

NREL Pyrheliometer Comparisons: November 4 & 29, 2021 (NPC-2021)

Ibrahim Reda and Afshin Andreas

National Renewable Energy Laboratory

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Technical Report
NREL/TP-1900-84231
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List of Acronyms and Abbreviations

AEMET	State Meteorological Agency (Spain)
AHF	Automatic Hickey-Frieden
BMS	Baseline Measurement System
BORCAL	Broadband Outdoor Radiometer Calibration
DOE	U.S. Department of Energy
IPC	International Pyrheliometer Comparison
IPC-XIII	Thirteenth International Pyrheliometer Comparisons
ISO	International Organization for Standardization
MST	Mountain Standard Time
NOAA/ESRL/GMD	National Oceanic and Atmospheric Administration's Earth System Research Laboratory, Global Monitoring Division
NPC	NREL Pyrheliometer Comparisons
NREL	National Renewable Energy Laboratory
PMOD/WRC	Physikalisch-Meteorologisches Observatorium Davos—World Radiation Center
SD _p	pooled standard deviation
SI	International System of Units
SRRL	Solar Radiation Research Laboratory
TSG	Transfer Standard Group
WMO	World Meteorological Organization
WRR	World Radiometric Reference
WRR-TF	World Radiometric Reference transfer factor
WSG	World Standard Group
%uA	Percentage Type-A standard uncertainty
NRdg	number of readings
uC	combined standard uncertainty
Eff DF	effective degrees of freedom

Executive Summary

Accurate measurements of direct normal (beam) solar irradiance from pyrheliometers¹ are important for developing and deploying solar energy conversion systems, for improving our understanding of Earth’s energy budget for climate change studies, and for other science and technology applications involving solar flux. Providing these measurements places many demands on the quality system used by the operator of commercially available radiometers. Maintaining accurate radiometer calibrations that are traceable to an international standard is the first step in producing research-quality solar irradiance measurements.

In 1977, the World Meteorological Organization (WMO) established the World Radiometric Reference (WRR) as the international standard for the measurement of direct normal solar irradiance (Fröhlich 1991). The WRR is an internationally recognized, detector-based measurement standard determined by the collective performance of six electrically self-calibrated absolute cavity radiometers comprising the World Standard Group (WSG). Various countries, including the United States,² have contributed these specialized radiometers to the Physikalisch-Meteorologisches Observatorium Davos—World Radiation Center (PMOD/WRC) to establish the WSG.

As with all measurement systems, Absolute Cavity Radiometers (ACR) are subject to performance changes over time. Therefore, PMOD/WRC in Davos, Switzerland, hosts an quinquennial International Pyrheliometer Comparison (IPC) event for transferring the WRR to participating radiometers by invitation.³ The National Renewable Energy Laboratory (NREL) has represented the U.S. Department of Energy (DOE) in each IPC since 1980. And NREL has developed and maintained a select group of absolute cavity radiometers with direct calibration traceability to the WRR, and it uses these reference instruments to calibrate pyrheliometers and pyranometers using the International Organization for Standardization (ISO) 17025-accredited Broadband Outdoor Radiometer Calibration (BORCAL) process (Reda et al. 2008).

To fill the gap between each IPC, NREL pyrheliometer comparisons (NPCs) are held annually at the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado. Open to all ACR owners and operators, each NPC provides an opportunity to determine the unique WRR transfer factor (WRR-TF) for each participating pyrheliometer. By adjusting all subsequent pyrheliometer measurements by the appropriate WRR-TF, the solar irradiance data are traceable to the WRR.

NPC-2021 was held November 4 and 29, 2021. Participants operated 6 ACRs to simultaneously measure clear-sky direct normal solar irradiance during this period. The Transfer Standard Group (TSG) of reference radiometers for NPC-2021 consisted of four NREL radiometers with direct traceability to the WRR, each having participated in the Thirteenth International Pyrheliometer Comparisons (IPC-XIII) in the fall of 2021 (delayed one year due to COVID-19). As a result of NPC-2021, each participating absolute cavity radiometer was assigned a new WRR-TF, which is computed as the reference irradiance determined by the TSG divided by the observed irradiance from the participating radiometer. The performance of the TSG during NPC-2021 was consistent

¹ Pyrheliometers are a type of radiometer used to measure solar irradiance (i.e., radiant flux in Watts per square meter) on a surface normal to the apparent solar disk within a 5.0° or 5.7° field of view, depending on the optical design of the instrument. A solar tracker is used to maintain proper alignment of the pyrheliometer with the sun during daylight periods.

