WRR to SI comparison with DARA

Markus Suter [1], Wolfgang Finsterle [1], Greg Kopp [2]
[1] PMOD/WRC, Dorfstrasse 33, CH-7260 Davos Dorf, Switzerland
[2] LASP, 1234 Innovation Drive, Boulder, CO, USA
E-mail: markus.suter@pmodwrc.ch

Abstract

In solar radiation measurements there are two different scales in use. The WRR scale is the reference scale of WMO that is officially used in meteorological measurements of solar radiation. The WRR standard is realized by a world standard group (WSG) of instruments and therefore a conventional reference.

The SI radiant power scale however is directly traceable to the basic SI units. It is realized with cryogenic laboratory radiometers.

Four comparisons between WRR and SI scales, using PMO6-radiometers, have been performed by PMOD/WRC in the past. The first three comparisons show good agreement within the stated uncertainties. The most recent comparison in 2010 however suggests that the WRR scale is 0.34 % higher than the SI scale. Unlike the earlier measurements this comparison has been carried out in irradiance mode e.g. using a beam that overfills the radiometric aperture. This was made possible by the new TSI Radiometer Facility (TRF) at LASP, Boulder, USA. The difference of the result is probably due to stray light effects in PMO6-Radiometers.

A fifth WRR to SI comparison is carried out with DARA, a new prototype instrument. DARA is a digitally controlled absolute radiometer, with different aperture geometry than PMO6-Radiometers. This will reduce stray light that was a major source of uncertainty in the earlier comparisons. As cryogenic radiometers operate under vacuum conditions and the WSG operates in ambient air, the most difficult task is still the transfer from air to vacuum. Therefore a lot of care is put into the air to vacuum ratio determination for this new prototype.

This fifth WRR to SI comparison yields a 0.3% difference between these two scales, the WRR scale being higher than the SI scale. this is in full agreement with the findings of the 2010 comparison.

1 Introduction

The WRR scale for solar irradiance commonly used in the meteorology community was defined in 1979 to homogenize solar irradiance measurements worldwide. It is also the official WMO reference scale. The WRR scale is represented by a group of five standard instruments, the so called World Standard Group (WSG). It is thus a conventional standard. These instruments are maintained by PMOD/WRC in Davos.

On the other hand there is the SI radiant power scale that is directly linked to the basic SI units. This scale is realized with cryogenic laboratory radiometers by the national metrology institutes. These instruments are regularly compared against each other in key comparisons [5].

To ensure the stability of the WSG several WRR to SI comparisons have been made, using PMO6 solar radiometers as transfer instruments. The results of these comparisons are listed in detail in Section 9. While the first three comparisons (1991,1995,2005) showed good agreement between the scales, the fourth comparison (2010) found the WRR to be 0.34% higher than the SI scale. Another hint that there might be a difference between the scales comes from the fact that space borne absolute radiometers tracable to the WRR showed a significant difference of 0.33% to the newer TIM/SORCE instrument that is not tracable to the WRR but absolutely characterized. [8]

The Digital Absolute Radiometer (DARA) is a 3-cavity absolute radiometer that was built in 2010 as a prototype for space borne application. The basic principle of operating is the substitution of the solar power with electrical power, as it is used in PMO6 radiometers [1] [3] and also in the TIM/SORCE instrument [7]. DARA was designed to reduce known problems with PMO6 radiometers, such as the high air to vacuum ratio or stray light. It therefore has a different aperture geometry than PMO6-type radiometers. DARA has the defining aperture in front like the TIM instrument, and the view limiting aperture in the back. It is also equipped with a digital controller loop that allows for faster shutter cycles, which make it less sensitive to temperature changes.

The DARA instrument has been proven a reliable instrument in two years of operation and testing. While all the previous WRR to SI comparisons have been carried out with PMO6-type radiometers, the comparison, using DARA as the transfer instrument can, reduce some systematic errors that might depend on the instrument type.

2 Measurement Set-up at LASP

The DARA instrument has been calibrated against a cryogenic radiometer at the Total Solar Irradiance Radiometer Facility (TRF). The TRF is located at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado in Boulder, USA. The facility allows indoor irradiance calibrations for solar radiometers with a high accuracy [6]. Previously the PMO6-PREMOS flight unit and the PMO6-VIRGO flight spare radiometers have been calibrated at the TRF. This is described in detail by Fehlmann [3]. The DARA calibration runs took place between September 29 and October 5, 2011 .

