NREL Pyrheliometer Comparisons: September 24 – October 5, 2018 (NPC-2018)

Ibrahim Reda, Mike Dooraghi, Afshin Andreas, and Aron Habte

National Renewable Energy Laboratory

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Technical Report
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Figure 1. NPC-2018 participants

Photo by Werner Slocum

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List of Acronyms

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
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
S/N	serial number of radiometer
%uA	Percentage Type-A standard uncertainty
NRdg	number of readings
uC	combined standard uncertainty
Eff DF	effective degrees of freedom

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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 the Earth's energy budget for climate change studies, and for other science and technology applications involving solar flux. These measurements place many demands on the quality system used by operators 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 (ASR) are subject to performance changes over time. Therefore, PMOD/WRC in Davos, Switzerland, hosts an International Pyrheliometer Comparison (IPC) for transferring the WRR to participating radiometers quinquennially by invitation. The National Renewable Energy Laboratory (NREL) has represented the U.S. Department of Energy (DOE) in each IPC since 1980. As a result, NREL has developed and maintained a select group of absolute cavity radiometers with direct calibration traceability to the WRR and 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-2018 was September 24 through October 5, 2018. Participants operated 43 ACRs to simultaneously measure clear-sky direct normal solar irradiance during this period. The Transfer Standard Group (TSG) of reference radiometers for NPC-2018 consisted of four NREL radiometers with direct traceability to the WRR, having participated in the Twelfth International Pyrheliometer Comparisons (IPC-XII) in the fall of 2015. As a result of NPC-2018, each participating absolute cavity radiometer was assigned a new WRR-TF, 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-2018 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.

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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 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. More than 2,300 reference irradiance measurements were collected by the TSG during NPC-2018. Clear-sky daily maximum direct normal irradiance level was 1017 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) in Switzerland (www.pmodwrc.ch). This reference 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). This 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 International Pyrheliometer Comparisons (IPC) held at the PMOD/WRC. The Twelfth IPC (IPC-XII) was completed in 2015 (Finsterle 2018). 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 WRR and therefore consistent with the international reference of solar radiation measurement.

In compliance with 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, during non-IPC years. The NREL Pyrheliometer Comparisons in 2018 (NPC-2018) was September 24 through October 5, 2018. Participants operated 43 absolute cavity radiometers during the comparisons. See Appendix A for the list of participants and affiliations.

The results presented in this report are based on clear-sky, direct normal solar irradiance data collected during the NPC. See Appendix B for environmental conditions.

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2 Reference Instruments

NREL developed the transfer standard group (TSG) of four absolute cavity radiometers 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-2018 data reduction. Table 1 provides a list of 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. IPC-XII Results Summary for the NPC-2018 TSG

Serial Number	WRR Factor (IPC-XI)	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:

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

where,

i = i^{th} cavity
m = number of reference cavities
S_i = standard deviation of the i^{th} cavity from IPC-XII
n_i = number of readings of the i^{th} cavity from IPC-XII

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3 Measurement Protocol

The decision to deploy instruments for a comparison was made daily. 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) absolute cavity was performed prior to 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 prior to 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 dataset was required to derive the WRR-TF for each pyrheliometer. Data from each pyrheliometer/operator system were emailed at the end of the day.

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4 Transferring the World Radiometric Reference

The primary purpose of an NREL pyrheliometer comparison is to transfer the current WRR from the NPC-TSG to each participating absolute cavity pyrheliometer. This requires that the participating pyrheliometers and the TSG collect simultaneous measurements of clear-sky direct normal (beam) solar irradiance. Because the NPC data analysis is intended for absolute cavity pyrheliometers only, users of pyrheliometers other than absolute cavity pyrheliometers might interpret their NPC results differently.

4.1 Calibration Requirements

Using WMO guidelines (Romero 1995), the following conditions were required before data collection was accomplished during NPC-2018:

- The radiation source was the sun, with irradiance levels > 700 Wm^{-2}.
- A Digital Multimeter with uncertainty > 0.05% reading or better was used to measure the thermopile signals from each radiometer.
- Solar trackers were aligned within ± 0.25° slope angle.
- 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.

4.2 Determining the Reference Irradiance

Four absolute cavity radiometers 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 AHF28968, for its participation in many IPCs.
2. By maintaining the mean of WRR for the TSG, a new WRR-TF for NPC-2018 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.

4.3 Data Analysis Criteria

AHF28968 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 are 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.

Additionally, all calculated ratios of the test instrument irradiance divided by AHF28968 irradiance that deviated from their mean by 0.3% were rejected (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.

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4.4 Measurements

NPC-2018 was completed for most participants on October 4, after more than 2,000 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 a variety of problems occurred with the measurement systems and operations.

4.5 Results

The historical results for the TSG are presented in Figure 2. 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-2018 WRR-TF did not change by more than a fraction of the standard deviation derived during IPC-XII in 2015 (see Figure 2. History of WRR reduction factors for NREL reference cavities).
- For NPC-2018 Proficiency Test, the results of the participating cavities in IPC-XII and NPC-2018 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 Figure 2. History of WRR reduction factors for NREL reference cavities

Table 2, E_n for all cavities was well within the interval -1 to +1 (i.e., the WRR from NPC-2018 is consistent with the WRR from IPC-XII).

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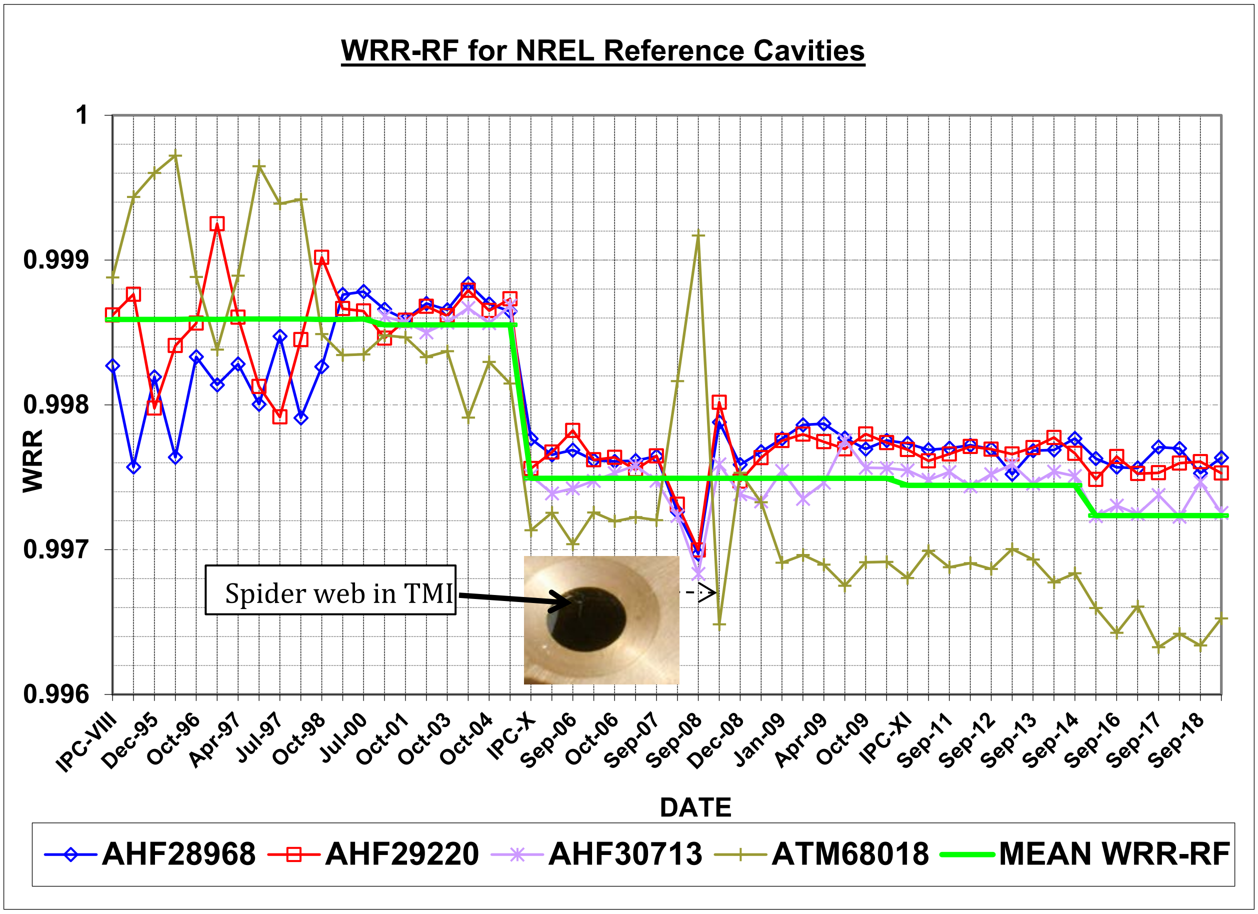

Figure 2. History of WRR reduction factors for NREL reference cavities

Table 2. Summary Results for Proficiency Test During NPC-2018

Participating Cavity	IPC-XII	%U95	NPC-2018	%U95	Red if abs(En) > 1
AHF 0000	1.00031	0.36	1.00275	0.39	-0.46
AHF 14915	0.99954	0.35	0.99954	0.38	0.00
AHF 17142	0.99795	0.39	0.99828	0.38	-0.06
AHF 23734	0.99819	0.35	0.99830	0.37	-0.02
AHF 28553	0.99774	0.35	0.99781	0.37	-0.01
AHF 28556	0.99541	0.36	0.99056	0.42	0.89
AHF 31041	0.99639	0.36	0.99663	0.38	-0.05
AHF 31105	0.99866	0.36	0.99861	0.38	0.01
AHF 31114AWX	1.00121	0.33	1.00093	0.38	0.06
AHF 32448AWX	0.99999	0.35	1.00017	0.38	-0.03
AHF 32455	1.00138	0.33	1.00140	0.39	0.00
AHF 37816	0.99959	0.33	0.99933	0.38	0.05
PMO6 0816	0.99984	0.45	1.00026	0.47	-0.07
PMO6 81109	0.99832	0.32	0.99823	0.39	0.02
PMO6 911204	0.99945	0.41	1.00013	0.41	-0.12
Pmo6cc 0103	0.99792	0.32	0.99911	0.39	-0.24
TMI 68835	1.000714	0.32	0.99983	0.41	0.17

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Table 3. Results for Radiometers Participating in NPC-2018

S/N	WRR (NPC-2018)	SD	NRDG	%U95
AHF 0000	1.00275	0.00073	1997	0.39
AHF 14915	0.99954	0.00063	1378	0.38
AHF 17142	0.99828	0.00061	1441	0.38
AHF 23734	0.99830	0.00038	1543	0.37
AHF 28486	0.99722	0.00064	1452	0.38
AHF 28553	0.99781	0.00049	1431	0.37
AHF 28556	0.99056	0.00103	1498	0.42
AHF 28560	1.00289	0.00089	1419	0.40
AHF 29219-Window	1.06176	0.00069	1495	0.38
AHF 29222-Window	1.05900	0.00068	1965	0.38
AHF 29223	0.99904	0.00072	1325	0.39
AHF 30110	1.06312	0.00087	968	0.40
AHF 30495-Window	1.05572	0.00085	1959	0.39
AHF 31041	0.99663	0.00067	1169	0.38
AHF 31104-Window	1.03877	0.00089	1258	0.40
AHF 31105	0.99861	0.00056	1183	0.38
AHF 31107	1.04821	0.00121	929	0.43
AHF 31108	0.99684	0.00074	1498	0.39
AHF 32452AWX-Window	1.03139	0.00091	1484	0.40
AHF 31113AWX-Window	1.05056	0.00075	1399	0.39
AHF 31114AWX	1.00093	0.00064	1407	0.38
AHF 32448AWX	1.00017	0.00065	1424	0.38
AHF 32455	1.00140	0.00072	2278	0.39
AHF 33392	0.99890	0.00058	1284	0.38
AHF 34926AWX	1.00117	0.00088	1408	0.40
AHF 37816	0.99933	0.00067	1406	0.38
PMO6 0816	1.00026	0.00155	335	0.47
PM06 1601	1.00310	0.00061	473	0.38
PMO6 81109	0.99823	0.00073	584	0.39
PMO6 911204	1.00013	0.00096	593	0.41
Pmo6cc 0103	0.99911	0.00073	360	0.39
PMO6cc 0401	1.02097	0.00074	374	0.39
PMO6cc 0803	1.00005	0.00078	382	0.39
PMO6 1611-Linard-00	1.00165	0.00075	1097	0.39
TMI 67603	0.99993	0.00070	1488	0.39
TMI 67811	0.99866	0.00104	1338	0.42
TMI 68020	0.99897	0.00096	1213	0.41
TMI 68022	0.99996	0.00144	1327	0.46
TMI 68835	0.99983	0.00099	2169	0.41

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

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

where,

U_{95} = Uncertainty of the WRR-TF (in percent) determined at NPC-2018 with 95% confidence level

1.96 = Coverage factor

u_A = Type A standard uncertainty = standard deviation of each participating radiometer (in %) determined at NPC-2018

u_B = Type B standard uncertainty

$u_B = \pm \sqrt{(\frac{0.3}{\sqrt{3}})^2 + 0.06^2}$

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 the following figures. These graphical summaries indicate the mean, standard deviation, and histograms of the WRR-TF determined during NPC-2018.

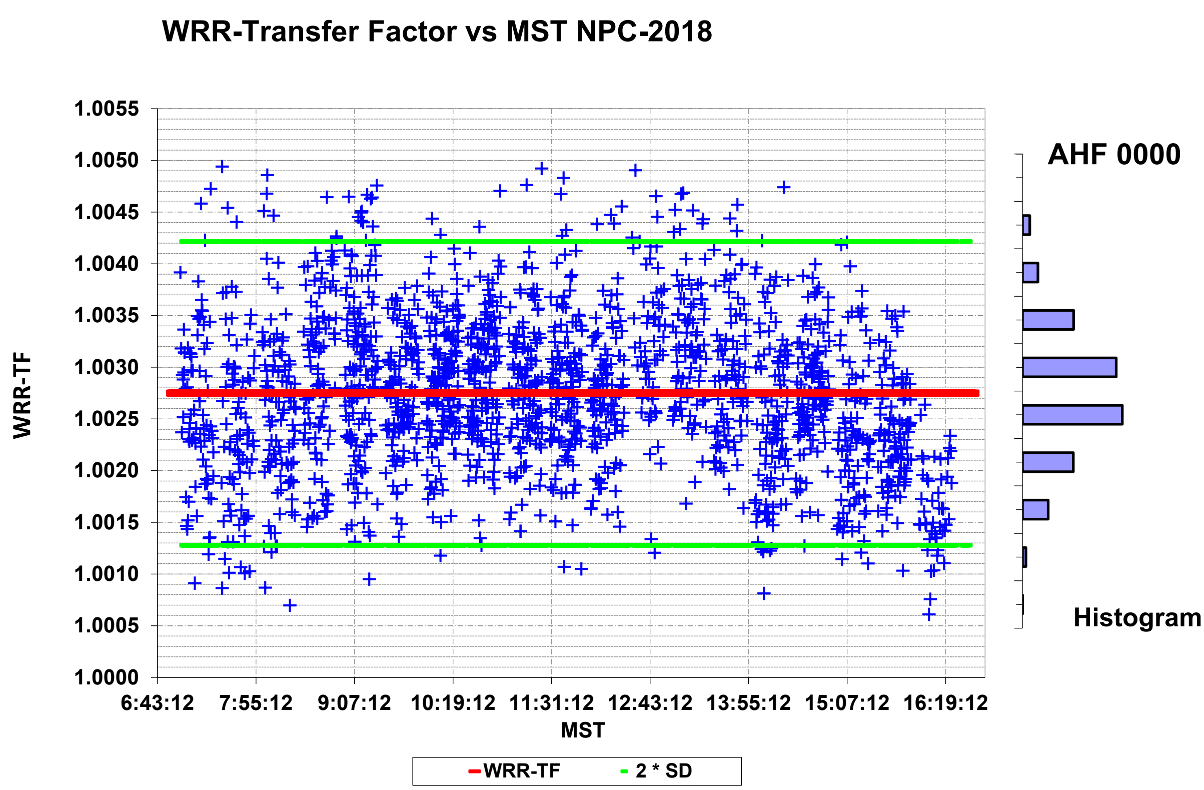

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Figure 3. WRR-Transfer Factor vs. Mountain Standard Time (MST) NPC-2018 for AHF 0000