² The WSG includes radiometers on permanent loan from the Eppley Laboratory, Inc., and NREL.

³ Appendix A lists the NPC-2021 participants and the pyrheliometers compared.

with previous comparisons, including IPC-XIII. The measurement performance of the TSG allowed the transfer of the WRR to each participating radiometer with an estimated uncertainty of $\pm 0.33\%$ with respect to the International System of Units.

The comparison protocol is based on data collection periods called *runs*. Each measurement run consists of an electrical self-calibration requiring five minutes for the Automatic Hickey-Frieden (AHF) cavities, a series of 100 solar irradiance measurements at 15-second intervals, and a post-calibration. more than 800 reference irradiance measurements during NPC-2021. The clear-sky daily maximum direct normal irradiance level was $1,007 \text{ Wm}^{-2}$.

Ancillary environmental conditions (e.g., broadband turbidity, ambient temperature, relative humidity, wind speed, precipitable water vapor, and spectral data) collected at SRRL during the comparison are available at https://midcdmz.nrel.gov/srrl_bms/.

NPCs are planned annually at the SRRL to ensure worldwide homogeneity of solar radiation measurements traceable to the WRR.

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1 Introduction

Accurate measurements of broadband solar irradiance require radiometers with proper design and performance characteristics, correct installation, and documented operation and maintenance procedures, including regular calibration. Calibrations of any measuring device must be traceable to a recognized reference standard. The World Radiometric Reference (WRR) is the internationally recognized measurement standard for direct normal irradiance measurements of broadband solar radiation (Fröhlich 1991).

The WRR was established by the World Meteorological Organization (WMO) in 1977 and has been maintained by the Physikalisch-Meteorologisches Observatorium Davos—World Radiation Center (PMOD/WRC)⁴ in Switzerland. The WRR is maintained for broadband solar irradiance with an absolute uncertainty of better than $\pm 0.3\%$ with respect to the International System of Units (SI) (Romero et al. 1996). The WRR standard is widely used to calibrate pyrheliometers and pyranometers with a wavelength response range that is compatible with the solar spectrum wavelengths of 280–3,000 nm.

Every five years, the WRR is transferred to WMO regional centers and other participants at the International Pyrheliometer Comparisons (IPC) event, which is held at the PMOD/WRC. The Thirteenth IPC (IPC-XIII) was completed in 2021 (Finsterle 2022). At each IPC, instantaneous measurements from the World Standard Group (WSG) are compared at 90-second intervals with the data from participating radiometers recorded under clear-sky conditions. A new WRR transfer factor (WRR-TF) is calculated for each participating radiometer based on the mean WRR of the WSG radiometers for each IPC. Multiplying the irradiance reading of each radiometer by its assigned WRR-TF will result in measurements that are traceable to SI units through the WRR and are therefore consistent with the international reference of solar radiation measurement.

In compliance with International Organization for Standardization (ISO) 17025 accreditation requirements for demonstrating interlaboratory proficiency, the National Renewable Energy Laboratory (NREL) hosts annual pyrheliometer comparisons at the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado, for non-IPC years. The NREL Pyrheliometer Comparisons in 2021 (NPC-2021) was November 4 and 29, 2021, at the SRRL. Participants operated absolute cavity radiometers during the comparisons. See Appendix A for a list of participants and affiliations.

The results presented in this report are based on clear-sky, direct normal solar irradiance data collected during NPC-2021. See https://midcdmz.nrel.gov/srrl_bms/ for the environmental conditions during NPC-2021.

⁴ <https://www.pmodwrc.ch>

2 Reference Instruments

NREL developed the transfer standard group (TSG) of four Absolute Cavity Radiometers (ACR) to serve as the transfer reference for each NPC. The radiometers comprising the TSG were included in the most recent IPC and maintain the WRR for NREL (see Table 1). Using the method described by Reda (1996), the mean of the TSG measurements was maintained for establishing the reference irradiance data for NPC-2021 data reduction. Table 1 lists the TSG absolute cavity radiometers with their WRR-TFs and pooled standard deviation (SD_p) as determined from the latest IPC in 2021 (Finsterle 2022).

