WMO International Pyrheliometer Comparison
IPC-XI
27 September - 15 October 2010
Davos, Switzerland

Final Report

Wolfgang Finsterle
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Chapter 1  Organization and Procedures

1.1  Introduction

The 11th International Pyrheliometer Comparison (IPC-XI) was held together with Regional Pyrheliometer Comparisons (RPCs) of all WMO Regional Associations (RA I to RA IV) from 27 September through 15 October 2010 at the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Centre (PMOD/WRC) in Davos, Switzerland.

The results presented in this report are based on the measurements carried out during the three weeks assigned to the IPC-XI. The favorable weather conditions allowed to acquire a large number of calibration points for most participating instruments. Cloudy and overcast days were used for technical preparations and training of participants as well as for a the IPC-XI symposium and Course on Radiation Measurement. A Saharan Dust Event (SDE) affected the measurements during several days starting October 8th. Analyzing the effect of the SDE on different types of instruments led to interesting findings which are summarized in dedicated section of this report.

1.2  Participation

Representatives from 17 Regional and 22 National Radiation Centers as well as 14 manufacturers and other institutions took part in the comparison. Additionally, two institutions who did not send a representative had their pyrheliometers operated by other participants, resulting in 88 participants operating 95 pyrheliometers from 42 countries. The six World Standard Group (WSG) and 24 additional pyrheliometers, including the new Cryogenic Solar Absolute Radiometer (CSAR), were operated by the WRC staff. A representative of WMO was attending during the first couple of days of IPC-XI.
Table 1.1: IPC-XI Participation: World, Regional and National Radiation Centers

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<td>WRC</td>
<td>Physikalisch-Meteorologisches Observatorium Davos/ World Radiation Center, Davos</td>
<td>W. Finsterle, A. Fehlmann, J. Gröbner, W. Schmutz, M. Suter, C. Thomann, C. Wehrli, R. Winkler (NPL)</td>
<td>PMO2, PMO5, CROM2L, PAC3, HF18748, MK67814, CIMEL, 0501657, 31144E6, DARA A, B, C, EPAC11402, CH1 970147, PMO6-0401, PMO6-79-122, PMO6-80022, AHF32455, CSAR, PMO6-0101, PMO6-0401, PMO6-0801, PMO6-0803, PMO6-0810, PMO6-0811, PMO6-0812, PMO6-0813, PMO6-0814, PMO6-0815, PMO6-0816, PMO8-P01, SIAR-2A, SIAR-2B</td>
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Table 1.2: IPC-XI Participation: Various Institutions and Manufacturers

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1.3 Data Acquisition and Evaluation

The signals from the WSG instruments and additional WRC radiometers were acquired by a new data acquisition system based on 17 National Instruments PXI-4065 6.5-digit digital multimeters with NI PXI-2501 24-channel multiplexers. The system was controlled by a LabView application running on an industrial PC and operated flawlessly. The LabView application also triggered the timing signals as well as the initialization and readout of the data entry form for manually operated instruments.
Organization and Procedures  Data Acquisition and Evaluation

(see below). The major operational advantage of this new system lies in the improved flexibility to add/remove instruments on the fly and to analyze data in near-real-time, allowing to quickly detect and fix potential problems with participating instruments, without loosing an entire day worth of measurements.

The participating instruments were operated with their standard pointing and data acquisition equipment, either manually or automated.

The data from the manually operated instruments were typed into a java based data entry form by the operator. WLAN connections were used to initialize the web interface and to dump its content to the central data acquisition computer at end of each measurement series. Participants could start the data entry form either on their own laptop computer or borrow one from the WRC. They were also required to keep written records as a backup copy of their data and to double-check for typing errors in the web interface.

The data from computer controlled instruments (synchronized to the timing of the IPC's measurement series) had to be written to ASCII files containing the instrument's serial number in the header and three columns for date, time, and irradiance, respectively. The ASCII files were then either uploaded to a dedicated directory on the IPC-XI FTP site or handed to the WRC staff on a USB memory stick. All data were ingested into the data acquisition and evaluation system at the end of each measurement day.

1.3.1 Timing of the Measurements

The measurements were taken in series of 21 minutes with a basic cadence of 90 seconds. Voice announcements and acoustic signals were used to inform the participants about the sequence of operation. All automated data acquisition systems were synchronized to Central European Time (CET). A network time server and a large reference clock on the measuring field were set up for this purpose. The time until the next measurement was also indicated on the web interface for manual operators. The timing for the different types of instrument was as follows:

- Ångström pyrheliometers: Before the start and after the end of the run the zero of the instrument was established. Alternating right and left strip readings were performed, starting with the right hand strip exposed to the sun. The following readings were paired as L-R, R-L, etc., yielding a total of 12 irradiance values per run.

- PAC3: the run started with the shutter closed, after 60 s the electrical heater\(^1\) was turned on for 40 s (this was introduced after IPC-III in order to have a well defined thermal state of the instrument independent of the operation sequence before the run). At 270 s the zero of the thermopile was read and the heater switched on for 180 seconds. At 450 s the heater voltage, current and thermopile were read, the heater turned off and the shutter opened. Starting at 540 s readings were taken every 90 s yielding 8 irradiance values per run. After the last reading the shutter was closed.

