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Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference

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ABSTRACT

This report describes the present method of establishing traceability of absolute cavity radiometers to the World Radiometric Reference (WRR) through the process employed in the International Pyrheliometer Comparisons (IPC). This method derives the WRR reduction factor for each of the participating cavity radiometers. An alternative method is proposed, described, and evaluated as a way to reduce the uncertainty in the comparison process. The two methods are compared using a sample of data from the recent IPC-VIII conducted from September 25th to October 13th, 1995 at the World Radiation Center in Davos, Switzerland. A description of absolute cavity radiometers is also included, using a PMO-6 as an example of active cavity radiometers, and a HF as an example of passive cavity radiometers.

Acknowledgements

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CHAPTER 1

Introduction

1.1 The World Radiometric Reference

The World Meteorological Organization (WMO) is an intergovernmental organization sponsored by the United Nations through which the United States and more than 160 other nations cooperate in meteorological and weather related science and engineering. The WMO promotes the development of reference instruments; conducts world wide and regional field comparisons and evaluations; and recommends test and calibration methods, and the corrections applied. WMO sanctions the Physikalisch Meteorologisches Observatorium Davos (PMOD) as its World Radiation Center to establish, maintain, and propagate to users the engineering measurement scale for solar radiation measurements called the World Radiometric Reference (WRR). This measurement scale is used by all nations that acquire and report solar radiation measurement data for weather and meteorological purposes, for solar energy and engineering purposes, and for space research.

The accuracy, precision, and stability of the WRR is crucial for current scientific and engineering activities. These activities include the developing, testing, and using solar energy devices and technologies; meteorological, weather and global climate change measurements and research; and solar research from space.[1] WRR was established through special comparisons, in 1977, of 15 absolute cavity radiometers of 9 types. Since WRR was established, the goal has been to ascertain and maintain its stability, accuracy, and precision through the World Standard Group (WSG) instruments.[2] This is necessary so that scientists and engineers have a common internationally accepted reference

for technical data and can accurately measure trends, such as changes in the world climate.

The following seven absolute cavity radiometers (three from the United States and four from Europe) now form the World Standard Group (WSG) that maintain WRR:

1.*PACRAD III: Built by and on indefinite loan from the United States' National Aeronautics and Space Administration.

2.*PMO-2: Built by and contributed by the Physikalisch Meteorologisches Observatorium Davos, Switzerland.

3. PMO-5: Built by and contributed by the Physikalisch Meteorologisches Observatorium Davos, Switzerland.

4.*CROM-2: Built by and contributed and operated by the Institute Royal Meteorologique de Belgique, Belgium.

5.*CROM-3: Built by and contributed and operated by the Institute Royal Meteorologique de Belgique, Belgium.

6. TMI-67814: Built by Technical Measurements, Inc. (TMI) and loaned from the National Renewable Energy Laboratory, Golden, CO, USA.

7. HF-18748: Built and contributed by The Eppley Laboratory Newport, RI, USA.

The four asterisked (*) instruments were part of the original group of instruments that were used in the initial development and definition of WRR; they have served as part of the WSG ever since.[1]

1.2 Radiometry at the Physikalisch Meteorologisches Observatorium Davos (PMOD)

The design and construction of absolute radiometers at PMOD started in the early seventies. Due to their primary use, the measurement of solar irradiance, these radiometers are optimized to measure irradiances around 1 Kw/m^2. The first model built was the PMO-2, which is since 1975 one of the World Standard Group (WSG) realizing the World Radiometric Reference (WRR). Since then a more refined version of the PMO radiometers (PMO-6) has been developed. Such instruments are used for the solar constant experiments of PMOD and for the subsistence of the World Standard Group.[2]

In order to assess the uncertainties of this kind of absolute radiometry more accurately, an important effort was put into the development of independent laboratory experiments. These are called characterization and consist of the accurate determination of all deviations of the radiometer from its ideal behavior.[2]

The calibration factor of absolute cavity radiometers is a function of: radiation loss (E_R), non-equivalence of the radiative and electrical heating (E_{NE}), scattered light (E_{ST}), diffraction losses (E_D), lead heating effect (E_{LE}) and area of the precision aperture. It is the uncertainty of these factors that determines the accuracy of the radiometer. The following accuracies were achieved in characterizing the PMO-6 absolute cavity radiometers:

a) The precision aperture diameter is measured with an accuracy greater than ±0.5 μm (±0.02 percent), and roundness with accuracy greater than ±0.2 μm.

b) The radiation loss is measured with an accuracy on the

order of ±0.005 percent.

c) The non-equivalence between solar irradiance and electrical heating is measured with accuracy ±0.05 percent.

d) The scattered light is measured with accuracy ±0.01 percent.

e) The leads heating is measured with accuracy ±0.001 percent.

f) The diffraction losses correction is normally neglected in solar measurements and as the different radiometers have very similar corrections, this effect is left out.[2]

1.3 Organization and sequence

This report is divided into eight chapters. Chapter 2 describes the PMO-6 absolute cavity radiometer as an example of active cavity radiometers. Chapter 3 describes first, the HF absolute cavity radiometer as an example of passive cavity radiometers; second, its recommended electrical calibration procedure during the outdoor comparisons of absolute cavity radiometers. Chapter 4 contains the calibration procedure of the International Pyrheliometer Comparisons IPC-VIII. Chapter 5 describes the PMOD method used to derive the WRR reduction factors for all the participating instruments, including those in the World Standard Group (WSG). Chapter 6 describes the proposed method to derive the WRR reduction factors in an effort to reduce the random component. Chapter 7 contains the calculations (using the two methods) of the WRR reduction factors for, HF28968 absolute cavity radiometer and each of the WSG instruments, using a sample of data collected during IPC-VIII. Chapter 8 reports the observations and conclusions.

CHAPTER 2

PMO-6 Absolute Cavity Radiometer

2.1 Description

The design of the PMO-6 absolute cavity radiometer is based on the principle of an electrically calibrated differential heat flux transducer with a cavity for the efficient absorption of the radiation to be measured. The cavity, which has an inverted cone inside a cylindrical shield, is painted with a specular black paint and is tied to a heat sink through a stainless steel thermal impedance. For the measurement of solar radiation, a view-limiting baffle mounted in front of the detector provides a full field of view of 5 degrees (the detector system is shown in Fig. 2.1). Only the primary cavity is used for radiation measurements. The temperature difference across the thermal impedance, sensing the heat flux, is measured with resistance thermometers mounted on the two cavities and not between the primary cavity and the heat sink. This differential arrangement compensates for the sudden changes in temperature of the heatsink and the rapid pressure changes, as long as the thermal time constants of the two cavity-thermal-impedance systems are equal.[2]

2.2 Operation

The instrument is operated in the "active" mode. That is, the temperature difference between the two cavities, the primary cavity and the compensating cavity, is kept constant by an automatic control loop for the current of the primary cavity's heater. Thus the difference in electrical power during the reference phase (electrical heating only) and during the irradiance phase (electrical and radiative

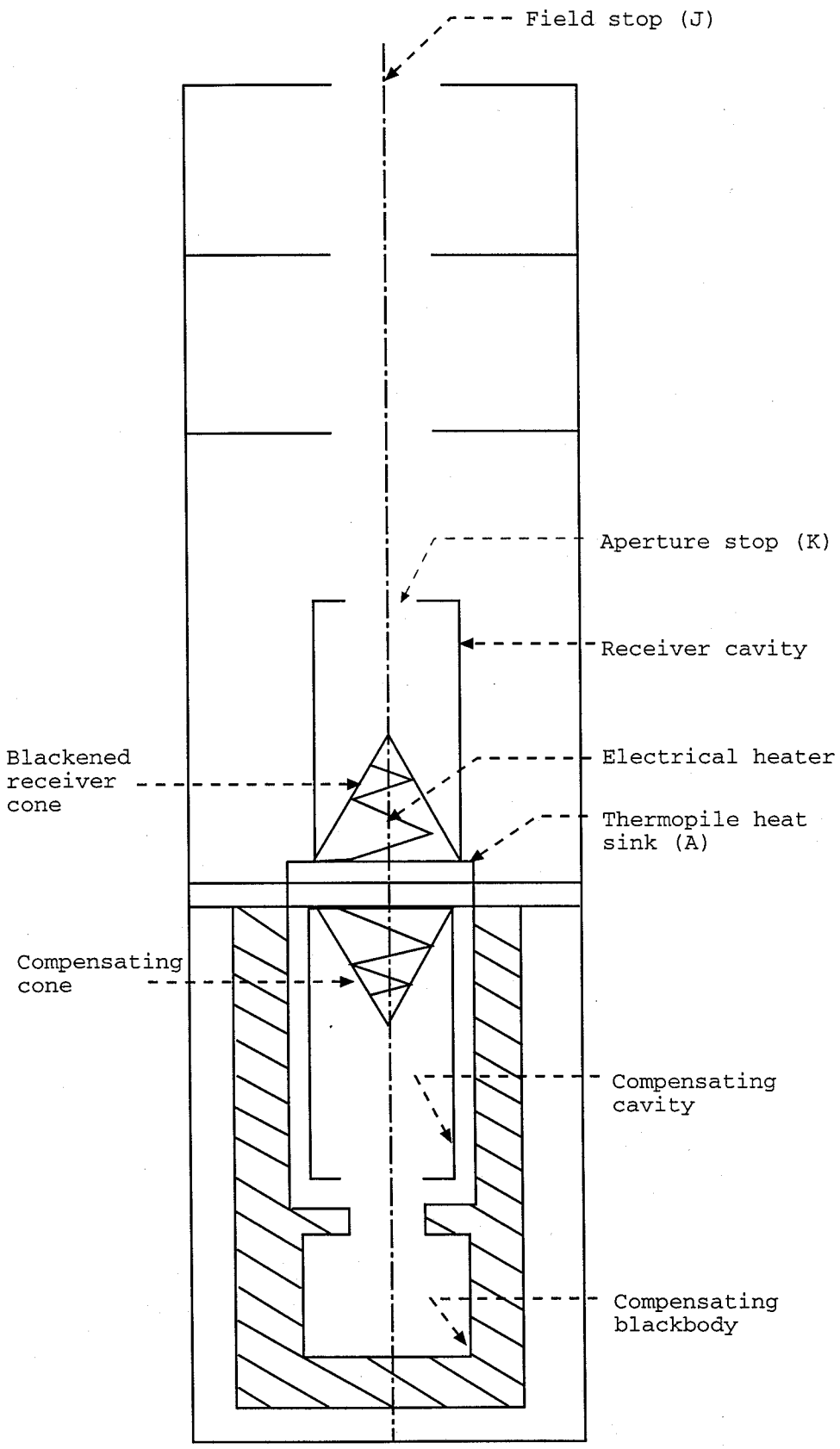


Fig.2.1 The Detector System for PMO-6

heating) is proportional to the incoming radiation, S,

$$S = k(P_{closed} - P_{open}), \qquad (2.1)$$

where:

P_{closed} = the electrical power (voltage times current) applied to the primary cavity when no radiation is applied to it and the primary aperture's shutter is closed. This power is always kept at equilibrium with the power applied to the compensating cavity using a current control loop

P_{open} = the power measured at the primary cavity when the solar radiation is applied and the primary aperture's shutter is open.

In equation (2.1), the parameter k is the calibration factor,

$$k = \frac{E_R \cdot E_{NE} \cdot E_{ST} \cdot E_D \cdot E_{LH}}{A_p}, \qquad (2.2)$$

where:

E_R = the radiation losses coefficient due to the finite reflectivity and the infrared emission of the heated black coating of the cavity

E_{NE} = the non-equivalence coefficient due to the effect of different temperature distributions during electrical and combined radiative and electrical heating

E_{ST} = the scattered light coefficient produced by the light reflected from the precision aperture to the baffle and back into the cavity

E_D = the diffraction losses coefficient due to diffracted light in the cavity

E_{LH} = the lead heating effect coefficient due to the heating of leads feeding the current to the cavity heater

A_P = the area of the precision aperture.[2]

CHAPTER 3

HF Absolute Cavity Radiometer

3.1 Description

The self-calibrating absolute cavity radiometer model HF, manufactured by The Eppley Laboratory, has been a reference standard level device since 1978. The sensor was originally developed for measurements from satellites and rockets. It consists of a balanced cavity receiver pair attached to a circular wire-wound and plated thermopile (Figs. 3.1, 3.2). The blackened cavity receivers are fitted with heater windings which allow for absolute operation using the electrical substitution method, which relates radiant power to electrical power in SI units (International System).

The forward cavity views the direct solar beam through a precision aperture having an area of 50 mm^2. The rear receiver views an ambient temperature blackbody. The HF radiometer element with baffle tube and blackbody are fitted into an outer tube that encloses the instrument.[3]

The cavity radiometer is operated, and the required parameters are measured, using an appropriate control box. The cavity can be operated in either manual or automatic mode. In the manual mode, the shutter can be controlled remotely from the control box and the data from the digital multimeter is logged manually. In the automatic mode, the cavity is controlled through a computer program, normally Quick Basic or Visual Basic. The program controls all operations, calculates sensitivities and irradiance results, performs first level statistical analysis, and stores and backs up all data. The control functions include shutter control, setting of the calibration heater power level,

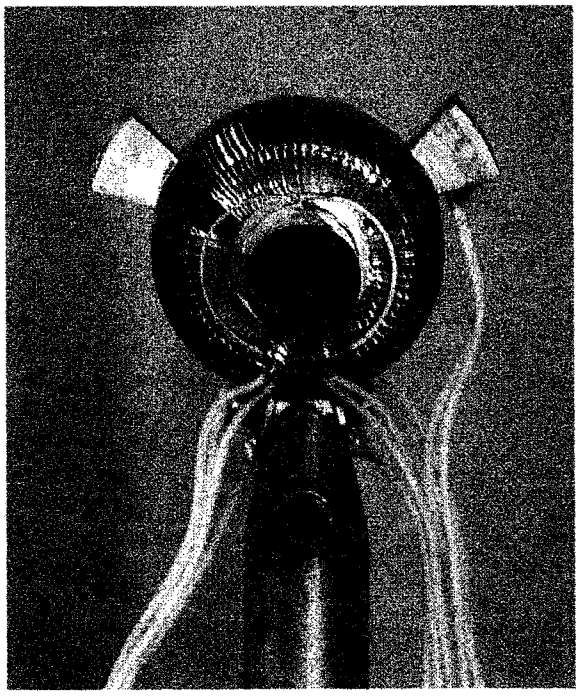


Fig. 3.1 HF Sensing Element, Front View

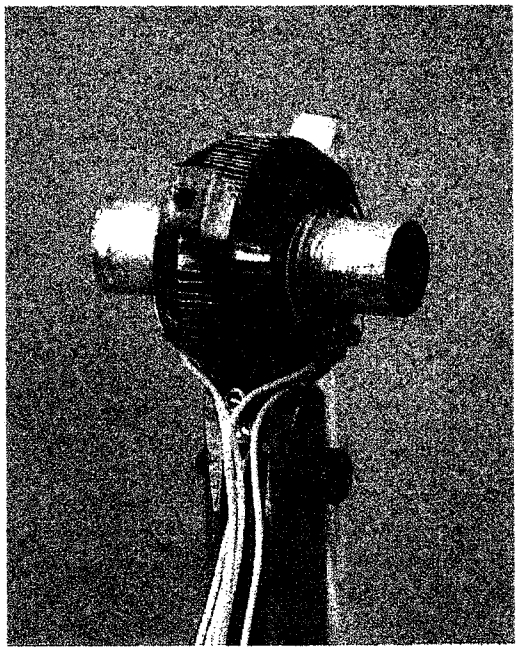


Fig.3.2 HF Sensing Element, Side View

activation of the calibration heater circuit, selection of the signals to be measured, and control of the digital multimeter measurement functions and ranges. The measured parameters include the thermopile signal; the heater voltage (approximately 2.0 to 2.7 V); and the heater current (approximately 15 to 20 mA, which is measured as the voltage drop across a 10 ohm precision resistor connected in series with the heater). The instrument temperature may also be measured using an internally mounted thermistor. The digital multimeter resolution of 100 nV allows for a thermopile signal measurement with resolution of 0.1 μV which is equivalent to approximately 0.1 W/m^2 (1 mV thermopile signal is equivalent to approximately 1000 W/m^2 of solar irradiance) (see simplified function diagram in Fig. 3.3).

The HF absolute cavity radiometer can be run in either active mode (similar to the PMO-6 discussed Chapter 2) or passive mode. Usually, the cavity is used in the passive mode and that is how it is calibrated and operated in all the International Pyrheliometer Comparisons (IPC). In the passive mode, the electrical power is applied only to the heater of the forward cavity to calculate its sensitivity at certain solar irradiance level (the calibration interval), and then turned off during the solar irradiance measurement. But in the active mode the electrical power is applied to both the forward cavity and the rear cavity, and it stays on during both the calibration interval and the solar irradiance measurement.

