NREL Pyrheliometer Comparisons: September 23 -October 4, 2019 (NPC-2019)

Ibrahim Reda, Afshin Andreas, Aron Habte, Peter Gotseff, Mark Kutchenreiter, and Martina Stoddard

National Renewable Energy Laboratory

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Technical Report
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NPC-2019 participants, by Dennis Schroeder

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-XII	Twelfth 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	National Renewable Energy Laboratory Pyrheliometer Comparisons
NREL	National Renewable Energy Laboratory
PMOD/WRC	Physikalisch-Meteorologisches Observatorium Davos—World Radiation Center
SDp	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 pyrheliometers[1] 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-2019 was held September 23 through October 4, 2019. Participants operated 31 ACRs to simultaneously measure clear-sky direct normal solar irradiance during this period. The Transfer Standard Group (TSG) of reference radiometers for NPC-2019 consisted of four NREL radiometers with direct traceability to the WRR, each having participated in the Twelfth International Pyrheliometer Comparisons (IPC-XII) in the fall of 2015. As a result of NPC-2019, 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-2019 was consistent with previous comparisons, including IPC-XII. The measurement performance of the TSG allowed

[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-2019 participants and the pyrheliometers compared.

the transfer of the WRR to each participating radiometer with an estimated uncertainty of ± 0.36% 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 49 solar irradiance measurements at 30-second intervals, and a post-calibration. ore than 3,000 reference irradiance measurements during NPC-2019. The clear-sky daily maximum direct normal irradiance level was 1,005 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 presented in Appendix B to document the environmental test conditions.

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 ± 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 Twelfth IPC (IPC-XII) was completed in 2015 (Finsterle 2019). 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 2019 (NPC-2019) was September 3 through October 4, 2019, 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-2109. See Appendix B for the environmental conditions during NPC-2019.

[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-2019 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 2015 (Finsterle 2016).

Table 1. Summary of IPC-XII Results for the NPC-2019 TSG

Serial Number	WRR Factor (IPC-XII)	Standard Deviation (%)	Number of Readings
AHF 28968	0.99763	0.063	519
AHF 29220	0.99749	0.0621	523
AHF 30713	0.99723	0.0639	525
ATMI 68018	0.99660	0.0669	522
Mean WRR for the TSG	0.99724	**SDp for the TSG:** 0.06%	

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

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

where:

- i = ith cavity
- m = number of reference cavities
- Si = standard deviation of the ith cavity, from IPC-XII
- n_i = number of readings of the ith cavity, from IPC-XII.

3 Measurement Protocol

The decision to deploy instruments for a comparison was made daily during NPC-2019. 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 49 observations at 30-second intervals (PMO6 used 90-, 80-, or 30-second open/closed-shutter cycles).

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. Calibration Requirements

Following WMO guidelines (Romero 1995), the following conditions were required before data collection was accomplished during NPC-2019:

- The radiation source was the sun, and irradiance levels were > 700 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 ± 0.25°.
- Wind speed was low (< 5 m/s) from the direction of the solar azimuth ± 30°.
- Cloud cover was < 1/8 of the sky dome, with an angular distance > 15° from the sun.

4.1 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 2).
3. The reference irradiance for each 30-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.

4.2 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 precalibration, or a similar cause for bias greater than expected from a properly functioning absolute cavity radiometer.

4.3 Measurements

NPC-2019 was completed for most participants on October 3, after more than 3,000 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. Additionally, some instruments experienced minor data loss because various problems occurred with the measurement systems or operations.

4.4 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-2019 WRR-TF did not change by more than a fraction of the standard deviation derived during IPC-XII in 2015 (see Figure 2.).

For NPC-2019 Proficiency Test, the results of the participating cavities in IPC-XII and NPC-2019 were evaluated using the following equation:

$$E_n = \frac{WRR_{IPC} - WRR_{NPC}}{\sqrt{U95^2_{IPC} + U95^2_{NPC}}} \qquad 2$$

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-2019 is consistent with the WRR from IPC-XII).

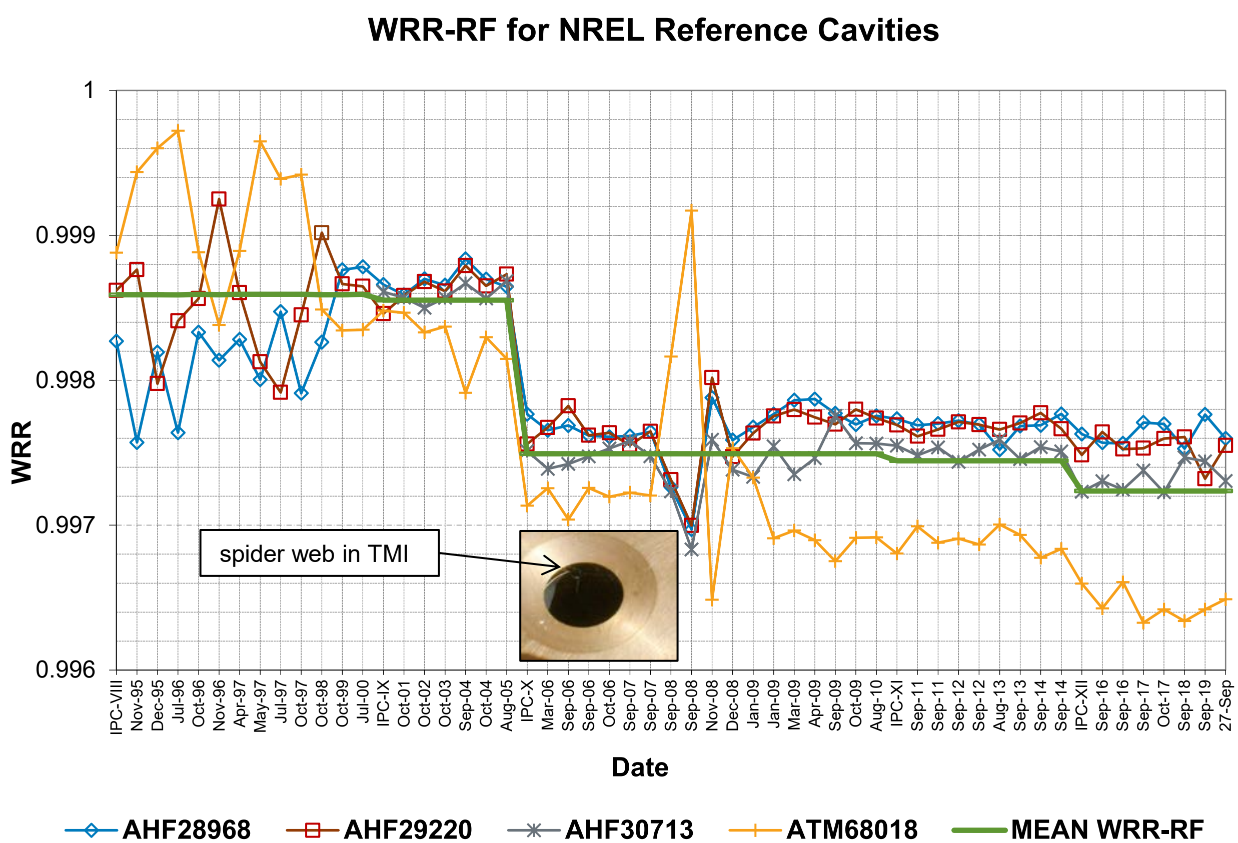

Figure 1. History of WRR reduction factors for NREL reference cavities

Table 2. Summary of Results for Proficiency Test During NPC-2019

IPC & NPC Proficiency Test Results					
Participating Cavity	IPC-XII	%U95	NPC-2019	%U95	Red if abs(En) > 1
AHF 0000	1.000307	0.35	1.00271	0.36	-0.48
AHF 14915	0.99954	0.35	0.99972	0.36	-0.04
AHF 23734	0.99819	0.35	0.99818	0.36	0.00
AHF 28553	0.99774	0.35	0.99767	0.36	0.01
AHF 31041	0.99639	0.36	0.99642	0.36	0.00
AHF 31105	0.99866	0.36	0.99801	0.36	0.13
AHF 31114AWX	1.00121	0.33	1.00141	0.36	-0.04
AHF 32448AWX	0.99999	0.35	1.00030	0.36	-0.06
AHF 32455	1.00138	0.33	1.00061	0.36	0.16
AHF 37816	0.99959	0.33	0.99929	0.36	0.06
PMO6 0816	0.99984	0.45	1.00020	0.36	-0.06
PMO6 81109	0.99832	0.32	0.99821	0.36	0.02
PMO6 911204	0.99945	0.41	1.00047	0.36	-0.19
Pmo6cc 0103	0.99792	0.32	0.99787	0.36	0.01
PMO6cc 105	1.00141	0.35	1.00116	0.36	0.05
PMO6cc 0404	0.99821	0.31	0.99952	0.36	-0.27
TMI 68835	1.000714	0.32	0.99984	0.36	0.18

Table 3. Summary of Results for Radiometers Participating in NPC-2019

S/N	WRR (NPC-2019)	SD	NRDG	%U95
AHF 0000	1.00270	0.0006	2782	0.36
AHF 14915	0.99972	0.0007	2759	0.36
AHF 23734	0.99818	0.0004	3160	0.36
AHF 28553	0.99767	0.0005	1915	0.36
AHF 28560	1.00251	0.0007	1818	0.36
AHF 29219-Window	1.05480	0.0183	3209	0.36
AHF 29222-Window	1.05756	0.0011	2897	0.36
AHF 30110	1.06767	0.0010	1022	0.36
AHF 30495-Window	1.05797	0.0015	2853	0.36
AHF 31041	0.99660	0.0006	839	0.36
AHF 31105	0.99801	0.0085	1242	0.36
AHF 31102	1.00052	0.0005	1776	0.36
AHF 31104-Window	1.03831	0.0008	2301	0.36
AHF 31108	0.99743	0.0012	1952	0.36
AHF 31114AWX	1.00141	0.0005	1863	0.36
AHF 31116AWX-Window	1.06591	0.0008	1883	0.36
AHF 32448AWX	1.00030	0.0006	1881	0.36
AHF 32452AWX-Window	1.03164	0.0012	3169	0.36
AHF 32455	1.00061	0.0006	1832	0.36
AHF 34926AWX	1.00028	0.0008	1866	0.36
AHF 37816	0.99929	0.0005	1804	0.36
PM06 1601	1.00317	0.0006	927	0.36
PMO6 0401	1.02134	0.0007	1845	0.36
PMO6 0816	1.00020	0.0012	936	0.36
PMO6 81109	0.99821	0.0006	965	0.36
PMO6 911204	1.00047	0.0008	1043	0.36
Pmo6cc 0103	0.99787	0.0007	705	0.36
PMO6-cc 0803	1.00019	0.0007	447	0.36
PMO6cc 105	1.00116	0.0006	401	0.36
PMO6cc 404	0.99952	0.0008	399	0.36
PMOD6 0807	1.00444	0.0009	667	0.36
TMI 67603	0.99986	0.0006	1941	0.36
TMI 68835	0.99984	0.0009	3037	0.36

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

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

where:

- U95 = uncertainty of the WRR-TF (in percent) determined at NPC-2019 with 95% confidence level
- 1.96 = coverage factor
- uA = Type A standard uncertainty = standard deviation of each participating radiometer (in %) determined at NPC-2019

- uB = Type B standard uncertainty
- uB = $\pm \sqrt{(\frac{0.3}{\sqrt{3}})^2 + 0.06^2}$

  where:

  - 0.3 = Estimated expanded uncertainty of the WRR scale with respect to SI, in %
  - $\sqrt{3}$ = Coverage factor for rectangular distribution
  - 0.06 = Pooled standard deviation of the four reference radiometers (TSG) that participated in IPC-XII (September/October 2015), in %.

The statistical analyses of WRR-TF for the participating pyrheliometers are presented in Figure 2 through Figure 33. These graphical summaries indicate the mean, standard deviation, and histograms of the WRR-TF determined during NPC-2019.