The TRF facility provides a 7.3 mm beam that overfills the aperture of the instrument. This allows calibrations in irradiance mode. The DARA instrument and the TRF cryogenic radiometer are alternately exposed to the beam, that is also monitored by a silicone diode. Both instruments are operated inside a vacuum chamber.

3 Data Evaluation and Results from the Comparison at LASP

Figure 1 shows the data, taken at the TRF. It shows the irradiance values of DARA and the Cryogenic radiometer vs. time. To compare the instruments the assumption that the beam is drifting linearly is made. Thus a line is fitted through both data, with the condition to have the same slope. The difference in irradiance between the two lines is then the difference in sensitivity of the instruments.

Table 1 shows the ratio between DARA and the cryogenic radiometer. The DARA instrument is reading lower than the cryogenic radiometer. However no corrections for lead heating and absorptivity are applied to the DARA data. In Table 2 the applied constants are listed.

	Cavity A	Cavity B	Cavity C
ratio to TRF	0.997849	0.997817	0.998748
error estimate	0.00037 (1σ)	0.00015 (1σ)	0.00030 (2σ)

Table 1: TRF Irradiance Calibration Results: Ratio of the DARA cavities A, B, C to the TRF Cryogenic radiometer. No corrections for diffraction, lead heating or absorptivity have been applied to the DARA data.

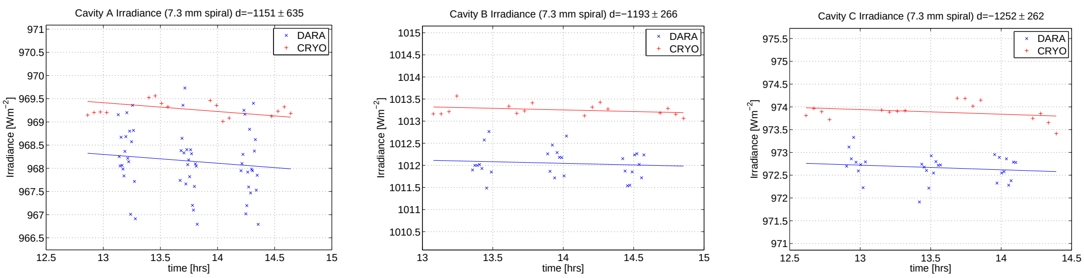

Figure 1: Calibration data from TRF Calibration with simple fit applied

Name	Value Used	Error Estimate
Aperture Area A	$19.6140 \cdot 10^{-6} m^2$	$\pm 0.0011 \cdot 10^{-6} m^2$
Aperture Area B	$19.6144 \cdot 10^{-6} m^2$	$\pm 0.0015 \cdot 10^{-6} m^2$
Aperture Area C	$19.6172 \cdot 10^{-6} m^2$	$\pm 0.0010 \cdot 10^{-6} m^2$
Electronics Calibration (CUI)	Temperature dependent	$\pm$ 100 ppm

Table 2: DARA Constants

4 Measurement Setup at PMOD/WRC

The DARA instrument has been compared against the World Standard Group (WSG) at PMOD, Switzerland. The WSG is representing the WRR standard for radiometric measurements. These measurements have been done in February 2012. The reference instrument (PMO2) and the DARA instrument measured the solar irradiance side by side at PMOD.

Four data runs, each a full day were performed. On Feb 21 and Feb 24 cavities A and B were measuring, on Feb 22 and on Feb 27 cavities A and C were measuring. This yields four days of data for cavity A and two for B and C respectively.

