4 - T_B^4\right)$$

Where U is the electrical output of the thermopile, C the sensitivity, T_B and T_D the pyrgeometer body and dome temperatures respectively, and k_i instrument constants.

The instrument constants k_i are determined in the laboratory by placing the test pyrgeometer at the aperture of a blackbody cavity and taking measurements at several combinations of cavity and pyrgeometer temperatures. The measurements are taken only when both the cavity and the pyrgeometer temperatures have stabilized (e.g. static conditions). In case of Eppley PIRs, the dome coefficient k_3 is obtained by differentially heating the dome of the pyrgeometer by a copper ring to produce a positive temperature difference of about 1 K between dome and body. In all other cases, the dome coefficient is set to 0.

Following the laboratory characterization to retrieve the instrument constants k_i, the test pyrgeometer is mounted in a ventilated unit with a heated airflow to the instrument dome (VHS-PMOD) on a shaded solar tracker beside the WISG pyrgeometers on the measurement platform of WRC-IRS. Measurements of downwelling longwave irradiance are stored as one-minute averages for a period lasting between a few days to several months, depending on customer demand and weather conditions. The sensitivity C of the test pyrgeometer is retrieved relative to the WISG average from a subset of nighttime measurements applying the following criteria:

1. Outliers are removed (U>0.001 V, U<-20 mV, $|T_D|$>40 °C, $|T_B|$>40 °C)
2. Any night containing rain is excluded (limit of 0.2 mm/10 min)
3. Stable atmospheric conditions, defined by the standard deviation of the WISG <2 Wm^{-2}
4. Net radiation measured by the WISG < -70 Wm^{-2}
5. Measurements from one night are used if there are at least 80% valid measurement points
6. Night is defined when the solar zenith angle is larger than 95°
7. Relative standard deviation of the test pyrgeometer signal <3%

The aim is to obtain sufficient measurements during cloud-free nights to determine the sensitivity C with adequate statistical significance (no quantitative criterion is currently defined when this is reached). Specifically, criteria 3, 4, and 7 are used to select stable atmospheric conditions with a large signal at the thermopile which usually correspond to clear sky nights.

The calibration uncertainty of the test pyrgeometer is obtained by taking into account the following uncertainty components (expressed as expanded uncertainty, 95% coverage interval):

- Uncertainty of the WISG based on the ASR and its internal variability, typically ±2.6 Wm^{-2}
- Uncertainty of the thermopile signal, ±1 ìV
- Uncertainty of the temperature measurements of ± 0.02 K
- Uncertainty of the instrument constants $[k_1,k_2,k_3]$ =[0.03 0.0008 0.2]
- Standard deviation of the retrieved sensitivities C

Stability of the WISG

The WISG is operated continuously on the outdoor platform of the WRC-IRS. Its stability is monitored by internal consistency checks of the four pyrgeometers comprising the WISG. As can be seen in Figure 1, the pyrgeometers of the WISG typically agree to within ±1 Wm^{-2}, with minor seasonal variations between the WISG pyrgeometers. While the absolute level of this reference group is important for radiation and energy budget studies, its long-term stability is relevant for long-term trend investigations, which, as is shown here, can be demonstrated to better than ±1 Wm^{-2}.

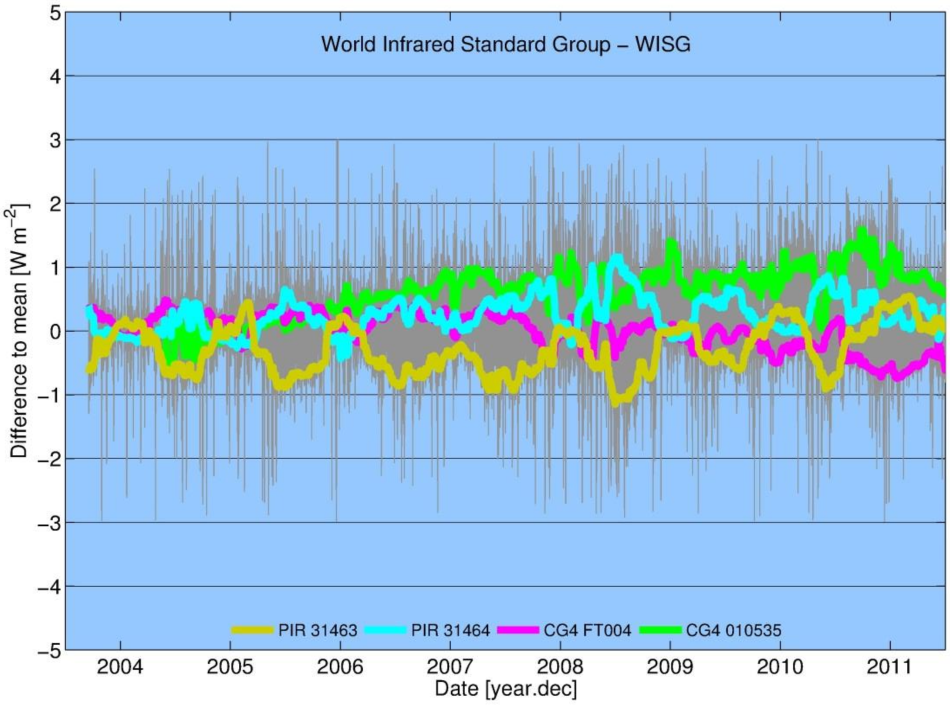


Figure 1. Night average differences of longwave irradiance measurements between the WISG pyrgeometers relative to their average. The thick lines represent a monthly running average.