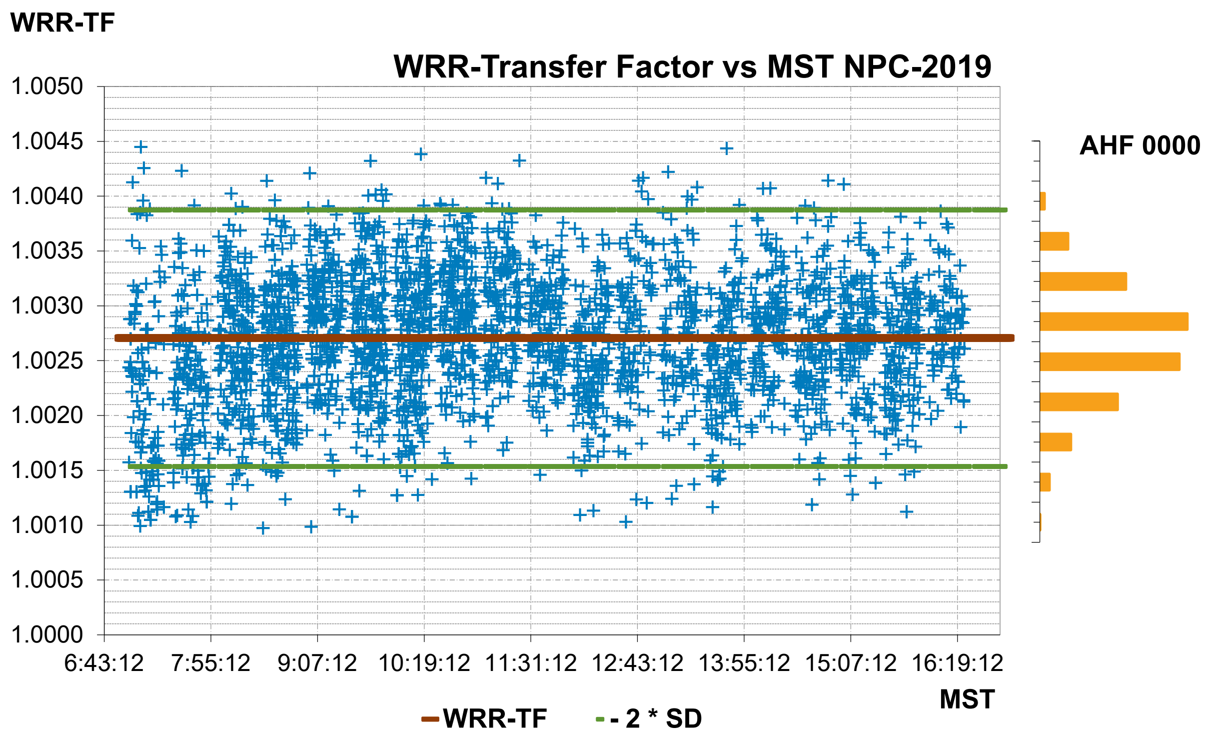

Figure 2. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 0000

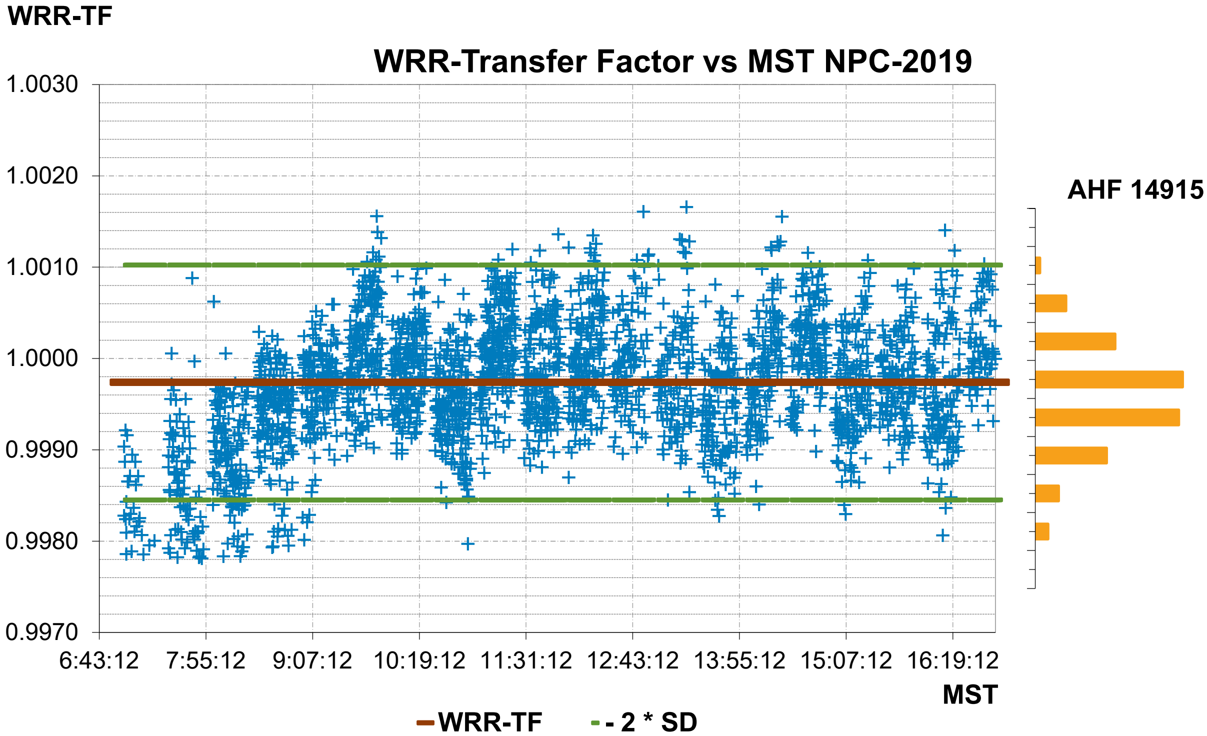

Figure 3. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 14915

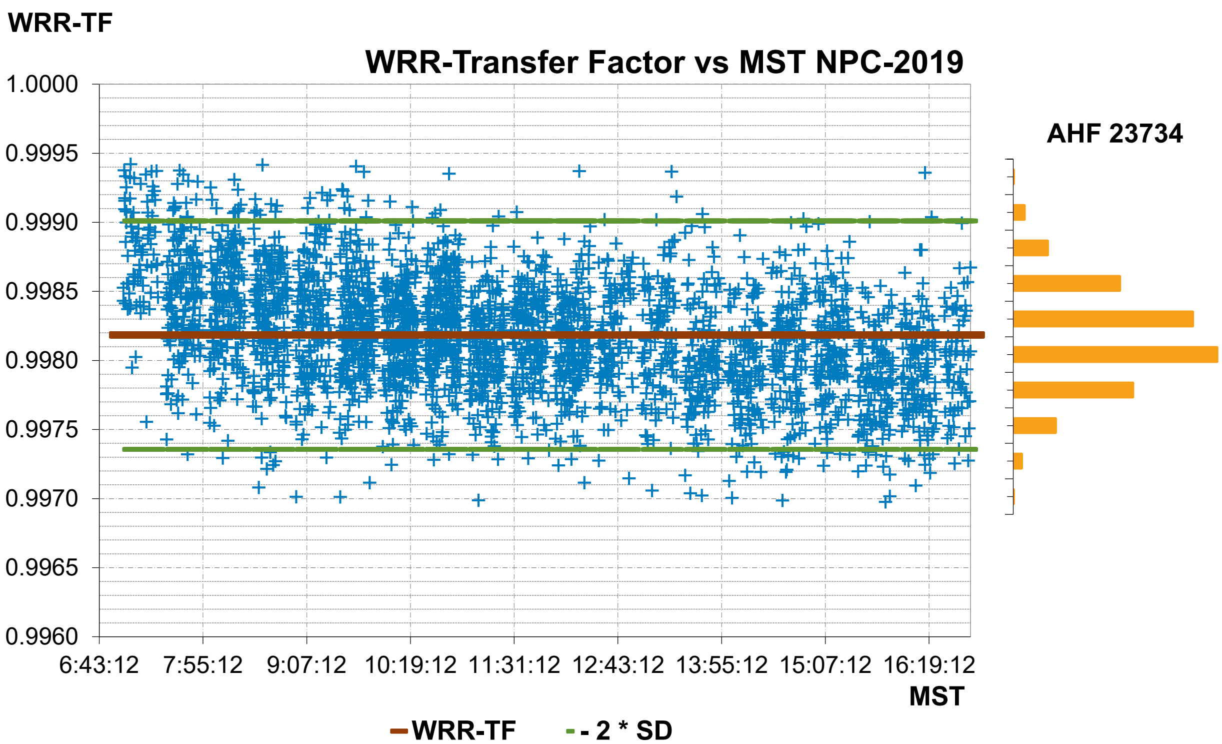

Figure 4. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF23734

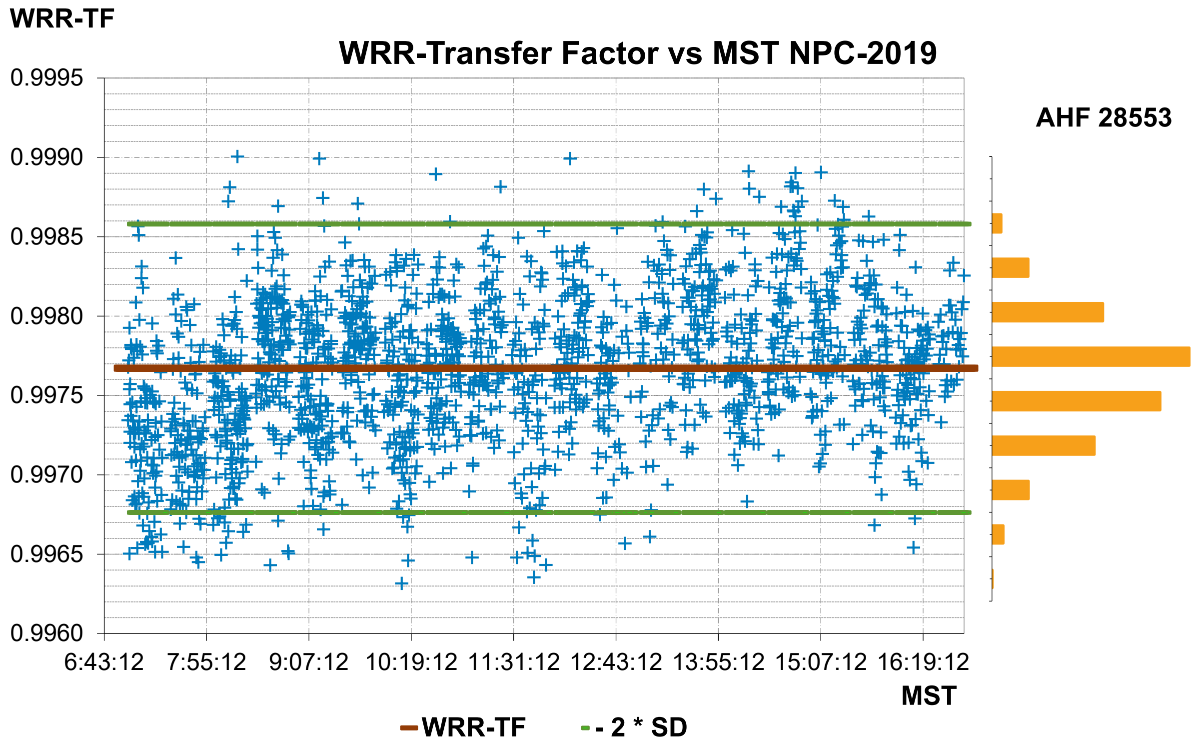

Figure 5. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF28553

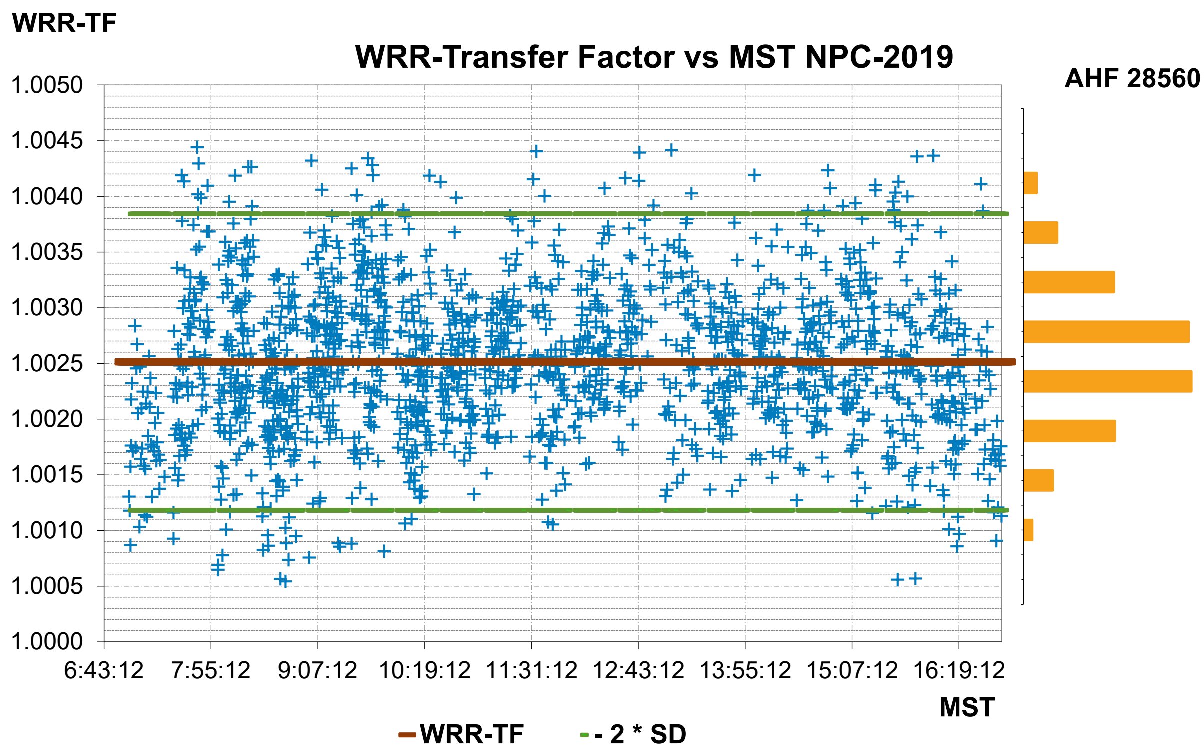

Figure 6. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 28560

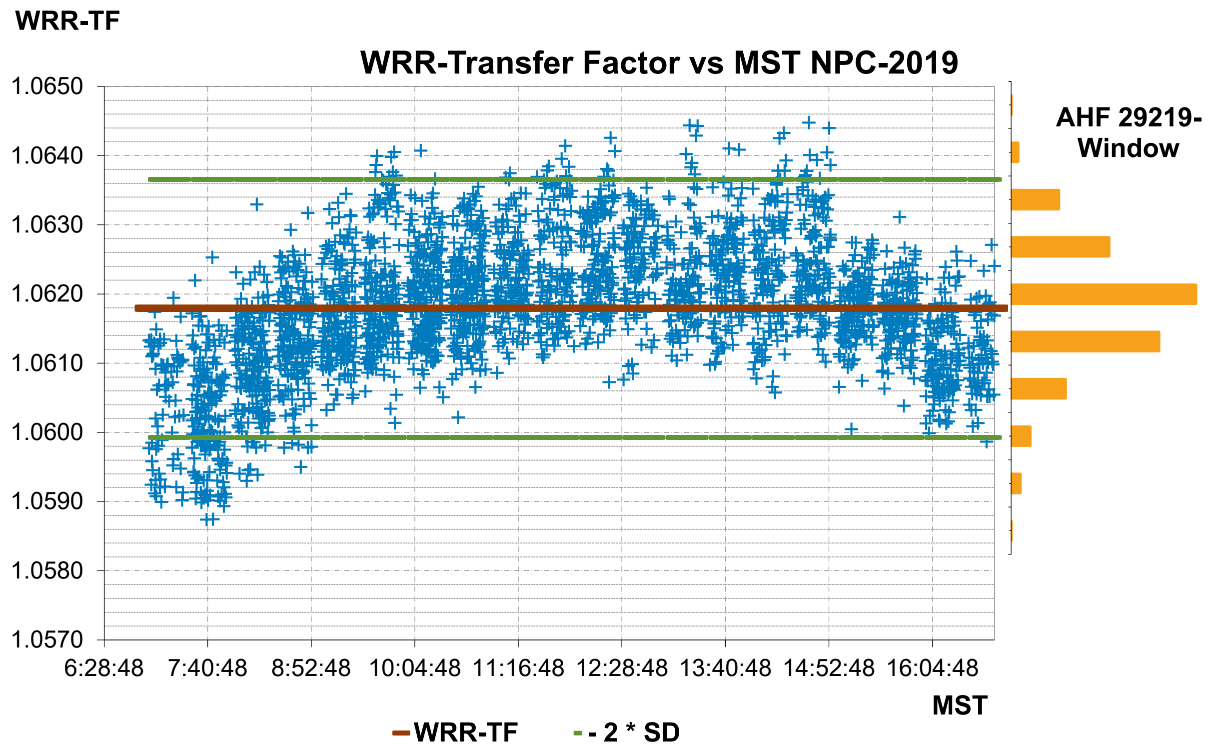

Figure 7. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 29219-Window

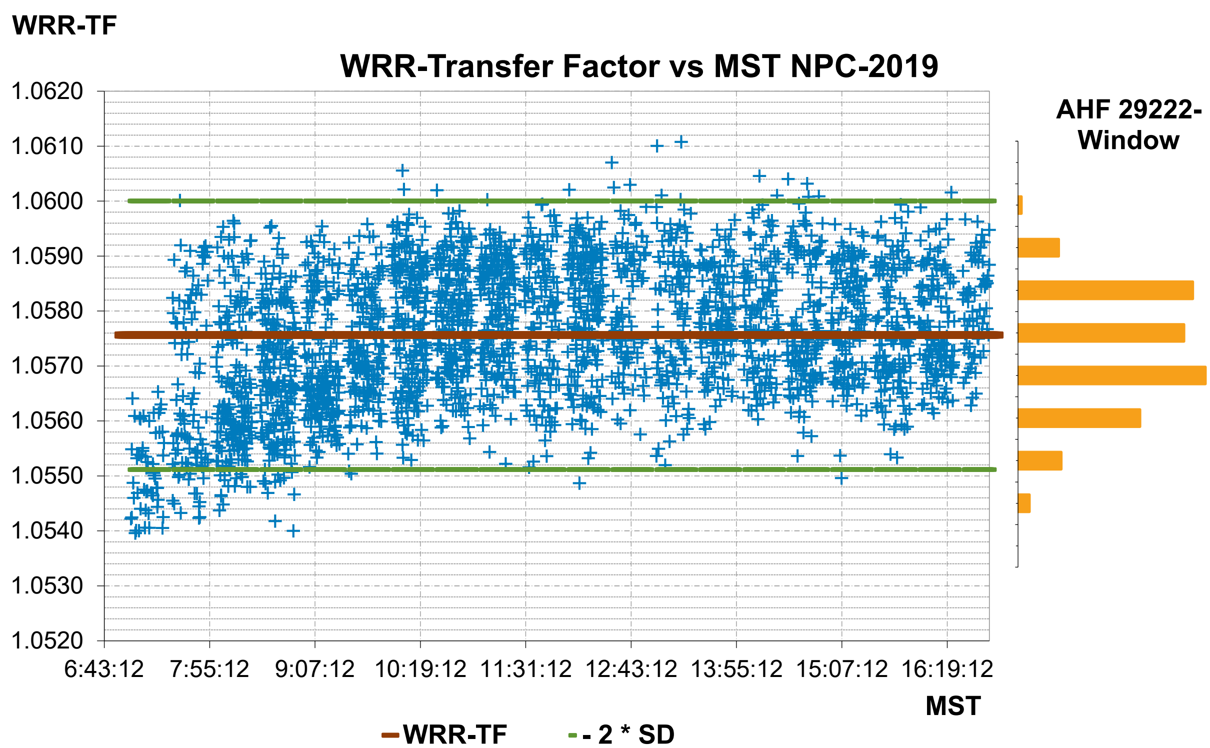

Figure 8. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 29222–Window

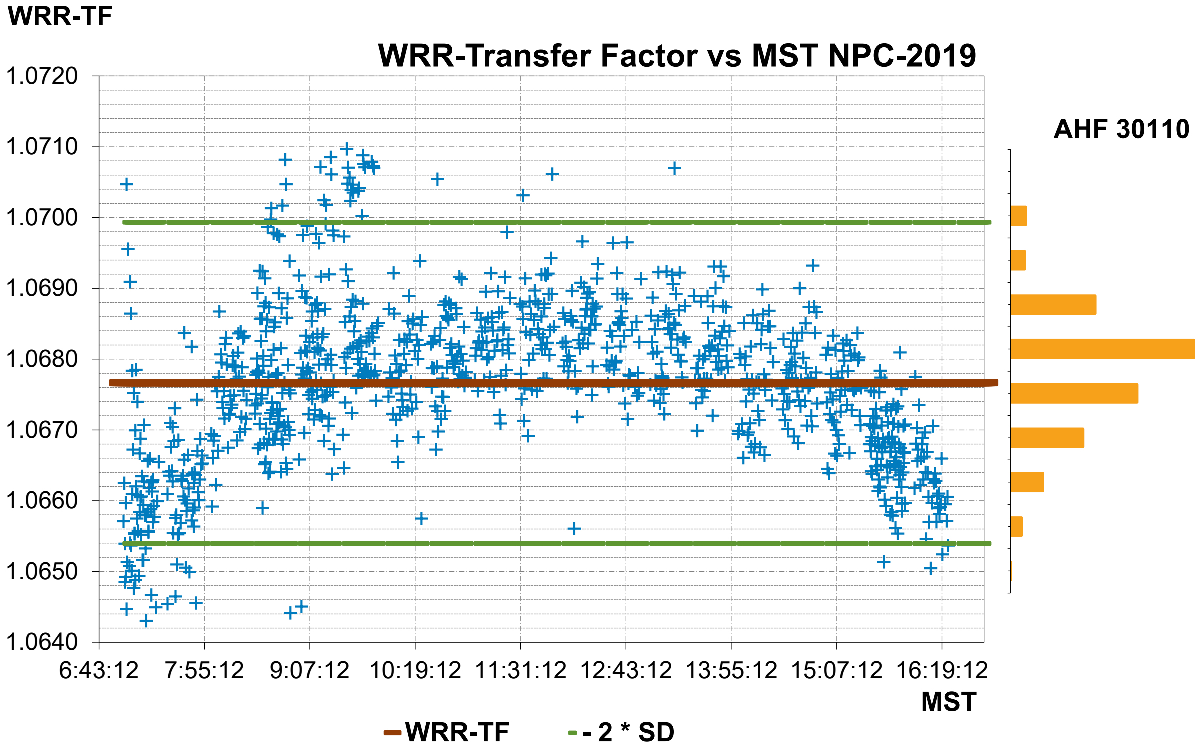

