NREL Pyrheliometer Comparisons: September 26 – October 7, 2016 (NPC-2016)

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National Renewable Energy Laboratory

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Figure 1. NPC-2016 participants
Photo by Tom Stoffel

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

Executive Summary

Accurate measurements of direct normal (beam) solar irradiance from pyrheliometers[1] are important for developing and deploying solar energy conversion systems, improving our understanding of the 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 and other types of pyrheliometers are subject to performance changes over time. Therefore, every five years the PMOD/WRC in Davos, Switzerland, hosts an International Pyrheliometer Comparison (IPC) for transferring the WRR to participating radiometers. 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).

National Renewable Energy Laboratory (NREL) pyrheliometer comparisons (NPCs) are held annually at the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado. Open to all pyrheliometer 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-2016 was September 26 through October 7, 2016. Participants operated 45 absolute cavity radiometers and 27 conventional thermopile-based pyrheliometers to simultaneously measure clear-sky direct normal solar irradiance during this period. The Transfer Standard Group (TSG) of reference radiometers for NPC-2016 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-2016, each participating absolute cavity radiometer was assigned a new WRR-TF, computed as the reference irradiance

[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.

determined by the TSG divided by the observed irradiance from the participating radiometer. The performance of the TSG during NPC-2016 was consistent with previous comparisons, including IPC-XII. The measurement performance of the TSG allowed 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 37 solar irradiance measurements at 20-second intervals, and a post-calibration. More than 3,300 reference irradiance measurements were collected by the TSG during NPC-2016. Clear-sky daily maximum direct normal irradiance levels ranged from 1000 Wm^{-2} to 1018 Wm^{-2}.

Ancillary environmental conditions (e.g., broadband turbidity, ambient temperature, relative humidity, wind speed, and vertical wind shear) 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 2016). 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, for non-IPC years. The NREL Pyrheliometer Comparisons in 2016 (NPC-2016) was September 26 through October 7, 2016, at the SRRL. Participants operated 42 absolute cavity radiometers and 27 conventional thermopile-based pyrheliometers 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.

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-2016 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-2016 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

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 37 observations at 20-second intervals (PMO6 used 80- or 90-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. Participants also agreed that a minimum of 10 runs should be made during

a period of at least three days to provide a variety of temperature and spectral irradiance conditions when computing the WRR-TF. 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.

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-2016:

- The radiation source was the sun, with irradiance levels > 700 Wm^{-2}.
- A Digital Multimeter with accuracy > 0.05% reading 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-2016 is recalculated for each of the TSG cavities (see Figure 2).
3. The reference irradiance for each 20-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.

Note that the ratios of windowed pyrheliometers do not have a normal distribution (see note under the histogram in the data figures), yet their uncertainty is calculated using a normal distribution for consistency with the NPC protocol for un-windowed pyrheliometers. Users must recalculate the uncertainty of their windowed pyrheliometers based on the actual distribution and their knowledge about the spectral effect due to the specifications of their respective windows.

4.4 Measurements

NPC-2016 was September 26 through October 7, 2016. The comparisons were completed for most participants on September 30, after more than 3,300 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-2016 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-2016 Proficiency Test, the results of the participating cavities in IPC-XII and NPC-2016 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-2016 is consistent with the WRR from IPC-XII).

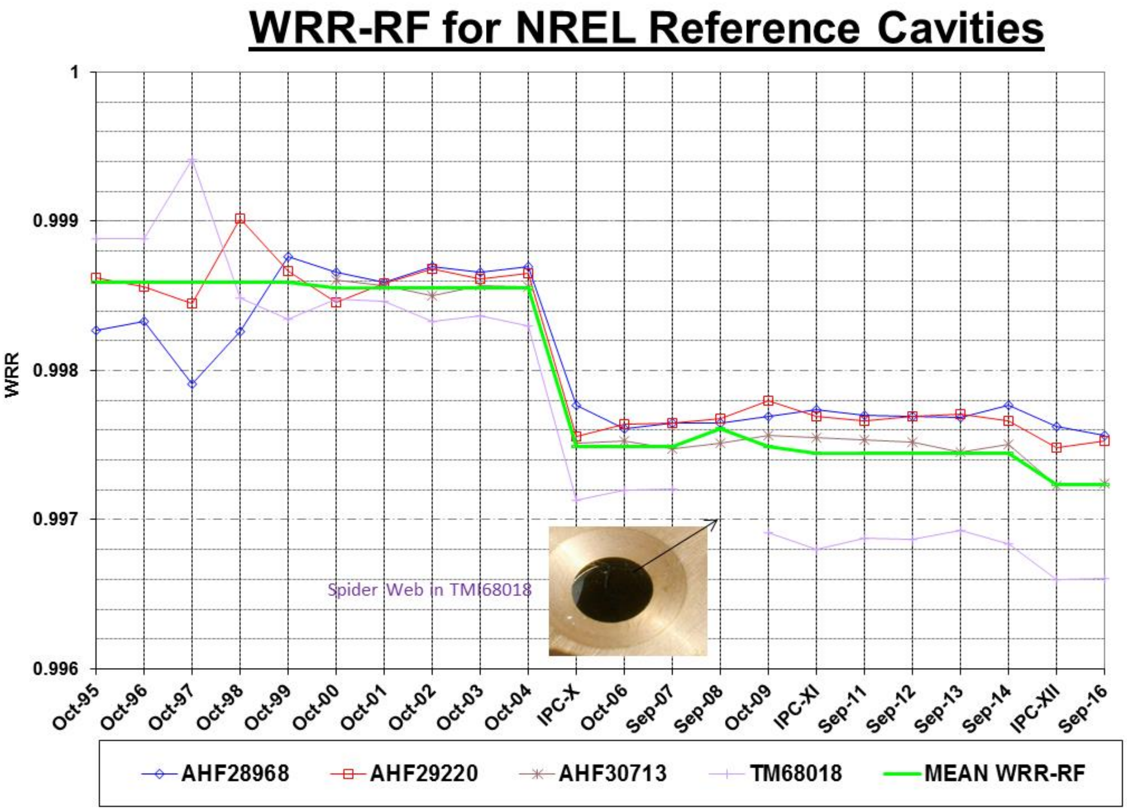


Figure 2. History of WRR reduction factors for NREL reference cavities

Table 2. Summary Results for Proficiency Test During NPC-2016

S/N	WRR (IPC-XII)	%U95 (IPC-XII)	WRR (NPC-2016)	%U95 (NPC-2016)	Red if abs(En) > 1
AHF 0000	1.00031	0.36	1.00243	0.38	-0.404
AHF 14917	0.99790	0.35	0.99817	0.37	-0.053
AHF 17142	0.99795	0.39	0.99841	0.41	-0.083
AHF 23734	0.99819	0.35	0.99802	0.37	0.033
AHF 28553	0.99774	0.35	0.99773	0.37	0.002
AHF 28556	0.99541	0.36	0.99518	0.38	0.044
AHF 28560	0.99928	0.39	1.00027	0.41	-0.176
AHF 30710	1.00097	0.35	1.00070	0.37	0.053
AHF 31041	0.99639	0.36	0.99648	0.38	-0.016
AHF 31105	0.99866	0.36	0.99870	0.38	-0.008
AHF 31114 AWX	1.00121	0.35	1.00144	0.37	-0.045
AHF 32448 AWX	0.99999	0.35	1.00027	0.37	-0.055
AHF 32455	1.00138	0.36	1.00147	0.38	-0.017
AHF 37816	0.999458	0.36	0.99959	0.38	-0.025
PMO6 0816	0.999947	0.41	0.99984	0.43	0.018
PMO6 81109	0.998317	0.36	0.99785	0.38	0.090
PMO6 911204	0.999446	0.36	0.99931	0.39	0.026
TMI 67502	1.000999	0.37	1.00092	0.39	0.015
TMI 68835	1.000714	0.37	1.00055	0.39	0.030

Table 3. Results for Radiometers Participating in NPC-2016

S/N	WRR-Reduction Factor (Testcav)	%uA	NRdg	uC	Eff DF	%U95
AHF 0000	1.00243	0.06	2243	0.20	2.08E+05	0.38
AHF 14917	0.99817	0.04	650	0.19	3.05E+05	0.37
AHF 15746	0.99967	0.19	1840	0.27	6.83E+03	0.52
AHF 17142	0.99841	0.09	2143	0.21	4.92E+04	0.41
AHF 23734	0.99802	0.04	2927	0.19	1.36E+06	0.37
AHF 28553	0.99773	0.04	2508	0.19	8.81E+05	0.37
AHF 28556	0.99518	0.06	2324	0.19	2.92E+05	0.38
AHF 28560	1.00027	0.09	1808	0.21	4.30E+04	0.41
AHF 29219-Windowed	1.06213	0.06	2222	0.19	2.19E+05	0.38
AHF 29222-Windowed	1.05902	0.07	3211	0.20	2.29E+05	0.39
AHF 29223	0.99945	0.06	2396	0.20	2.20E+05	0.38
AHF 30495	0.99831	0.05	3211	0.19	4.92E+05	0.38
AHF 30710	1.00070	0.04	1761	0.19	6.60E+05	0.37
AHF 30710-Windowed	1.07082	0.07	336	0.20	2.69E+04	0.38
AHF 31041	0.99648	0.07	1809	0.20	1.42E+05	0.38
AHF 31102	1.00040	0.09	2785	0.21	6.63E+04	0.41
AHF 31105	0.99870	0.06	1806	0.19	2.54E+05	0.38
AHF 31108	0.99679	0.06	2892	0.19	2.76E+05	0.38
AHF 31114AWX	1.00144	0.05	2512	0.19	6.55E+05	0.37
AHF 31116AWX	1.00108	0.05	1291	0.19	3.34E+05	0.37
AHF 31116AWX-Windowed	1.05386	0.06	1263	0.20	1.19E+05	0.38
AHF 32448AWX	1.00027	0.05	2504	0.19	5.60E+05	0.37
AHF 32452AWX-Windowed	1.03179	0.11	2937	0.21	4.39E+04	0.42
AHF 32455	1.00147	0.06	3239	0.19	3.05E+05	0.38
AHF 34926	1.00049	0.07	3044	0.20	1.85E+05	0.39
AHF 37816	0.99959	0.06	1174	0.19	1.22E+05	0.38
CH1 040370	0.99514	0.18	2972	0.26	1.25E+04	0.51
CH1 060460	1.00282	0.13	2968	0.23	2.60E+04	0.44
CH1 070541	0.99701	0.17	3172	0.25	1.54E+04	0.49
CH1 080066	1.00611	0.12	1737	0.22	1.98E+04	0.43
CH1 70571	0.98607	0.18	2436	0.26	1.04E+04	0.50
CH1 930018	1.00549	0.24	2949	0.31	7.26E+03	0.60
CHP1 090127	0.99595	0.19	3163	0.26	1.23E+04	0.52
CHP1 110533	0.99953	0.18	2927	0.26	1.20E+04	0.51
CHP1 110628	1.00261	0.24	2764	0.30	7.13E+03	0.59

S/N	WRR-Reduction Factor (Testcav)	%uA	NRdg	uC	Eff DF	%U95
CHP1 131132	0.99247	0.13	2746	0.23	2.40E+04	0.44
CHP1 160338	1.00046	0.14	1674	0.23	1.18E+04	0.46
CHP1 160360	0.99006	0.09	2702	0.21	6.21E+04	0.41
CHP1 90062	1.00274	0.13	2733	0.23	2.35E+04	0.45
CMP-V 130040	1.00043	0.10	2304	0.21	3.97E+04	0.42
DR01 8375	0.97292	0.23	2506	0.30	6.64E+03	0.58
DR01 8395	0.99138	0.13	2673	0.23	2.24E+04	0.45
DR01 8396	0.99653	0.37	2953	0.41	4.65E+03	0.80
DR02 9234	0.99749	0.16	2914	0.25	1.48E+04	0.49
MS56 P13019	0.99476	0.19	2405	0.27	9.07E+03	0.52
MS56 P13019-TC	0.99382	0.19	2389	0.26	9.04E+03	0.52
MS56 REF03	1.00246	0.21	2682	0.28	8.78E+03	0.54
MS56 REF04	1.00465	0.27	1878	0.33	3.96E+03	0.65
MS57 001	0.99967	0.09	2627	0.21	6.16E+04	0.41
MS57 002	1.00064	0.12	2705	0.22	3.02E+04	0.43
NIP 26544E6	0.99756	0.35	971	0.40	1.58E+03	0.78
PMO6 0816	0.99984	0.12	323	0.22	3.62E+03	0.43
PMO6 1102	0.99909	0.13	287	0.23	2.67E+03	0.44
PMO6 81109	0.99785	0.06	699	0.19	9.60E+04	0.38
PMO6 81109 [320/40]	0.99829	0.09	1119	0.21	2.82E+04	0.40
PMO6 911204	0.99931	0.07	706	0.20	5.10E+04	0.39
Pmo6cc 0103	0.99791	0.07	407	0.20	2.99E+04	0.39
PMO6cc 0401	1.02086	0.06	437	0.19	5.77E+04	0.38
PMO6-cc 0803	1.00044	0.06	440	0.20	3.99E+04	0.38
sNIP 37881	0.99948	0.22	2821	0.28	8.45E+03	0.56
sNIP 37909	0.99995	0.21	2823	0.28	8.94E+03	0.55
TMI 67502	1.00092	0.07	2575	0.20	1.51E+05	0.39
TMI 67603	0.99967	0.06	2861	0.19	3.08E+05	0.38
TMI 67811	0.99752	0.21	2260	0.28	7.10E+03	0.55
TMI 68020	0.99826	0.12	2599	0.22	3.21E+04	0.43
TMI 68022	0.99860	0.22	2274	0.29	6.72E+03	0.56
TMI 68835	1.00055	0.08	2527	0.20	1.15E+05	0.39
TMI 69036	1.00020	0.09	2918	0.21	7.13E+04	0.41

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-2016 with 95% confidence level

1.96 = Coverage factor

u_A = Type A standard uncertainty = standard deviation of each participating radiometer (in %) determined at NPC-2016

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-2016.

