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NREL Pyrheliometer Comparison September 16 to 27, 2013 (NPC-2013)

Ibrahim Reda, Mike Dooraghi, and Aron Habte

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NREL/TP-3B10-60749
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Figure 1. NPC-2013 participants: *Photo by Tom Stoffel, NREL*

List of Acronyms

BMS	Baseline Measurement System
BORCAL	Broadband Outdoor Radiometer Calibration
DOE	U.S. Department of Energy
IPC	International Pyrheliometer Comparison
IPC-XI	Eleventh International Pyrheliometer Comparisons
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

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 seven 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 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 ISO 17025 accredited Broadband Outdoor Radiometer Calibration (BORCAL) process (Reda et al. 2008).

NPCs are held annually at the 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-2013 was held September 16–27, 2013. Participants operated 33 absolute cavity radiometers and 18 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-2013 consisted of four NREL radiometers with direct traceability to the WRR, having participated in the Eleventh International Pyrheliometer Comparisons (IPC-XI) in the fall of 2010. As a result of NPC-2013, 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-2013 was consistent with previous comparisons,

[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.

including IPC-XI. The measurement performance of the TSG allowed the transfer of the WRR to each participating radiometer with an estimated uncertainty of ± 0.33% with respect to the International System of Units.

The comparison protocol is based on data collection periods called *runs*. Each measurement run consists of an electrical self-calibration requiring 6 minutes for the AHF cavities, a series of 37 solar irradiance measurements at 20-second intervals, and a post calibration. More than 2000 reference irradiance measurements were collected by the TSG during NPC-2013. Clear-sky daily maximum direct normal irradiance levels ranged from 960 Wm^{-2} to 1000 Wm^{-2}.

Ancillary environmental conditions (e.g., broadband turbidity, ambient temperature, relative humidity, wind speed, and vertical wind sheer) 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 Eleventh IPC (IPC-XI) was completed in 2010 (Finsterle 2011). 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 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 seventeenth National Renewable Energy Laboratory Pyrheliometer Comparisons (NPC-2013) was held September 16–27, 2013, at the SRRL. Participants operated 33 absolute cavity radiometers and 18 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 participated 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-2013 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 2010 (Finsterle 2011).

Table 1. IPC-XI Results Summary for the NPC-2013 TSG

Serial Number	WRR Factor (IPC-XI)	Standard Deviation (%)	Number of Readings
AHF 28968	0.99773	0.0656	420
AHF 29220	0.99769	0.0669	418
AHF 30713	0.99755	0.0679	421
TMI 68018	0.99680	0.0642	415
Mean WRR for the TSG	0.99744	**SDp for the TSG:** 0.07%	

The SD_p for the TSG was computed from the following equation:

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

where,

$i = i^{th}$ cavity

m = number of reference cavities

S_i = standard deviation of the i^{th} cavity, from IPC-XI

n_i = number of readings of the i^{th} cavity, from IPC-XI

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 a 40-second open-/closed-shutter cycle). Each group of observations is called a *run*. An electrical self-calibration of each 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 6-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 200 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 3 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 collected at the end of the day using USB flash memory.

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-2013:

- The radiation source was the sun, with irradiance levels > 700 Wm^{-2}.
- Digital multimeters with accuracy > 0.05% reading were 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 that are maintained by NREL and that participated in IPC-XI 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-2013 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 2 seconds centered on the comparison reading—i.e., 1 second before and 1 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 similar cause for a 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 histograms 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-2013 was held September 16–27, 2013. The comparisons were completed on September 20, after more than 2000 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-2013 WRR-TF did not change by more than a fraction of the standard deviation derived during IPC-XI in 2010. (See Figure 2.)
- For the control standards—i.e., cavities that participated in IPC-XI and NPC-2013—their new WRR-TF, from NPC-2013, were consistent with their IPC-XI results. (See Table 2.)

Results for each radiometer participating in NPC-2013 are presented in Table 3.