Figure 9. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 30110

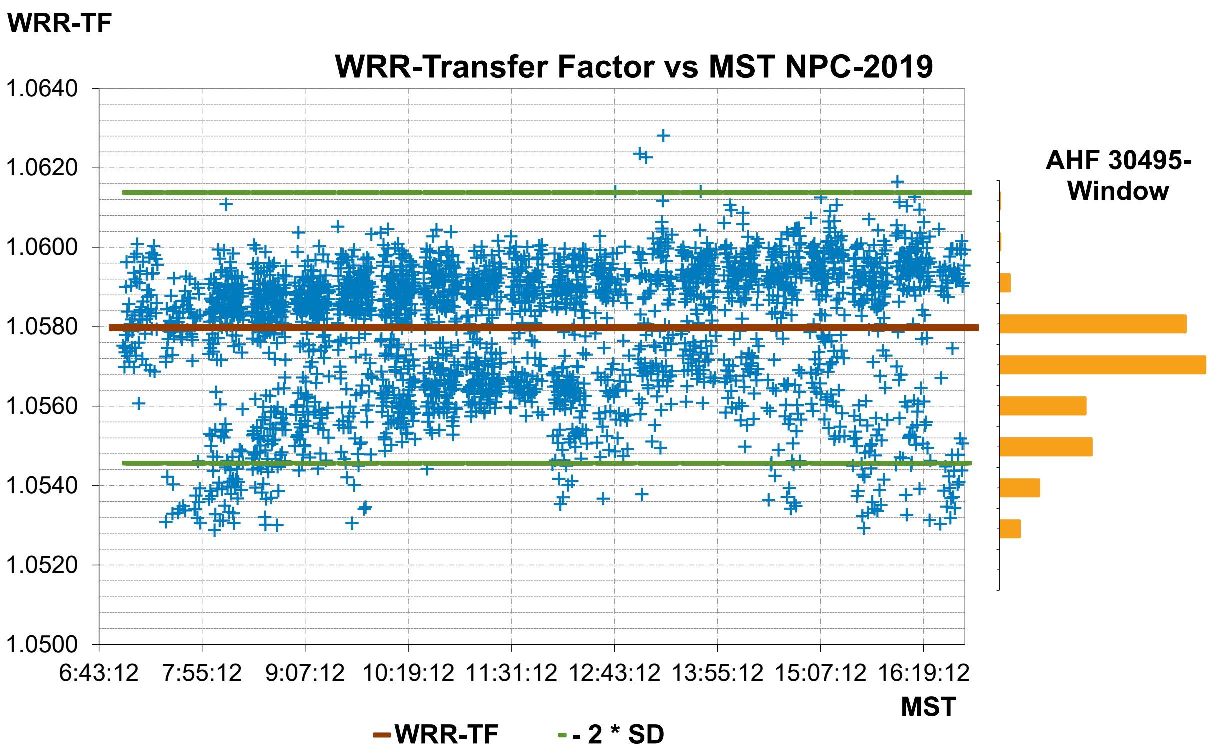

Figure 10. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 30495-Window

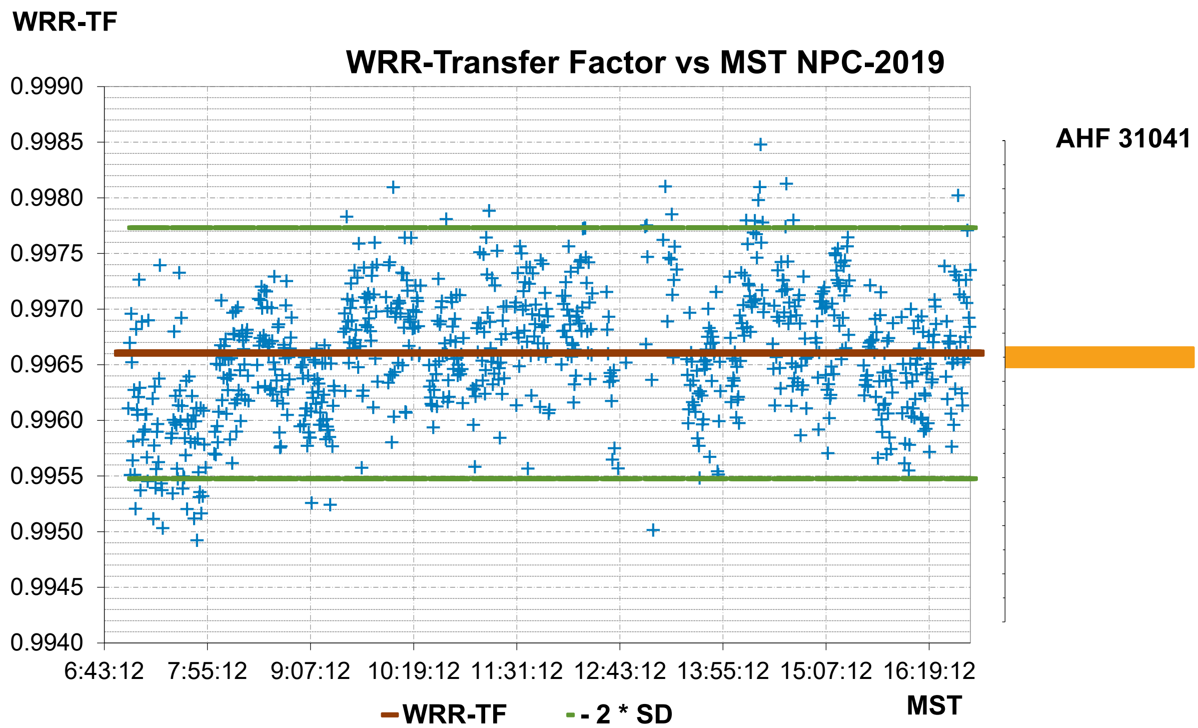

Figure 11. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 31041

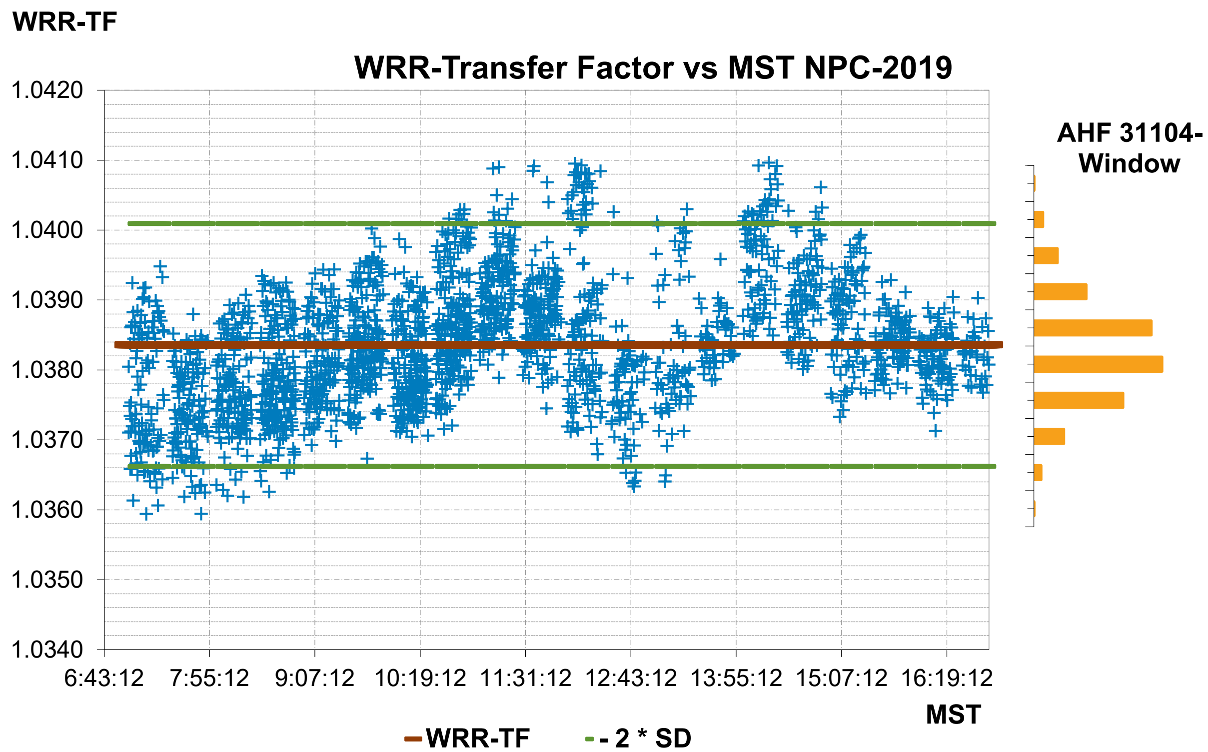

Figure 12. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 31104-Window

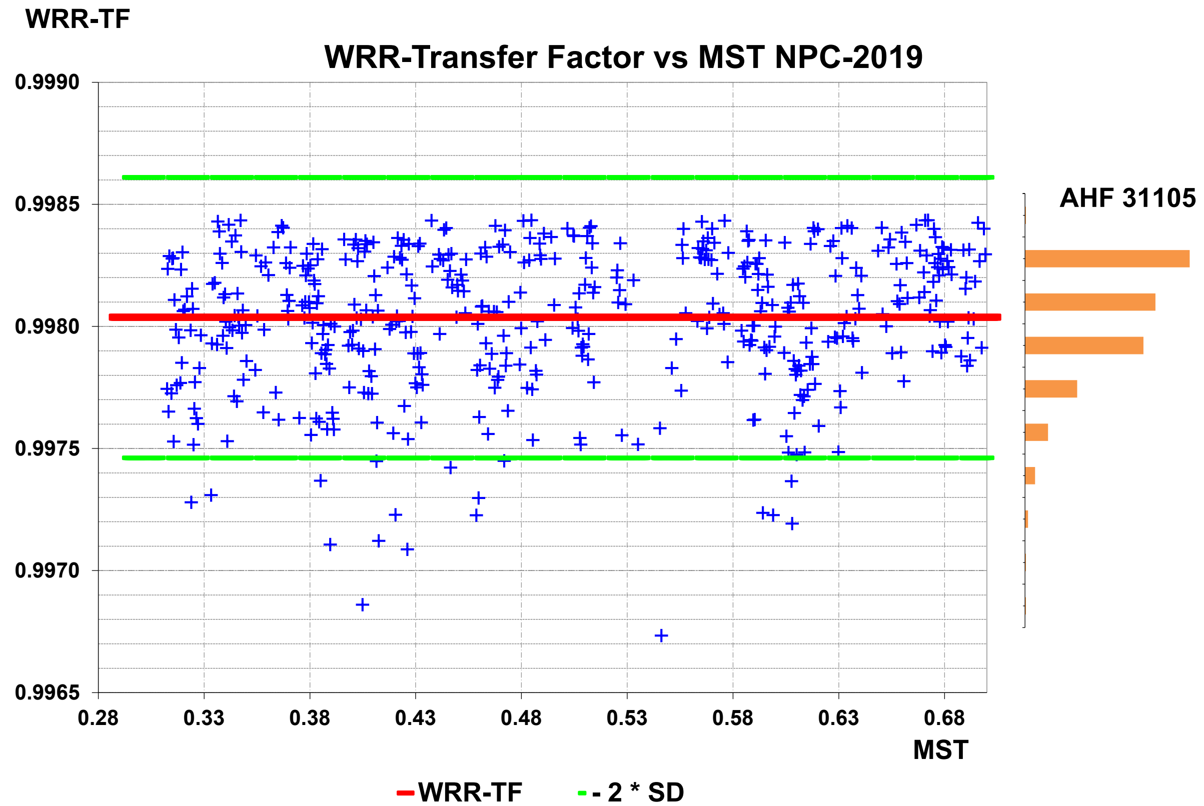

Figure 13. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 31105

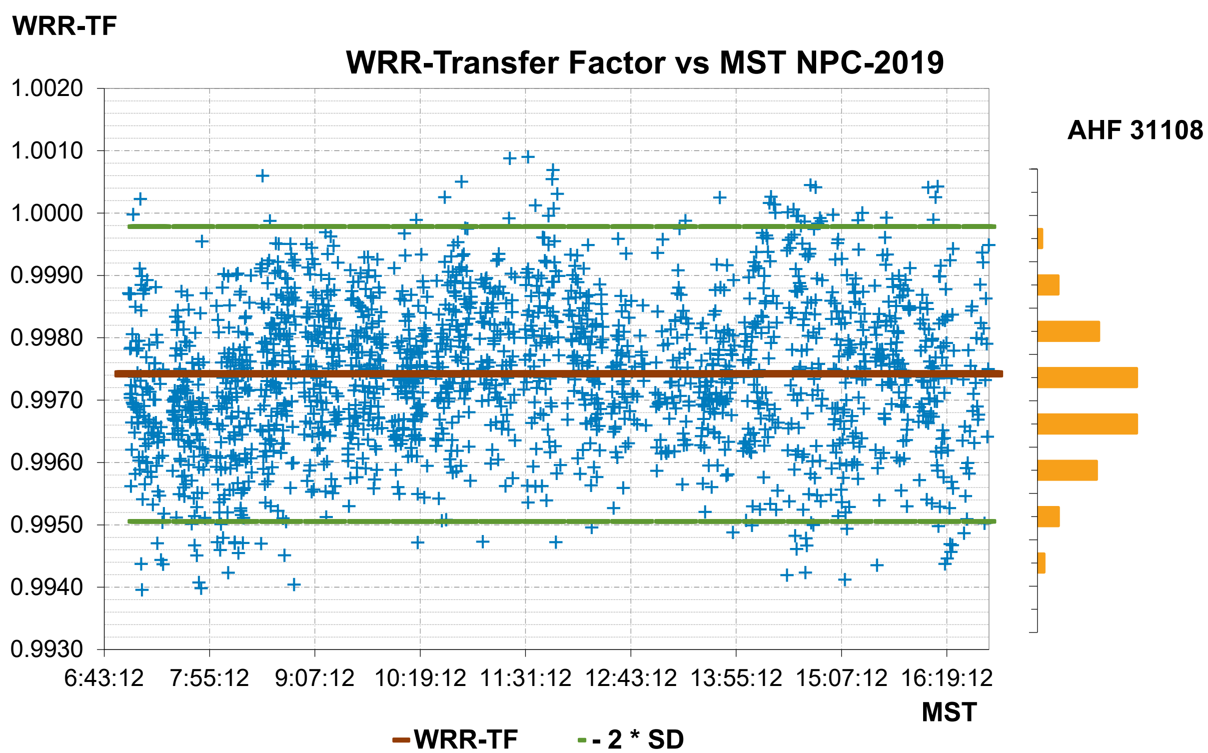

Figure 14. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 31108

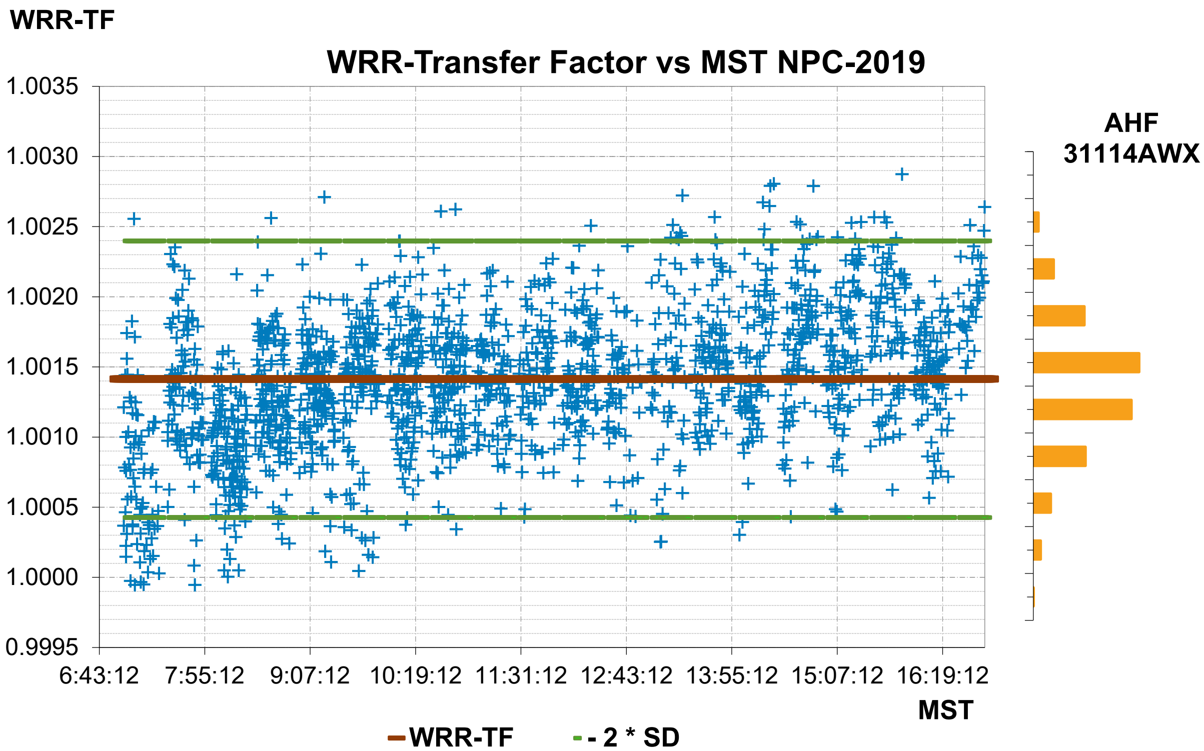

Figure 15. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 31114AWX

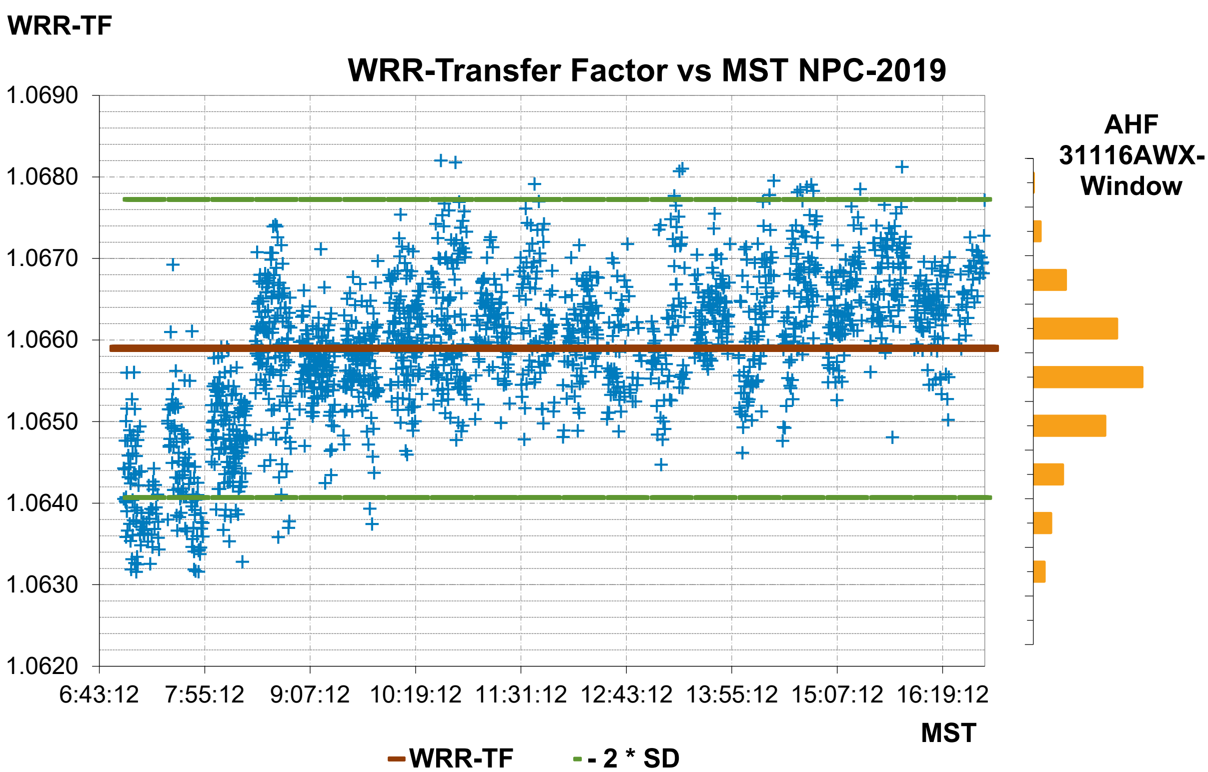