Table 1. Summary of IPC-XIII Results for the NPC-2021 TSG

Serial Number	WRR Factor (IPC-XIII)	Standard Deviation (%)	Number of Readings
AHF28968	0.99802	0.0714	1066
AHF29220	0.99779	0.0696	1060
AHF30713	0.99760	0.0668	1058
TMI68018	0.99685	0.0738	1108
Mean WRR for the TSG	0.99756	SD_p for the TSG: 0.0705%	

The pooled standard deviation, SD_p , for the TSG was computed from the following equation:

$$SD_p = \sqrt{\frac{\sum_{i=1}^m n_i * S_i^2}{\sum_{i=1}^m n_i}} \quad 1$$

where:

- $i = i^{\text{th}}$ cavity
- $m = \text{number of reference cavities}$
- $S_i = \text{standard deviation of the } i^{\text{th}} \text{ cavity, from IPC-XIII}$
- $n_i = \text{number of readings of the } i^{\text{th}} \text{ cavity, from IPC-XIII.}$

3 Measurement Protocol

The decision to deploy instruments for a comparison was made daily during NPC-2021. Data were collected only during clear-sky conditions, which were determined visually and from the stability of pyrheliometer readings. Simultaneous direct normal solar irradiance measurements were taken by most cavity radiometers in groups of 100 observations at 15-second intervals.

Each group of observations is called a *run*. An electrical self-calibration of each Automatic Hickey-Frieden (AHF) ACR was performed before each run. Previous WRR-TFs determined from results of IPCs or NPCs were *not* applied to the observations. The original manufacturer's calibration factor was used according to the standard operating procedure provided by the manufacturer for each radiometer. A timekeeper announced the beginning of each calibration period and gave a five-minute countdown before the start of each run to facilitate the AHF cavity self-calibrations and the simultaneous start for each participant.

By consensus, at least 300 observations from each radiometer were required to determine the WRR-TF for an NPC. A statistically significant data set was required to derive the WRR-TF for each pyrheliometer. Data from each pyrheliometer/operator system were emailed at the end of the day.

4 Transferring of the World Radiometric Reference

The primary purpose of an NPC is to transfer the current WRR from the NPC-TSG to each participating ACR. This requires that the participating pyrheliometers and the TSG collect simultaneous measurements of clear-sky direct normal (beam) solar irradiance.

4.1 Calibration Requirements

Following WMO guidelines (Romero 1995), the following conditions were required before data collection was accomplished during NPC-2021:

- The radiation source was the sun, and irradiance levels were $> 700 \text{ Wm}^{-2}$.
- A Digital Multimeter with an uncertainty $< 0.05\%$ or better was used to measure the thermopile signals from each radiometer.
- Solar trackers were aligned with a slope angle within $\pm 0.25^\circ$.
- Wind speed was low ($< 5 \text{ m/s}$) from the direction of the solar azimuth $\pm 30^\circ$.
- Cloud cover was $< 1/8$ of the sky dome, with an angular distance $> 15^\circ$ from the sun.

4.2 Determining the Reference Irradiance

Four ACRs that are maintained by NREL and were part of IPC-XII were used as the TSG to transfer the WRR in the comparison. The WRR-TF for each TSG is presented in Table 1 (above). The reference irradiance at each reading was calculated using the following steps, as described by Reda (1996):

1. Each irradiance reading of the TSG is divided by the irradiance measured by AHF 28968, for its participation in many IPCs.
2. By maintaining the mean of WRR for the TSG, a new WRR-TF for NPC-2019 is recalculated for each of the TSG cavities (see Figure 1).
3. The reference irradiance for each 15-second observation in a run is computed as the mean of the simultaneous reference irradiances measured by the TSG. The reference irradiance reading for each cavity in the TSG is the irradiance reading of the cavity multiplied by its new WRR-TF calculated in Step 2.

4.3 Data Analysis Criteria

AHF 28968 was used to check irradiance stability at the time of each comparison reading during a run. Stable irradiance readings are defined to within 1.0 Wm^{-2} during an interval of two seconds centered on each reading time (i.e., one second before and one second after the recorded reading). Unstable irradiance readings were marked in the data record and automatically rejected from the data analysis; historically, this has affected fewer than 10% of the data collected during an NPC. Also rejected were all calculated ratios of the test instrument irradiance divided by AHF 28968 irradiance that deviated from their mean by 0.3% (Reda 1996). Typically, data rejected from the analysis in this manner were the result of failed tracker alignment, problems with the pre-calibration, or a similar cause for bias greater than expected from a properly functioning absolute cavity radiometer.

4.4 Measurements

NPC-2021 was completed for all participants on November 29, after more than 800 data points were collected by the reference cavities during the requisite clear-sky conditions. The actual

number of readings for each participating radiometer compared with the reference irradiance varied according to the data analysis selection criteria described above.

4.5 Results

The historical results for the TSG are presented in Figure 1. To evaluate the performance of these instruments, the standard deviations of each radiometer were monitored during the comparisons. The results suggest successful performance of the TSG during this NPC.