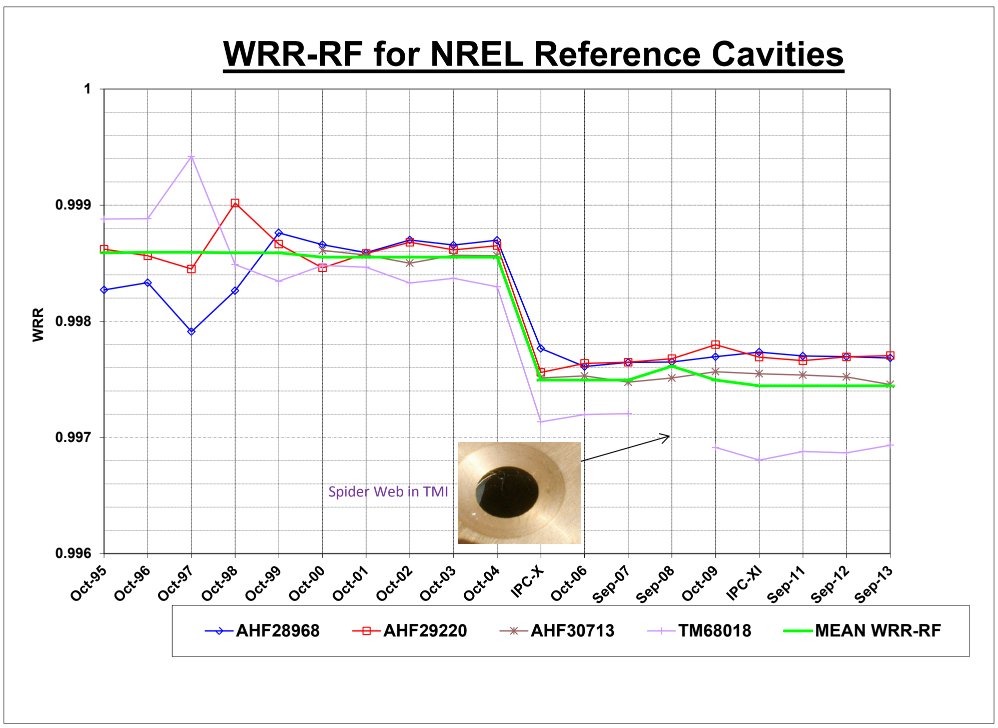


Figure 2. History of WRR reduction factors for NREL reference cavities

Table 2. Summary Results for the Control Standards for NPC-2013

S/N	WRR (IPC-XI)	WRR (NPC-2013)	SD% (NPC-2013)	WRR_{IPC} - WRR_{NPC} %
AHF14915	0.999682	1.00002	0.10	-0.03
AHF17142	0.998358	0.99807	0.06	0.03
AHF23734	0.998281	0.99811	0.04	0.02
AHF28553	0.996842	0.99762	0.05	-0.08
AHF31041	0.996286	0.99905	0.04	-0.28
AHF31105	0.999964	0.99905	0.05	0.09
AHF31114AWX	1.001244	1.00170	0.05	-0.05
AHF32448AWX	0.999939	1.00026	0.07	-0.03
AHF32455	1.000276	1.00066	0.06	-0.04
PMO6 81109	0.998577	0.99834	0.07	0.02
PMO6 911204	0.999711	0.99904	0.07	0.07
PMO6cc 0103*	0.999424	0.99824	0.07	0.12
PMO6cc 0401	1.020979	1.02107	0.06	-0.01
PMO6cc 0803	1.000364	1.00049	0.06	-0.01
TMI67502	0.999294	1.00011	0.07	-0.08
TMI68835	1.00098	1.00123	0.07	-0.03

** from IPC-X*

Table 3. Results for Radiometers Participating in NPC-2013

S/N	WRR-Reduction Factor (Testcav)	$\%u_A$	NRdg	u_C	Eff DF	$\%U_{95}$
00347	**0.99980**	**0.13**	**1953**	0.23	17941	0.44
070541	**1.00009**	**0.20**	**2006**	0.27	6778	0.54
90062	**1.00141**	**0.14**	**1934**	0.23	13824	0.46
090127	**1.00289**	**0.15**	**2005**	0.24	11879	0.47
110620	**0.98997**	**0.20**	**1950**	0.27	6922	0.53
CH1 040370	**0.99248**	**0.16**	**1828**	0.25	9519	0.49
CH1 060460	**0.99910**	**0.12**	**1882**	0.22	19930	0.44
CH1 930018	**1.00009**	**0.28**	**1953**	0.33	4088	0.65
CH1P 110533	**0.99897**	**0.29**	**1841**	0.34	3667	0.67
AHF14915	**1.00002**	**0.10**	**1133**	0.21	24389	0.41
AHF17142	**0.99807**	**0.06**	**1714**	0.19	200078	0.38
AHF21182	**1.00050**	**0.08**	**1936**	0.20	73721	0.40
AHF23734	**0.99811**	**0.04**	**1998**	0.19	1011792	0.37
AHF28553	**0.99762**	**0.05**	**1476**	0.19	254307	0.38