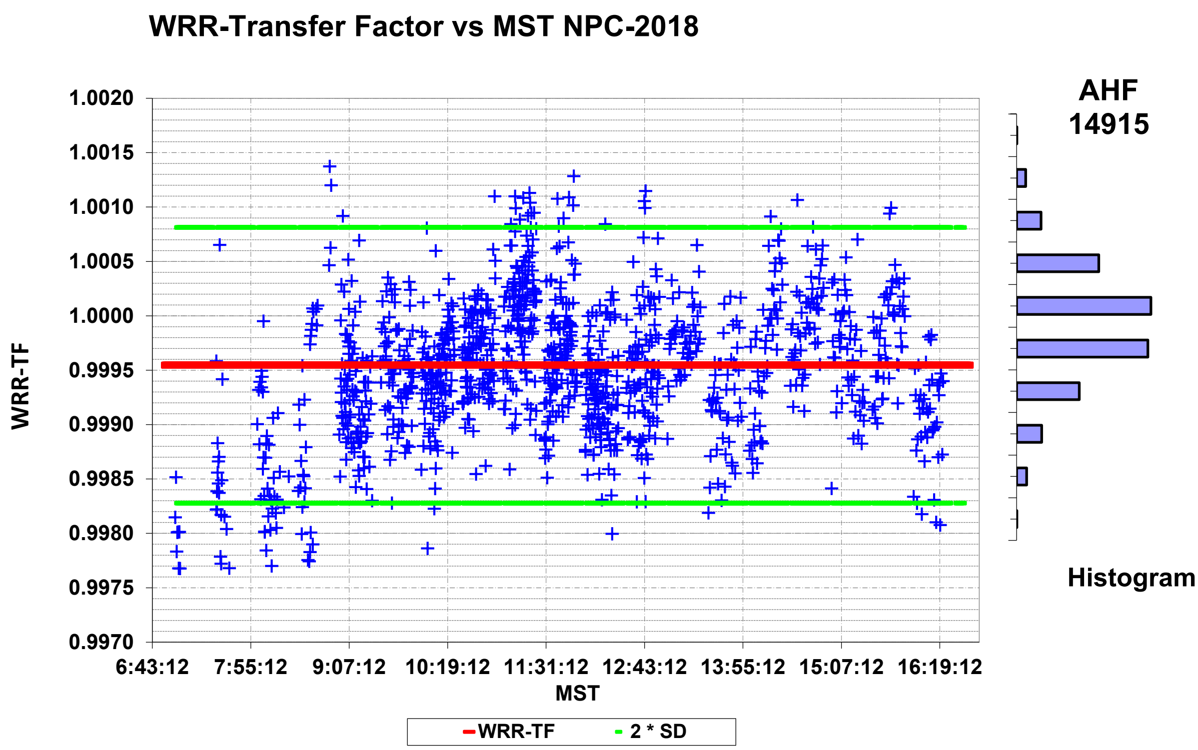

Figure 4. WRR-Transfer Factor vs. MST NPC-2018 for AHF 14915

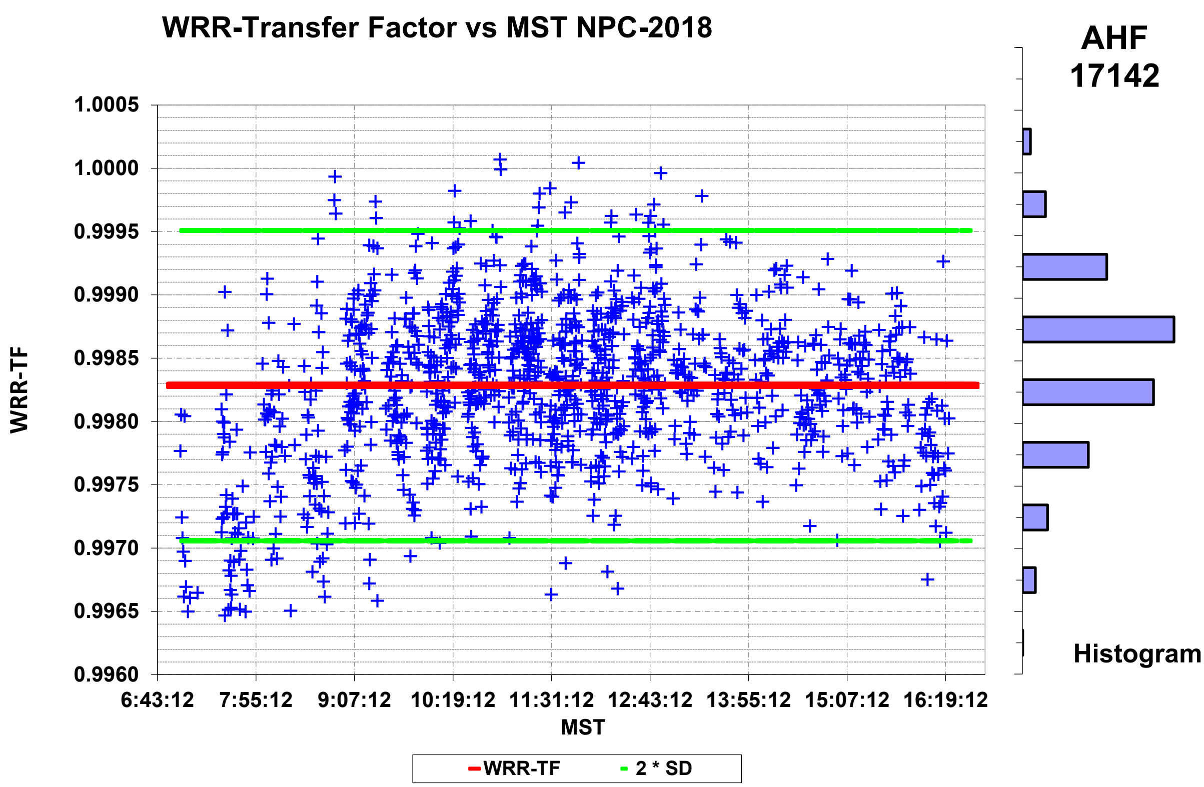

Figure 5. WRR-Transfer Factor vs. MST NPC-2018 for AHF 17142

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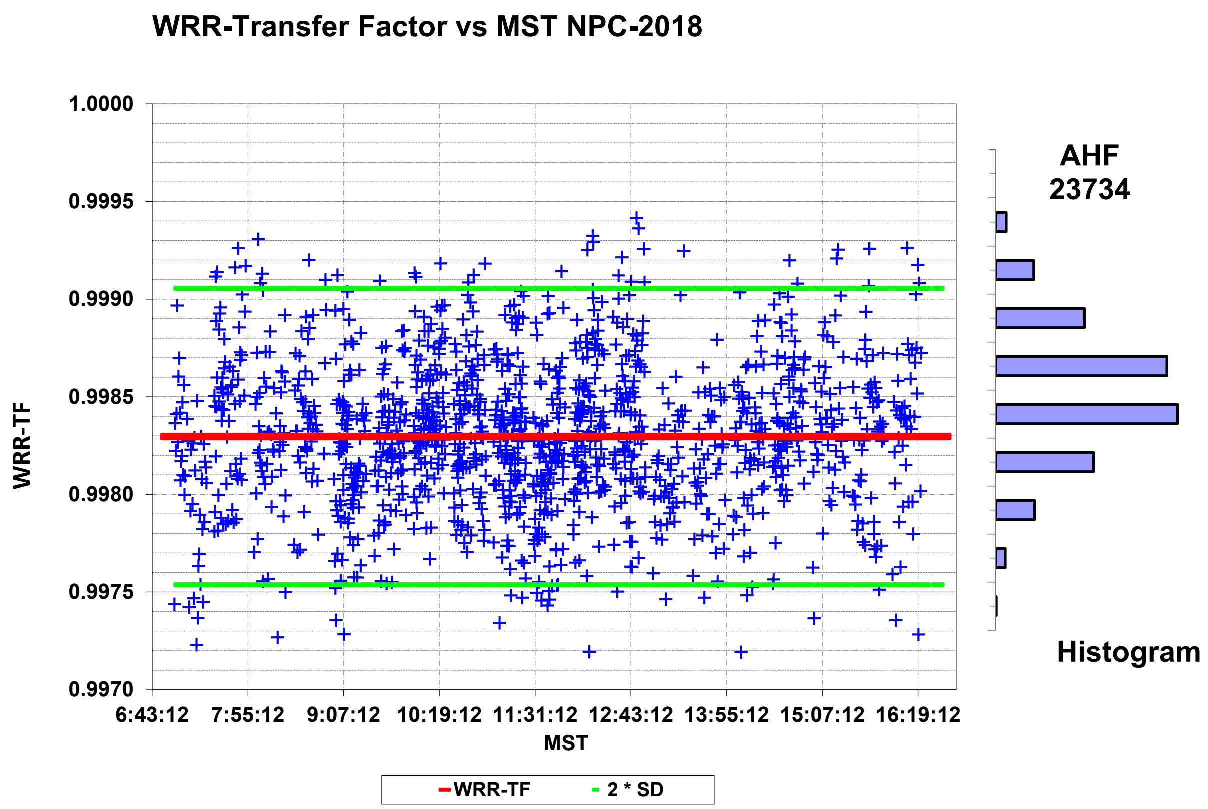

Figure 6. WRR-Transfer Factor vs. MST NPC-2018 for AHF23734

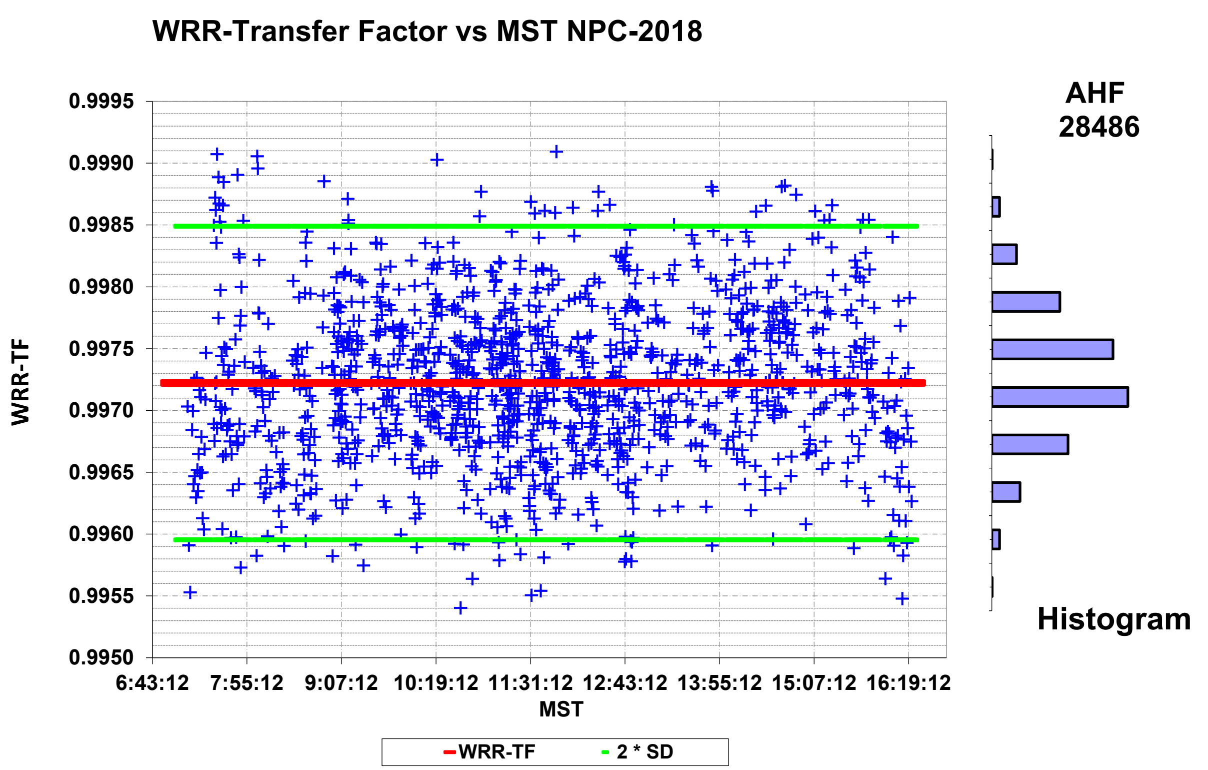

Figure 7. WRR-Transfer Factor vs. MST NPC-2018 for AHF 28486

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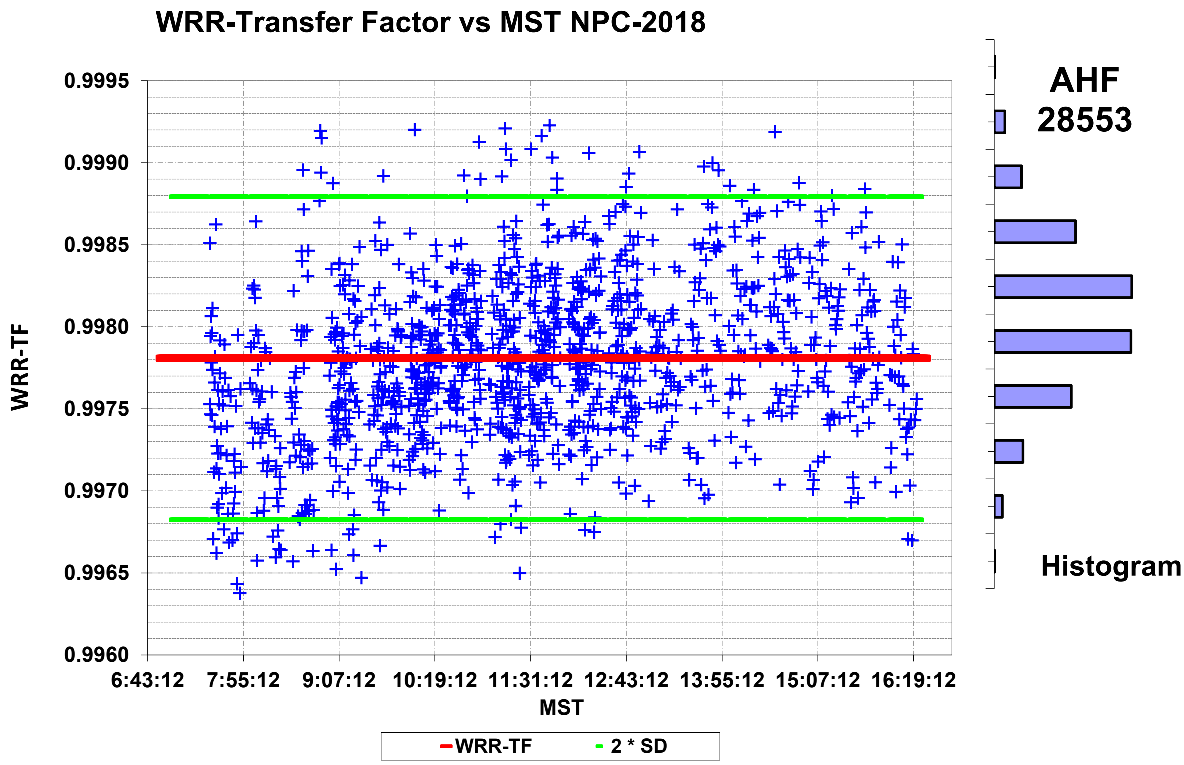

Figure 8. WRR-Transfer Factor vs. MST NPC-2018 for AHF28553

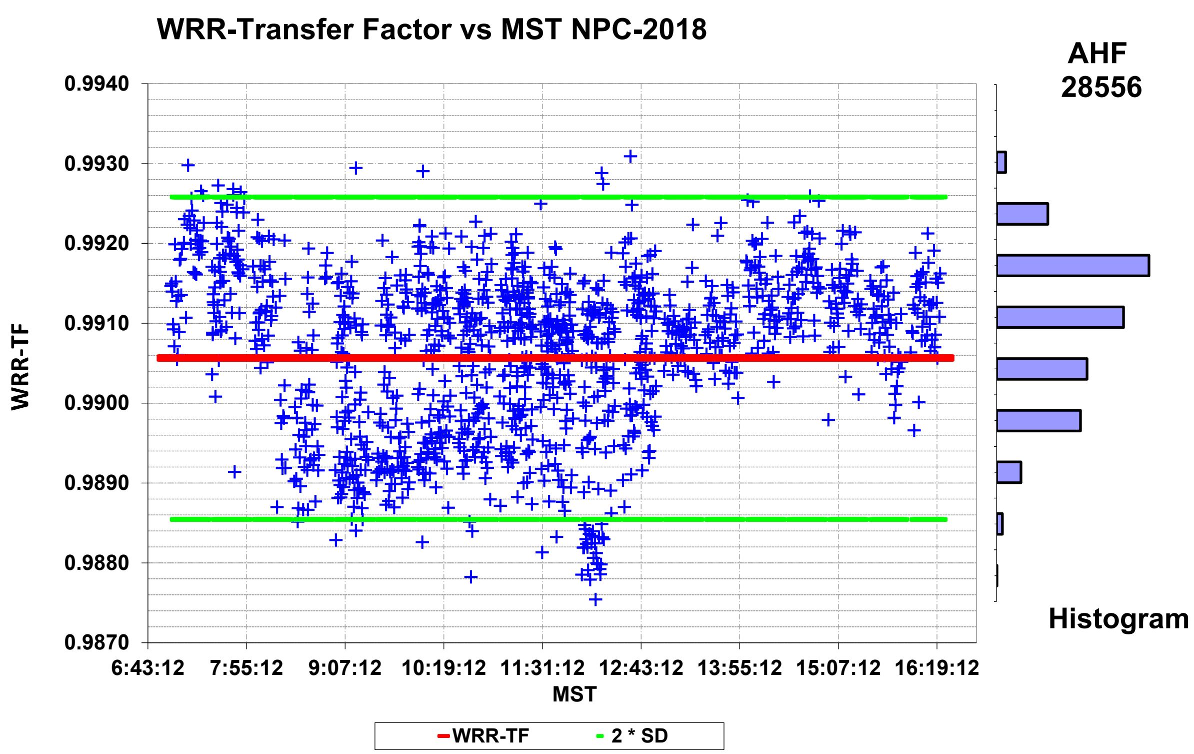

Figure 9. WRR-Transfer Factor vs. MST NPC-2018 for AHF 28556

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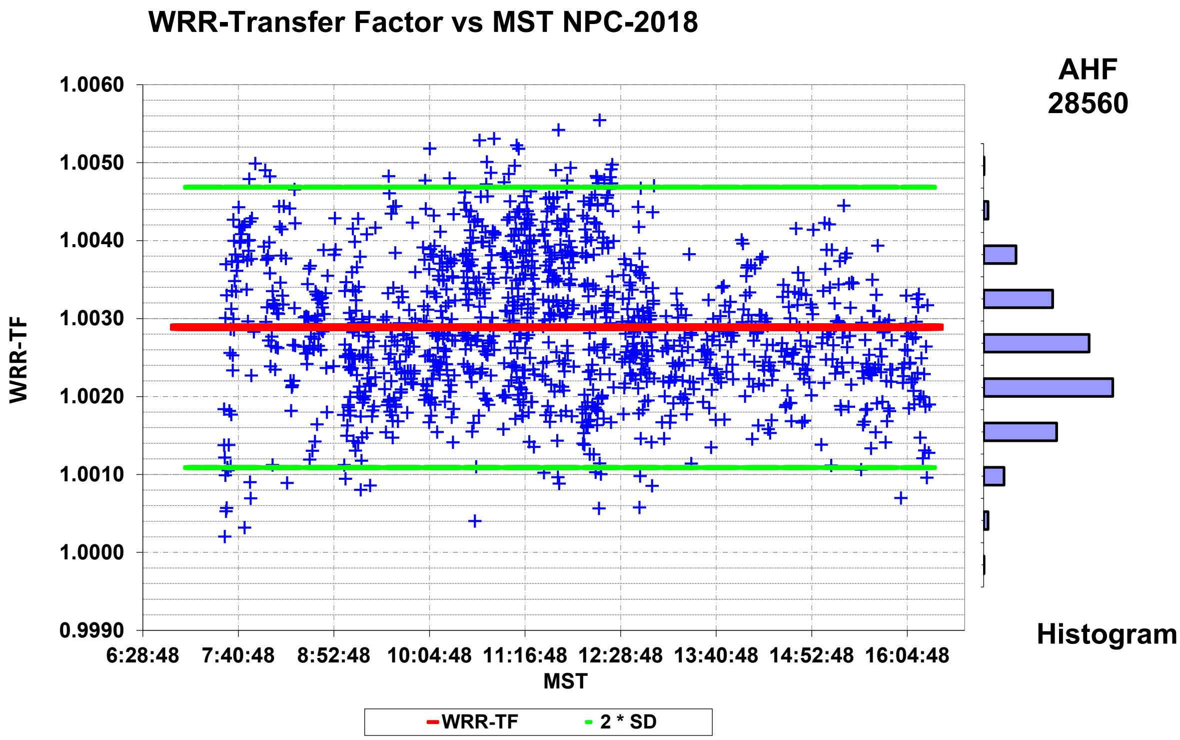