Calibration of a test pyrgeometer (retrieval of the sensitivity C)

As mentioned previously, a test pyrgeometer is calibrated relative to the average of the WISG and its sensitivity C is retrieved by minimizing the residuals. As an example, Figure 2 shows the residuals of a test pyrgeometer (Eppley PIR) relative to the WISG.

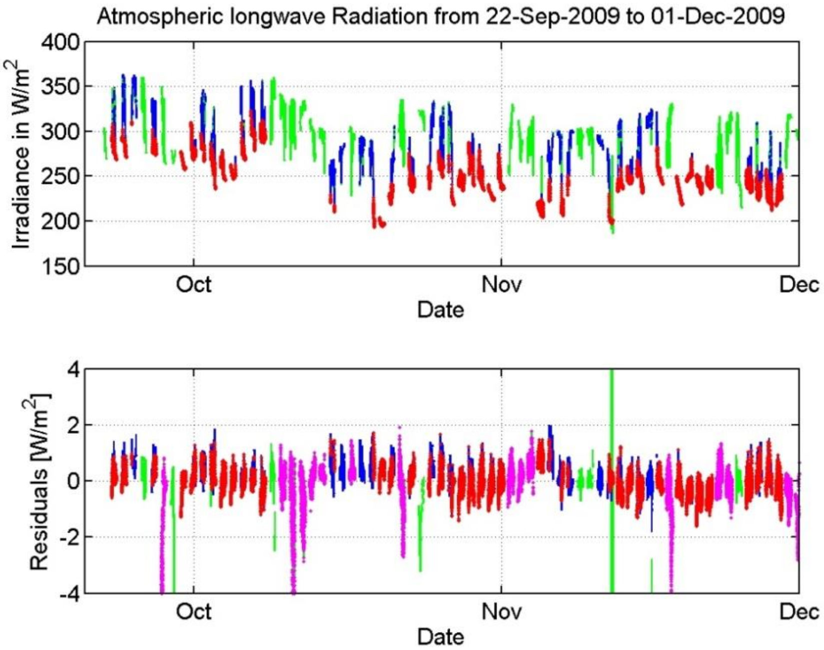


Figure 2. Atmospheric downwelling longwave irradiance measurements by a test pyrgeometer (Eppley PIR) and the WISG (one minute averages). The upper figure shows the actual measurements, while the lower figure shows the residuals relative to the WISG. The red dots represent the measurements used for the retrieval of C, the blue dots correspond to the measurements fulfilling all criteria but with net radiation also higher than -70 Wm^{-2}, while the pink dots correspond to measurements excluded due to precipitation.

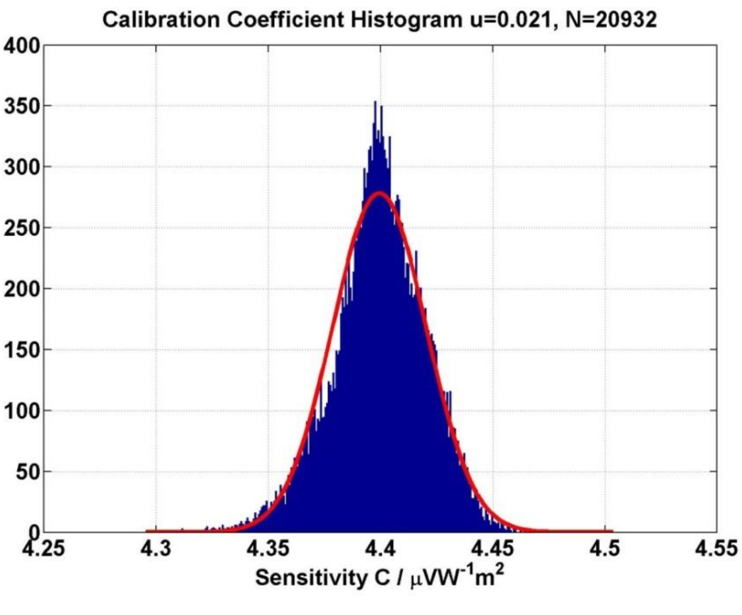


Figure 3. Histogram of the sensitivities C retrieved from the measurements shown in Figure 2 for a test pyrgeometer. The red curve corresponds to the best fit of a normal distribution with a standard deviation of 0.021 ìVW^{-1}m^{2}.

The histogram of the sensitivities C retrieved from the measurements displayed in Figure 2 is shown in Figure 3 and demonstrates that for this particular instrument the residuals follow closely a normal distribution with a standard deviation of 0.45%. The corresponding standard deviation of the residuals in terms of atmospheric longwave radiation is 0.4 Wm^{-2}.