S/N	WRR-Reduction Factor (Testcav)	%u_A	NRdg	u_C	Eff DF	%U_{95}
AHF28556	**0.99517**	**0.05**	**1749**	0.19	295589	0.38
AHF29219-Window	**1.06090**	**0.09**	**2008**	0.20	65246	0.40
AHF29222-Window	**1.05896**	**0.08**	**1876**	0.20	92983	0.39
AHF30110-Window	**1.06290**	**0.08**	**1731**	0.20	73021	0.40
AHF30494	**0.99764**	**0.09**	**1911**	0.21	46320	0.41
AHF30495	**0.99832**	**0.05**	**1852**	0.19	541404	0.37
AHF31041	**0.99655**	**0.06**	**1718**	0.19	217999	0.38
AHF31104	**0.99905**	**0.04**	**1999**	0.19	1318422	0.37
AHF31105	**0.99905**	**0.05**	**1724**	0.19	418649	0.38
AHF31107-Window	**1.04486**	**0.09**	**1856**	0.21	44554	0.41
AHF31108	**0.99723**	**0.06**	**1942**	0.19	237148	0.38
AHF31114AWX	**1.00170**	**0.05**	**1450**	0.19	255166	0.38
AHF32448AWX	**1.00026**	**0.07**	**1019**	0.20	59933	0.39
AHF32452AWX-Window	**1.03154**	**0.08**	**1880**	0.20	87952	0.39
AHF32455	**1.00066**	**0.06**	**1835**	0.19	249037	0.38
AHF34926	**1.00036**	**0.07**	**1828**	0.20	123425	0.39
CP01P 002	**0.99688**	**0.16**	**1585**	0.24	8724	0.48
CP01T 002	**0.99668**	**0.14**	**1738**	0.23	14092	0.45
CP01U 002	**0.99014**	**0.61**	**1739**	0.63	2080	1.24
DR02-0041	**1.00082**	**0.29**	**1831**	0.34	3655	0.67
MS56_PRH-REF.02	**0.99933**	**0.38**	**1812**	0.42	2768	0.83
MS56_PRH-REF.03	**1.00303**	**0.26**	**1772**	0.32	3966	0.63
PMO6 81109	**0.99834**	**0.07**	**498**	0.20	39737	0.39
PMO6 911204	**0.99904**	**0.07**	**500**	0.20	28085	0.39
PMO6cc 0103	**0.99824**	**0.07**	**245**	0.20	16943	0.39
PMO6cc 0401	**1.02107**	**0.06**	**243**	0.19	27344	0.38
PMO6-cc 0803	**1.00049**	**0.06**	**242**	0.20	23983	0.38
Ref 1	**0.99891**	**0.25**	**2013**	0.31	4837	0.61
sNIP 36477	**1.00183**	**0.18**	**1349**	0.26	6019	0.50
sNIP 37441	**1.00069**	**0.16**	**1091**	0.25	5886	0.48
TMI67502	**1.00011**	**0.07**	**1600**	0.20	104946	0.39
TMI67603	**0.99996**	**0.06**	**1948**	0.19	275799	0.38
TMI67811	**0.99932**	**0.11**	**944**	0.21	14963	0.42
TMI68020	**0.99970**	**0.09**	**1761**	0.21	52194	0.40
TMI68022	**0.99995**	**0.12**	**945**	0.22	9768	0.44
TMI68835	**1.00123**	**0.07**	**1697**	0.20	86989	0.39

S/N	WRR-Reduction Factor (Testcav)	$\%u_A$	NRdg	u_C	Eff DF	$\%U_{95}$
TMI69036	**1.00044**	**0.07**	**1960**	0.20	136206	0.39

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

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

where,

U_{95} = Uncertainty of the WRR-TF (in percent) determined at NPC-2013 with 95% confidence level