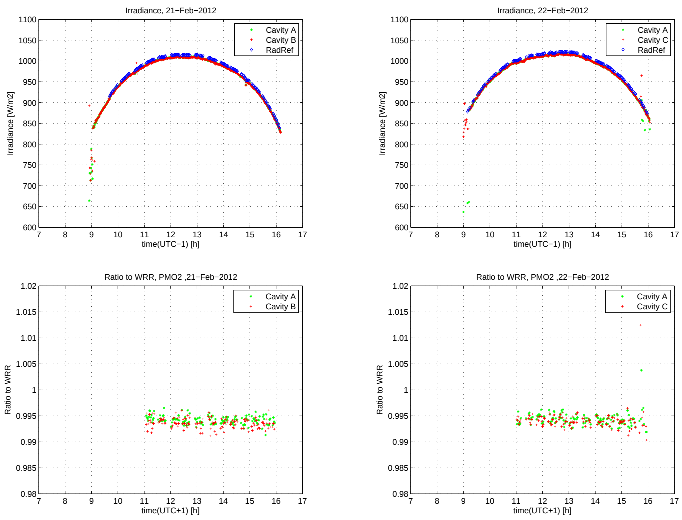

Figure 2: Calibration Raw Data: Irradiance on top, ratio to WRR on the bottom

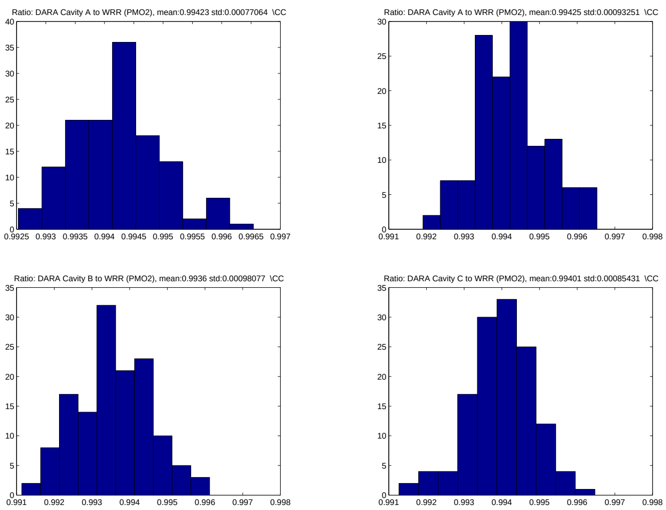

Figure 3: Calibration Histograms, Feb 21 on the left, Feb 22 on the right

5 Data Evaluation and Results from the Comparison at PMOD

Figure 2 shows the irradiance data and the corresponding ratios to WRR (PMO2) for Feb 21 and Feb 22. A Circumsolar Correction has been applied to this data. This method has been described by Fehlmann (2011) [3]. No air to vacuum or diffraction correction is applied to this data. Figure 3 shows the histograms of the WRR ratios. Tables 3 list the ratio to WRR for each measurement day.

	Cavity A	Cavity B	Cavity C
Feb 21	0.9942 $\pm$ 0.0007 (std)	0.9936 $\pm$ 0.0010 (std)	
Feb 22	0.9943 $\pm$ 0.0009 (std)		0.9940 $\pm$ 0.0009 (std)
Feb 24	0.9939 $\pm$ 0.0007 (std)	0.9931 $\pm$ 0.0009 (std)	
Feb 27	0.9942 $\pm$ 0.0009 (std)		0.9941 $\pm$ 0.0008 (std)
weighted mean	0.99412	0.99340	0.99402
stat uncertainty	0.00004 (1σ)	0.0006 (1σ)	0.0006 (2σ)
calibration uncertainty	0.00035	0.00035	0.00035
total uncertainty	0.00035	0.00036	0.00036

Table 3: Ratio to WRR (Raw Data, with only circumsolar correction applied)

6 Transfer Factors

6.1 Air to Vacuum Ratio

An important correction when transferring a WRR calibration into vacuum is the air to vacuum ratio of an instrument. This effect is found in previous types of radiometers, and is thought to originate from spurious heat flow through the air that is not exactly equal in the measurement/calibration phases. For example for the PMO6-PREMOS radiometers this air to vacuum correction is around 1.006 [3]. It means that the instrument is reading too low at ambient air conditions. The DARA instrument has been designed to have a very low air to vacuum ratio. Yet this needs to be confirmed experimentally. A lot of care is put into the determination of the air to vacuum ratio.

To determine the air to vacuum ratio, the DARA instrument is placed in the vacuum chamber that is mounted on to the WRC Solar tracker. This vacuum chamber has a window that is placed in front of one of the DARA apertures.

A PMO6 radiometer is mounted next to the vacuum chamber to act as reference instrument. A similar window to the one at the vacuum chamber is mounted onto the PMO6 Radiometer.

The DARA instrument is now operated in vacuum for two hours, then the vacuum chamber is filled with nitrogen to ambient pressure. The next two hours the instrument is operated in ambient pressure conditions, afterwards the chamber gets evacuated again. This cycle is then repeated until the end of a measurement day.

The two hours timespan is selected, so that the instrument can adjust to the conditions for one hour. After one hour the instrument is in acceptable thermal equilibrium. Then data can be taken without being influenced by large thermal drifts for the second hour.

Figure 4 shows such a measurement series. The air to vacuum difference is fitted for each sequence of vacuum-air-vacuum or air-vacuum-air. Thus for a measurement day as shown in Figure 4 three estimates of the air to vacuum ratio are determined. For cavity A and C three days of data each have been taken, although not each day gives enough data as to make three estimates per day. For cavity B no air to vacuum ratio is measured to date, thus no WRR to SI comparison can be made with this cavity. The overall air to vacuum correction factors with error estimates are listed in Table 4.