- HF- and TMI-type pyrheliometers: the run started with the shutter closed, after 90 s the thermopile zero was read and the electrical heater\(^1\) turned on until at 180 s the voltage, current and thermopile were read. The heater was then switched off and the shutter opened. From 270 s onward the thermopile signal was recorded every 90 s yielding 11 irradiance values per run. Some automated instruments performed the electrical calibration in between the series and/or read the irradiance every 30 seconds, consequently providing up to 39 irradiance values per run.

\(^1\)The heater voltage was manually selected before each run to match the expected level of solar irradiance.
• PMO-, SIAR- and CROM-type pyrheliometers: the run started with a reference phase (shutter closed) of 90 s, followed by a measurement phase (shutter open) of 90 s. This sequence was repeated for the next 18 minutes. A total of 6 open and 7 closed readings were taken yielding a total of 6 irradiance values during a run. PMO2 was read at twice that pace, with a reference phase of 45 s and a measurement phase of 45 s, producing 13 irradiance values per run so that for all readings of the basic sequence a PMO2 irradiance was available.

• Normal Incidence Pyrheliometers (NIP, CH1, etc.): These pyrheliometers recorded 12 irradiance values every 90 s after an initial zero reading at 90 seconds. Some instruments omitted the initial zero reading, thus yielding 13 irradiance readings.

• Other pyrheliometers: Prototype instruments such as the CSAR, DARA or TIM-Witness were using various modes of operation which are specific to their design. They all share the principle of electrical substitution and were synchronized to the 90-seconds base cadence.

1.3.2 Data Evaluation

For each instrument the irradiance was obtained with the appropriate evaluation procedure as listed below. After each day a graphical print-out of the ratios to PMO2 was put on display in the “Data Center” room to be reviewed by the participants. This simple but effective measure of quality control revealed instrumental problems in several cases which subsequently could be fixed quickly.

“Quick-look” print-outs were also produced during the day when an instrument was suspected to malfunction.

The procedure used to calculate the irradiance $S$ of each instrument type is described below. The notations are:

- $V_{th}$: output of the thermopile
- $U_h$, $U_i$: voltage across the heater (h) or across the standard resistor (i)
- $R_n$: standard resistor
- $C_1$: calibration factor
- $C_2$: correction factor for lead heating
- $P$: electrical power in the active cavities

• Ångström-pyrheliometers: the current through the right or left strip was measured as voltage drop across a standard resistor and the irradiance was obtained as:

$$S = C_1 \frac{U_i \text{(left)} U_i \text{(right)}}{R_n^2}$$

This corresponds to the geometric mean of the irradiances at the time of right and left readings. Thus, the ratio to WRR was calculated using the geometric mean of the WSG irradiances at the corresponding instances.

• PAC3, HF, and TMI type pyrheliometers: the irradiance was calculated from the thermopile output $V_{th}$ (irrad) when the receiver was irradiated. The sensitivity was determined by the calibration during which the cavity was shaded and electrically heated and $U_h$ and $U_i$ were measured together with the corresponding thermopile output $V_{th}$ (cal). Furthermore, the zero of the thermopile $V_{th}$ (zero) was measured and subtracted from all thermopile readings.

$$S = C_1 \frac{V_{th}\text{(irrad)} - V_{th}\text{(zero)}}{V_{th}\text{(cal)} - V_{th}\text{(zero)}} \frac{U_i}{R_n} \left( U_h - \frac{U_i}{R_n} C_2 \right)$$

• PMO-, SIAR- and CROM-type pyrheliometers: the irradiance was obtained from $P$ (closed) averaged from the closed values before and after the open reading $P$ (open).

$$S = C_1 (P\text{(closed)} - P\text{(open)})$$
The power calculation was done according to the prescription of the instrument type with

\[ P = U_i^2 \quad \text{or} \quad P = U_i U_i \quad \text{or} \quad P = U_i \frac{U_i}{R_{in}} \]

The SIAR-type radiometers slightly deviate from this scheme in that they subtract the open power from the preceding closed power rather than the average of the preceding and successive closed readings.

- Normal Incidence Pyrheliometer (NIP, CH1, etc.): the thermopile reading was divided by the calibration factor after subtraction of the zero point reading\(^1\).
- PMO2: As during preceding IPCs, PMO2 was used as the reference instrument for the daily summaries because it can be operated fast enough to provide an irradiance value every 90 seconds. The values of PMO2 were obtained with the algorithm for PMO-type pyrheliometers. At the end of the open phase, 6 readings were taken in rapid succession within about two seconds. The standard deviation of the 6 readings was used during the final evaluation as a quality control parameter to assess the atmospheric stability during each acquisition sequence (see Sect. 2.1).

### 1.3.3 Auxiliary Data

The meteorological parameters (air temperature, relative humidity, atmospheric pressure) were obtained from the MeteoSwiss' automated weather station SwissMetNet located at PMOD/WRC (see Sect. 4.2). Wind speed and direction sensors were set up at the south and west corners of the measuring field as well as by the WSG tracker.

A cloud sensor flagged all data points when clouds were within 15 degrees of the Sun. The flagged points were not used to evaluate Ångstrom type pyrheliometers.

Precision Filter Radiometers (PFR) were used to determine Aerosol Optical Depth (AOD) at four wavelengths (367.6 nm, 412.0 nm, 501.2 nm, and 862.4 nm, see Sect. 4.3).