Figure 16. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 31116AWX-Window

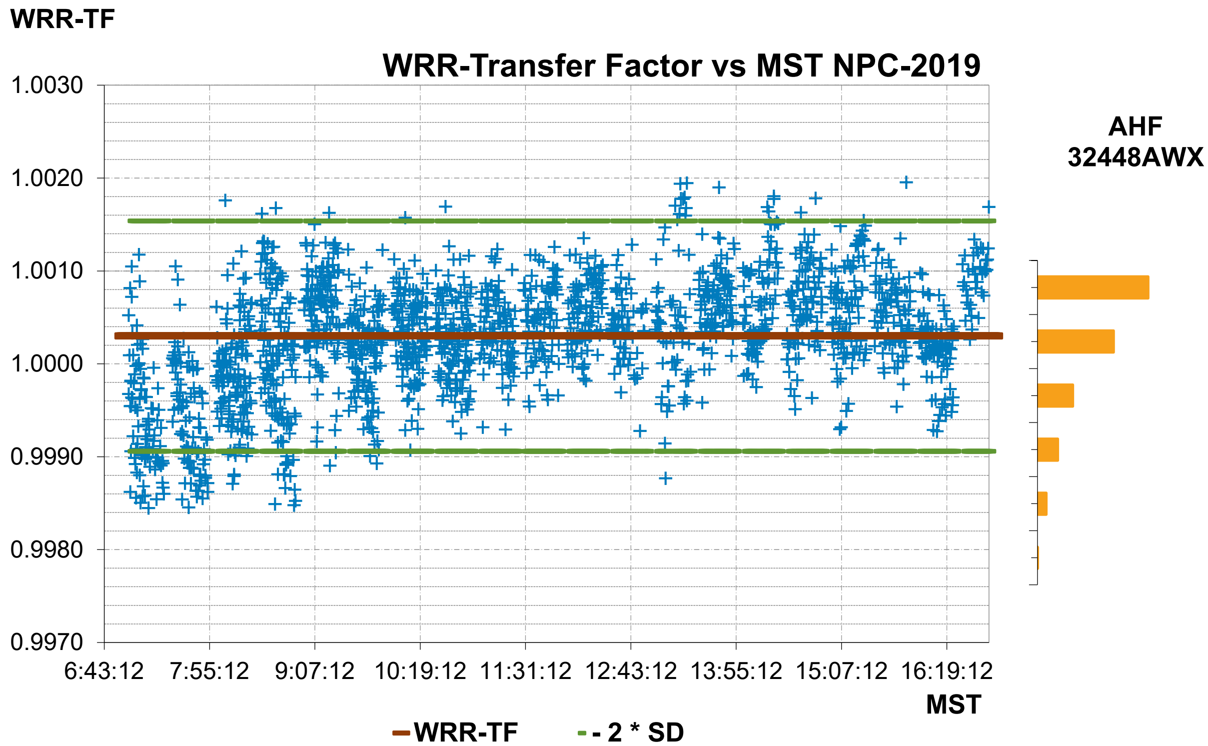

Figure 17. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 31116AWX-Window

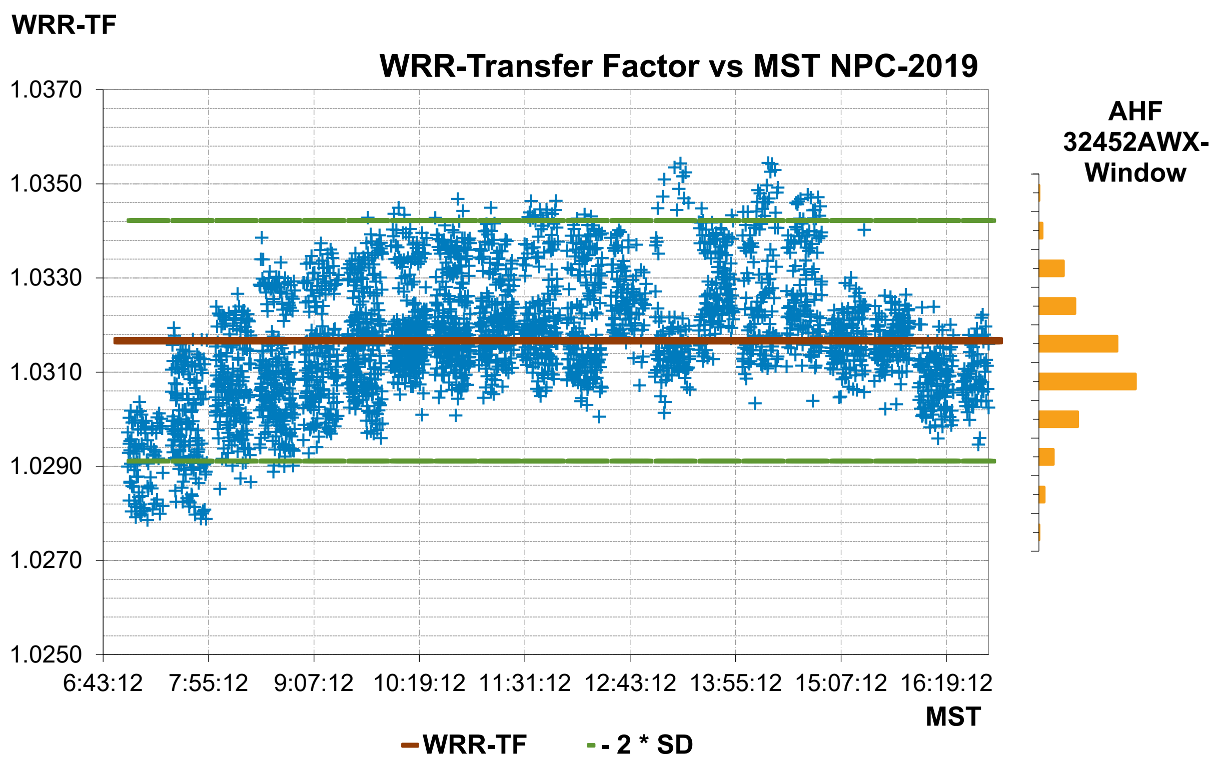

Figure 18. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 32452AWX-Window

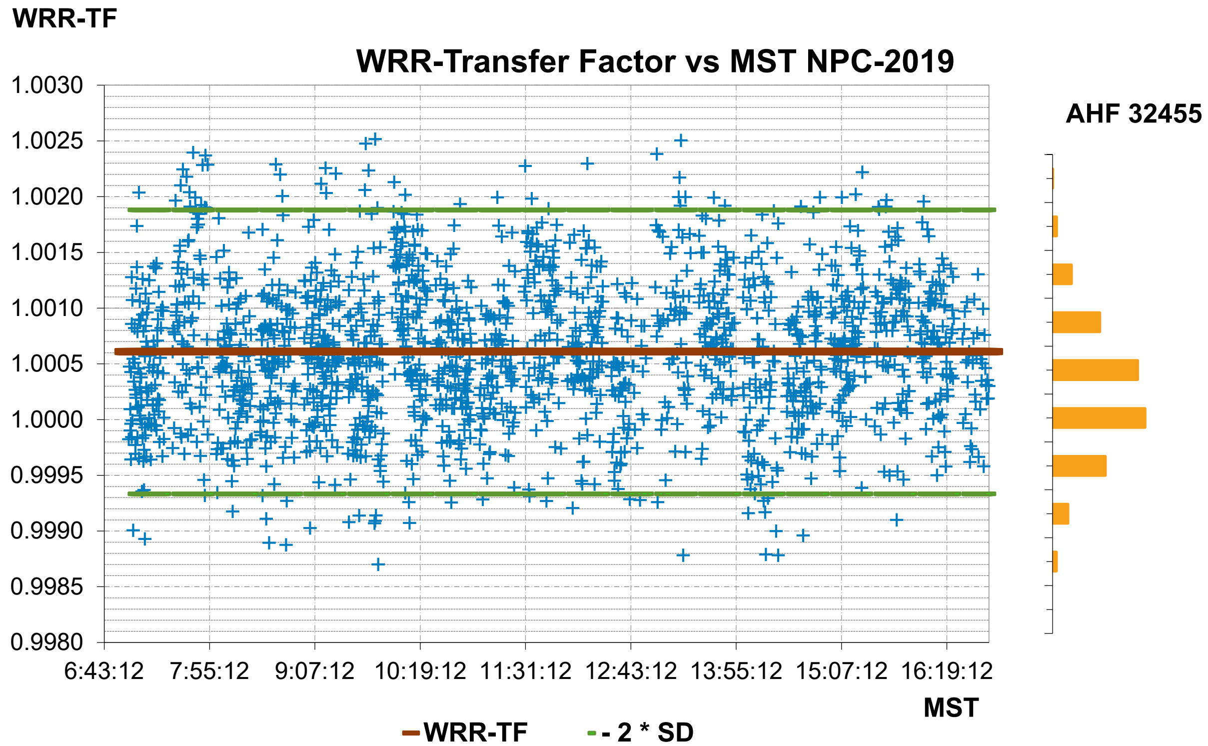

Figure 19. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 32455

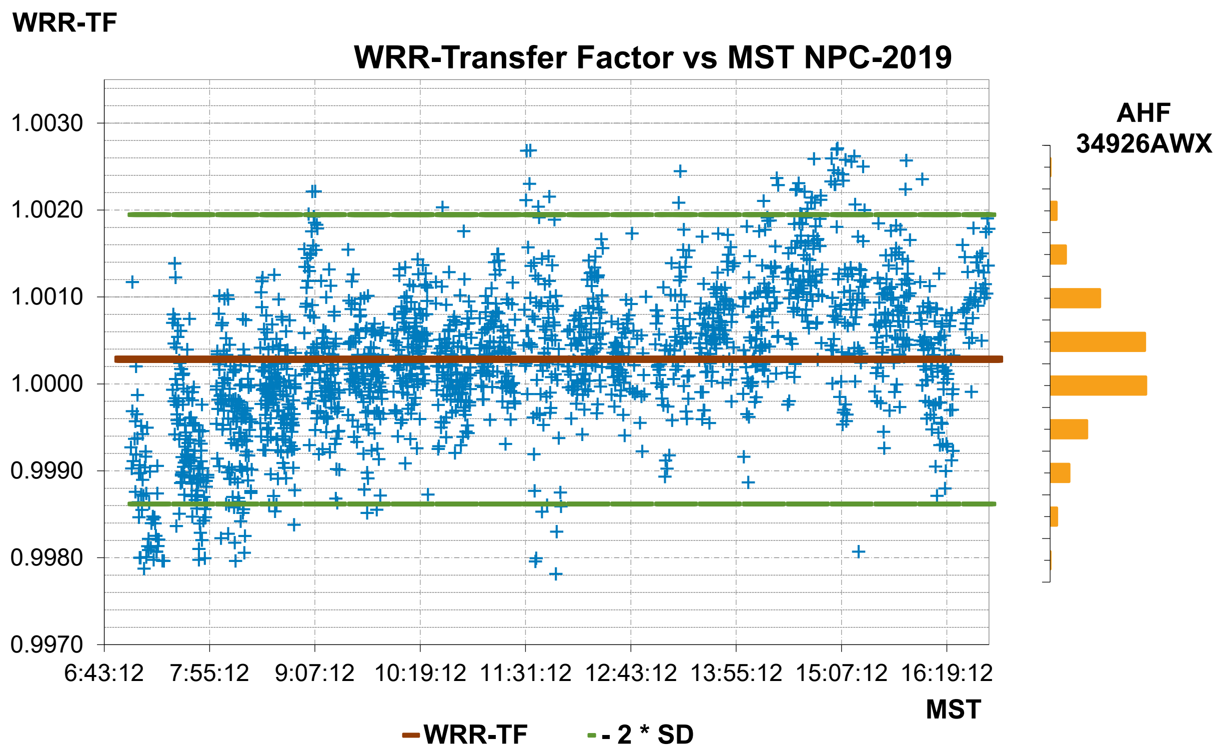

Figure 20. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 34926AWX

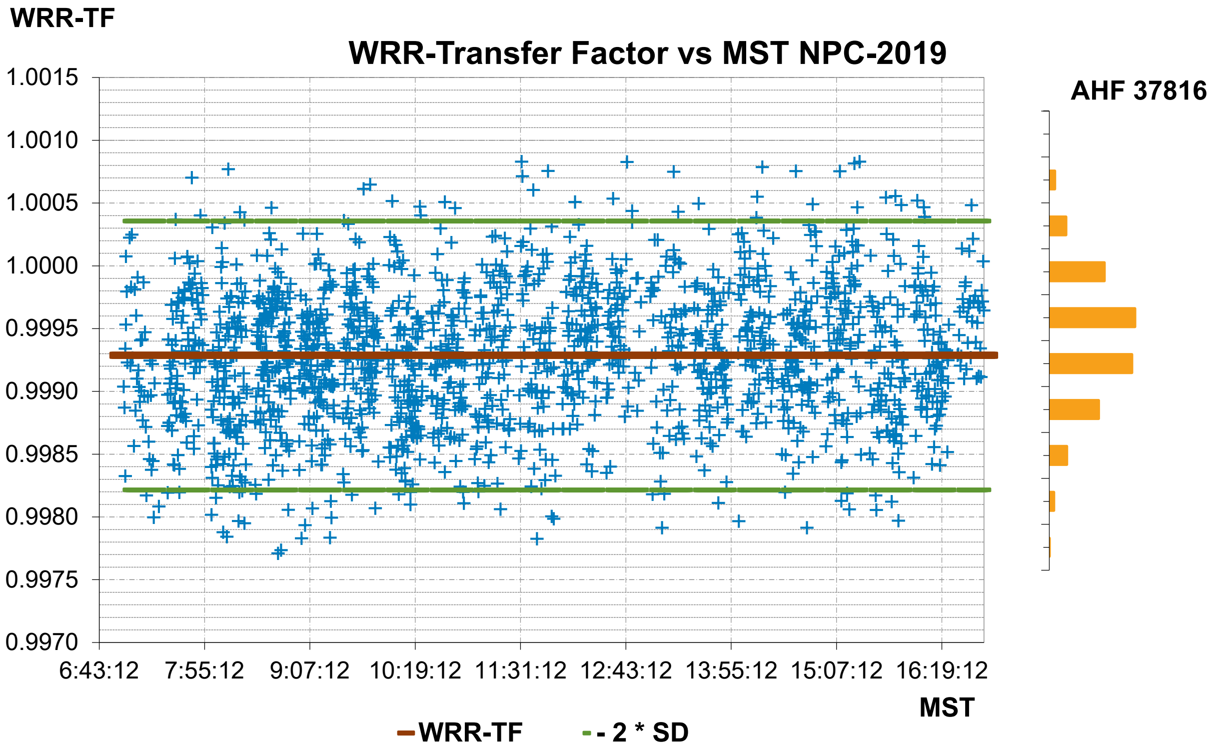

Figure 21. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for AHF 37816

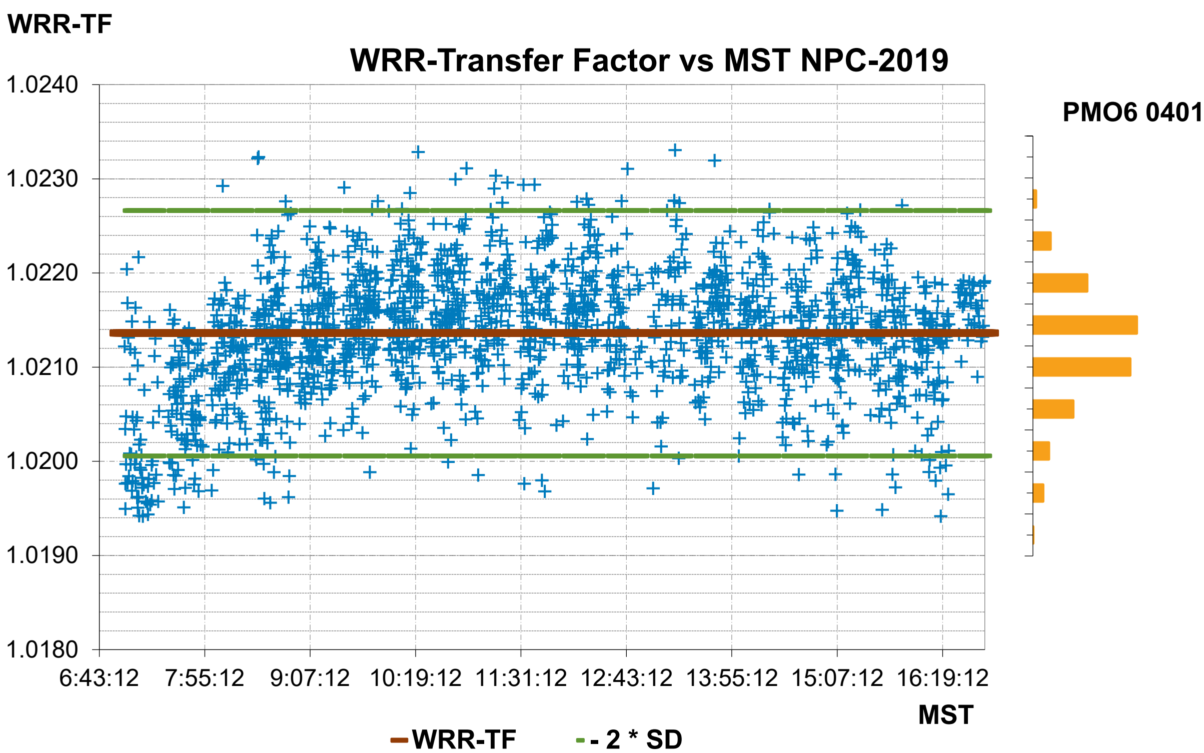

Figure 22. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6 0401

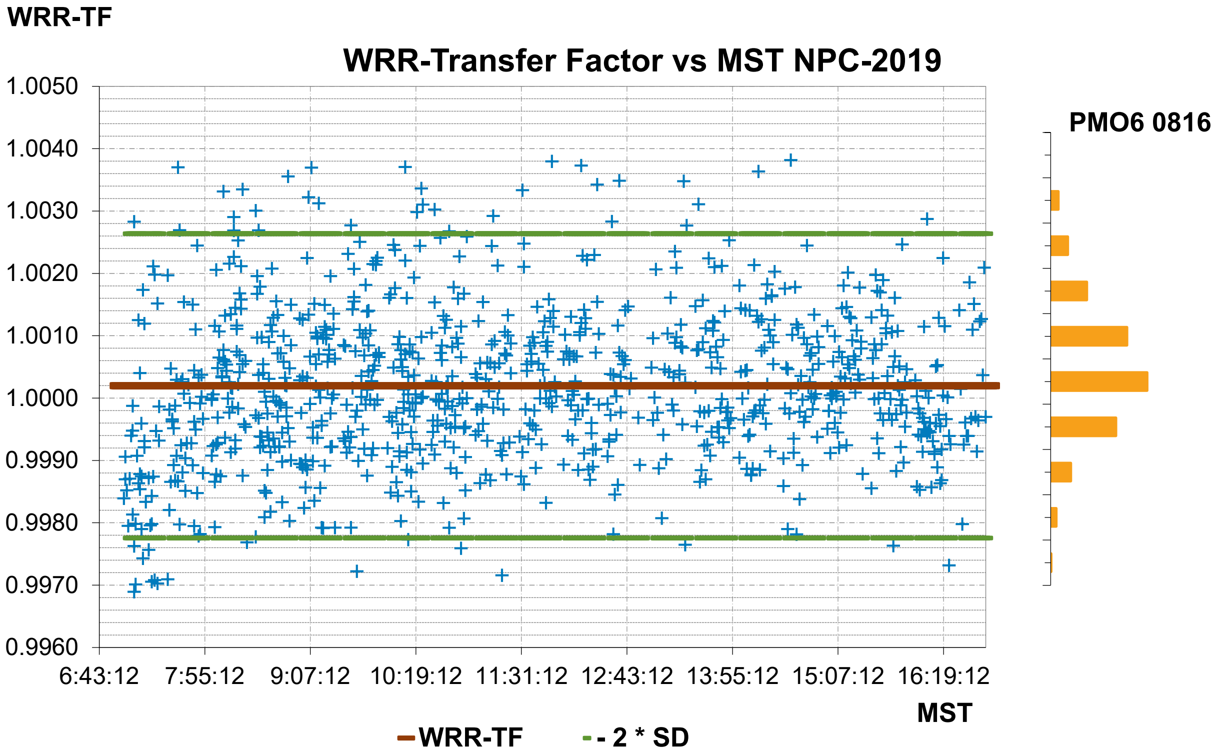