For the TSG, the NPC-2021 WRR-TF did not change by more than a fraction of the standard deviation derived during IPC-XIII in 2021 (see Figure 1. History of WRR reduction factors for NREL reference cavities).

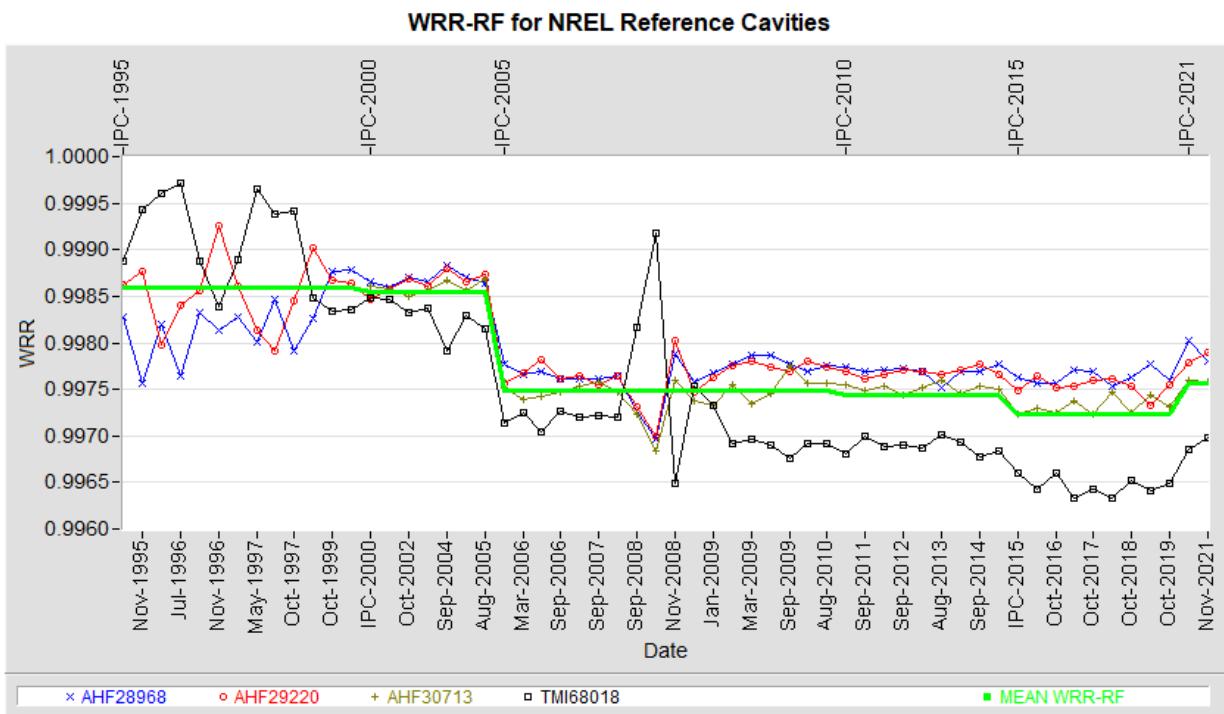


Figure 1. History of WRR reduction factors for NREL reference cavities. Note that in 2008, a spider web was discovered in TMI68018.

For NPC-2021 Proficiency Test, the results of the participating cavities in IPC-XIII and NPC-2021 were evaluated using the following equation:

$$E_n = \frac{WRR_{NPC} - WRR_{IPC}}{\sqrt{U95_{NPC}^2 + U95_{IPC}^2}} \quad 2$$

where E_n must lie in the interval -1 to +1.

From Table 2, E_n for all cavities was well within the interval -1 to +1 (i.e., the WRR from NPC-2021 is consistent with the WRR from IPC-XIII).

Results for each radiometer participating in NPC-2021 are presented in Table 3.

Table 2. Summary of Results for Proficiency Test During NPC-2021

Participating Cavity	NPC-2021	%U95	IPC-XIII	%U95	En
AHF23734	0.99855	0.37	0.99867	0.34	-0.02

Table 3. Summary of Results for Radiometers Participating in NPC-2021

Cavity	WRR (NPC-2021)	SD	NRDG	%U95
AHF23734	0.99855	0.0003	853	0.37
AHF29219	1.06142	0.0005	778	0.38
AHF29222	1.05878	0.0005	623	0.38
AHF30495	1.05571	0.0005	625	0.38
AHF31104	1.03864	0.0004	437	0.38
AHF32452	1.03125	0.0006	441	0.38