The measurements and inversion results (mainly scattering phase functions) from the Aerosol Robotic Network (AERONET) Davos station (located at PMOD/WRC) were used to correct for aureole effects (circumsolar radiation) in cavity pyrheliometers according to their view-limiting geometry\(^2\).

### 1.4 Approval and Dissemination of the Results

According to Resolution 1 of CIMO-XI an Ad-hoc Group was established to discuss the preliminary results of the IPC-XI, based upon criteria defined by the WRC, evaluate the above reference and recommend the updating of the calibration factors of the participating instruments. It was chaired by the Bruce W. Forgan, (Australia, RA V) and composed as follows: Kolawole Muyiulu (Nigeria, RA I), Meena Lysko (South Africa, RA I), Rajendra Sharma (India, RA II), Pedro Mostraj Aquilera (Chile, RA III), David Halliwell (Canada, RA IV), Don Nelson (USA, RA IV), Thomas Carlund (Sweden, RA VI), Martin Mair (Austria, RA VI), Krunoslav Premec (Croatia, RA VI). The WRC was represented by Wolfgang Finsterle.

The procedures used to compute the new WRR factors of the WSG and participating instruments are explained in Section 2.2.

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\(^1\)Some operators assumed a vanishing zero signal. They did not perform zero readings.

\(^2\)The WMO CIMO Guide (WMO-No. 8) definition for direct solar radiation explicitly includes an aureole component. As to the view-limiting geometry the CIMO Guide further recommends "[...] that the opening half-angle be 2.5° and the slope angle 1°". We therefore apply a correction to reduce the aureole effect to the recommended view-limiting geometry. For instruments which obey the CIMO recommendations this correction vanishes (c.f. Sect. 2.5).
Chapter 2 Measurements and Results

Measurements were taken on 14 days (2010 September 28, October 2, 3, 4, and 6 - 15). October 8th and 12th were the most productive days, each yielding 17 series of 21 minutes duration. In total 164 series were acquired. All data from September 28th (1 series), October 2nd (10 series), 4th (3 series), and 6th (15 series) were rejected due to bad or unstable weather conditions on those days. Of the remaining days all data points that satisfy the following data selection criteria were considered in the final evaluation.

2.1 Data Selection Criteria for the Final Evaluation

The Ad-hoc Group responsible for the approval of the final evaluation procedure (c.f. Sect. 1.4) agreed on the following criteria for the acceptance of IPC-XI data:

1. Any series or part there-of were the field of view of Angstrom pyrheliometers is obscured by local topographic features (e.g. mountain sides) shall not be considered as valid data.

2. That no measurements be used for Angstrom pyrheliometers if a cloud is within 15 degrees of the sun. No measurements will be used for the absolute cavity radiometers (field of view = 5 degrees) if a cloud is within 8 degrees of the sun.

3. That no measurements be used if the wind speed is greater than 2.5 m/s.

4. That no data be used if the 500 nm AOD is greater than 0.120.

5. That an individual point be excluded from the series if the variation of the 8 fast PMO2 measurements is greater than 0.5 Wm$^{-2}$.

6. That a minimum of 150 acceptable data points be taken by PMO2 over a minimum of three days during the comparison period. 0.5 Wm$^{-2}$.

7. That the minimum number of acceptable data points be 150 for the PMO2 taken over a minimum of three days during the comparison period.

2.2 Computation of the New WRR Factors

2.2.1 WSG Instruments

The WRR factor $WRR_{i,IPC}$ for the WSG instrument $i$, $i \in \{\text{PMO2, CROM2L, MK67814, HF18748, PAC3, PMO5}\}$, by definition is the ratio of the WRR to the WSG instrument $i$ averaged over the duration of the IPC:

$$WRR_{i,IPC-XI} = \left\{ \frac{WRR(t)}{WSG_i(t)} \right\}_t,$$

where $WRR(t)$ and $WSG_i(t)$ are the reference irradiance and the irradiance measured by WSG instrument $i$ at the time $t$, and $\langle x(t) \rangle_t$ denotes the temporal average of $x(t)$. The reference irradiance ($WRR$) is defined as the mean value of the simultaneous readings of at least four WSG instruments, multiplied by their corresponding WRR factors from the previous IPC. Because the ratios of PAC3 and
Table 2.1: New WRR-factors for the WSG instruments computed using PMO2, PMO5, CROM2L, and MK67814 and the IPC-X WRR-factors.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>WRR factor</th>
<th>WRR factor</th>
<th>Standard Uncertainty</th>
<th># of points</th>
<th>Change [ppm]</th>
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<tbody>
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<td></td>
<td>IPC-X</td>
<td>IPC-XI</td>
<td>( \frac{\sigma}{\sqrt{N-1}} ) [ppm]</td>
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<td>5</td>
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<td>0.999052</td>
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<td>70</td>
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<td>CROM2L</td>
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<td>1.002117</td>
<td>26</td>
<td>381</td>
<td>1000</td>
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<td>HF18748</td>
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<td>0.997138</td>
<td>26</td>
<td>493</td>
<td>867</td>
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</table>

HF18748 with respect to the WRR suffered from inexplicable jumps during the past five years these two instruments were not used to compute the reference irradiance during IPC-XI. With \( j \in \{\text{PMO2}, \text{CROM2L}, \text{MK67814}, \text{PMO5}\} \) we calculate the reference irradiance as

\[
WRR(t) = \langle WS_G_j(t) \ast WRR_{j,\text{IPC-XI}} \rangle_j.
\]

We thus get

\[
WRR_{i,\text{IPC-XI}} = \left\langle \frac{\langle WS_G_j(t) \ast WRR_{j,\text{IPC-XI}} \rangle_j}{WS_G_i(t)} \right\rangle_t,
\]

where \( i \in \{\text{PMO2}, \text{CROM2L}, \text{MK67814}, \text{HF18748, PAC3, PMO5}\} \) and \( j \in \{\text{PMO2}, \text{CROM2L}, \text{MK67814, PMO5}\} \).