Figure 23. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6 0816

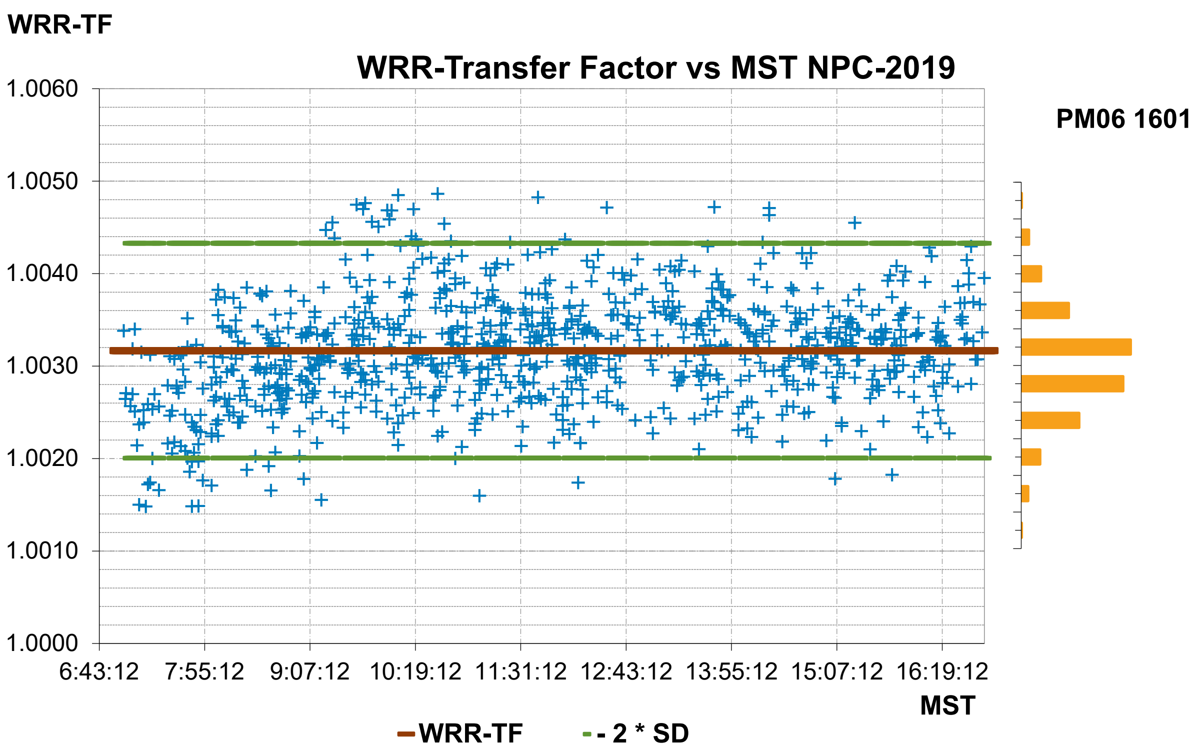

Figure 24. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6 1601

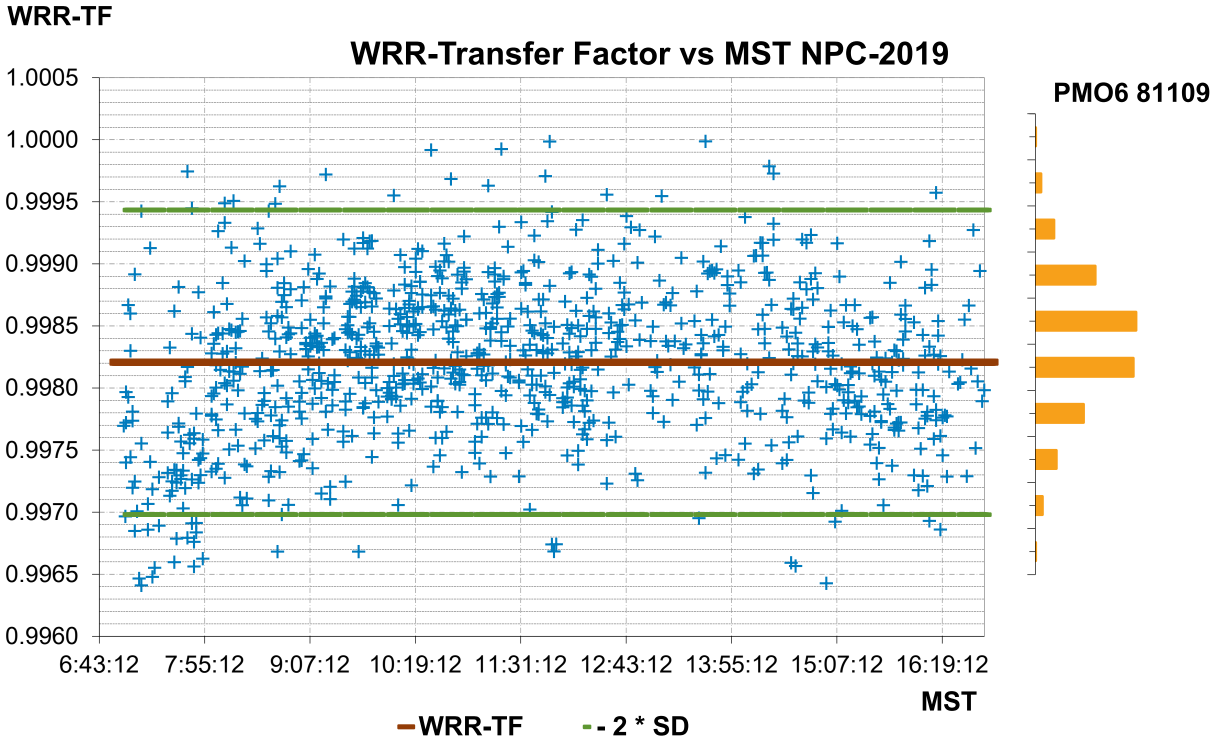

Figure 25. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6 81109

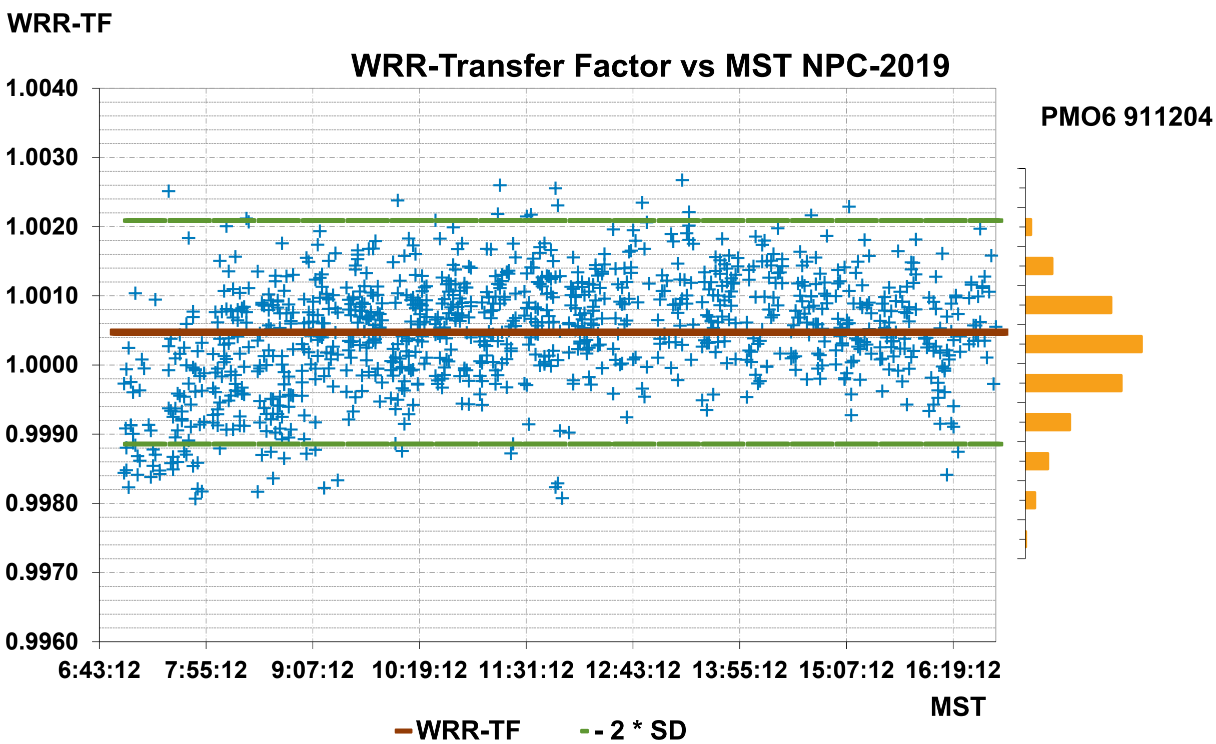

Figure 26. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6 911204

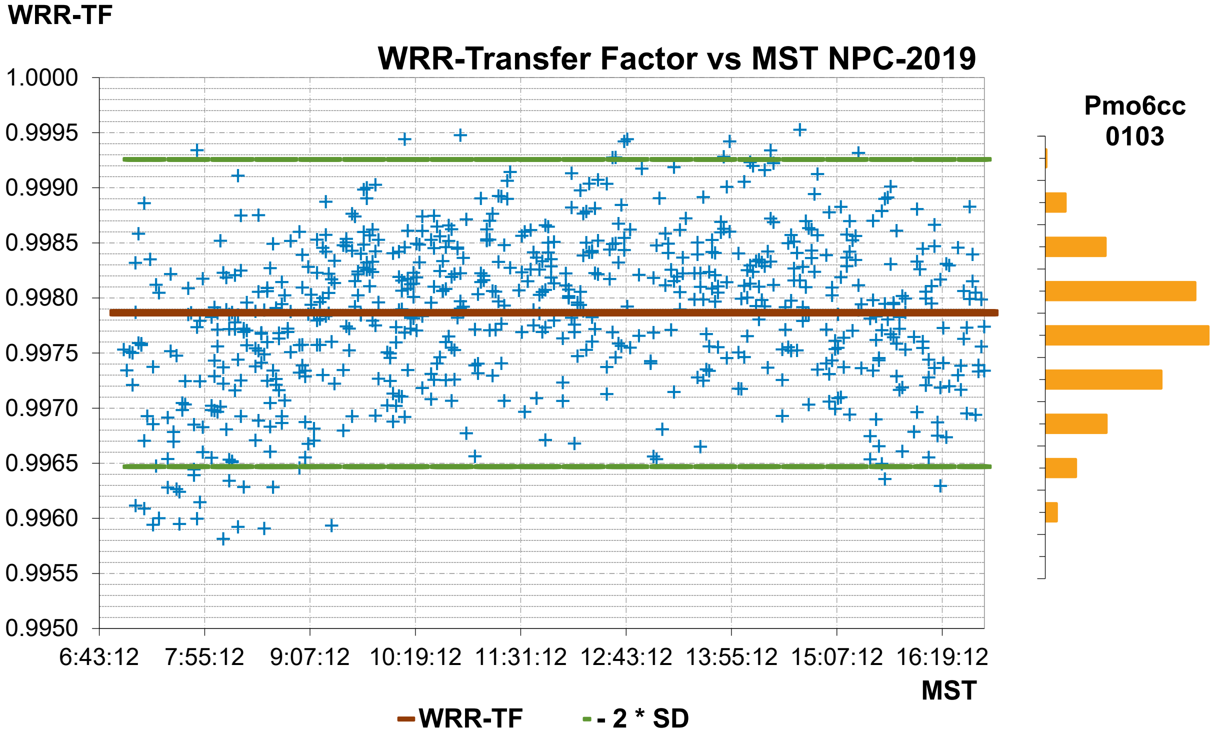

Figure 27. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6cc 0103

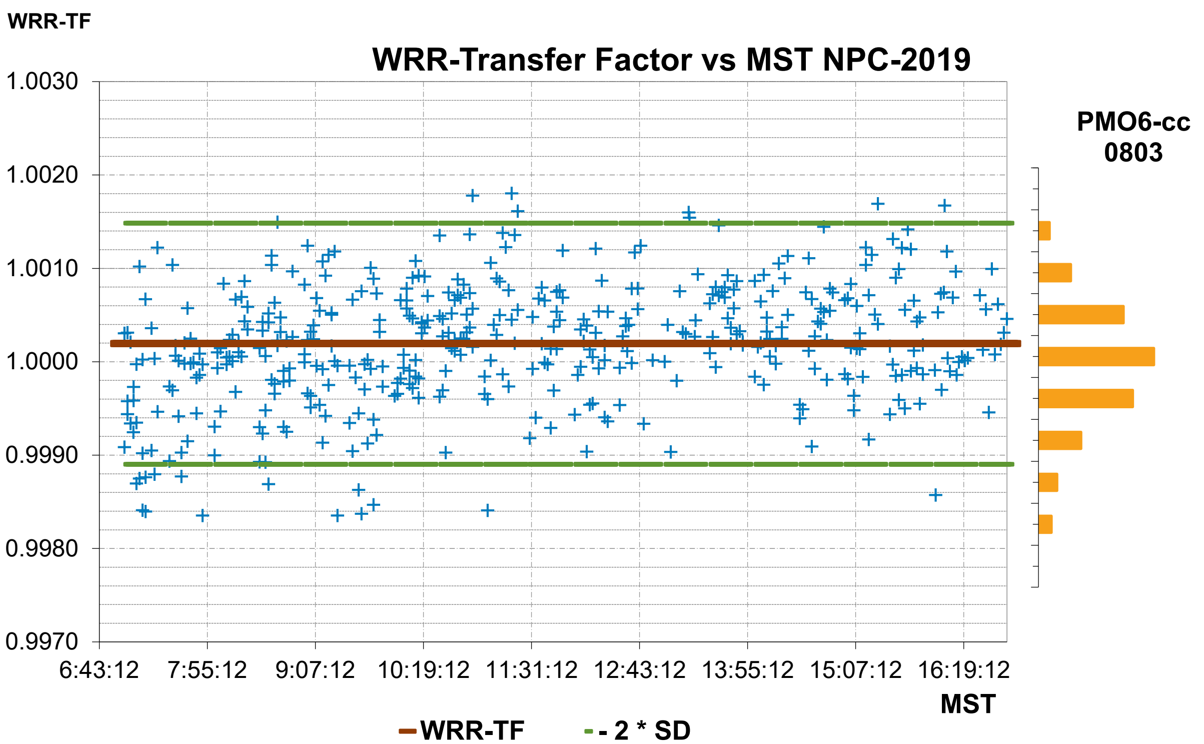

Figure 28. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6cc 0803

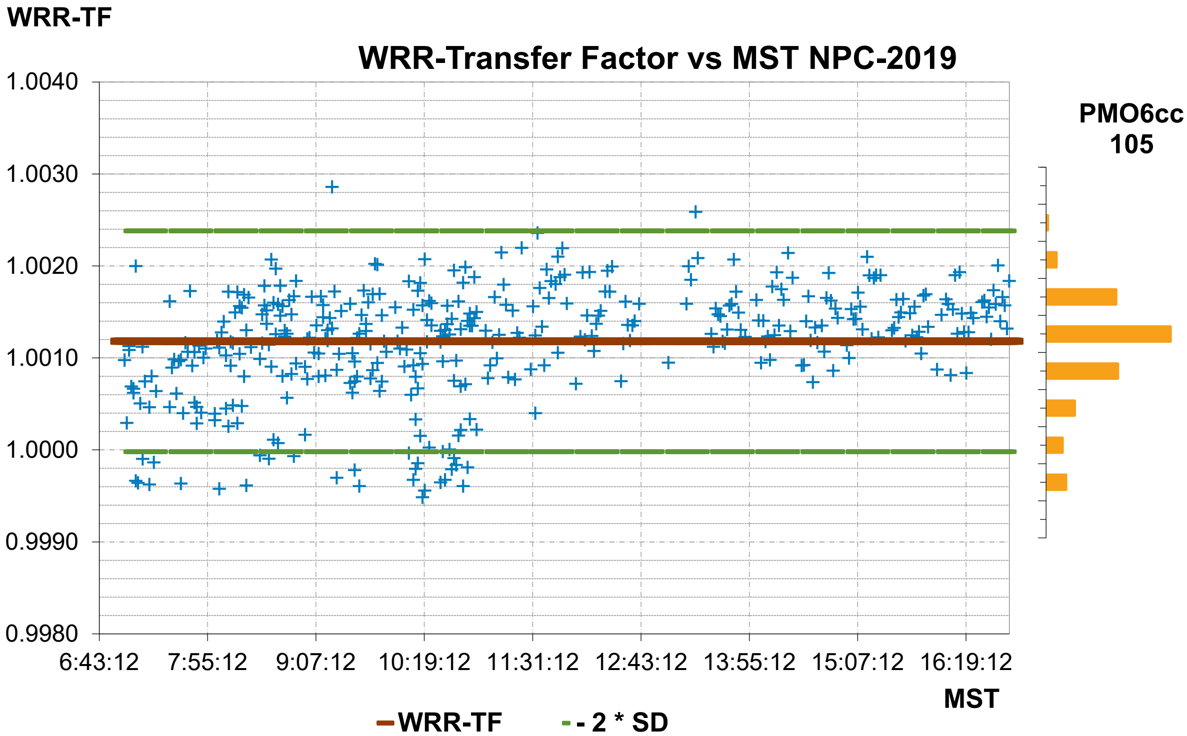

Figure 29. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6-cc 105

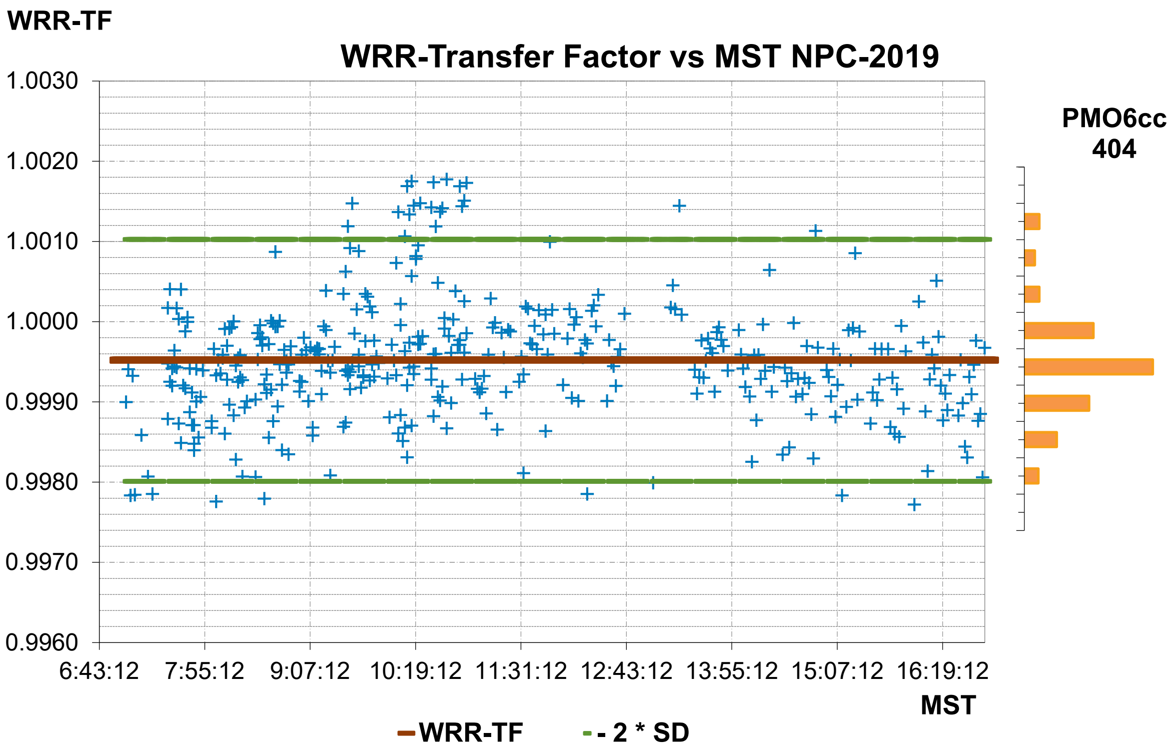

Figure 30. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMO6cc 404