Figure 10. WRR-Transfer Factor vs. MST NPC-2018 for AHF 28560

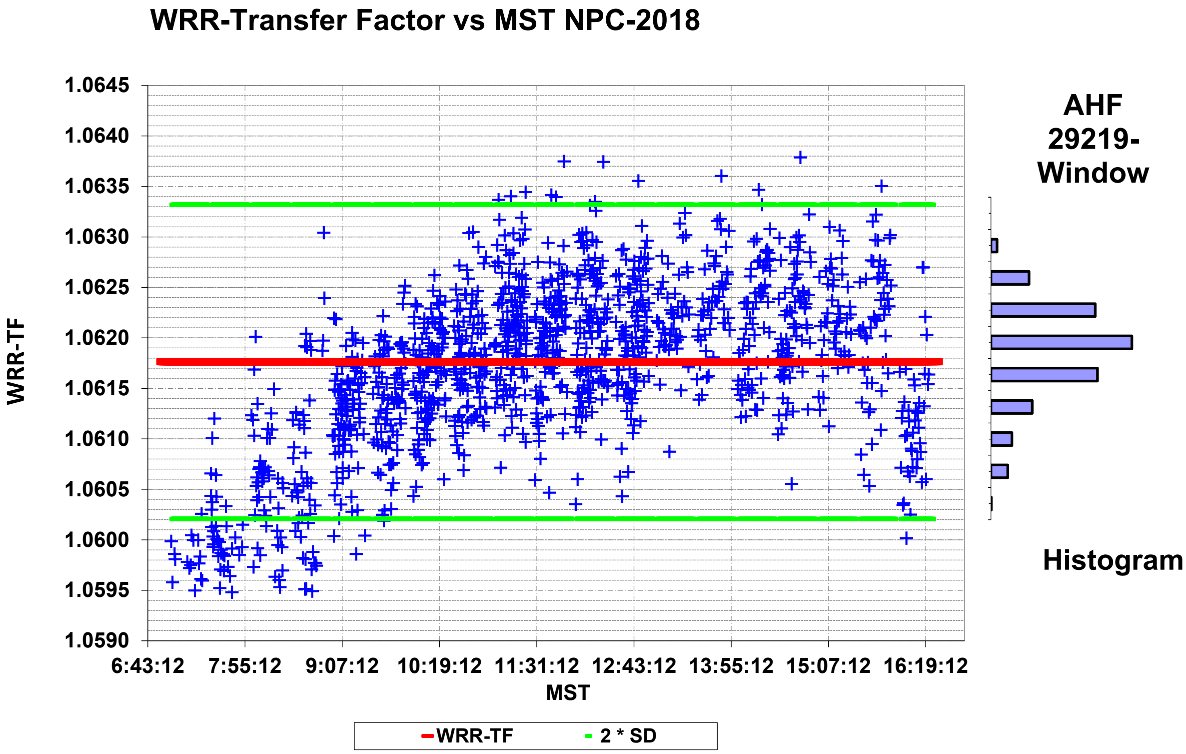

Figure 11. WRR-Transfer Factor vs. MST NPC-2018 for AHF 29219 - Windowed

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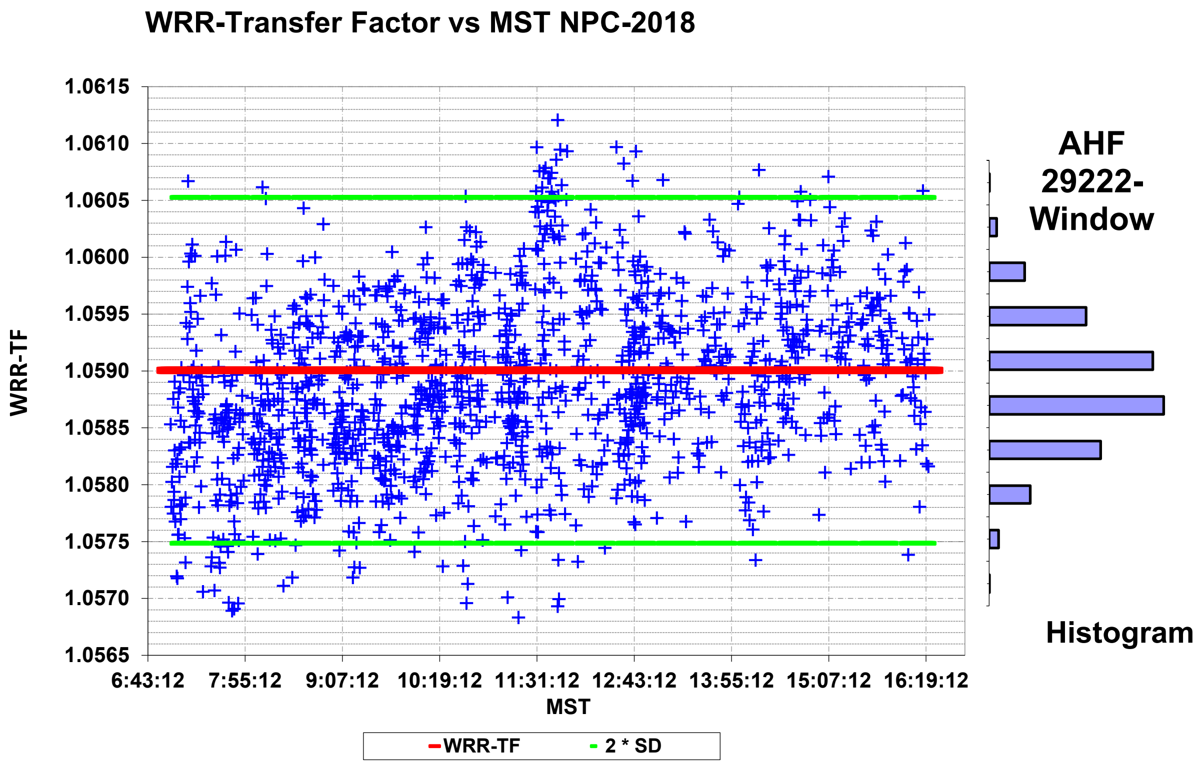

Figure 12. WRR-Transfer Factor vs. MST NPC-2018 for AHF 29222 – Windowed

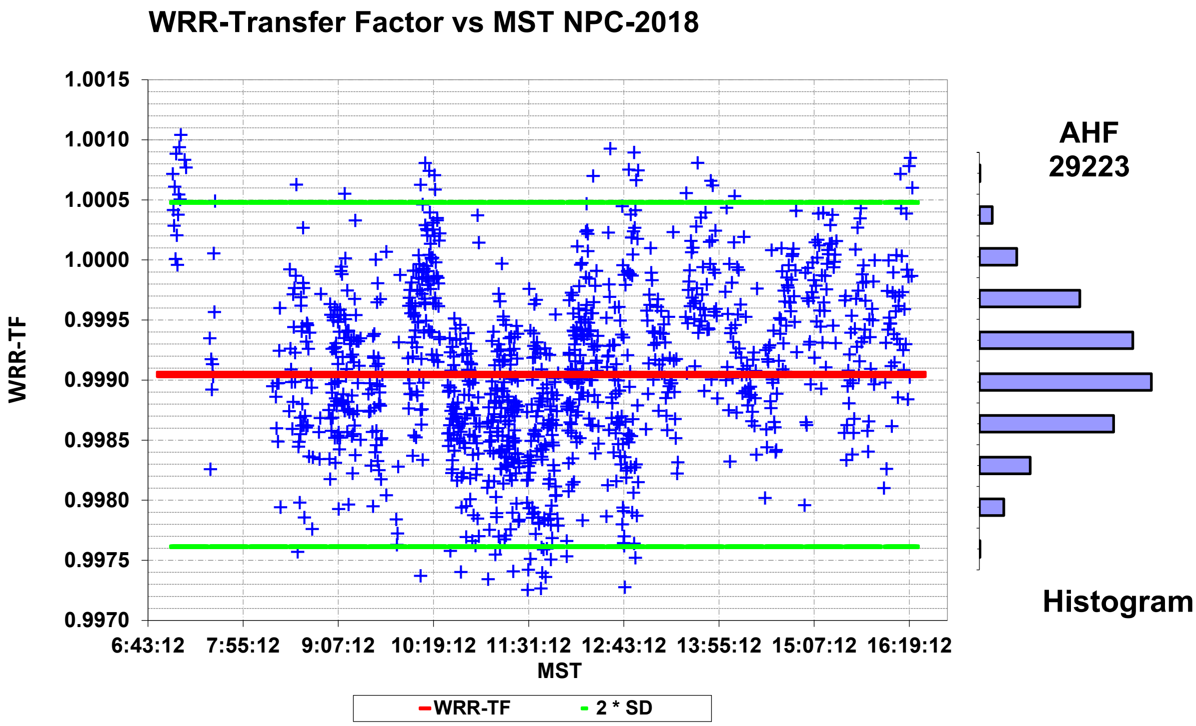

Figure 13. WRR-Transfer Factor vs. MST NPC-2018 for AHF 29223

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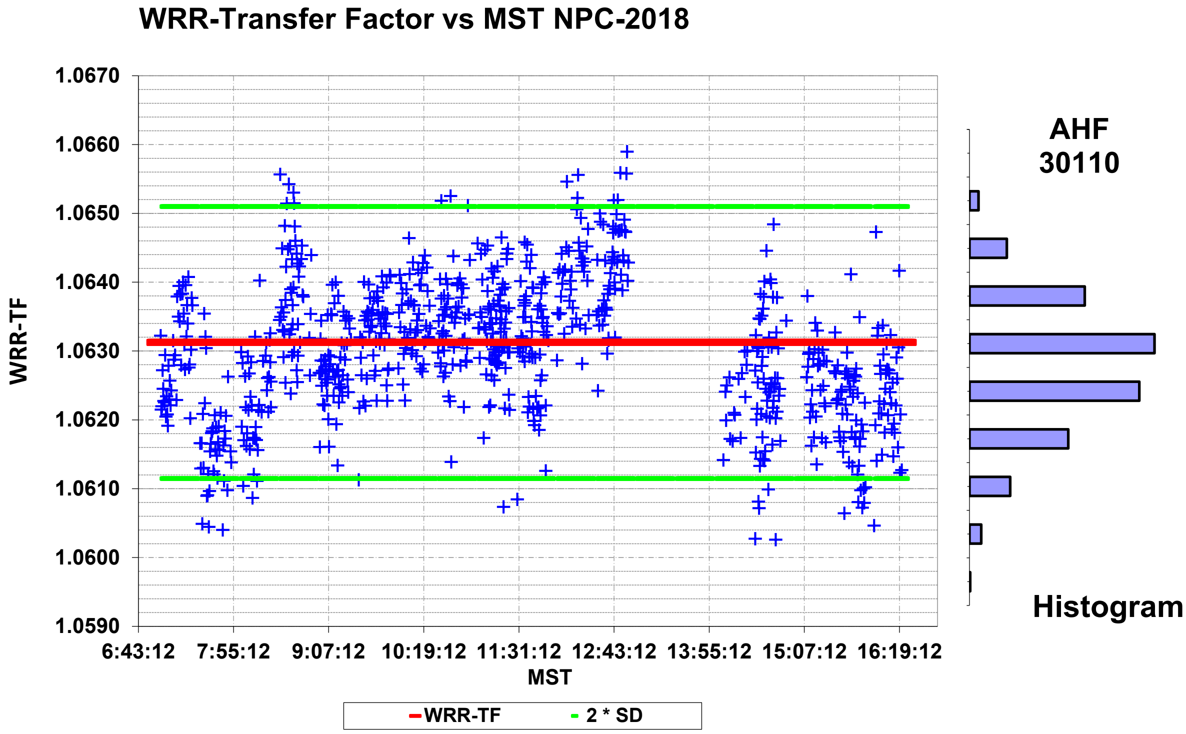

Figure 14. WRR-Transfer Factor vs. MST NPC-2018 for AHF 30110

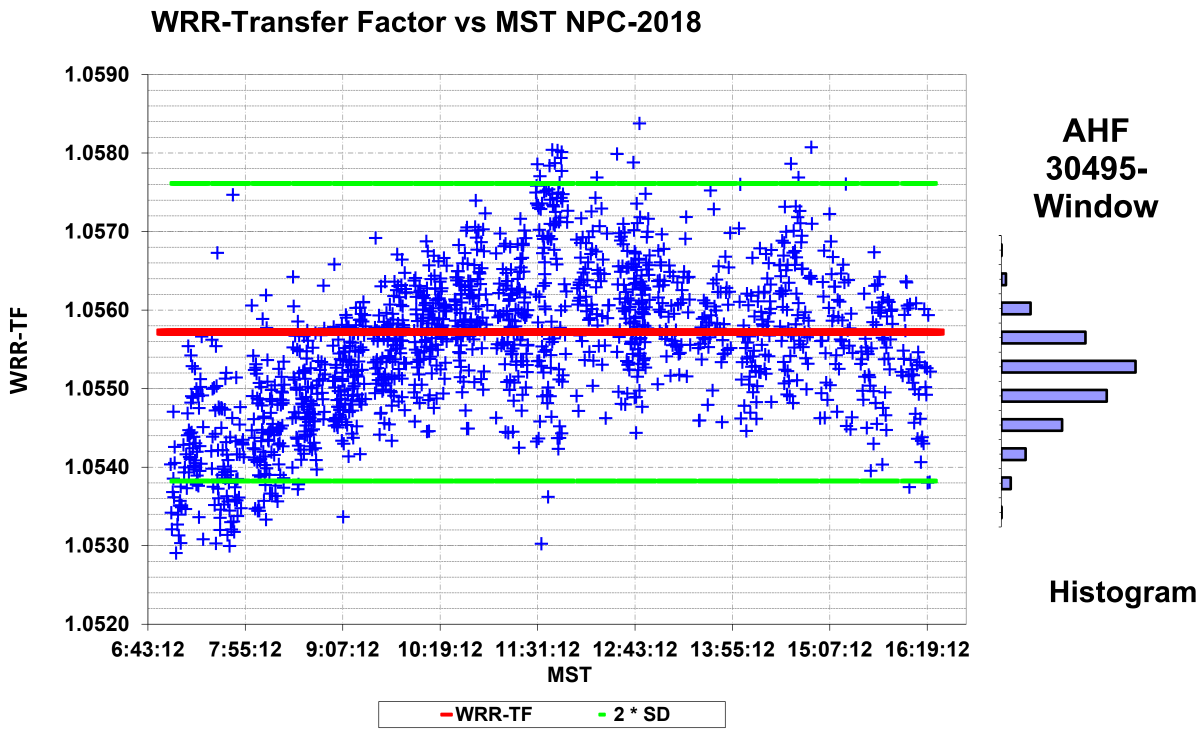

Figure 15. WRR-Transfer Factor vs. MST NPC-2018 for AHF 310495-Window

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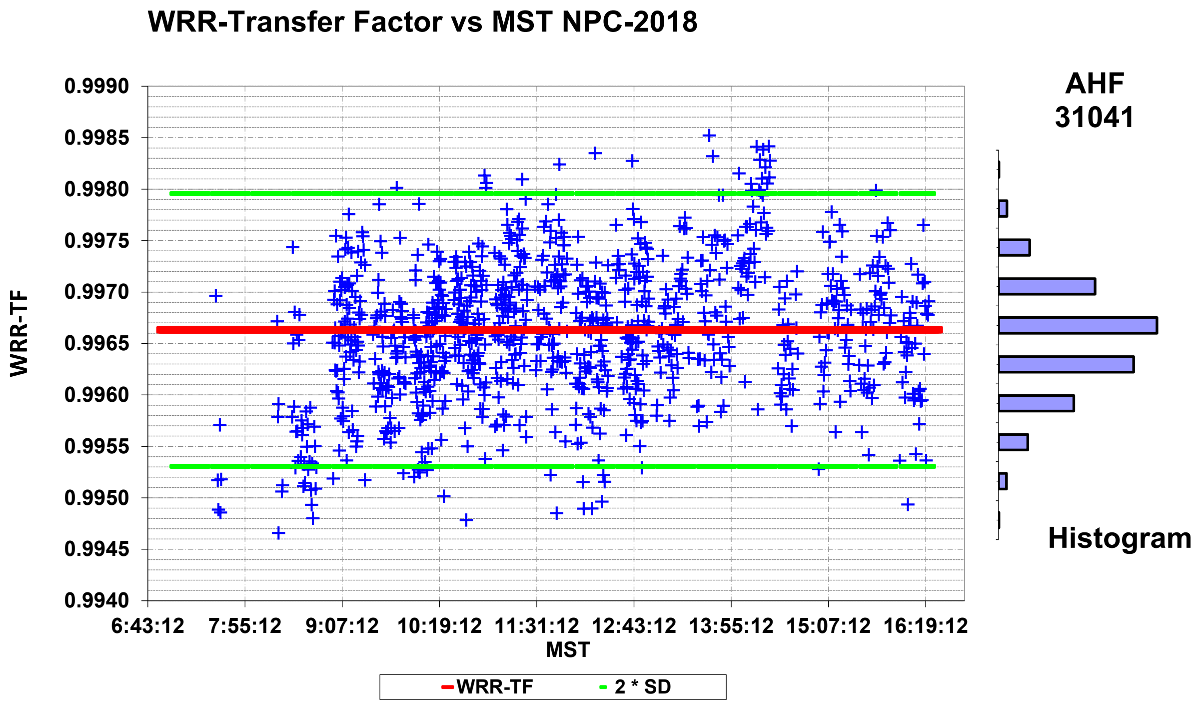

Figure 16. WRR-Transfer Factor vs. MST NPC-2018 for AHF 31041

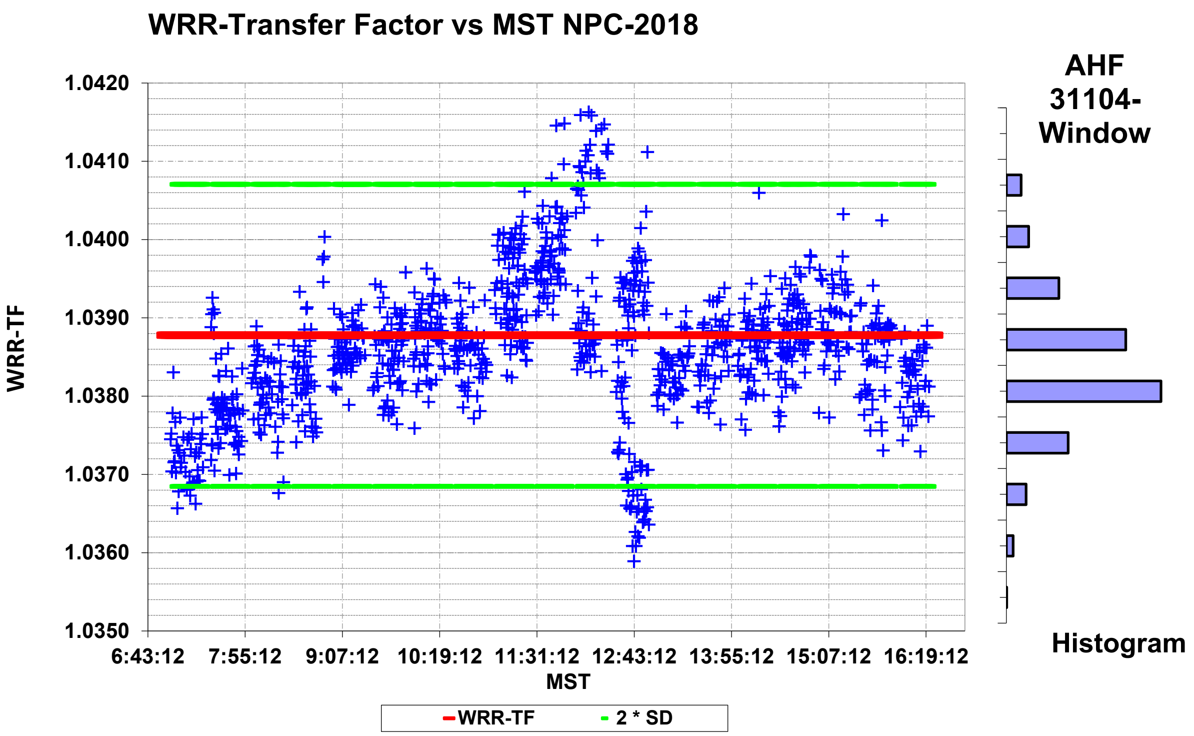

Figure 17. WRR-Transfer Factor vs. MST NPC-2018 for AHF 31104-Window

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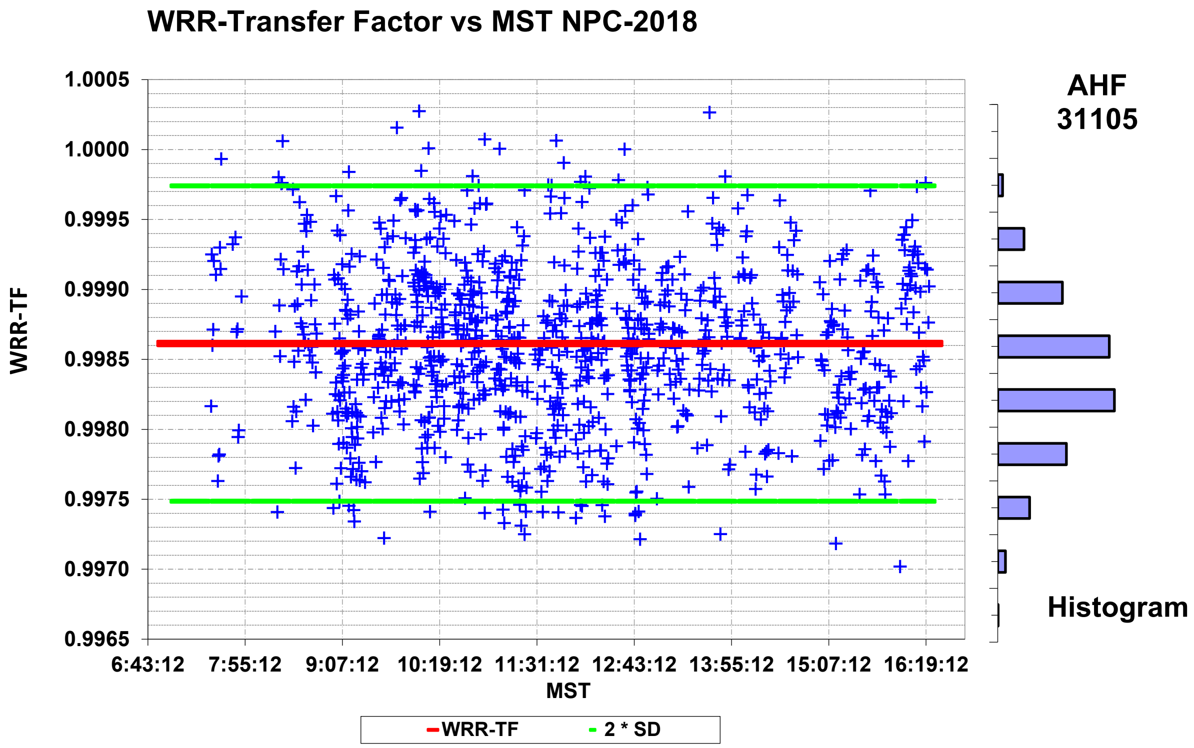