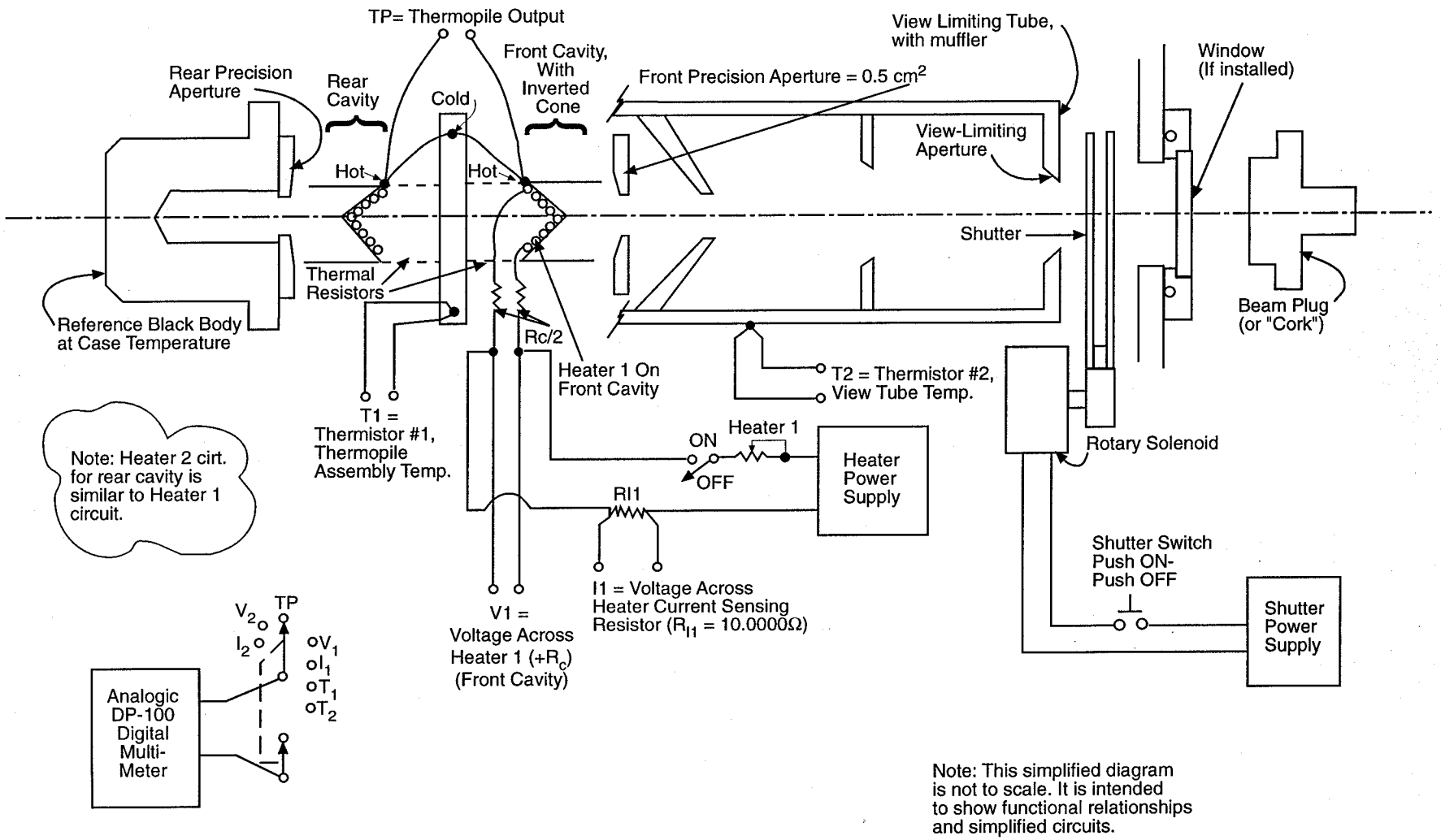


Fig. 3.3 Eppley Hickey-Frieden System Diagram

3.2 HF Electrical Calibration Procedure and operation

The following procedure is recommended during the comparisons of absolute cavity radiometers to reduce the errors in measuring the cavity zero and TP_e (thermopile output voltage due to electrical power).

a) Mount the radiometer on the tracker, and adjust the system so that the radiometer is perfectly aligned with the sun's normal incidence.

b) Connect cable from the control unit to the radiometer, turn on the control unit, and let the whole system warm up for at least 1 hour to stabilize with the outdoor environment.

c) On the radiometer, block the solar irradiance using the metal beam plug provided, and close the shutter by pressing the Shutter ON/OFF switch.

d) On the control unit, set the Function switch to TP (Thermopile) position and Heater 1 and Heater 2 switches to off (electrical power is turned off) with the Low/High switches on Low positions.

e) Wait until the reading on the Digital Multimeter (DMM) stabilizes (90 to 120 seconds), and record the reading of the DMM as TP_0 (Thermopile Zero) in mVDC.

f) Remove the metal beam plug from the radiometer, open the shutter and wait for 30 to 60 seconds, and record the DMM reading as TP_s (thermopile output voltage due to solar irradiance) in mVDC.

g) Estimate the solar irradiance change during the solar

irradiance measurement interval, and record it as ±x in mVDC.

h) Close the shutter, turn on Heater 1 and adjust Heater 1 control until the DMM reading equals $TP_s \pm x$. Wait until the DMM reading stabilizes (40 to 90 seconds), and record the reading as TP_e in mVDC.

i) Set the Function switch to V1 position, wait until heater voltage reading on DMM stabilizes (15 seconds), and record the reading as V_1 in VDC.

j) Set the Function switch to I1, wait until heater current reading on DMM stabilizes (15 seconds), and record the reading as V_{RI} in VDC (measured as a voltage reading because it is the voltage drop across a precision 10 ohm resistor R_I that is connected in series with the heater for accurate current measurement).

k) Calculate the multiplier factor at the solar irradiance level being measured, M ($W/m^2/mV$),

$$M = \frac{\frac{V_{RI}}{R_I} * (V_1 - \frac{V_{RI}}{R_I} * R_c) * C_f * 10^4}{TP_e - TP_0}, \qquad (3.1)$$

where:

R_c = the heater leads correction resistance, which typically is 0.066 ohm

C_f = the calibration factor provided by the manufacturer. C_f is approximately 2 because the aperture area is 0.5 cm^2 (value differs for different radiometers).

l) Set the Function switch to TP, turn off Heater 1 and at the same time open the shutter (to keep the thermal heat of the cavity as close as possible to the solar irradiance level through the transition).

m) To calculate the solar irradiance (W/m^2), multiply each TP reading taken from the DMM (mV) by the factor M calculated during the calibration.

n) After taking a number of readings in a period of time (usually that period is 10 to 30 minutes), perform the calibration once again and note the M factor and cavity zero readings. Then, linearly interpolate the M factor and cavity zero values for each irradiance reading, then recalculate the irradiance.

CHAPTER 4

International Pyrheliometer Comparisons IPC-VIII

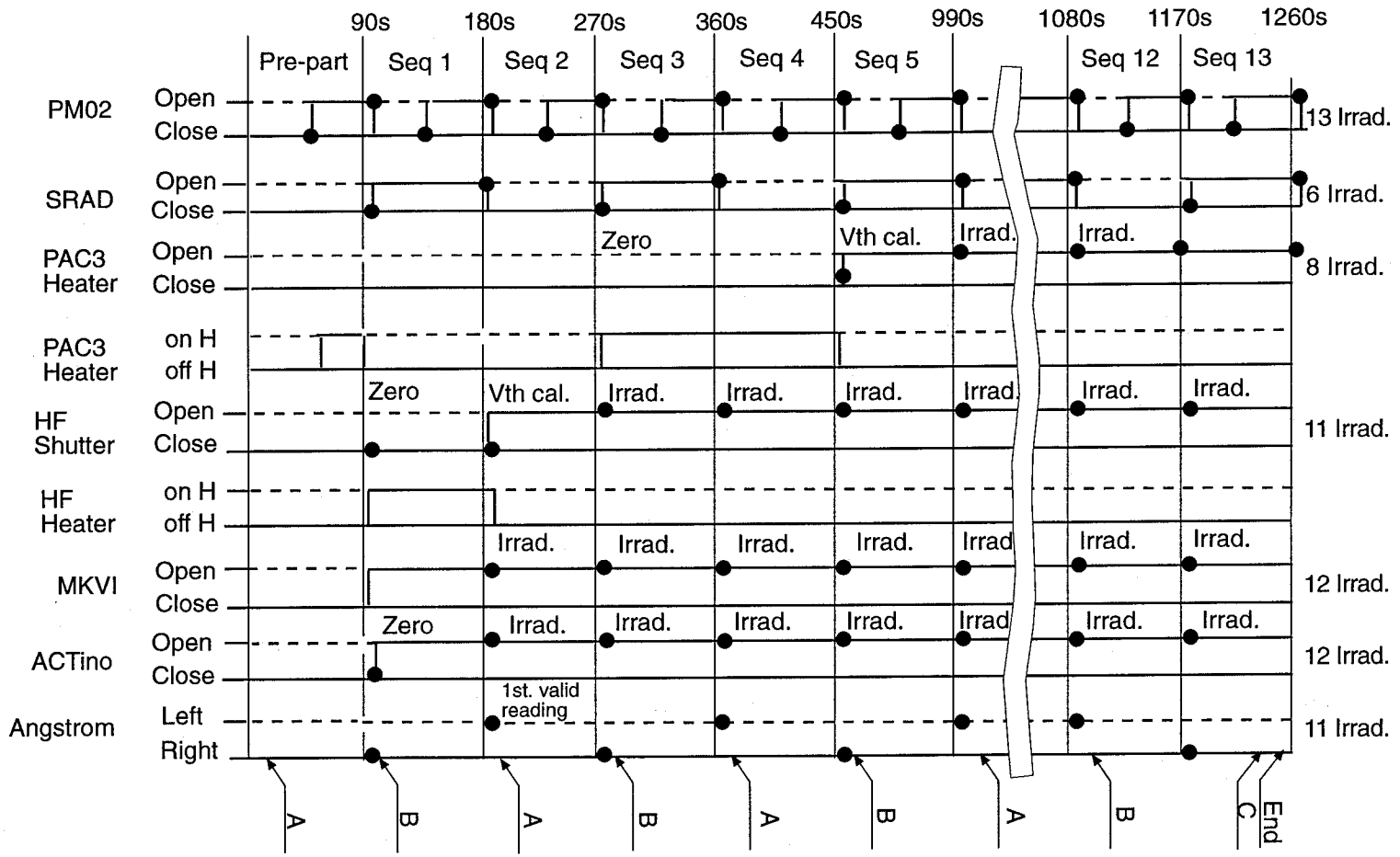
4.1 Introduction

The Executive Council of the World Meteorological Organization (WMO) authorized the 8th International Pyrheliometer Comparisons (IPC-VIII) to be held at the Physikalisch Meteorologisches Observatorium Davos, World Radiation Center (PMOD/WRC) from 9/25/95 to 10/13/95. The technical organization was delegated to PMOD/WRC, whereas the overall responsibility for ratification and dissemination of the final results rests with the WMO Commission for Instruments and Methods of Observation (CIMO) Working Group on Radiation and Atmospheric Turbidity Measurements.[4,5] Sixty five participants representing thirty eight countries participated in the comparison. A WRR reduction factor will be calculated for each participating solar cavity radiometer. For a cavity radiometer to be traceable to the World Radiometric Reference, each of its irradiance readings will be multiplied by its WRR reduction factor. The method of calculating the WRR reduction factor described in this chapter has been used by PMOD/WRC for the past several International Pyrheliometer Comparisons, and it might be used for IPC-VIII.

4.2 Data Acquisition and Evaluation

a) Timing

The measurements are taken in runs lasting 21 minutes with a basic sampling of 90 seconds. Voice announcements before and buzzer signals during each event are used to inform the participants about the sequence.[6] The timing for the different instrument types is shown in Fig. 4.1.



A: Please shade and heat the right hand strip
B: Please shade and heat left hand strip
End: Please check your zero point
C: The series is over

● Reading

Fig. 4.1 Timing for Different Instument Types During IPC-VIII

For nine instruments, of which HF28968 was one, the first irradiance reading was at 90 seconds after T_0, and a total of 13 irradiance readings per run were recorded, which resulted in a larger data sample than the other participating instruments.

b) Acquisition

The analog data-acquisition system is based on eight parallel DVM HP3478A with scanners and is used for WSG instruments, the radiometers of PMOD/WRC, and the auxiliary data. For the input data from the participants, Burr-Brown types TM27 and TM2700 microterminals are used. The whole system is controlled by an HP computer series 9200, which also stores and evaluates the data.[6] For HF28968 and a small group of other instruments, the data were entered manually on a PC then copied to a floppy disk at the end of each day.

c) Data evaluation

For each instrument the irradiance and ratio to PMO2 is obtained with the corresponding evaluation procedure. After each run, a summary of measured values and evaluated irradiances is printed and distributed for checking by the participants and, if necessary, the raw data are edited for gross errors. Updated summaries with the mean values of ratio and the standard deviation for each instrument are made available during the course of the comparison.[6]

PMO2 is used as the working reference instrument. The irradiance values of PMO2 are obtained with the algorithm of the active cavity radiometers with P_{closed} as mean of the closed readings (no sun irradiance) and after the current open phase (sun irradiance). At the end of the open phase,

eight P_{open} readings are taken, separated by approximately 0.7 second. The first of these readings is used as reference for the values entered by participants and the WSG instruments at the appropriate time. The standard deviation of these eight irradiance readings is also used as a quality control parameter to judge the stability of the solar irradiance for the data point to minimize the effect of different time constants between different types of instruments, so if the standard deviation is higher than 0.3 percent of reading, the data point would be rejected.[6]

d) Auxiliary data

The meteorological parameters are taken from the automatic weather station of the Swiss Meteorological Service located at PMOD/WRC. From this system 10 minutes values are available which are averaged over the period of a run. The values are air temperature, atmospheric pressure, global irradiance, and sky radiation. Close to the measuring benches, the wind speed and direction is measured, not as a meteorological parameter, but as an indication at the measuring site. Moreover, an instrument temperature and the daily ozone values are also given. Sunphotometer measurements are used to determine total vertical optical depth.[6]

4.3 Calibration requirements

a) Radiation source:

- The radiation source is the sun, with recommended irradiance level greater than 700 W/m^2 during measurement runs.[6]

b) Measuring equipment:

- Digital multimeters with at least 0.05% of reading resolution, accurate and stable over at least 1 year, including temperature drift, better than ±0.1% of reading. DMM should be protected from sun and wind and it should be connected to signals using shielded low-noise cabling.

- Sun tracker's admissible misalignment is ±0.25° slope angle.

c) Environmental variables:

- Wind speed should be low, particularly if blowing from the direction of the sun's azimuth ±30°.

- Cloud cover should be less than 1/8, clouds at an angular distance larger than 15°, and Link turbidity factor as low as possible.

- Ambient air temperature and pressure changes, in principle, have no influence on Absolute Cavity Radiometers.[6]

Chapter 5

PMOD/WRC Method to Determine the WRR Reduction Factor for Each of the Participating Instruments

The nomenclature used in this chapter has been developed to clarify the PMOD/WRC procedure. Steps (a) through (d) are used to establish the ratio of each participating instrument in IPC-VIII (including the WSG instruments) to PMO2, which is the transfer instrument for the whole procedure. Steps (e) and (f) are used to compute the $WRR_{IPC8,k}$ reduction factor for each instrument in the WSG using PMO2 as a transfer instrument. Steps (g) through (i) are not used by WRC/PMOD but have been added here to show that using the technique in step (f) produces no difference between the means of the $WRR_{IPC8,k}$ and the $WRR_{IPC7,k}$ reduction factors for the same WSG instruments. Similarity of the means is the primary assumption of this method. Step (j) is used to calculate the $WRR_{IPC8,k}$ reduction factor for each participating instrument. Step (k) is used to show how well WRR is defined by the WSG.

a) For each reading, calculate the ratio of the irradiance reading of each participating instrument, including the WSG instruments, to the irradiance reading of PMO2, $R_{j,k}$,

$$R_{j,k} = \frac{I_{j,k}}{I_{j,PMO2}}, \qquad (5.1)$$

where:

$I_{j,k}$ = the jth irradiance reading of the kth instrument (W/m^2)

$I_{j,PMO2}$ = the jth irradiance reading of PMO2 (W/m^2).

b) Calculate the mean of the ratios $R_{j,k}$ for each participating instrument, $\bar{R}'_k$,

$$\bar{R}'_k = \frac{\sum_{j=1}^{N} R_{j,k}}{N}, \qquad (5.2)$$

where N is the number of irradiance readings.

c) Calculate the standard deviation of the ratios $R_{j,k}$ for each instrument, SD'_k,

$$SD'_k = \sqrt{\frac{\sum_{j=1}^{N} (R_{j,k} - \bar{R}'_k)^2}{N-1}}. \qquad (5.3)$$

d) Values of $R_{j,k}$ that deviate more than 0.3 percent from the mean $\bar{R}'_k$ are rejected, and a new $\bar{R}_k$ and SD_k are calculated using Equations 5.2 and 5.3.

e) In order to define the World Radiometric Reference (WRR) for IPC-VIII, the results of the WSG are analyzed by the Commission for Instruments and Methods of Observation (CIMO). This commission then decides which of the seven reference instruments will define WRR for IPC-VIII. The reference instruments for IPC-VIII are PMO2, PMO5, CROM2L, CROM3L and MKVI67814 only. PACRAD III had an insect inside the cavity in April 1992. After the instrument was cleaned, its ratio to PMO2 decreased from 0.99917 to 0.9975 and has stayed the same since then. HF18748, which had an insect during IPC-VII, was not considered for defining WRR for IPC-VIII. Both instruments have not acquired enough measurement history to show the stability of their ratios

to PMO2. Figs. 5.1 through 5.6 show the ratios of each of the WSG to PMO2 since 1990.

f) For each of the WSG instruments, calculate the $WRR_{IPC8,k}$ reduction factor using the following procedure:

i. Calculate the ratios $W_{IPC8,k}$,

$$W_{IPC8,k} = WRR_{IPC7,k} * \frac{\overline{R}_k}{WRR_{IPC7,PMO2}}, \qquad (5.4)$$

where:

$WRR_{IPC7,k}$ = the WRR reduction factor for the kth instrument in the WSG during IPC-VII

$\overline{R}_k$ = the mean of ratios of the irradiance reading of the kth instrument in the WSG to the irradiance reading of PMO2 for N readings (after rejecting the outlier ratios)

$WRR_{IPC7,PMO2}$ = the WRR reduction factor of PMO2 calculated during IPC-VII.[4,5]

ii. Calculate the mean of the ratios $W_{IPC8,k}$, M_8,

$$M_8 = \frac{\sum_{k=1}^{n} W_{IPC8,k}}{n}, \qquad (5.5)$$

where n is the number of WSG instruments that defines WRR during IPC-VIII.