2.2.2 Participating Instruments

For each participating instrument \( k \) the new WRR factor is calculated according to

\[
WRR_{k,\text{IPC-XI}} = \left\langle \frac{WRR(t)}{Irr_k(t)} \right\rangle_t,
\]

where \( Irr_k(t) \) is the irradiance measured by the instrument \( k \) at the time \( t \) and \( WRR(t) \) the constantaneous reference irradiance.

Temporal averaging is done by fitting a gaussian to the distribution of WRR-to-instrument ratios. Outliers are successively removed until the ratios are normally distributed with a probability higher than 90%, or until all ratios are within a certain range of their arithmetic mean value\(^1\).

The new WRR factors for the WSG and all participating instruments are listed in Table 2.2.

2.3 Status of the WSG and Transfer of the WRR

The main objective of the periodic IPC’s is the dissemination of the World Radiometric Reference (WRR) in order to ensure worldwide homogeneity of meteorological radiation measurements. The

\(^1\)This threshold range usually is ±0.002 for cavity pyrheliometers. However, for most Ångströms, NIP's and some cavities a different range had to be chosen manually in order to make the most plausible selection of data points.
Measurements and Results

Status of the WSG and Transfer of the WRR

WRR is realized by the WSG which is frequently inter-compared at PMOD/WRC to detect possible deviations of individual radiometers with respect to the group average and to ensure the stability of the WRR. In addition to this internal stability check the stability of the WRR is assessed during IPCs by comparing the WSG to other pyrheliometers that have participated in previous IPC's.

Since IPC-X, which was held in 2005, two member instruments of the WSG failed in internal stability checks. The instrument HF18748 suffered from several sensitivity drops of up to \(-0.1\%\). The sensitivity of PAC3 also dropped sharply by \(-0.05\%\) in summer 2011. Non-intrusive checks of both instruments did not reveal any contamination in their cavities.

The WRR factors of the remaining four WSG instruments (PMO2, PMO5, CROM2L, MK67814) changed by less than \(\pm 50\) ppm per year. These instruments are considered stable over the past five years and were used to calculate the new WRR.

Table 2.2: The new WRR factors for the participating instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>(C_1)</th>
<th>(C_2)</th>
<th>WRR Factor</th>
<th>(\sigma) [ppm]</th>
<th>(N) used</th>
<th>(N) tot</th>
<th>Country/Owner</th>
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IPC-XI  

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Table 2.2: (continued)

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<th>Instrument</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>WRR Factor</th>
<th>$\sigma$ [ppm]</th>
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<td>1589</td>
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<td>TIM68016</td>
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<td>0.999858</td>
<td>758</td>
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<td>0.000</td>
<td>0.996804</td>
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<td>415</td>
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<td>0.000</td>
<td>0.998613</td>
<td>921</td>
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<td>0.000</td>
<td>1.000980</td>
<td>1049</td>
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<td>4686</td>
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<td>TIM69137</td>
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<td>1.001752</td>
<td>841</td>
<td>467</td>
<td>4520</td>
<td>Australia</td>
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</tbody>
</table>

2.4 External stability check of the WSG

In Section 2.3 the stability of the WSG was checked by analyzing the trends of individual members of the WSG with respect to the group’s average. Here we present an external assessment of the stability of the WSG with respect to all cavity radiometers which have participated in at least two IPCs since 1980 (c.f. Fig. 2.1). This analysis confirms the long-term stability of the WSG within the required uncertainty level of 0.3%. Compared to last IPC (IPC-X, 2005) the WRR factors of HF-type instruments changed by $-151$ ppm on average. For the “SlowRad” instruments the apparent change is $+316$ ppm. The statistical uncertainties (1-$\sigma$) of these averages are 340 ppm (HF) and 960 ppm ("SlowRad"), respectively. We thus conclude that the WSG has not significantly drifted over the past five years. For completeness the history of WRR factors since 1980 (IPC-V) is given in Table 2.3 for all participating instruments. Note that in this table the raw WRR factors are listed while normalized factors were used for assessing the stability of the WSG. Normalization was necessary because some instruments used different calibration factors at different times, which produces spurious changes in their WRR factors.