Figure 18. WRR-Transfer Factor vs. MST NPC-2018 for AHF 31105

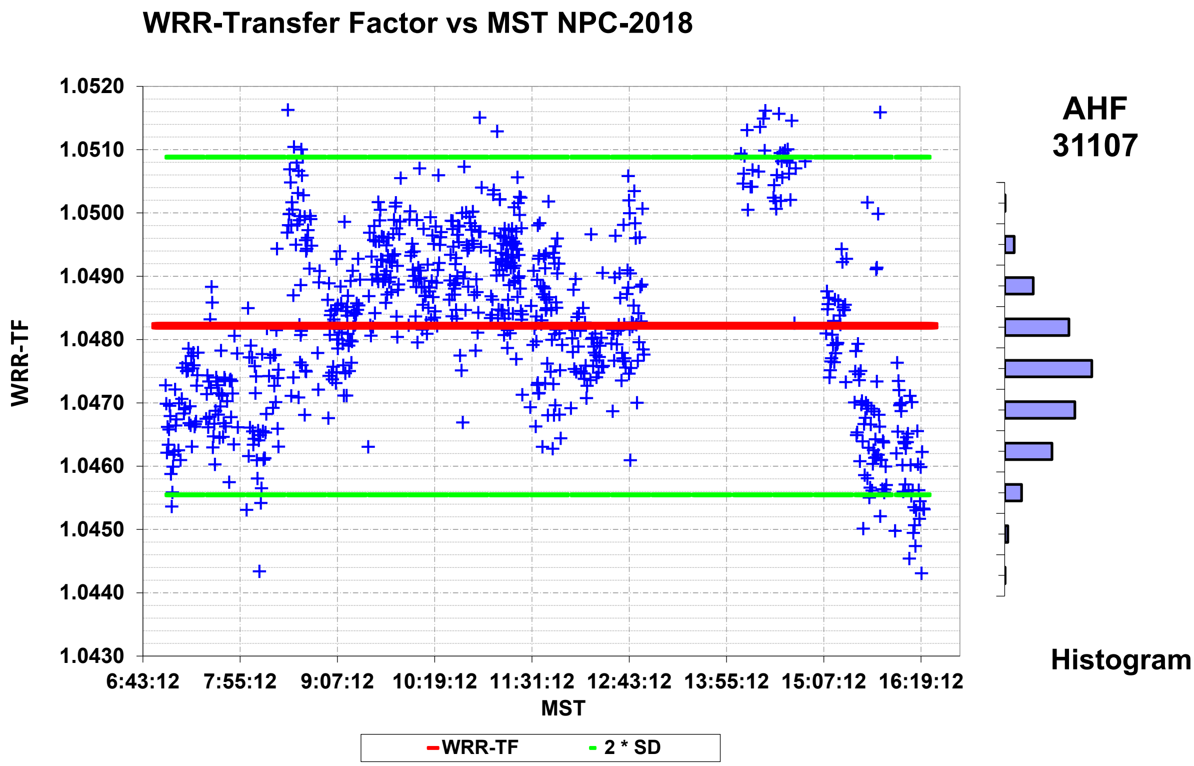

Figure 19. WRR-Transfer Factor vs. MST NPC-2018 for AHF 31107

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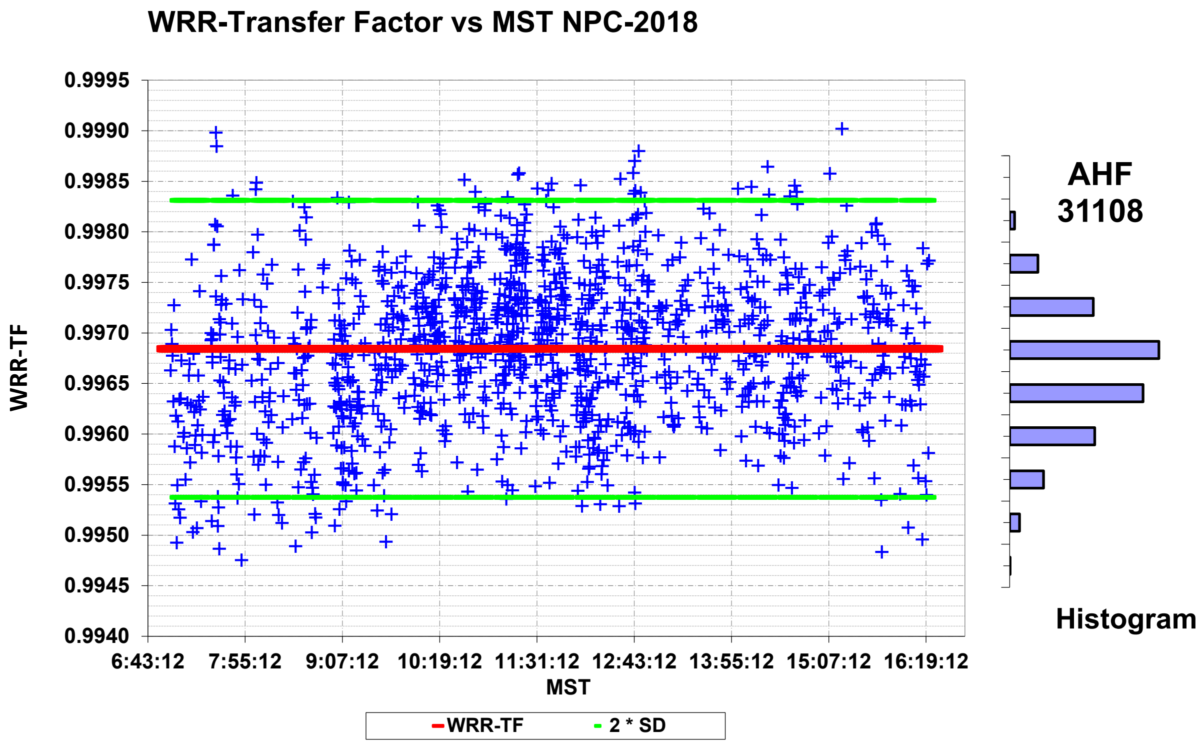

Figure 20. WRR-Transfer Factor vs. MST NPC-2018 for AHF 31108

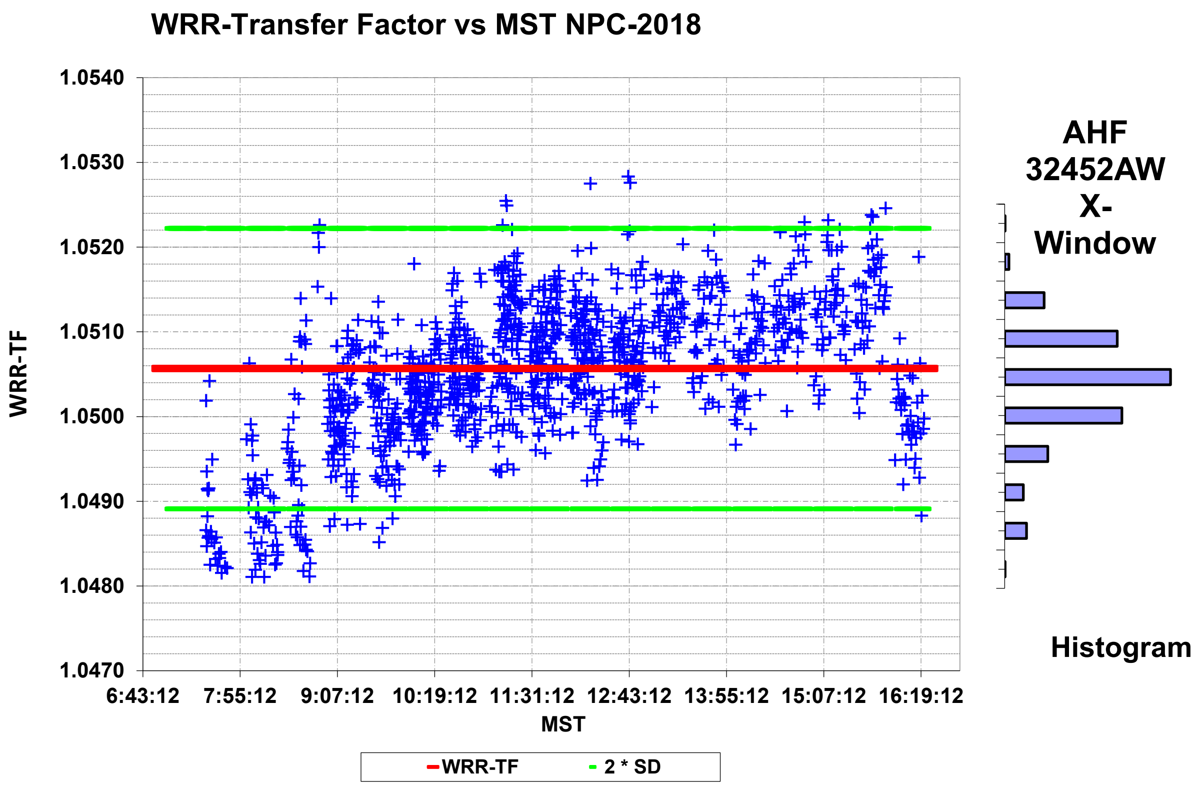

Figure 21. WRR-Transfer Factor vs. MST NPC-2018 for AHF 32452AWX-Window

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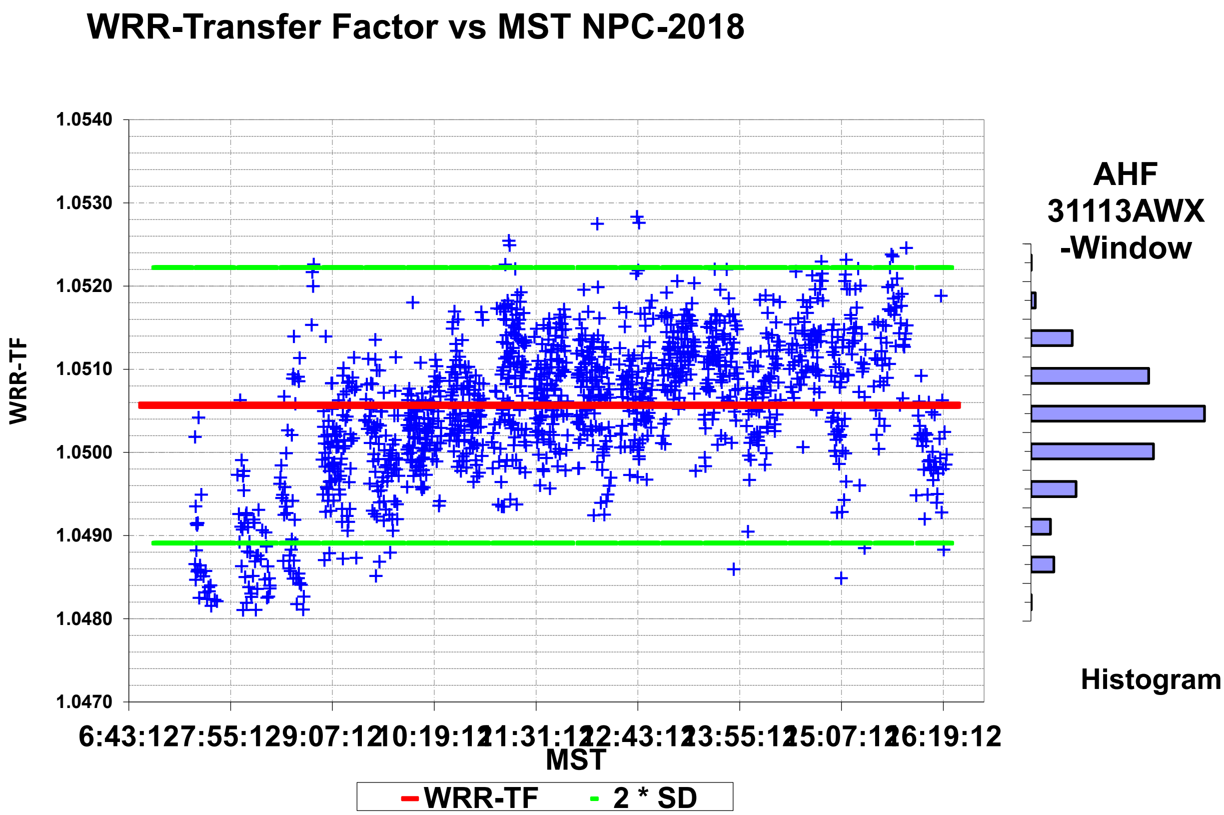

Figure 22. WRR-Transfer Factor vs. MST NPC-2018 for AHF 31113AWX-Window

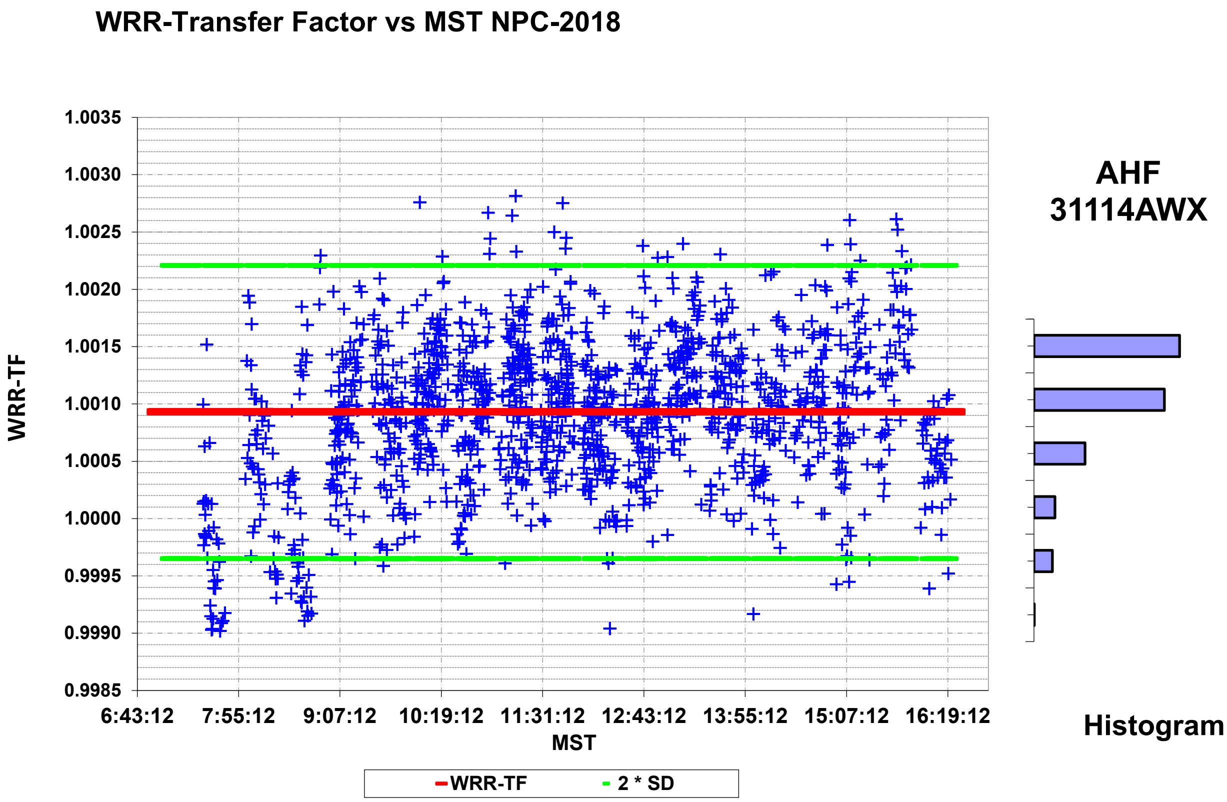

Figure 23. WRR-Transfer Factor vs. MST NPC-2018 for AHF 31114AWX

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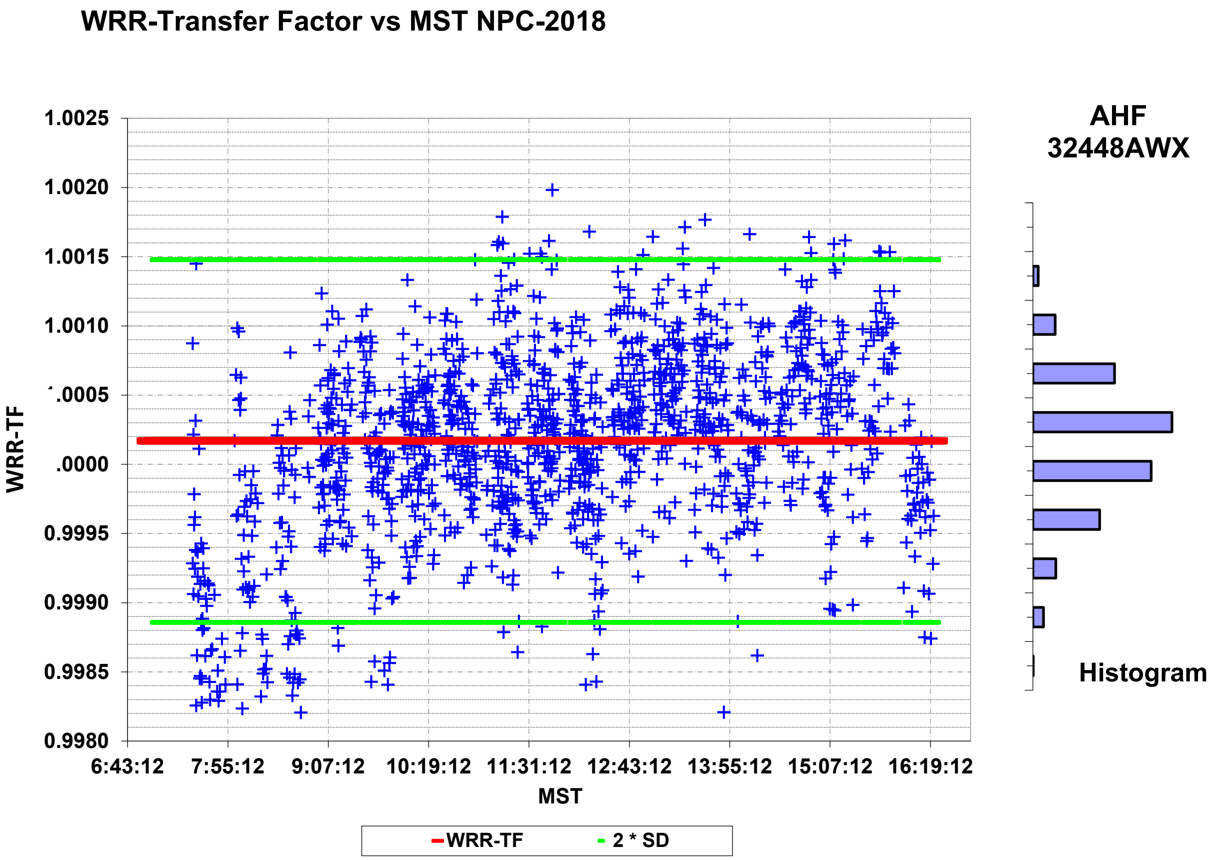