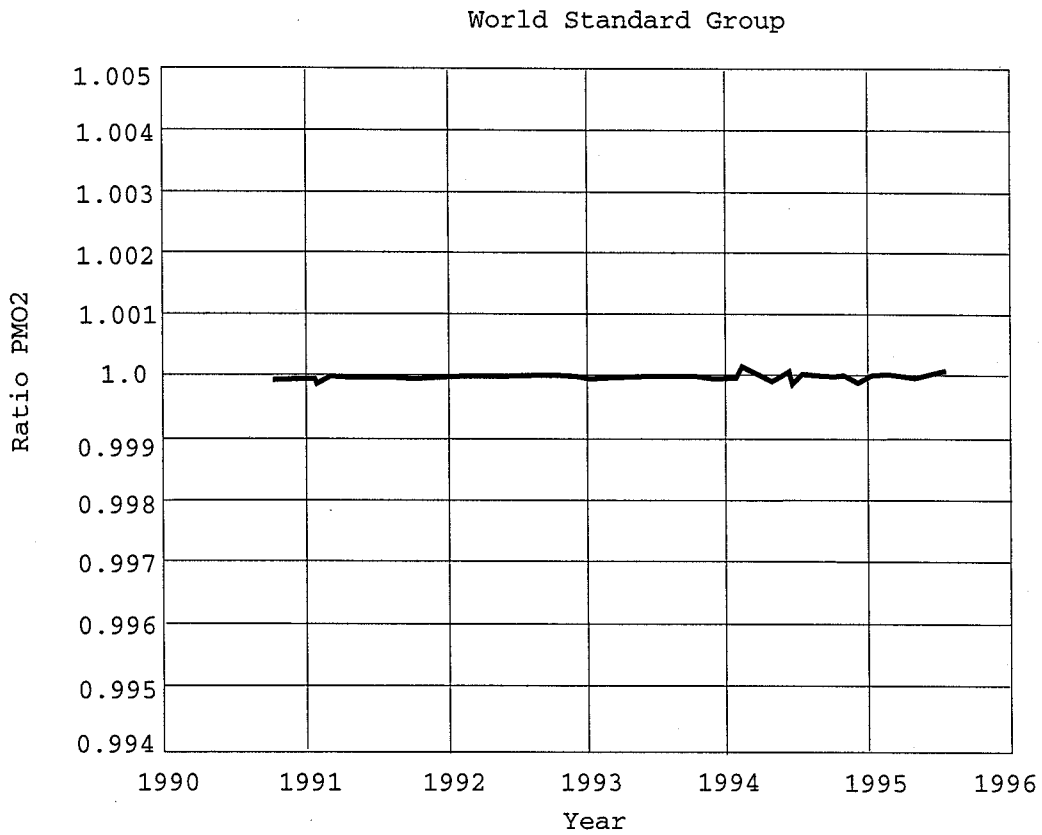


Fig.5.1 PM02 Ratio to PMO2

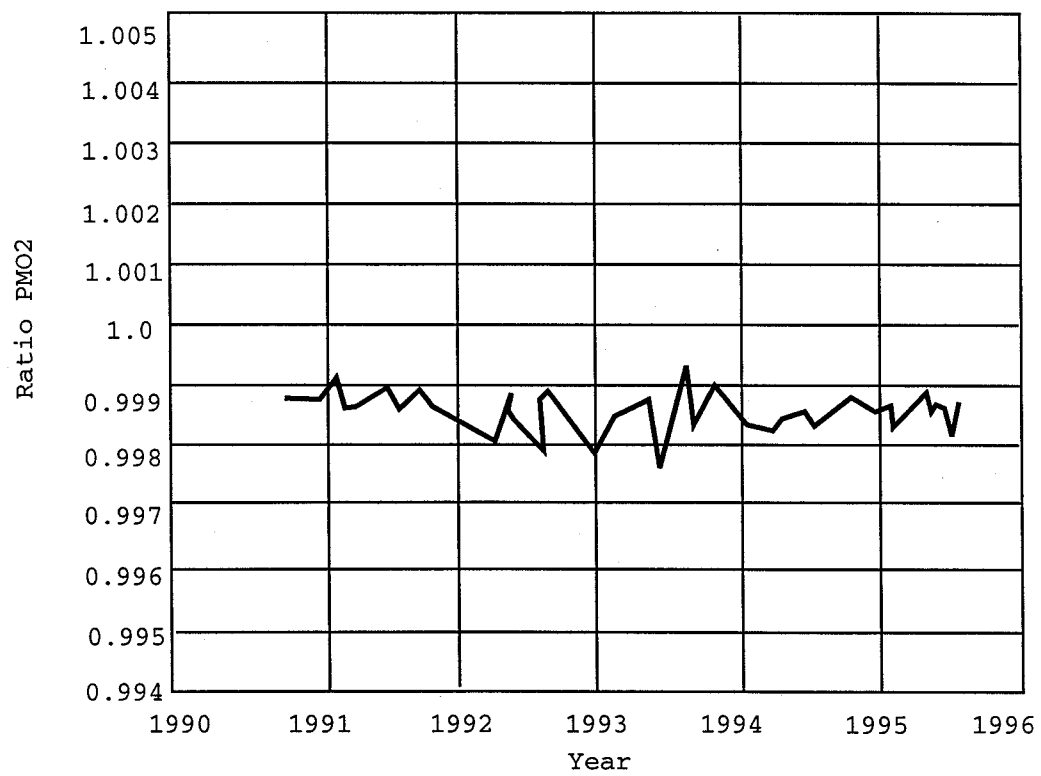


Fig.5.2 PM05 Ratio to PMO2

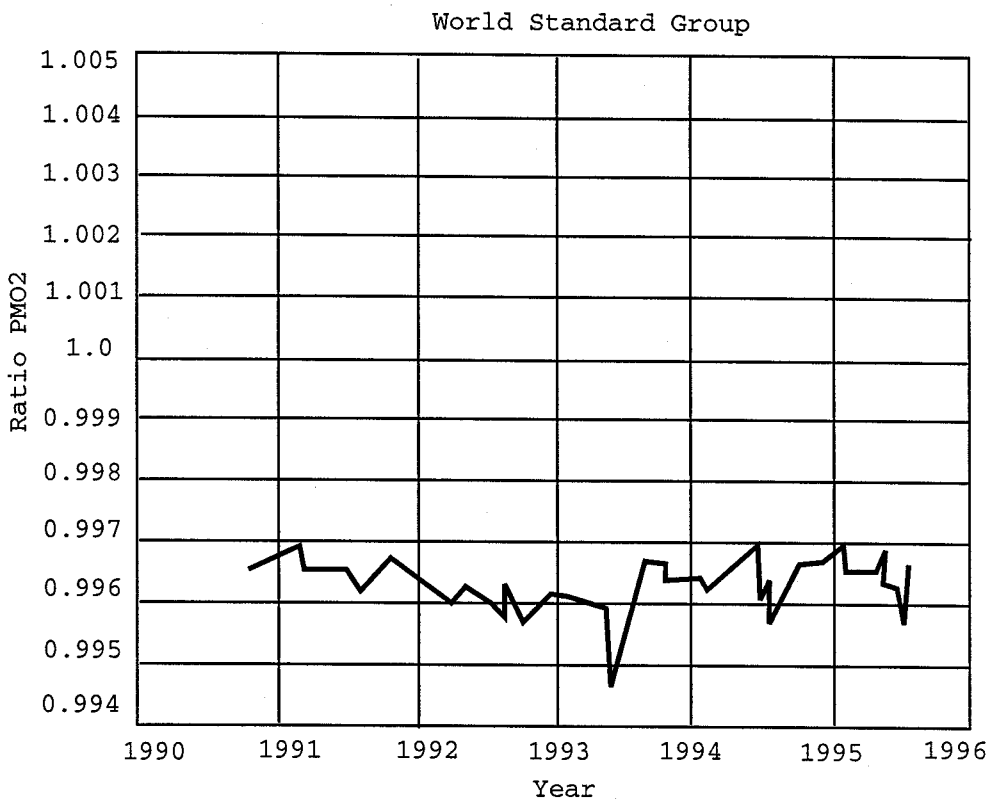


Fig.5.3 CROM2L Ratio to PMO2

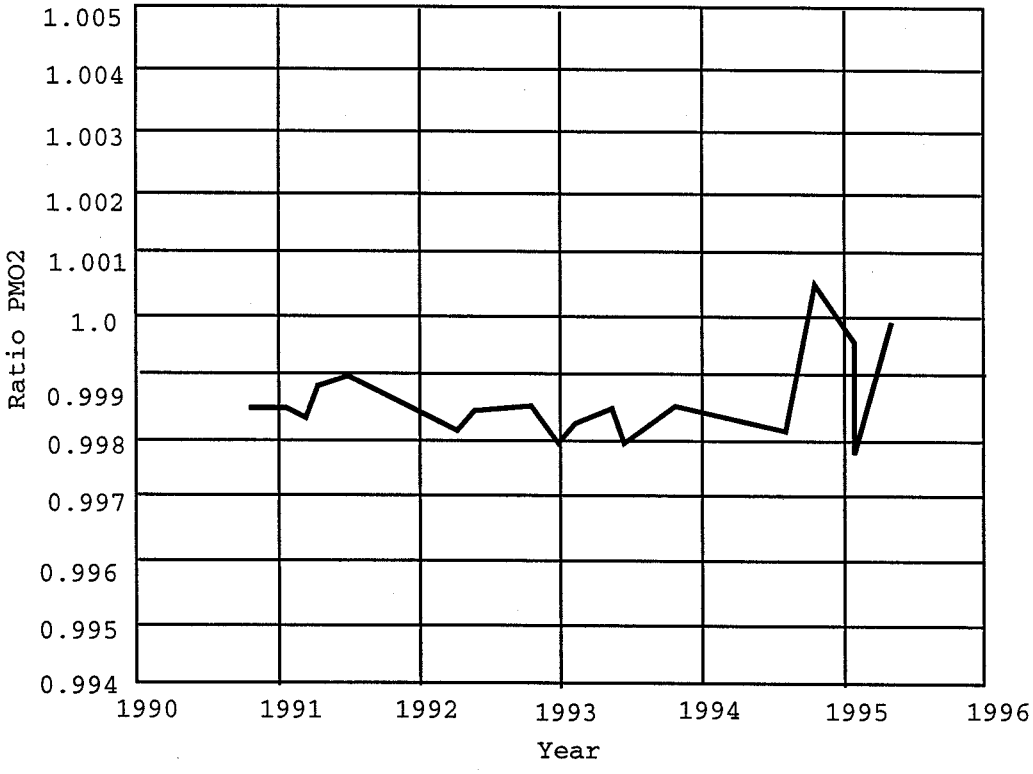


Fig.5.4 MK 67814 Ratio to PMO2

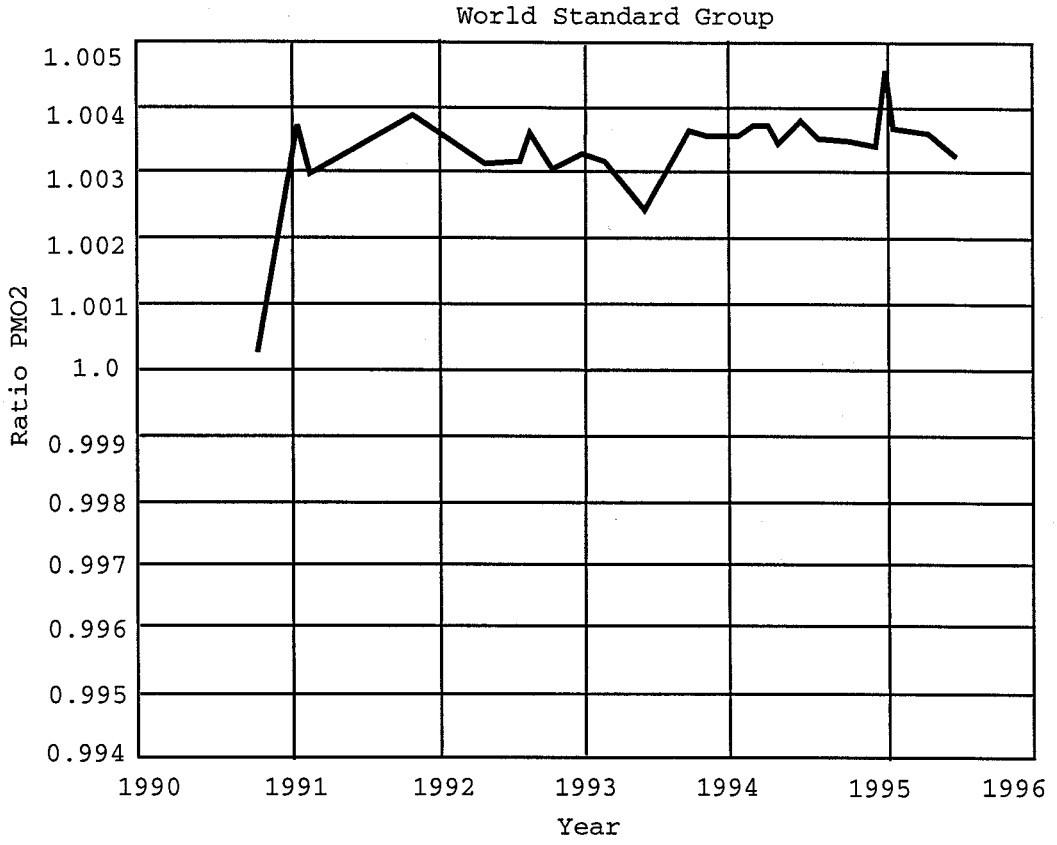


Fig. 5.5 HF18748 Ratio to PMO2

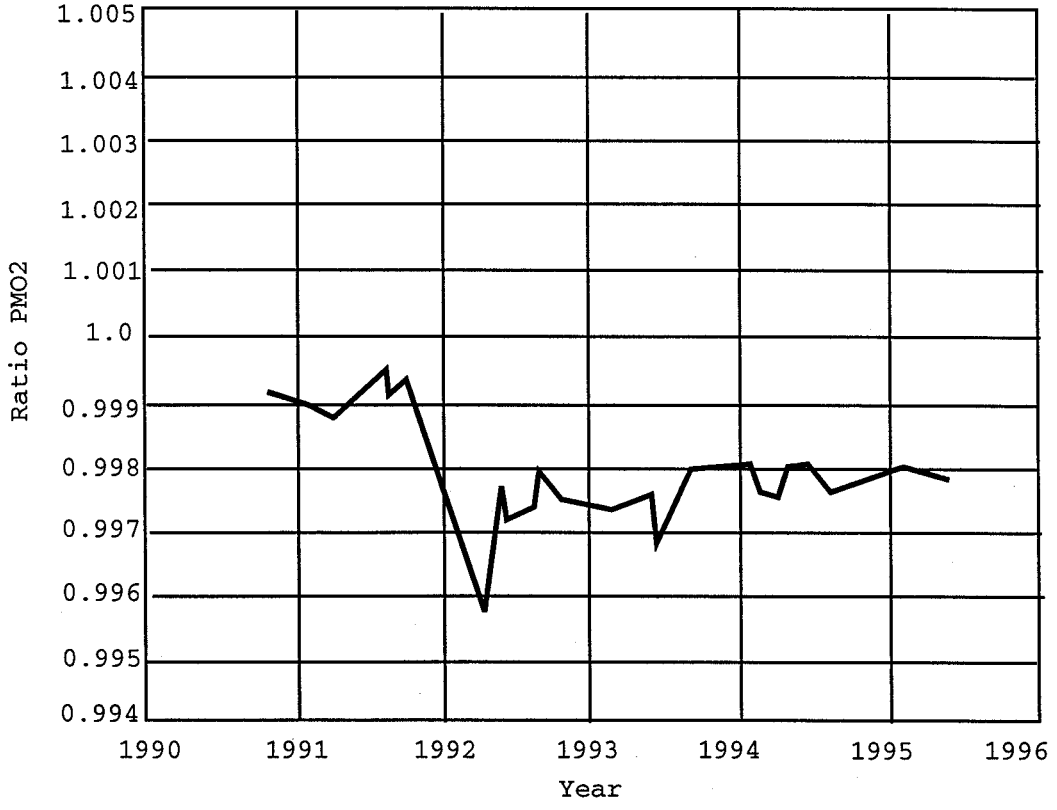


Fig. 5.6 PAC3 Ratio to PMO2

iii. Calculate the deviation of each $W_{IPC8,k}$ from the mean M_8, $D_{IPC8,k}$,

$$D_{IPC8,k} = W_{IPC8,k} - M_8. \qquad (5.6)$$

iv. Finally, calculate the $WRR_{IPC8,k}$ reduction factor for each instrument in the WSG,

$$WRR_{IPC8,k} = WRR_{IPC7,k} - D_{IPC8,k}. \qquad (5.7)$$

g) Calculate the mean, M_{IPC8}, of the $WRR_{IPC8,k}$ reduction factors of the WSG instruments,

$$M_{IPC8} = \frac{\sum_{k=1}^{n} WRR_{IPC8,k}}{n}. \qquad (5.8)$$

h) Calculate the mean, M_{IPC7}, of the $WRR_{IPC7,k}$ reduction factors of the same WSG instruments that are used to derive M_{IPC8},

$$M_{IPC7} = \frac{\sum_{k=1}^{n} WRR_{IPC7,k}}{n}. \qquad (5.9)$$

i) Calculate the change of the mean of WRR reduction factors of the WSG instruments, D,

$$D = M_{IPC8} - M_{IPC7}. \qquad (5.10)$$

D should equal zero because the primary assumption of this

method is that the mean of WRR reduction factors of the WSG is constant.

j) Calculate the $WRR_{IPC8,k}$ for each participating instrument,

$$WRR_{IPC8,k} = \frac{WRR_{IPC8,PMO2}}{\overline{R}_k}. \qquad (5.11)$$

k) Calculate the mean of WRR_{IPC8} reduction factors for all the participating instruments in IPC-VIII that have WRR_{IPC7} reduction factors, including the WSG, to evaluate how well WRR is represented by the WSG.[4,5]

CHAPTER 6

Proposed Method to Determine the WRR Reduction Factor for Each of the Participating Instruments

This method is based on the fact that the standard deviations of the WRR reduction factors of the WSG are different. Thus, the influence of the instrument that has larger standard deviation on determining the reference irradiance at a specific time should be less than the influence of the instrument that has a smaller standard deviation.[7] Step (a) divides the whole population of data into different samples, each of which represent a different group of instruments from the WSG. Steps (b) through (j) are used to calculate the weighting factor for each of the WSG instruments for each data sample. Steps (k) through (m) are used to calculate the WRR reduction factor and the standard deviation for each of the WSG instruments for IPC-VIII. Step (n) is used to recalculate the new weighting factor for each of the WSG instruments for each data sample because the standard deviations of the WRR(IPC8) reduction factors are different from the standard deviations calculated in step (f). Steps (o) through (r) are used to calculate the WRR reduction factor and the standard deviation for each of the participating instruments in IPC-VIII. Steps (s) through (u) are used to evaluate the change in the mean of the WRR reduction factors of the WSG. Step (v) is used to evaluate how well WRR is represented by the WSG.

a) After determining the instruments from the WSG that would define WRR for IPC-VIII, divide the whole population of irradiance readings into samples. Each sample should have at least three participating instruments of the WSG and the participating instruments should be the same in each sample (see pages 47 and 48).

b) Multiply each irradiance reading of each instrument of the WSG by the instrument's WRR reduction factor from IPC-VII,

$$I_{j,k} = i_{j,k} * WRR_{IPC7,k} \quad , \qquad (6.1)$$

where $i_{j,k}$ is the jth irradiance reading of the kth instrument of the WSG (W/m^2).

c) Calculate the reference irradiance, $I''_{ref.,j}$, for each reading,

$$I''_{ref.,j} = \frac{\sum_{k=1}^{n} I_{j,k}}{n}, \qquad (6.2)$$

where n is the number of instruments from the WSG that participated in the jth irradiance reading.

d) Calculate the ratio of the reference irradiance of each reading to the original irradiance reading of each instrument, $R''_{j,k}$,

$$R''_{j,k} = \frac{I''_{ref.,j}}{i_{j,k}}. \qquad (6.3)$$

e) Calculate the mean of all the ratios $R''_{j,k}$ for each of the WSG instruments, $\bar{R}''_{k}$,

$$\overline{R''}_k = \frac{\sum_{j=1}^{N} R''_{j,k}}{N}, \qquad (6.4)$$

where N is the number of irradiance readings of the kth instrument in the whole population.

f) Calculate the standard deviation of the ratios $R''_{j,k}$ for each of the WSG instruments using the whole population, SD''_k,

$$SD''_k = \sqrt{\frac{\sum_{j=1}^{N} (\overline{R''}_k - R''_{j,k})^2}{N-1}}. \qquad (6.5)$$

g) Reject all the ratios, $R''_{j,k}$, that deviate more than 0.3 percent from the mean $\overline{R}''_k$. It is most important to reject also the irradiance reading from which that rejected ratio was derived, because that irradiance reading will affect the value of the reference irradiance. Then, recalculate the ratios, $R'_{j,k}$, their means, $\overline{R}'_k$, and their standard deviations, SD'_k, using Equations 6.3, 6.4 and 6.5.

h) Calculate the total bias error, B_k, for each instrument of the WSG. The main source of bias errors is the digital multimeter used to measure electrical signals such as heater voltage, heater current, thermopile voltage, and thermistor resistance.