Table 2.3: The history of WRR factors. In this table the raw factors are listed. They depend on the calibration constant which was used which may have changed with time. In the WSG-stability analysis presented in Section 2.4 and Figure 2.1 these factors were re-normalized accordingly.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>IPC-V</th>
<th>IPC-VI</th>
<th>IPC-VII</th>
<th>IPC-VIII</th>
<th>IPC-IX</th>
<th>IPC-X</th>
<th>IPC-XI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A212</td>
<td>1.019121</td>
<td>0.999320</td>
<td>1.001542</td>
<td>1.001750</td>
<td>1.000560</td>
<td>1.003381</td>
<td>0.996482</td>
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Measurements and Results

<table>
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<th>External stability check of the WSG</th>
</tr>
</thead>
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<tr>
<td>A576</td>
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<td>A702</td>
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<td>A13439</td>
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<tr>
<td>A13444</td>
</tr>
<tr>
<td>A18020</td>
</tr>
<tr>
<td>CH1940072</td>
</tr>
<tr>
<td>EP A C11402</td>
</tr>
<tr>
<td>EP A C13617</td>
</tr>
<tr>
<td>HF15744</td>
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<tr>
<td>HF17159</td>
</tr>
<tr>
<td>HF17162</td>
</tr>
<tr>
<td>HF18747</td>
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<tr>
<td>HF19746</td>
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<tr>
<td>HF20406</td>
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<td>HF21574</td>
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<tr>
<td>HF27159</td>
</tr>
<tr>
<td>HF27162</td>
</tr>
<tr>
<td>HF27796</td>
</tr>
<tr>
<td>HF29223</td>
</tr>
<tr>
<td>AHF14915</td>
</tr>
<tr>
<td>AHF17142</td>
</tr>
<tr>
<td>AHF18742</td>
</tr>
<tr>
<td>AHF21670</td>
</tr>
<tr>
<td>AHF21798</td>
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<td>AHF22853</td>
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<td>AHF22896</td>
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<td>AHF30497</td>
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<td>AHF30716</td>
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<td>AHF31041</td>
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<td>AHF31105</td>
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<td>TM69137</td>
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<tr>
<td>MAR-1-2</td>
</tr>
<tr>
<td>CR0M9L</td>
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</tbody>
</table>
2.5 Saharan Dust Event (SDE)

During the night of October 7th/8th a dust cloud from the Sahara desert has been transported over Switzerland by high-altitude winds. The appearance of the dust particles is reflected in an excess of large particles (> 1 μm) in the AERONET inversion results on the corresponding days (c.f. Fig. 2.2). The particle distribution significantly affects the scattering phase function (scattering angle) and thus changes the aureole radiation. Instruments with different view-limiting geometries see either more or less of this change. We use the view-limiting geometries from Table 2.4 together with the scattering phase functions (see Sect. 4.5), the Aerosol Optical Depth (AOD, see Sect. 4.3), and other scattering parameters (Sect. 4.4) to calculate the aureole correction with SMARTS (Gueymard, C. A., Solar Energy, 71(5), 2001) depending on the view-limiting geometry of each type of cavity radiometer.

The aureole correction is calculated with respect to the view-limiting geometry recommended by the CIMO Guide. Hence, all HF- and PMO6-type radiometers which follow the CIMO recommendations very closely do not need this correction, although we applied it for sake of consistency. On the other hand, on October 8th the correction can be as large as −0.2% in the case of the SIAR. Also PMO2 and PMO5 require large corrections of −500 ppm and +600 ppm, respectively.

The correction factors for the WSG are plotted in Figure 2.3.

---

2 Interestingly, the SDE effect is not very distinct in most Ångströms (c.f. Chap. 3.1). Probably because the area of sky at large angular distance from the sun is small in the elongated field-of-view. In other words, the “radiation-weighted” effective field-of-view of Ångströms might not be too different the CIMO recommendations. Because of the smallness of the SDE effect and the difficulties to reduce the rectangular to a circular view-limiting geometry we did not apply the SDE correction to Ångströms. In the case of thermopile instruments (NIPs, CH1s etc.) their level of accuracy does not warrant to apply the correction.
Figure 2.1: The historic development of the WRR factors of all cavity radiometers which have participated in at least two IPC’s since 1980 (IPC-V). The top panel shows how the WRR factors of HF-type pyrheliometers (including PAC, EPAC, and TMI) changed between consecutive IPCs since 1980 (IPC-V). The same is shown on the bottom panel for “SlowRad”-type radiometers, i.e. radiometers with alternating open/closed measurements. Note that in this analysis all WRR factors are normalized to the calibration constant which was used at the time.
Figure 2.2: The size distribution of aerosol particles measured by the AERONET Davos station on October 7th (top panel) and 8th (bottom panel). The excess in large particles (> 1µm) gradually normalizes during the following week. The size distribution significantly affects the scattering phase function and thus the aureole radiation.
Figure 2.3: The aureole correction before and during the Saharan dust event depending on type of instrument. The correction was applied to all cavity instruments. In the top panel the symbols for HF/AHF are hidden behind MK/TMI, CROM, and EPAC. (Calculations and graphics by André Fehlmann.)
Table 2.4: The view-limiting geometries for each type of instrument (all dimensions in mm).