The residuals can be correlated to a variety of parameters, such as thermopile signal, pyrgeometer body temperature, etc… to check for systematic dependencies to these parameters. In this particular example, no significant correlations can be observed. A particularly interesting parameter is the integrated atmospheric water vapour (IWV), obtained from GPS time delay measurements determined at PMOD/WRC by the automatic GNSS-network of Switzerland (AGNES). Figure 4 shows the residuals and the sensitivities C with respect to this parameter.

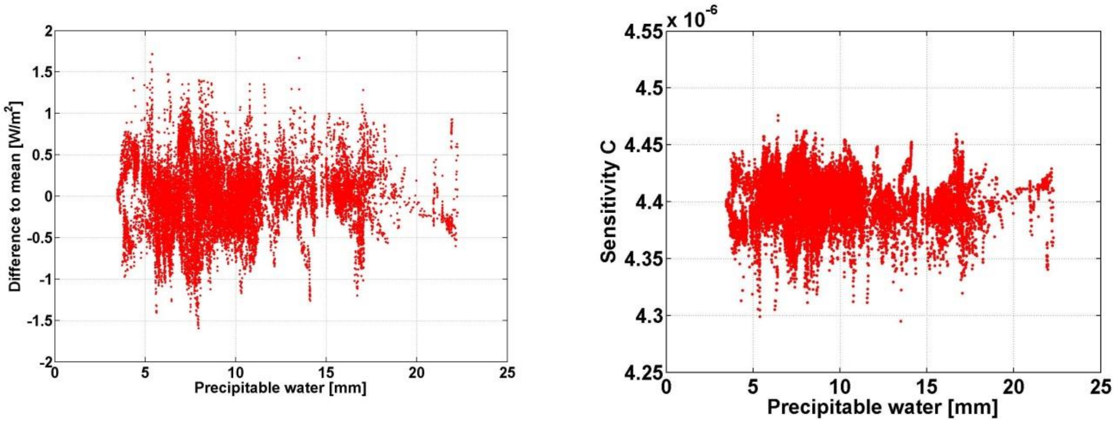


Figure 4. The left figure shows the residuals versus the integrated water vapour while the right figure shows the sensitivities C retrieved relative to the WISG versus the integrated water vapour.

In this particular example, the sensitivity C and the corresponding expanded uncertainty (applying a coverage factor k=2, which for a normal distribution corresponds to a coverage probability of approximately 95%) retrieved by comparison to the WISG are:

$$C = 4.40 \pm 0.15 \mu V W^{-1} m^{2} .$$

While the calibration relative to the WISG can be obtained with a relative expanded uncertainty (with a 95% coverage probability) of only 0.9% (see Figure 3 above), the expanded uncertainty of the WISG of ±2.7 Wm^{-2} is mainly responsible for the large uncertainty of the calibration. Therefore, a calibration with respect to the WISG has an uncertainty of typically less than 1%, while the absolute uncertainty is limited by the traceability of the WISG to the SI.

Calibration of Kipp&Zonen CG4 pyrgeometers

Since 2001, Kipp&Zonen CG4 pyrgeometers have increasingly been calibrated at WRC-IRS, becoming the second largest group of pyrgeometers after the Eppley PIR. While only 1 CG4 and 11 PIR were calibrated in 2001, near parity was reached in 2010 with calibrations of 15 CG4 and 16 PIR. While the calibration procedure was not modified with the advent of the CG4 pyrgeometer, apart from the absence of a dome thermistor, some systematic variabilities between certain CG4 pyrgeometers and the WISG have been observed, especially during cold weather conditions at Davos.

The modified pyrgeometer CG4 FT006 with Dome 030669

At PMOD, the domes of CG4 FT006 and of CG4 030669 (instruments manufactured in 2001 and 2003 respectively) were exchanged and mounted on the respective thermopile bodies of each CG4 (see Gröbner, 2010). In the following section the results of CG4 FT006 before and after the modification will be analysed. For simplicity reasons, the modified pyrgeometer CG4 FT006 with the dome of 030669 will be renamed CG4 030669 in the remaining document. The original and modified pyrgeometer was compared to the WISG during two subsequent years, the residuals of which are shown in Figure 5. When investigating the best correlation of the residuals with atmospheric or instrumental parameters, the best correlation was obtained with respect to integrated water vapour.

Unmodified CG4 FT006 (Aug 2007 - Feb 2008) **Modified CG4 030669 (Feb 2008 - Feb 2009)**