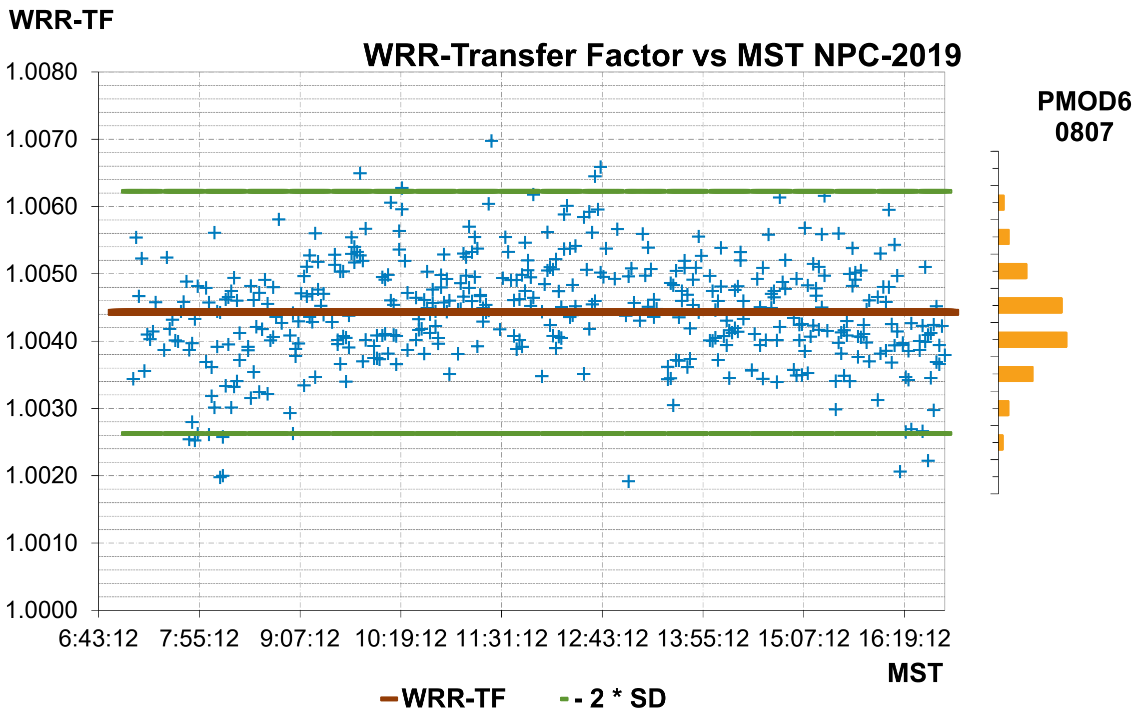

Figure 31. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for PMOD6 0806

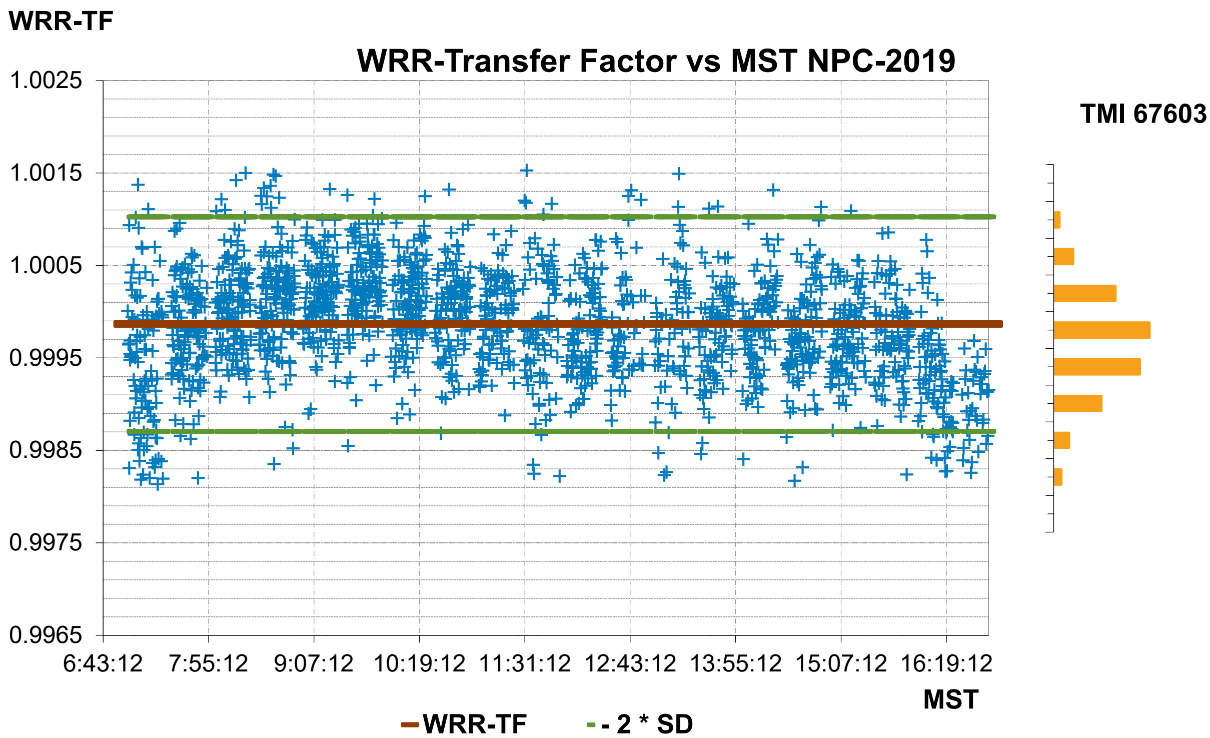

Figure 32. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for TMI 67603

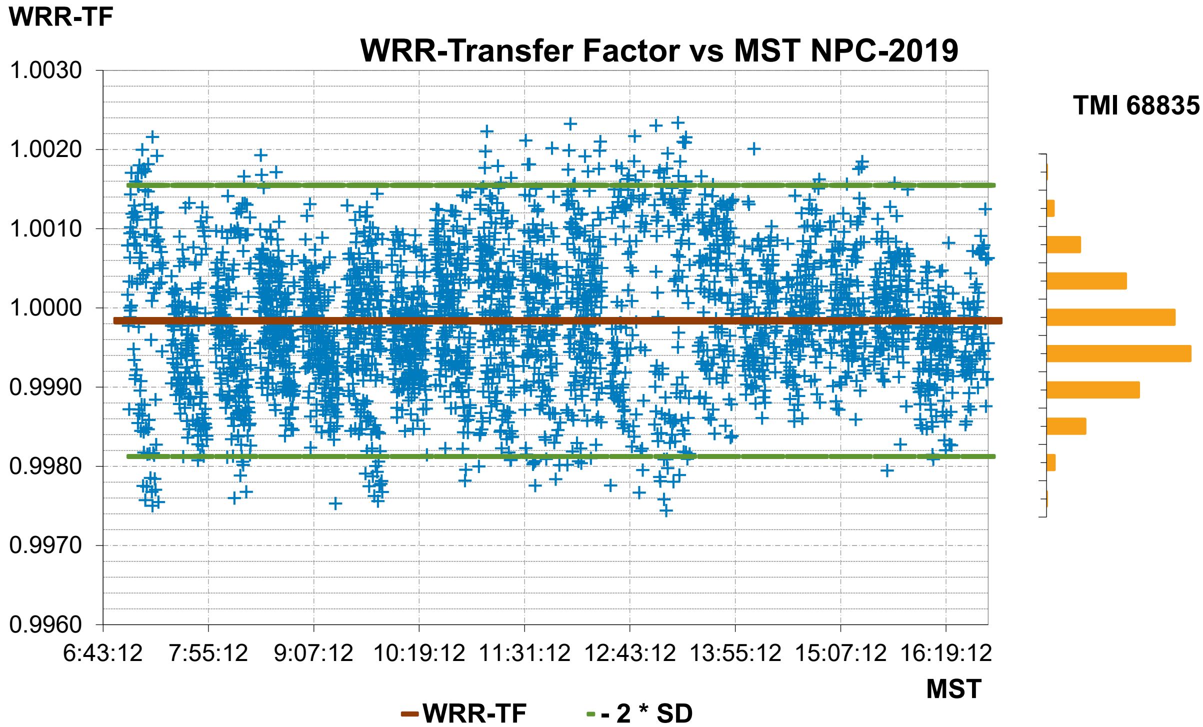

Figure 33. WRR-Transfer Factor vs. Mountain Standard Time NPC-2019 for TMI 68835

4.5 Recommendations

As a result of the comparisons made during NPC-2019, we suggest participants observe the following measurement practices:

- For the purpose of pyrheliometer comparisons, such as NPC-2019, 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-2019 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]

Time-series plots and other graphical presentations of these data collected during the pyrheliometer comparisons are presented in Appendix B.