Figure 24. WRR-Transfer Factor vs. MST NPC-2018 for AHF 32448AWX

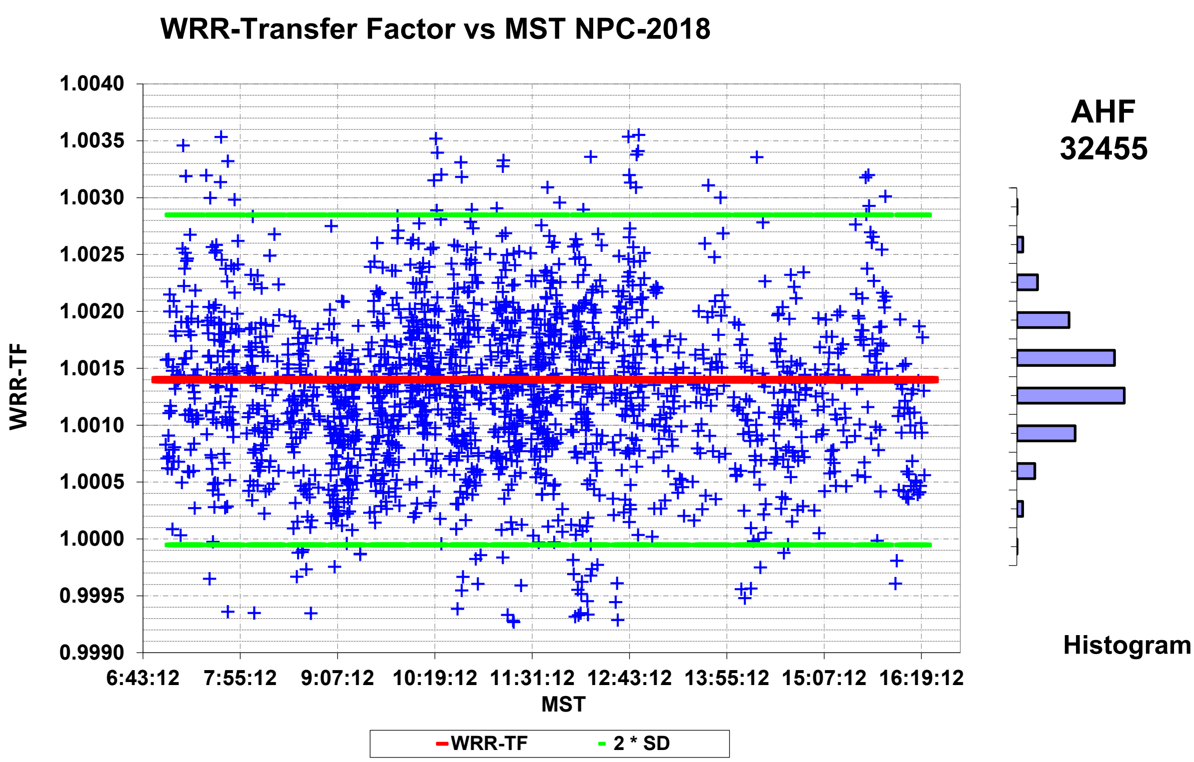

Figure 25. WRR-Transfer Factor vs. MST NPC-2018 for AHF 32455

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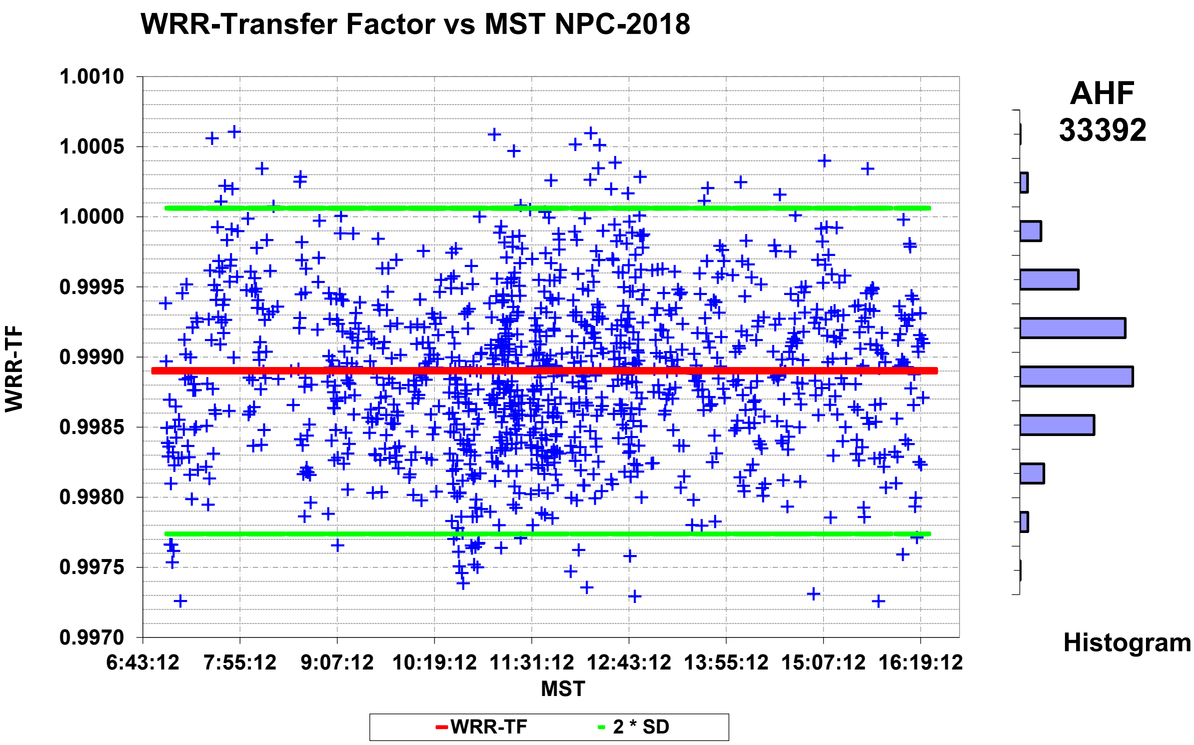

Figure 26. WRR-Transfer Factor vs. MST NPC-2018 for AHF 33392

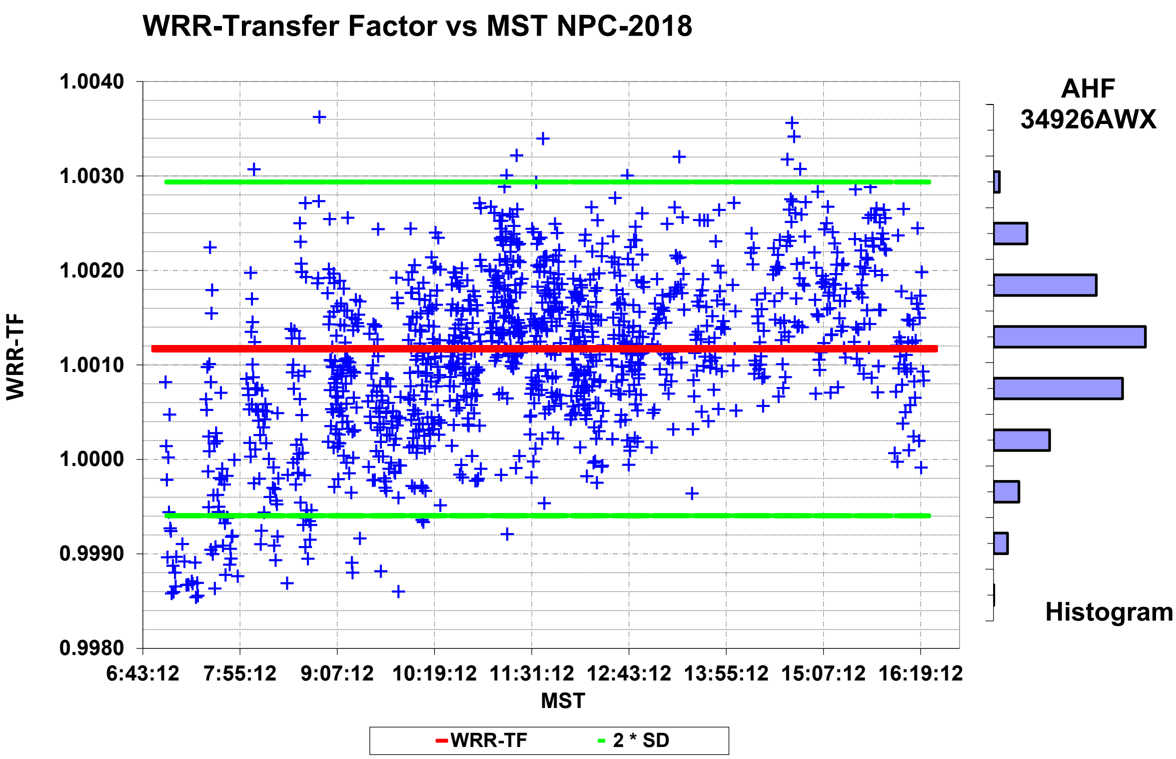

Figure 27. WRR-Transfer Factor vs. MST NPC-2018 for AHF 34926AWX

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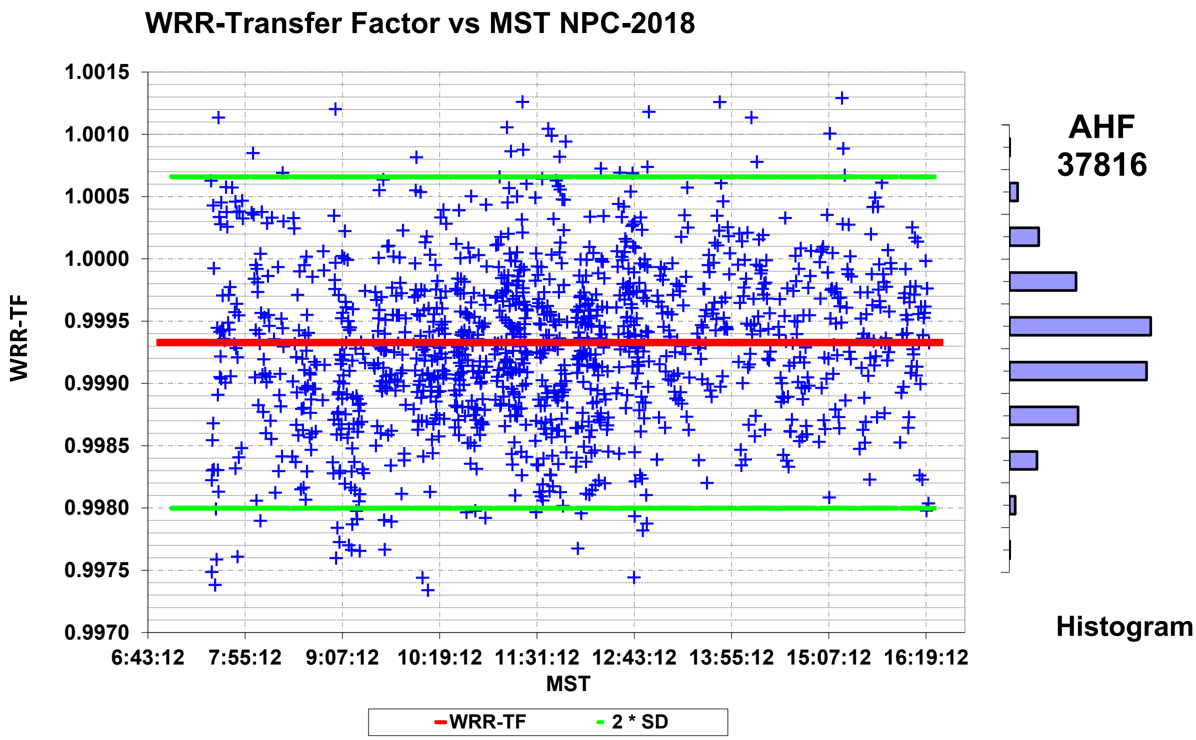

Figure 28. WRR-Transfer Factor vs. MST NPC-2018 for AHF 37816

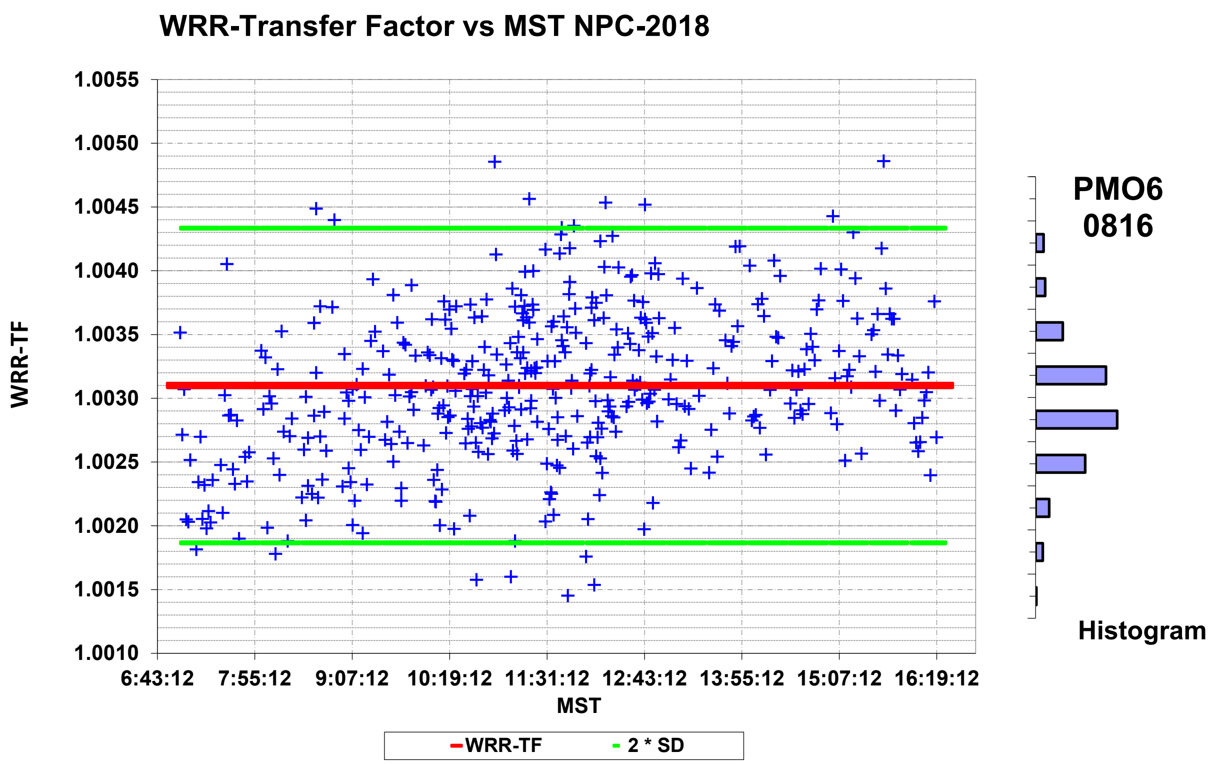

Figure 29. WRR-Transfer Factor vs. MST NPC-2018 for PMO6 0816

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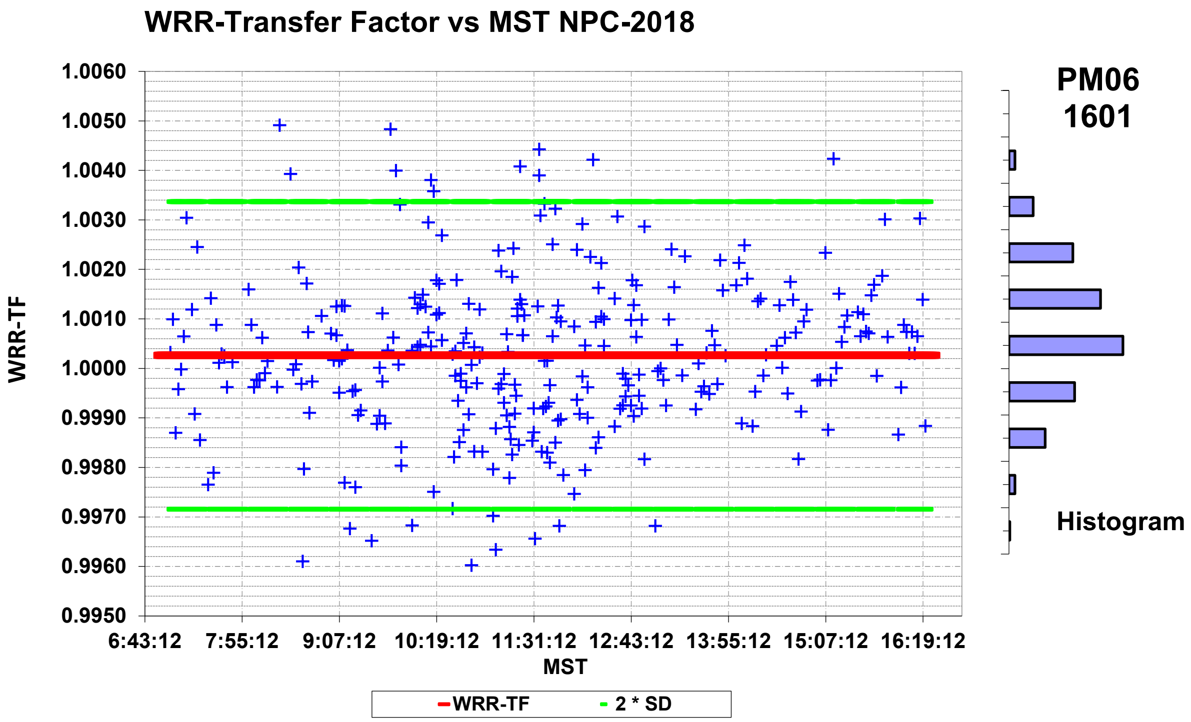