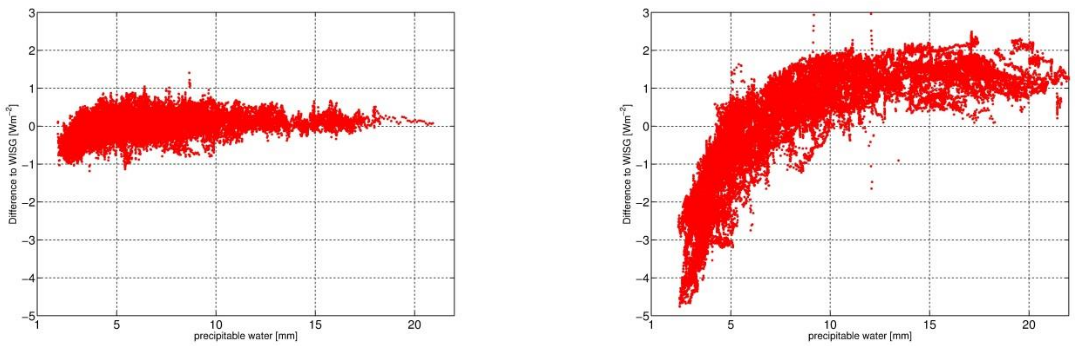


Figure 5. The left figure shows the residuals of the unmodified CG4 FT006 with respect to the WISG while the right figure shows the residuals of the modified pyrgeometer with the dome of CG4 030669 with respect to the WISG. The residuals are displayed with respect to the IWV as this is the parameter showing the best correlation.

The resulting dependence of the residuals between the pyrgeometer and the WISG with respect to the IWV is striking and obviously due to the exchange of the domes. The reason for the observed deviations with respect to IWV could not be ascertained so far; it is likely that spectral differences between these domes (especially the solar blind coating) are responsible for this behaviour, since the spectrum of downwelling longwave irradiance below an IWV of 10 mm differs significantly from spectra with larger IWV, especially in the wavelength range of the second atmospheric window, between 18 and 25 ìm.

Similarly to the example shown in Figure 2 for an Eppley PIR, Figures 6 and 7 show the residuals of CG4 030669 with respect to the WISG for the same period from September to December 2009:

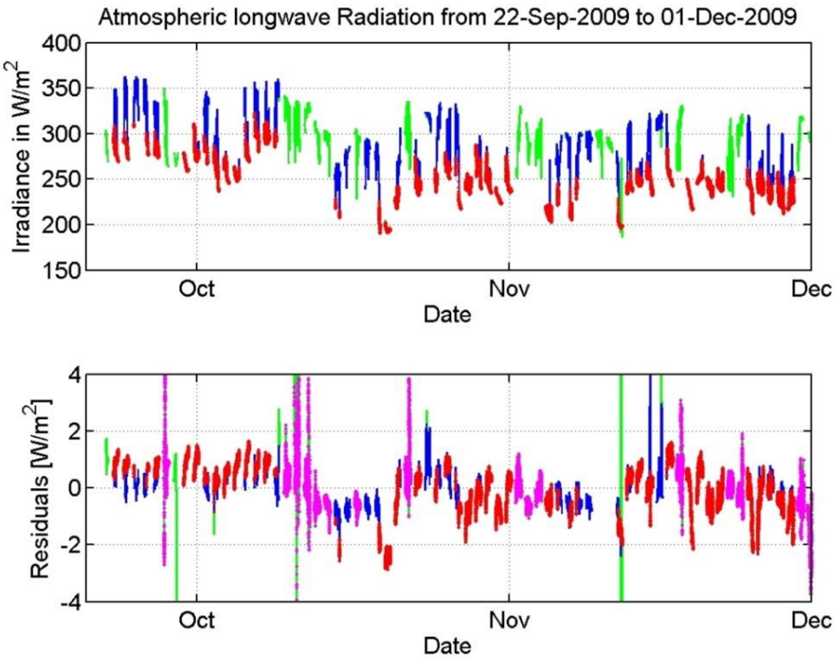


Figure 6. Atmospheric downwelling longwave irradiance measurements by a CG4 pyrgeometer (CG4 030669) and the WISG (one minute averages). The upper figure shows the actual measurements, while the lower figure shows the residuals relative to the WISG. The red dots represent the measurements used for the retrieval of C, the blue dots correspond to the measurements fulfilling all criteria but with net radiation also higher than -70 Wm^{-2}, while the pink dots correspond to measurements excluded due to precipitation.

As can be seen in the figure, the residuals of this CG4 with respect to the WISG show large deviations of up to -3 Wm^{-2} for certain periods. The histogram of the sensitivities C retrieved from the measurements displayed in Figure 6 is shown in Figure 7 below and shows that this pyrgeometer behaves differently to the Eppley PIR shown previously.

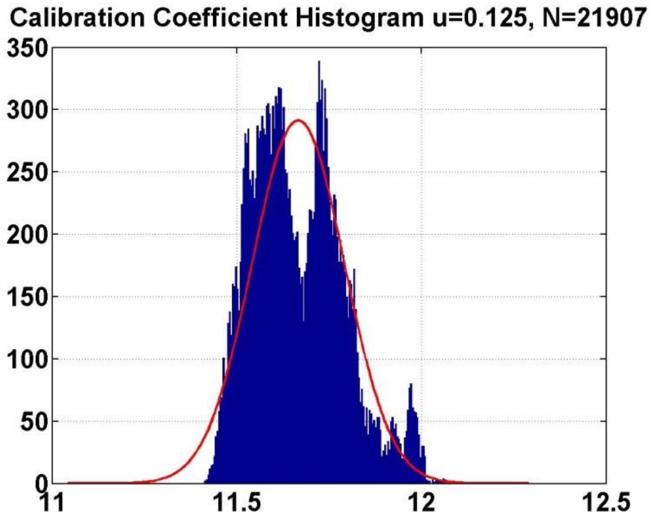


Figure 7. Histogram of the sensitivities C retrieved from the measurements shown in Figure 6 for the CG4 030669 pyrgeometer. The red curve corresponds to the best fit of a normal distribution with a standard deviation of 0.125 ìVW^{-1}m^{2}.