$$B_k = \sqrt{\sum_{g=1}^{m} (B_{g,k})^2}, \qquad (6.6)$$

where $B_{g,k}$ is the gth bias error for the kth instrument.

i) Calculate the total uncertainty for each of the WSG instruments, $U'_{99,k}$,

$$U'_{99,k} = B_K + 2 * SD'_k. \qquad (6.7)$$

j) Calculate the weighting factor for each of the WSG instruments for each data sample, $W'_{n,k}$. The number and type of participating instruments from the WSG are going to be different for each sample, which will result in different weighting factors for each sample,

$$W'_{n,k} = \frac{\left(\frac{1}{U'_{99,k}}\right)^2}{\sum_{k=1}^{n} \left(\frac{1}{U'_{99,k}}\right)^2}, \qquad (6.8)$$

where n is the number of participating instruments from the WSG in the sample.

k) Recalculate the weighted reference irradiance of the WSG for each irradiance reading, using $WRR_{IPC7,k}$ reduction factors, $I'_{ref.,j}$,

$$I'_{ref.,j} = \sum_{k=1}^{n} W'_{n,k} * WRR_{IPC7,k} * i_{j,k}. \qquad (6.9)$$

l) Calculate the ratio of each of the weighted reference irradiance to the original irradiance reading of each of the WSG instruments, $R_{j,k}$,

$$R_{j,k} = \frac{I'_{ref.,j}}{i_{j,k}}, \qquad (6.10)$$

where $i_{j,k}$ is the original irradiance reading (without being multiplied by the WRR reduction factor) of the kth WSG instrument (W/m^2).

m) Calculate the mean and the standard deviation of the ratios $R_{j,k}$ for the kth instrument of the WSG using Equations 6.4 and 6.5. The mean is the $WRR_{IPC8,k}$ reduction factor for the kth instrument of the WSG and the standard deviation is the $SD_{IPC8,k}$ for the same instrument.

n) From the standard deviations in step (m) recalculate the weighting factor, $W_{n,k}$, for each of the WSG instruments using Equations 6.7 and 6.8. Each data sample will have different weighting factors.

o) Using the $WRR_{IPC8,k}$ reduction factor for each of the WSG, calculate the weighted reference irradiance for each irradiance reading, $I_{ref.,j}$,

$$I_{ref.,j} = \sum_{k=1}^{n} W_{n,k} * WRR_{IPC8,k} * i_{j,k}. \qquad (6.11)$$

p) For each of the participating instruments calculate the ratio of the weighted reference irradiance to the instrument irradiance reading, $WRR_{IPC8,j,k}$,

$$WRR_{IPC8,j,k} = \frac{I_{ref.,j}}{i_{j,k}}. \qquad (6.12)$$

q) Calculate the $WRR_{IPC8,k}$ reduction factor for each of the participating instruments,

$$WRR_{IPC8,k} = \frac{\sum_{j=1}^{N} WRR_{IPC8,j,k}}{N}. \qquad (6.13)$$

r) Calculate the standard deviation for each participating instrument, $SD_{IPC8,k}$,

$$SD_{IPC8,k} = \sqrt{\frac{\sum_{j=1}^{N} (WRR_{IPC8,k} - WRR_{IPC8,j,k})^2}{N-1}}. \qquad (6.14)$$

s) Calculate the mean of $WRR_{IPC8,k}$ reduction factors for the WSG, M_{IPC8},

$$M_{IPC8} = \sum_{k=1}^{n} \frac{WRR_{IPC8,k}}{n}, \qquad (6.15)$$

where n is the total number of instruments from the WSG that defines the WRR for IPC-VIII.

t) Calculate the mean of $WRR_{IPC7,k}$ reduction factors for the

WSG instruments that define the WRR for IPC-VIII, M_{IPC7},

$$M_{IPC7} = \sum_{k=1}^{n} \frac{WRR_{IPC7,k}}{n}. \qquad (6.16)$$

u) Calculate the change of the mean of WRR, D,

$$D = M_{IPC8} - M_{IPC7}. \qquad (6.17)$$

D is the change of the mean of WRR that should be monitored at every WSG comparison, and after a period of time the two methods should be evaluated through a comparison using an absolute cavity radiometer or a group of absolute cavity radiometers that is more accurate.

v) Calculate the mean of $WRR_{IPC8,k}$ reduction factors for all the participating instruments, including the WSG instruments, that have $WRR_{IPC7,k}$ reduction factors and compare it with the mean of $WRR_{IPC8,k}$ reduction factor for the WSG instruments. This comparison allows one to evaluate how well WRR is represented by the WSG instruments for IPC-VIII.

CHAPTER 7

Calculation of WRR Reduction Factor of HF28968 Using the PMOD/WRC and the Proposed Methods

In this chapter, the WRR reduction factor for HF28968 is calculated using the PMOD/WRC method and then the proposed method. The data used in the calculations are raw data that were collected during the comparison (IPC-VIII) under clear skies and around solar noon. The calculated WRR reduction factor in this chapter might differ from the WRR reduction factor assigned by PMOD/WRC due to using a small data sample. Tables 7.1 and 7.2 are the printout of a spreadsheet software used for the calculations.

7.1 PMOD/WRC method

The following rows, cells, or columns in Table 7.1 describe the sequence of the PMOD/WRC procedure used to calculate the WRR reduction factor for HF28968.

a) Columns B through G contain the irradiance readings for the WSG instruments and HF28968.

b) Columns H through L contain the ratios of each irradiance reading to PMO2.

c) Cells H137 through L137 contain the means of the ratios to PMO2 in their corresponding column (e.g., cell H137 is the mean of the ratios in cells H2 through H134).

d) Cells H139 through L139 contain the standard deviations of the means of the ratios in step (c).

e) Cells H152 through L152 contain the means of the ratios

to PMO2 after rejecting the ratios that are 0.3 percent lower or higher than the mean.

f) Cells H154 through L154 contain the standard deviations for the means in step (e).

g) Cells M3 through Q3 contain the WRR reduction factors for the WSG Instruments from IPC-VII.

h) Cells M5 through Q5 contain the ratios calculated using Equation 5.4.

i) Cell N6 contains the mean of the ratios in step (h).

j) Cells M8 through Q8 contain the difference between the mean in cell N6 and each of the ratios in cells M5 through Q5 respectively.

k) Cells M10 through Q10 cotain the WRR reduction factors for the WSG instruments from IPC-VIII, which are calculated by subtracting cells M8 through Q8 from cells M3 through Q3 respectively.

l) Cells O13 and O14 contain the means of the WRR reduction factors of the WSG instruments during IPC-VII and IPC_VIII. The two means should equal if the data were processed properly.

m) Cells O17 and O18 contain the WRR reduction factor and the standard deviation of HF28968.

	A	B	C	D	E	F	G
1	Date/Time	PMO2	PMO5	CROM2L	CROM3R	MK67814	HF28968
2	10/2/95						
3	11:22:30	1023.9					1023.5
4	11:24:00	1022.2	1020.7	1019	1028.2		1022.9
5	11:25:30	1020.5					1022.4
6	11:27:00	1021.2	1020.3	1020.7	1029.8		1021.7
7	11:28:30	1020.1					1019.7
8	11:30:00	1018.6	1018.1	1019.1	1027.6		1019.1
9	11:31:30	1019.4					1021.4
10	11:33:00	1018.2	1017.8	1015.7	1018.5		1020.1
11	11:34:30	1018.8					1020.5
12	11:36:00	1016.9	1015.8	1013.6	1015.9		1017.7
13	11:37:30	1016.2					1017.6
14	11:39:00	1015.1	1013.4	1010.7	1011.2		1016.9
15	11:40:30	1016					1017.7
16	10/3/95						
17	10:19:30	934.2					933.8
18	10:21:00	932.6	931.9	929.1	935.6		933
19	10:22:30	933.7					934.8
20	10:24:00	932.7	931.1	930	935.2		934.9
21	10:25:30	936.3					936.9
22	10:27:00	938	936.6	934.4	939.3		938.5
23	10:28:30	939.1					939.8
24	10:30:00	940.2	938.4	934.3	946.2		941.1
25	10:31:30	939.9					941.8
26	10:33:00	942.5	941	939.9	942.5		942.8
27	10:34:30	941.5					942
28	10:36:00	942	940.8	939.3	946.6		943.1
29	10:37:30	943.6					945.4
30	10/11/95						
31	11:01:30	938.1					939.9
32	11:03:00	938.6	938	936.4	934.1		940.2
33	11:04:30	939.5				939.6	941
34	11:06:00	941.6	940.5	939.3	939.3	941.9	942.8
35	11:07:30	942.2				941.9	944.1
36	11:09:00	941.4	940.3	937.6	937.6	941.9	942.9
37	11:10:30	941.1				941.9	942.3
38	11:12:00	941.9	940.4	941.1	941.1	941.9	942.8
39	11:13:30	948.3				948.6	946.6
40	11:15:00	948.7	946.9	950	950	948.5	948.5
41	11:16:30	948.3				948.5	948.9
42	11:18:00	946.7	945.8	944.6	944.6	946.3	950
43	11:19:30	947				948.5	949.8
44	11:55:30	950.1					
45	11:57:00	950.8	949.4	953.3	953.3		952.3
46	11:58:30	952.1				948.3	952.1
47	12:00:00	951.9	951.4	951	951	950.7	954.2
48	12:01:30	951.6				950.7	953.4
49	12:03:00	954.1	953.2	951.9	951.9	952.8	954.9
50	12:04:30	953.3				952.9	955.1
51	12:06:00	954.7	954.4	956.9	956.9	955.2	956.8
52	12:07:30	954.8				952.9	956.1
53	12:09:00	956.6	954.3	952	952	955.2	958

Table 7.1 PMOD/WRC Method to Calculate WRR Reduction Factor for HF28968

	A	B	C	D	E	F	G
54	12:10:30	956.6				955.2	959.7
55	12:12:00	956.9	956.4	958.8	958.8	957.6	959.8
56	12:13:30	955.1				955.3	958.8
57	12:22:30	957.1					957.7
58	12:24:00	956.7	954.8	952.6	950.2		957
59	12:25:30	958.6				955.9	959.4
60	12:27:00	956.8	954.9	953.2	957.6	955.9	957.2
61	12:28:30	958.1				955.9	958.8
62	12:30:00	960.2	958.4	957.1	964.9	958.3	962
63	12:31:30	958.5				958.3	959.9
64	12:33:00	954.8	953.3	952.4	957	953.7	956.3
65	12:34:30	957.8				958.3	960.3
66	12:36:00	959	957.4	955.5	963.6	958.3	960.7
67	12:37:30	958.7				958.3	960.9
68	12:39:00	958	956.8	954.9	958.5	958.3	960.6
69	12:40:30	959.4				958.3	961.3
70	12:49:30	955.9					956.5
71	12:51:00	953.6	953.2	951.5	952.8		955.6
72	12:52:30	954.2				951.5	956.5
73	12:54:00	953.5	952.5	949.2	952.8	949.1	954.3
74	12:55:30	956.3				953.7	958.7
75	12:57:00	954.6	953.4	951.6	955.1	951.4	955.7
76	12:58:30	956.8				953.7	956.5
77	13:00:00	953.8	952.7	951.2	954.5	951.4	955.7
78	13:01:30	951.6				949.1	953.4
79	13:03:00	954	952.7	950.1	955.3	951.4	954.6
80	13:04:30	952				949.1	953.7
81	13:06:00	949.3	948.3	954.4	948	946.9	951.2
82	13:07:30	949.9				949.1	952.6
83	13:16:30	946.3					946.5
84	13:18:00	945.8	943.8	942.2	945.6		946
85	13:19:30	943.9				942.4	944.7
86	13:21:00	942.5	940.6	938.8	940.9	940.2	943.2
87	13:22:30	940.9				940.2	942
88	13:24:00	937.3	936.5	936	941.4	935.9	938.7
89	13:25:30	937.7				935.8	938.7
90	13:27:00	937.8	935.7	933.7	938.4	935.9	938.7
91	13:28:30	937				935.9	937.3
92	13:30:00	934.4	933.5	931.2	935.1	933.6	934.7
93	13:31:30	933.4				933.6	935.6
94	13:33:00	937.9	936	933.3	937.6	935.9	938.7
95	13:34:30	935.1				933.7	936.5
96	13:43:30	926.3					927.3
97	13:45:00	927.6	926.3	924.3	928.3		929.1
98	13:46:30	926.6				925.6	927
99	13:48:00	925.4	924.1	922.3	926.5	925.6	926.8
100	13:49:30	926.6				925.6	927.7
101	13:51:00	923.5	922.3	920.8	925.3	923.5	924.6
102	13:52:30	922.3				921.3	923.3
103	13:54:00	921.1	921	918.1	923.1	921.3	924.4
104	13:55:30	921.8				921.3	922.7
105	13:57:00	921	919.6	916.9	920.7	921.3	922.5
106	13:58:30	918.2				916.7	919.5
107	14:00:00	915.2	913.5	912.4	916.4	914.3	916.8

Table 7.1 PMOD/WRC Method to Calculate WRR Reduction Factor for HF28968

	A	B	C	D	E	F	G
108	14:01:30	914.9				914.4	916.2
109	**10/12/95**						
110	11:55:30	1000.2					1001.5
111	11:57:00	1000.6	999.7	997.9	1001.5		1001.9
112	11:58:30	1000.5				999.4	1002.1
113	12:00:00	1000.2	999.9	998.1	1002.3	999.3	1001.4
114	12:01:30	1001				999.4	1001.8
115	12:03:00	1001.4	1000.2	994.8	1012.3	999.4	1002.6
116	12:04:30	1002				999.4	1003.5
117	12:06:00	1003.1	1001.4	999.8	997	1001.4	1004
118	12:07:30	1002.2				1001.5	1003.1
119	12:09:00	1001.8	1000.8	998.9	1007	1001.4	1003.2
120	12:10:30	1001.1				999.5	1001.7
121	12:12:00	1000.7	1000.1	998.7	1005.6	999.5	1002
122	12:13:30	1000.4				1001.5	1001.8
123	12:22:30	999.3					1001.1
124	12:24:00	1000.6	999.5	998.3	1000.5		1001.9
125	12:25:30	999.5				997.2	1001.5
126	12:27:00	1000.4	999.6	997.5	999.1	999.2	1001.5
127	12:28:30	1000				997.2	1002
128	12:30:00	1000.3	998.9	999.9	999.8	999.2	1002.1
129	12:31:30	1000.1				999.2	1002.1
130	12:33:00	1000.5	1000.4	998.9	996.3	999.2	1002.6
131	12:34:30	1000				999.2	1002
132	12:36:00	998.9	997.4	995.4	1010.6	997.2	1001.7
133	12:37:30	999.5				997.2	1001.1
134	12:39:00	999.5	997.2	997.4	995.1	997.2	1001.1
135	12:40:30	998.7				997.2	1001
136							
137							
138							
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Table 7.1 PMOD/WRC Method to Calculate WRR Reduction Factor for HF28968

	H	I	J	K	L
1	PMO5/PMO2	CROM2L/PMO2	CROM3R/PMO2	MK67814/PMO2	HF28968/PMO2
2	=R(j,PMO5)	=R(j,CROM2L)	=R(j,CROM3R)	=R(j,MK67814)	=R(i,HF28968)
3					0.9996093
4	0.9985326	0.9968695	1.0058697		1.0006848
5					1.0018618
6	0.9991187	0.9995104	1.0084215		1.0004896
7					0.9996079
8	0.9995091	1.0004909	1.0088357		1.0004909
9					1.0019619
10	0.9996071	0.9975447	1.0002946		1.0018660
11					1.0016686
12	0.9989183	0.9967548	0.9990166		1.0007867
13					1.0013777
14	0.9983253	0.9956655	0.9961580		1.0017732
15					1.0016732
16					
17					0.9995718
18	0.9992494	0.9962471	1.0032168		1.0004289
19					1.0011781
20	0.9982846	0.9971052	1.0026804		1.0023587
21					1.0006408
22	0.9985075	0.9961620	1.0013859		1.0005330
23					1.0007454
24	0.9980855	0.9937247	1.0063816		1.0009572
25					1.0020215
26	0.9984085	0.9972414	1.0000000		1.0003183
27					1.0005311
28	0.9987261	0.9971338	1.0048832		1.0011677
29					1.0019076
30					
31					1.0019188
32	0.9993608	0.9976561	0.9952056		1.0017047
33				1.0001064	1.0015966
34	0.9988318	0.9975573	0.9975573	1.0003186	1.0012744
35				0.9996816	1.0020166
36	0.9988315	0.9959635	0.9959635	1.0005311	1.0015934
37				1.0008501	1.0012751
38	0.9984075	0.9991507	0.9991507	1.0000000	1.0009555
39				1.0003164	0.9982073
40	0.9981027	1.0013703	1.0013703	0.9997892	0.9997892
41				1.0002109	1.0006327
42	0.9990493	0.9977818	0.9977818	0.9995775	1.0034858
43				1.0015839	1.0029567
44					
45	0.9985276	1.0026294	1.0026294		1.0015776
46				0.9960088	1.0000000
47	0.9994747	0.9990545	0.9990545	0.9987394	1.0024162
48				0.9990542	1.0018916
49	0.9990567	0.9976942	0.9976942	0.9986375	1.0008385
50				0.9995804	1.0018882
51	0.9996858	1.0023044	1.0023044	1.0005237	1.0021996
52				0.9980101	1.0013615
53	0.9975957	0.9951913	0.9951913	0.9985365	1.0014635

Table 7.1 PMOD/WRC Method to Calculate WRR Reduction Factor for HF28968

	H	I	J	K	L
54				0.9985365	1.0032406
55	0.9994775	1.0019856	1.0019856	1.0007315	1.0030306
56				1.0002094	1.0038739
57					1.0006269
58	0.9980140	0.9957144	0.9932058		1.0003136
59				0.9971834	1.0008346
60	0.9980142	0.9962375	1.0008361	0.9990594	1.0004181
61				0.9977038	1.0007306
62	0.9981254	0.9967715	1.0048948	0.9980212	1.0018746
63				0.9997913	1.0014606
64	0.9984290	0.9974864	1.0023041	0.9988479	1.0015710
65				1.0005220	1.0026101
66	0.9983316	0.9963504	1.0047967	0.9992701	1.0017727
67				0.9995828	1.0022948
68	0.9987474	0.9967641	1.0005219	1.0003132	1.0027140
69				0.9988535	1.0019804
70					1.0006277
71	0.9995805	0.9977978	0.9991611		1.0020973
72				0.9971704	1.0024104
73	0.9989512	0.9954903	0.9992659	0.9953854	1.0008390
74				0.9972812	1.0025097
75	0.9987429	0.9968573	1.0005238	0.9966478	1.0011523
76				0.9967600	0.9996865
77	0.9988467	0.9972741	1.0007339	0.9974837	1.0019920
78				0.9973728	1.0018916
79	0.9986373	0.9959119	1.0013627	0.9972746	1.0006289
80				0.9969538	1.0017857
81	0.9989466	1.0053724	0.9986306	0.9974718	1.0020015
82				0.9991578	1.0028424
83					1.0002113
84	0.9978854	0.9961937	0.9997885		1.0002115
85				0.9984108	1.0008475
86	0.9979841	0.9960743	0.9983024	0.9975597	1.0007427
87				0.9992560	1.0011691
88	0.9991465	0.9986130	1.0043743	0.9985063	1.0014937
89				0.9979738	1.0010664
90	0.9977607	0.9956281	1.0006398	0.9979740	1.0009597
91				0.9988260	1.0003202
92	0.9990368	0.9965753	1.0007491	0.9991438	1.0003211
93				1.0002143	1.0023570
94	0.9979742	0.9950954	0.9996801	0.9978676	1.0008530
95				0.9985028	1.0014972
96					1.0010796
97	0.9985985	0.9964424	1.0007546		1.0016171
98				0.9989208	1.0004317
99	0.9985952	0.9966501	1.0011887	1.0002161	1.0015129
100				0.9989208	1.0011871
101	0.9987006	0.9970763	1.0019491	1.0000000	1.0011911
102				0.9989158	1.0010842
103	0.9998914	0.9967430	1.0021713	1.0002171	1.0035827
104				0.9994576	1.0009764
105	0.9984799	0.9955483	0.9996743	1.0003257	1.0016287
106				0.9983664	1.0014158
107	0.9981425	0.9969406	1.0013112	0.9990166	1.0017483