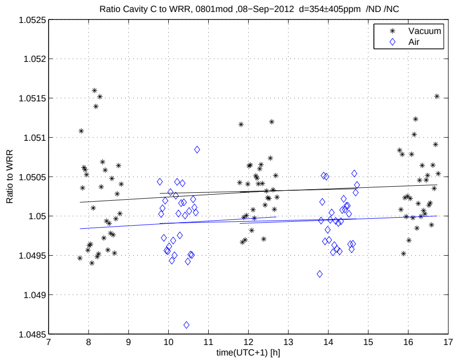

Figure 4: Air to vacuum determination for DARA cavity C. The air to vacuum ratio is determined for each vac/air/vac or air/vac/air set respectively.

6.2 Diffraction Correction

The DARA instrument has a defining aperture (5mm diam) in front of the instrument. The view limiting aperture (6.9 mm diam) is 54.1 mm behind the front (defining) aperture. Due to diffraction effects not all of the light entering the defining aperture will reach the cavity that is behind the view limiting aperture.

The amount of light that is lost due to diffraction depends on the wavelength and is therefore not the same when measuring the sun or measuring only at one wavelength at the TRF. Therefore it is necessary to apply a transfer factor that is the ratio of the diffraction corrections of the two individual corrections at 532 nm and for sunlight respectively.

These corrections have been determined with a computer program from the National Institute of Standards and Technology (NIST) [11]. Calculating the diffraction correction for the specific DARA geometry the convergence was not very reliable. So a rather high uncertainty is added to the diffraction transfer function.

	Cavity A	Cavity B	Cavity C
Air to Vacuum Correction	1.00022 ± 0.00015 (1σ)		1.00035 ± 0.0002 (1σ)
Diffraction Transfer Factor	1.0005 ± 0.0004 (syst)		1.0005 ± 0.0004 (syst)

Table 4: Transfer Factors

7 Uncertainty Budget

The contributions to the total uncertainty are listed in Table 5. The main contributions come from the WRR calibration in case of cavities B and C and also from the TRF calibration for cavity A. This is due to the large scatter of the instrument readings. For cavity A this can be seen in Figure 1. The large scatter is originating from unstable behaviour of the DARA controller loop. The source of this problem might be some interaction between the TRF laser scanning frequency and the DARA controller loop. For the calibration of cavity B and C the controller loop settings have been adjusted, so that there is less noise and more stable measurements.

	Cavity A	Cavity B	Cavity C
DARA readout electronics	0.00014	0.00014	0.00014
Air to vacuum Correction	0.00015		0.0002
Diffraction Transfer Factor	0.00023	0.00023	0.00023
WRR calibration	0.00035	0.00036	0.00036
TRF calibration	0.00037	0.00015	0.00015
Total uncertainty	0.00060	-	0.00051

Table 5: Relative Uncertainties (1σ level)

8 Results

Equation 1 shows how the WRR to SI ratio is computed. The ratio of the comparison DARA against the TRF is divided by the ratio of the comparison DARA to WRR. $C_{Air-Vac}$ and $C_{Diffraction-Transfer}$ are the transfer factors listed in Table 4.

$$\frac{WRR}{TRF(SI)} = \frac{(ratio\, DARA\, to\, TRF)}{(ratio\, DARA\, to\, WRR) \cdot C_{Air\, Vac} \cdot C_{Diffraction\, Transfer})} \tag{1}$$

Linking the results from the calibrations against the WRR and the cryogenic radiometer at the TRF, it is found that the WRR scale is 0.3% higher than the SI scale. Both cavities show a remarkably good agreement in this value. Table 6 shows the individual results for both instruments.

	Cavity A	Cavity C
WRR/TRF(SI)	1.0030 $\pm$ 0.0012	1.0029 $\pm$ 0.0010

Table 6: WRR to SI ratio with uncertainties (2σ)

9 Comparison with previous WRR to SI comparisons

Previously four WRR to SI comparisons have been carried out, starting in 1991. The 1991, the 1995 and the 2005 comparisons yielded results that were compatible with the assumption that the scales are equal within the uncertainties. The 2010 comparison however showed that there is a difference of 0.34 % between the scales. Unlike earlier comparisons the 2010 comparison was carried out in Irradinace mode. This means that the beam in the laboratory is overfilling the radiometer apertures when doing SI calibrations. This simulates a similar situation as the measurement of sunlight, whereas in the earlier comparisons the beam was underfilling the apertures. When doing the SI comparison in power mode, additional transfer factors, such as the aperture area and stray light corrections need to be taken into account. Fehlmann et al. [2] suggests that in the earlier comparison stray light was heavily underestimated. Table 7 shows the results from these comparisons. It can be seen that also in the 2010 comparison the Power Mode result is lower than the Irradiance mode result.