1.96 = Coverage factor

u_A = Type A standard uncertainty = standard deviation of each participating radiometer (in %) determined at NPC-2013

u_B = Type B standard uncertainty

$u_B = \pm \sqrt{(\frac{0.3}{\sqrt{3}})^2 + 0.07^2}$

where,

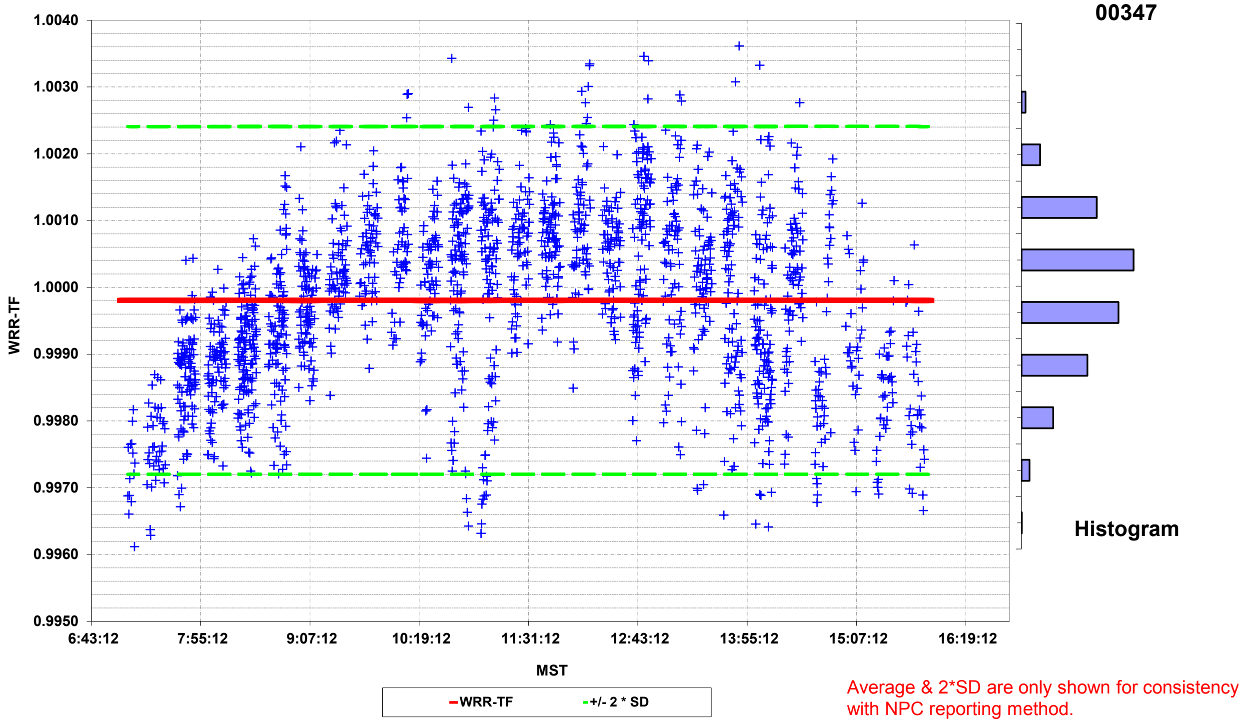
0.3 = Estimated expanded uncertainty (± %) of the WRR scale with respect to SI