Table 7.1 PMOD/WRC Method to Calculate WRR Reduction Factor for HF28968

	H	I	J	K	L
108				0.9994535	1.0014209
109					
110					1.0012997
111	0.9991005	0.9973016	1.0008995		1.0012992
112				0.9989005	1.0015992
113	0.9997001	0.9979004	1.0020996	0.9991002	1.0011998
114				0.9984016	1.0007992
115	0.9988017	0.9934092	1.0108848	0.9980028	1.0011983
116				0.9974052	1.0014970
117	0.9983053	0.9967102	0.9939189	0.9983053	1.0008972
118				0.9993015	1.0008980
119	0.9990018	0.9971052	1.0051907	0.9996007	1.0013975
120				0.9984018	1.0005993
121	0.9994004	0.9980014	1.0048966	0.9988008	1.0012991
122				1.0010996	1.0013994
123					1.0018013
124	0.9989007	0.9977014	0.9999001		1.0012992
125				0.9976988	1.0020010
126	0.9992003	0.9971012	0.9987005	0.9988005	1.0010996
127				0.9972000	1.0020000
128	0.9986004	0.9996001	0.9995001	0.9989003	1.0017995
129				0.9991001	1.0019998
130	0.9999000	0.9984008	0.9958021	0.9987006	1.0020990
131				0.9992000	1.0020000
132	0.9984983	0.9964961	1.0117129	0.9982981	1.0028031
133				0.9976988	1.0016008
134	0.9976988	0.9978989	0.9955978	0.9976988	1.0016008
135				0.9984980	1.0023030
136	**MEAN= R(k)'=**				
137	0.9987391	0.9974337	1.0009826	0.9988273	1.0013782
138	**SD(k)'=**				
139	0.0005648	0.0020621	0.0037683	0.0011913	0.0008673
140	**MEAN OF CROM2L/PMO2, REJECTING READINGS NUMBER I8,24,40,45,51,**				
141	**55,81 AND 115= 8 READINGS=**				
142		0.9970142			
143		0.0010445			
144	**MEAN OF CROM3R/PMO2, REJECTING READING NUMBER J4,6,8,14,24,28,**				
145	**32,34,36,42,49,53,58,62,66,88,115,117,119,121,130,132 AND 134= 23 READINGS=**				
146			1.0006416		
147			0.0012786		
148	**MEAN OF MK67814/PMO2 AFTER REJECTING READING NUMBER K73=**				
149				0.9988669	
150				0.0011865	
151	**MEAN= R(k)=**				
152	0.9987391	0.9970142	1.0006416	0.9988669	1.0013782
153	**SD=**				
154	0.0005648	0.0010445	0.0012786	0.0011865	0.0008673
155					
156	**PMO2**	**PMO5**	**CROM2L**	**CPOM3R**	**MK67814**
157	**WRR(IPC7,K)=**				
158	0.9994370	1.0006300	1.0029400	0.9989010	1.0009400
159	**W(IPC8,K)=**				
160	1.0000000	0.9999313	1.0005087	1.0001049	1.0003690

Table 7.1 PMOD/WRC Method to Calculate WRR Reduction Factor for HF28968

	M	N	O	P	Q	R	S
1	PMO2	PMO5	CROM2L	CROM3R	MK67814		
2	WRR(IPC7,K)=						
3	0.9994370	1.0006300	1.0029400	0.9989010	1.0009400		
4	W(IPC8,K)=						
5	1.0000000	0.9999313	1.0005087	1.0001049	1.0003690		
6	MEAN=M=	1.0001828					
7	D(k)=						
8	-0.000183	-0.000252	0.0003259	-7.78E-05	0.0001862		
9	WRR(IPC8,K)=						
10	0.9996198	1.0008815	1.0026141	0.9989788	1.0007538		
11	NOTE, INSTRUMENTS THAT HAVE MORE READINGS HAVE LARGER						
12	CHANGE IN THEIR WRR REDUCTION FACTOR						
13	MEAN= M(IPC7)=		1.0005696				
14	MEAN= M(IPC8)=		1.0005696				
15	D=		0				
16							
17	WRR(IPC8,HF28968)=		0.998244				
18	SD(IPC8,HF28968)=		0.0008673				
19							
20							
21							
22							
23							
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Table 7.1 PMOD/WRC Method to Calculate WRR Reduction Factor for HF28968

7.2 Proposed method

The following rows, cells, or columns in Table 7.2 describe the sequence of the proposed method used to calculate the WRR reduction factor for HF28968.

a) Columns B through F contain the irradiance readings of the WSG instruments; the whole population of data is divided into seven samples. Rows 6 through 11, 13 through 25, 28 through 30, 34 through 48, 51 through 52, 56 through 58 and 61 through 83, are samples, 1, 2, 3, 4, 5, 6 and 7 respectively.

b) Columns G through K contain the ratios of irradiances of the WSG instruments to a reference irradiance using Equations 6.1 through 6.3.

c) Cells G86 through K86 contain the mean of ratios in step (b) after rejecting the outliers.

d) Cells G88 through K88 contain the standard deviations of the mean of ratios in step (c).

e) Cells G95 through K95, G97 through K97, G99 through K99, G101 through K101, G103 through K103, G105 through K105 and G92 through K92 contain the weighting factors for each of the WSG instruments for samples, 1, 2, 3, 4, 5, 6, and 7 respectively. The weighting factor is calculated using Equations 6.7 and 6.8.

f) Column L contains a reference irradiance calculated using Equation 6.9.

g) Columns M through Q contain the ratios of the irradiances

in columns B through F to the reference irradiances in column L.

h) Cells M86 through Q86 contain the WRR reduction factors for the WSG instruments during IPC-VIII, which is the mean of the ratios in step (g).

i) Cells M88 through Q88 contain the standard deviations of the means in step (h).

j) The weighting factors are recalculated in the same rows as in step (e) but using columns M through Q instead of columns G through K.

k) Column R contains the reference irradiance calculated using Equation 6.11.

l) Column S contains a sample of irradiance readings for HF28968 during IPC-VIII.

m) Column T contains the ratio of column R to column l.

n) Cell T86 contains the mean of the ratios in step (m), which is the WRR reduction factor for HF28968 during IPC-VIII.

o) Cell T88 contains the standard deviation of the WRR reduction factor for HF28968 during IPC-VIII.

	A	B	C	D	E	F
1	Date/Time	PMO2	PMO5	CROM2L	CROM3R	MK67814
2	WRR from (IPC7):					
3		0.999437	1.00063	1.00294	0.998901	1.00094
4						
5	**10/2/95**					
6	11:24:00	1022.2	1020.7	1019		
7	11:27:00	1021.2	1020.3	1020.7		
8	11:39:00	1015.1	1013.4	1010.7		
9	**10/11/95**					
10	11:03:00	938.6	938	936.4		
11	12:24:00	956.7	954.8	952.6		
12						
13	11:33:00	1018.2	1017.8	1015.7	1018.5	
14	11:36:00	1016.9	1015.8	1013.6	1015.9	
15	**10/3/95**					
16	10:21:00	932.6	931.9	929.1	935.6	
17	10:24:00	932.7	931.1	930	935.2	
18	10:27:00	938	936.6	934.4	939.3	
19	**10/11/95**					
20	12:51:00	953.6	953.2	951.5	952.8	
21	13:18:00	945.8	943.8	942.2	945.6	
22	13:45:00	927.6	926.3	924.3	928.3	
23	**10/12/95**					
24	11:57:00	1000.6	999.7	997.9	1001.5	
25	12:24:00	1000.6	999.5	998.3	1000.5	
26						
27	**10/3/95**					
28	10:33:00	942.5	941		942.5	
29	**10/11/95**					
30	11:57:00	950.8	949.4		953.3	
31						
32						
33	**10/11/95**					
34	11:06:00	941.6	940.5	939.3		941.9
35	11:09:00	941.4	940.3	937.6		941.9
36	11:18:00	946.7	945.8	944.6		946.3
37	12:03:00	954.1	953.2	951.9		952.8
38	12:09:00	956.6	954.3	952		955.2
39	12:30:00	960.2	958.4	957.1		958.3
40	12:36:00	959	957.4	955.5		958.3
41	13:24:00	937.3	936.5	936		935.9
42	**10/12/95**					
43	12:06:00	1003.1	1001.4	999.8		1001.4
44	12:09:00	1001.8	1000.8	998.9		1001.4
45	12:12:00	1000.7	1000.1	998.7		999.5
46	12:33:00	1000.5	1000.4	998.9		999.2
47	12:36:00	998.9	997.4	995.4		997.2
48	12:39:00	999.5	997.2	997.4		997.2
49						
50	**10/11/95**					
51	11:15:00	948.7	946.9		950	948.5
52	12:06:00	954.7	954.4		956.9	955.2
53						

Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

	A	B	C	D	E	F
54						
55	**10/11/95**					
56	13:06:00	949.3	948.3			946.9
57	**10/12/95**					
58	12:03:00	1001.4	1000.2			999.4
59						
60	**10/11/95**					
61	11:12:00	941.9	940.4	941.1	941.1	941.9
62	12:00:00	951.9	951.4	951	951	950.7
63	12:12:00	956.9	956.4	958.8	958.8	957.6
64	12:27:00	956.8	954.9	953.2	957.6	955.9
65	12:33:00	954.8	953.3	952.4	957	953.7
66	12:39:00	958	956.8	954.9	958.5	958.3
67	12:54:00	953.5	952.5	949.2	952.8	949.1
68	12:57:00	954.6	953.4	951.6	955.1	951.4
69	13:00:00	953.8	952.7	951.2	954.5	951.4
70	13:03:00	954	952.7	950.1	955.3	951.4
71	13:21:00	942.5	940.6	938.8	940.9	940.2
72	13:27:00	937.8	935.7	933.7	938.4	935.9
73	13:30:00	934.4	933.5	931.2	935.1	933.6
74	13:33:00	937.9	936	933.3	937.6	935.9
75	13:48:00	925.4	924.1	922.3	926.5	925.6
76	13:51:00	923.5	922.3	920.8	925.3	923.5
77	13:54:00	921.1	921	918.1	923.1	921.3
78	13:57:00	921	919.6	916.9	920.7	921.3
79	14:00:00	915.2	913.5	912.4	916.4	914.3
80	**10/12/95**					
81	12:00:00	1000.2	999.9	998.1	1002.3	999.3
82	12:27:00	1000.4	999.6	997.5	999.1	999.2
83	12:30:00	1000.3	998.9	999.9	999.8	999.2
84						
85						
86						
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Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

	G	H	I	J	K	L
1	R"(j,PMO2)	R"(j,PMO5)	R"(j,CROM2L)	R"(j,CROM3R)	R"(j,MK67814)	I'(ref.,j)
2						
3						
4						
5						
6	0.999466	1.000935	1.002605			1021.54
7	1.000545	1.001427	1.001035			1021.19
8	0.998995	1.000670	1.003344			1014.17
9						
10	1.000006	1.000645	1.002355			938.47
11	0.998907	1.000895	1.003207			955.69
12						
13	0.999837	1.000230	1.002298	0.999542		1018.08
14	0.999147	1.000229	1.002400	1.000131		1016.24
15						
16	1.000152	1.000903	1.003919	0.996945		932.49
17	0.999991	1.001710	1.002895	0.997318		932.24
18	0.999487	1.000981	1.003338	0.998104		937.39
19						
20	0.999610	1.000030	1.001817	1.000450		953.40
21	0.998941	1.001058	1.002758	0.999152		944.77
22	0.999423	1.000825	1.002991	0.998669		927.01
23						
24	0.999800	1.000700	1.002505	0.998902		1000.30
25	0.999601	1.000701	1.001904	0.999701		1000.15
26						
27						
28	0.999125	1.000718		0.999125		941.72
29						
30	1.000040	1.001515		0.997418		950.37
31						
32						
33						
34	1.000162	1.001332	1.002611		0.999843	941.44
35	0.999815	1.000985	1.003867		0.999285	941.09
36	1.000087	1.001039	1.002310		1.000510	946.55
37	0.999832	1.000776	1.002142		1.001196	953.81
38	0.998813	1.001221	1.003640		1.000277	955.43
39	0.999213	1.001090	1.002450		1.001194	959.35
40	0.999472	1.001142	1.003133		1.000202	958.36
41	1.000052	1.000906	1.001441		1.001548	937.13
42						
43	0.999314	1.001010	1.002612		1.001010	1002.32
44	0.999911	1.000910	1.002814		1.000311	1001.54
45	1.000036	1.000636	1.002038		1.001236	1000.60
46	1.000236	1.000336	1.001838		1.001537	1000.64
47	0.999307	1.000810	1.002820		1.001010	998.18
48	0.999308	1.001613	1.001412		1.001613	998.52
49						
50						
51	0.999792	1.001692		0.998424	1.000003	948.14
52	1.000605	1.000919		0.998304	1.000081	954.97
53						

Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

	G	H	I	J	K	L
54						
55						
56	0.999141	1.000194			1.001673	948.67
57						
58	0.999270	1.000468			1.001269	1000.75
59						
60						
61	0.999911	1.001506	1.000761	1.000761	0.999911	941.56
62	0.999834	1.000359	1.000780	1.000780	1.001096	951.77
63	1.001406	1.001930	0.999422	0.999422	1.000674	957.57
64	0.999396	1.001385	1.003171	0.998561	1.000337	956.05
65	0.999981	1.001554	1.002501	0.997682	1.001134	954.43
66	0.999837	1.001091	1.003083	0.999315	0.999524	957.70
67	0.998385	0.999433	1.002907	0.999118	1.003013	952.43
68	0.999121	1.000379	1.002271	0.998598	1.002482	953.85
69	0.999435	1.000589	1.002167	0.998702	1.001956	953.26
70	0.999204	1.000567	1.003305	0.997844	1.001934	953.27
71	0.998551	1.000568	1.002487	1.000249	1.000994	941.33
72	0.998967	1.001209	1.003353	0.998328	1.000995	936.77
73	0.999668	1.000632	1.003103	0.998920	1.000525	934.07
74	0.998690	1.000717	1.003612	0.999009	1.000824	936.79
75	0.999897	1.001304	1.003258	0.998710	0.999681	925.09
76	1.000112	1.001414	1.003045	0.998167	1.000112	923.31
77	1.000372	1.000480	1.003641	0.998204	1.000155	921.34
78	0.999373	1.000894	1.003841	0.999698	0.999047	920.43
79	0.999649	1.001510	1.002717	0.998340	1.000633	914.63
80						
81	1.000328	1.000628	1.002432	0.998232	1.001229	1000.36
82	0.999328	1.000128	1.002234	1.000629	1.000529	999.93
83	0.999889	1.001291	1.000289	1.000389	1.000990	999.95
84						
85	**R"(k)=**					
86	0.99962755	1.00089153	1.002527008	0.998940082	1.000789312	
87	**SD"(k)=**					
88	0.00055147	0.00048267	0.000925781	0.000985592	0.000829701	
89	**(1/SD"(k))^2=**					
90	3288234.09	4292304.62	1166765.713	1029450.916	1452634.548	
91	**WF'(k) WHEN ALL INSTRUMENTS FROM THE WSG ARE PARTICIPATING=**					
92	0.29282393	0.38223845	0.103902859	0.091674697	0.12936006	
93	**SUM=**	1				
94	**WF'(k) WHEN PMO2,PMO5 AND CROM2L ARE PARTICIPATING=**					
95	0.37591399	0.49070027	0.133385744			
96	**WF'(k) WHEN PMO2, PMO5, CROM2L AND CROM3R ARE PARTICIPATING=**					
97	0.33633184	0.43903161	0.119340791	0.105295763		
98	**WF'(k) WHEN PMO2, PMO5 AND CROM3R ARE PARTICIPATING=**					
99	0.38190918	0.49852611		0.11956471		
100	**WF'(k) WHEN PMO2,PMO5, CROM2L AND MK67814 ARE PARTICIPATING=**					
101	0.32237782	0.4208167	0.11438948		0.142416004	
102	**WF'(k) WHEN PMO2, PMO5, CROM3R AND MK67814 ARE PARTICIPATING=**					
103	0.32677699	0.42655917		0.102304419	0.144359416	
104	**WF'(k) WHEN PMO2, PMO5 AND MK67814 ARE PARTICIPATING=**					
105	0.3640176	0.47517129			0.160811102	

Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

	M	N	O	P	Q
1	R(i,PMO2)	R(j,PMO5)	R(j,CROM2L)	R(j,CROM3R)	R(j,MK67814)
2					
3					
4					
5					
6	0.999350345	1.00081897	1.002488639		
7	0.999991421	1.000873507	1.000481277		
8	0.99908749	1.00076348	1.003436936		
9					
10	0.999862214	1.000501784	1.002211313		
11	0.9989412	1.000929039	1.003240653		
12					
13	0.999886904	1.000279864	1.002347983	0.999592387	
14	0.999355319	1.000437511	1.002608942	1.000339033	
15					
16	0.999881785	1.000632849	1.003648426	0.996675665	
17	0.999504203	1.001221749	1.00240599	0.996832304	
18	0.999353094	1.000846895	1.003203341	0.99796998	
19					
20	0.999786282	1.000205832	1.001992852	1.000625734	
21	0.998915587	1.001032382	1.002732288	0.999126863	
22	0.999360263	1.000762798	1.002928248	0.998606679	
23					
24	0.999698868	1.000598867	1.002403735	0.998800487	
25	0.99955379	1.000653849	1.001856679	0.999653696	
26					
27					
28	0.999173745	1.000766477		0.999173745	
29					
30	0.999547174	1.001021122		0.996925893	
31					
32					
33					
34	0.999827056	1.000996445	1.002275265		0.999508606
35	0.999674386	1.000843844	1.003725967		0.999143717
36	0.999838763	1.000790185	1.002061568		1.000261394
37	0.999697818	1.00064172	1.002008286		1.001061805
38	0.998781059	1.001188264	1.003607102		1.000244934
39	0.999111965	1.000988428	1.00234804		1.001092882
40	0.999328499	1.000998569	1.002989043		1.000058469
41	0.999822352	1.000676445	1.001210994		1.001317972
42					
43	0.999221154	1.000917455	1.002519244		1.000917455
44	0.999744442	1.000743387	1.002646894		1.000143781
45	0.999901088	1.000500969	1.001903494		1.00110157
46	1.000143013	1.000242987	1.001745004		1.00144424
47	0.99927689	1.000779712	1.002790521		1.00098043
48	0.999015746	1.001319934	1.001119148		1.001319934
49					
50					
51	0.999407759	1.001307573		0.998040148	0.999618493
52	1.000285064	1.000599487		0.997985317	0.999761464
53					

Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

	M	N	O	P	Q
54					
55					
56	0.999337763	1.000391583			1.001870671
57					
58	0.999354327	1.000553312			1.001354235
59					
60					
61	0.999637419	1.001231907	1.00048718	1.00048718	0.999637419
62	0.999863574	1.000389044	1.000809817	1.000809817	1.00112563
63	1.000696422	1.00121958	0.998713398	0.998713398	0.999964918
64	0.999215976	1.001204153	1.002989767	0.998381209	1.000156759
65	0.999611824	1.001184694	1.002130795	0.997313865	1.000764778
66	0.99968485	1.000938636	1.002930241	0.999163366	0.999371895
67	0.998877003	0.999925693	1.003402046	0.999610855	1.003507768
68	0.999218435	1.000476105	1.002368556	0.998695339	1.002579271
69	0.999429041	1.000582995	1.00216087	0.998696091	1.001950199
70	0.999237509	1.000601011	1.00333921	0.997877717	1.00196824
71	0.998761241	1.000778726	1.002697561	1.000459634	1.001204499
72	0.998896999	1.001138833	1.003283288	0.998258318	1.000924891
73	0.999645283	1.000609054	1.00308049	0.998896965	1.000501877
74	0.998821489	1.000849011	1.003744427	0.999141077	1.000955951
75	0.999663256	1.001069557	1.003023287	0.998476392	0.999447253
76	0.999789637	1.001090458	1.002721253	0.997844731	0.999789637
77	1.000258837	1.000367443	1.003527301	0.998091664	1.000041696
78	0.999379858	1.000901315	1.003848674	0.999705495	0.999054433
79	0.999376273	1.001236086	1.002443188	0.998067618	1.000360018
80					
81	1.000155056	1.000455133	1.00225938	0.99805955	1.001055827
82	0.999530556	1.0003305	1.002436459	1.000831116	1.000730953
83	0.999647673	1.001048721	1.000047572	1.000147597	1.000748166
84	**WRR(IPC8)**				
85	**PMO2**	**PMO5**	**CROM2L**	**CROM3R**	**MK67814**
86	0.999516088	1.000779929	1.002419267	0.99883547	1.000676103
87	**SD(k)=**				
88	0.00040699	0.00032042	0.000985037	0.001113079	0.000940421
89	**(1/SD(k))^2=**				
90	6037150.257	9740021.616	1030610.526	807138.9198	1130720.495
91	**WF'(k) WHEN ALL INSTRUMENTS FROM THE WSG ARE PARTICIPATING=**				
92	0.322056205	0.519588591	0.054978674	0.043057417	0.060319113
93	**SUM=**	1			
94	**WF'(k) WHEN PMO2,PMO5 AND CROM2L ARE PARTICIPATING=**				
95	0.359187792	0.579494747	0.06131746		
96	**WF'(k) WHEN PMO2, PMO5, CROM2L AND CROM3R ARE PARTICIPATING=**				
97	0.342729334	0.552941534	0.058507813	0.045821318	
98	**WF'(k) WHEN PMO2, PMO5 AND CROM3R ARE PARTICIPATING=**				
99	0.364027805	0.58730337		0.048668825	
100	**WF'(k) WHEN PMO2,PMO5, CROM2L AND MH67814 ARE PARTICIPATING=**				
101	0.336547051	0.542967363	0.057452427		0.063033158
102	**WF'(k) WHEN PMO2, PMO5, CROM3R AND MK67814 ARE PARTICIPATING=**				
103	0.340792526	0.549816789		0.045562376	0.063828309
104	**WF'(k) WHEN PMO2, PMO5 AND MK67814 ARE PARTICIPATING=**				
105	0.357061077	0.576063616			0.066875307

Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

	R	S	T
1	WRR(IPC8,j)	i(j,HF28968)	WRR(IPC8,j,HF)
2			
3			
4			
5			
6	1021.57	1022.9	0.99869913
7	1021.08	1021.7	0.999395947
8	1014.28	1016.9	0.997420162
9			
10	938.52	940.2	0.998210065
11	955.75	957	0.998698127
12			
13	1018.21	1020.1	0.998142998
14	1016.41	1017.7	0.998733845
15			
16	932.47	933	0.999436578
17	932.10	934.9	0.997005415
18	937.41	938.5	0.998833462
19			
20	953.56	955.6	0.99786098
21	944.81	946	0.998739203
22	927.05	929.1	0.997790334
23			
24	1000.34	1001.9	0.998441457
25	1000.21	1001.9	0.998308727
26			
27			
28	941.83	942.8	0.998971806
29			
30	950.31	952.3	0.997913256
31			
32			
33			
34	941.31	942.8	0.998414529
35	941.03	942.9	0.998018196
36	946.48	950	0.996298439
37	953.82	954.9	0.998873456
38	955.42	958	0.997306988
39	959.35	962	0.997243484
40	958.31	960.7	0.997511224
41	937.12	938.7	0.998313301
42			
43	1002.32	1004	0.998329325
44	1001.51	1003.2	0.998312875
45	1000.63	1002	0.998628461
46	1000.71	1002.6	0.998118944
47	998.22	1001.7	0.996523854
48	998.43	1001.1	0.997329218
49			
50			
51	948.00	948.5	0.999469589
52	954.91	956.8	0.998024108
53			

Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

	R	S	T
54			
55			
56	948.87	951.2	0.997548646
57			
58	1000.90	1002.6	0.998300916
59			
60			
61	941.39	942.8	0.998507506
62	951.83	954.2	0.99752081
63	957.23	959.8	0.997317815
64	955.95	957.2	0.998694747
65	954.27	956.3	0.997879468
66	957.60	960.6	0.99687918
67	952.80	954.3	0.998431339
68	954.00	955.7	0.998216097
69	953.33	955.7	0.997515705
70	953.36	954.6	0.998705135
71	941.45	943.2	0.998146782
72	936.74	938.7	0.997915211
73	934.09	934.7	0.999343136
74	936.87	938.7	0.998055551
75	924.96	926.8	0.998012245
76	923.15	924.6	0.998430799
77	921.32	924.4	0.99667282
78	920.39	922.5	0.997717964
79	914.50	916.8	0.997491694
80			
81	1000.34	1001.4	0.998938854
82	1000.07	1001.5	0.998571168
83	999.84	1002.1	0.997739958
84			
85	**MEAN, M(IPC8)**		**WRR(IPC8,HF28968)**
86	1.00		**0.998103001**
87			**SD(IPC8,HF28968)**
88	**MEAN, M(IPC7)**		**0.000697432**
89	1.00		
90	**D= -124 ppm**		
91			
92			
93			
94			
95			
96			
97			
98			
99			
100			
101			
102			
103			
104			
105			

Table 7.2 Proposed Method to Calculate WRR reduction Factor for HF28968

Chapter 8

Observations and Conclusions Drawn from the International Pyrheliometer Comparisons IPC-VIII

8.1. Using the PMOD/WRC method, a single instrument, PMO2, is used as a transfer instrument through which all instruments are compared to each other, resulting in a larger random component of uncertainty than if that transfer instrument were not interposed in the process.

8.2. Using the PMOD/WRC method, if an irradiance reading of PMO2 were out of tolerance, then all ratios to PMO2 would be rejected for that irradiance reading, which would result in rejection of good data.

8.3. The proposed method showed, independently, that PMO2 has a small standard deviation. This finding supports the PMOD/WRC choice to use it as a transfer instrument for its stability during the comparison. The proposed method also showed that PMO5 has an even smaller standard deviation than PMO2, which makes PMO5 a good candidate for future considerations and that CROM2L and CROM3R have the largest standard deviations of all the WSG.

8.4. The standard deviation of the WRR reduction factor derived by using the proposed method is smaller than the standard deviation derived by using the PMOD/WRC method (see Table 8.1).

8.5. The difference between the WRR reduction factors derived by each method is much smaller than the standard deviations (see Table 8.1). Thus, the results of both methods are comparable.

Table 8.1 WRR Reduction Factor for HF28968

	PMOD/WRC Method	Proposed Method	Difference WRC - Prop.
WRR	0.998244	0.998103	0.000141
SD	0.000867	0.000697	0.000170

8.6. Fig. 8.1 and 8.2 show the WRR reduction factors and standard deviations calculated using the PMOD/WRC method and the proposed method.

8.7. Fig. 8.3 shows the means of WRR reduction factors of the WSG instruments, the difference between the means using the two methods is on the order of 0.01 percent, which is smaller than the standard deviations of the two methods.

8.8. Figs. 8.4 through 8.6 show the change of the M factor with time and irradiance calibration levels, which are the irradiance levels at which the HF28968 calibrations were performed, on three different days. Figs. 8.7 through 8.9 show the change of temperature of the sensing element, in degrees centigrade, with time and irradiance calibration levels for the three days.

Fig. 8.8 shows that the temperature of the sensing element decreased between 8:37 to 10:02; Fig. 8.5 shows that the M factor increased during the same period. When the temperature increased, during the period 10:02 to 13:12, the M Factor decreased. From 13:12 to 15:53, the rate of temperature change was different, the M factor changed in the same way, inversely proportional to the change in temperature. The same trend is shown in Figs. 8.4, 8.6, 8.7 and 8.9 for two other days. Fig. 8.10 shows the change of the M factor with temperature for the three