The new result agrees well with the result from 2010 (Irradiance Mode) and supports the findings that there is indeed a difference between the WRR and the SI scale.

Year	Publications	Ratio WRR/SI	Remarks
1991	[4] [9]	1.0011 $\pm$ 0.003 (2σ)	Power Mode
1995	[4] [10]	1.0013 $\pm$ 0.003 (2σ)	Power Mode
2005	[4]	0.9999 $\pm$ 0.0016 (2σ)	Power Mode
2010	[2]	1.0018 $\pm$ 0.0018 (2σ)	Power Mode
2010	[2]	1.0034 $\pm$ 0.0018 (2σ)	Irradiance Mode

Table 7: Results of the previous four WRR to SI comparisons

10 Comparison with the DARA absolute characterisation

The fact that the DARA instrument is reading about 2200 ppm lower than the cryogenic radiometer (Table 1) is not surprising as no corrections for lead heating and absorptivity are applied. The lead heating correction has been measured for the DARA cavities and has been found in the order of 500 to 600 ppm. This reduces the difference to the cryogenic radiometer. The remaining difference of roughly 1600 ppm can be explained by diffraction ($\approx 1000 \pm 300$ ppm) and reflectivity of the DARA cavities that has not yet been measured. The findings from the absolute characterisation of DARA, that however is not yet completed, already gives some hint to support its compatibility with the SI scale, rather than with the WRR scale.

11 Conclusion

This fifth WRR to SI calibration confirms the findings of Fehlmann et al. [2] that the WRR scale is higher than the SI scale. This confirmation is important as these scale differences also have implications on the value of the solar constant [2].

The DARA instrument has proven reliable as a transfer instrument. Especially the low air to vacuum ratio compared to PMO6 instruments will make this new generation of radiometers more suitable for such comparisons, as the air to vacuum ratio was always a major source of uncertainty.

Some improvements in reducing the uncertainties are possible by increasing the amount of data (air to vacuum ratio) and a more detailed treatment of the diffraction transfer factor. However the uncertainty of the WRR calibration is difficult to reduce as this is an outdoor measurement containing environment variables that cannot be controlled. Another improvement will be made when the air to vacuum ratio of cavity B is determined and a third result can confirm the findings of cavities A and C.

References

[1] R. W. Brusa and C. Fröhlich. Absolute radiometers (PMO6) and their experimental characterisation. *Applied Optics*, 25:4173–4180, 1986.

[2] A. Fehlmann, G. Kopp, W. Schmutz, R. Winkler, W. Finsterle, and N. Fox. Fourth World Radiometric Reference to SI radiometric scale comparison and implications for on-orbit measurements of the total solar irradiance. *Metrologia*, 49:34, April 2012.

[3] André Fehlmann. *Metrology of Solar Radiometry*. PhD thesis, Universität Zürich, 2011.

[4] W. Finsterle, P. Blattner, S. Moebus, I. Rüedi, C. Wehrli, M. White, and W. Schmutz. Third comparison of the World Radiometric Reference and the SI radiometric scale. *Metrologia*, 45:377–381, August 2008.

[5] R. Goebel, M. Stock, and R. Köhler. Report on the international comparison of cryogenic radiometers based on transfer detectors. *BIPM Report*, 2000.

[6] G. Kopp, K. Heuerman, D. Harber, and G. Drake. The TSI Radiometer Facility: absolute calibrations for total solar irradiance instruments. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 6677 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, October 2007.

[7] G. Kopp and G. Lawrence. The Total Irradiance Monitor (TIM): Instrument Design. *Solar Physics*, 230:91–109, August 2005.

[8] G. Kopp, G. Lawrence, and G. Rottman. The Total Irradiance Monitor (TIM): Science Results. *Solar Physics*, 230:129–139, August 2005.

[9] J. Romero, N. P. Fox, and C. Fröhlich. First Comparison of the Solar and an SI Radiometric Scale. *Metrologia*, 28:125–128, January 1991.

[10] J. Romero, N. P. Fox, and C. Fröhlich. Improved comparison of the World Radiometric Reference and the SI radiometric scale. *Metrologia*, 32:523, May 1996.

[11] E. L. Shirley and R. U. Datla. NIST Computer Program for Diffraction Corrections in Radiometry. Optical Properties and Infrared Technology Group, Optical Technology Division, 1999.