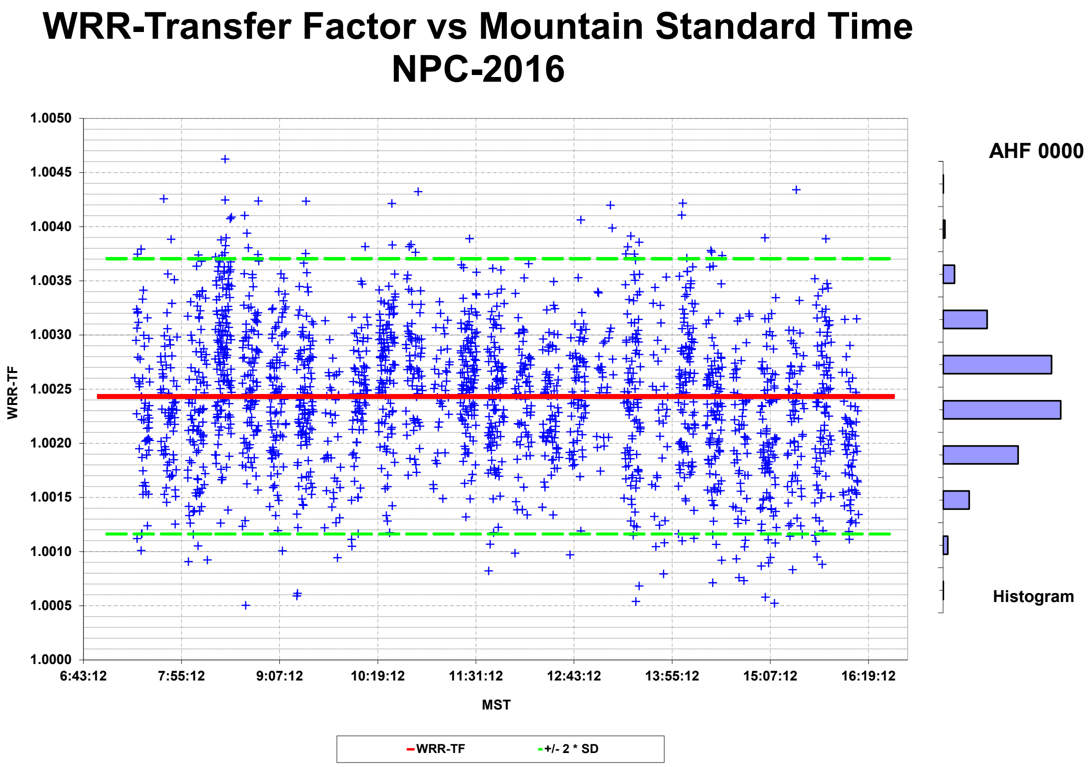


Figure 3. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 0000

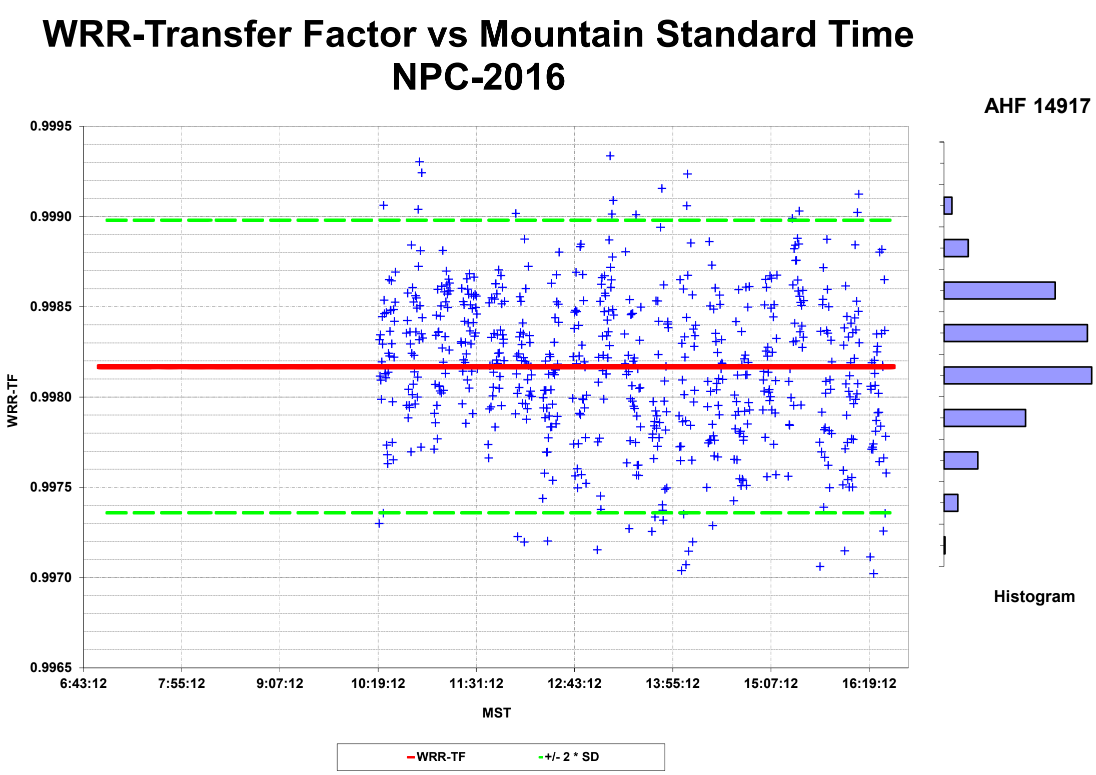


Figure 4. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 14917

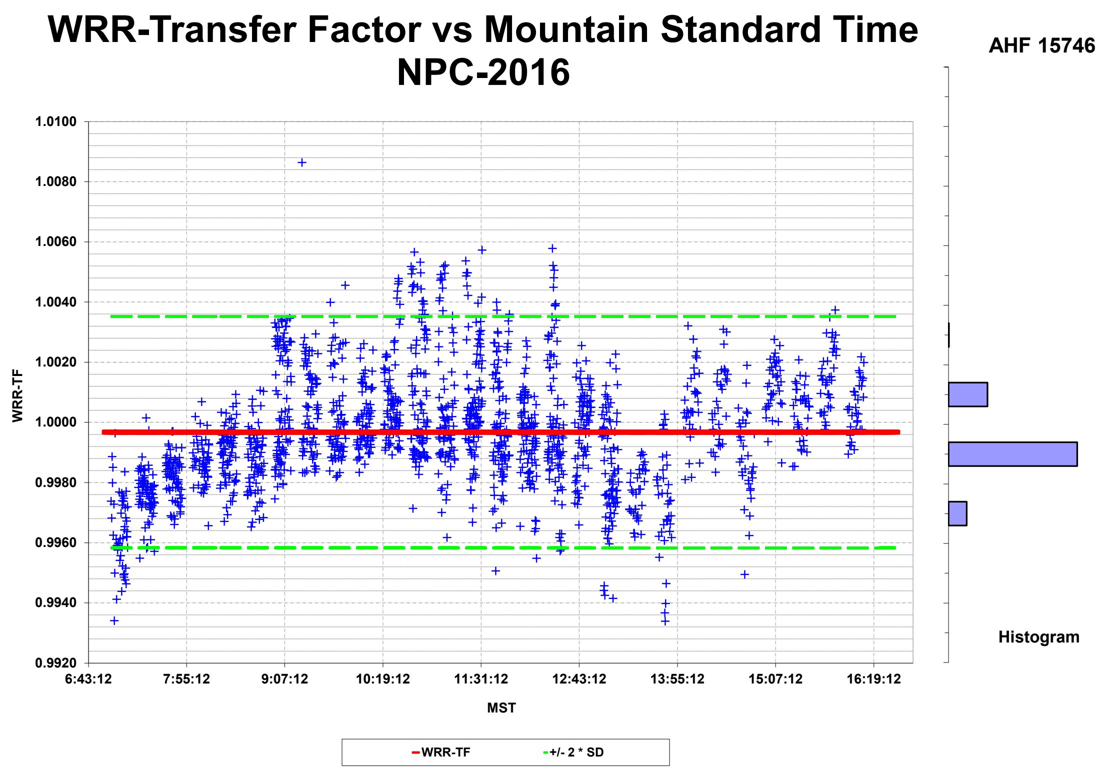


Figure 5. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 15746

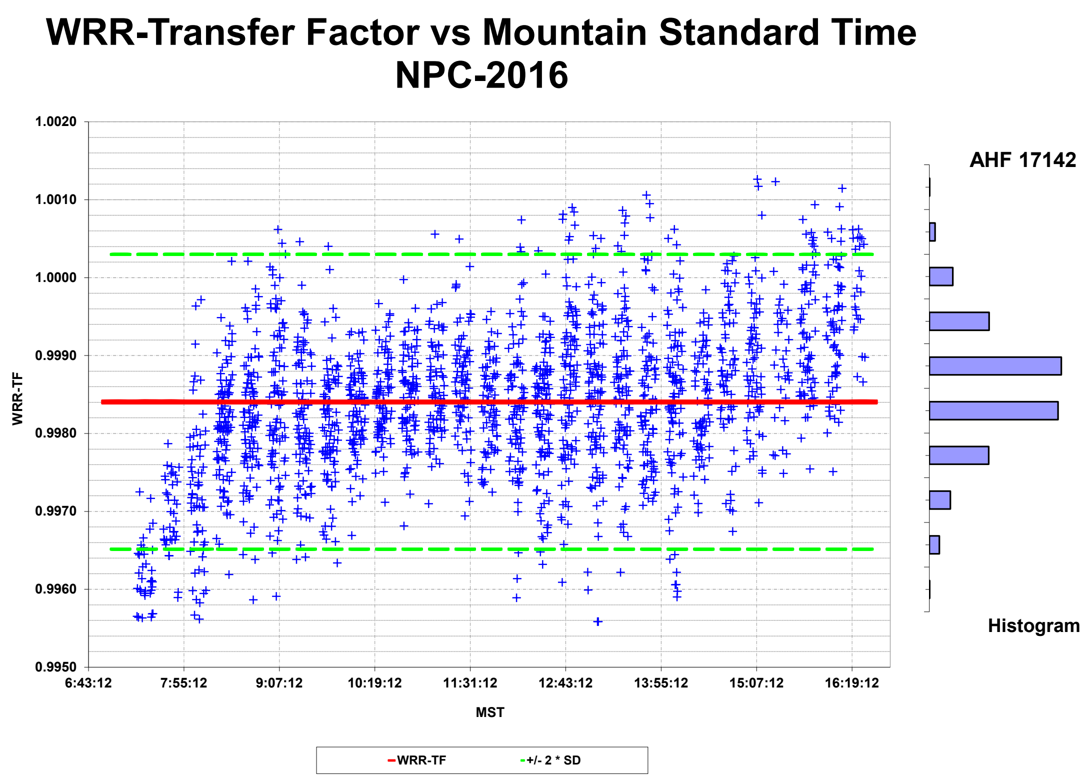


Figure 6. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF17142

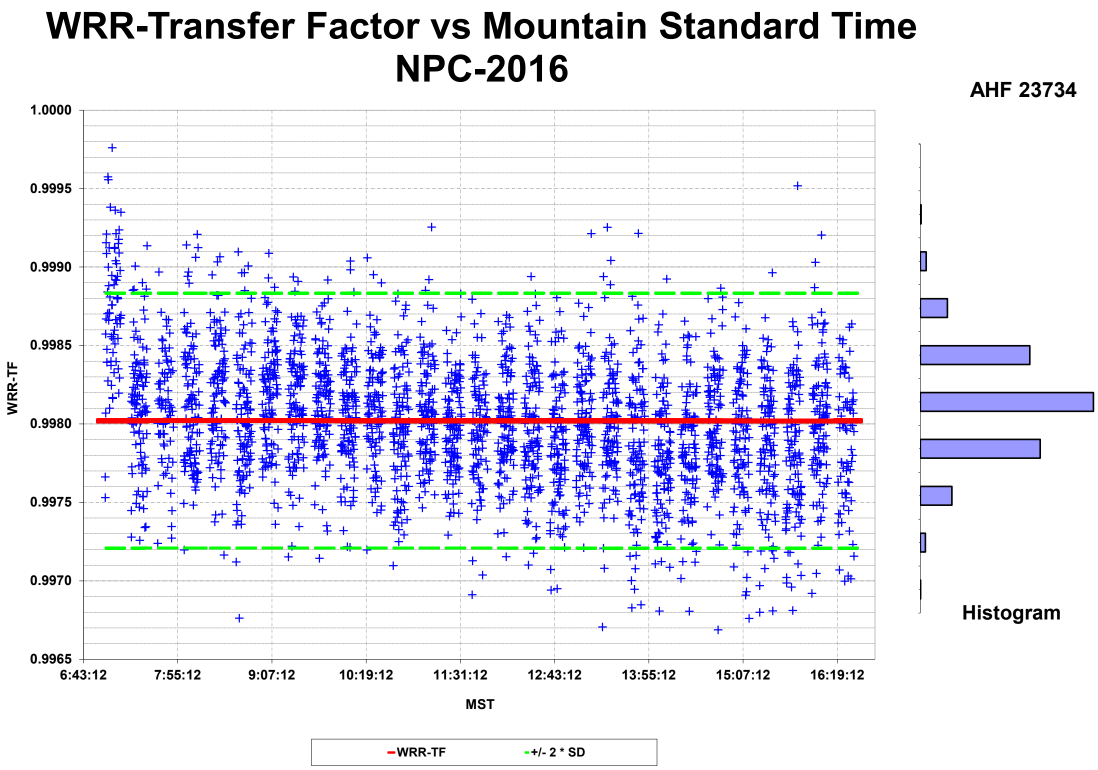


Figure 7. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 23734

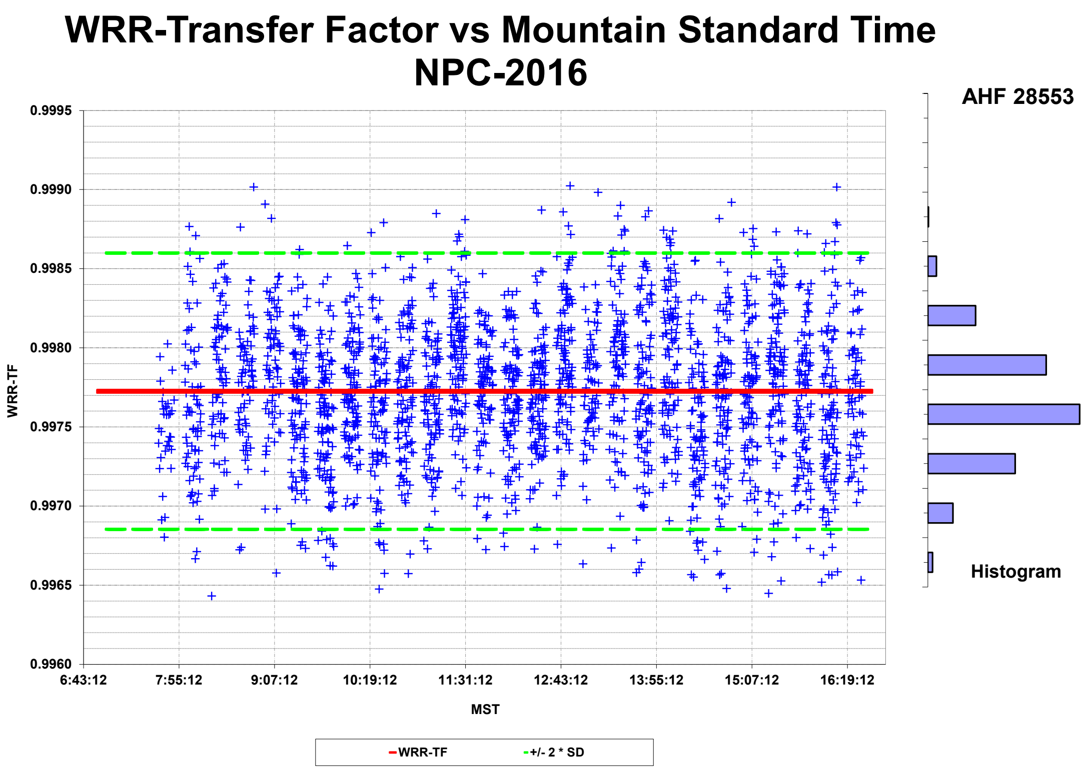


Figure 8. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF28553

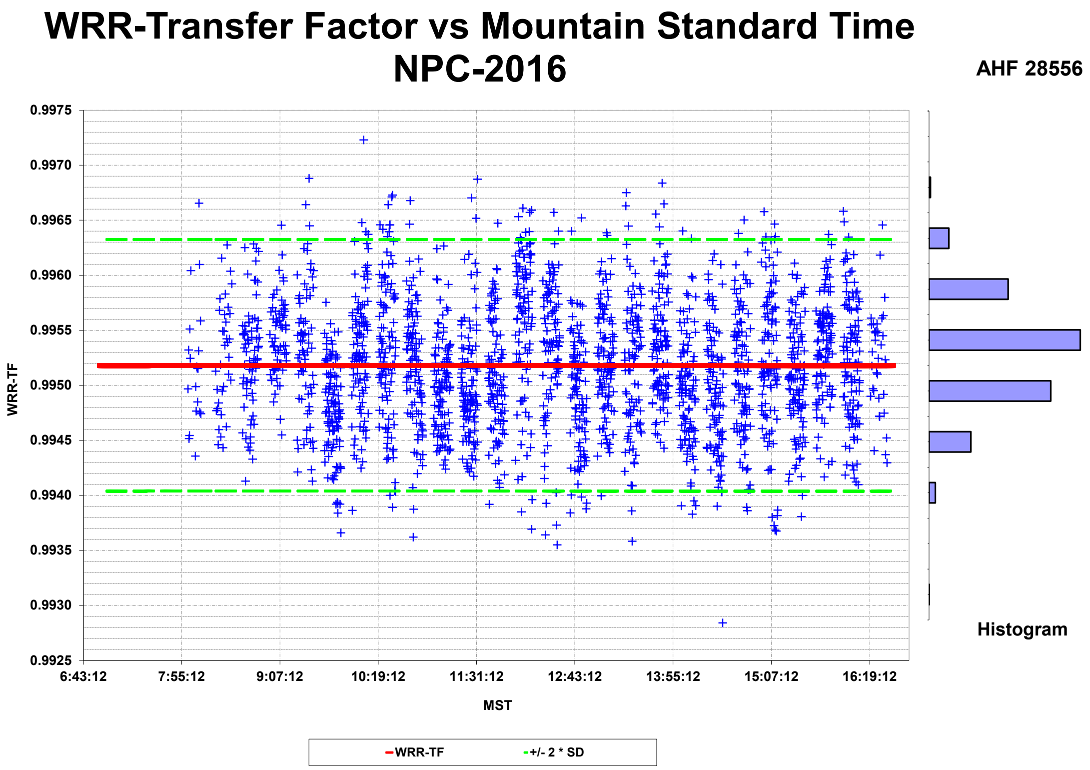


Figure 9. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 28556

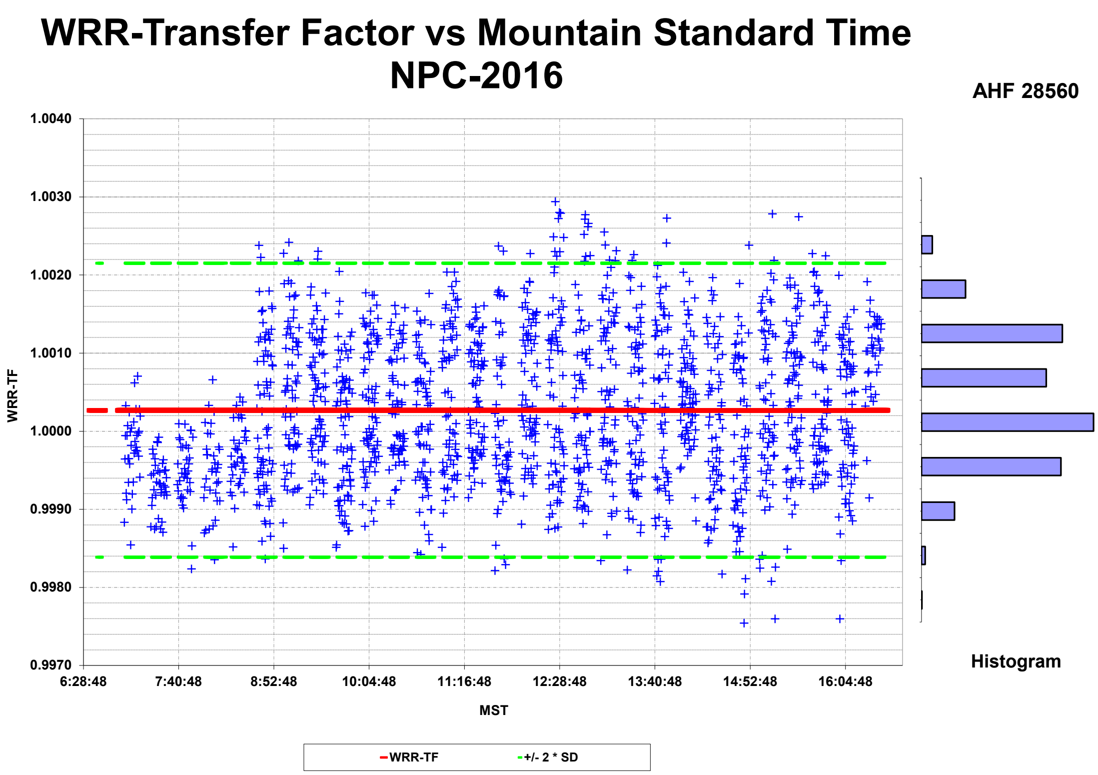


Figure 10. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 28560

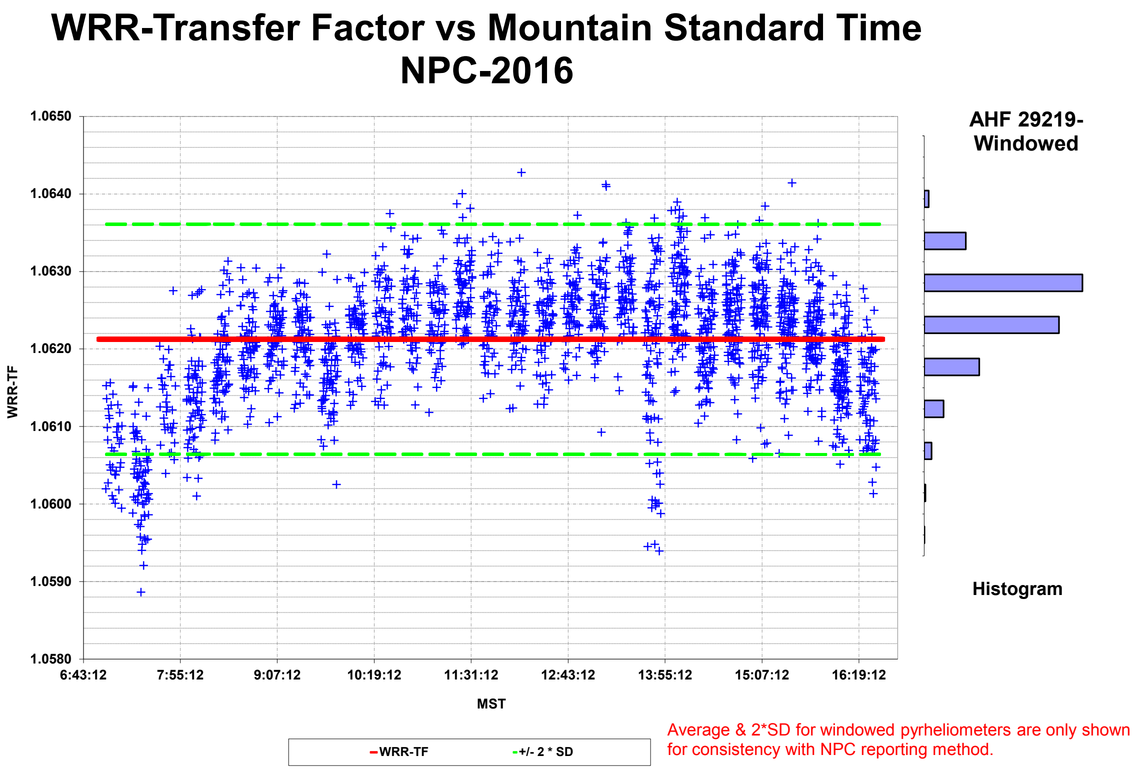


Figure 11. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 29219 - Windowed

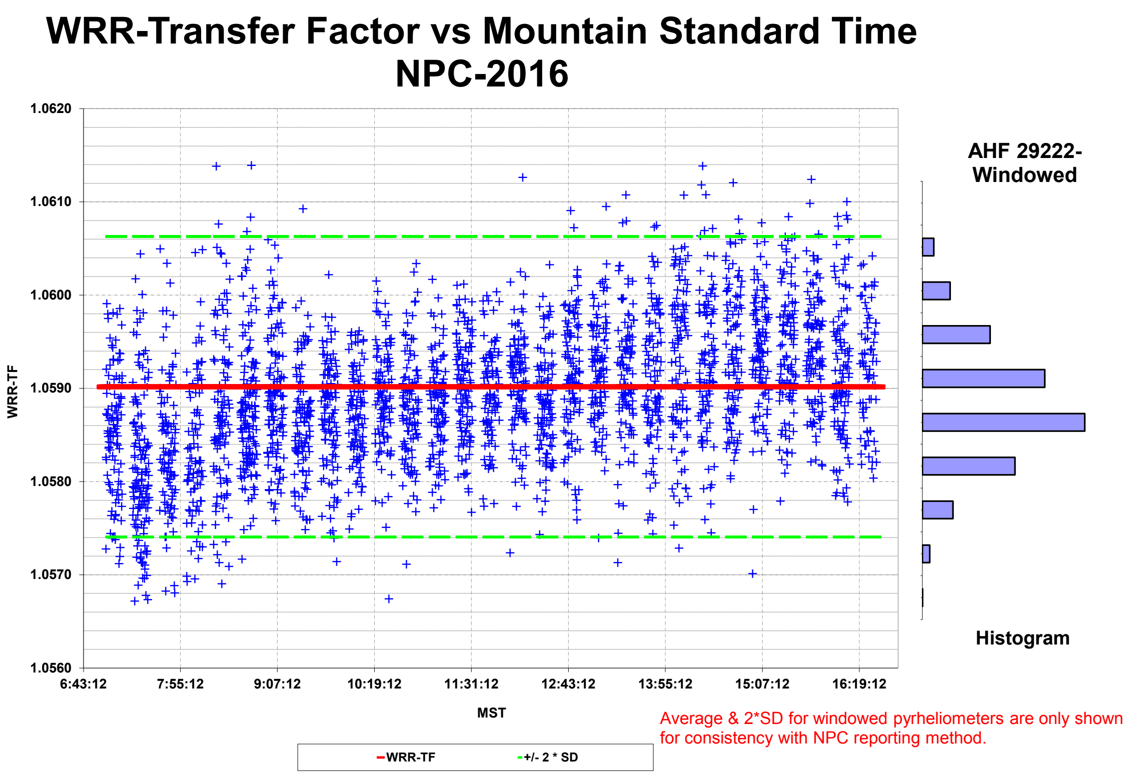


Figure 12. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 29222 – Windowed

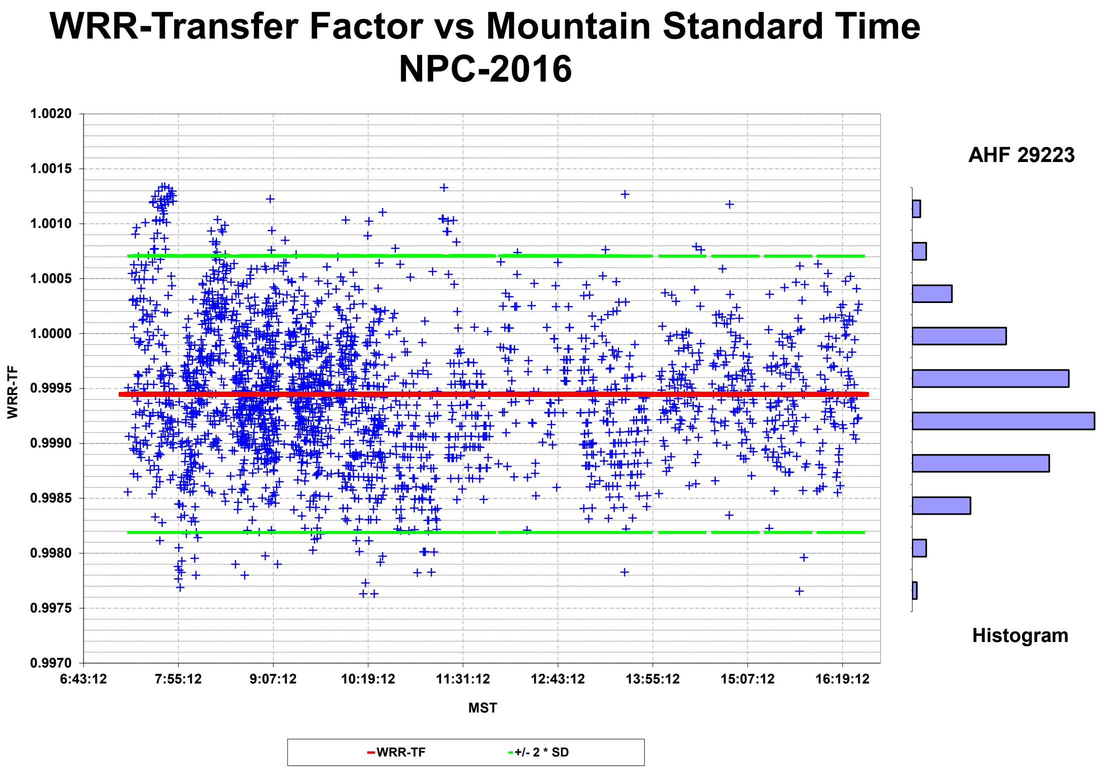


Figure 13. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF29233

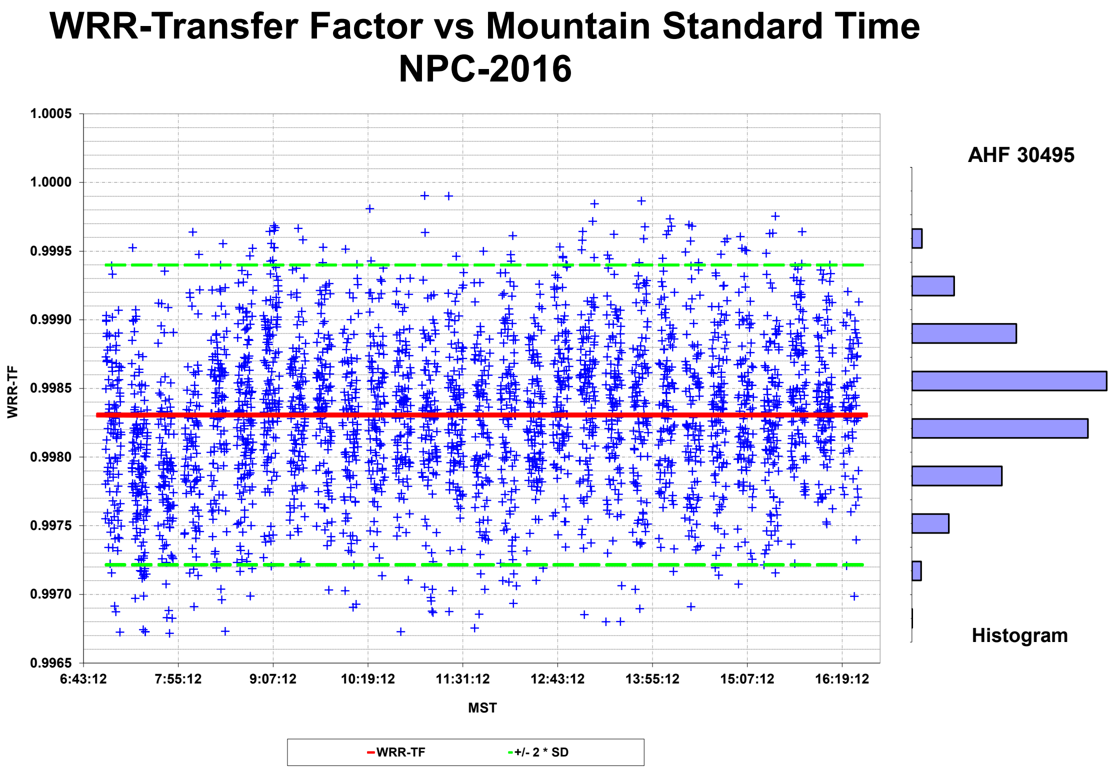


Figure 14. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 30495