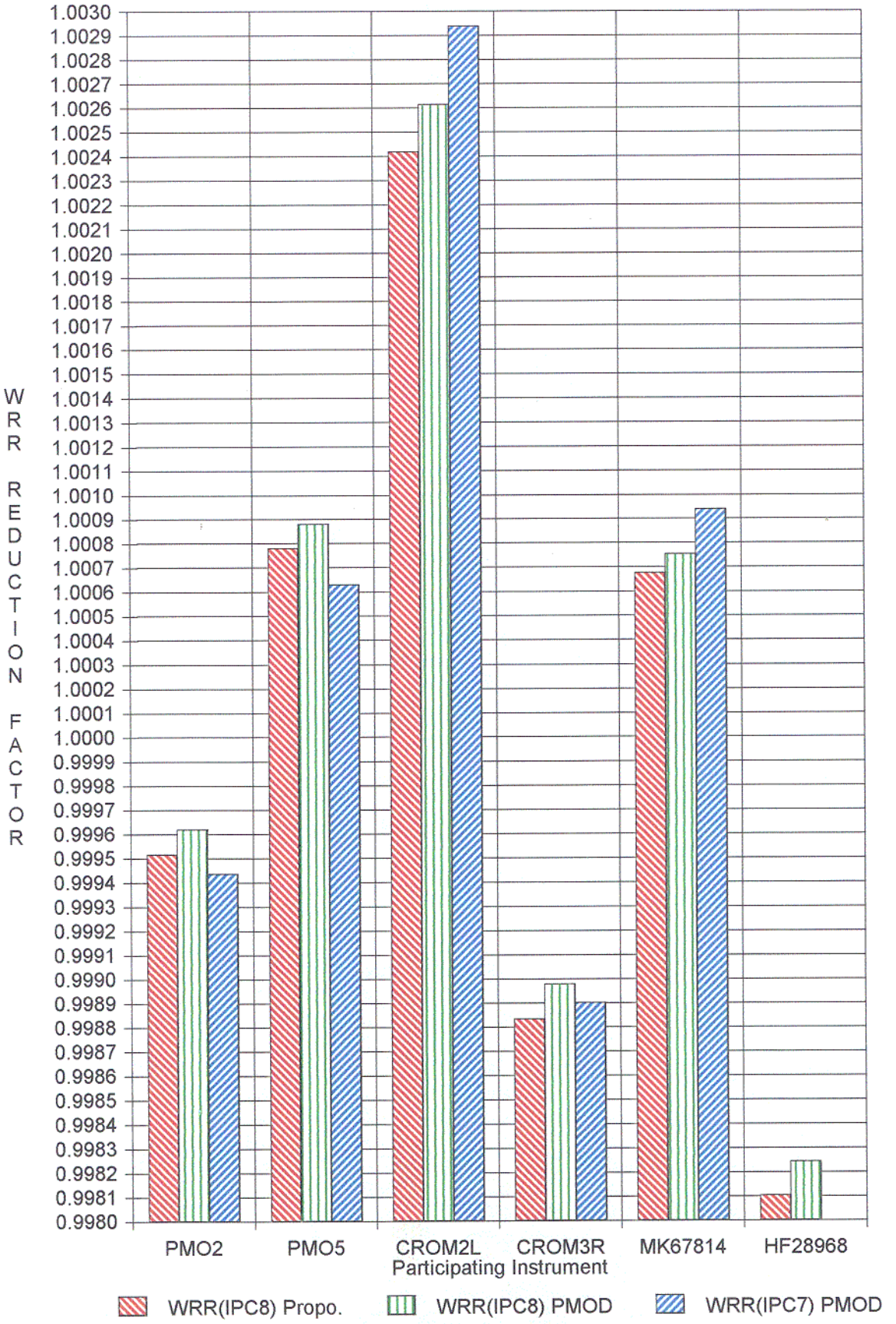

Fig. 8.1 WRR Reduction Factors

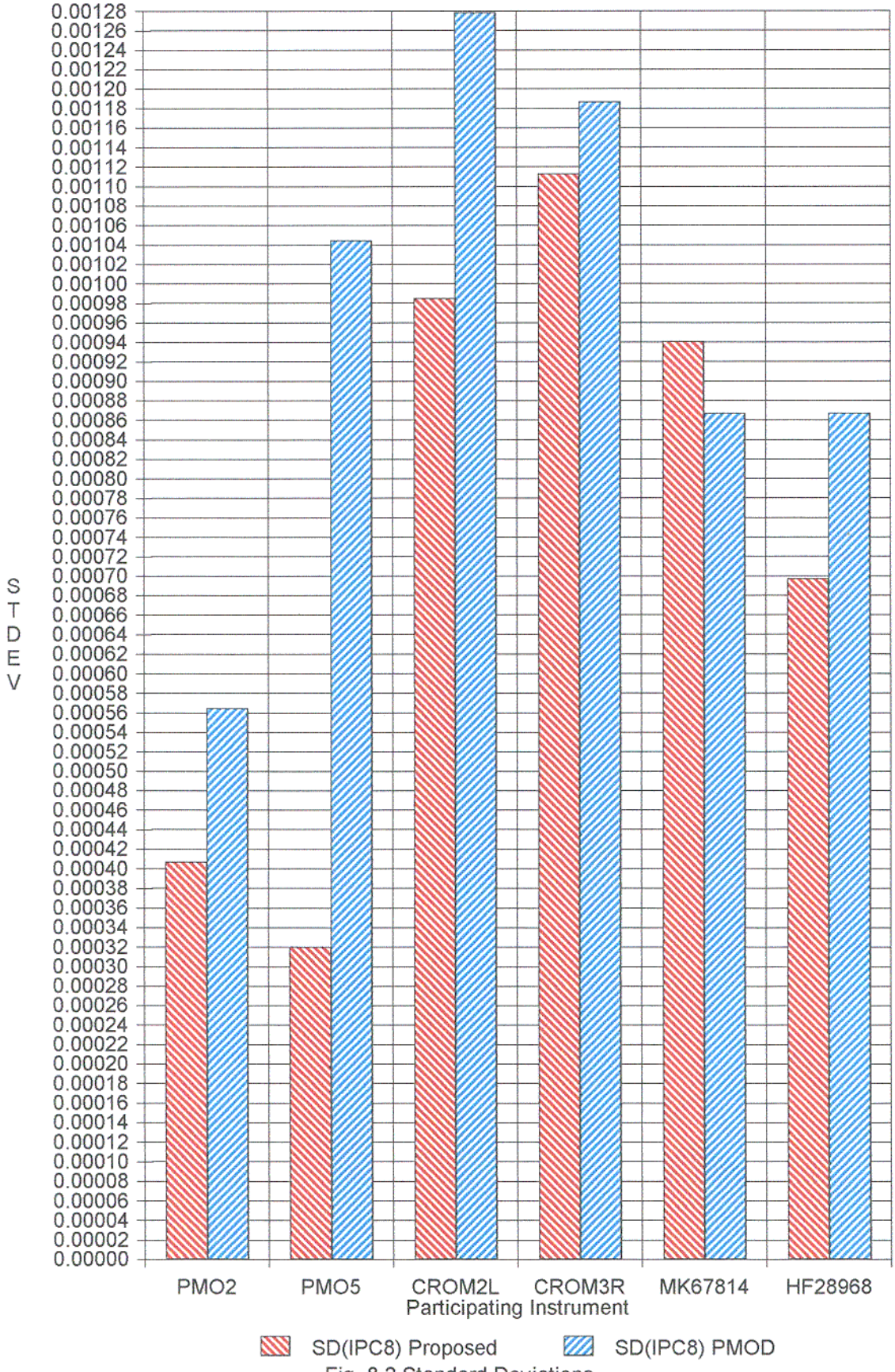

Fig. 8.2 Standard Deviations

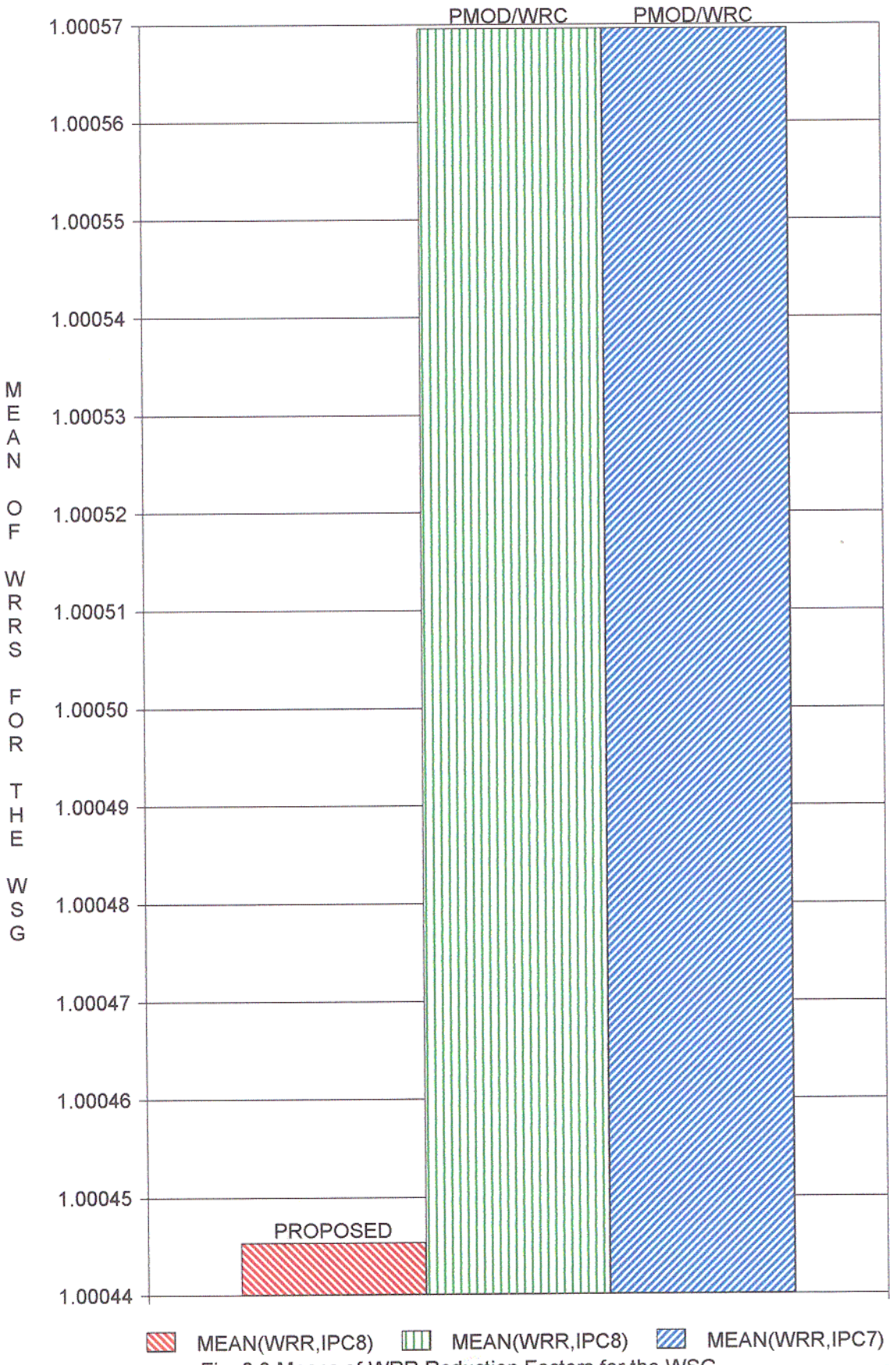

Fig. 8.3 Means of WRR Reduction Factors for the WSG

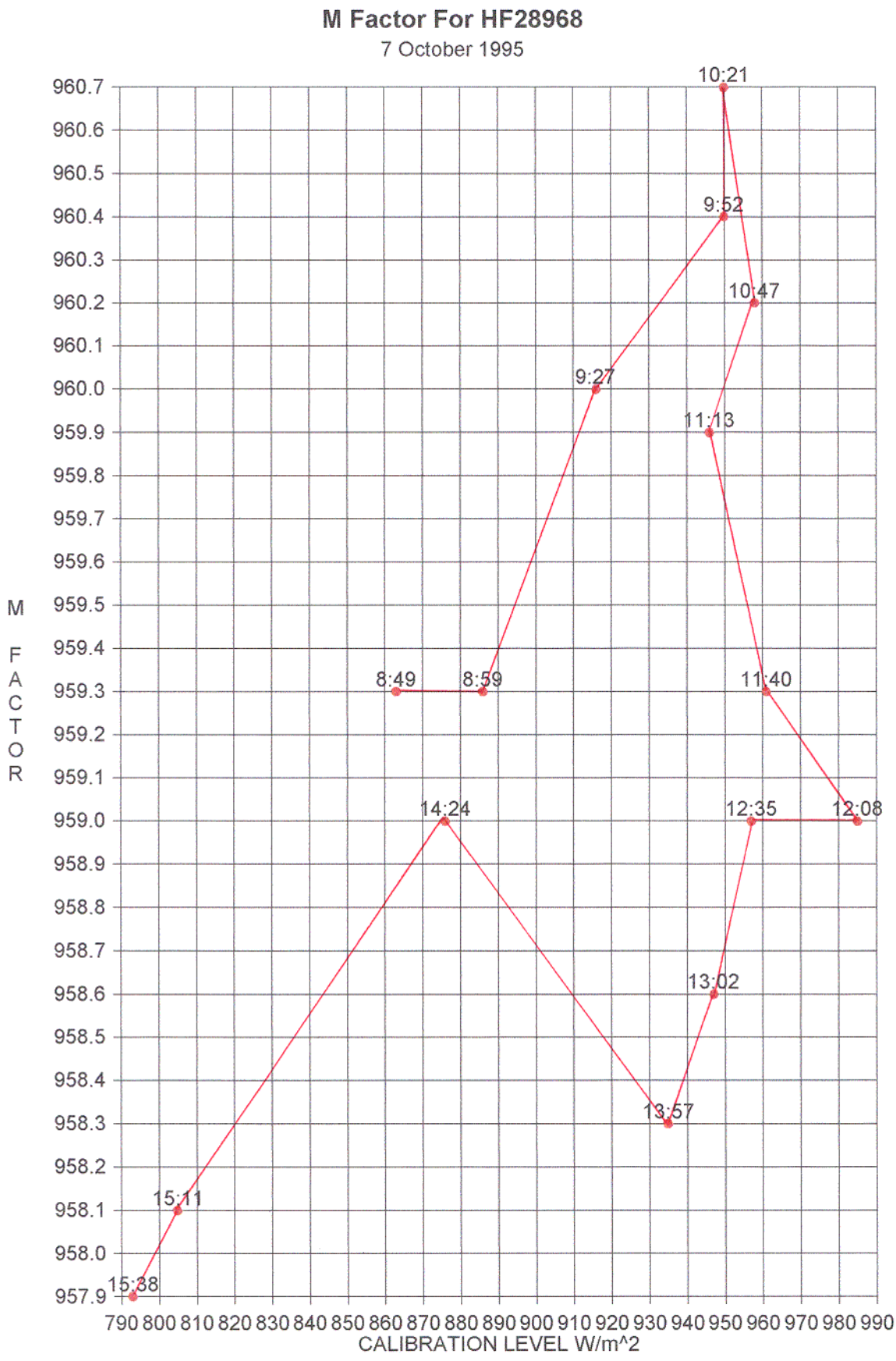

Fig. 8.4 Change of The M Factor With Different Irradiance Calibration Levels And Time

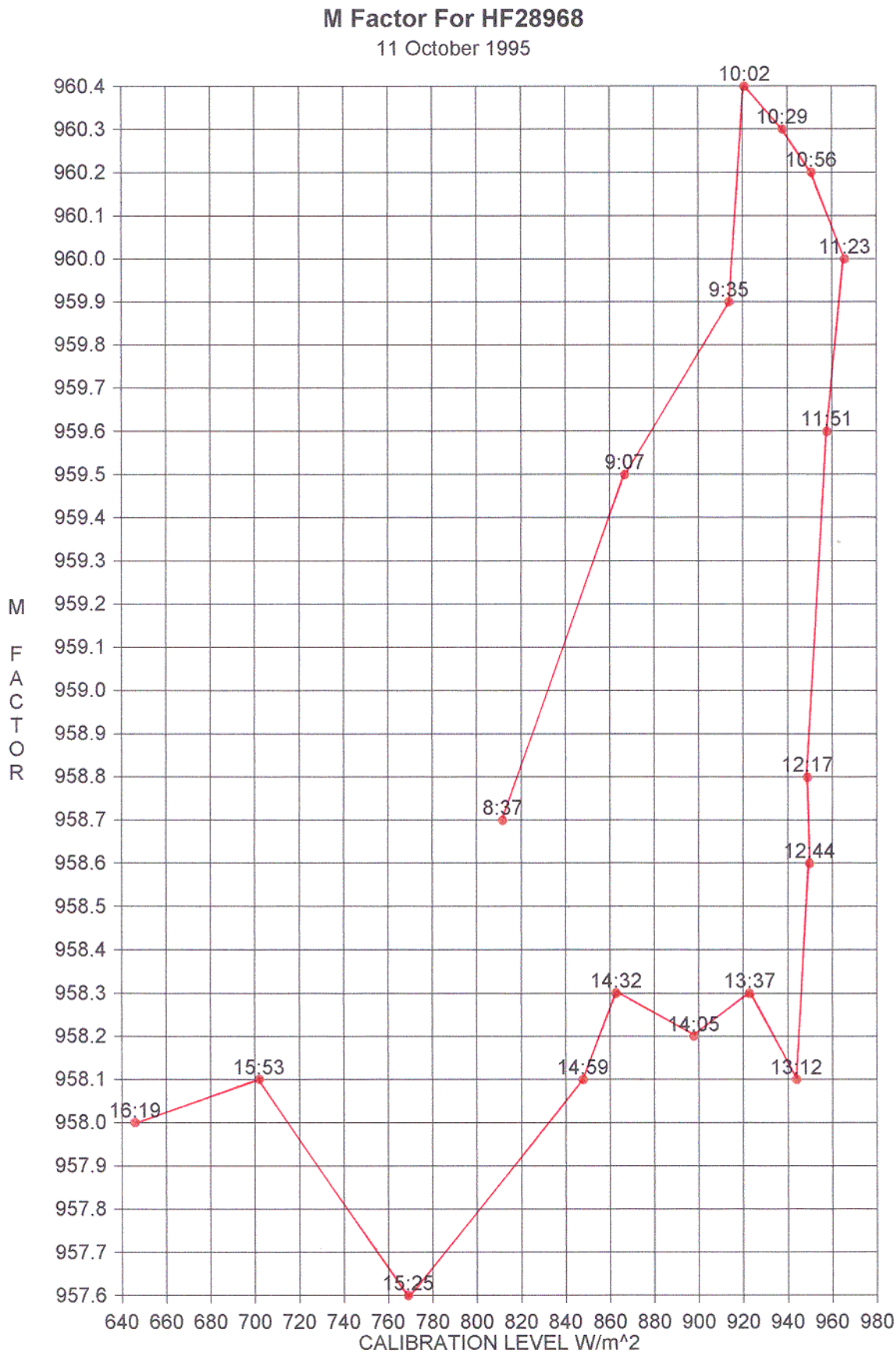

Fig. 8.5 Change of The M Factor With Different Irradiance Calibration Levels And Time

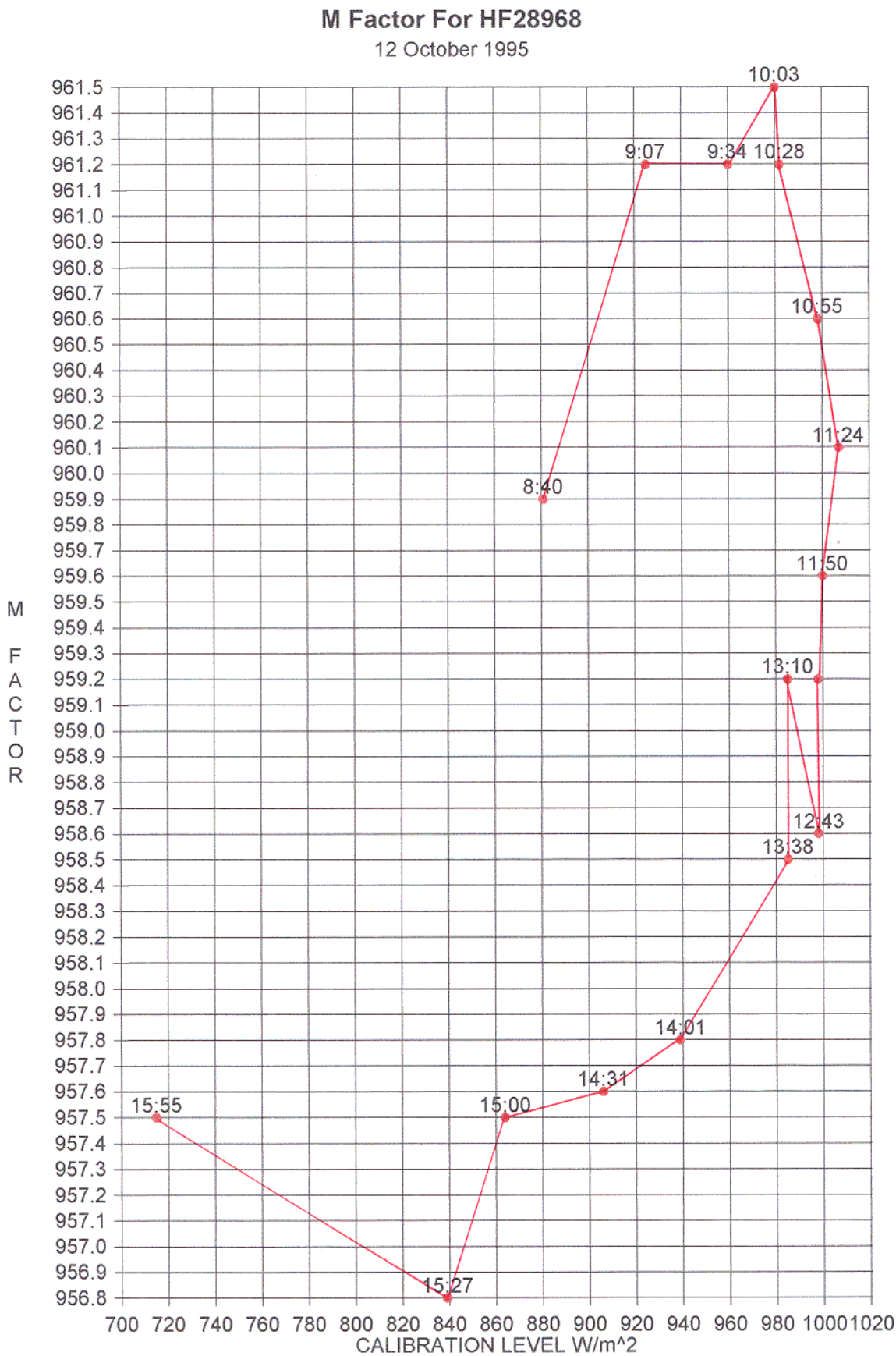

Fig. 8.6 Change of The M Factor With Different Irradiance Calibration Levels And Time

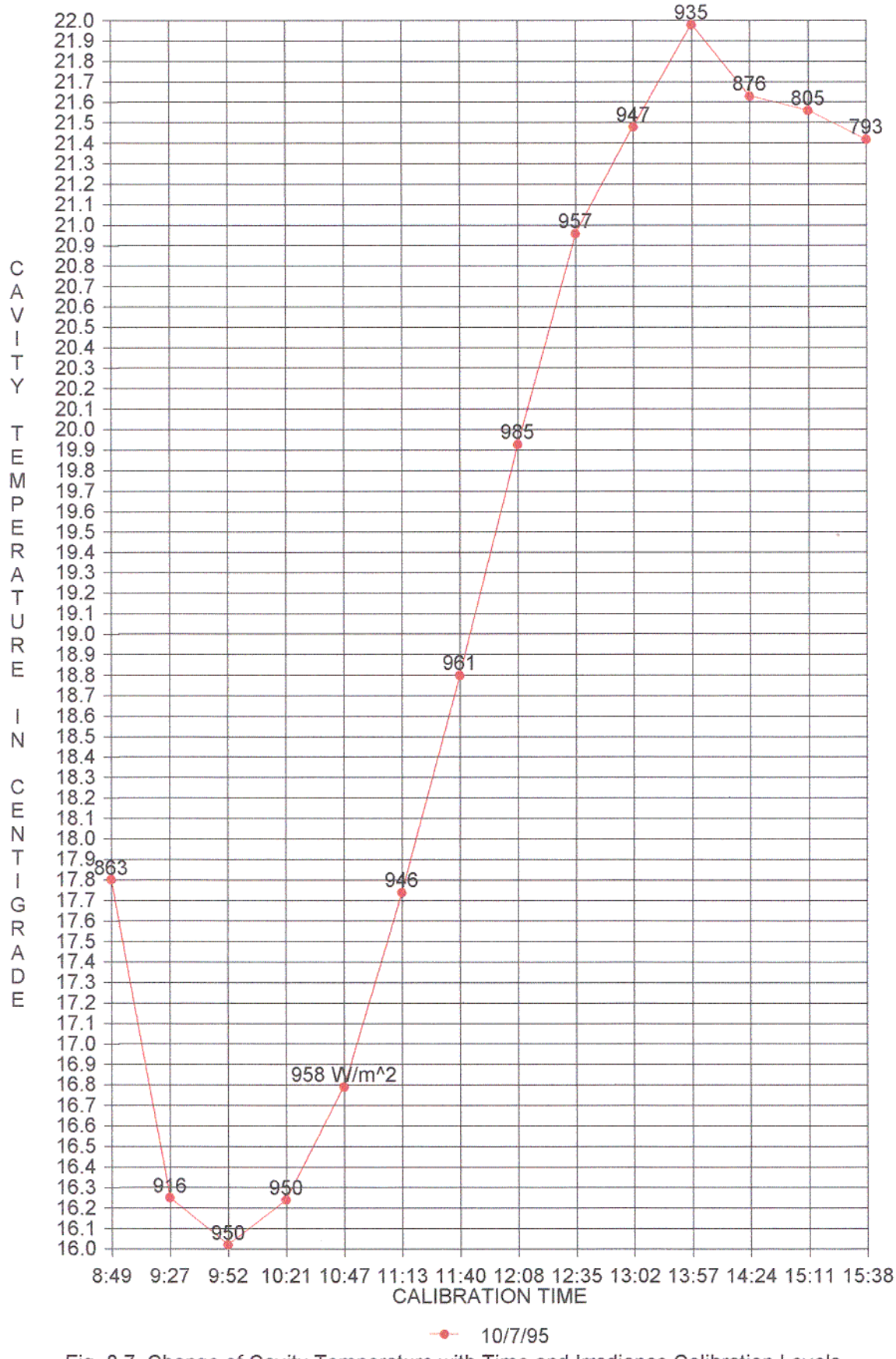

Fig. 8.7 Change of Cavity Temperature with Time and Irradiance Calibration Levels