Figure 30. WRR-Transfer Factor vs. MST NPC-2018 for PMO6 1601

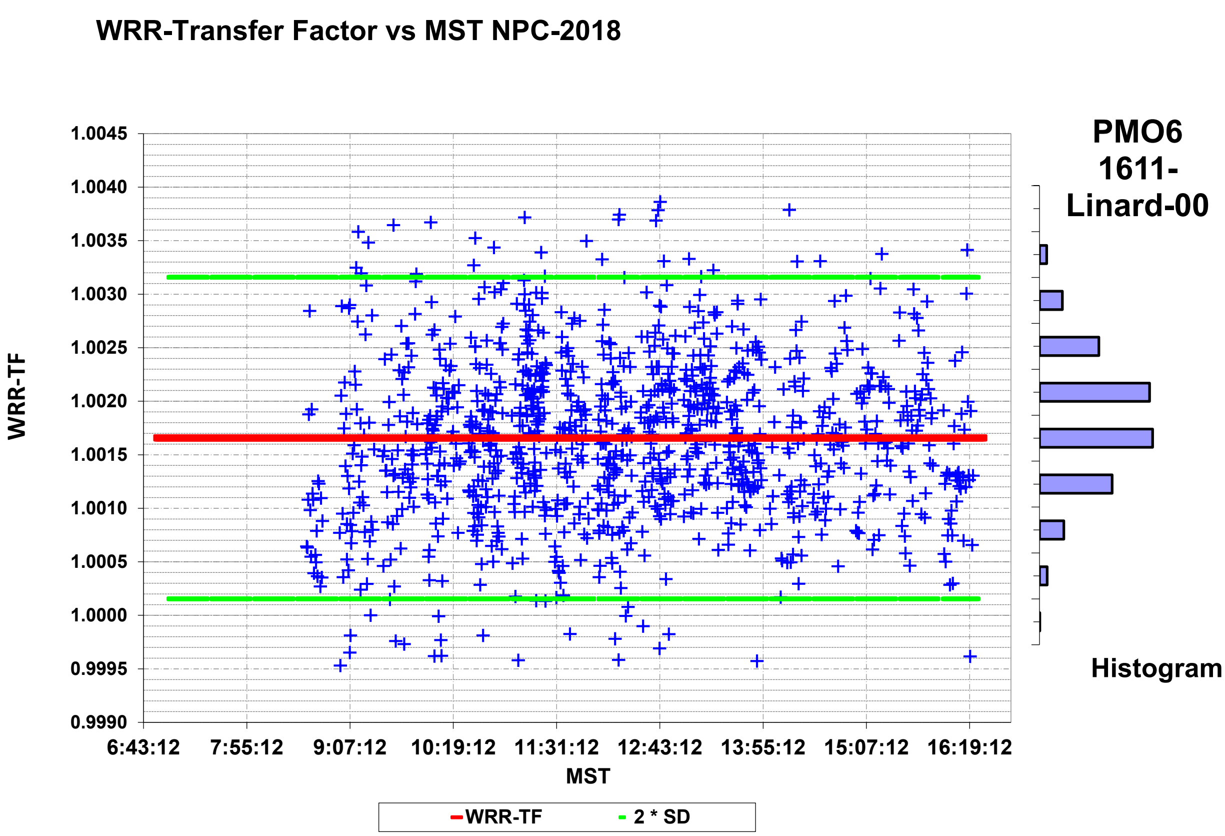

Figure 31. WRR-Transfer Factor vs. MST NPC-2018 for PMO6 1611-Linard-00

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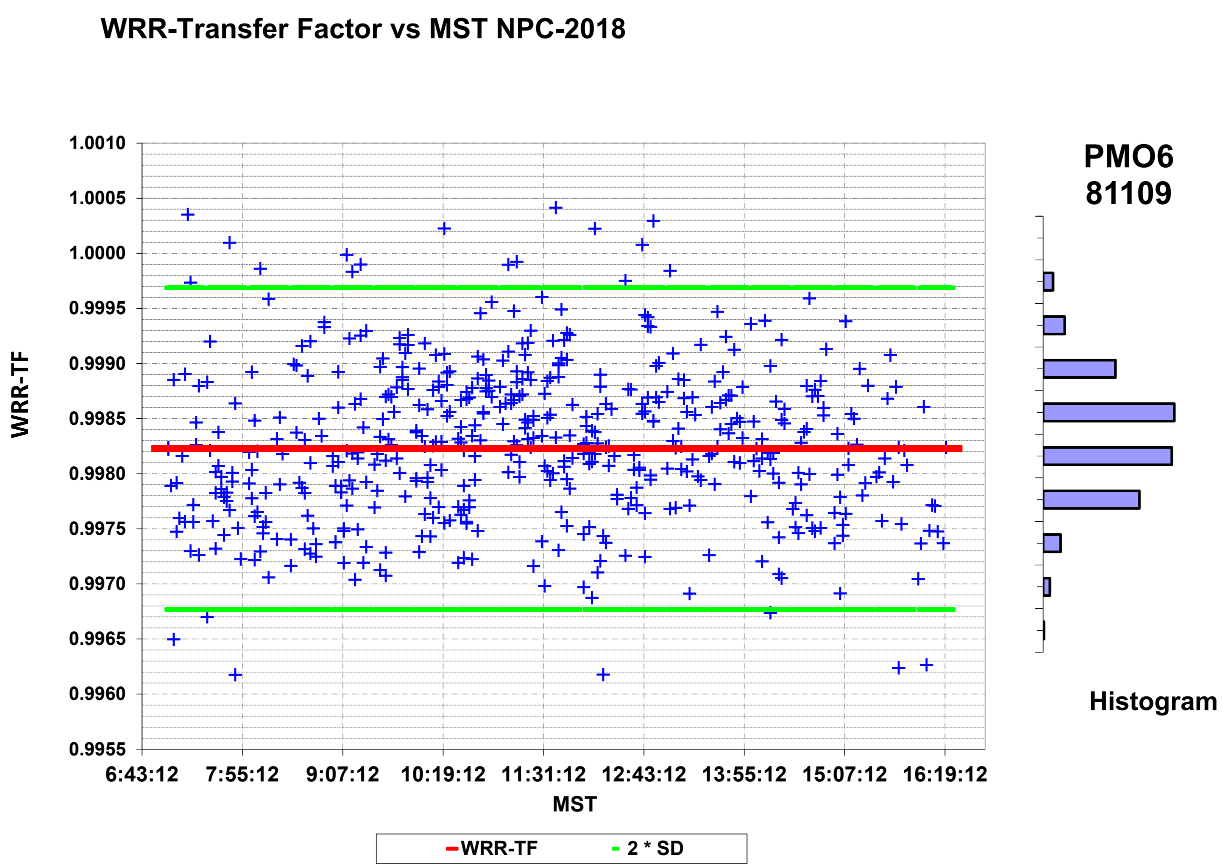

Figure 32. WRR-Transfer Factor vs. MST NPC-2018 for PMO6 81109

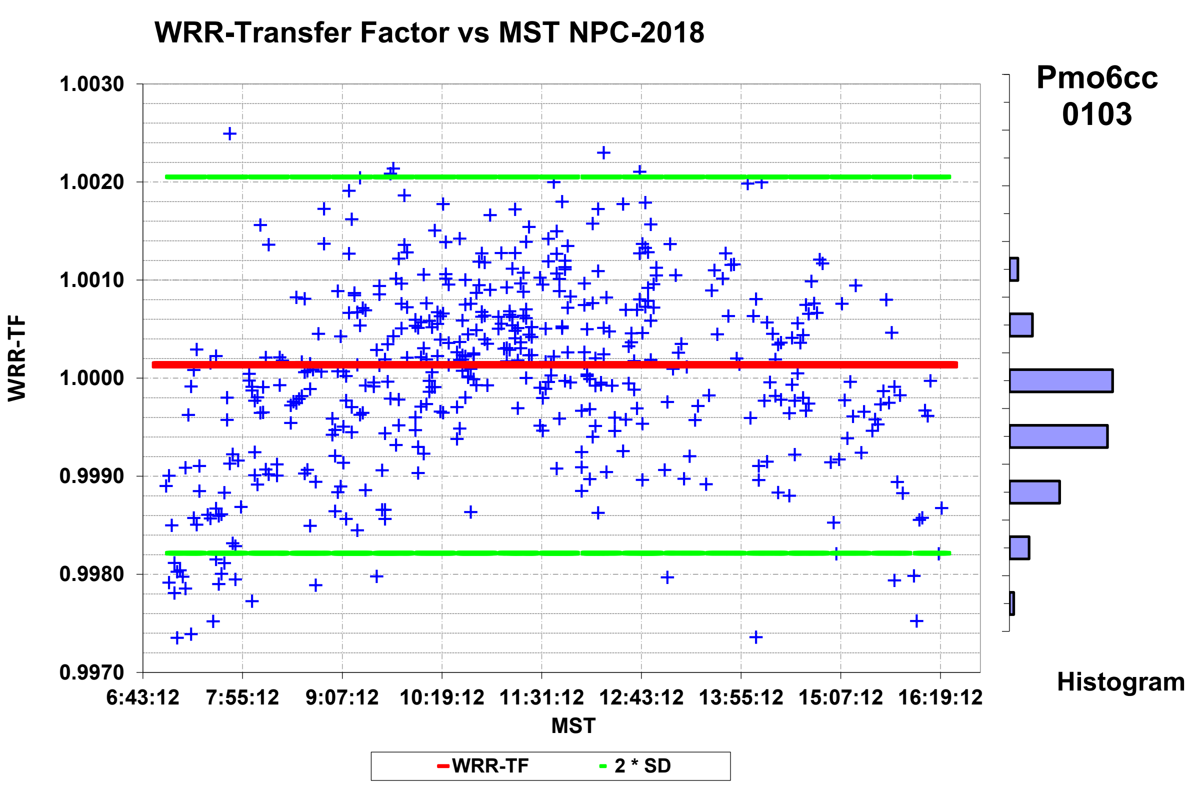

Figure 33. WRR-Transfer Factor vs. MST NPC-2018 for PMO6cc 0103

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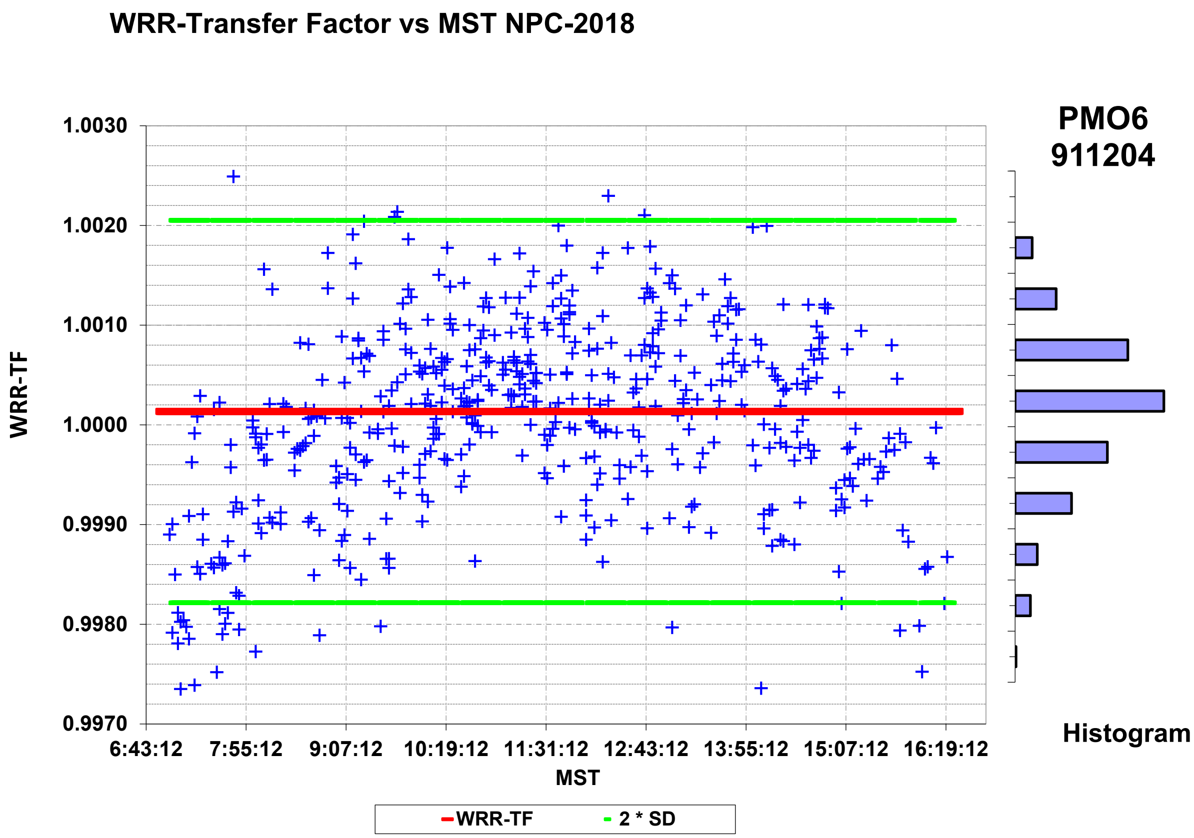

Figure 34. WRR-Transfer Factor vs. MST NPC-2018 for PMO6 911204

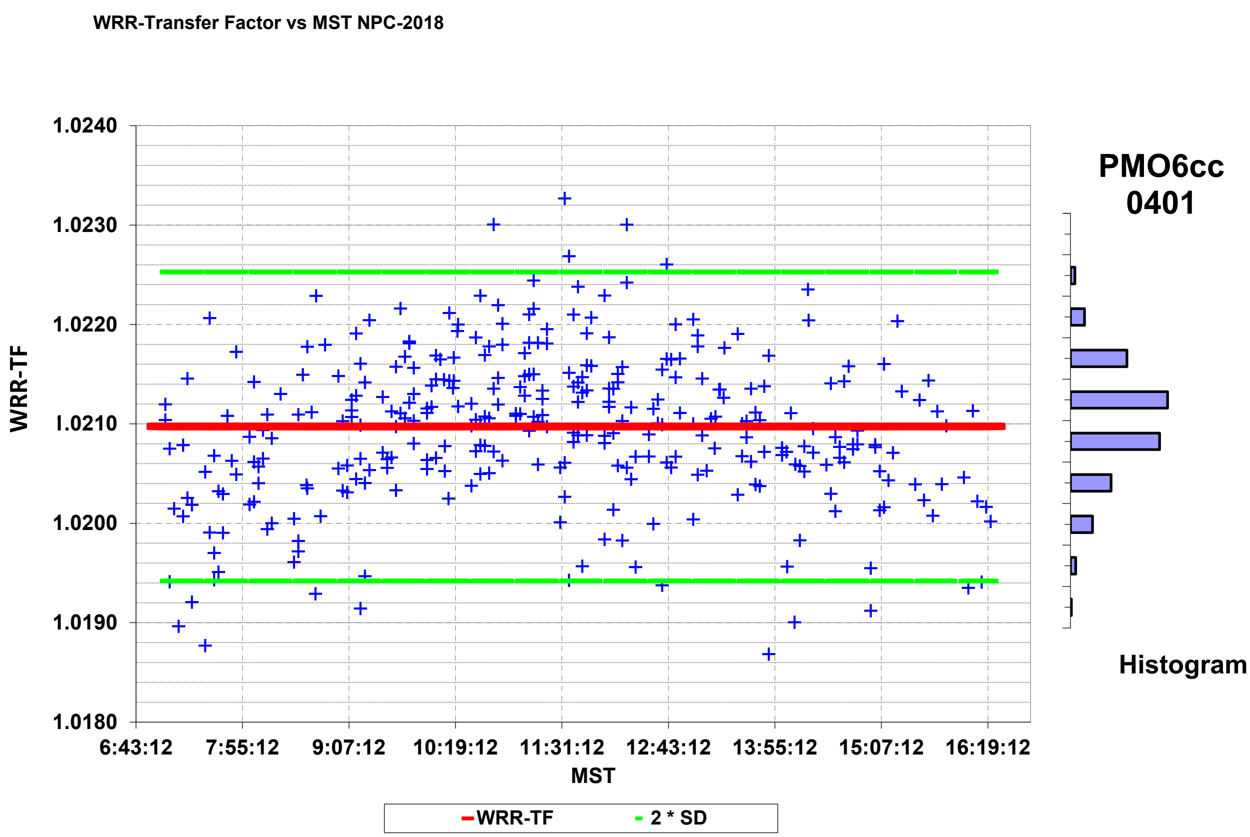

Figure 35. WRR-Transfer Factor vs. MST NPC-2018 for PMO6cc 0401

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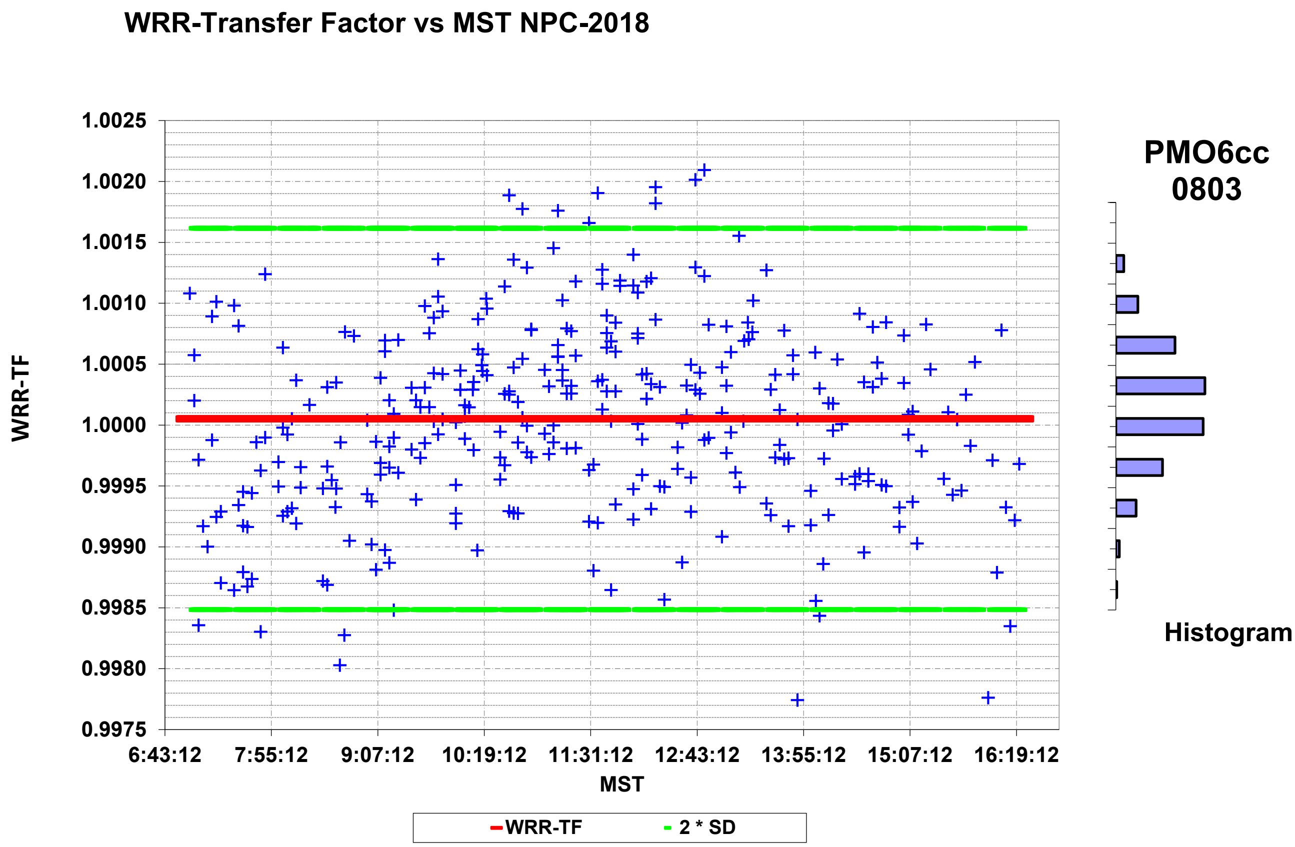