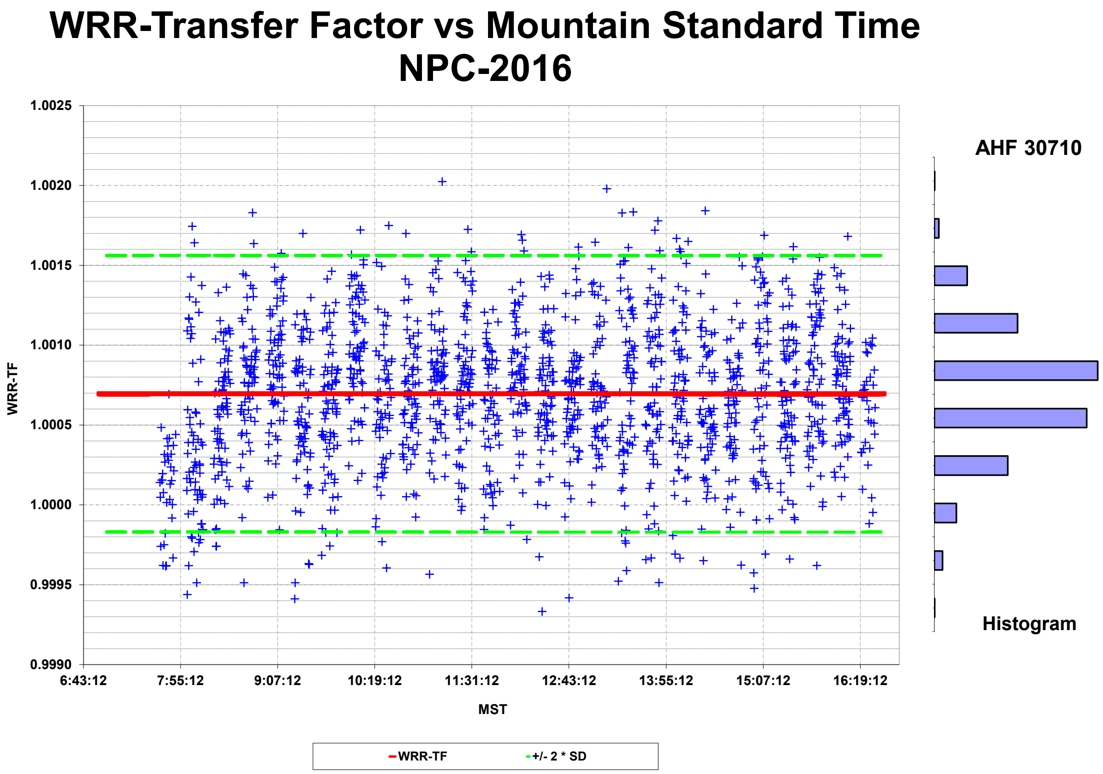


Figure 15. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 30710

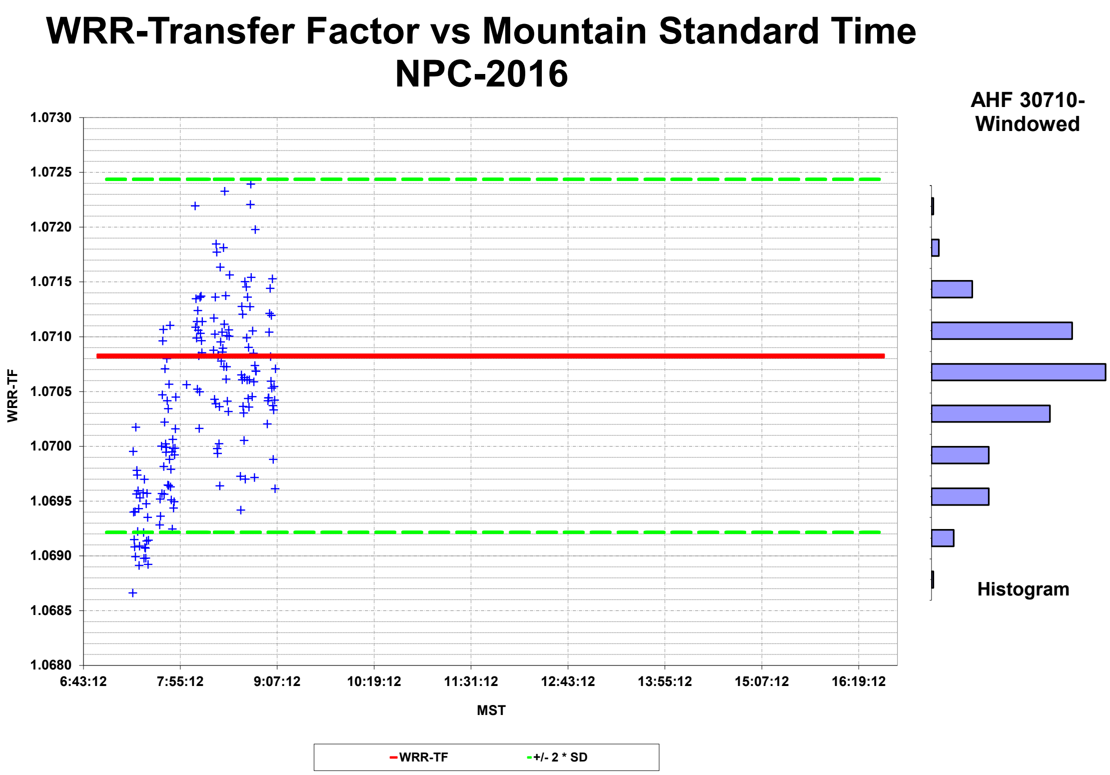


Figure 16. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 30710 – Windowed

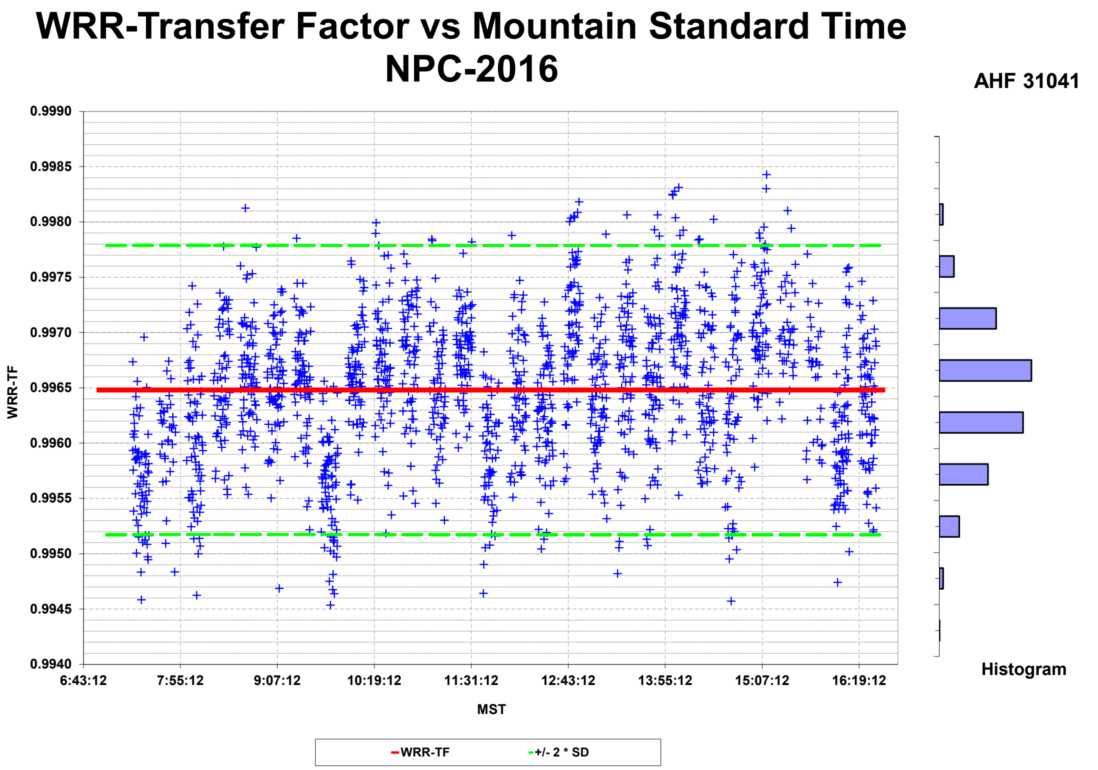


Figure 17. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 31041

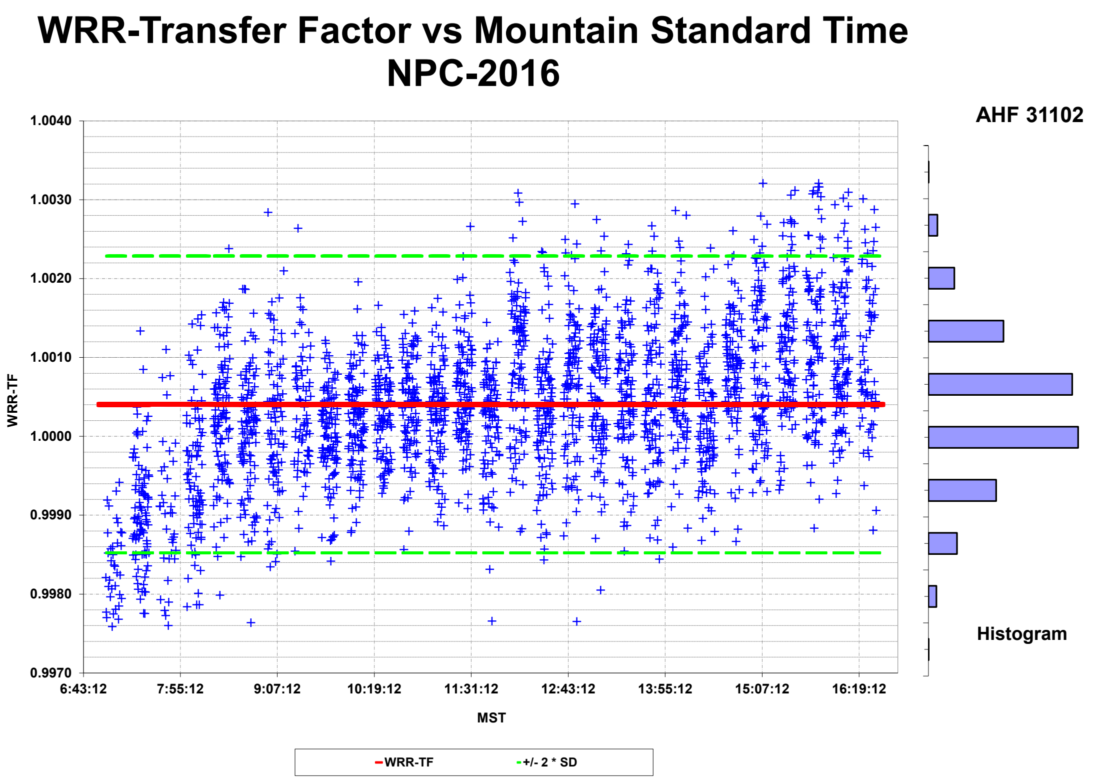


Figure 18. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 31102

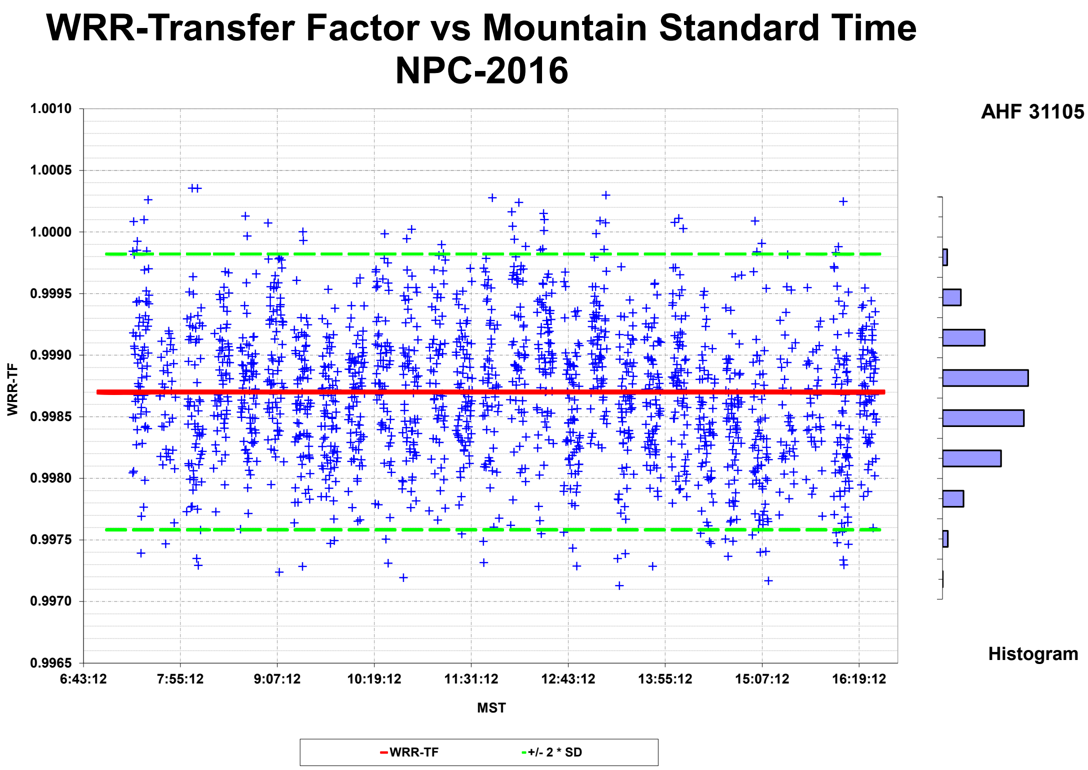


Figure 19. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 31105

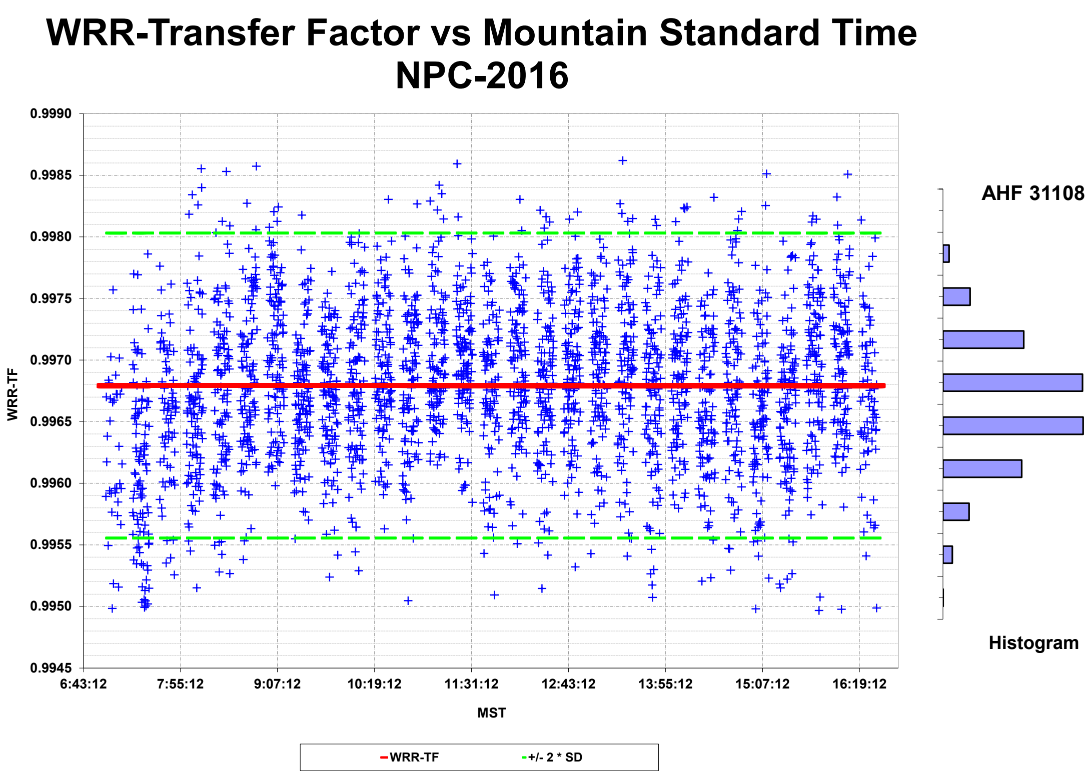


Figure 20. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 31108

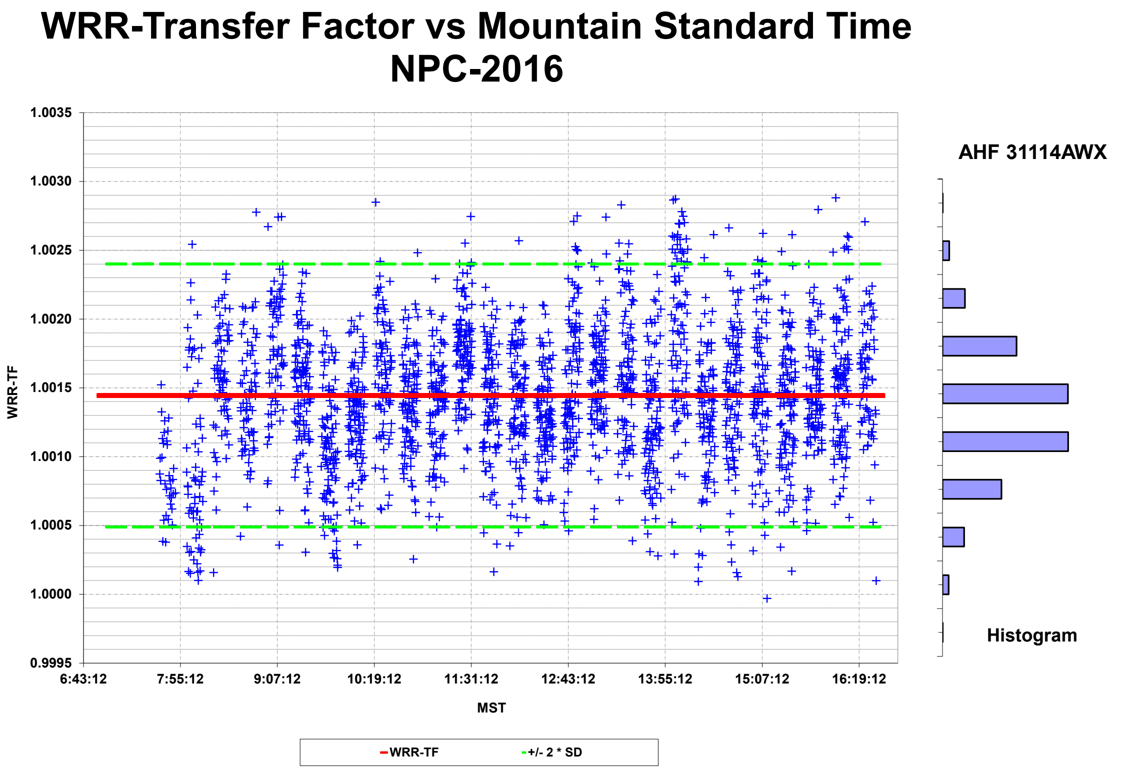


Figure 21. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 31114AWX

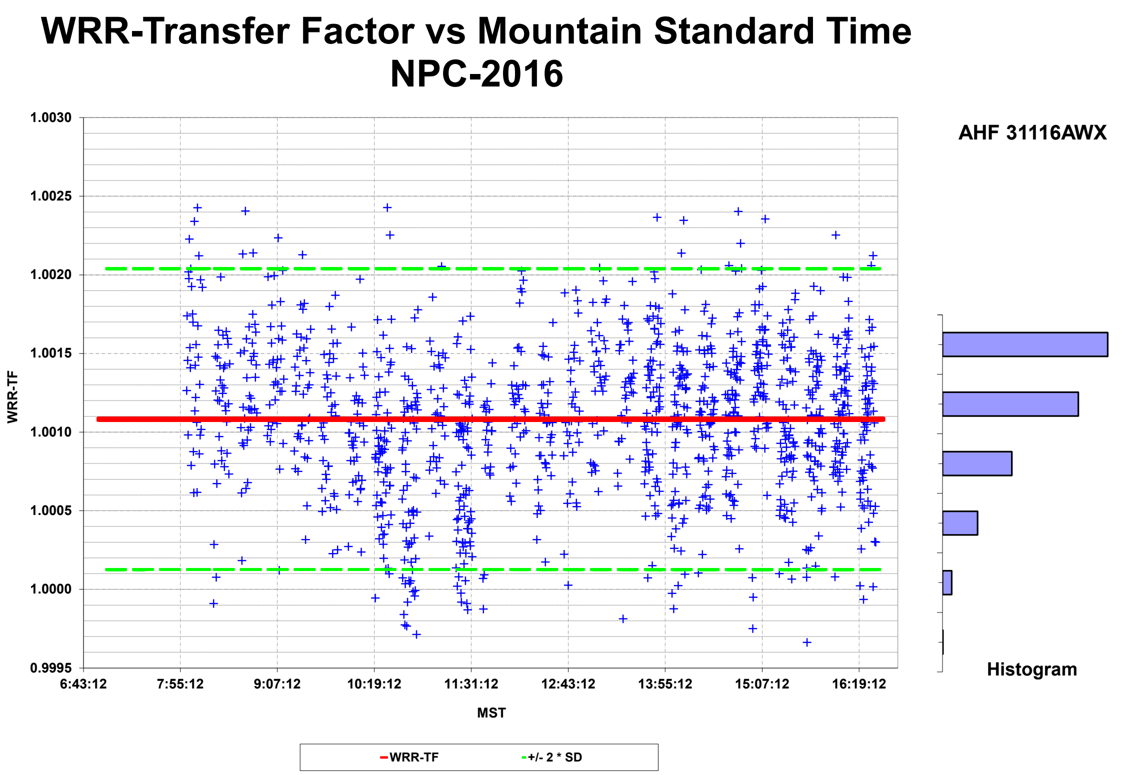


Figure 22. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 31116AWX

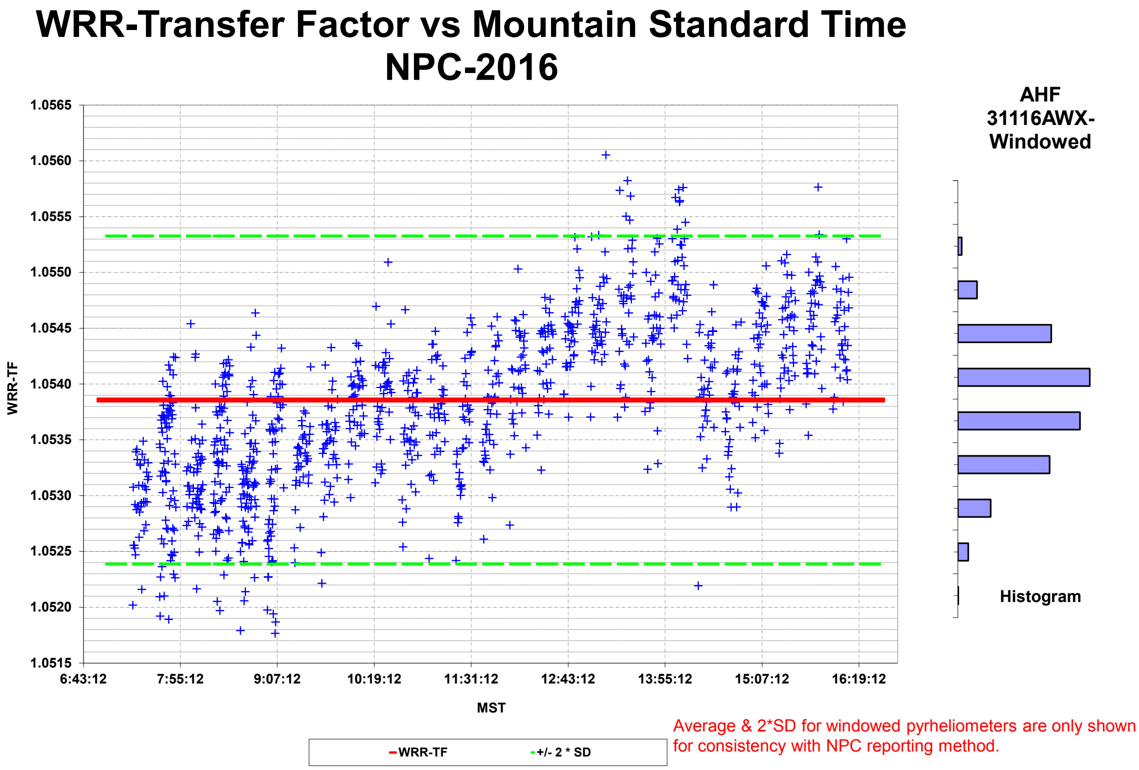


Figure 23. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 31116AWX – Windowed

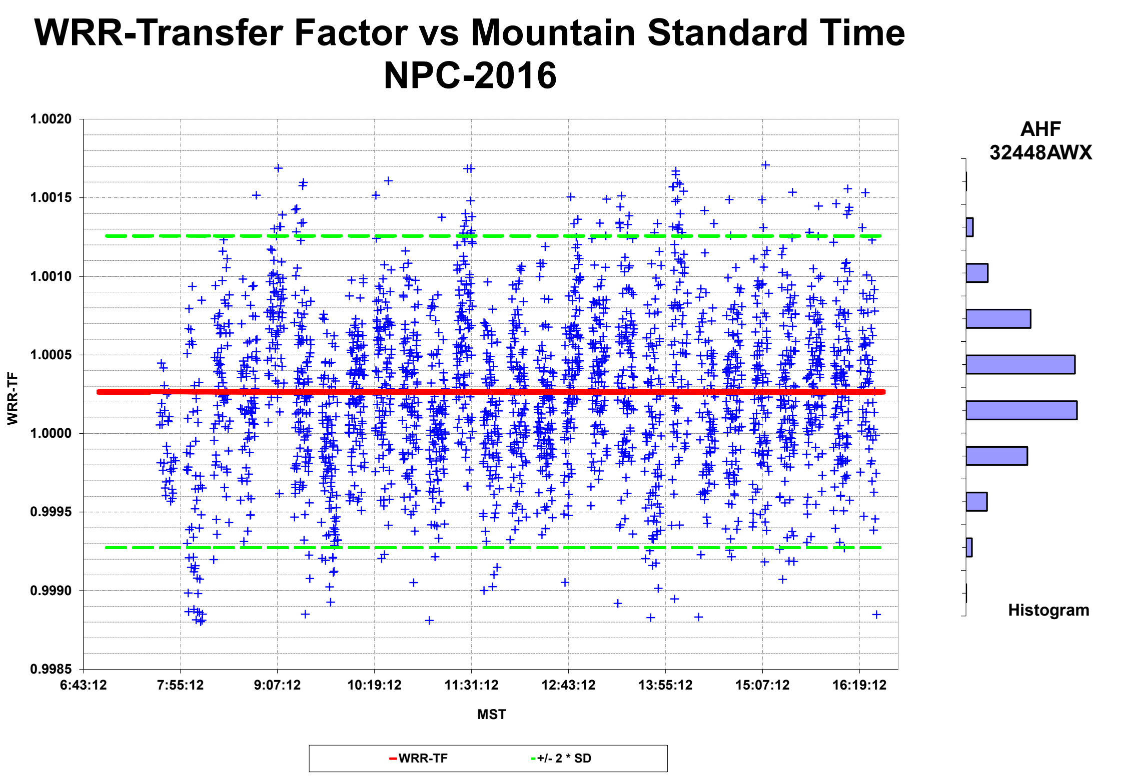
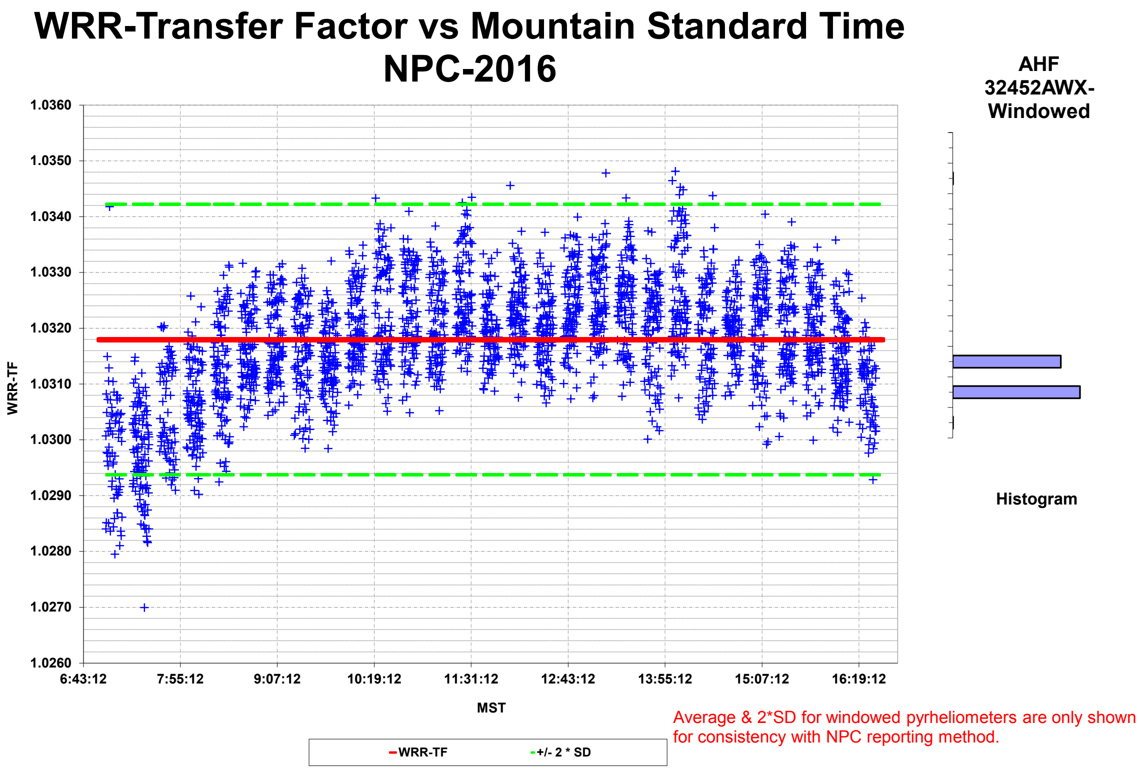


Figure 24. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 32448AWX



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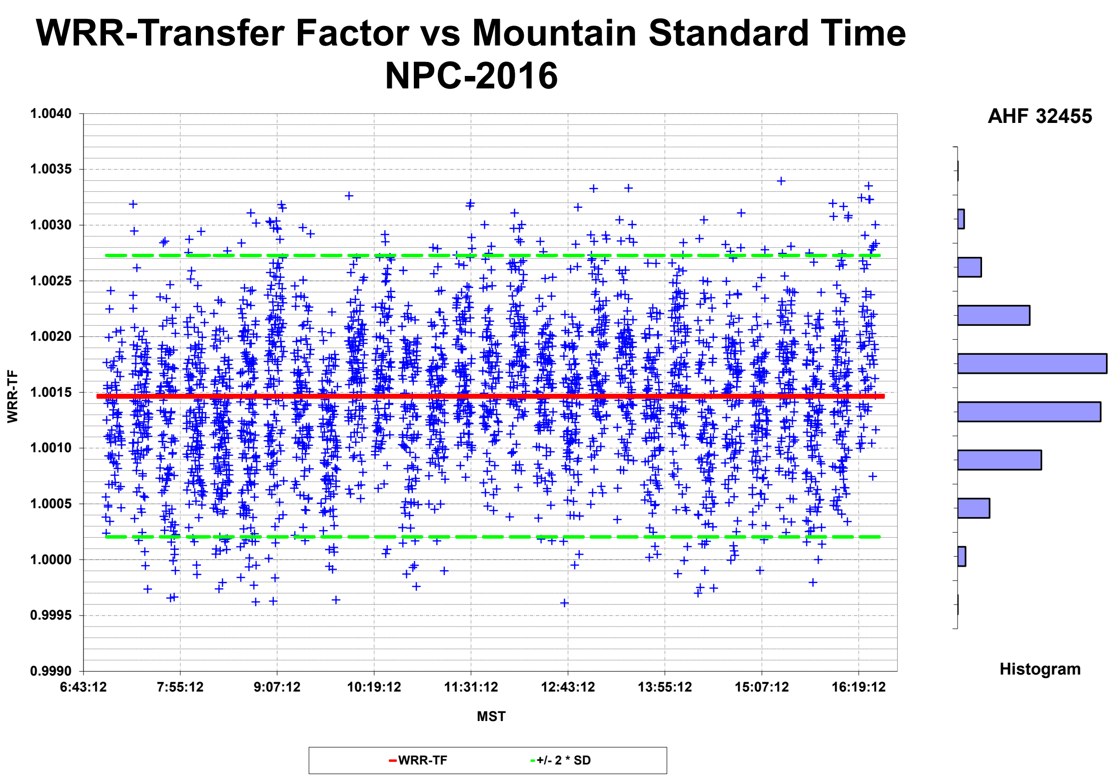