In contrast to the Eppley PIR for the same period, the corresponding standard deviation of the residuals in terms of atmospheric longwave radiation is 0.9 Wm^{-2}, e.g. about two times larger than the Eppley PIR.

When investigating the best correlation of the residuals with atmospheric or instrumental parameters, the best correlation is obtained with respect to integrated water vapour as shown in the figures below:

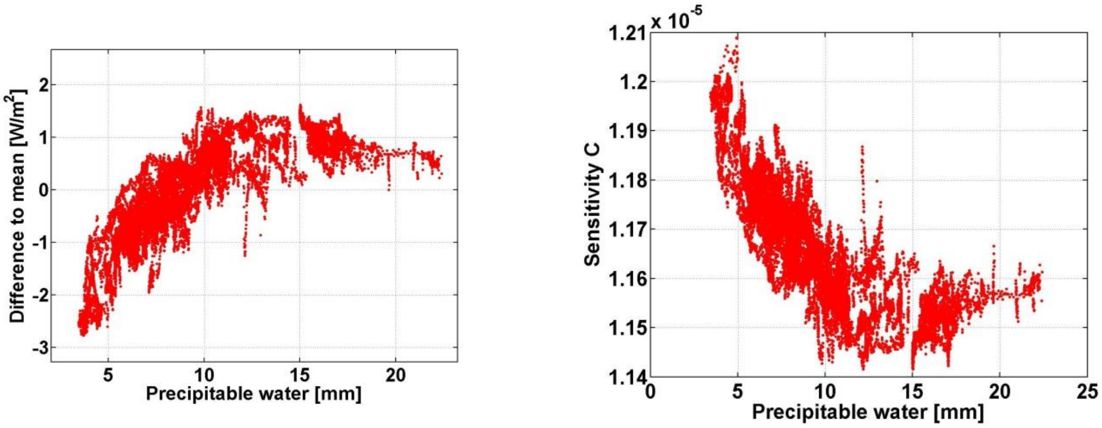


Figure 8. The left figure shows the residuals versus the integrated water vapour while the right figure shows the sensitivities C retrieved relative to the WISG versus the integrated water vapour.

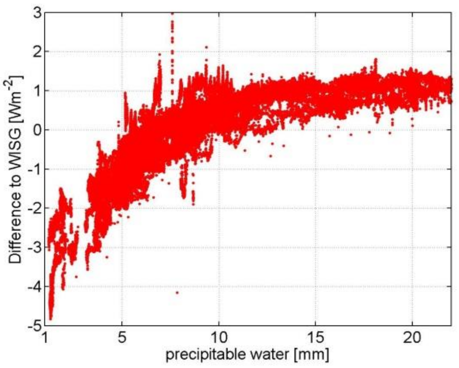
The residuals show a clear correlation with IWV, decreasing significantly below approximately 10 mm. In this particular example, residuals of up to 3 Wm^{-2} are observed between this CG4 and the WISG. The relative change in the retrieved sensitivity between very dry (<5 mm) and standard atmospheric water vapour conditions (around 20 mm) is larger than 4%. With respect to the WISG, this pyrgeometer underestimates atmospheric longwave irradiances under conditions with very little precipitable water vapour. In the remaining report, CG4 030669 is used with a sensitivity of 11.55 ìVW^{-1}m^2 retrieved by a calibration relative to the WISG for conditions with IWV larger than 10 mm, as shown in the right figure of Figure 8.

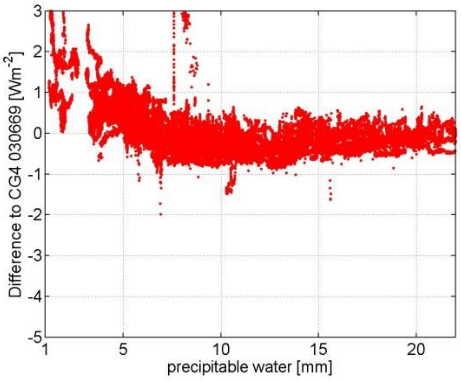
CG4 Pyrgeometers versus WISG and CG4 030669

Interestingly, similar deviations with respect to the WISG are seen between all investigated CG4's manufactured after about 2003 (judging by the first two digits of the instrument serial number). The following table shows the residuals between several CG4 (or CGR4) calibrated at PMOD/WRC relative to the WISG, with respect to the IWV in the left column, while the same data is shown with respect to CG4_030669 in the right column (this pyrgeometer belongs to the PMOD/WRC and is operated continuously besides the WISG).