<table>
<thead>
<tr>
<th>Instrument (Type)</th>
<th>front aperture radius</th>
<th>rear aperture radius</th>
<th>distance between apertures</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM02</td>
<td>3.6</td>
<td>2.5</td>
<td>75.0</td>
</tr>
<tr>
<td>PM05</td>
<td>3.7</td>
<td>2.5</td>
<td>95.4</td>
</tr>
<tr>
<td>PM06</td>
<td>4.2</td>
<td>2.5</td>
<td>98.5</td>
</tr>
<tr>
<td>PAC3</td>
<td>8.18</td>
<td>5.64</td>
<td>190.5</td>
</tr>
<tr>
<td>CR0M2L</td>
<td>6.29</td>
<td>5.0</td>
<td>144.05</td>
</tr>
<tr>
<td>HF</td>
<td>5.81</td>
<td>3.99</td>
<td>134.7</td>
</tr>
<tr>
<td>TMI</td>
<td>8.2</td>
<td>5.56</td>
<td>187.6</td>
</tr>
<tr>
<td>SIAR</td>
<td>5.7</td>
<td>4.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Chapter 3  Conclusions and Recommendations

Despite the partial failure of two WSG instruments (PAC3 and HF18748, c.f. Sect. 2.4) the WRR is considered stable within the limits required by the WMO-CIMO Guide. The new WRR factors are calculated based on the average readings of PMO2, PMO5, CROM2L, and MK67814. Compared to IPC-X most participating instruments show insignificant changes in their WRR factors, which confirms the stability of the WRR. The recommended WRR factors are listed in Table 2.2.

The flexibility offered by the new data acquisition system allowed for quick response in case of suspected problems with individual instruments. In several cases small stability issues of participating instruments could be identified and fixed with only minimal loss of observing time.

The Saharan Dust Event (SDE) which affected the measurements from October 8th through 13th revealed the susceptibility of direct solar irradiance measurements to atmospheric conditions and emphasized the importance to follow the recommendations concerning view-limiting geometry. While it was possible to compensate for the geometry-induced SDE effect the required auxiliary data (AOD, scattering phase function) and sophisticated models are not normally available at field sites. We thus strongly recommend the use of pyrheliometers which obey the CIMO recommendations for view-limiting geometry.

3.1 Graphical Representation of the Results

On the following pages are the data plots for each instrument. The deviation from WRR is plotted in percents. All the points which were used for the analysis (i.e., the points fulfilling the selection criteria listed in Sect. 2.1) have been plotted with a corresponding histogram on the side.
Graphical Representation of the Results

Conclusions and Recommendations

0501657: WRR factor=1.014360, σ=0.010459, n=551

080002: WRR factor=1.000250, σ=0.001669, n=547

080004: WRR factor=1.007380, σ=0.004469, n=417
Conclusions and Recommendations

Graphical Representation of the Results

080015: WRR factor=0.997799, $\sigma=0.001671$, n=554

0804: WRR factor=0.999914, $\sigma=0.000645$, n=364

090090: WRR factor=1.003660, $\sigma=0.001191$, n=554
Graphical Representation of the Results

Conclusions and Recommendations

- **21451E6**: WRR factor = 0.999193, $\sigma = 0.007685$, $n = 453$
- **25738E6**: WRR factor = 0.998843, $\sigma = 0.006614$, $n = 453$
- **28335**: WRR factor = 1.009040, $\sigma = 0.005413$, $n = 424$
Conclusions and Recommendations

Graphical Representation of the Results

31144E6: WRR factor=0.997184, σ=0.005621, n=554

79-122: WRR factor=0.999401, σ=0.000638, n=540

79-123: WRR factor=0.937200, σ=0.005746, n=344
Graphical Representation of the Results

Conclusions and Recommendations

80022: WRR factor=1.003080, σ=0.000541, n=493

850402: WRR factor=1.003287, σ=0.001234, n=102

850405: WRR factor=1.000560, σ=0.001610, n=420
Conclusions and Recommendations

Graphical Representation of the Results

850409: WRR factor=1.004180, σ=0.000576, n=539

970147: WRR factor=0.996057, σ=0.001739, n=554

A12578: WRR factor=1.008580, σ=0.004598, n=134
A13439: WRR factor=1.001350, σ =0.001471, n=396

A13444: WRR factor=1.036800, σ =0.003676, n=312

A18020: WRR factor=1.002650, σ =0.001472, n=323

Graphical Representation of the Results

Conclusions and Recommendations
Conclusions and Recommendations

Graphical Representation of the Results

A212: WRR factor=0.996482, $\sigma$=0.003106, n=258

A26839: WRR factor=1.007550, $\sigma$=0.002085, n=361

A576: WRR factor=0.990369, $\sigma$=0.003963, n=382
Graphical Representation of the Results

Conclusions and Recommendations

A702: WRR factor=0.998769, $\sigma=0.004789$, n=373

AHF-AWX34320: WRR factor=0.992830, $\sigma=0.000839$, n=442

AHF-AWX34321: WRR factor=0.994550, $\sigma=0.000843$, n=442
Conclusions and Recommendations

Graphical Representation of the Results

AHF14915: WRR factor=0.999682, σ=0.000920, n=392

AHF17142: WRR factor=0.998358, σ=0.000908, n=397

AHF18742: WRR factor=1.002280, σ=0.002283, n=361
Graphical Representation of the Results

Conclusions and Recommendations

AHF23734: WRR factor = 0.998281, $\sigma = 0.000659$, n = 412

AHF27798: WRR factor = 0.999018, $\sigma = 0.000989$, n = 395

AHF28486: WRR factor = 0.997308, $\sigma = 0.000672$, n = 422
Graphical Representation of the Results