Figure 26. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 32455

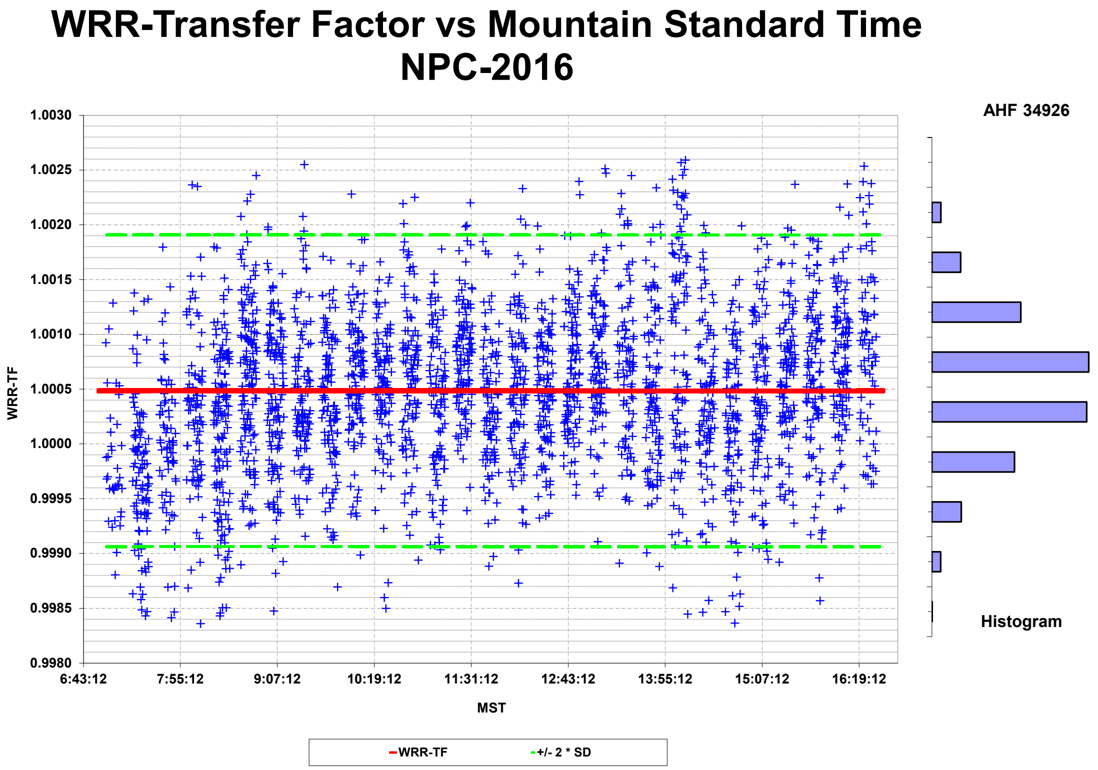


Figure 27. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 34926

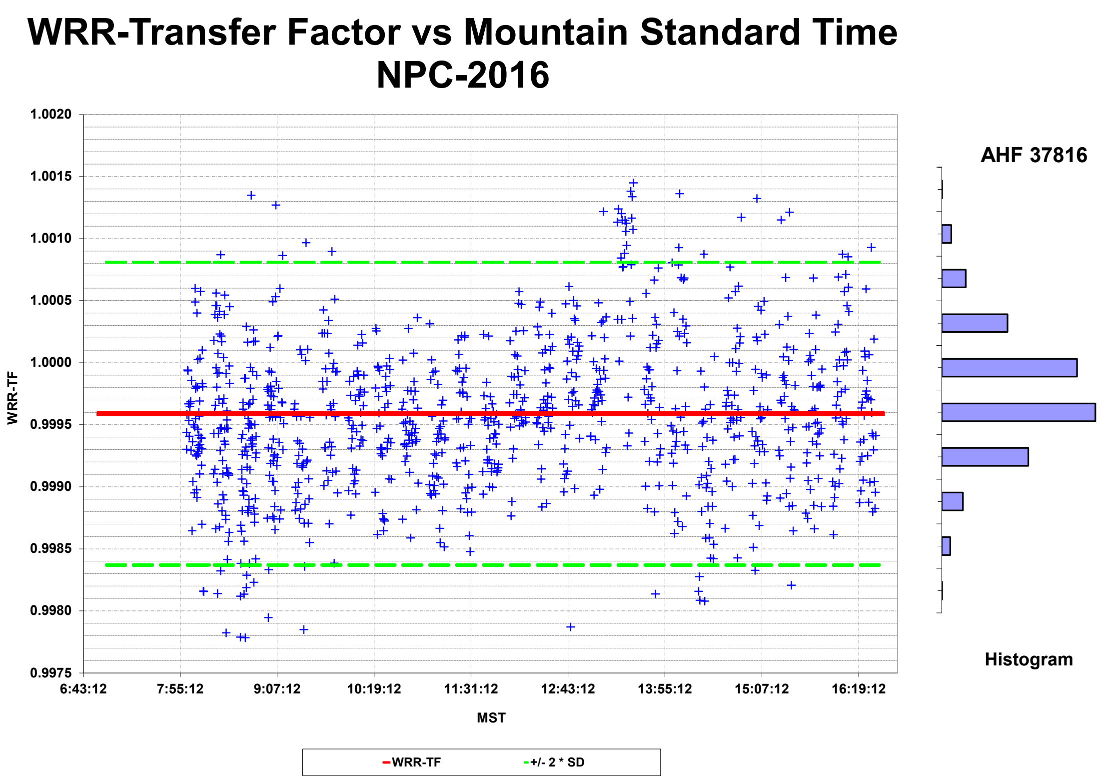


Figure 28. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for AHF 37816

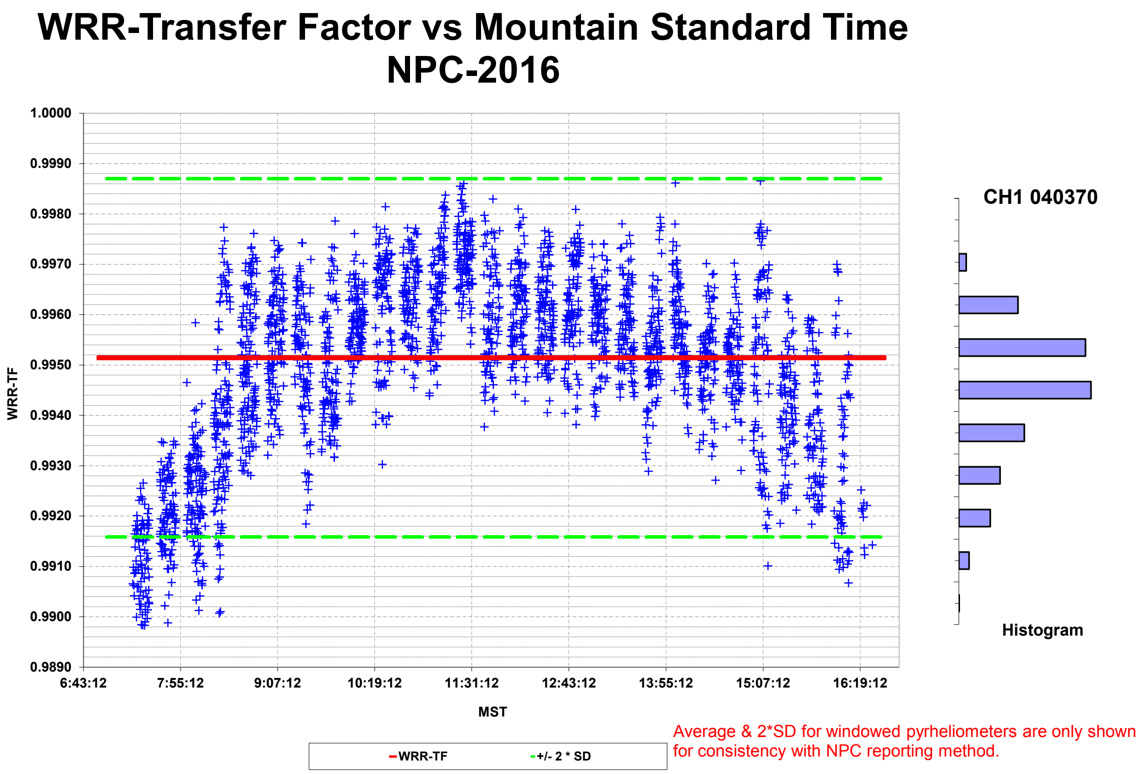


Figure 29. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CH1 040370

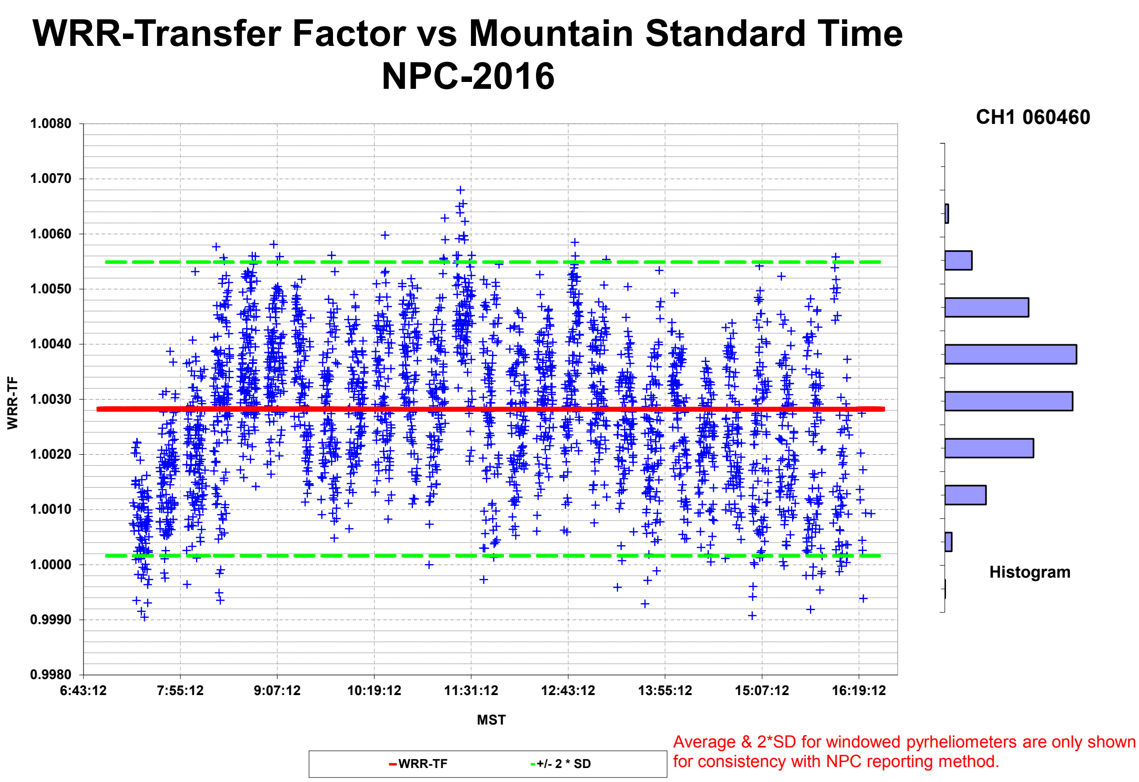


Figure 30. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CH1 060460

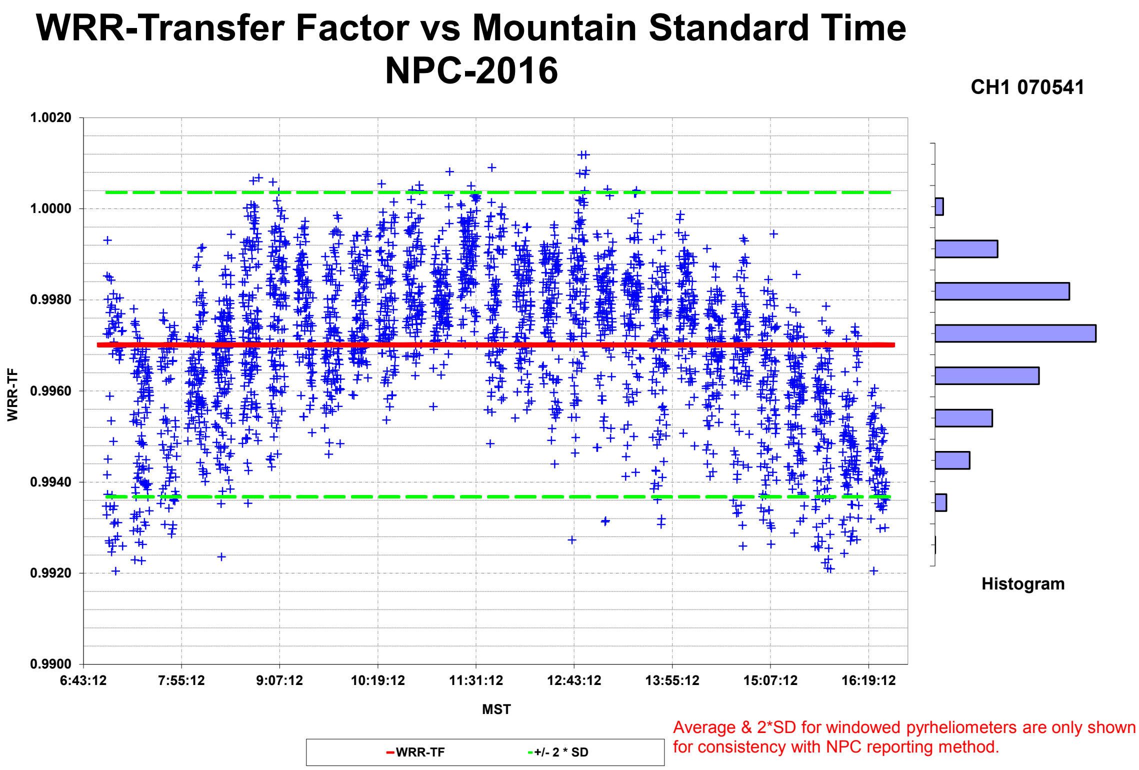


Figure 31. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CH1 070541

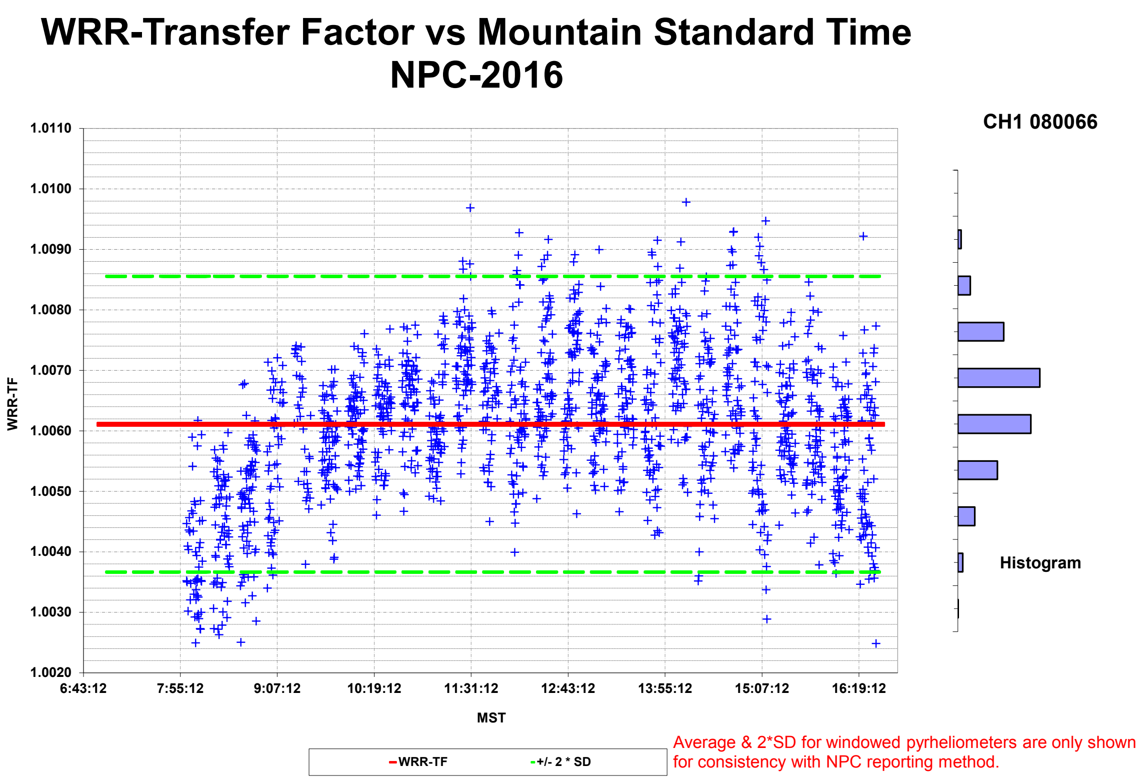


Figure 32. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CH1 080066

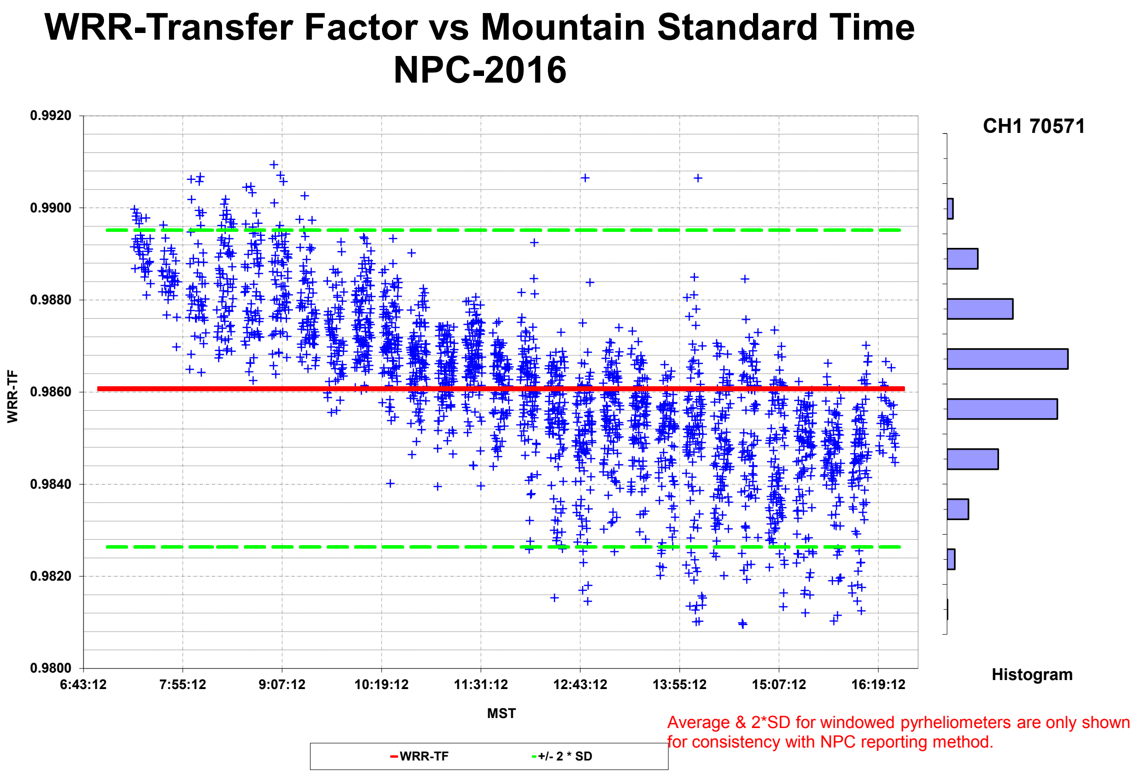


Figure 33. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CH1 70571

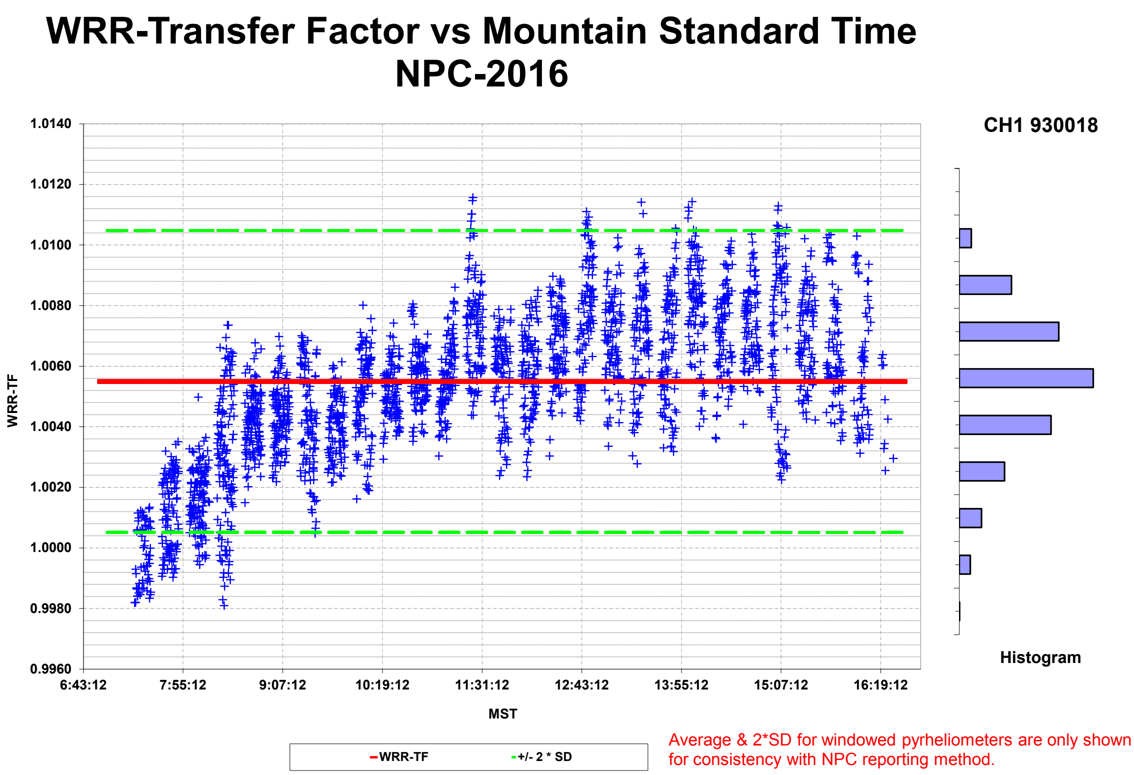


Figure 34. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CH1 930018

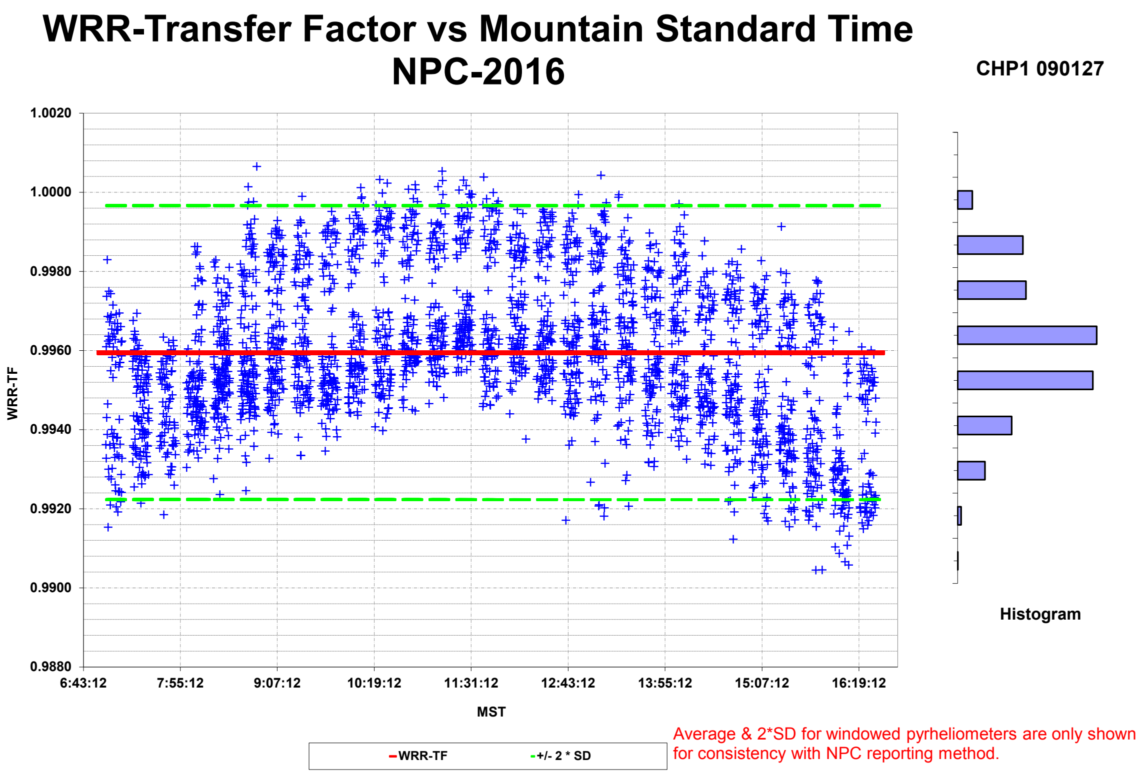


Figure 35. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CHP1 090127

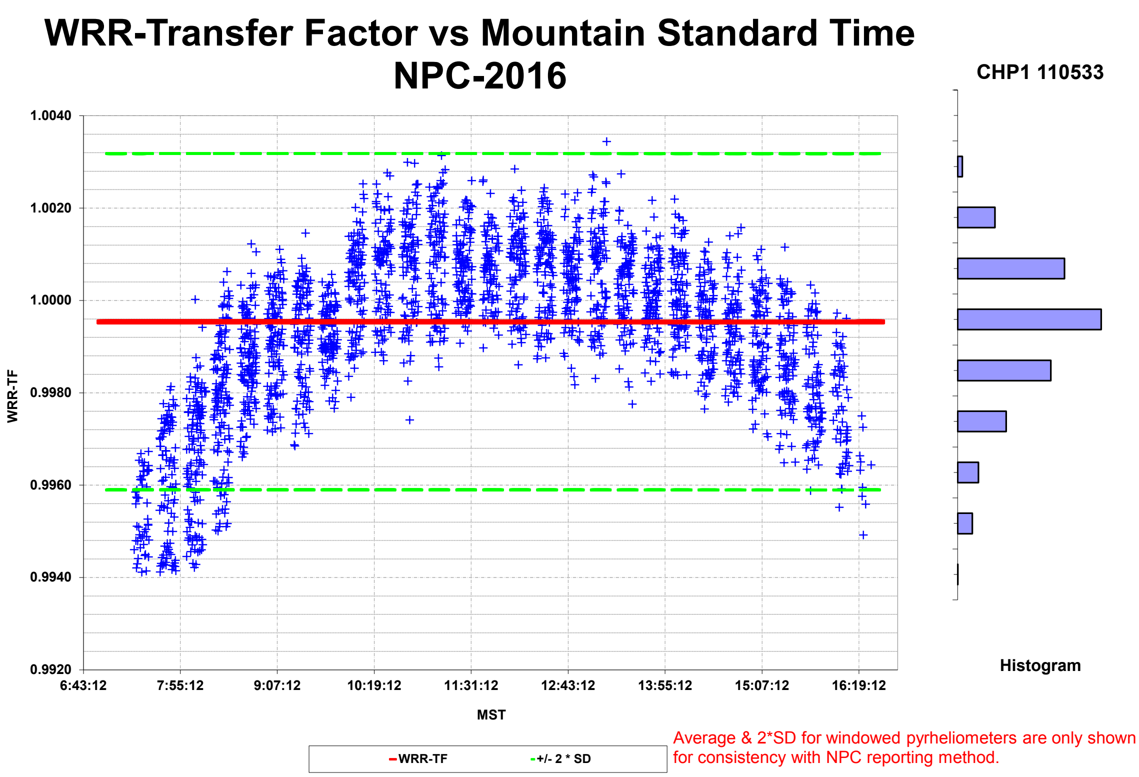


Figure 36. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CHP1 110533