The uncertainty of the WRR-TF associated with each participating radiometer with respect to SI was calculated using the following equation:

$$U_{95} = \pm 1.96 * \sqrt{u_A^2 + u_B^2} \quad 3$$

where:

- U95 = uncertainty of the WRR-TF (in percent) determined at NPC-2021 with 95% confidence level
- 1.96 = coverage factor
- uA = Type A standard uncertainty = standard deviation of each participating radiometer (in %) determined at NPC-2021
- uB = Type B standard uncertainty
- $u_B = \pm \sqrt{\left(\frac{0.3}{\sqrt{3}}\right)^2 + 0.0705^2}$
where:
 - 0.3 = Estimated expanded uncertainty of the WRR scale with respect to SI, in %
 - $\sqrt{3}$ = Coverage factor for rectangular distribution
 - 0.0705 = Pooled standard deviation of the four reference radiometers (TSG) that participated in IPC-XIII (September/October 2021), in %.

The statistical analyses of WRR-TF for the participating pyrheliometers are presented in Figure 2 through Figure 7. These graphical summaries indicate the mean, standard deviation, and histograms of the WRR-TF determined during NPC-2021. If the participating pyrheliometer has a known WRR from a previous year, the percentage change in the WRR is listed in Table 4.

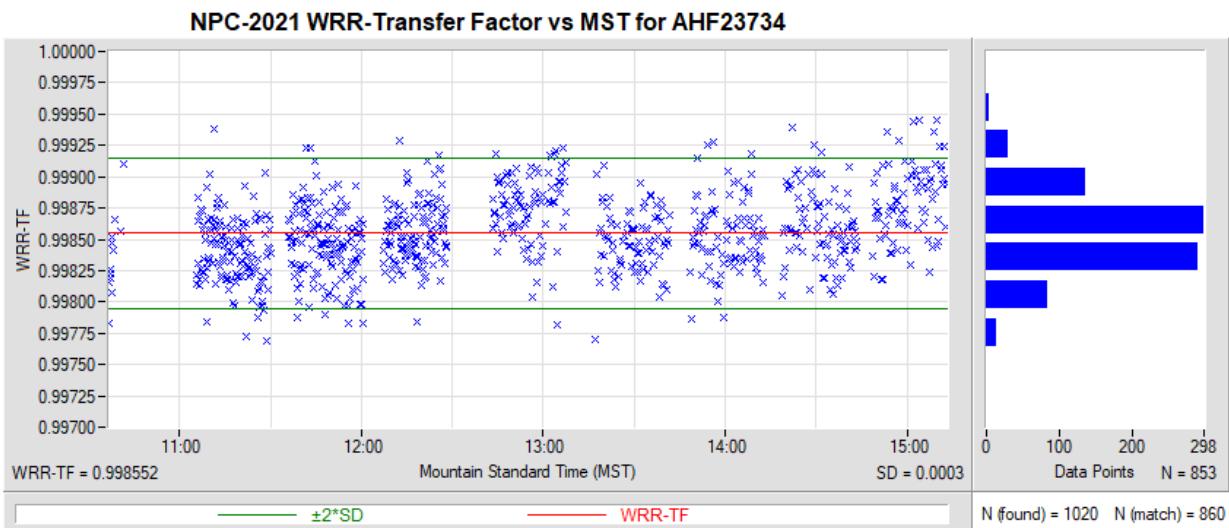


Figure 2. WRR-Transfer Factor vs. Mountain Standard Time NPC-2021 for AHF 23734

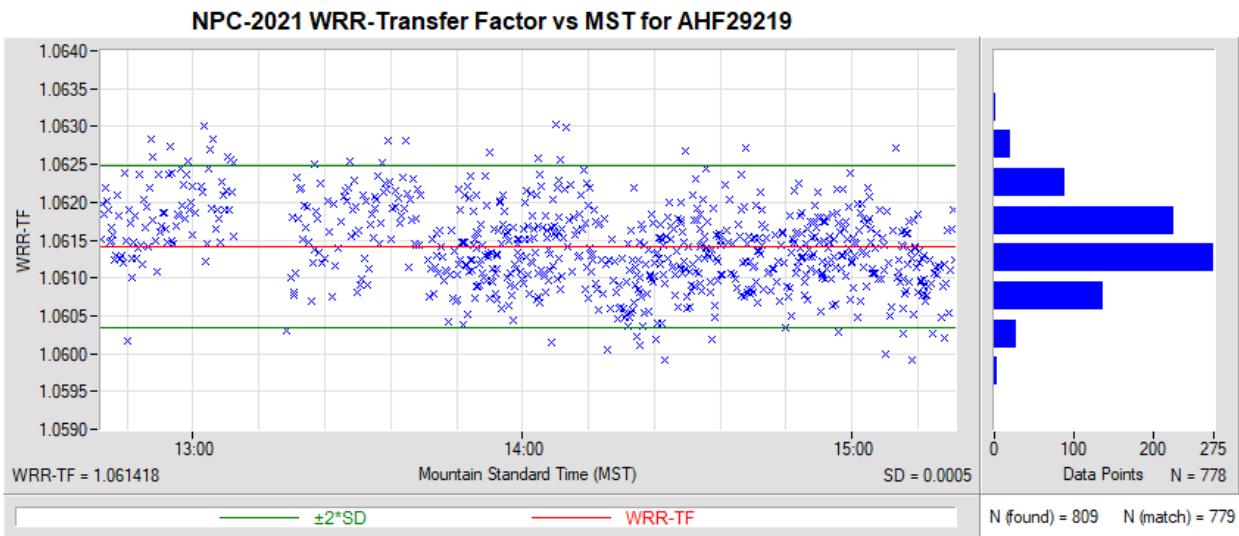


Figure 3. WRR-Transfer Factor vs. Mountain Standard Time NPC-2021 for AHF 29219 (Window)

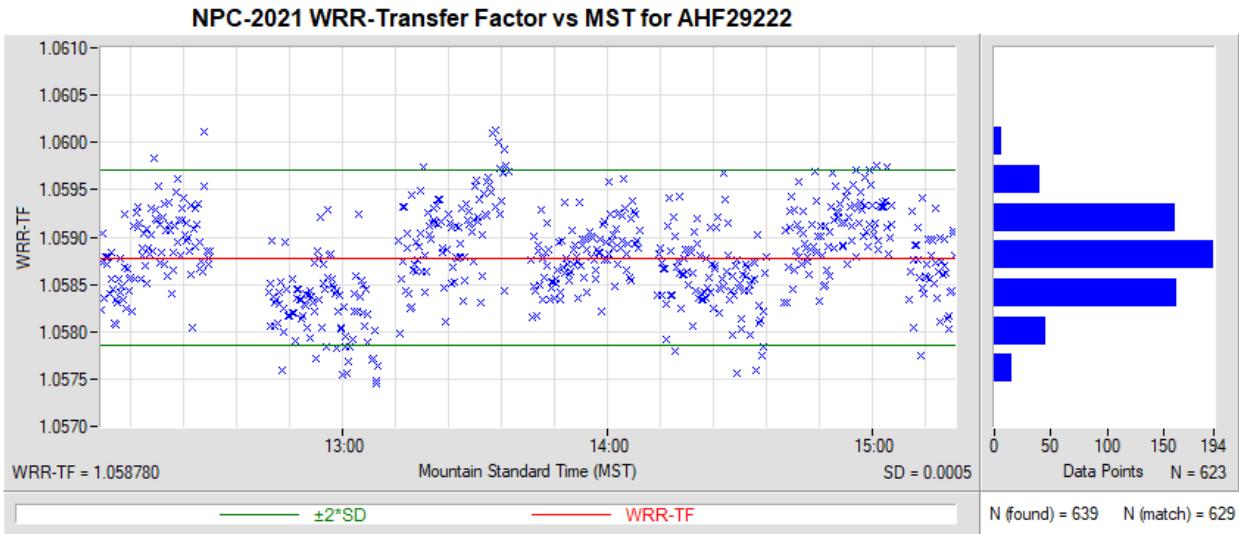


Figure 4. WRR-Transfer Factor vs. Mountain Standard Time NPC-2021 for AHF 29222 (Window)