$\sqrt{3}$ = Coverage factor for rectangular distribution

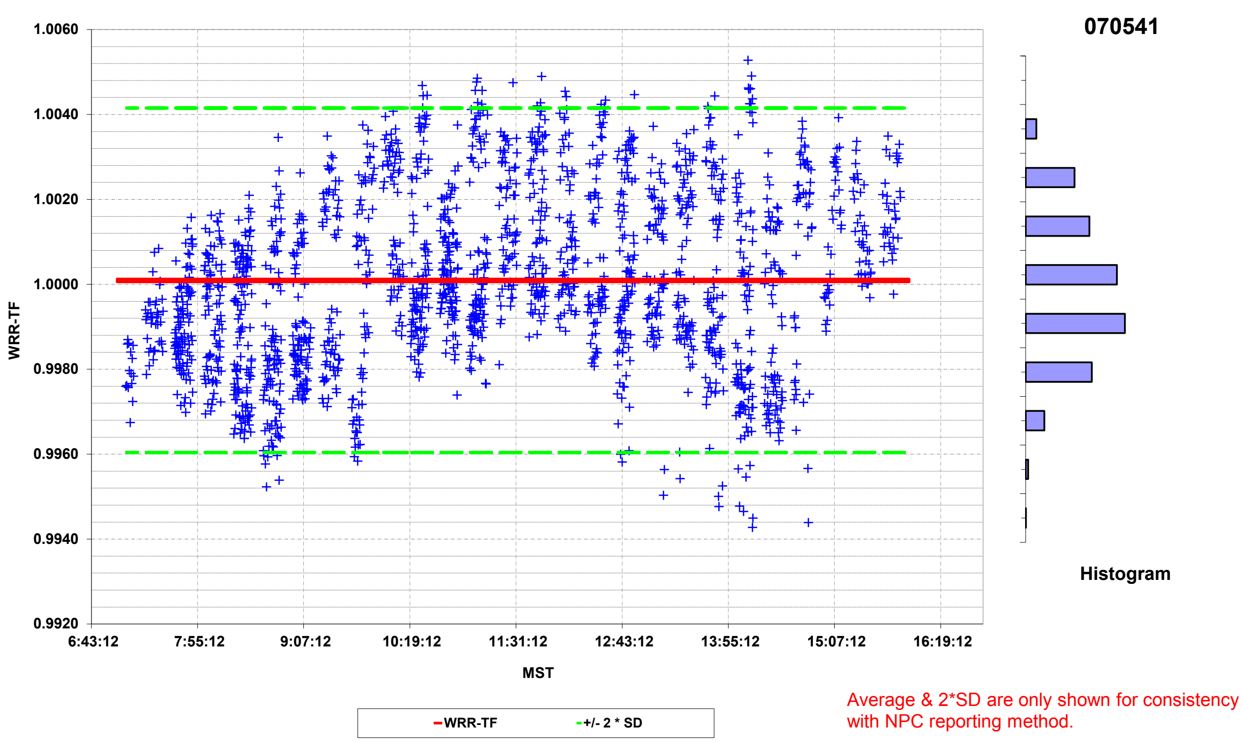
0.07 = Pooled standard deviation of the four reference radiometers (TSG) that participated in IPC-XI (September/October 2010).

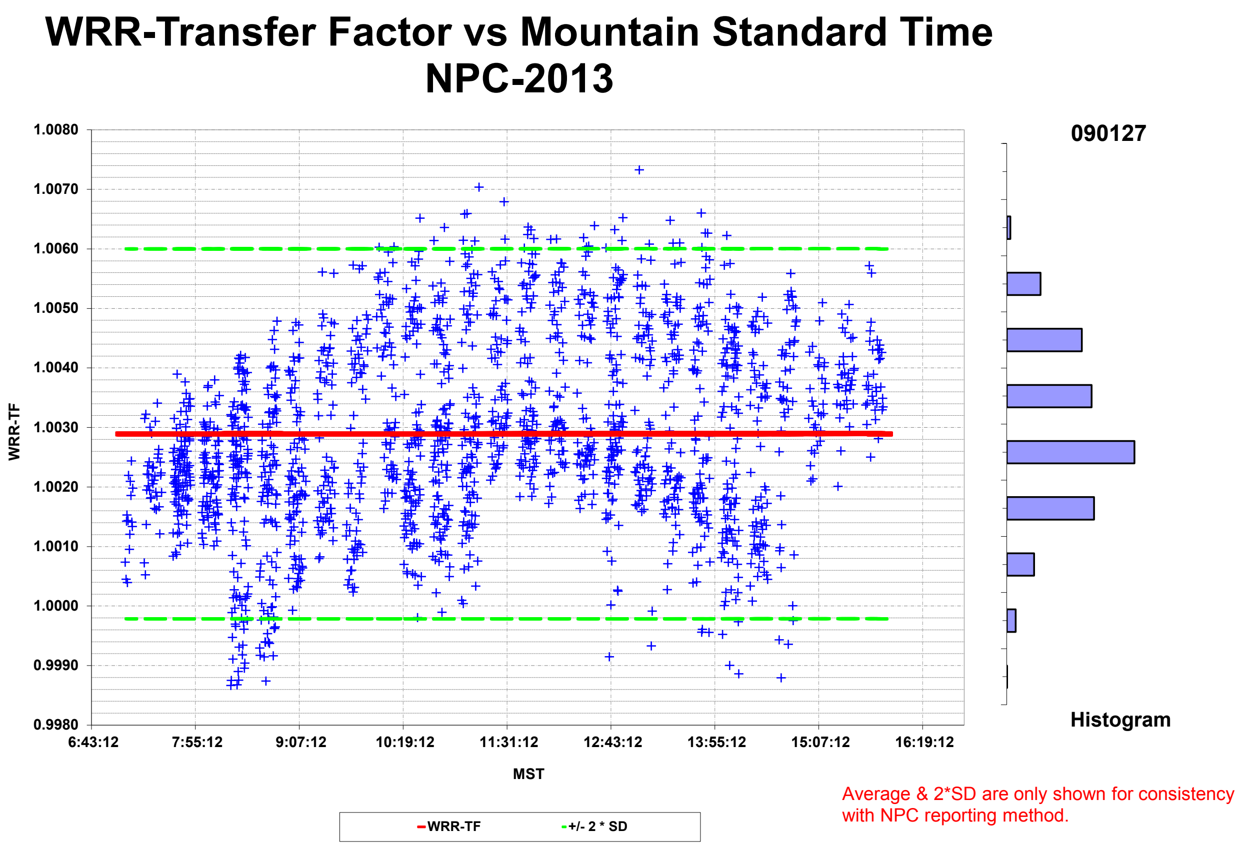
The statistical analyses of WRR-TF for 51 participating pyrheliometers are presented in the following figures. These graphical summaries indicate the mean, standard deviation, and histograms of the WRR-TF determined during NPC-2013.