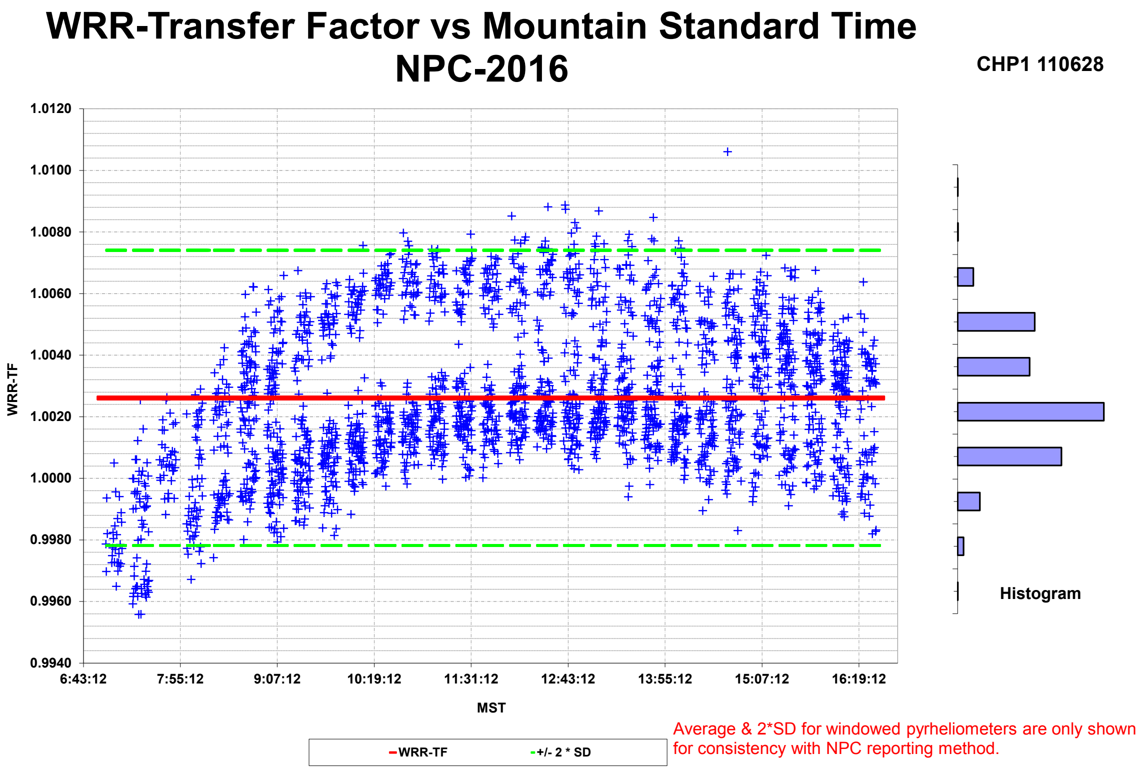


Figure 37. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CHP1 110628

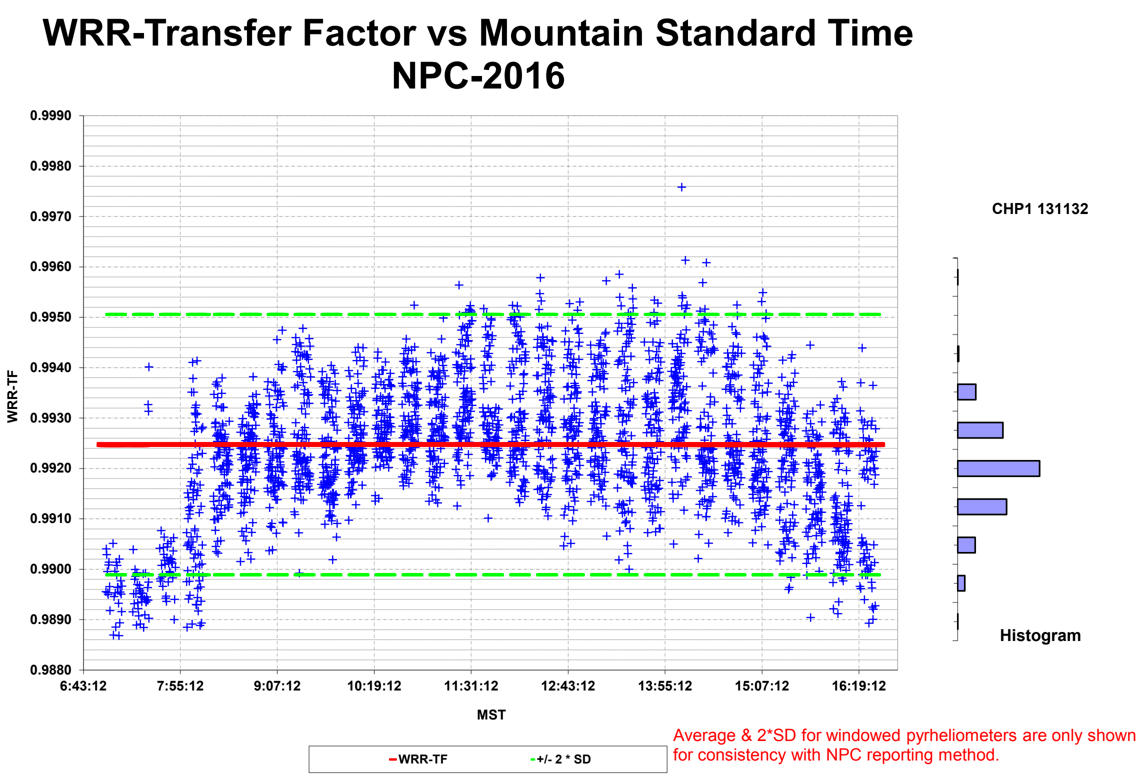


Figure 38. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CHP1 131132

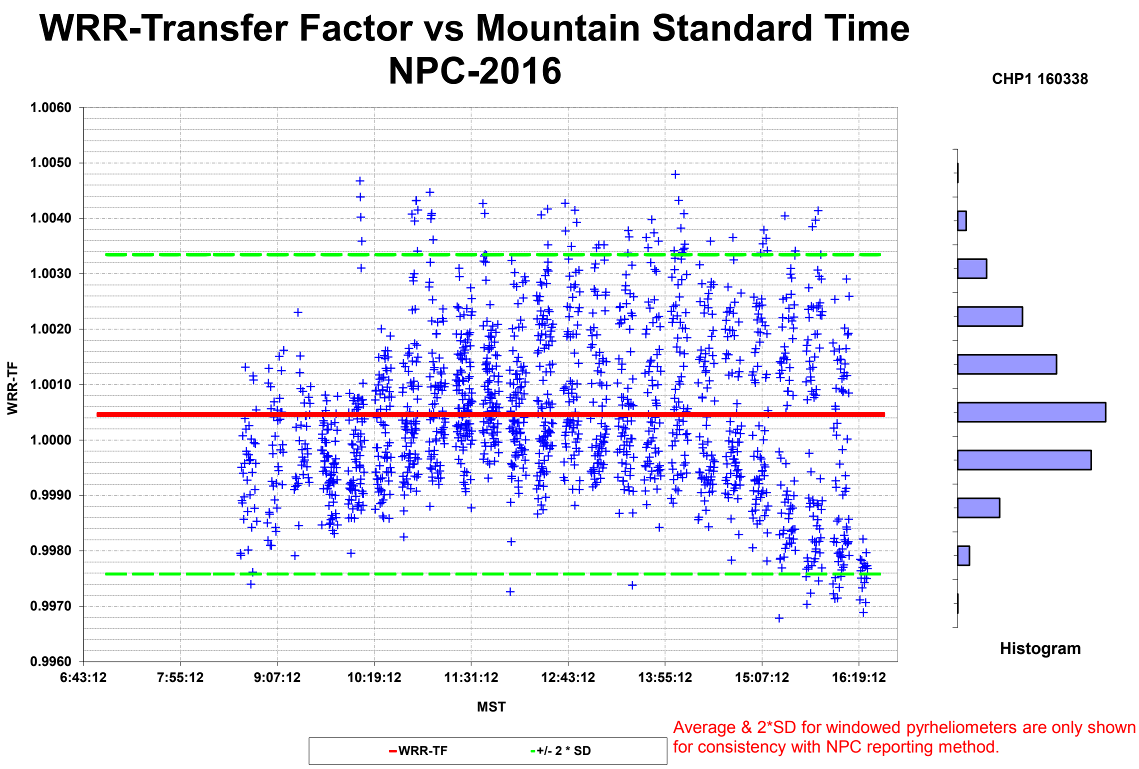


Figure 39. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CHP1 160338

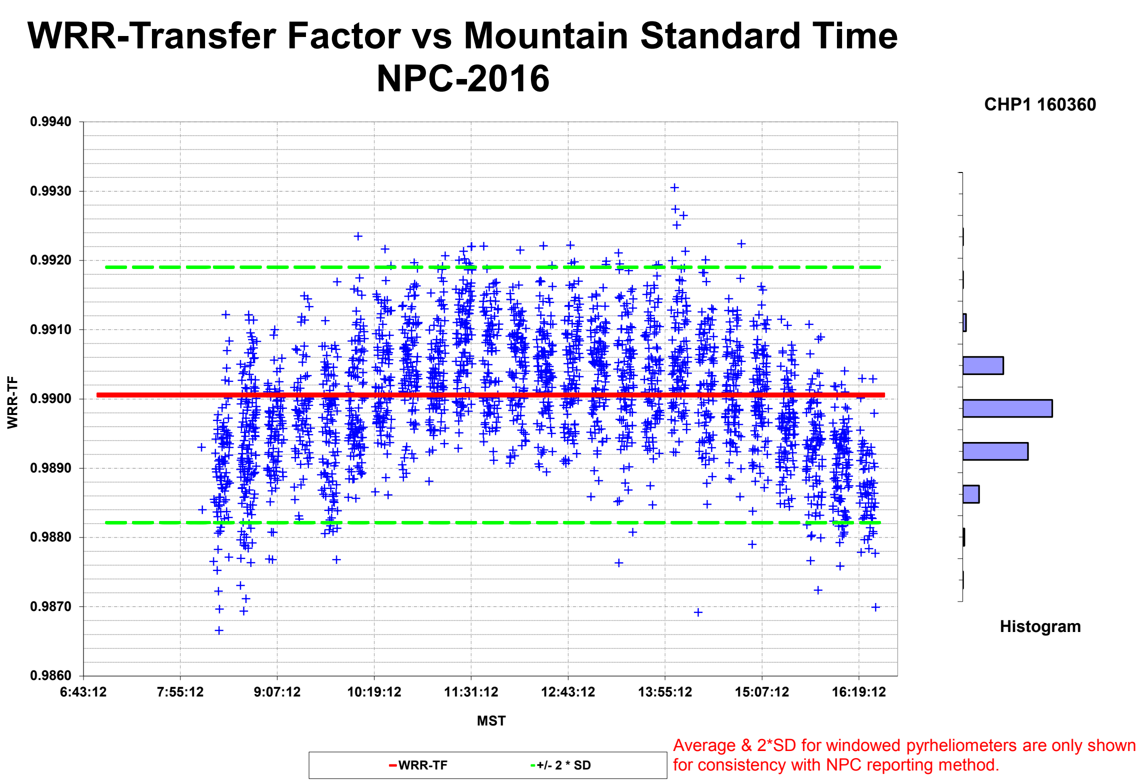


Figure 40. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CHP1 160360

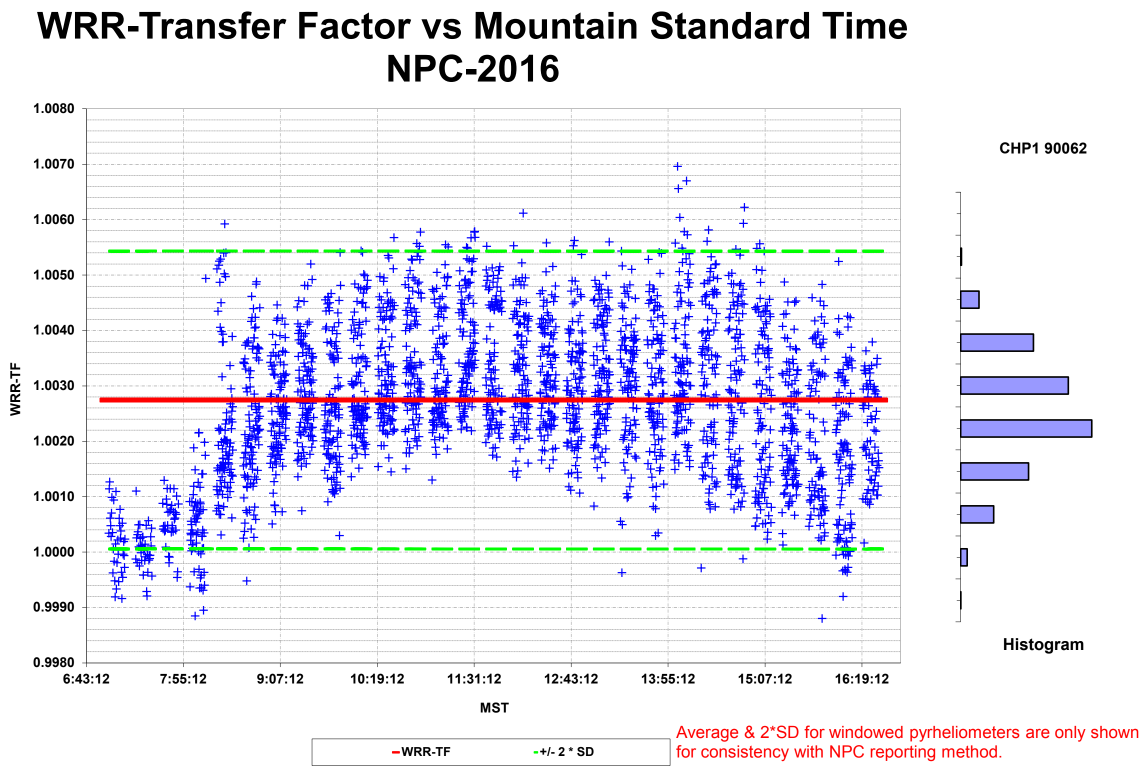


Figure 41. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CHP1 900062

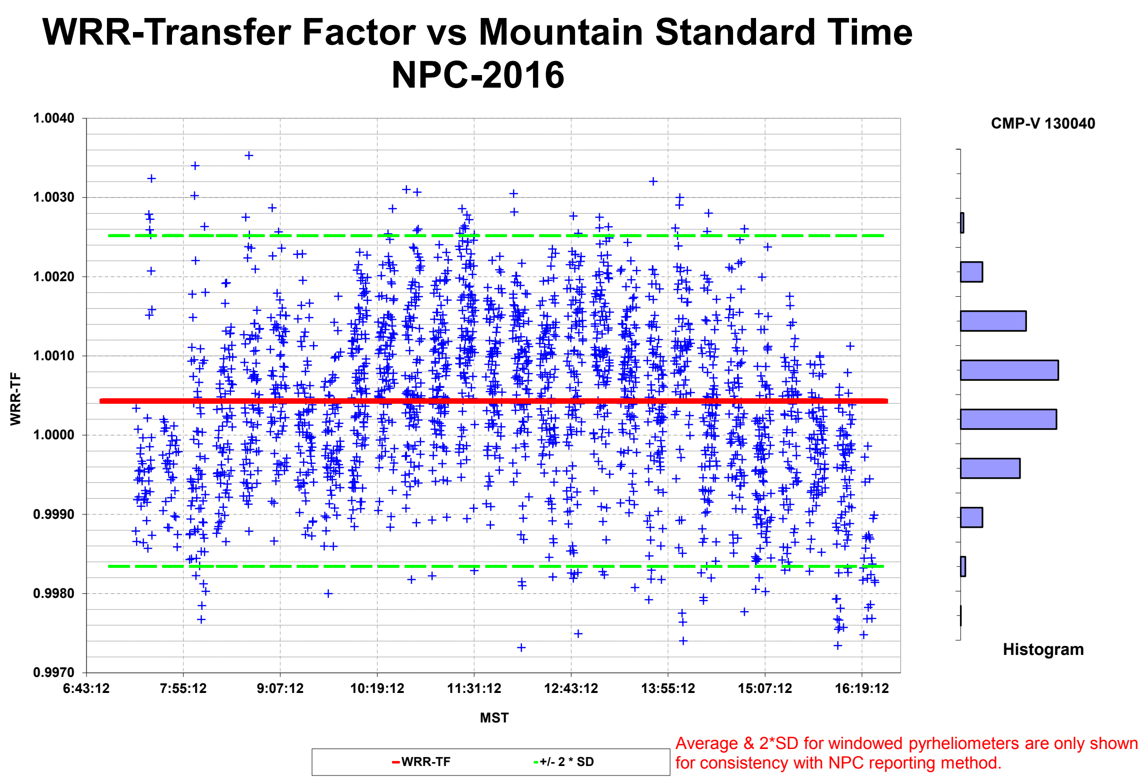


Figure 42. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for CMP-V 130040

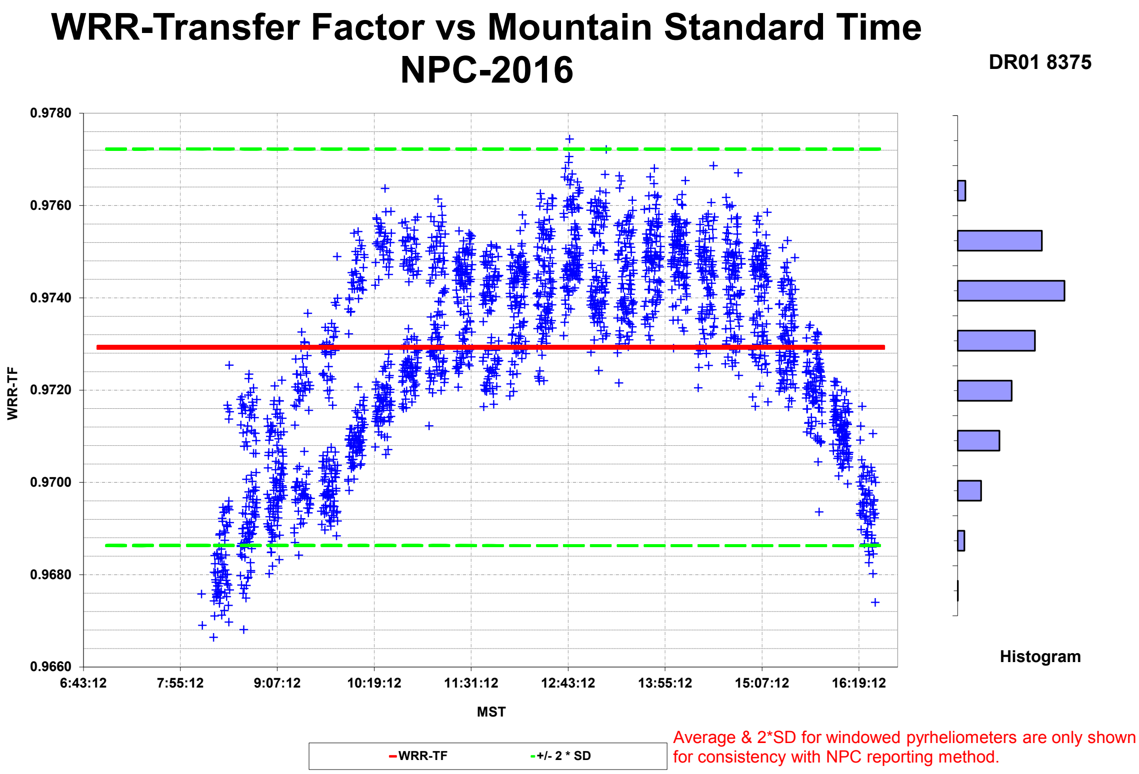


Figure 43. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for DR01 8375

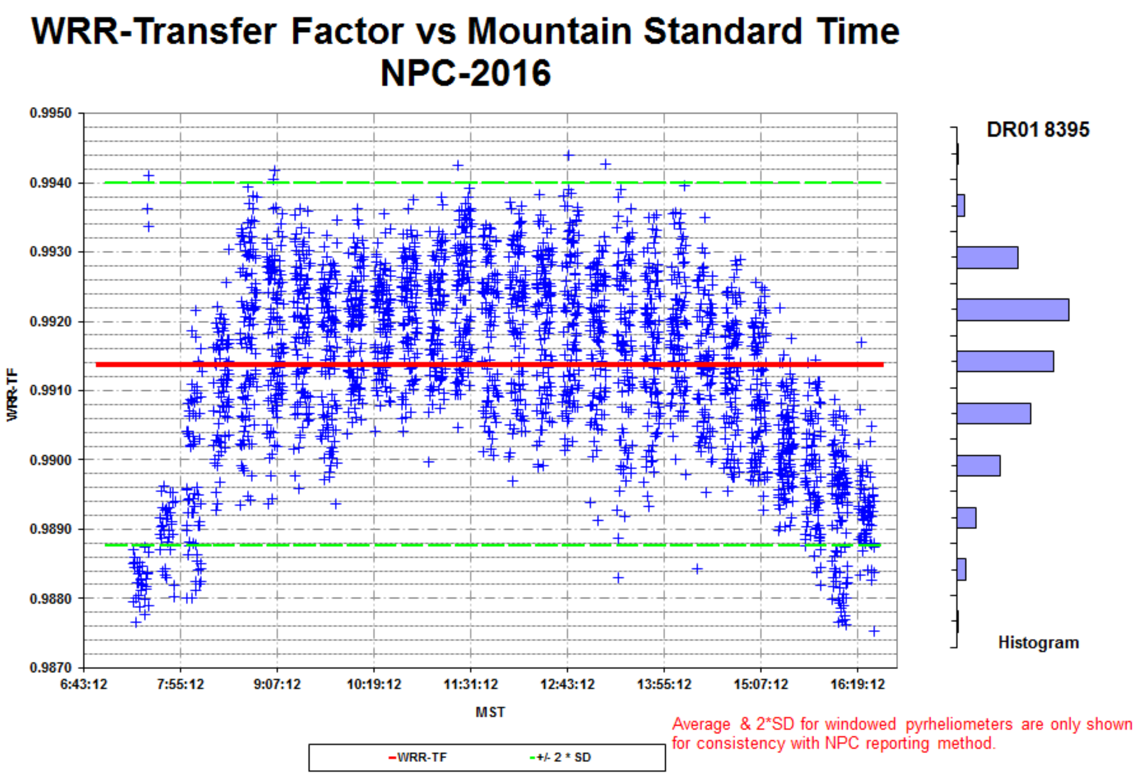


Figure 44. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for DR01 8395

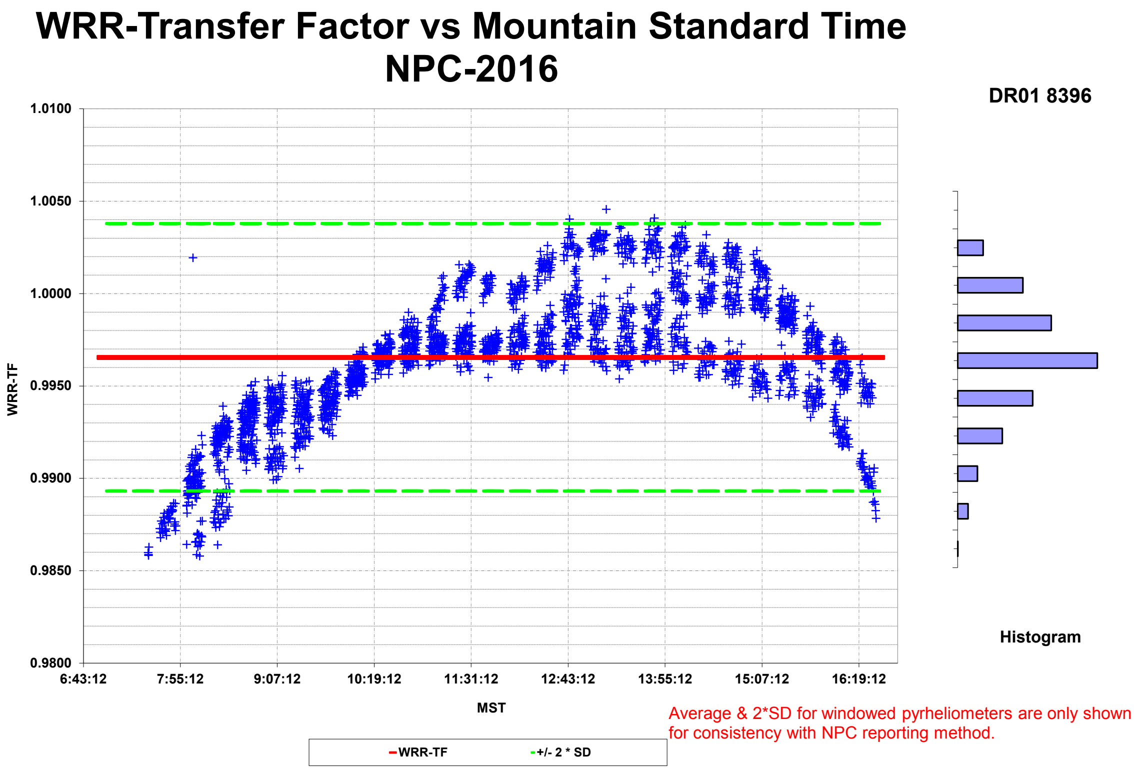


Figure 45. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for DR01 8396

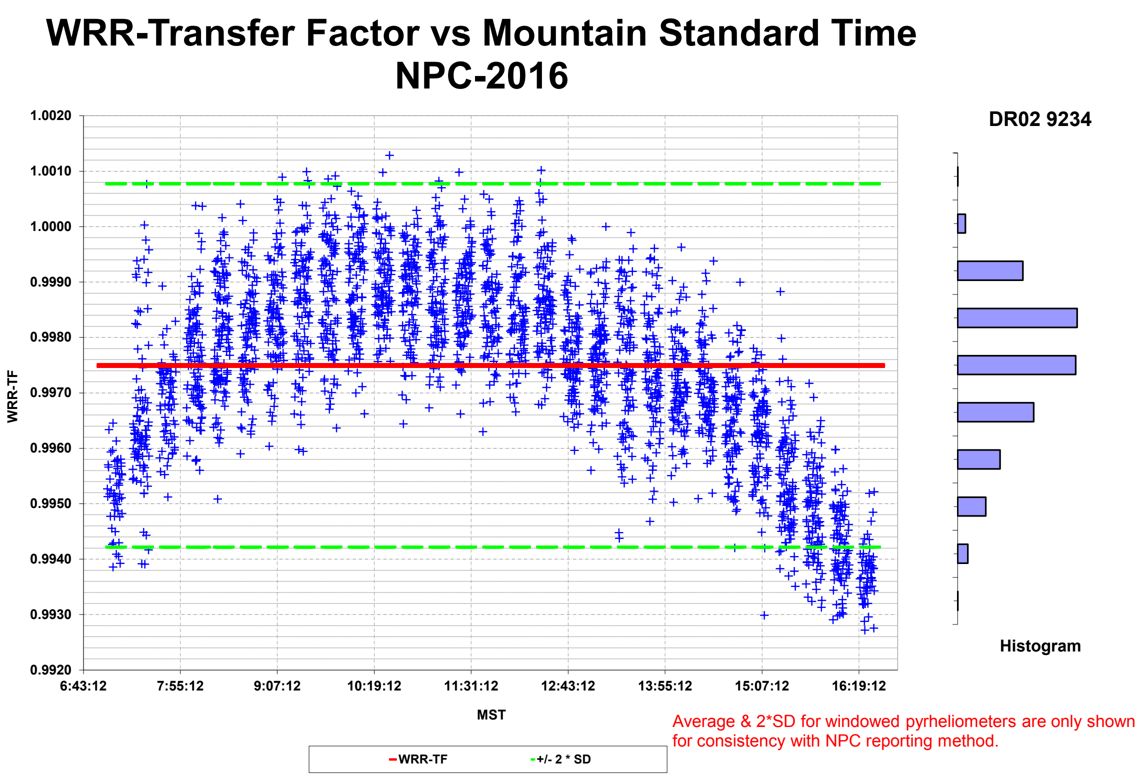


Figure 46. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for DR02 9234

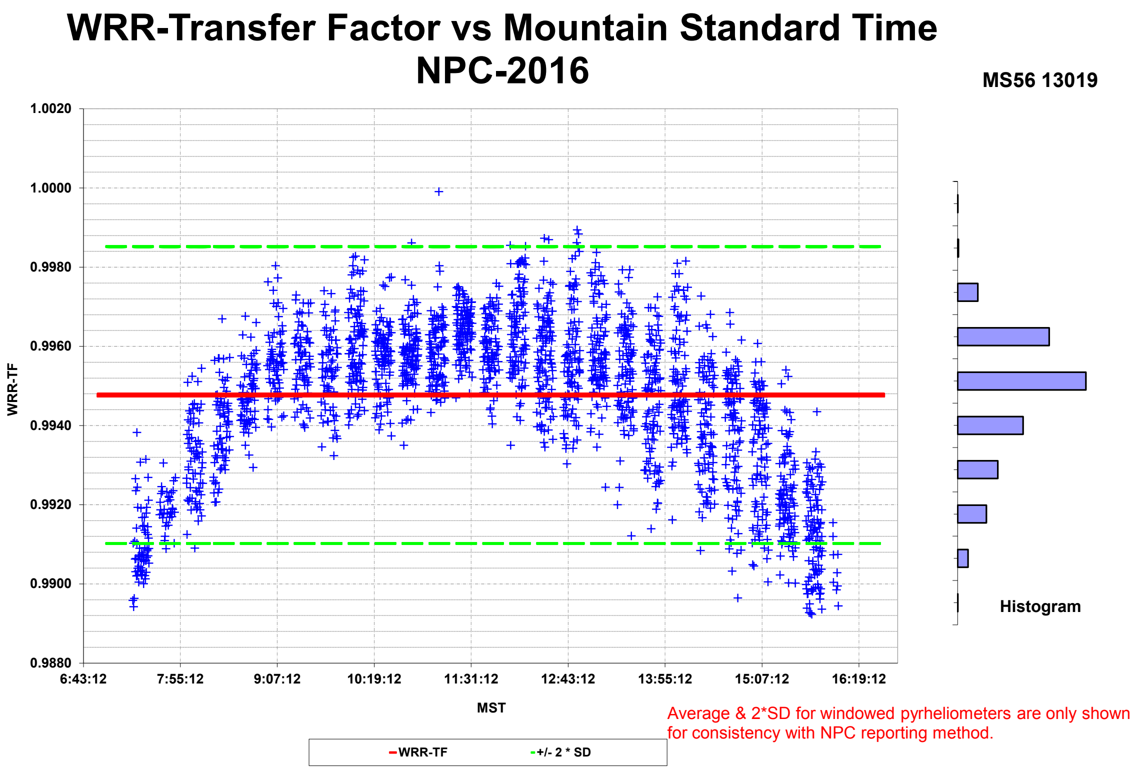