[5] http:www.nrel.gov/midc/srrl_bms/

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Fröhlich, C. 1991. "History of Solar Radiometry and the World Radiometric Reference." *Metrologia* 28(3): 111–115.

Reda, I. 1996. *Calibration of a Solar Absolute Cavity Radiometer With Traceability to the World Radiometric Reference.* Golden, CO: The National Renewable Energy Laboratory. NREL/TP-463-20619. https://doi.org/10.2172/15000940.

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Physikalisch-Meteorologisches Observatorium Davos—World Radiation Center (PMOD/WRC). 1996. *International Pyrheliometer Comparison, IPC VIII, 25 September–13 October 1995, Results and Symposium.* Working Report No. 188. Davos Dorf, Switzerland: Swiss Meteorological Institute; 115 pp.

Appendix A. List of Participants and Pyrheliometers

Table A-1. List of Participants and Pyrheliometers

Serial Number of Radiometer	Operator 1	Operator 2	Affiliation
PMO6cc 105	Irene Melero Asensio	n/a	AEMET
PMO6cc 404	Irene Melero Asensio	n/a	AEMET
AHF 17142	Patrick Smith	Caitlin Hale	Atlas Material Testing Technology, LLC
AHF 28556	Patrick Smith	Caitlin Hale	Atlas Material Testing Technology, LLC
PM06 1601	Singh Ajay	n/a	Campbell Scientific, Inc.
AHF 29222	Craig Webb	James Martin	DOE Atmospheric Radiation Measurement (ARM) Program
AHF 30495-Window	Craig Webb	James Martin	DOE Atmospheric Radiation Measurement (ARM) Program
PMO6 0816	Ayako Imai	Makoto Shiobara	EKO Instruments
AHF 14915	Tom Kirk	n/a	Eppley Laboratory, Inc.
AHF 0000	Wim Zaaiman	n/a	European Commission Directorate General JRC
PMO6 81109	Wim Zaaiman	n/a	European Commission Directorate General JRC
PMO6 911204	Wim Zaaiman	n/a	European Commission Directorate General JRC
TMI 68835	Wim Zaaiman	n/a	European Commission Directorate General JRC
AHF 28560	Erik Naranen	n/a	ISO-CAL North America, LLC
AHF 37816	Erik Naranen	n/a	ISO-CAL North America, LLC
AHF 30110	Mohammed Al Harbi	Sultan Bin Gasem	King Abdullah City for Atomic and Renewable Energy (KACARE
AHF 31107	Mohammed Al Harbi	Saad AlQahtani	King Abdullah City for Atomic and Renewable Energy (KACARE)
PMO6 0807	Joop Mes	Victor Cassella	Kipp & Zonen USA, Inc.
PMO6cc 0103	Joop Mes	Victor Cassella	Kipp & Zonen USA, Inc.
AHF 31102	Nai-Ju Hsueh	Kun-Wei Lin	National Central University, Taiwan
AHF 23734	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Cell and Module Certification)

Serial Number of Radiometer	Operator 1	Operator 2	Affiliation
AHF 28968	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Metrology and SePA)
AHF 29219	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Metrology and SePA)
AHF 29220	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Metrology and SePA)
AHF 30713	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Metrology and SePA)
AHF 31104-Window	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Metrology and SePA)
AHF 32452AWX	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Metrology and SePA)
TMI 68018	Afshin Andreas	Mark Kutchenreiter	National Renewable Energy Laboratory (Metrology and SePA)
AHF 28553	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 31114AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 31116AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 32448AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 32455	Wolfgang Finsterle	n/a	PMOD/WRC
PMO6 0401	Wolfgang Finsterle	n/a	PMOD/WRC
PMO6cc 0803	Wolfgang Finsterle	n/a	PMOD/WRC
AHF 31108	Bill Boyson	Charles Robinson	Sandia National Laboratories (Photovoltaic Systems Evaluation Laboratory)
TMI 67603	Bill Boyson	Charles Robinson	Sandia National Laboratories (Photovoltaic Systems Evaluation Laboratory)
AHF 31041	Fred Denn	n/a	Science Systems and Applications, Inc.
AHF 31105	Fred Denn	n/a	Science Systems and Applications, Inc.
AHF 34926AWX	Josh Peterson	n/a	University of Oregon Solar Radiation Monitoring Laboratory

Appendix B. Ancillary Data Summaries

The measurement performance of an ACR can be affected by several environmental parameters. Potentially relevant meteorological data collected during the NPC are presented in this appendix.

The Baseline Measurement System has been in continuous operation at the SRRL since 1981. Baseline Measurement System data are recorded as one-minute averages of three-second samples for each instrument.[6] Time-series plots and other graphical presentations of these data acquired during the NPC-2019 measurements are presented here.

[6] Additional information about the SRRL and the Baseline Measurement System can be found on the Measurement and Instrumentation Data Center at http://www.nrel.gov/midc/srrl_bms/.

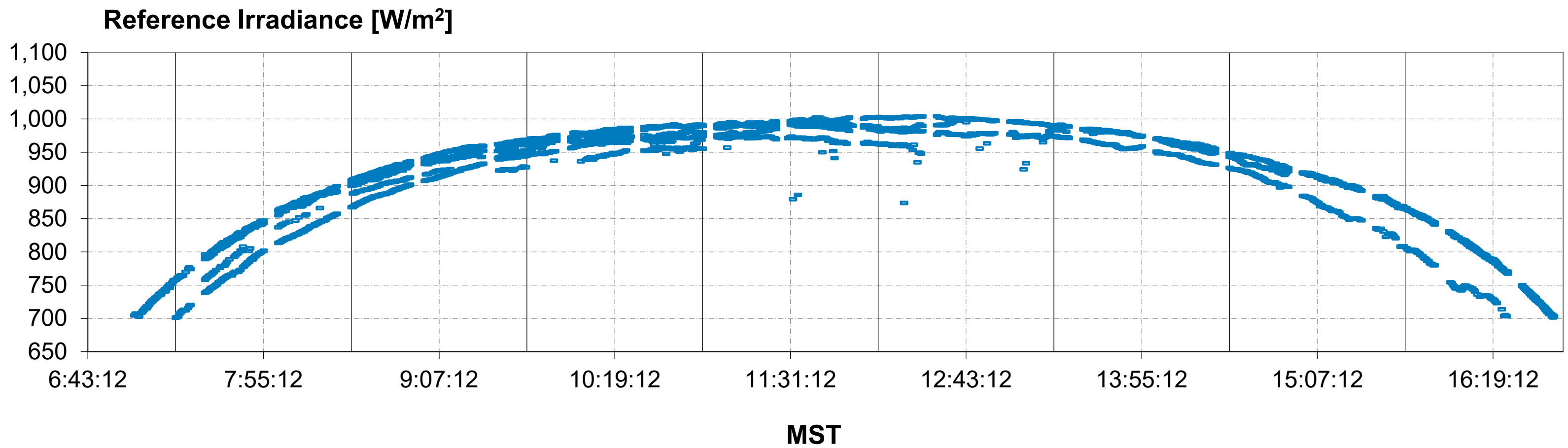

Figure B-1. Reference Irradiance (W/m2)

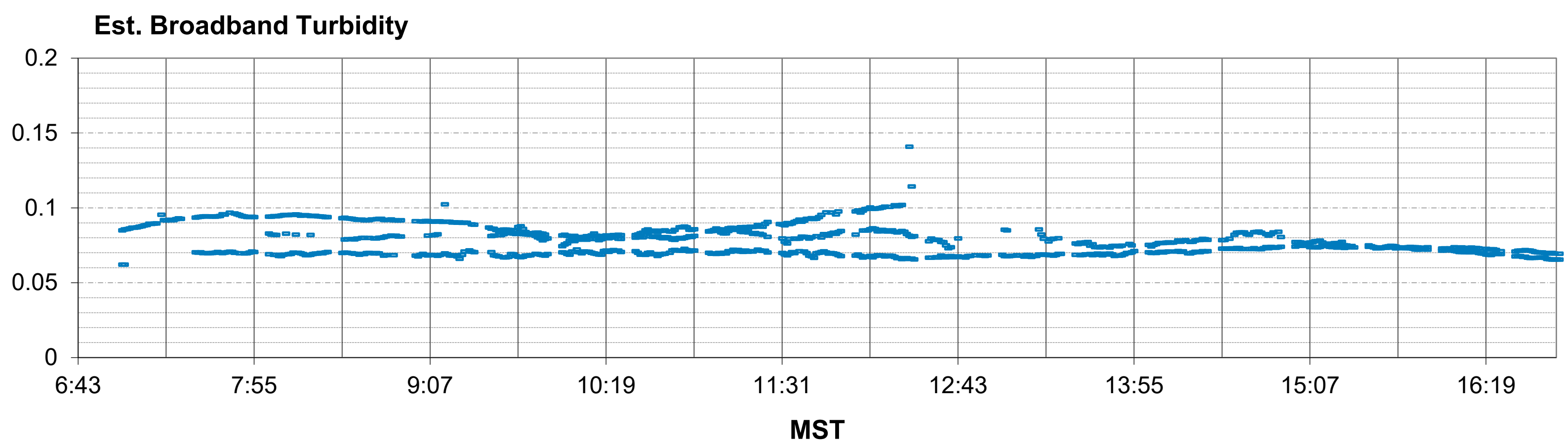

Figure B-2. Estimated broadband turbidity

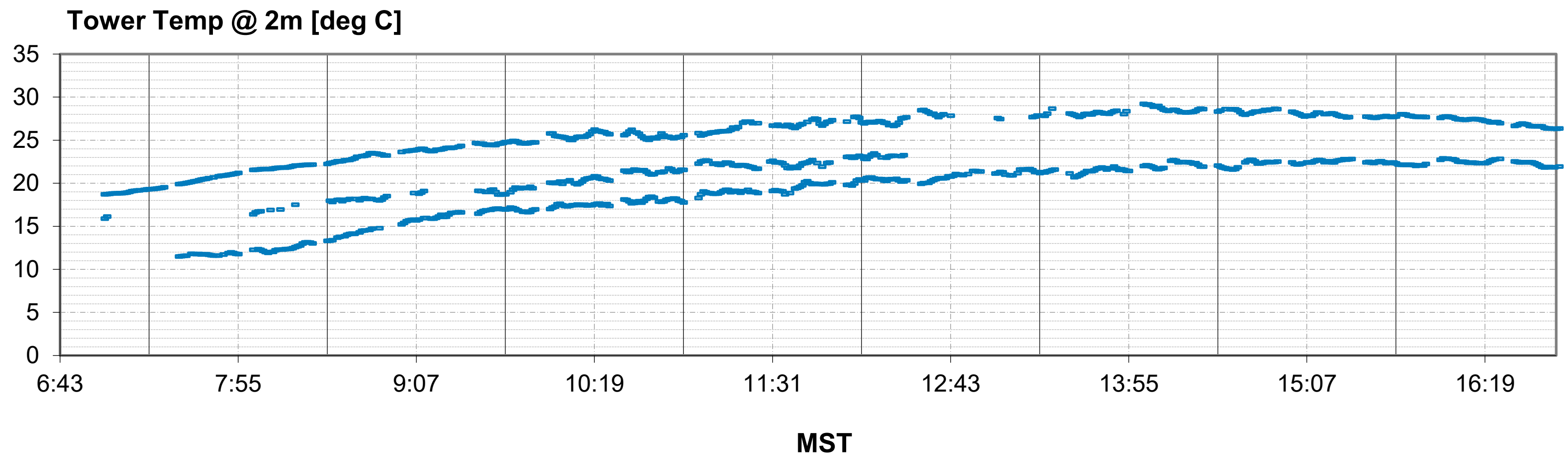

Figure B-3. Tower temperature at 2 m (deg. C)

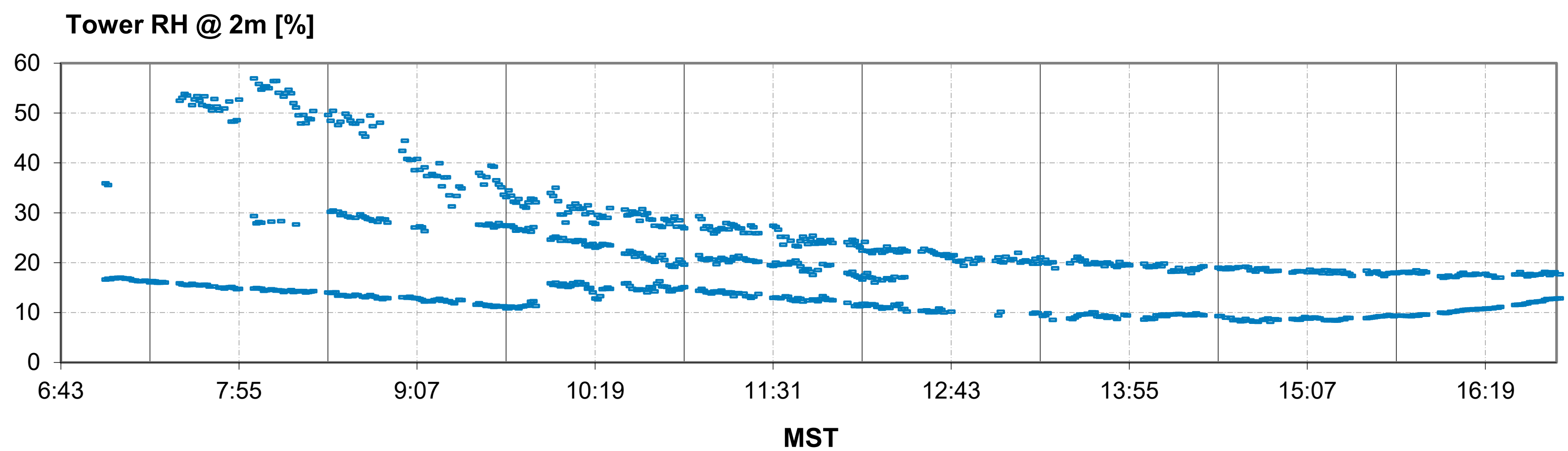

Figure B-4. Tower relative humidity at 2 m (%)

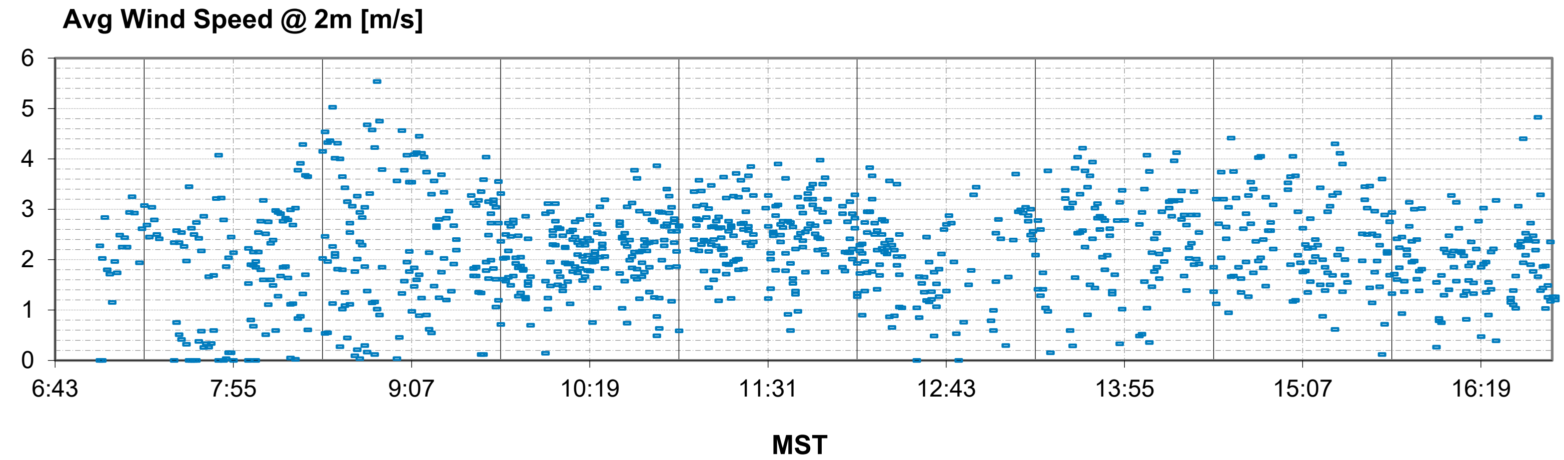

Figure B-5. Average wind speed at 2 m (m/s)