Figure 36. WRR-Transfer Factor vs. MST NPC-2018 for PMO6cc 0803

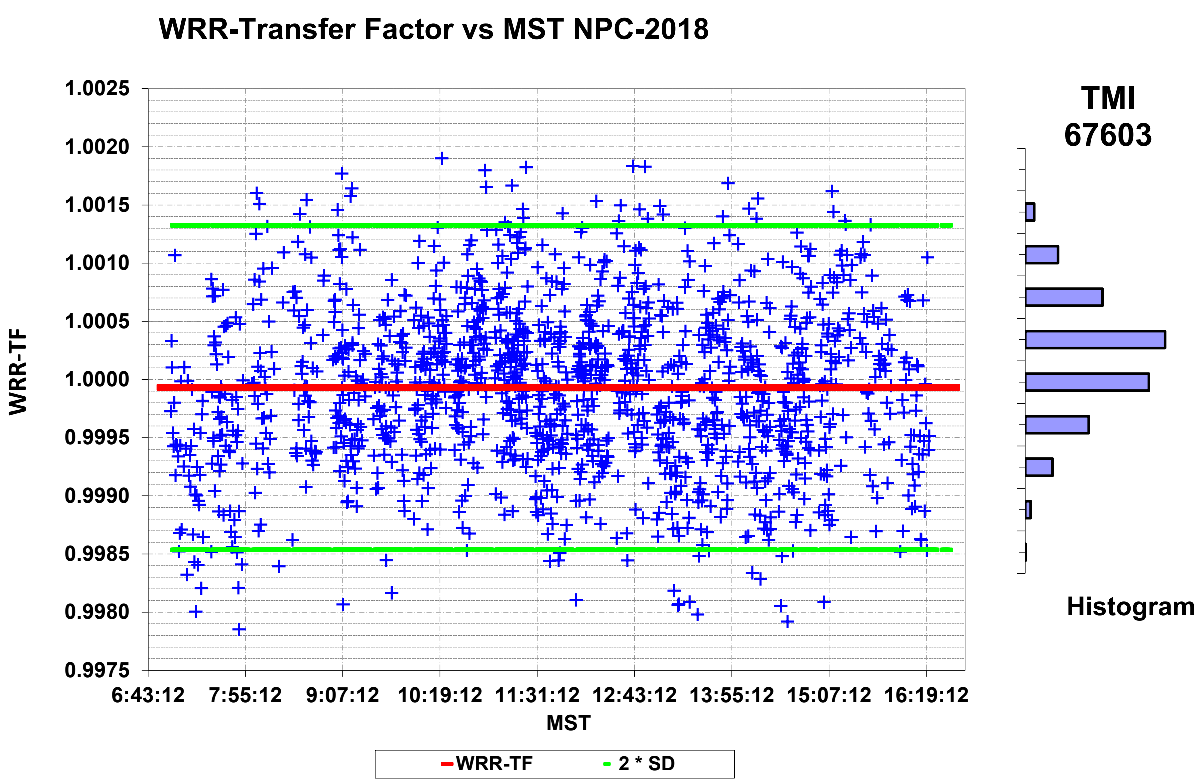

Figure 37. WRR-Transfer Factor vs. MST NPC-2018 for TMI 67603

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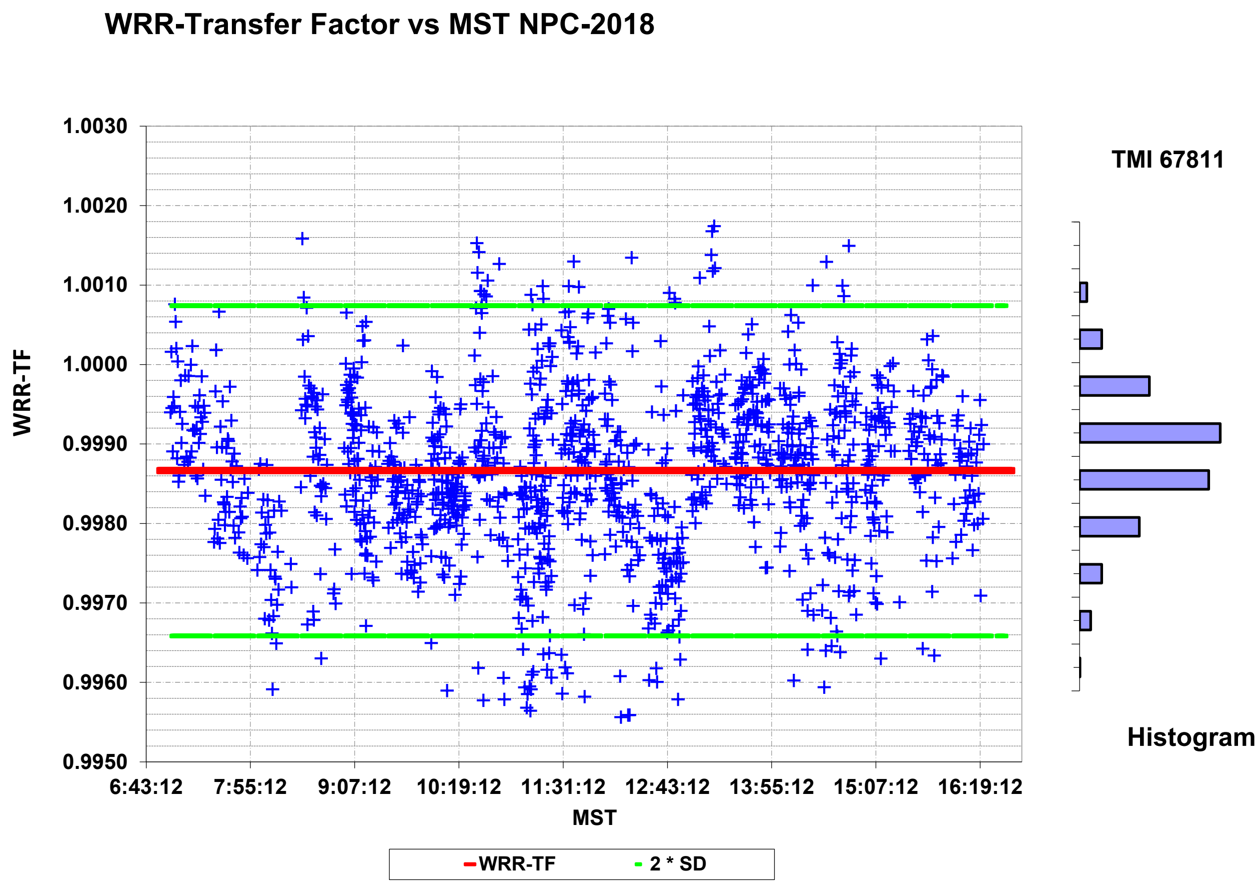

Figure 38. WRR-Transfer Factor vs. MST NPC-2018 for TMI 67811

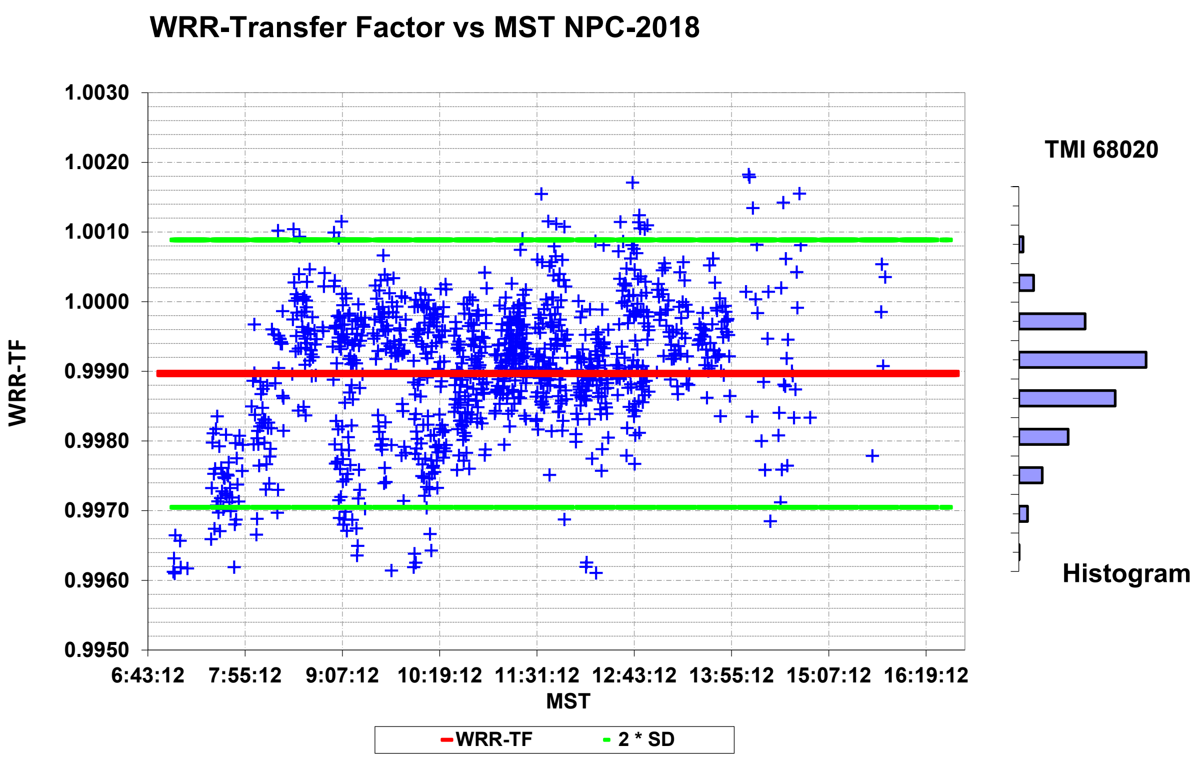

Figure 39. WRR-Transfer Factor vs. MST NPC-2018 for TMI 68020

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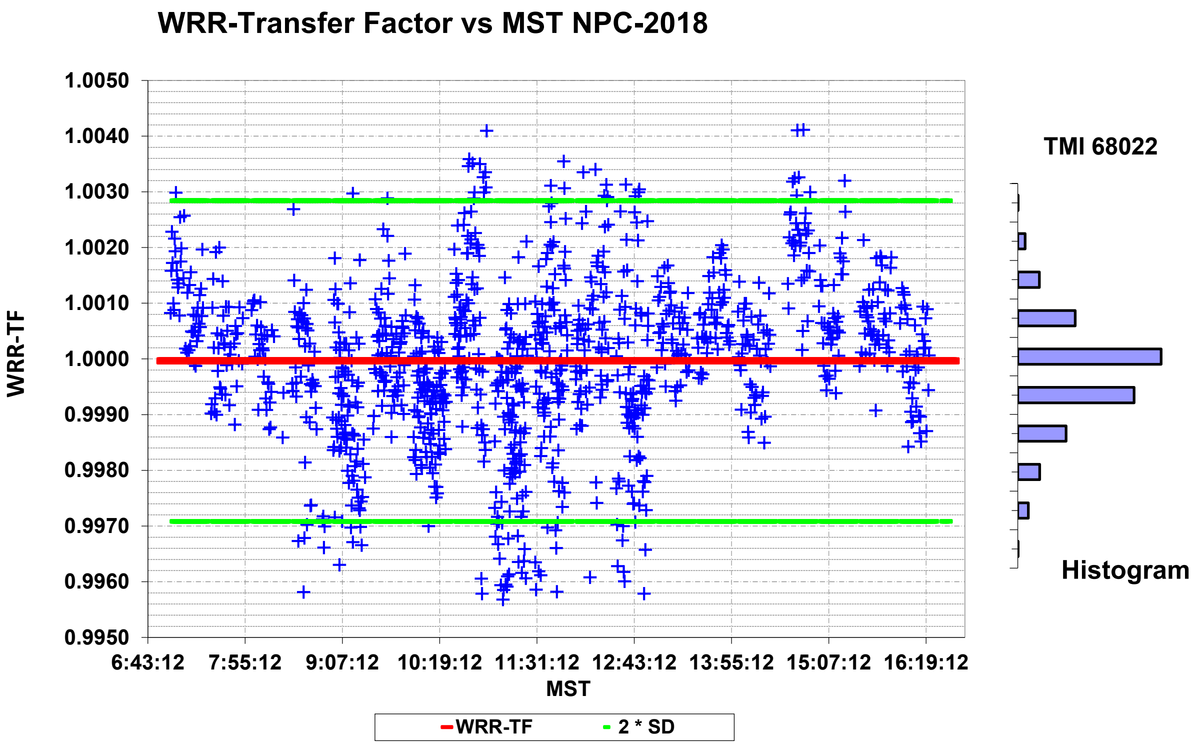

Figure 40. WRR-Transfer Factor vs. MST NPC-2018 for TMI 68022

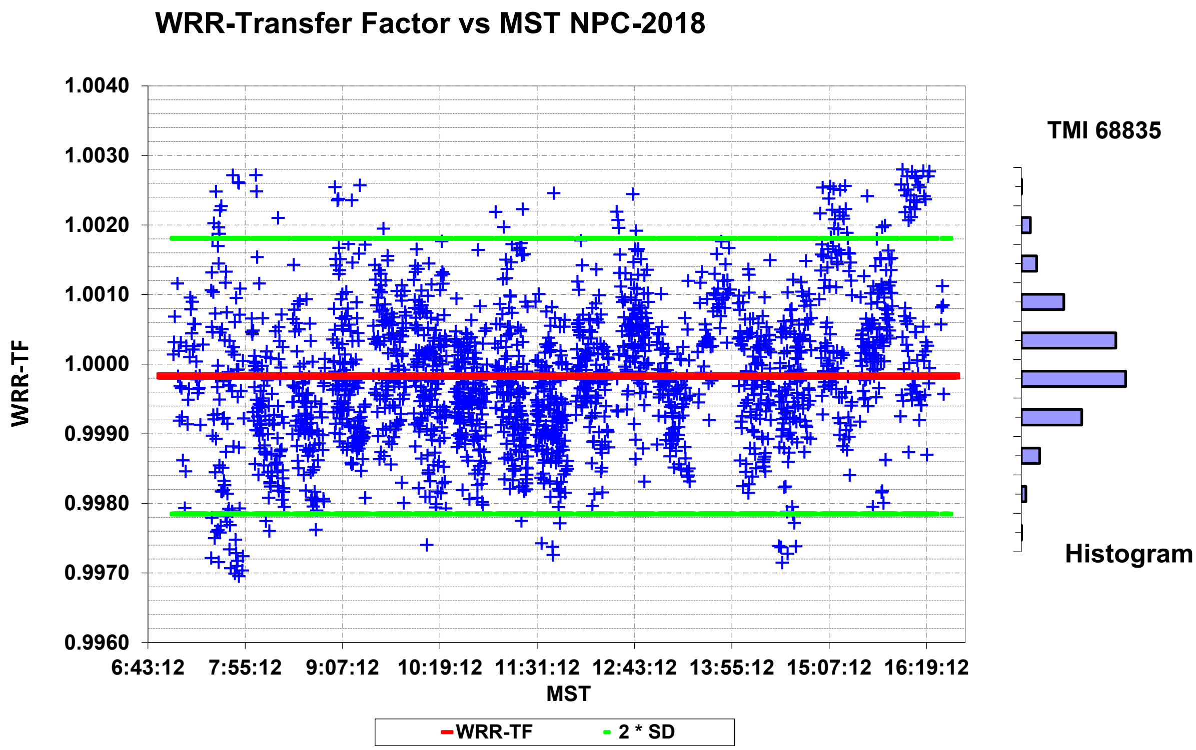

Figure 41. WRR-Transfer Factor vs. MST NPC-2018 for TMI 68835

4.6 Recommendations

As a result of these comparisons, it is suggested that participants observe the following measurement practices:

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- For the purpose of pyrheliometer comparisons, such as NPC-2018, it is recommended that 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. This 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. This approach is recommended to realize the benefits of participating in the NPC.

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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 comparisons using the meteorological station at SRRL. Additional information, including data and graphical summaries, can be found at the Measurements and Instrumentation Data Center: www.nrel.gov/midc/srrl_bms.

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

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Appendix A: List of Participants and Pyrheliometers

S/N	**Operator 1**	**Operator 2**	**Affiliation**
AHF 29223	Adriana Gonzalez		UNAM
AHF 23734	Afshin Andreas	Mike Dooraghi	National Renewable Energy Laboratory (NREL) (Metrology, SePA, and Cell & Module Certification Group)
AHF 29219-Window	Afshin Andreas	Mike Dooraghi	NREL (Metrology, SePA, and Cell & Module Certification Group)
AHF 31104-Window	Afshin Andreas	Mike Dooraghi	NREL (Metrology, SePA, and Cell & Module Certification Group)
AHF 32452AWX-Window	Afshin Andreas	Mike Dooraghi	NREL (Metrology, SePA, and Cell & Module Certification Group)
PM06 1601	Ajay Singh	Matt Perry	Campbell Scientific Inc.
PMO6 0816	Akiyama Akihito	Will Beuttell	EKO Instruments
AHF 33392	Anthony Bucholtz		Naval Research Laboratory
AHF 31108	Bill Boyson	Charles Robinson	Sandia National Laboratories (Photovoltaic Systems Evaluation Lab)
TMI 67603	Bill Boyson	Charles Robinson	Sandia National Laboratories (Photovoltaic Systems Evaluation Lab)
AHF 32455	Christian Thomann		PMOD/WRC
PMO6cc 0401	Christian Thomann		PMOD/WRC
PMO6cc 0803	Christian Thomann		PMOD/WRC
AHF 29222-Window	Craig Webb		DOE Atmospheric Radiation Measurement (ARM) Program
AHF 30495-Window	Craig Webb		DOE Atmospheric Radiation Measurement (ARM) Program
AHF 28553	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
S/N	**Operator 1**	**Operator 2**	**Affiliation**
AHF 31113AWX-Window	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD

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AHF 31114AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 32448AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 28560	Erik Naranen		ISO-CAL North America, LLC
AHF 37816	Erik Naranen		ISO-CAL North America, LLC
AHF 31041	Fred Denn		Science Systems & Applications, Inc.
AHF 31105	Fred Denn		Science Systems & Applications, Inc.
AHF28968	Ibrahim Reda	Mike Dooraghi	NREL (Metrology and SePA)
AHF29220	Ibrahim Reda	Mike Dooraghi	NREL (Metrology and SePA)
AHF30713	Ibrahim Reda	Mike Dooraghi	NREL (Metrology and SePA)
TMI68018	Ibrahim Reda	Mike Dooraghi	NREL (Metrology and SePA)
TMI 68020	Jim Goza	Gian Mazzadi-Smith	Lockheed Martin
AHF 28486	Jose Balenzategui		CIEMAT
AHF 34926AWX	Josh Peterson		SRML University of Oregon
PMO6 1611-Linard-00	Markus Suter		Davos Instruments
AFH 30110	Mohammed Al Harbi		King Abdullah City for Atomic and Renewable Energy (KACARE)
AHF 31107	Mohammed Al Harbi		King Abdullah City for Atomic and Renewable Energy (KACARE)
AHF 17142	Patrick Smith		Atlas Material Testing Technology, LLC
AHF 28556	Patrick Smith		Atlas Material Testing Technology, LLC
TMI 67811	Tim Moss	Alan Nelson	Sandia National Labs (Concentrating Solar Energy)

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S/N	Operator 1	Operator 2	Affiliation
TMI 68022	Tim Moss	Alan Nelson	Sandia National Labs (Concentrating Solar Energy)
AHF 14915	Tom Kirk		EPPLEY LAB
Pmo6cc 0103	Victor Cassella	Joop Mes	Kipp & Zonen USA, Inc
AHF 0000	Wim Zaaiman		European Commission Directorate General JRC
PMO6 81109	Wim Zaaiman		European Commission Directorate General JRC
PMO6 911204	Wim Zaaiman		European Commission Directorate General JRC
TMI 68835	Wim Zaaiman		European Commission Directorate General JRC

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Appendix B: Ancillary Data Summaries

The measurement performance of an absolute cavity can be affected by several environmental parameters. Potentially relevant meteorological data collected during the NPC are presented in this appendix. The BMS has been in continuous operation at the SRRL since 1981. BMS data are recorded as 1-minute averages of 3-second samples for each instrument. (Additional information about SRRL and the BMS can be found at the Measurement and Instrumentation Data Center: http://www.nrel.gov/midc/srrl_bms/).

Time-series plots and other graphical presentations of these data acquired during the NPC-2018 measurements are presented here.

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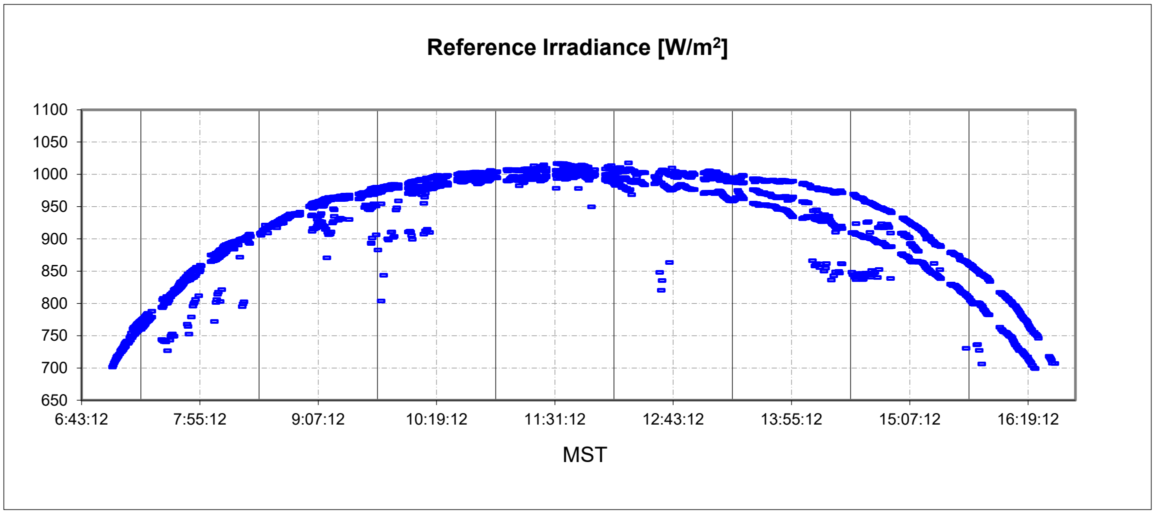