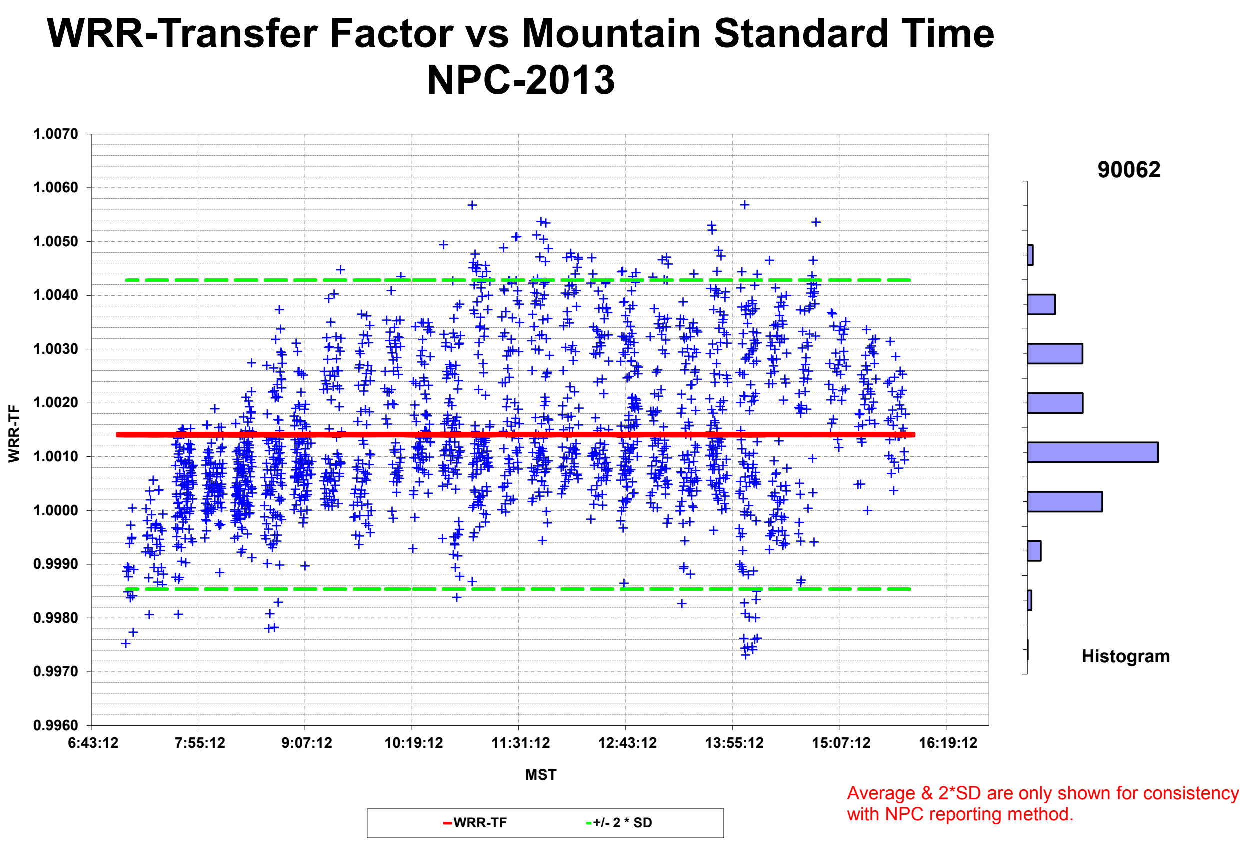
WRR-Transfer Factor vs Mountain Standard Time
NPC-2013