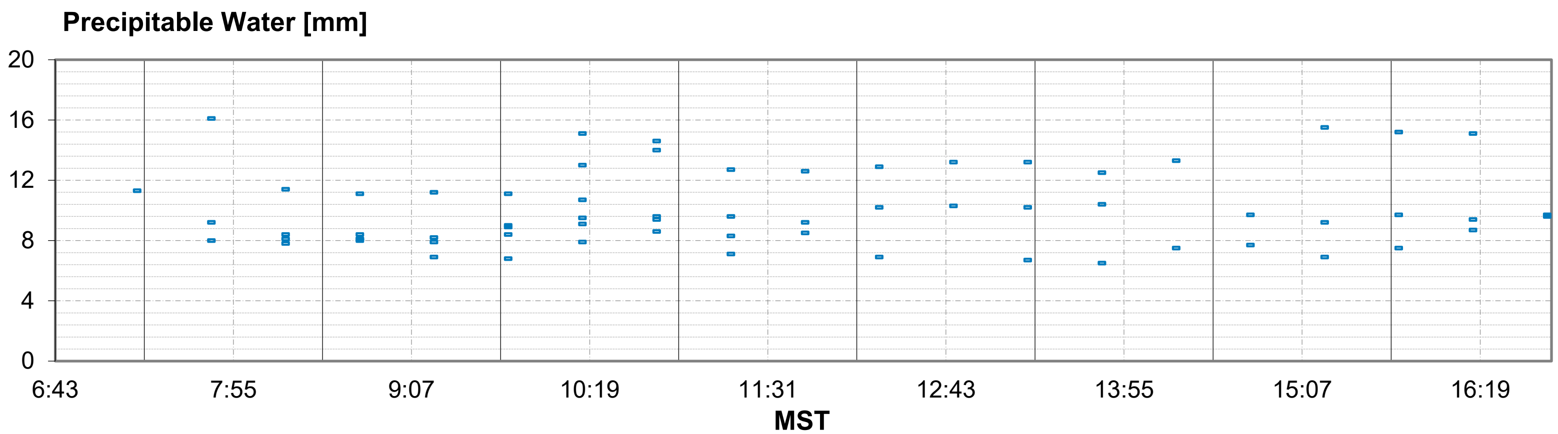

Figure B-6. Precipitable water (mm)

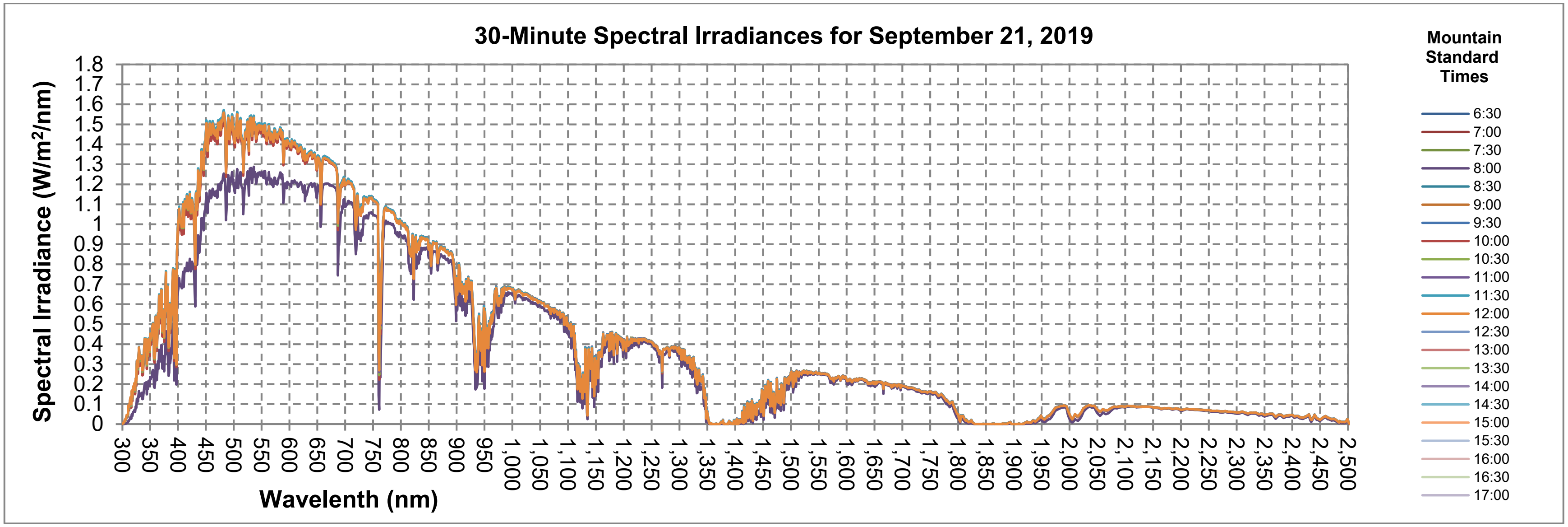

Figure B-7. 30-minute spectral irradiances for September 21, 2019

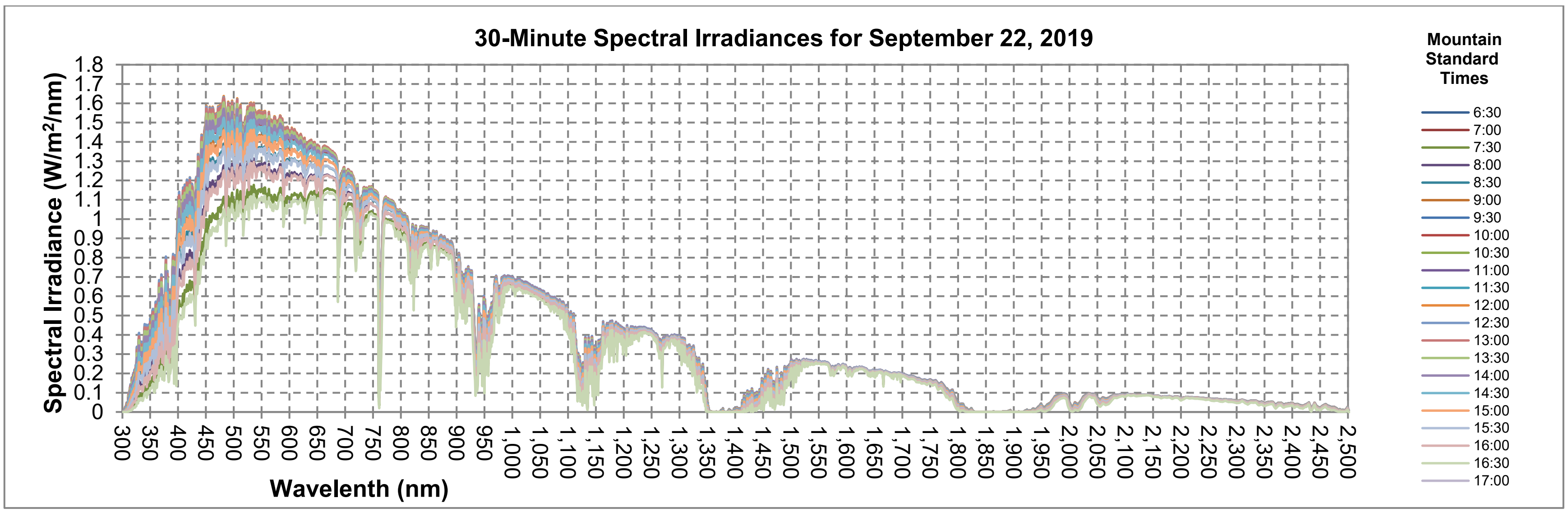

Figure B-8. 30-minute spectral irradiances for September 22, 2019

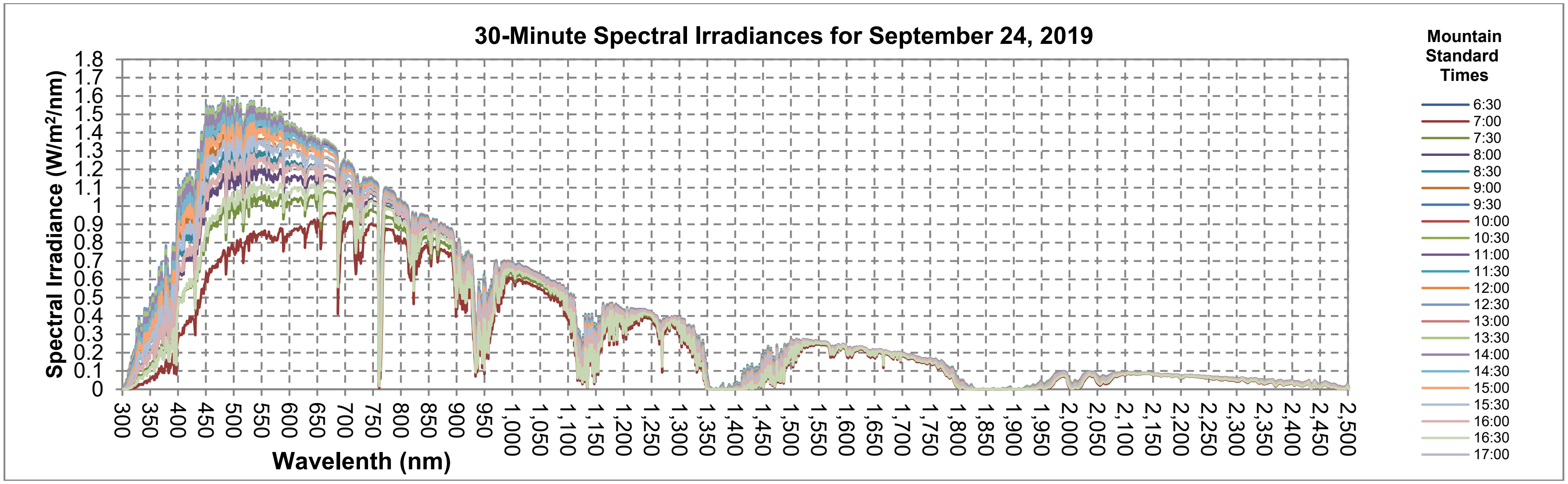

Figure B-9. 30-minute spectral irradiances for September 24, 2019

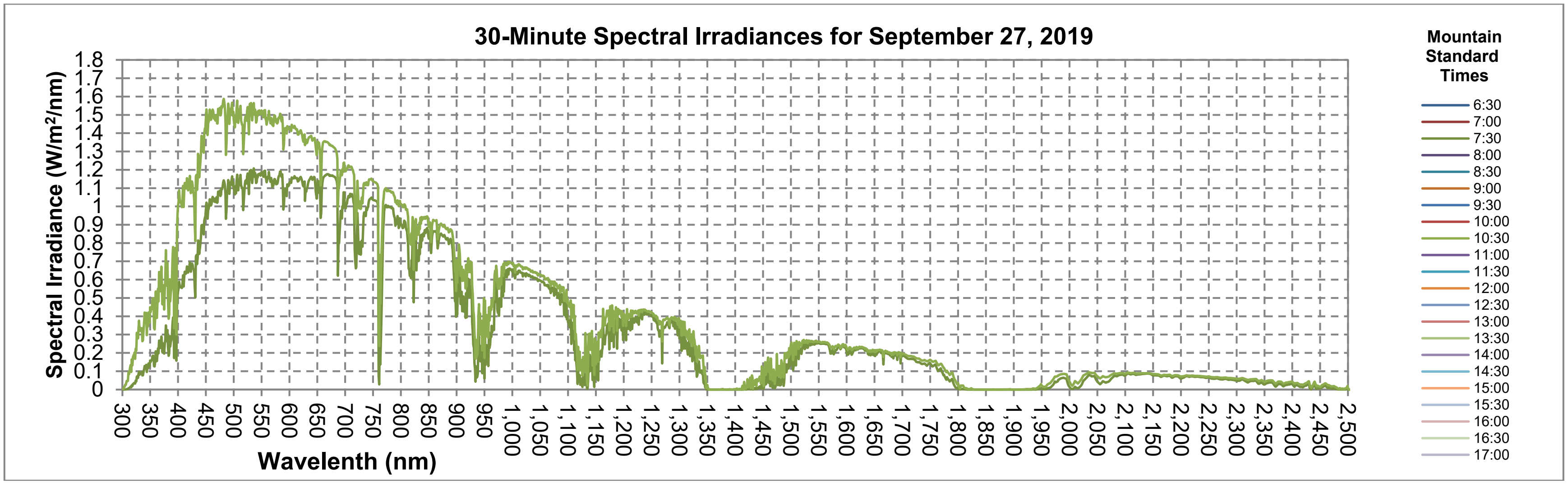

Figure B-10. 30-minute spectral irradiances for September 27, 2019

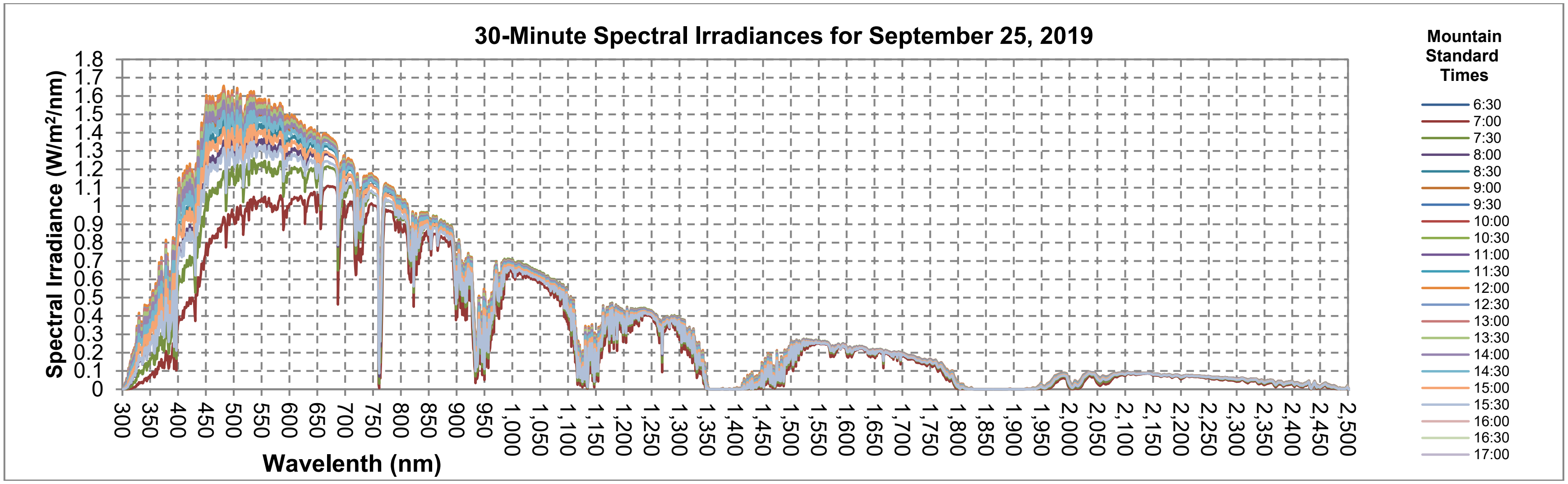

Figure B-11. 30-minute spectral irradiances for September 25, 2019

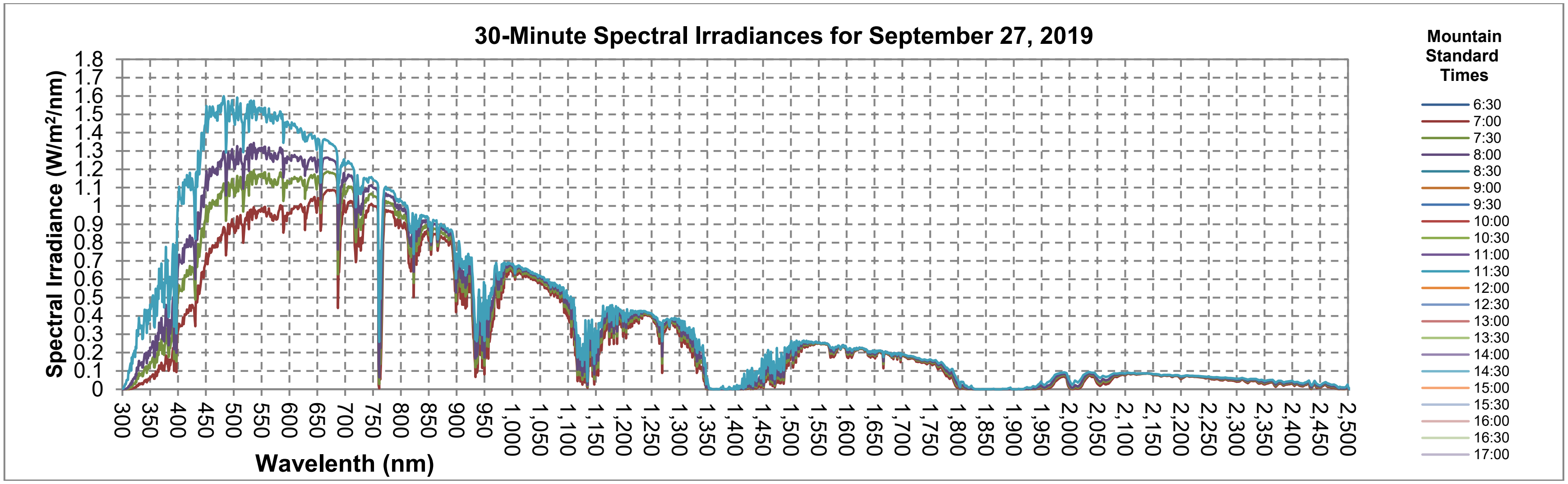

Figure B-12. 30-Minute Spectral Irradiances for September 27, 2019