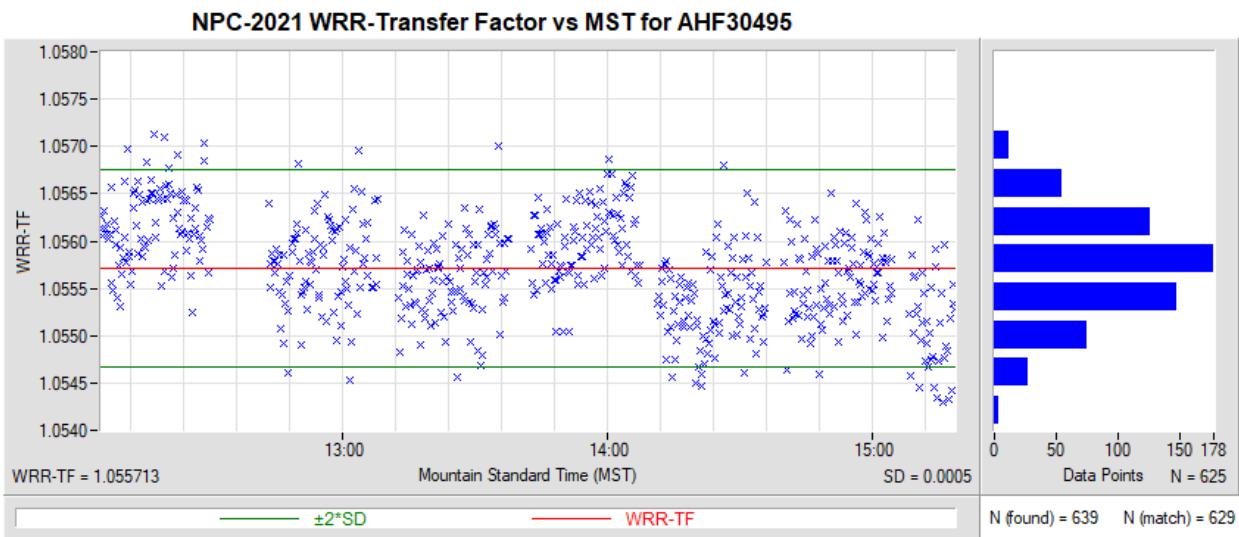


Figure 5. WRR-Transfer Factor vs. Mountain Standard Time NPC-2021 for AHF 30495 (Window)

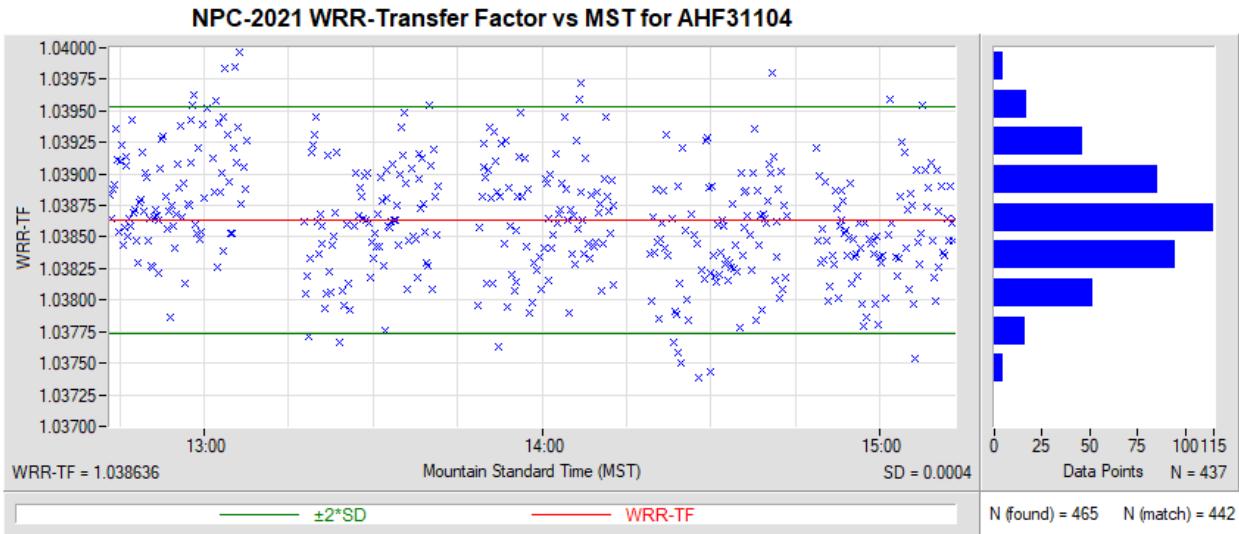


Figure 6. WRR-Transfer Factor vs. Mountain Standard Time NPC-2021 for AHF 31104 (Window)