Figure 47. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for MS56 13019

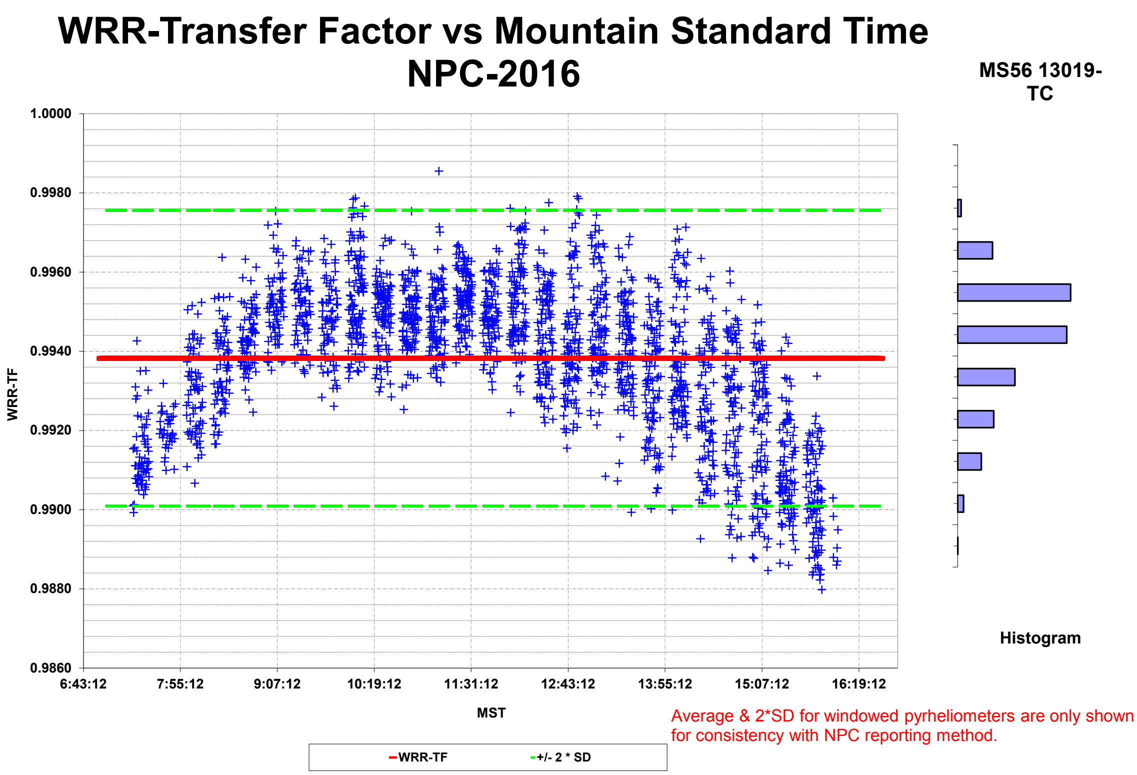


Figure 48. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for MS56 13019-TC

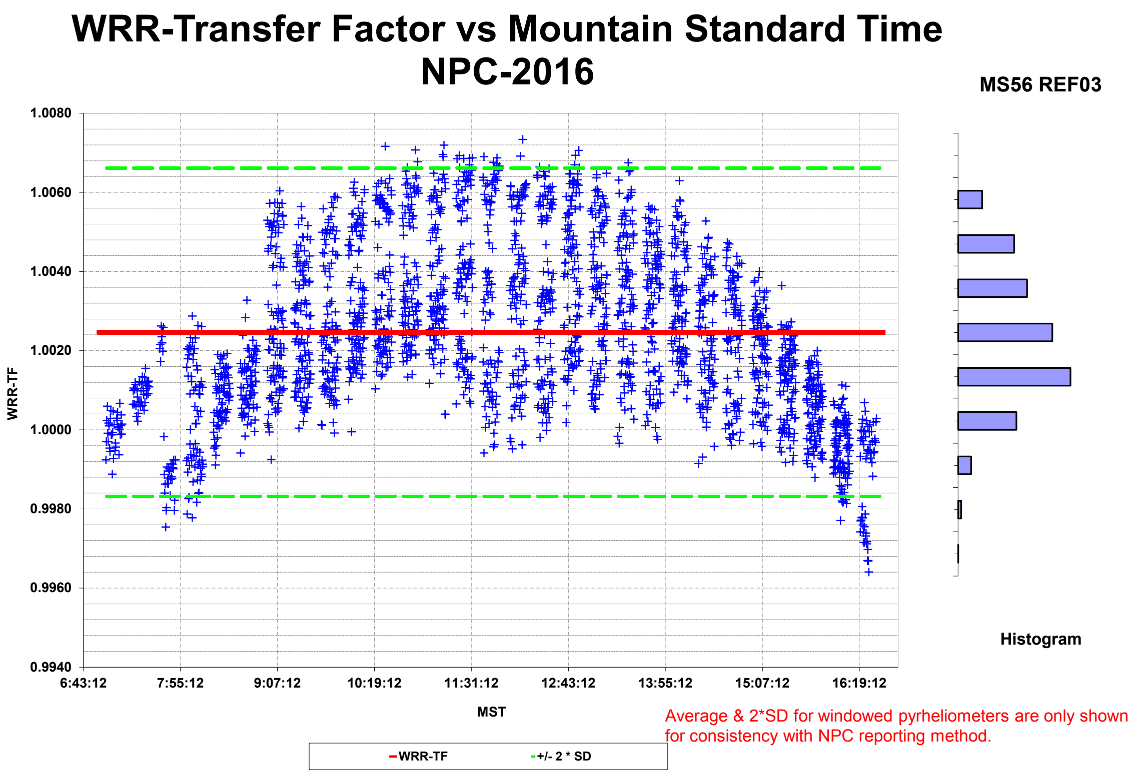


Figure 49. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for MS56 REF03

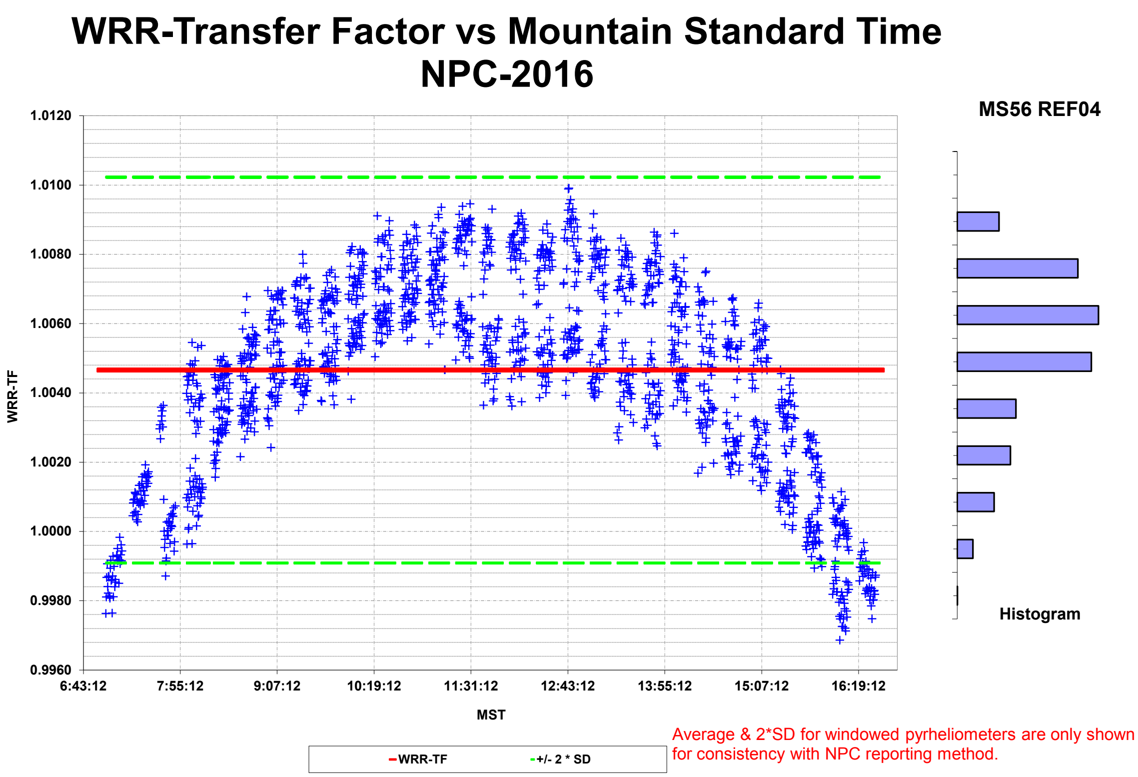


Figure 50. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for MS56 REF04

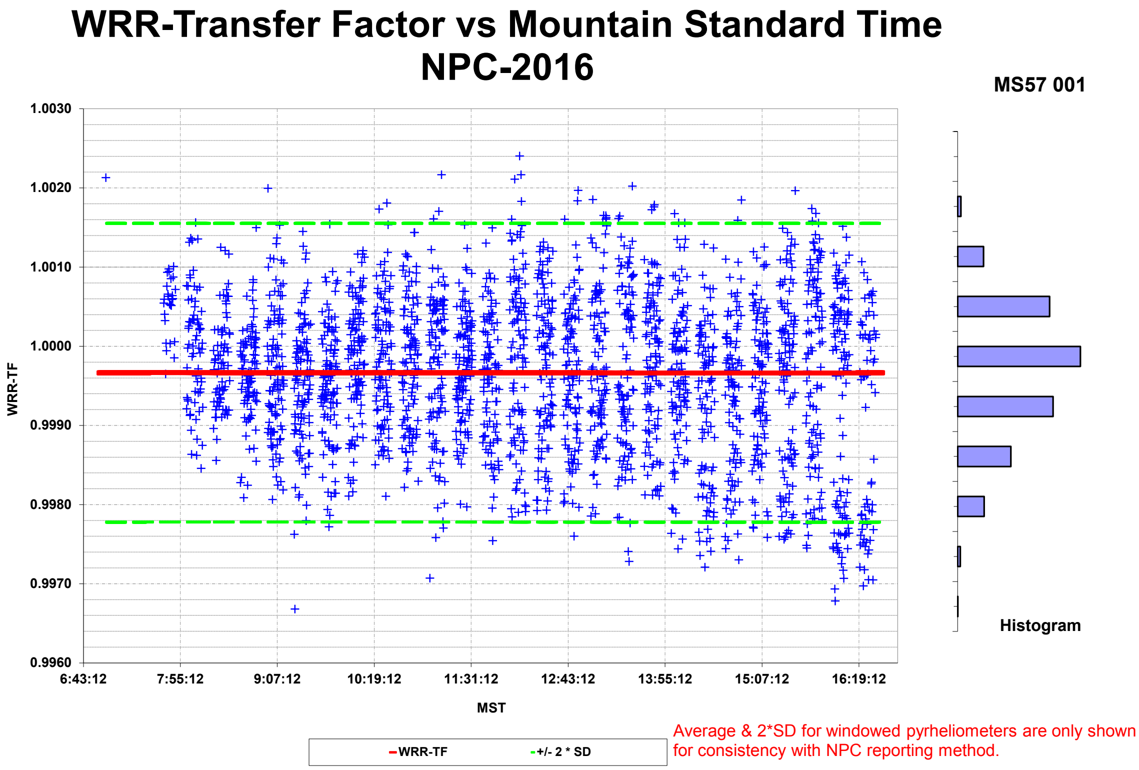


Figure 51. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for MS57 001

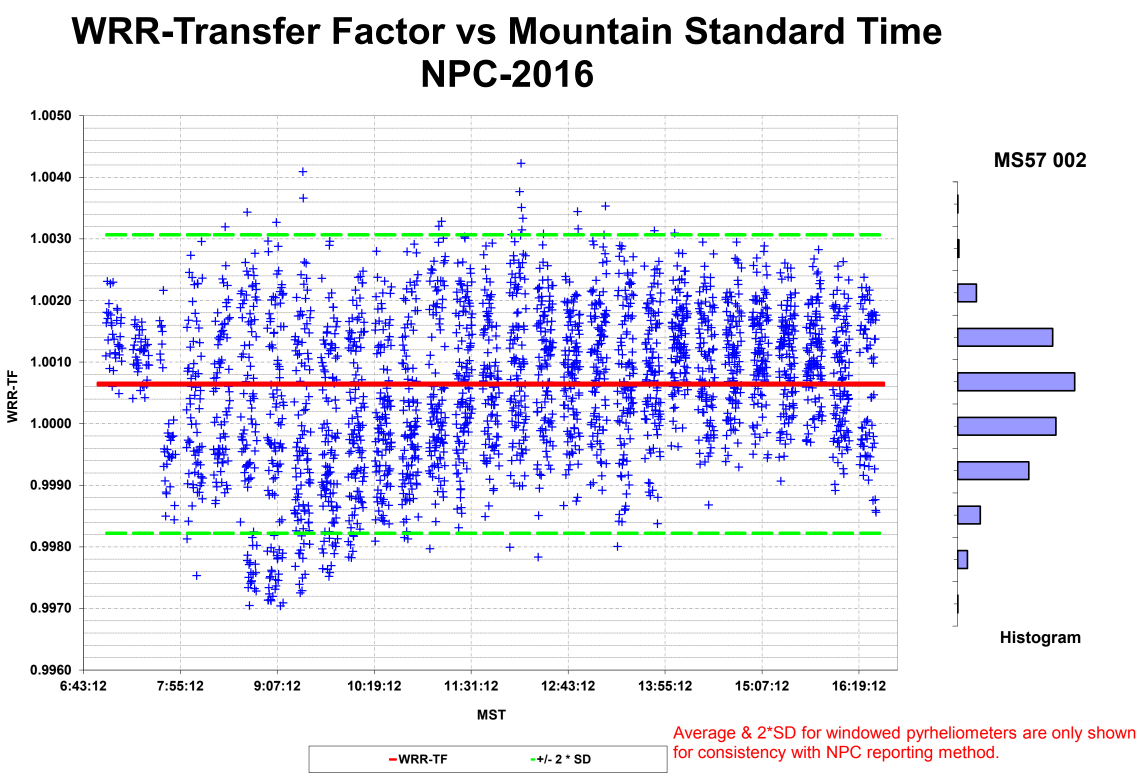


Figure 52. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for MS57 002

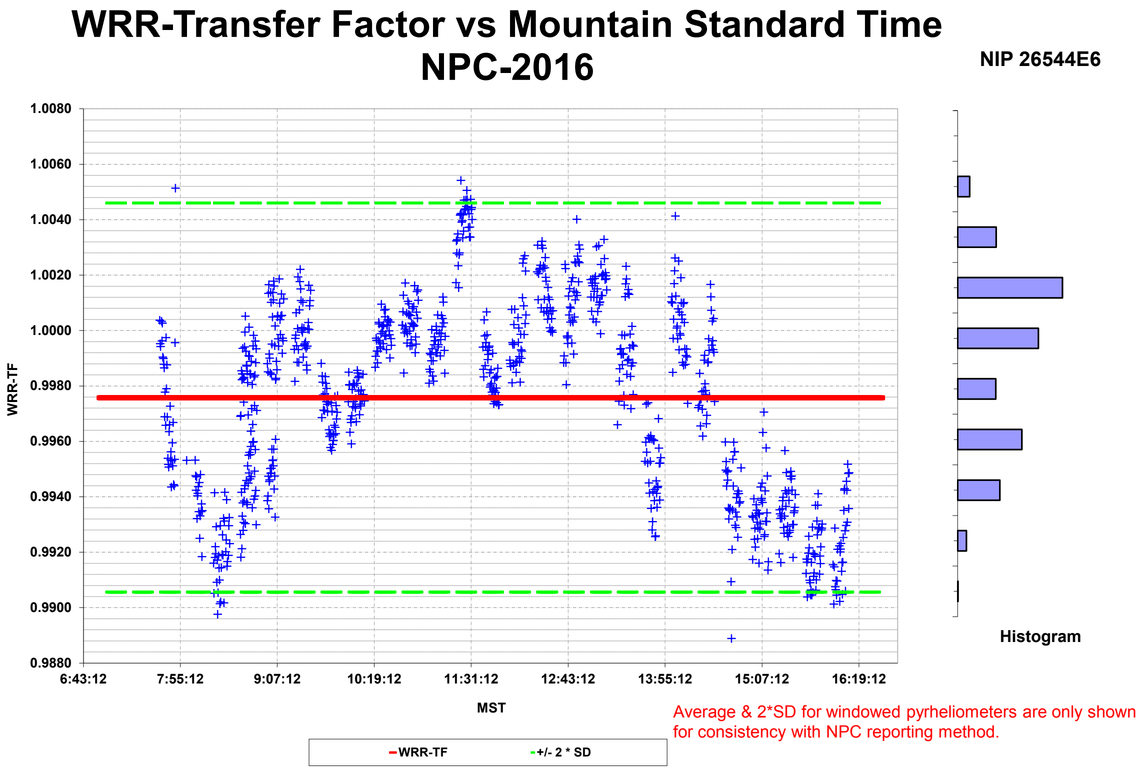


Figure 53. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for NIP 26544E6

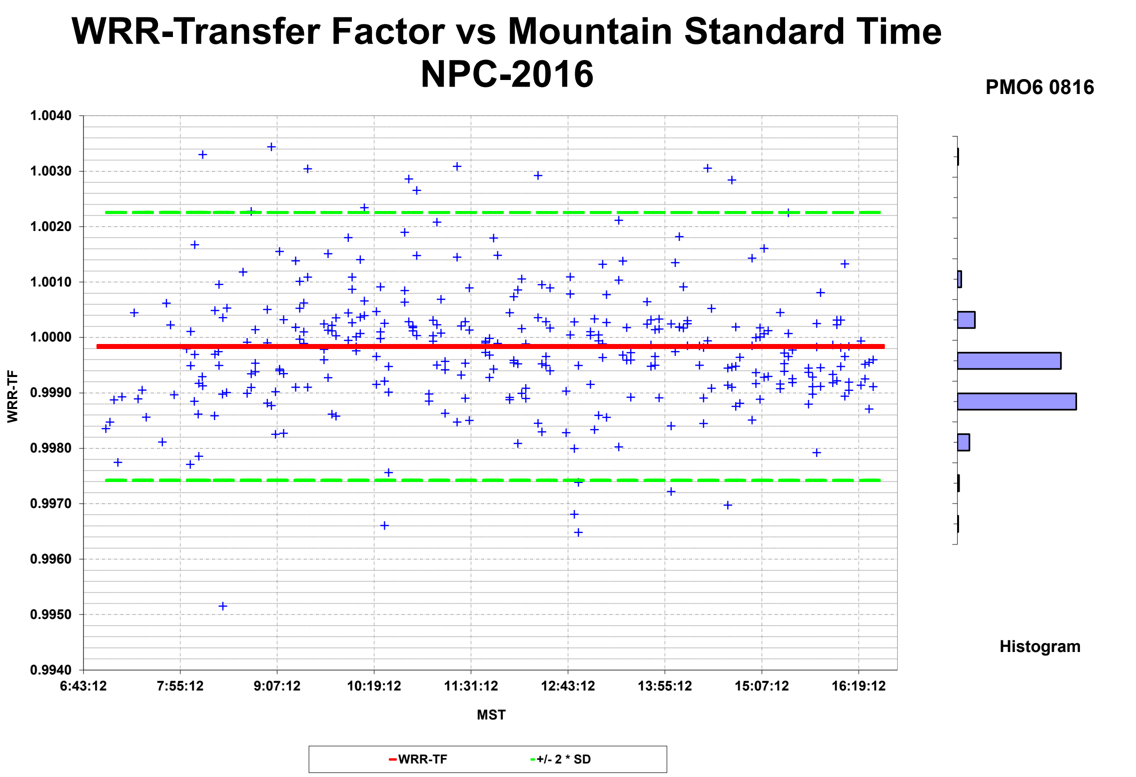


Figure 54. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for PMO6 0816

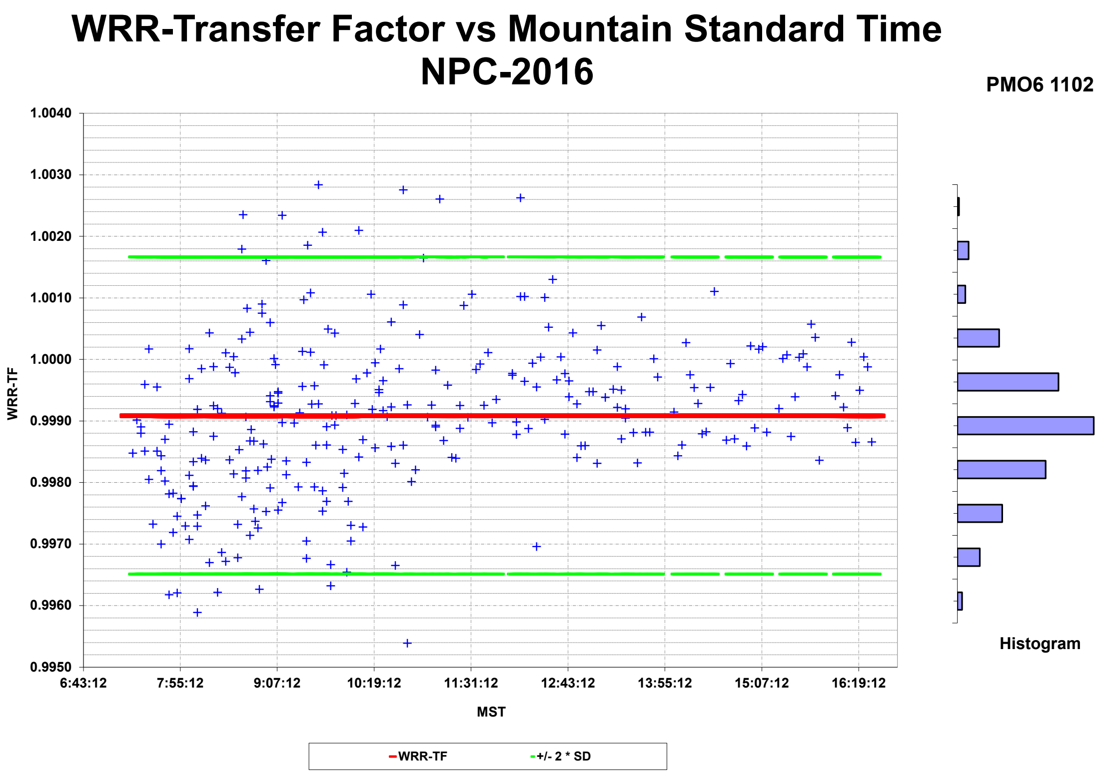


Figure 55. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for PMO6 1102

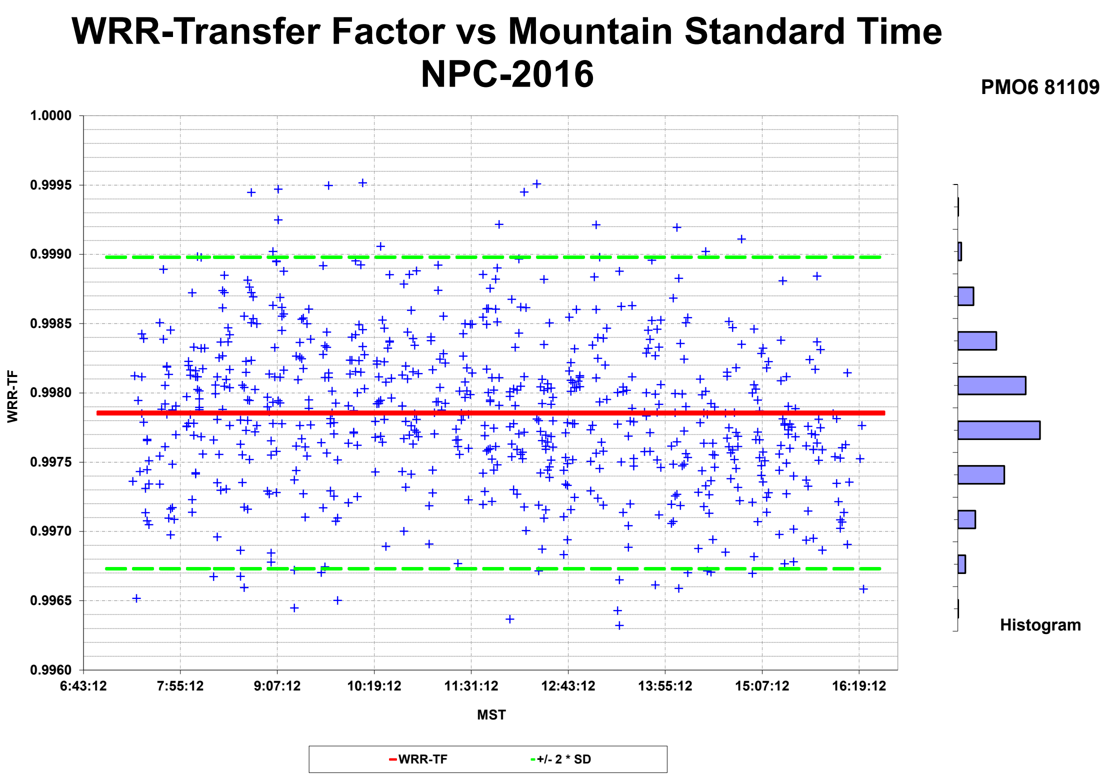


Figure 56. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for PMO6 81109

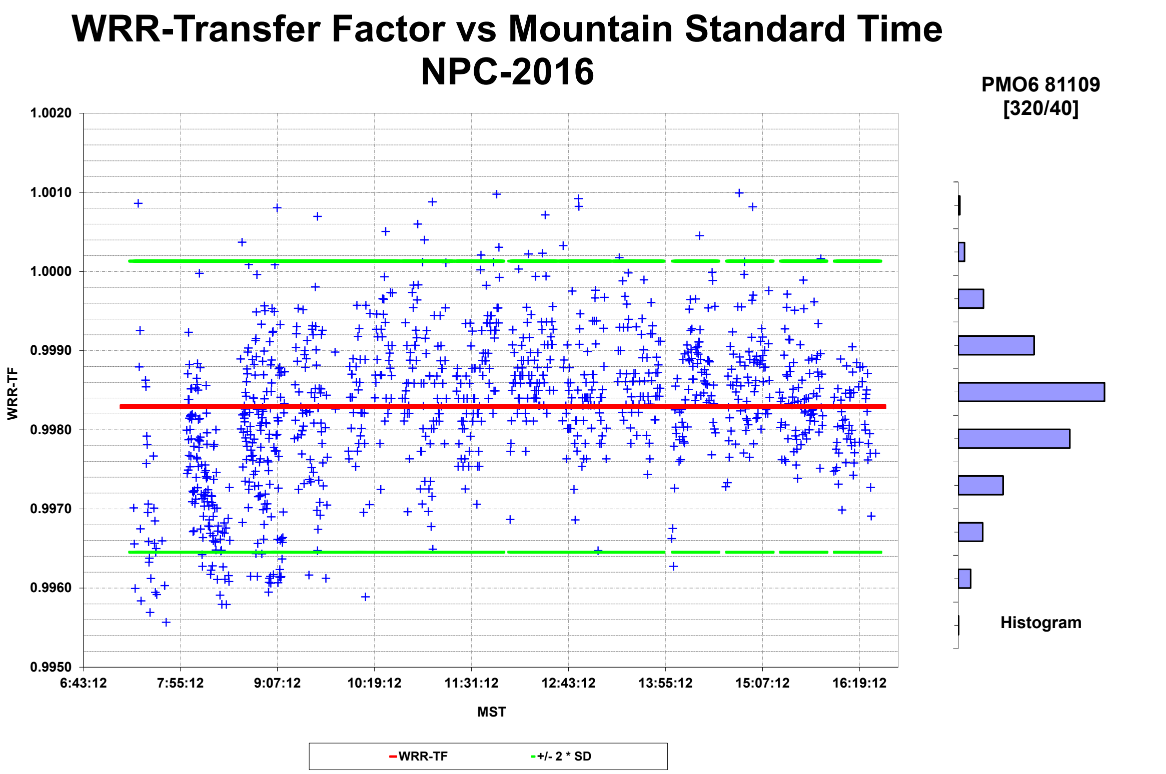


Figure 57. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for PMO6 81109 [320/40]