Conclusions and Recommendations

AHF29223: WRR factor=0.997352, \( \sigma = 0.000739 \), n=384

AHF29225: WRR factor=0.996896, \( \sigma = 0.001026 \), n=336

AHF30112: WRR factor=1.011730, \( \sigma = 0.001995 \), n=74
Conclusions and Recommendations

Graphical Representation of the Results

AHF30713: WRR factor=0.997548, σ =0.000679, n=421

AHF30716: WRR factor=0.997136, σ =0.000656, n=360

AHF31041: WRR factor=0.996286, σ =0.000699, n=441
Conclusions and Recommendations

Graphical Representation of the Results

AHF32446: WRR factor = 1.000050, \( \sigma = 0.000745 \), \( n = 444 \)

AHF32455: WRR factor = 1.000280, \( \sigma = 0.000596 \), \( n = 401 \)

AHF33396: WRR factor = 0.998079, \( \sigma = 0.000924 \), \( n = 396 \)
AHF36011: WRR factor=0.996933, σ =0.002191, n=367

AHF36013: WRR factor=1.058110, σ =0.002462, n=384

AWX31114: WRR factor=1.001240, σ =0.000893, n=462
Conclusions and Recommendations

Graphical Representation of the Results

AWX32448: WRR factor=0.999939, $\sigma=0.001149$, $n=465$

AWX33393: WRR factor=0.999362, $\sigma=0.000819$, $n=427$

CH1020283: WRR factor=0.997677, $\sigma=0.001423$, $n=516$
Graphical Representation of the Results

**Conclusions and Recommendations**

**CH1060460**: WRR factor = 1.002330, \( \sigma = 0.002039 \), \( n = 449 \)

**CH1930018**: WRR factor = 1.000750, \( \sigma = 0.003259 \), \( n = 453 \)

**CH1940068**: WRR factor = 0.997717, \( \sigma = 0.000954 \), \( n = 147 \)
Conclusions and Recommendations

Graphical Representation of the Results

CH1940072: WRR factor = 1.007580, σ = 0.002526, n = 439

CH1950086: WRR factor = 1.005040, σ = 0.001323, n = 329

CHP100288: WRR factor = 0.999634, σ = 0.001924, n = 434

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Graphical Representation of the Results

Conclusions and Recommendations

CHP1100245: WRR factor=1.000490, $\sigma =0.001414$, $n=449$

CHP1REF1: WRR factor=0.997956, $\sigma =0.001897$, $n=179$

CP01P: WRR factor=1.021933, $\sigma =0.000905$, $n=47$
Conclusions and Recommendations

Graphical Representation of the Results

**CP01T**: WRR factor = 1.008928, \( \sigma = 0.000635 \), n = 47

**CP01U**: WRR factor = 1.018302, \( \sigma = 0.001805 \), n = 49

**CR09L**: WRR factor = 0.998363, \( \sigma = 0.000881 \), n = 220
CROM2L: WRR factor = 1.003166, \(\sigma = 0.000451\), n = 544

CSAR: WRR factor = 0.992123, \(\sigma = 0.000515\), n = 28

DARAAREFB: WRR factor = 1.004210, \(\sigma = 0.000847\), n = 143
Conclusions and Recommendations

Graphical Representation of the Results

**DARAAREFC**: WRR factor = 1.004358, \( \sigma = 0.001266 \), \( n = 141 \)

**DARABREFC**: WRR factor = 1.006060, \( \sigma = 0.001339 \), \( n = 214 \)

**DARACREFB**: WRR factor = 1.004984, \( \sigma = 0.001168 \), \( n = 143 \)
Conclusions and Recommendations

Graphical Representation of the Results

HF15744: WRR factor=0.998085, σ=0.000707, n=303

HF18747: WRR factor=1.001870, σ=0.000731, n=483

HF18748: WRR factor=0.997230, σ=0.000569, n=493
Graphical Representation of the Results

Conclusions and Recommendations
Conclusions and Recommendations

Graphical Representation of the Results

HF27159: WRR factor = 1.000020, $\sigma = 0.000950$, $n = 514$

HF27160: WRR factor = 0.996467, $\sigma = 0.000777$, $n = 468$

HF27162: WRR factor = 0.999212, $\sigma = 0.001049$, $n = 345$
Graphical Representation of the Results

Conclusions and Recommendations
Conclusions and Recommendations

Graphical Representation of the Results

**MAR-1-3: WRR factor=0.999991, \( \sigma =0.000884 \), n= 92**

**MK67814: WRR factor=1.000450, \( \sigma =0.000466 \), n=497**

**MS54-S07122: WRR factor=1.003000, \( \sigma =0.001012 \), n= 94**
Graphical Representation of the Results

Conclusions and Recommendations

\[ NIP31822E6: \text{WRR factor}=0.996873, \sigma=0.005184, n=349 \]

\[ PAC3: \text{WRR factor}=1.002195, \sigma=0.000510, n=381 \]

\[ PMO2: \text{WRR factor}=0.998604, \sigma=0.000691, n=554 \]
Conclusions and Recommendations

Graphical Representation of the Results

**PMO5: WRR factor=0.999044, \( \sigma =0.000528 \), n=554**

![Graph for PMO5](image1)

**PMO6-0101-CERNY-PS: WRR factor=1.005155, \( \sigma =0.000465 \), n=437**

![Graph for PMO6-0101-CERNY-PS](image2)