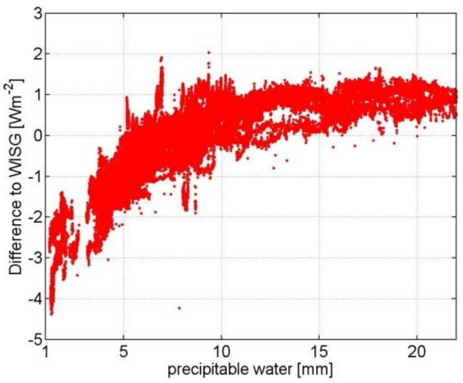
Table 1. The left figures show the residuals of several CG4 or CGR4 pyrgeometers with respect to the WISG while the right figures show the same measurement data relative to CG4 030669. The residuals of each dataset are obtained from fitting the measurement data to the pyrgeometer equation using either the WISG or CG4 030669 as reference.

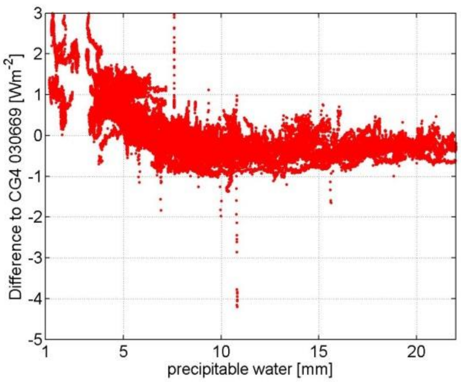
CGR4 110350 (Sep 2011-Feb 2012)



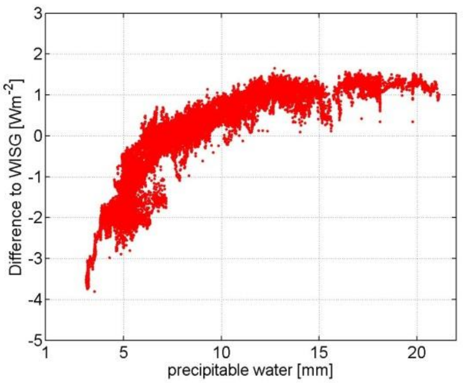


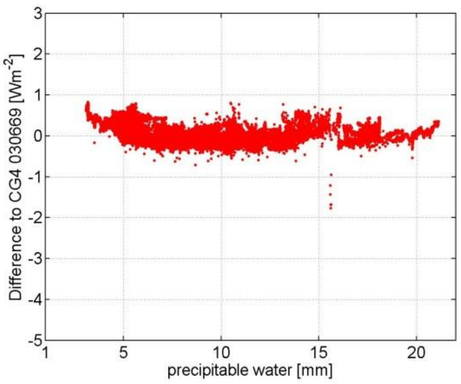
CGR4 110349 (Sep 2011-Feb 2012)



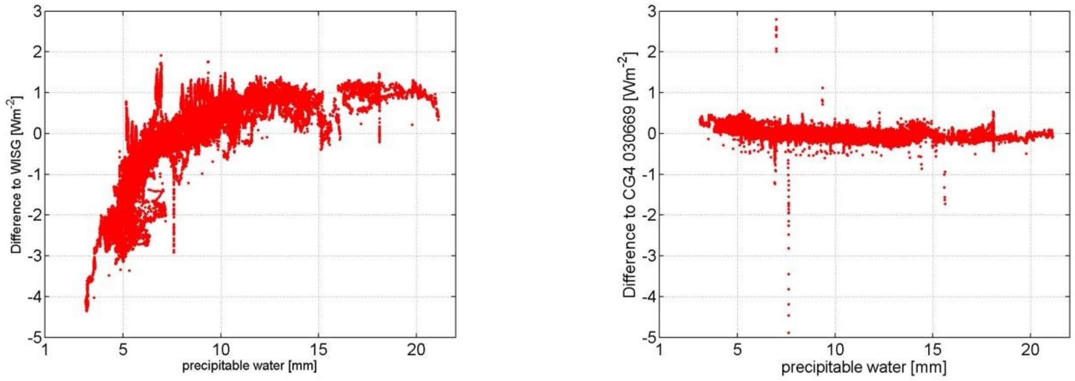


CGR4 070038 (Sep-Dec 2011)