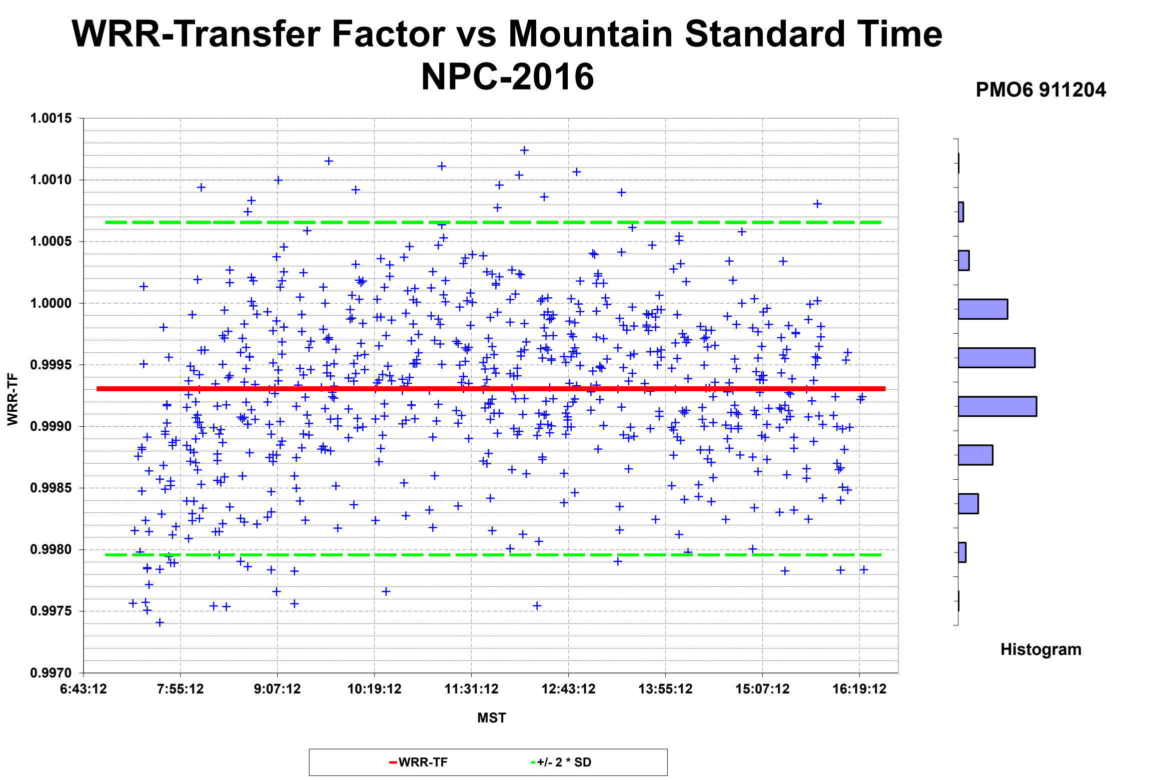


Figure 58. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for PMO6 911204

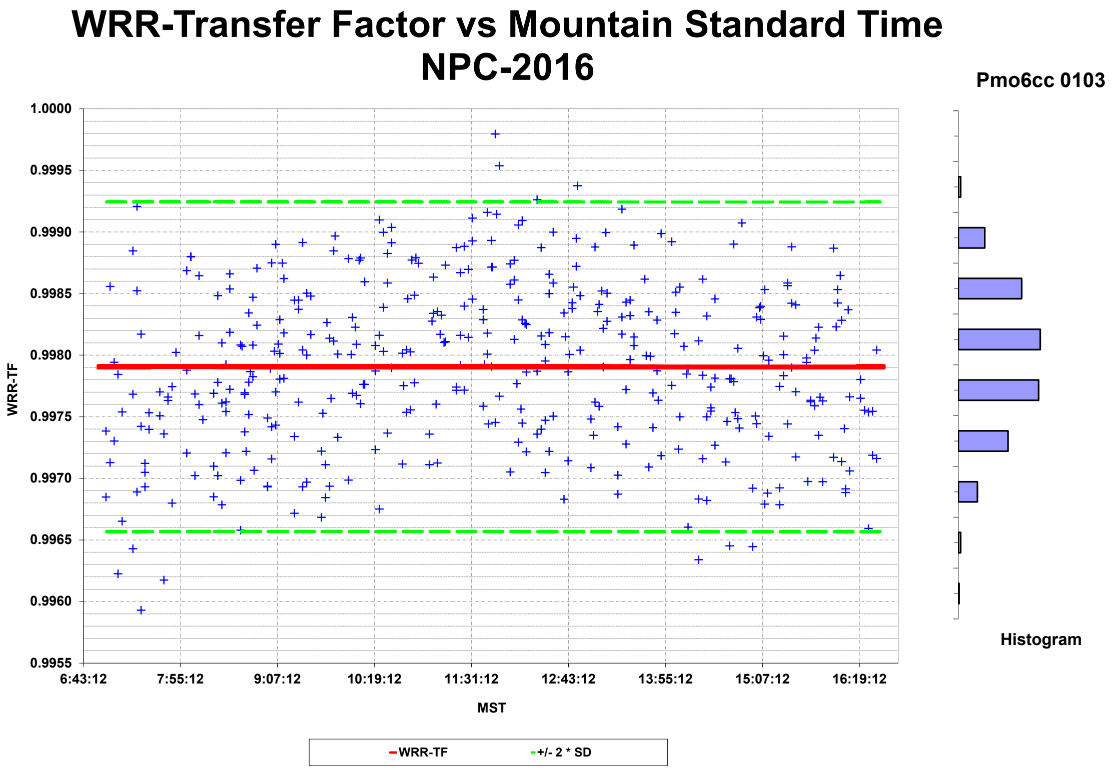


Figure 59. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for Pmo6cc 0103

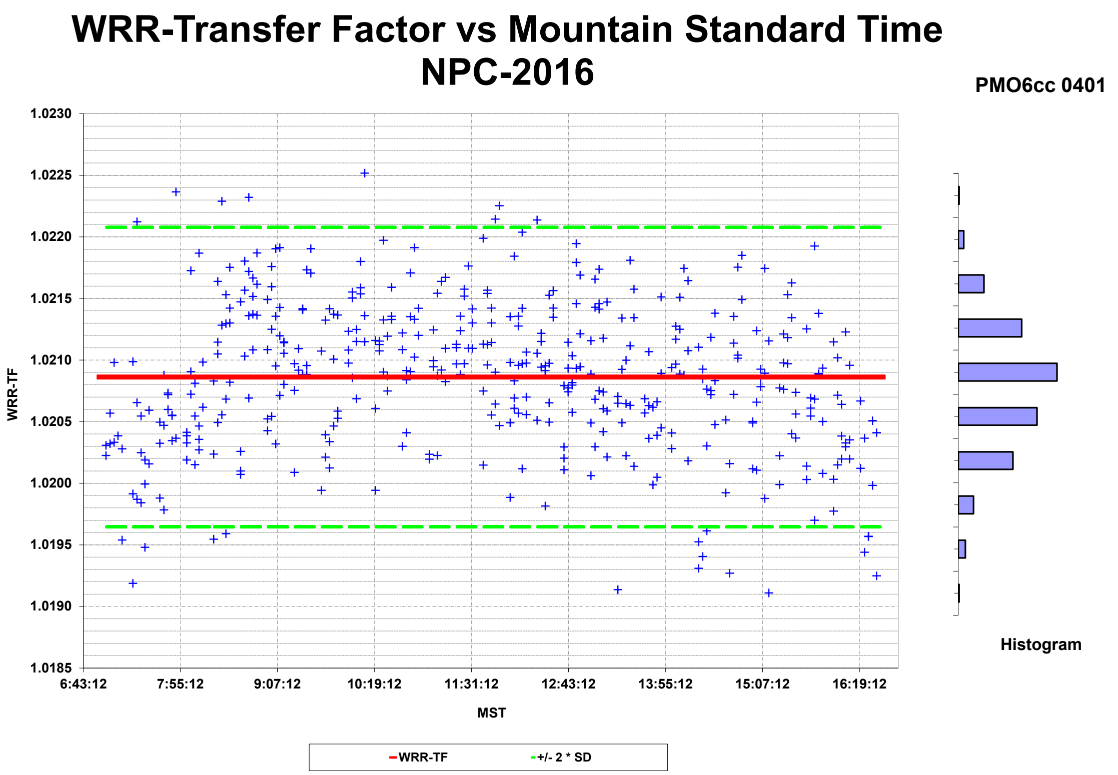


Figure 60. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for PMO6cc 0401

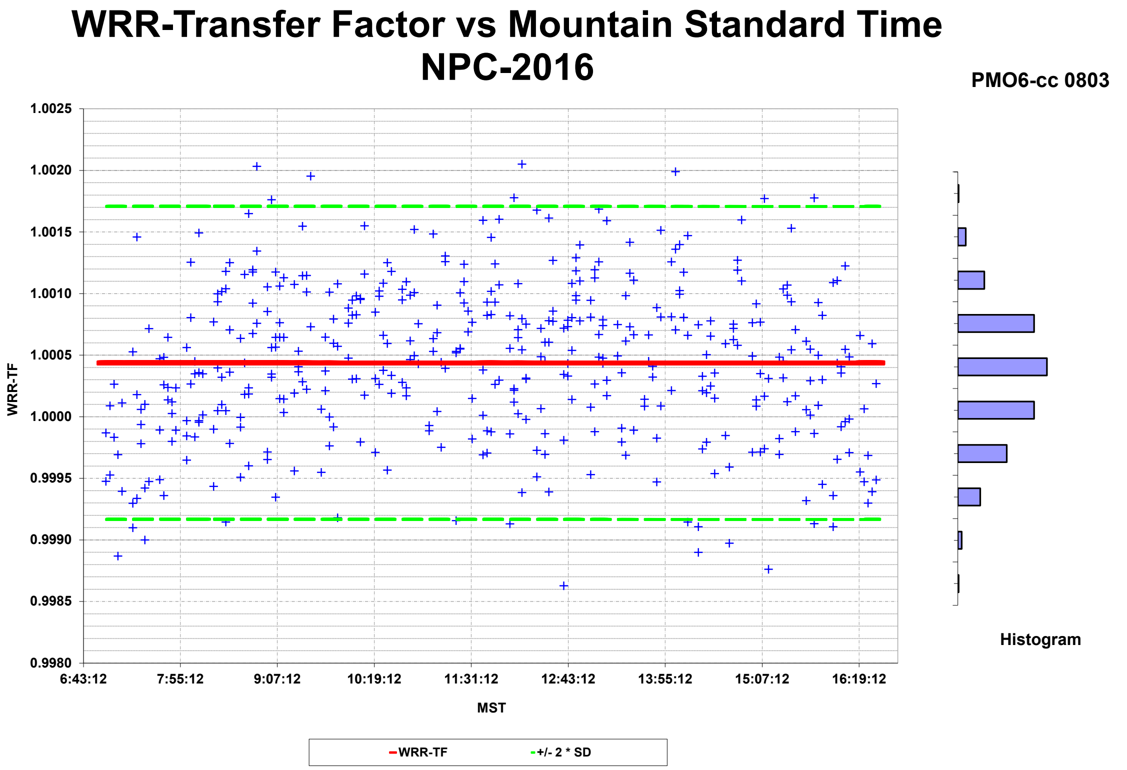


Figure 61. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for PMO6-cc 0803

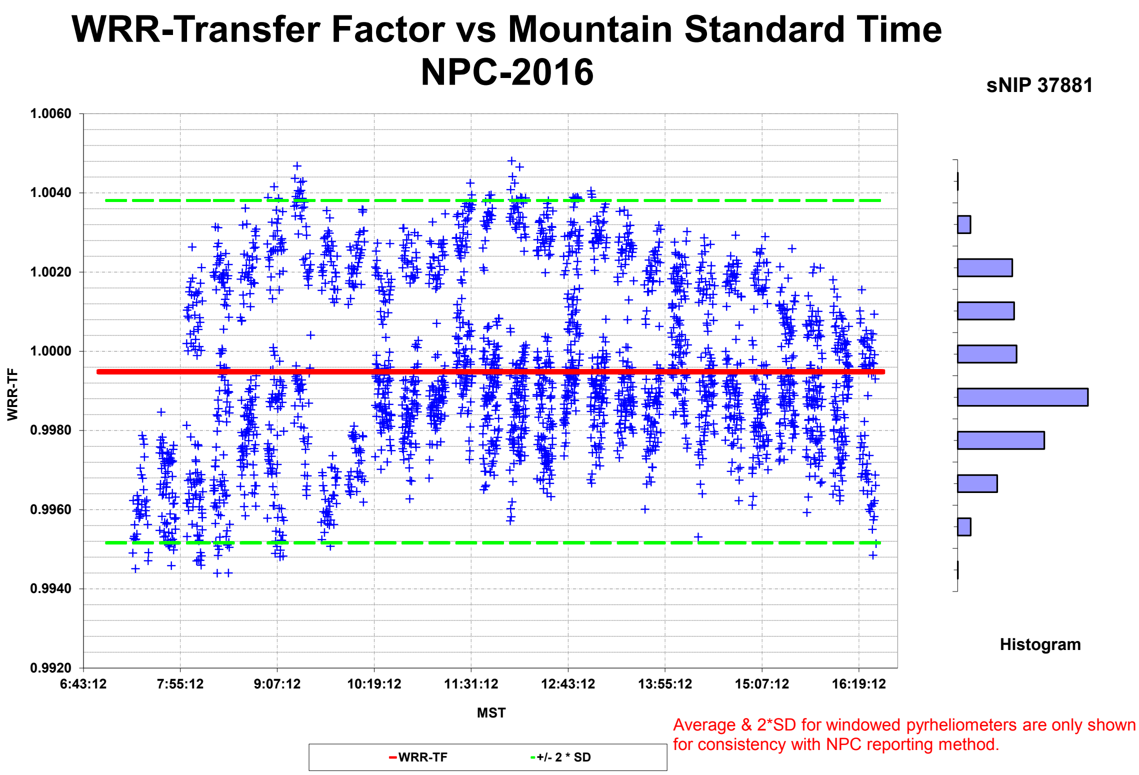


Figure 62. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for sNIP 37881

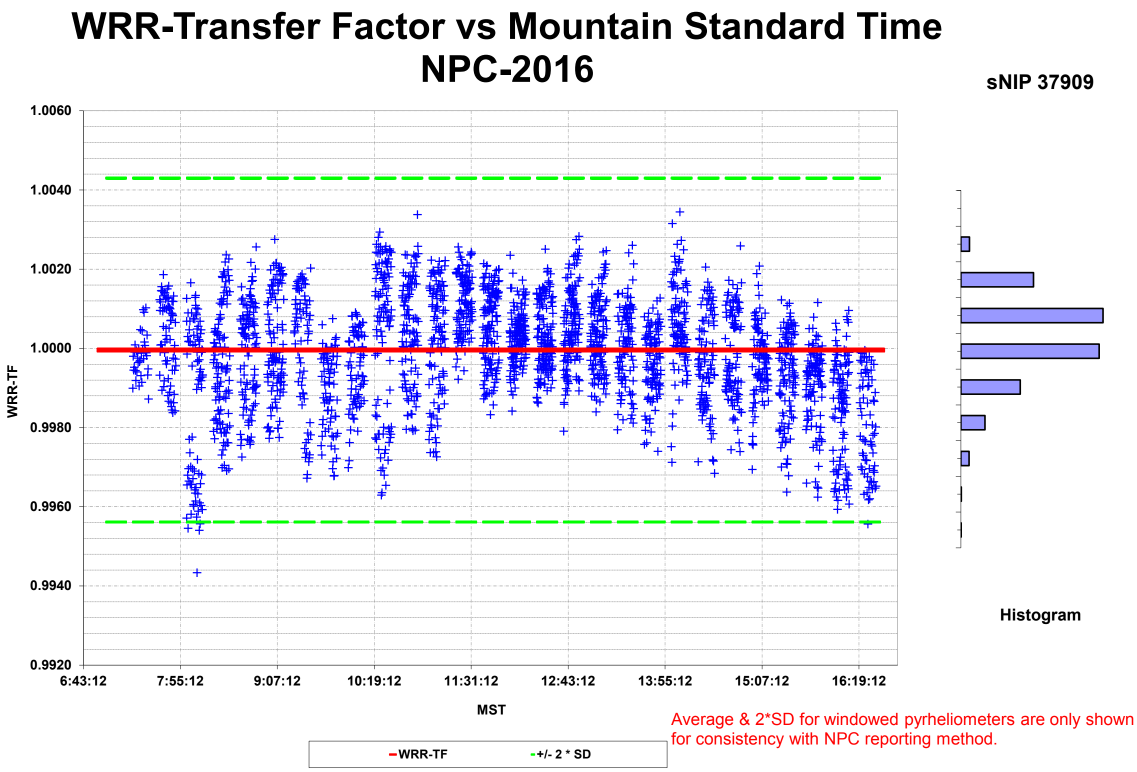


Figure 63. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for sNIP 37909

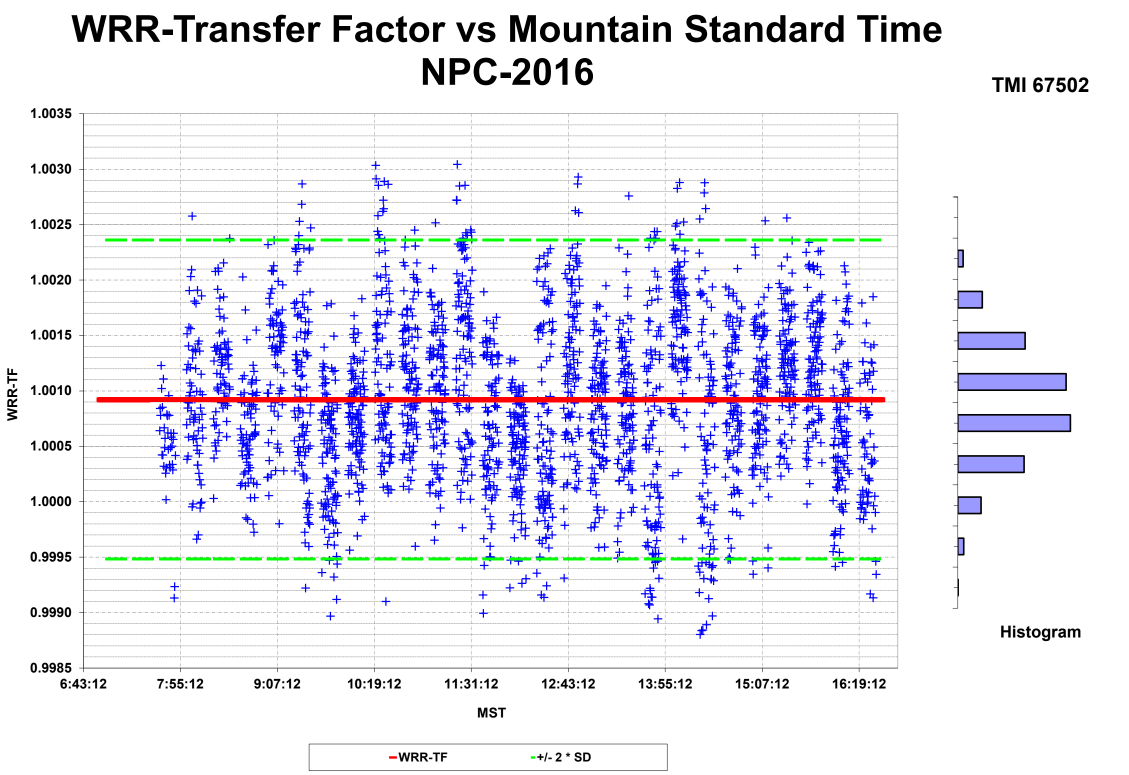


Figure 64. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for TMI 67502

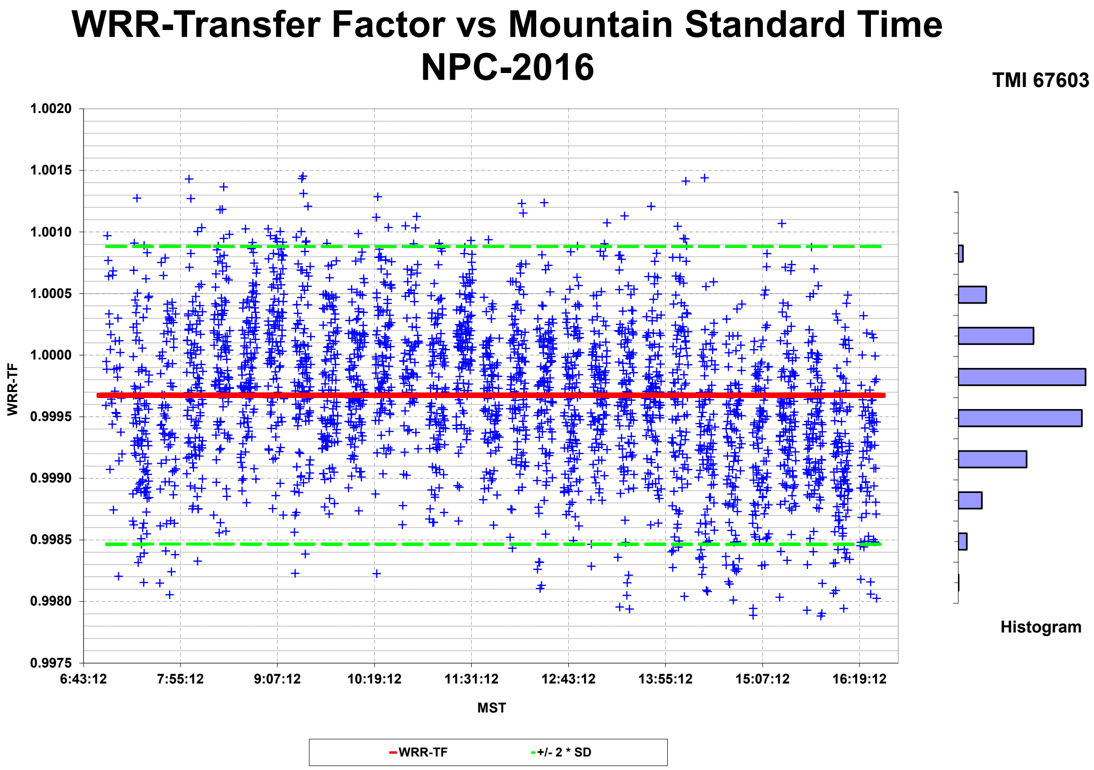


Figure 65. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for TMI 67603

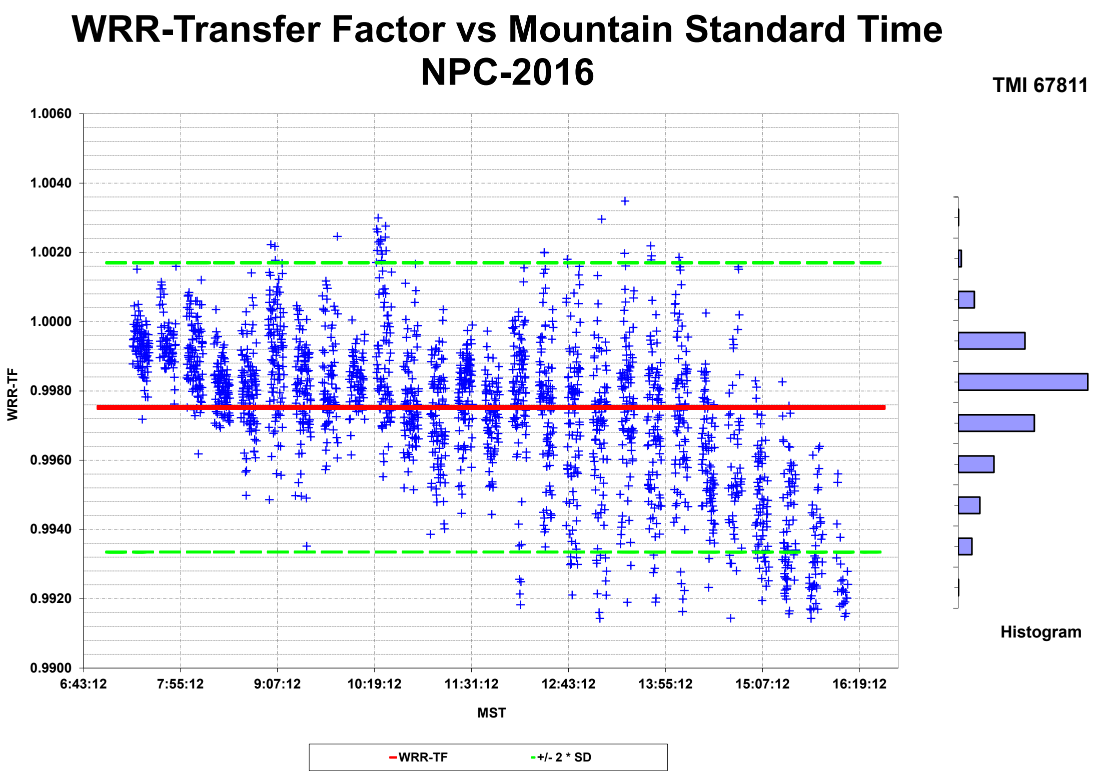


Figure 66. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for TMI 67811

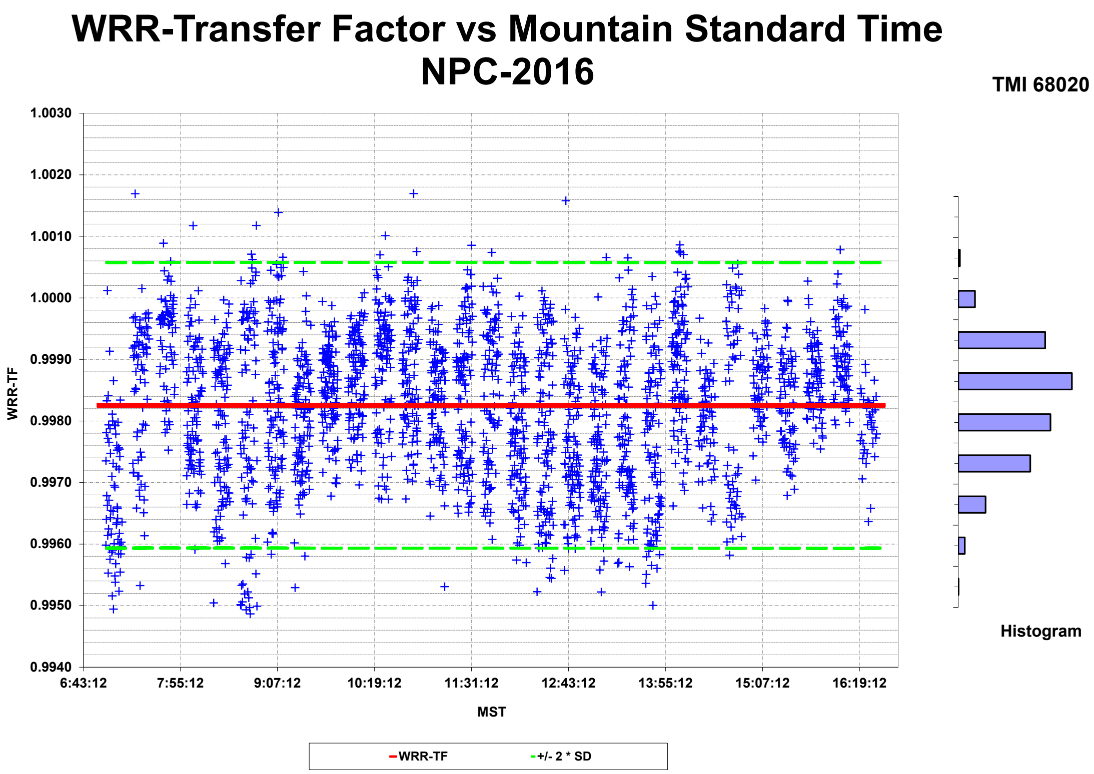


Figure 67. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for TMI 68020

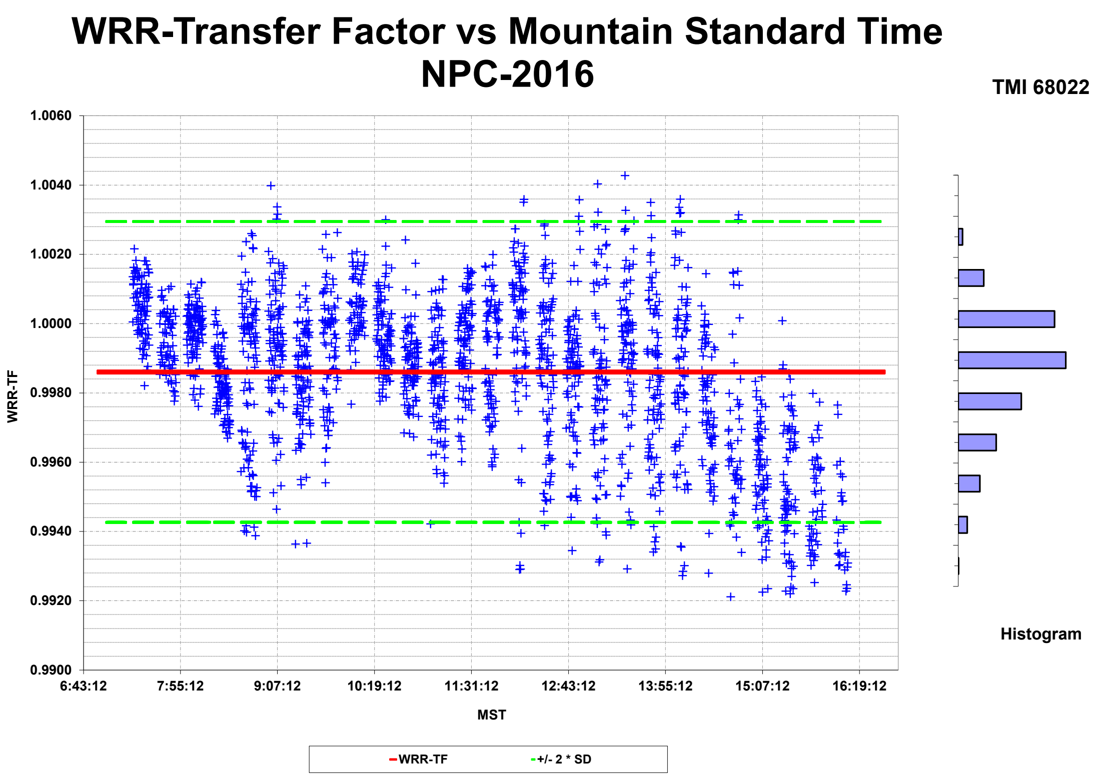


Figure 68. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for TMI 68022

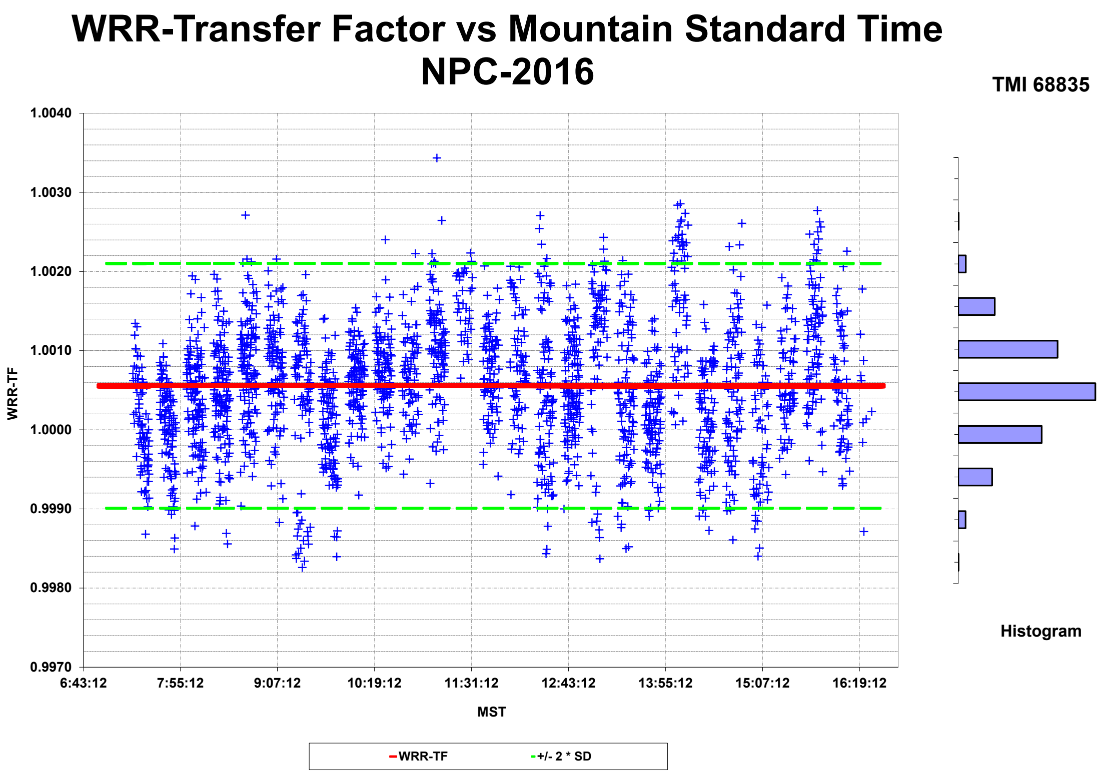


Figure 69. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for TMI 68835

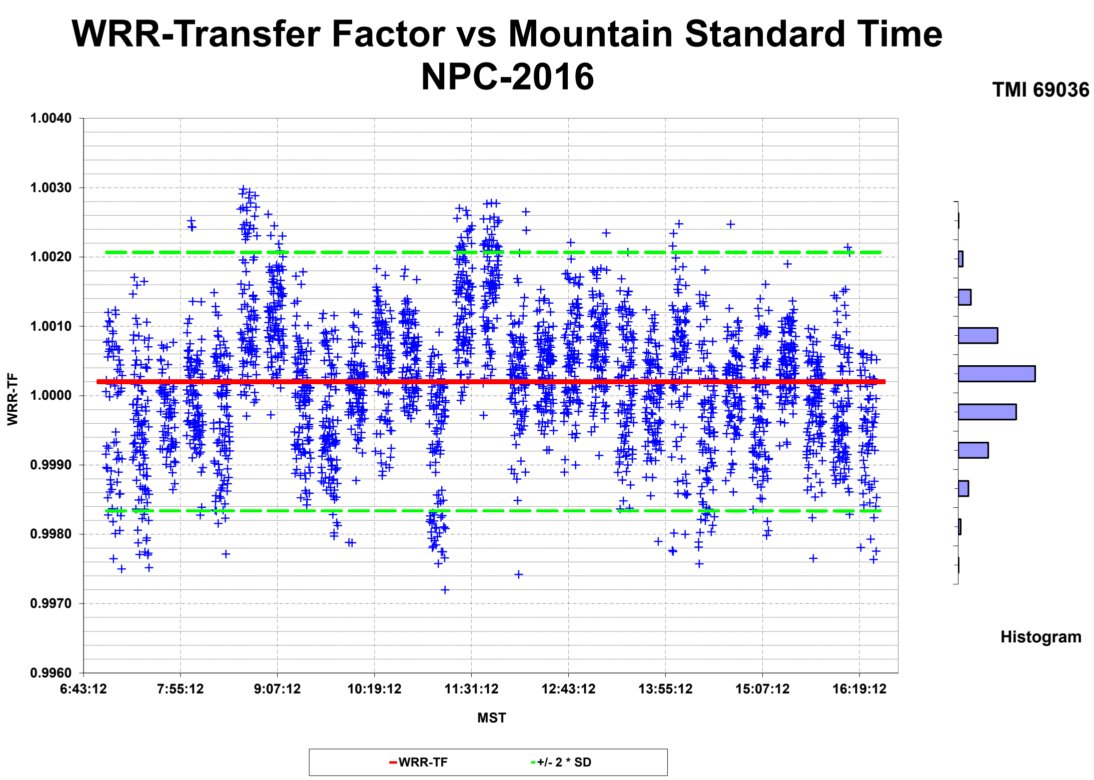


Figure 70. WRR-Transfer Factor vs. Mountain Standard Time NPC-2016 for TMI 69036

4.6 Recommendations

As a result of these comparisons, we suggest that participants observe the following measurement practices:

- For the purpose of pyrheliometer comparisons, such as NPC-2016, we recommend 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. We recommend this approach to realize the benefits of participating in the NPC.
- For future pyrheliometer comparisons, we strongly urge participants to provide their irradiance readings in the following format:

    Serial number

    ##, MM/DD/YYYY, HH:MM:SS, IRR

where,

Serial number = Instrument serial number (first line only)

= Reading number (1 to 37) within the run

MM/DD/YYYY = Month, Day, Year of the reading

HH:MM:SS = Hour, minute, and second of the reading (local standard time, 24-hour clock)

IRR = Computed irradiance (Wm-2) with resolution of XXXX.XX

The file naming convention is suggested to include the radiometer serial number and date of observations (e.g., AHF30713_09202013 would correspond to data from AHF30713 on September 20, 2013).