WRR-Transfer Factor vs Mountain Standard Time
NPC-2013




WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
090127
WRR-TF
MST
Histogram
WRR-TF
+/- 2 * SD
Average & 2*SD are only shown for consistency with NPC reporting method.


WRR-Transfer Factor vs Mountain Standard Time
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Histogram
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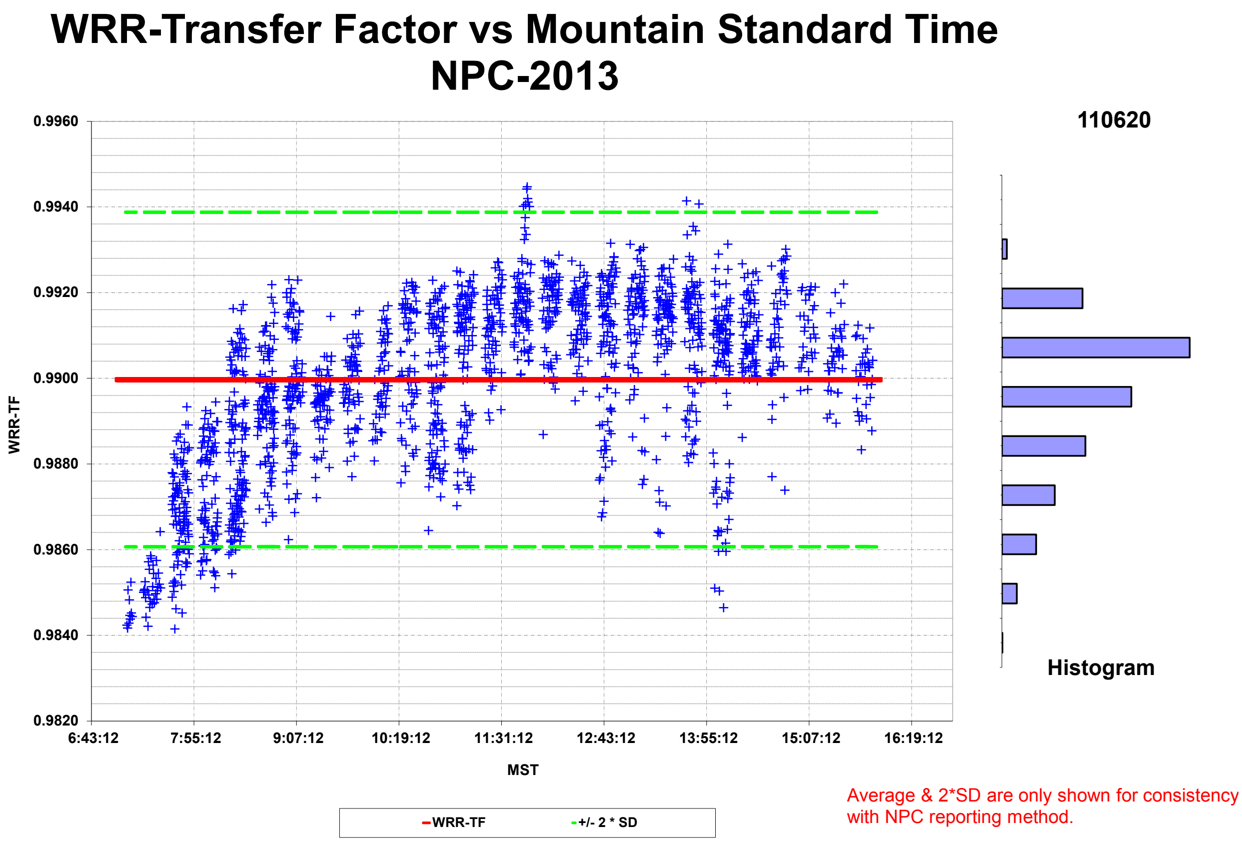
+/- 2 * SD
Average & 2*SD are only shown for consistency with NPC reporting method.