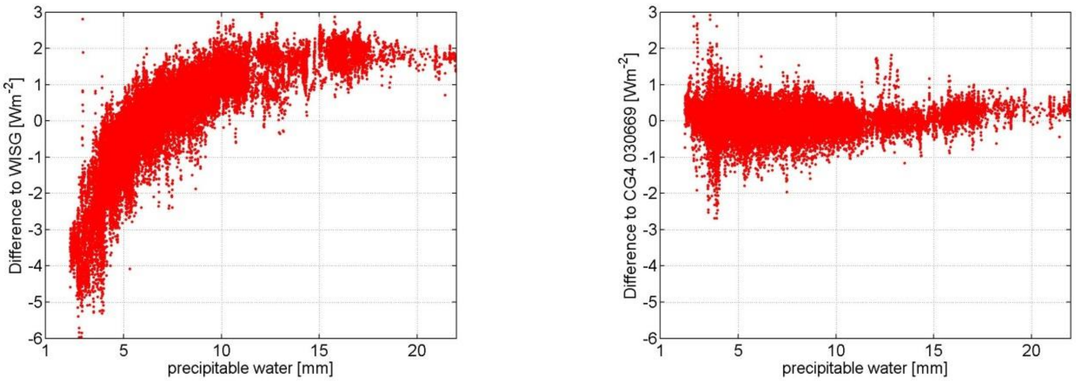




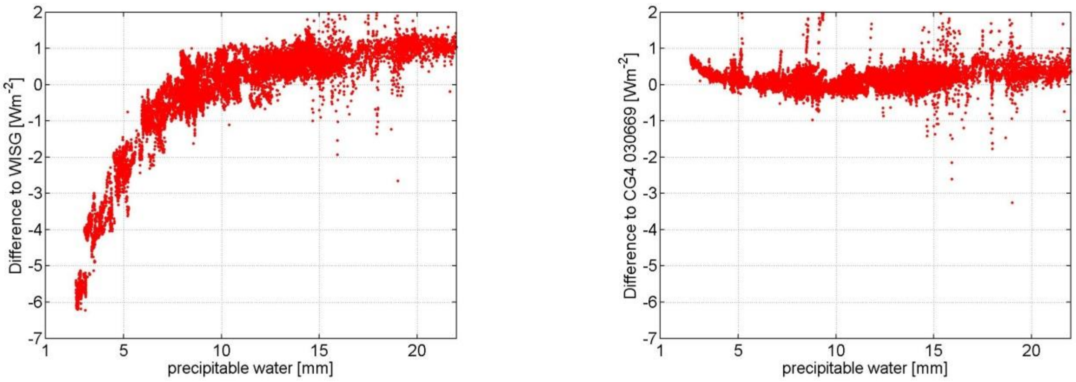
CG4 010536 (new dome since 2005) (Sep-Dec 2011)



CG4 060881 (Sep 2009 to Jan 2010)



CG4 070039 (Sep 2009 to Jan 2010)



As can be seen in the figures, all CG4 (CGR4) pyrgeometers show significant deviations with respect to the WISG for IWV lower than 10 mm. These deviations are instrument dependent and under-estimate atmospheric longwave irradiances by as much as 6 Wm^{-2} for IWV amounts as low as 2 mm. One should note that two pyrgeometers of the WISG are CG4 type pyrgeometers, built before 2000, which do agree with the overall WISG group of pyrgeometers and do not show these increasing discrepancies with decreasing IWV.

However as can be seen on the right hand side of the table, the CG4 pyrgeometer group agrees remarkably well between each other, showing deviations of less than ±2 Wm^{-2} for the whole sampled IWV range.

Comparison to the IRIS Radiometers

The previous section has shown that deviations between the WISG group of pyrgeometers and CG4 (CGR4) pyrgeometers have been observed with respect to the atmospheric IWV. However from these measurements alone it is not possible to decide which group of instruments is responsible for these deviations.

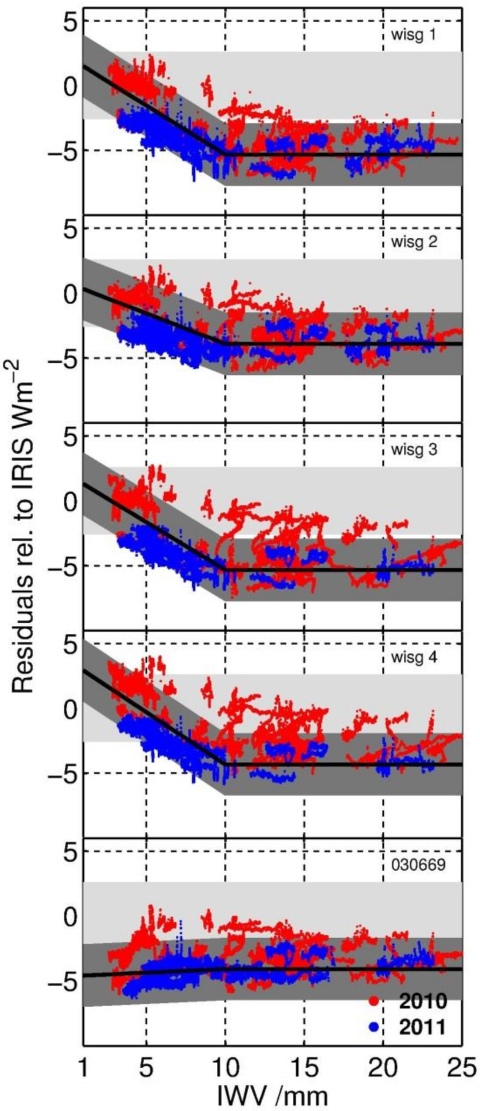


Figure 9. Residuals of the WISG and CG4 030669 pyrgeometers to IRIS#2 and IRIS#4 with respect to integrated water vapour. The thick black line represents a linear fit to the combined residuals for 2010 and 2011. The slope is determined for IWV smaller than 10 mm, while it is set to a constant value at larger IWV. The light grey area corresponds to the estimated uncertainty of the WISG based on the ASR, ±2.6 Wm^{-2}, while the dark grey area corresponds to the estimated uncertainty of the IRIS radiometer, ±2.4 Wm^{-2}.