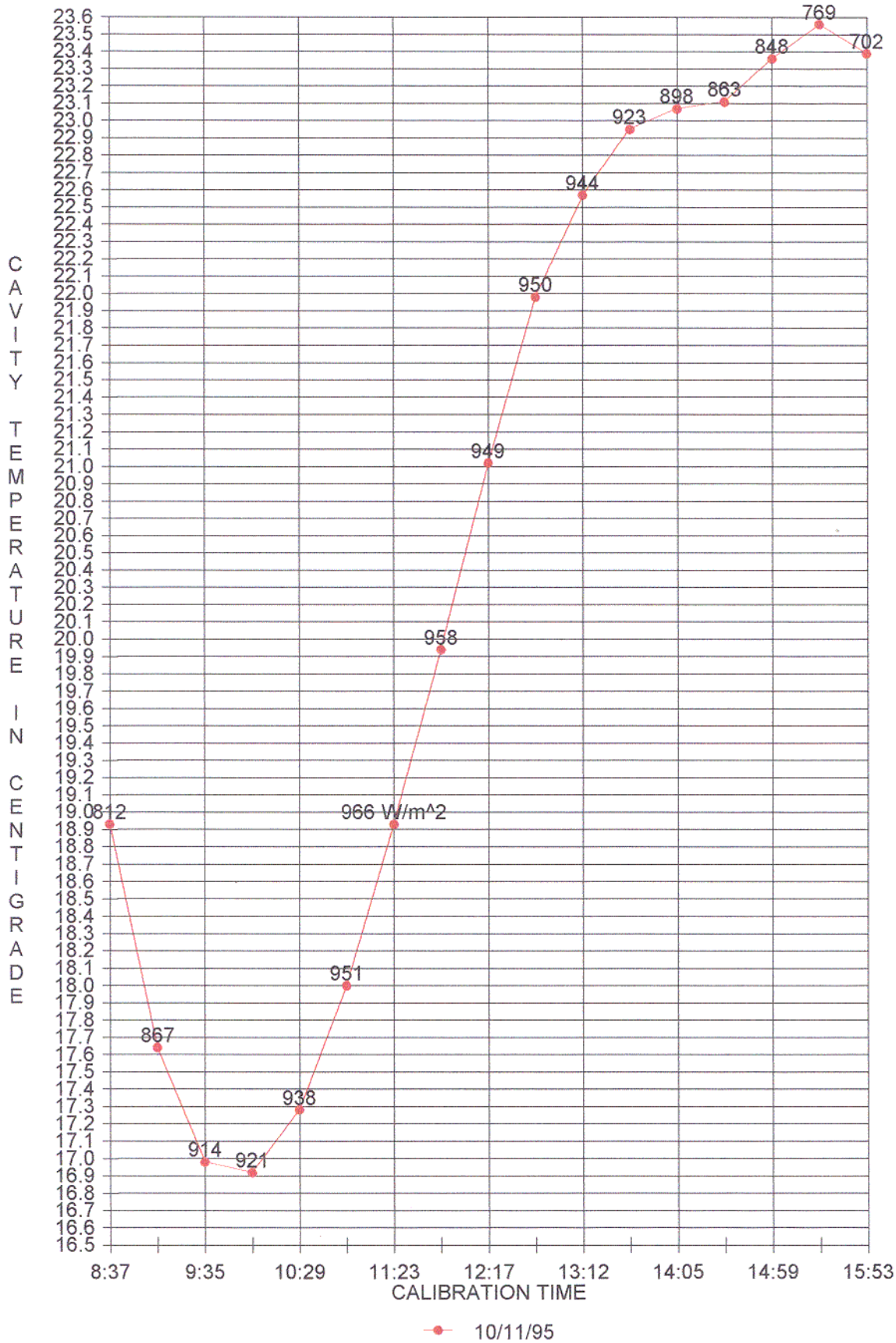

Fig. 8.8 Change of Cavity Temperature with Time and Irradiance Calibration Levels

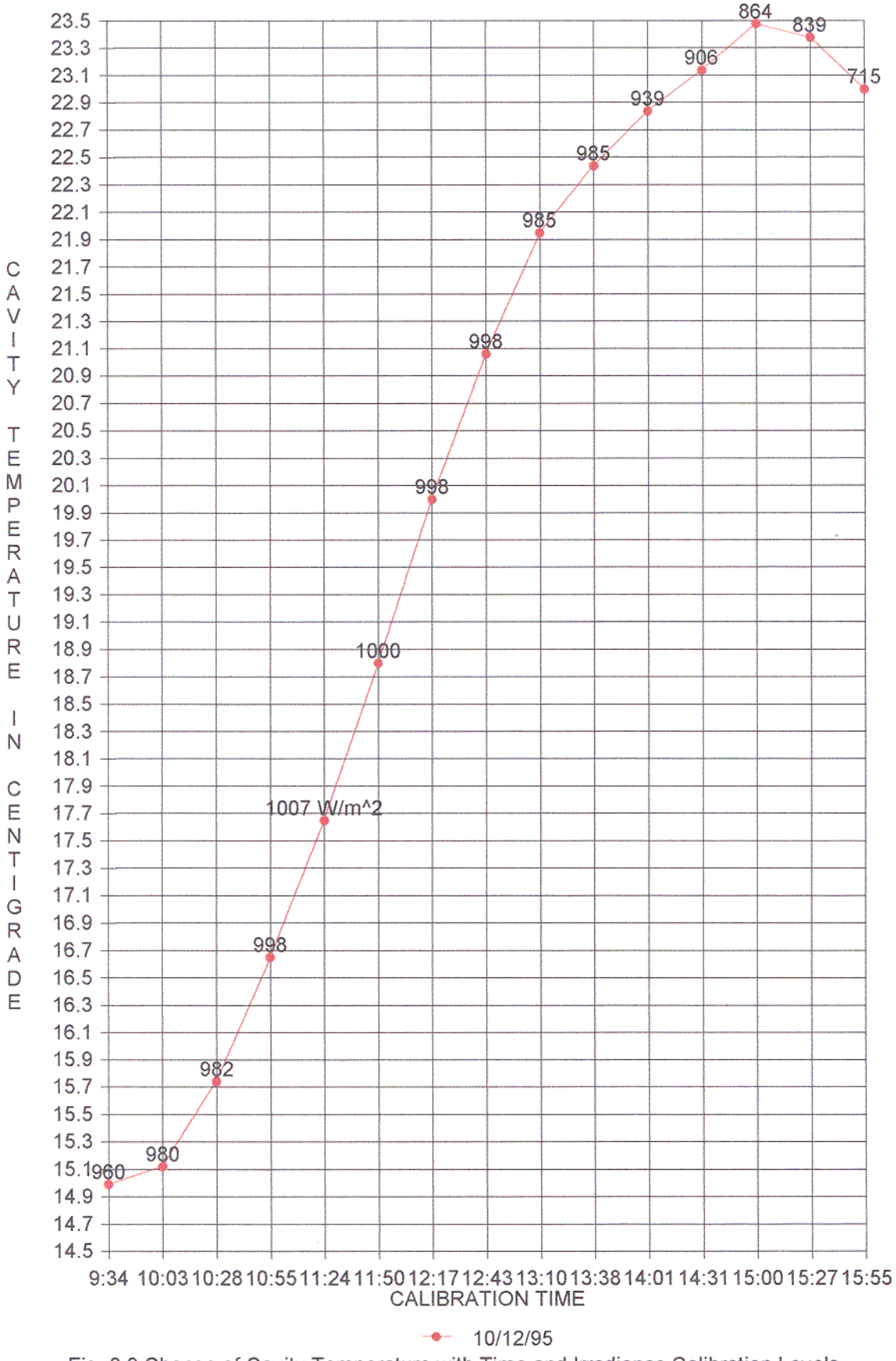

Fig. 8.9 Change of Cavity Temperature with Time and Irradiance Calibration Levels

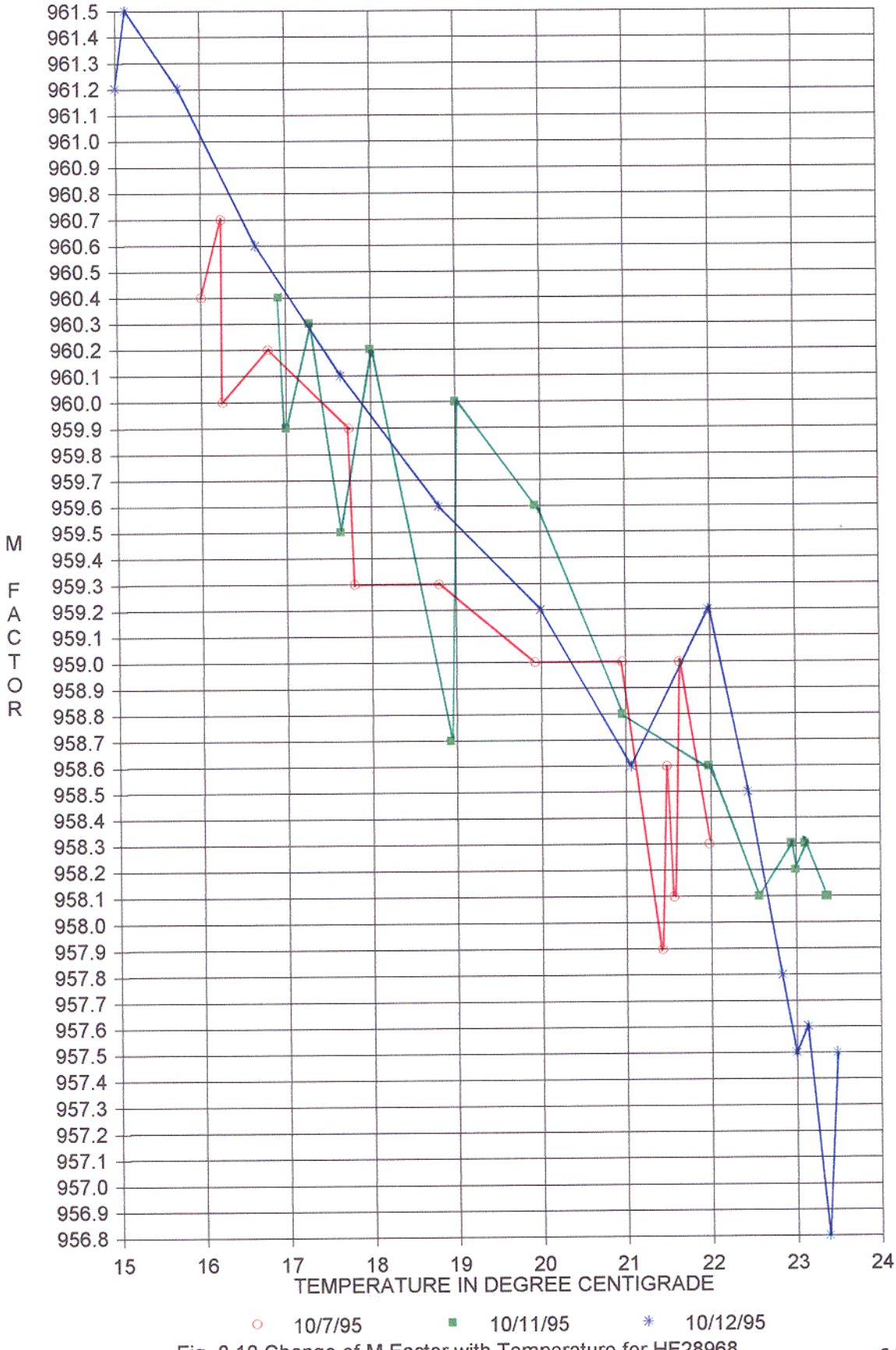

Fig. 8.10 Change of M Factor with Temperature for HF28968

days, the slope of the three days trend is approximately -0.44; then, the change of the M factor with temperature is approximately -0.44/°C (-0.046 percent/°C). That shows the importance of calibrating the absolute cavity radiometers more often when large changes in ambient temperature are expected.

8.9. Table 8.2 shows the calculated M factor when the HF28968 is calibrated at three different irradiance levels and temperature of the sensing element is at 18.9 °C. The values are obtained using Figures 8.4 through 8.9.

Table 8.2 Change of the M Factor for HF28968

Date	10/11/1995	10/7/1995	10/12/1995
Irradiance Cal. Levels	812 W/m^2	960 W/m^2	1000 W/m^2
Temperature	18.9 °C	18.9 °C	18.9 °C
M Factor	958.7	959.3	959.6

If the HF28968 is calibrated at an irradiance level that equals 812 W/m^2, and the irradiance to be measured is at 1000 W/m^2, then an error of -0.9, (958.7 is subtracted from 959.6), will be noticed in the irradiance reading at 1000 W/m^2. This error, which appears because the output voltage of the thermopile will be multiplied by 958.7 instead of 959.6, is on the order of -0.09 percent of the irradiance being measured, which is on the same order of magnitude of the standard deviation of the WRR reduction factor (0.08 percent). This shows the importance of minimizing this error to improve the measurement process during absolute cavity radiometers comparisons. The change in the M factor is attributed to the change of the cavity sensitivity with the change in irradiance levels, the change in barometric pressure, and/or the noise from the

Digital Multimeter, the control box, and the signal connection from the control box to the DMM. Noise can be minimized by using Digital Multimeters with less noise and better zero stability; and also by using, thermal insulated, and electromagnetic interference (EMI) shielded signal connection from the control box to the DMM. Changing barometric pressure changes the thermal impedance inside the sensing element; although the changes are negligible, they should be characterized in the future by monitoring the barometric pressure during the cavity calibrations (M factor calculations). After eliminating the errors due to noise, and characterizing the barometric pressure effect on cavity sensitivity, the change of the M factor with irradiance levels can be characterized.

8.11. Fig. 8.11 shows the difference in the irradiance readings during a run of 13 readings, when the calibration is done at irradiance levels of 812 W/m^2 and 908 W/m^2. The difference is in the order of 0.07 percent of the irradiance being measured. The temperature of the sensing element is the same during both calibrations. These results show the importance of calibrating the HF28968 (calculating the M factor) using electrical power that is as close as possible to the irradiance level being measured during the comparisons of absolute cavity radiometers.

8.12. The temperature dependency of absolute cavity radiometers shows the need to develop the cryogenic absolute cavity solar radiometers to define the WRR with a smaller uncertainty than 0.3 percent.

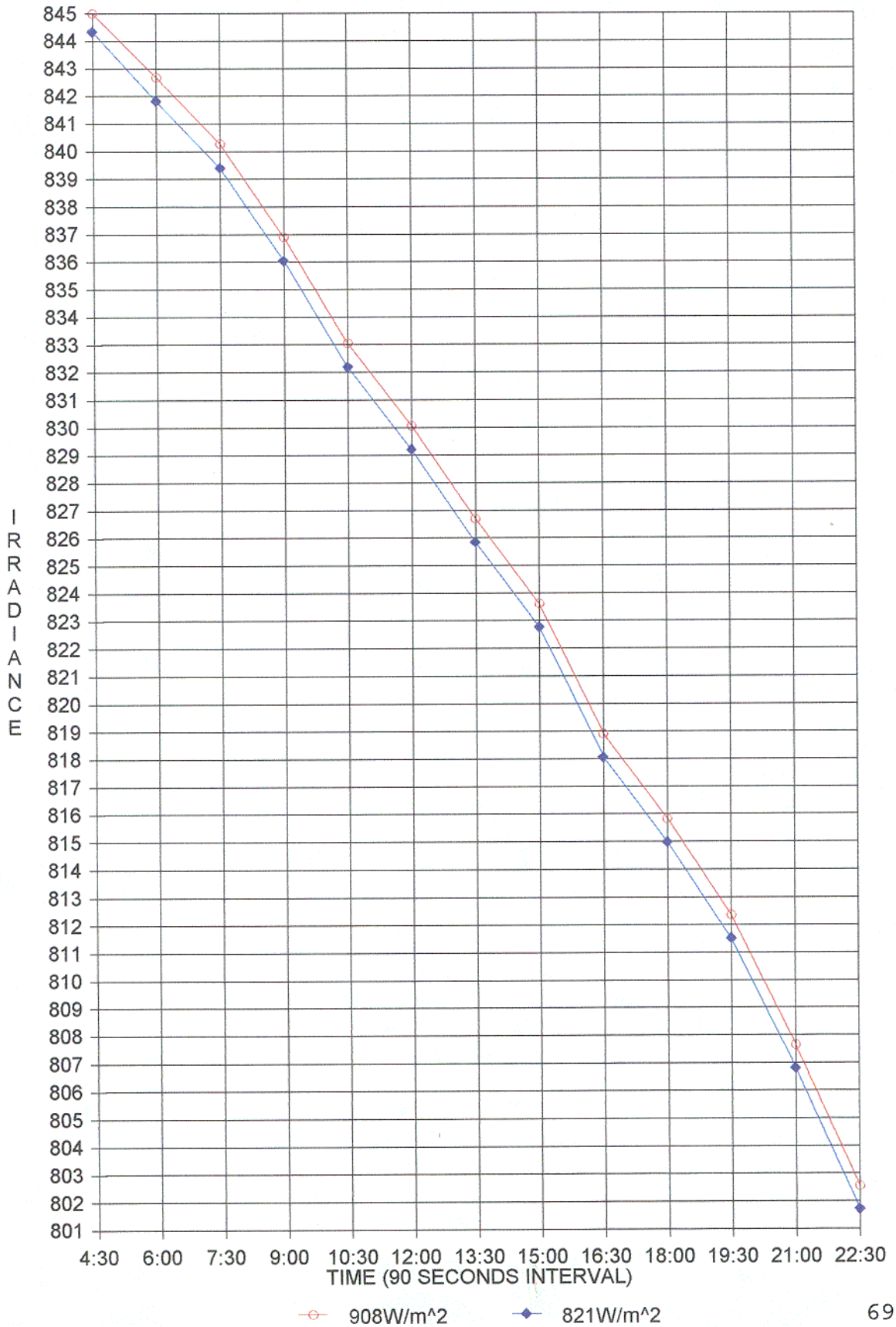

Fig. 8.11 Irradiance Readings with Time and Irradiance Calibration Levels

References

1. Wells, Chester. (16 March 1993). Personal Communication. "The NREL Reference Absolute Cavity Radiometer at the World Radiation Center in Davos, Switzerland." NREL, Golden, Colorado, USA; 3p.

2. Fröhlich, C.; Philipona, R.; Romero, J.; Wehrli, C. (September 1995). "Radiometry at the Physikalisch Meteorologisches Observatorium Davos and World Radiation Center." *Journal of Optical Engineering*. Vol.34, no.9; pp.2757-66.

3. Karoli, Alton R.; Hickey, John R.; Frieden, Roger G. (7-8 April,1983). "Self Calibrating Cavity Radiometers at the Eppley Laboratory: Capabilities and Applications." Proceedings of *The International Society for Optical Engineering*. Vol.416, SPIE, Bellingham, WA, USA; pp.43-50.

4. Swiss Meteorological Institute. (December 1985). "International Pyrheliometer Comparisons IPC VI." Part I of Working Report No. 137, Davos and Zurich, Switzerland; p.4.

5. Swiss Meteorological Institute. (March 1991). "International Pyrheliometer Comparisons IPC VII." Working Report No. 162,Davos and Zurich, Switzerland; p.7.

6. Romero, José. (September 1995). "Direct Solar Irradiance Measurements with Pyrheliometers: Instruments and Calibrations." IPC VIII, Davos, Switzerland; 16p.

7. Dieck, R. H. (Copy right 1992, second printing January 1995). "Weighting Method for Multiple Results." Unit 6 in *Measurement Uncertainty: Methods and Applications*. North Carolina, Instrument Society of America; pp.117-24.

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13. ABSTRACT (*Maximum 200 words*)

This report describes the present method of establishing traceability of absolute cavity radiometers to the World Radiometric Reference (WRR) through the process employed in the International Pyrheliometer Comparisons (IPC). This method derives the WRR reduction factor for each of the participating cavity radiometers. An alternative method is proposed, described, and evaluated as a way to reduce the uncertainty in the comparison process. The two methods are compared using a sample of data from the recent IPC-VIII conducted from September 25th to October 13th, 1995 at the World Radiation Center in Davos, Switzerland. A description of absolute cavity radiometers is also included, using a PMO-6 as an example of active cavity radiometers, and a HF as an example of passive cavity radiometers.

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