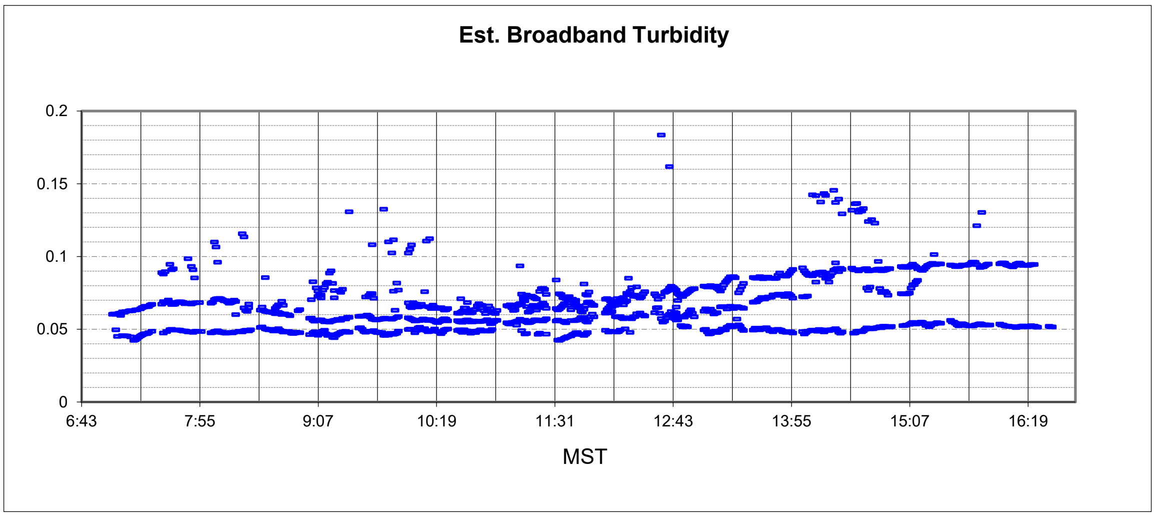

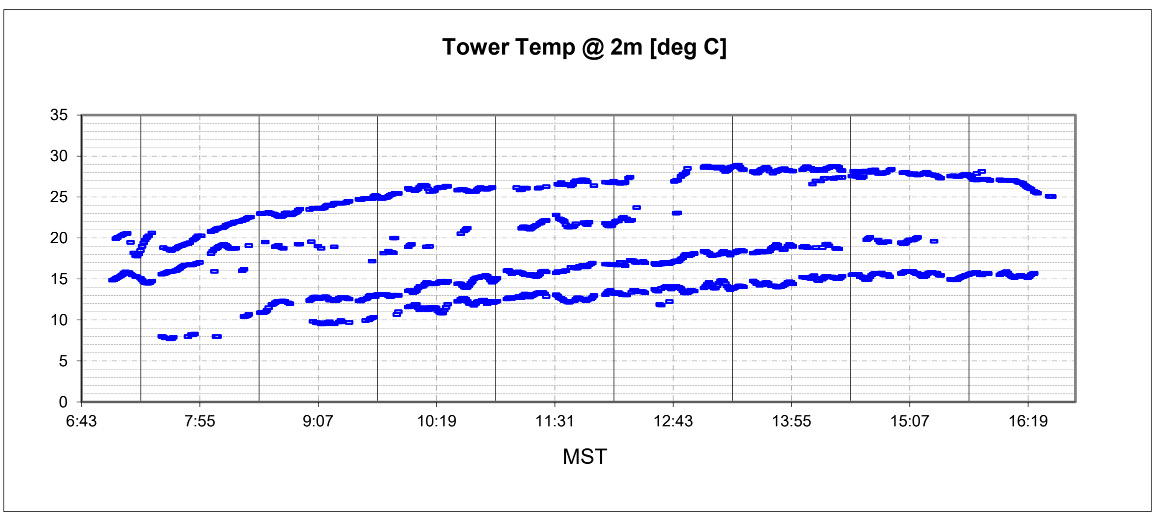

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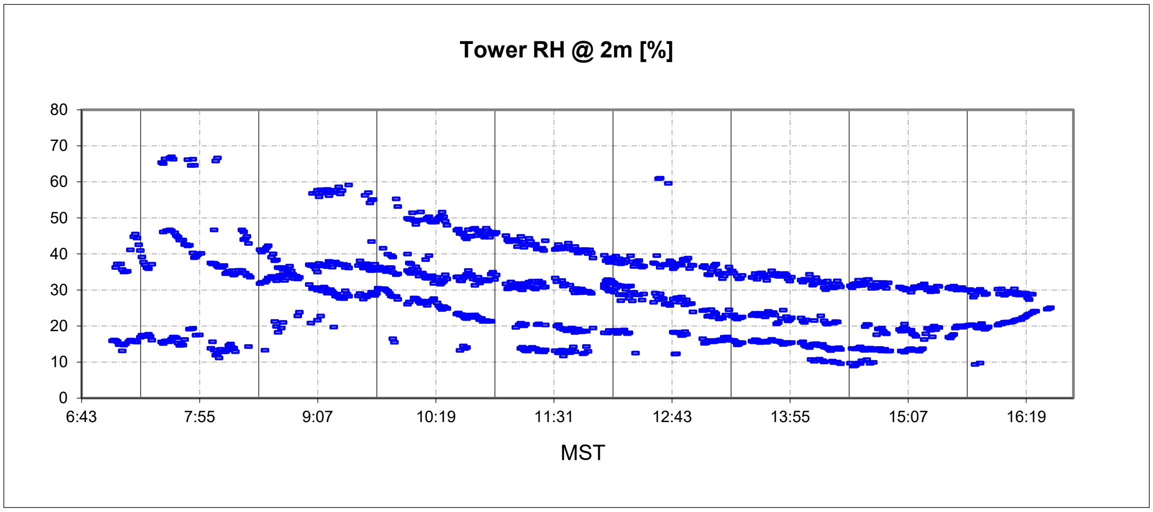

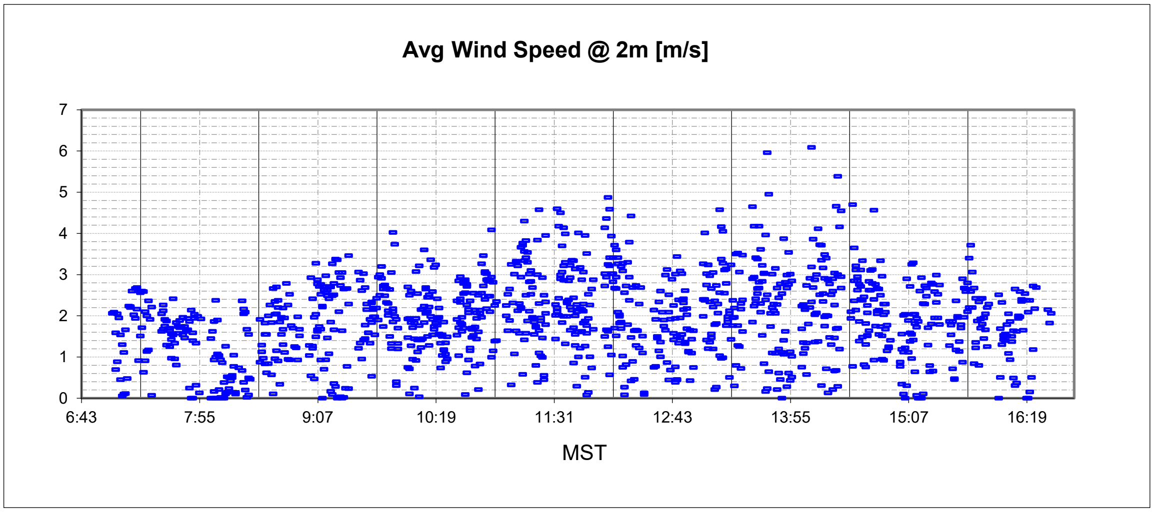

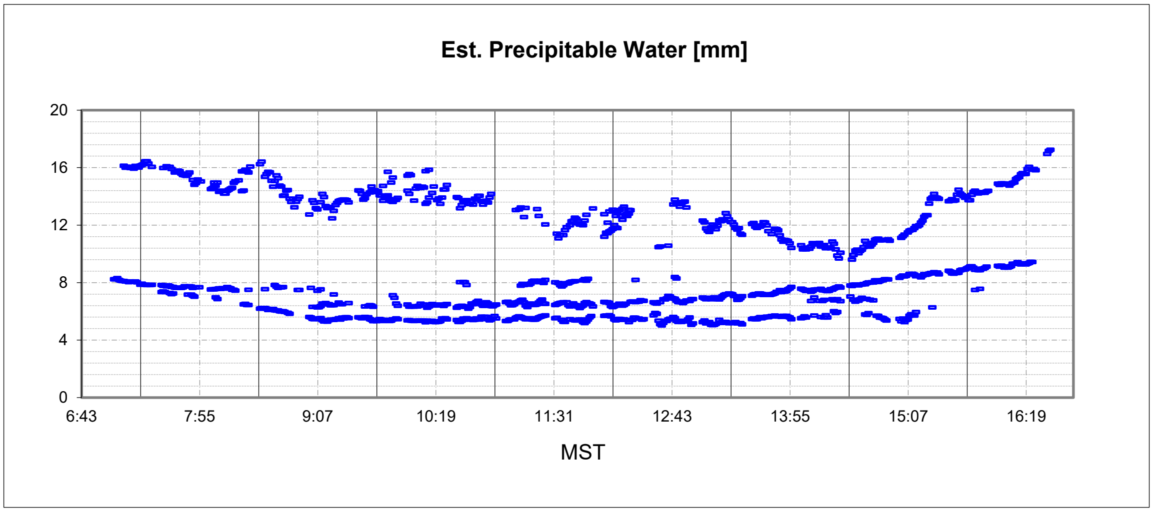

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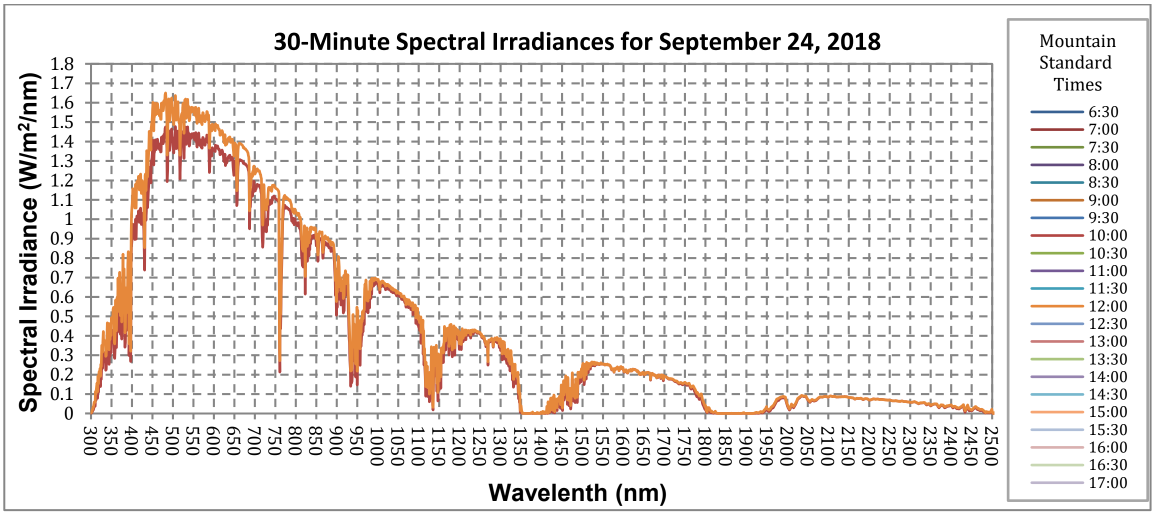

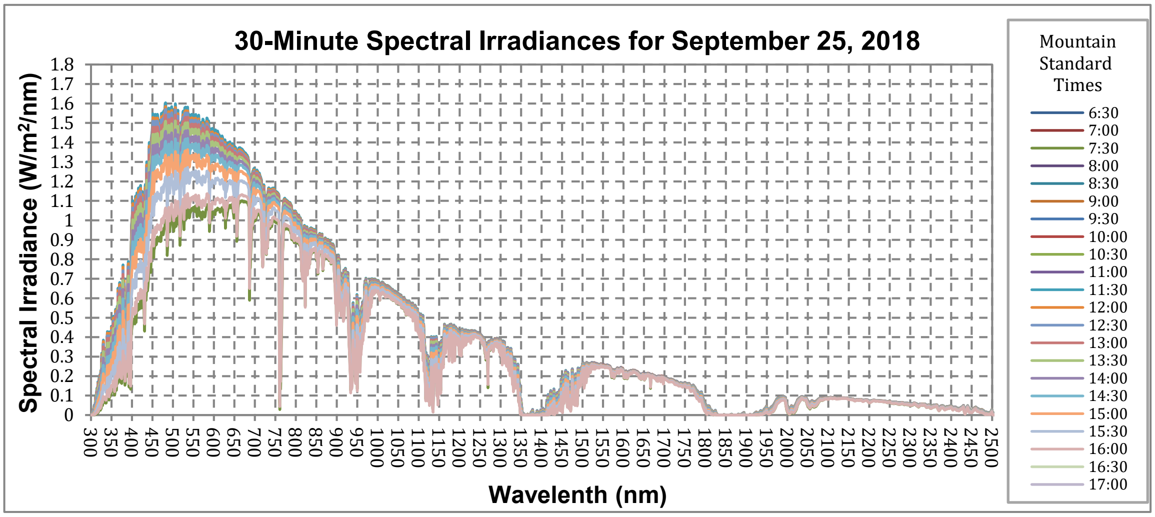

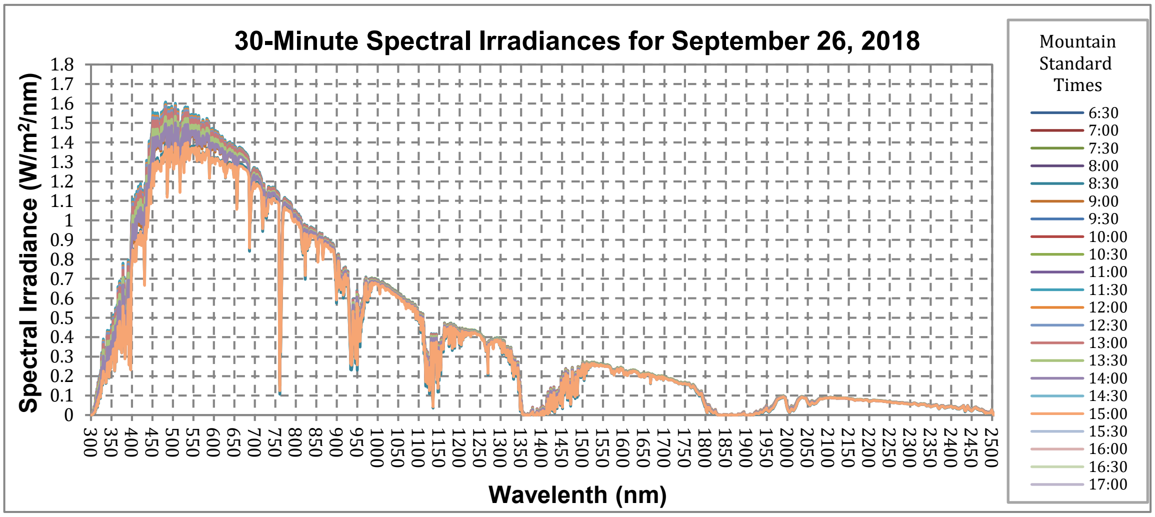

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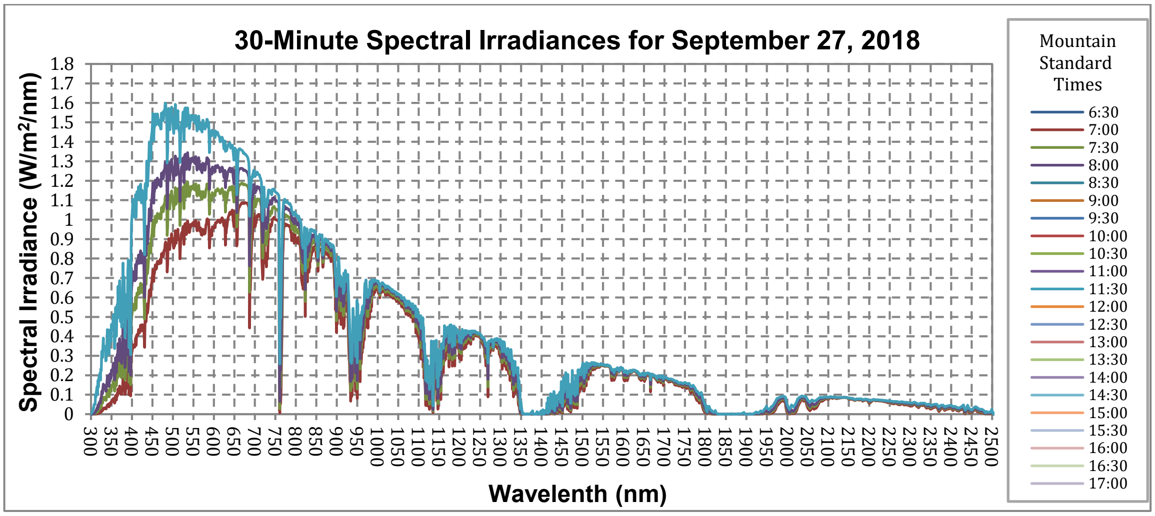

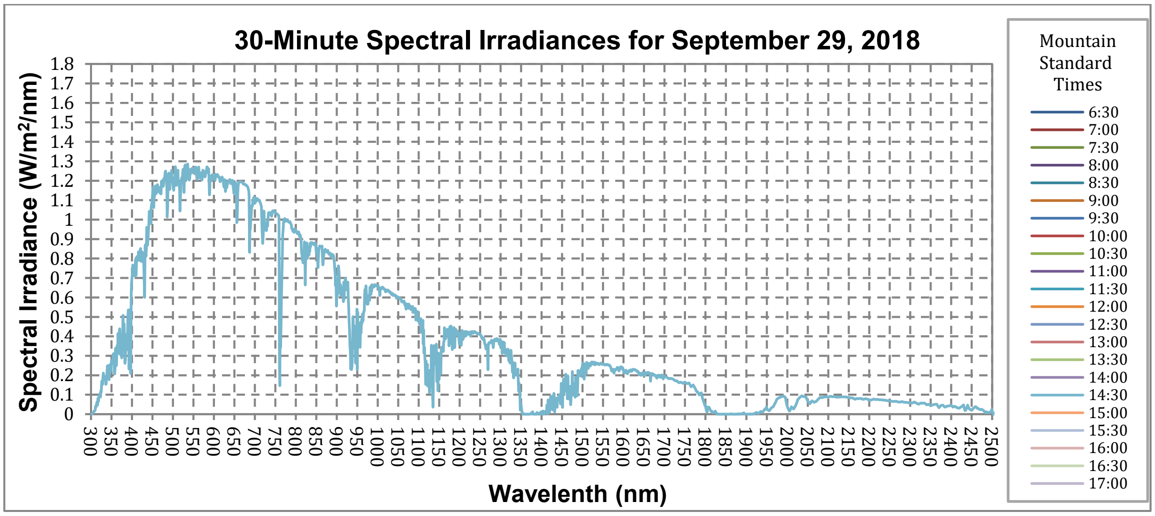

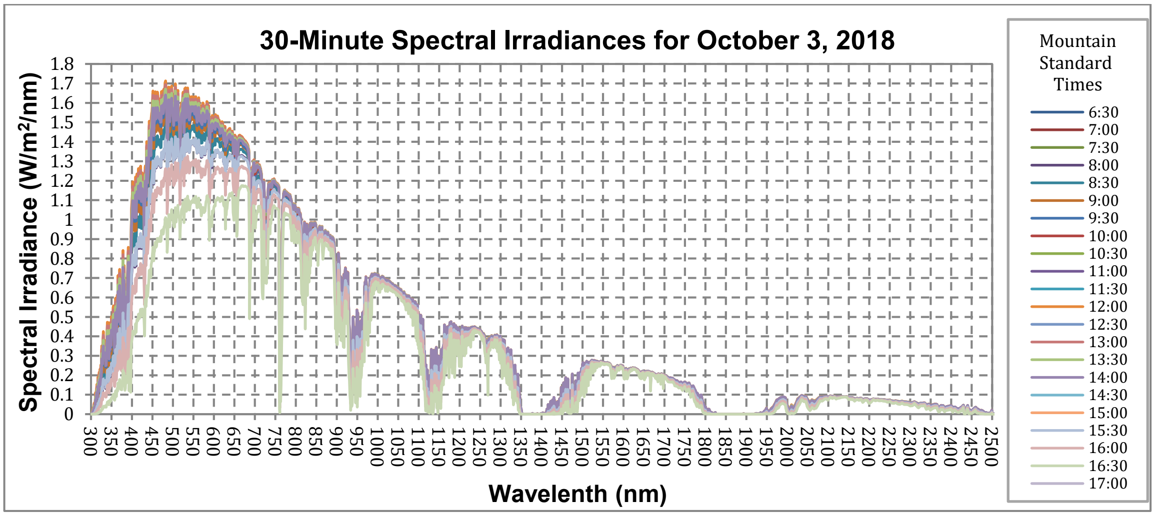

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