The new IRIS Radiometer has been designed to measure atmospheric downwelling longwave irradiance without spectral windows using a novel integrating sphere design with a pyroelectric detector. The instrument has been in operation since 2009 and several instruments were constructed, of which currently four are in operation, two of which at PMOD/WRC. Optimal measurement conditions are encountered during clear sky conditions at nighttime. Figure 9 shows the comparison of downwelling longwave irradiance measurements between the WISG and IRIS radiometers #2 and #4 from respectively 73 nights in 2010 (red dots) and 59 nights in 2011 (blue dots). The residuals are plotted against the integrated water vapour in order to demonstrate the systematic dependence on this atmospheric parameter. The thick black lines are linear fits to the residuals for the two IWV ranges above and below 10 mm. The light gray area corresponds to the uncertainty of the WISG of ±2.6 Wm^{-2}, based on the ASR uncertainty [Philipona, 2001a] while the dark gray area represents the uncertainty of the IRIS radiometers of ±2.4 Wm^{-2} [Gröbner, 2012] applied to the linear fit average.

Two distinct regimes can be observed : During relatively warm and humid conditions (IWV larger than 10 mm), the difference between the WISG and IRIS radiometers is constant, with IRIS measuring larger irradiances; during cold and dry conditions (IWV smaller than 10 mm), the difference between the WISG and IRIS gradually decreases. The specific offset and slope for each WISG radiometer is summarised in Table 2.

Table 2. Observed differences between WISG pyrgeometers and CG4 030669 with IRIS#2 (2010) and IRIS#4 (2011). The linear fit is used for IWV smaller than 10mm, while for larger IWV, the difference between pyrgeometer and IRIS is constant and equal to the offset. The standard deviation of the residuals is based on 18458 (73 nights) and 18925 (59 nights) 1 minute measurements for 2010 and 2011, respectively.

Instrument	Linear Fit		Standard Deviation of Residuals in Wm^{-2}	
	Offset at IWV ≥10 mm [Wm^{-2}]	Slope [$Wm^{-2}mm_{IWV}^{-1}$]	2010	2011
WISG1	-5.3	-0.76	1.70	1.12
WISG2	-3.9	-0.47	1.54	1.02
WISG3	-5.3	-0.74	1.85	1.04
WISG4	-4.3	-0.81	1.87	0.98
Average WISG	-4.6	-0.69	---	---
CG4 030669	-4.1	0.04	1.25	0.76

The average offset between the IRIS and WISG is 4.6 Wm^{-2} which remains within the respective estimated uncertainties of the WISG and IRIS. While a constant offset between the WISG and IRIS would be only a matter of implementing a scale change, the observed variability with IWV between the WISG and the IRIS radiometer necessitates a more thorough analysis:

- The variability with respect to IWV implies a spectral mismatch between the IRIS and WISG radiometers. Since the IRIS radiometers are windowless and use pyroelectric detectors with an organic black coating having a spectrally flat responsivity, the spectral mismatch is attributed to the domes of the WISG pyrgeometers, and, as shown in Table 2, variable between different instruments.
- As noted previously [Gröbner, 2010], the calibration of PIR pyrgeometers, when combining the results from the IPASRC-I and –II campaigns, implicitly showed that these pyrgeometers measured higher irradiances during the IPASRC-II campaign with respect to the ASR than during the IPASRC-I campaign. For example the discrepancy of the WISG1 radiometer was +4.1 Wm^{-2}, consistent with the observed change of +4.6 Wm^{-2} between the warm and cold conditions encountered in Davos.
- As mentioned previously, the exchange of the dome of CG4 FT006 with the one of CG4 030669 showed that the observed variability with IWV could be attributed to the dome of the pyrgeometer and not to the thermopile and electrical circuitry.

Conclusion

1) There exists two groups of commercial pyrgeometers, the Eppley PIR and CG4 (CGR4) pyrgeometers manufactured since 2003, showing significant deviations between each other with respect to integrated water vapour at IWV amounts below approximately 10 mm.
2) The atmospheric longwave irradiance measurements of the WISG pyrgeometers have a systematic dependence on IWV when it is below about 10 mm. This corresponds to the cold and dry conditions encountered in winter in Davos.
3) Pyrgeometer calibrations at the WRC-IRS are based on the WISG. To improve the consistency of the pyrgeometer calibrations performed at the WRC-IRS, the following actions are suggested:

- Routine calibrations are only performed at IWV above 10 mm. This restricts the calibration season at Davos from March to November.
- Specific cold season calibrations should span the IWV range between at least 3 and 15 mm in order to determine the dependency on IWV of the pyrgeometer due to its spectral mismatch.
- Eventually, the WISG measurements should be corrected with the correction functions derived with respect to the IRIS radiometers and shown in Table 2.

4) The observed average offset of 4.6 Wm^{-2} between the IRIS and WISG (IRIS measuring higher than WISG) needs to be confirmed by independent measurements such as [Reda, 2012] before updating the WISG calibration coefficients.

Acknowledgments

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