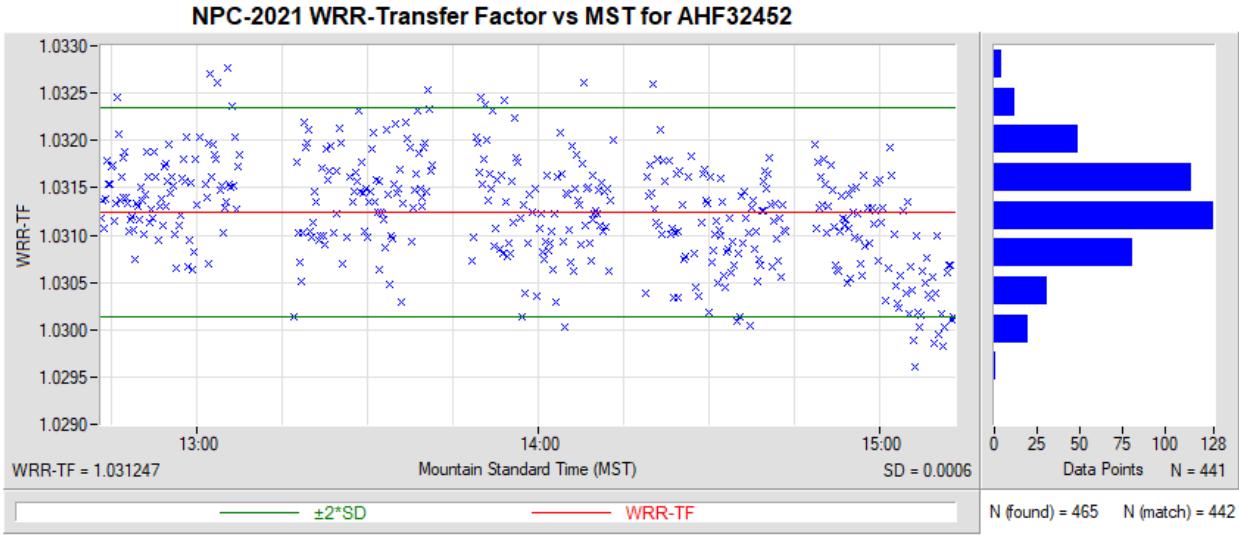


Figure 7. WRR-Transfer Factor vs. Mountain Standard Time NPC-2021 for AHF 32452 (Window)

Table 4. Summary of Percent Change for Radiometers with a known WRR from a previous year

Cavity	WRR (NPC-2021)	WRR (previous)	Previous Year	%Change
AHF23734	0.99855	0.99818	2019	0.04
AHF29219	1.06142	1.06179	2019	-0.04
AHF29222	1.05878	1.05756	2019	0.12
AHF30495	1.05571	1.05797	2019	-0.21
AHF31104	1.03864	1.03836	2019	0.03
AHF32452	1.03125	1.03166	2019	-0.04

4.6 Recommendations

As a result of the comparisons made during NPC-2021, we suggest participants observe the following measurement practices:

- For the purpose of pyrheliometer comparisons, such as NPC-2021, we recommend the user apply only the manufacturer's calibration factor, not the WRR-TF or the new calibration factor, to report his or her absolute cavity radiometer's irradiance readings. Doing so eliminates the possibility of compounding WRR factors from previous comparisons.
- For data collection in the field, the manufacturer's calibration factor should be used to calculate the cavity responsivity. Each irradiance reading should then be *multiplied* by the appropriate WRR-TF to provide homogeneity of solar radiation measurements that are traceable to the WRR. We recommend this approach to realize the benefits of participating in the NPC.

5 Ancillary Data

The environmental conditions (i.e., temperature, relative humidity, barometric pressure, wind speed, precipitable water vapor, and spectral data) were measured during the NPC-2021 comparisons using the meteorological station at the SRRL. Additional information, including Baseline Measurement System data and graphical summaries, can be found on the Measurements and Instrumentation Data Center website.⁵

⁵ http://www.nrel.gov/midc/srrl_bms/

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Appendix A. List of Participants and Pyrheliometers

Table A-1. List of Participants and Pyrheliometers

Serial Number of Radiometer	Operator	Affiliation
AHF 29222 (Window)	Afshin Andreas	DOE Atmospheric Radiation Measurement (ARM) Program
AHF 30495 (Window)	Afshin Andreas	DOE Atmospheric Radiation Measurement (ARM) Program
AHF 23734	Afshin Andreas	National Renewable Energy Laboratory (Cell and Module Certification)
AHF 28968 (Reference)	Afshin Andreas	National Renewable Energy Laboratory (Metrology and SePA)
AHF 29219 (Window)	Afshin Andreas	National Renewable Energy Laboratory (Metrology and SePA)
AHF 29220 (Reference)	Afshin Andreas	National Renewable Energy Laboratory (Metrology and SePA)
AHF 30713 (Reference)	Afshin Andreas	National Renewable Energy Laboratory (Metrology and SePA)
AHF 31104 (Window)	Afshin Andreas	National Renewable Energy Laboratory (Metrology and SePA)
AHF 32452 (AWX-Window)	Afshin Andreas	National Renewable Energy Laboratory (Metrology and SePA)
TMI 68018 (Reference)	Afshin Andreas	National Renewable Energy Laboratory (Metrology and SePA)