**PMO6-0101-CERNY-T: WRR factor=1.004938, \( \sigma =0.000505 \), n=486**

![Graph for PMO6-0101-CERNY-T](image3)
Graphical Representation of the Results

**PMO6-0301: WRR factor=1.000588, σ=0.000821, n=426**

**PMO6-0401D: WRR factor=1.020980, σ=0.000488, n=312**

**PMO6-0405: WRR factor=0.999684, σ=0.000594, n=414**
Conclusions and Recommendations

Graphical Representation of the Results

PMO6-0801D: WRR factor=1.137201, \( \sigma =0.001542, n=484 \)

PMO6-0802: WRR factor=1.001435, \( \sigma =0.034318, n=161 \)

PMO6-0803D: WRR factor=1.000364, \( \sigma =0.000473, n=312 \)
Graphical Representation of the Results

PMO6-0810D: WRR factor=1.018938, σ=0.000509, n=389

PMO6-0811D: WRR factor=1.000835, σ=0.000542, n=496

PMO6-0812D: WRR factor=1.004392, σ=0.000671, n=501

Conclusions and Recommendations
Conclusions and Recommendations

Graphical Representation of the Results

PMO6-0814D: WRR factor=1.002749, \( \sigma =0.000745 \), \( n=271 \)

PMO6-0815D: WRR factor=1.001582, \( \sigma =0.000549 \), \( n=458 \)

PMO6-0816D: WRR factor=1.015310, \( \sigma =0.008572 \), \( n=242 \)
Graphical Representation of the Results

Conclusions and Recommendations

PMO6-5: WRR factor=0.999116, σ=0.000725, n=419

PMO6-81109: WRR factor=0.998577, σ=0.000708, n=426

PMO6-850410: WRR factor=0.990890, σ=0.001145, n=434
Conclusions and Recommendations

Graphical Representation of the Results

PMO6-911204: WRR factor=0.999711, σ=0.001049, n=437

PMO6-CC0403: WRR factor=1.000160, σ=0.000732, n=425

PMO6850406: WRR factor=1.000200, σ=0.000877, n=323
Graphical Representation of the Results

PMO8-P01: WRR factor = 0.994812, σ = 0.006959, n = 497

PMO811108: WRR factor = 1.000660, σ = 0.000727, n = 417

SIAR-1A: WRR factor = 1.002400, σ = 0.000997, n = 440

Conclusions and Recommendations
Conclusions and Recommendations

Graphical Representation of the Results

SIAR-2A: WRR factor=0.991696, $\sigma=0.000732$, $n=495$

SIAR-2B: WRR factor=1.000290, $\sigma=0.000668$, $n=427$

SIAR-2C: WRR factor=0.999839, $\sigma=0.001125$, $n=441$
Graphical Representation of the Results

Conclusions and Recommendations

**TIM-WITNESS:** WRR factor = 0.997303, \( \sigma = 0.001417, n = 278 \)

**TMI67502:** WRR factor = 0.999294, \( \sigma = 0.001024, n = 454 \)

**TMI67604:** WRR factor = 0.998226, \( \sigma = 0.001341, n = 440 \)
Conclusions and Recommendations

Graphical Representation of the Results

TMI68016: WRR factor = 0.999858, σ = 0.000758, n = 462

TMI68018: WRR factor = 0.996804, σ = 0.000642, n = 415

TMI68025: WRR factor = 0.998613, σ = 0.000920, n = 436
Graphical Representation of the Results

Conclusions and Recommendations

TMI68835: WRR factor=1.000980, σ=0.001050, n=436

TMI69137: WRR factor=1.001750, σ=0.000843, n=467
Chapter 4  Auxiliary Data

4.1  Direct and Diffuse Irradiance

Direct (WRR) and diffuse irradiance (shaded K&Z CM22 S/N 020059).
4.2 Meteorological Data

Meteorological parameters measured by the SwissMetNet Davos station of MeteoSwiss (adjacent to IPC-XI measuring field).
A four-channel Precision Filter Radiometer (PFR) was used to determine AOD.
4.4 Scattering parameters

Ångström exponents ($\alpha$) from PFR AOD data. Scattering asymmetry, single scattering albedo (SSA), and water column ($H_2O$) based on data from the AERONET Davos station. Ozon ($O_3$) measured by the WRC Brewer #163.
4.5 Scattering phase functions

Scattering phase functions derived from AERONET inversions. These data were used to correct for the aureole effect in pyrheliometers with non-standard viewing geometries.
Chapter 5  Symposium

5.1  To Build and Share Knowledge

On cloudy, overcast, or rainy days when no measurements were possible the IPC-XI symposium and course on radiation measurement were held. Radiation experts from PMOD/WRC as well as may IPC-XI participants presented their work and/or national radiation infrastructure in order to share and build knowledge.

Over the three weeks, more than 30 talks and presentations were given, most of which are available for download on the IPC-XI ftp site ftp://ftp.pmodwrc.ch/stealth/ipc-xi.

5.2  Artistic Representation

During IPC-XI an art photographer was collecting photographic and video material for an art project in Bergen, Norway. Many of the photographs as well as a short movie are available on the IPC-XI ftp site ftp://ftp.pmodwrc.ch/stealth/ipc-xi/presentations/from ellen/.
Chapter 6 Supplementary Information

6.1 Addresses of Participants
### Addresses of Participants

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