5 Ancillary Data

The environmental conditions (i.e., temperature, relative humidity, barometric pressure, wind speed, vertical wind shear, 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.

References

Finsterle, W. (2016). *WMO International Pyrheliometer Comparison, IPC-XII, 28 September – 16 October 2015: Final Report.* WMO IOM Report No. 124. Davos, Switzerland; 98 pp.

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

Reda, I. (1996). *Calibration of a Solar Absolute Cavity Radiometer With Traceability to the World Radiometric Reference.* NREL/TP-463-20619. Golden, CO: The National Renewable Energy Laboratory. Accessed April 9, 2013: www.nrel.gov/docs/legosti/fy96/20619.pdf

Reda, I.; Myers, D.; Stoffel, T. (December 2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure* (NCSLI Journal of Measurement Science) (3:4); pp. 58-66. NREL/JA-581-41370.

Romero, J. (1995). *Direct Solar Irradiance Measurements with Pyrheliometers: Instruments and Calibrations. IPC-VIII.* Davos, Switzerland. 16 pp.

Romero, J.; Fox, N.P.; Fröhlich, C. (May 1996). "Improved Comparison of the World Radiometric Reference and the SI Radiometric Scale." *Metrologia* (32:6); pp. 523-524.

WRC/PMOD (1996). *International Pyrheliometer Comparison, IPC VIII, 25 September – 13 October 1995, Results and Symposium.* Working Report No. 188. Davos Dorf, Switzerland: Swiss Meteorological Institute, Dorfstrasse 33, CH-7260; 115 pp.

Appendix A: List of Participants and Pyrheliometers

S/N	Operator 1	Operator 2	Affiliation
AHF 0000	Wim Zaaiman		JRC
AHF 14917	Emiel Hall	Jim Wendell	NOAA
AHF 15746	Ajay Singh		Campbell Scientific Inc.
AHF 17142	Patrick Smith		Atlas Material Testing Technology, LLC
AHF 23734	Ibrahim Reda	Afshin Andreas Mike Dooraghi	NREL
AHF 28553	Emiel Hall	Jim Wendell	NOAA
AHF 28556	Patrick Smith		Atlas Material Testing Technology, LLC
AHF 28560	Erik Naranen		ISO-CAL North America, LLC
AHF 29219-Windowed	Ibrahim Reda	Afshin Andreas Mike Dooraghi	NREL
AHF 29222-Windowed	Craig Webb		DOE Atmospheric Radiation Measurement (ARM) Program
AHF 29223	Mike Dooraghi		UNAM
AHF 30495	Craig Webb		DOE Atmospheric Radiation Measurement (ARM) Program
AHF 30710	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 30710-Windowed	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 31041	Fred Denn		NASA Langley
AHF 31102	ChengMin Yao	Cheng-Hsien Hsu	National Central University
AHF 31105	Fred Denn		NASA Langley
AHF 31108	Bill Boyson	Craig Carmignani	Sandia National Laboratories
AHF 31114AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 31116AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 31116AWX-Windowed	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 32448AWX	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
AHF 32452AWX-Windowed	Ibrahim Reda	Afshin Andreas Mike Dooraghi	NREL
AHF 32455	Christian Thomann		PMOD/WRC
AHF 34926	Rich Kessler		University of Oregon
AHF 37816	Erik Naranen		ISO-CAL North America, LLC
CH1 040370	Wim Zaaiman		JRC
CH1 060460	Wim Zaaiman		JRC

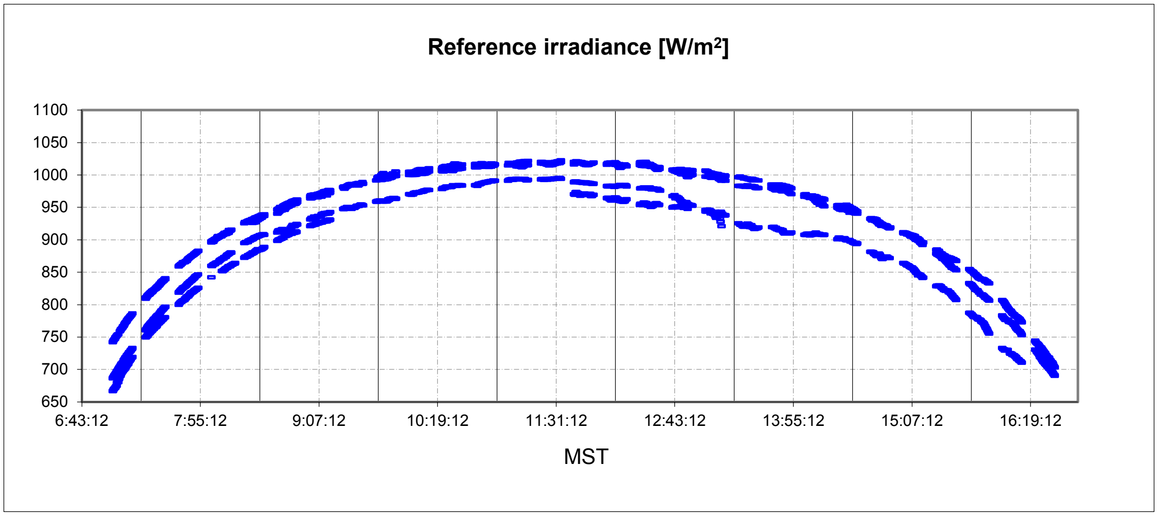
S/N	Operator 1	Operator 2	Affiliation
CH1 070541	Victor Cassella	Joop Mes	Kipp & Zonen USA, Inc
CH1 080066	ChengMin Yao	Cheng-Hsien Hsu	National Central University
CH1 70571	James Augustyn		Augustyn + Company
CH1 930018	Wim Zaaiman		JRC
CHP1 090127	Victor Cassella	Joop Mes	Kipp & Zonen USA, Inc
CHP1 110533	Wim Zaaiman		JRC
CHP1 110628	Ajay Singh		Campbell Scientific Inc.
CHP1 131132	Justin Robinson		GroundWork Renewables Inc.
CHP1 160338	ChengMin Yao	Cheng-Hsien Hsu	National Central University
CHP1 160360	IL-SUNG Zo	SE-HUN Rim	Gangneung-Wonju National University
CHP1 90062	Justin Robinson		GroundWork Renewables Inc.
CMP-V 130040	James Augustyn		Augustyn + Company
DR01 8375	Justin Robinson		GroundWork Renewables Inc.
DR01 8395	Justin Robinson		GroundWork Renewables Inc.
DR01 8396	Jörgen Konings	Robert Dolce	HuksefluxUSA, Inc.
DR02 9234	Jörgen Konings	Robert Dolce	HuksefluxUSA, Inc.
MS56 P13019	James Augustyn		Augustyn + Company
MS56 P13019-TC	James Augustyn		Augustyn + Company
MS56 REF03	William Beuttell	Tsukasa Kobashi Kazunori Shibayama	EKO Instruments USA, Inc
MS56 REF04	William Beuttell	Tsukasa Kobashi Kazunori Shibayama	EKO Instruments USA, Inc
MS57 001	William Beuttell	Tsukasa Kobashi Kazunori Shibayama	EKO Instruments USA, Inc
MS57 002	William Beuttell	Tsukasa Kobashi Kazunori Shibayama	EKO Instruments USA, Inc
NIP 26544E6	ChengMin Yao	Cheng-Hsien Hsu	National Central University
PMO6 0816	William Beuttell	Tsukasa Kobashi Kazunori Shibayama	EKO Instruments USA, Inc
PMO6 1102	Mike Dooraghi		UNAM
PMO6 81109	Wim Zaaiman		JRC
PMO6 911204	Wim Zaaiman		JRC
Pmo6cc 0103	Victor Cassella	Joop Mes	Kipp & Zonen USA, Inc
PMO6cc 0401	Christian Thomann		PMOD/WRC

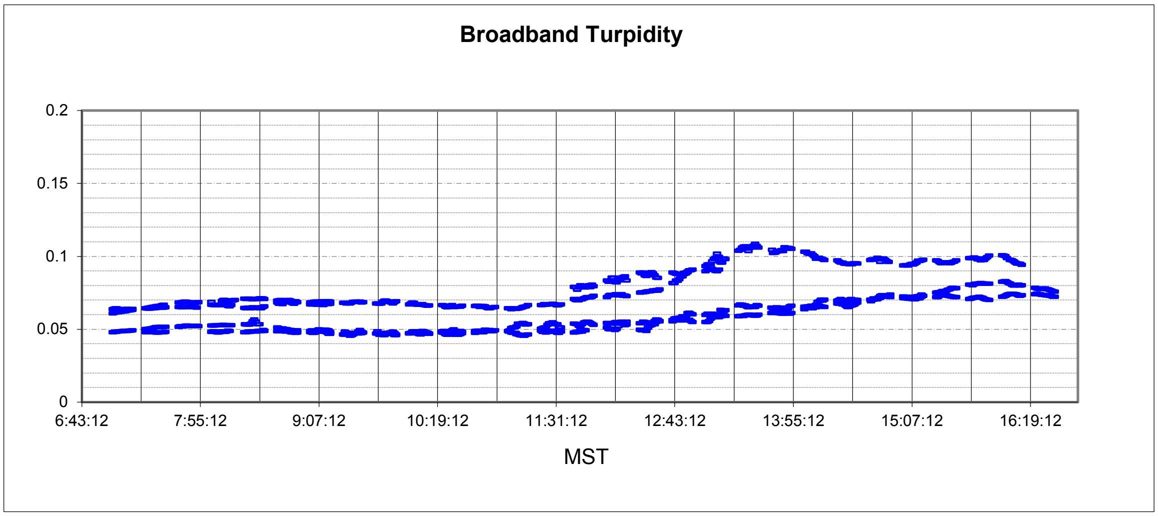
S/N	Operator 1	Operator 2	Affiliation
PMO6-cc 0803	Christian Thomann		PMOD/WRC
sNIP 37881	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
sNIP 37909	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
TMI 67502	Emiel Hall	Jim Wendell	NOAA/ESRL/GMD
TMI 67603	Bill Boyson	Craig Carmignani	Sandia National Laboratories
TMI 67811	Tim Moss		Sandia National Laboratories
TMI 68020	Mark Goochey		Lockheed Martin
TMI 68022	Tim Moss		Sandia National Laboratories
TMI 68835	Wim Zaaiman		JRC
TMI 69036	Ibrahim Reda	Afshin Andreas Mike Dooraghi	NREL

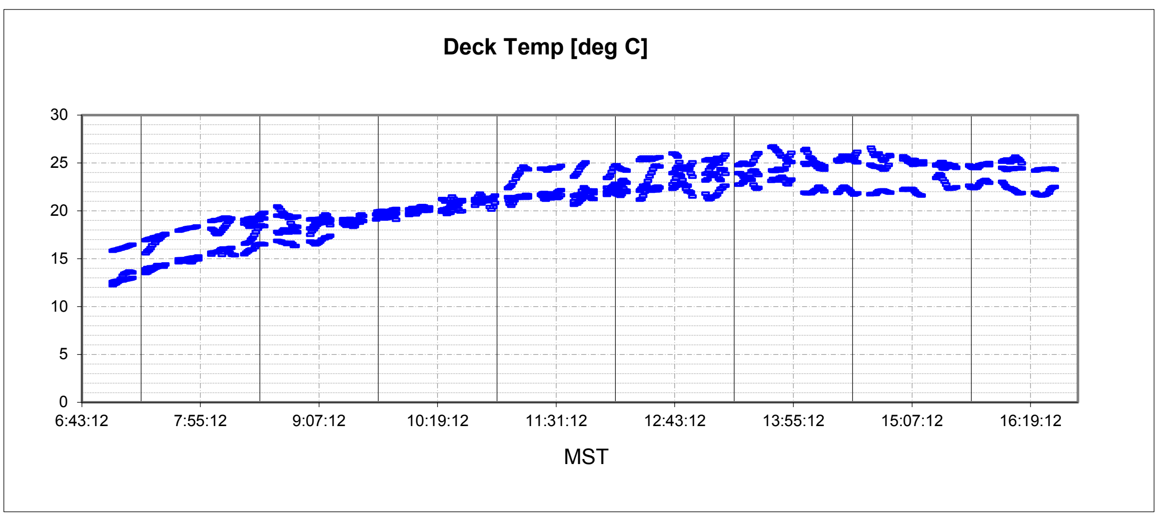
Appendix B: Ancillary Data Summaries

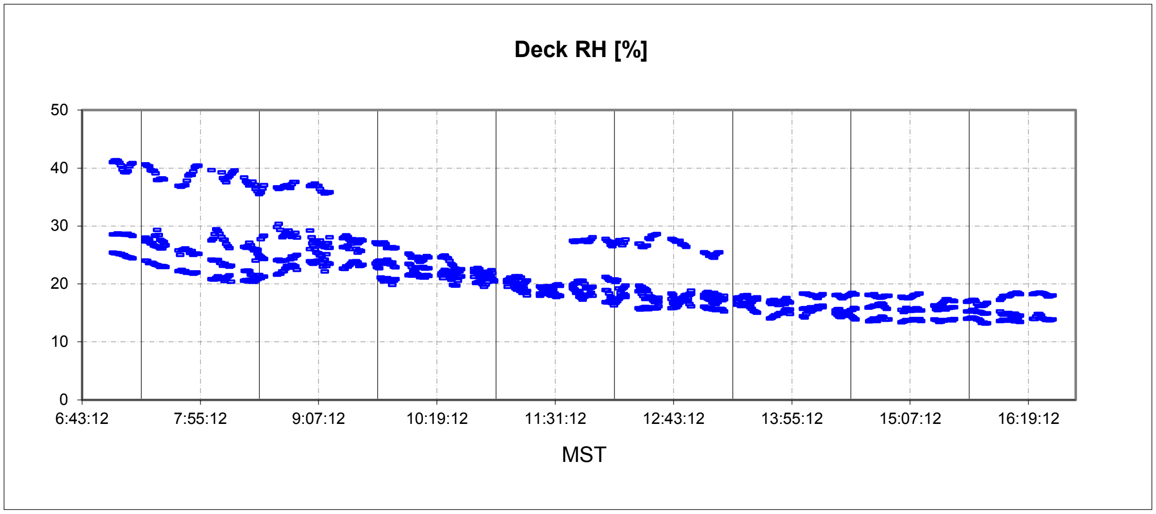
The measurement performance of an absolute cavity can be affected by several environmental parameters. Potentially relevant meteorological data collected during the NPC are presented in this appendix. The BMS has been in continuous operation at the SRRL since 1981. BMS data are recorded as 1-minute averages 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/)

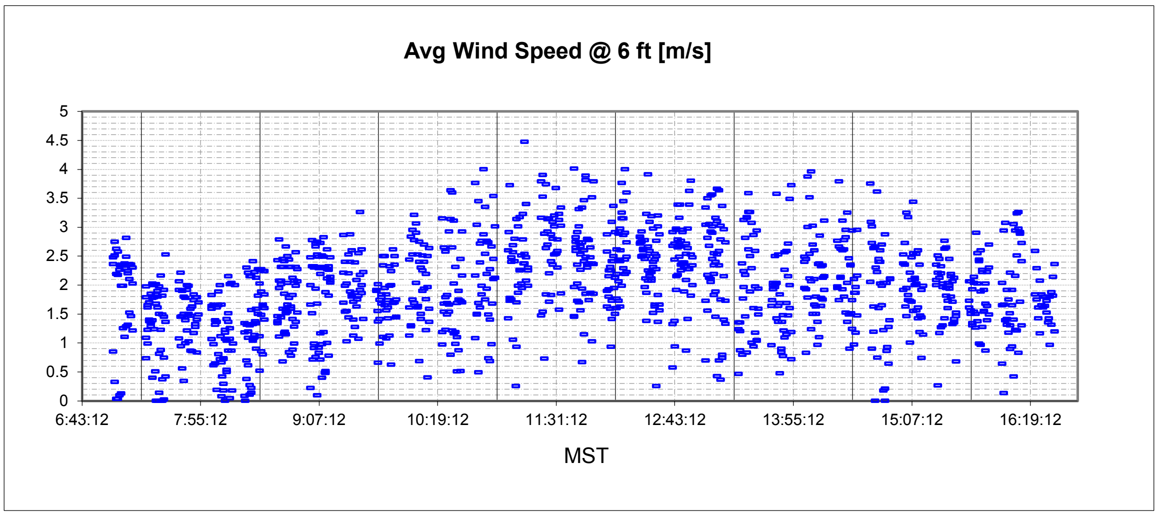
Time-series plots and other graphical presentations of these data acquired during the NPC-2016 measurements are presented here.

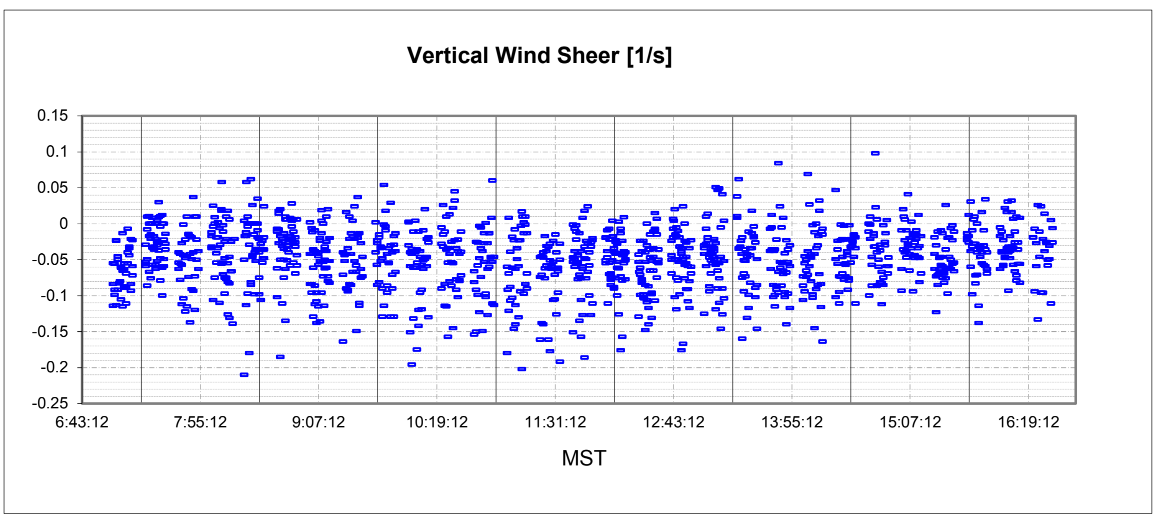

Reference irradiance [W/m²]
1100
1050
1000
950
900
850
800
750
700
650
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST

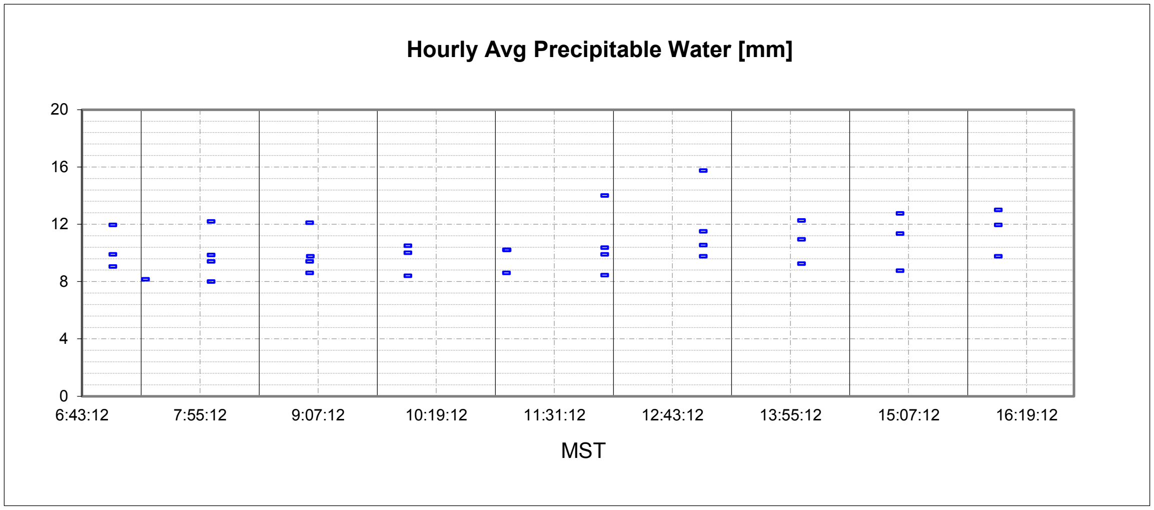

Broadband Turpidity
0.2
0.15
0.1
0.05
0
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST

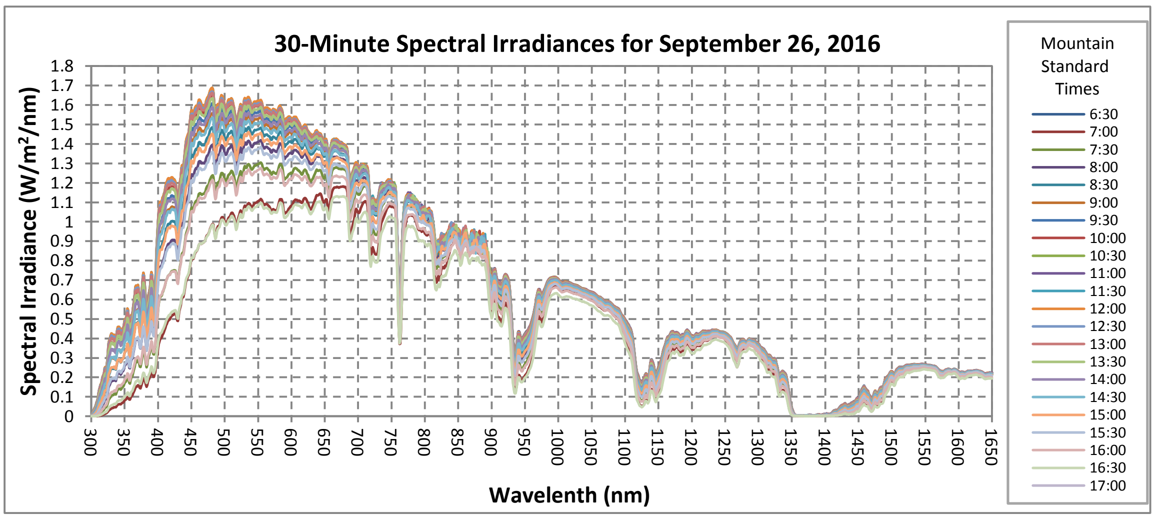

Deck Temp [deg C]
30
25
20
15
10
5
0
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST

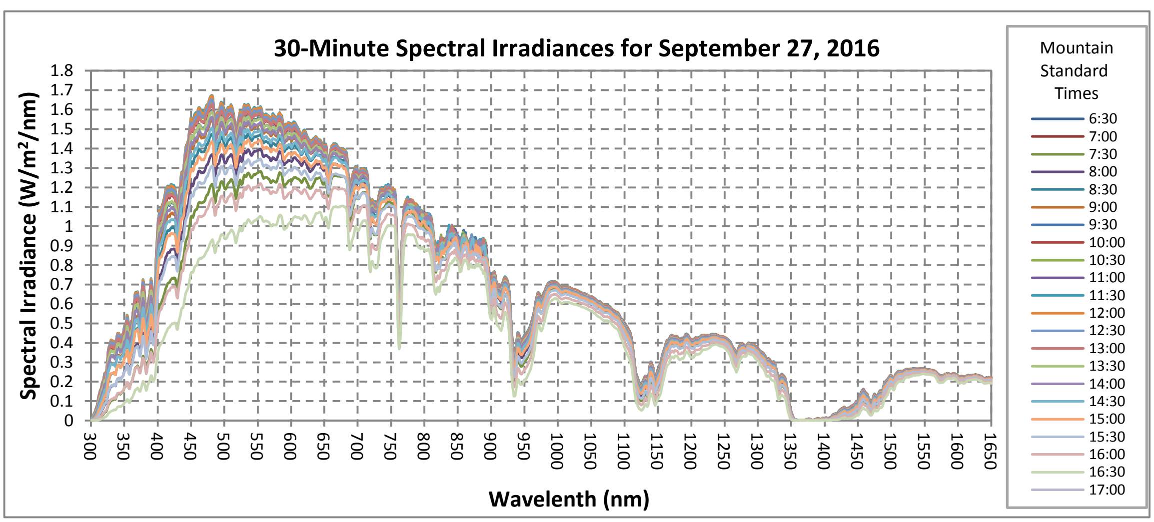

Deck RH [%]
50
40
30
20
10
0
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST

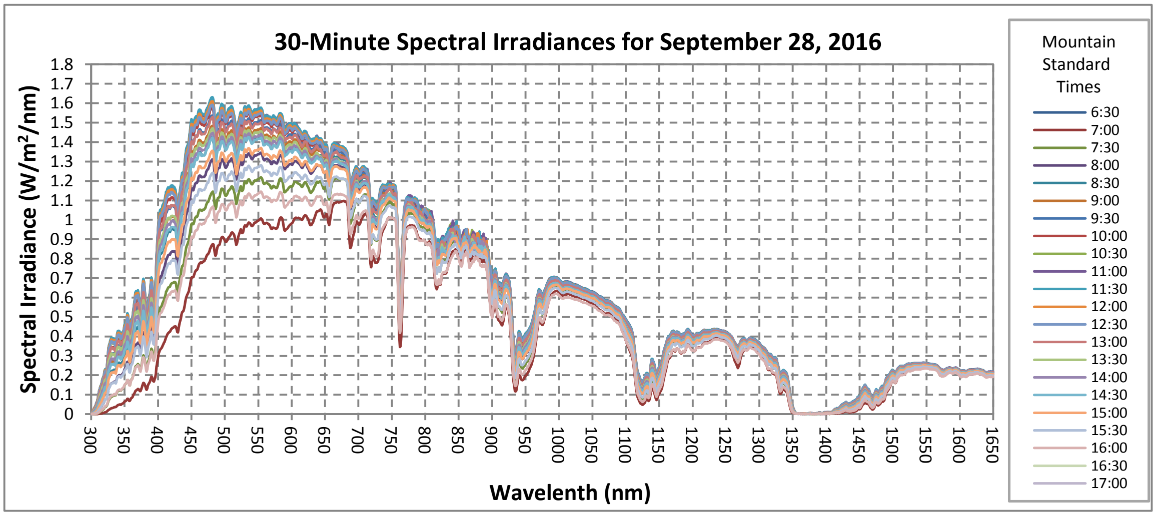

Avg Wind Speed @ 6 ft [m/s]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST

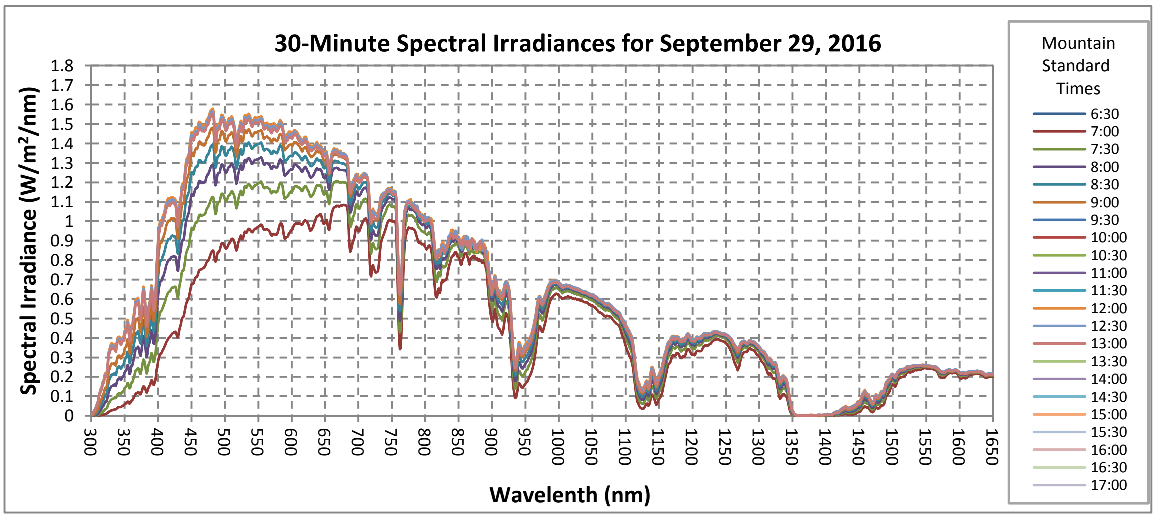

Vertical Wind Sheer [1/s]
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST


Hourly Avg Precipitable Water [mm]
0
4
8
12
16
20
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST


30-Minute Spectral Irradiances for September 26, 2016
Spectral Irradiance (W/m²/nm)
Wavelenth (nm)
Mountain Standard Times
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00


30-Minute Spectral Irradiances for September 27, 2016
Spectral Irradiance (W/m²/nm)
Wavelenth (nm)
Mountain Standard Times
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00


30-Minute Spectral Irradiances for September 28, 2016
Spectral Irradiance (W/m²/nm)
Wavelenth (nm)
Mountain Standard Times
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00


30-Minute Spectral Irradiances for September 29, 2016
Spectral Irradiance (W/m²/nm)
Wavelenth (nm)
Mountain Standard Times
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00