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
110620
0.9960
0.9940
0.9920
0.9900
0.9880
0.9860
0.9840
0.9820
WRR-TF
6:43:12
7:55:12
9:07:12
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Histogram
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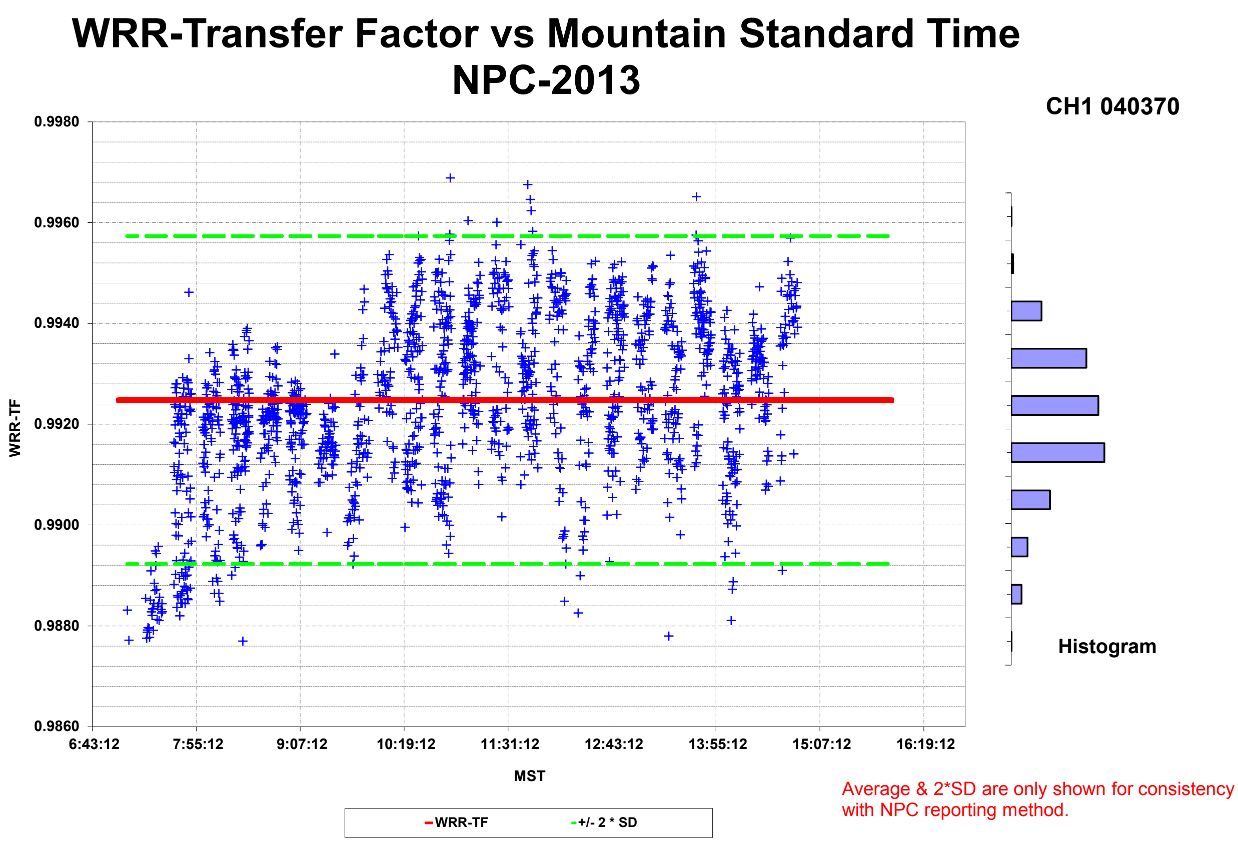
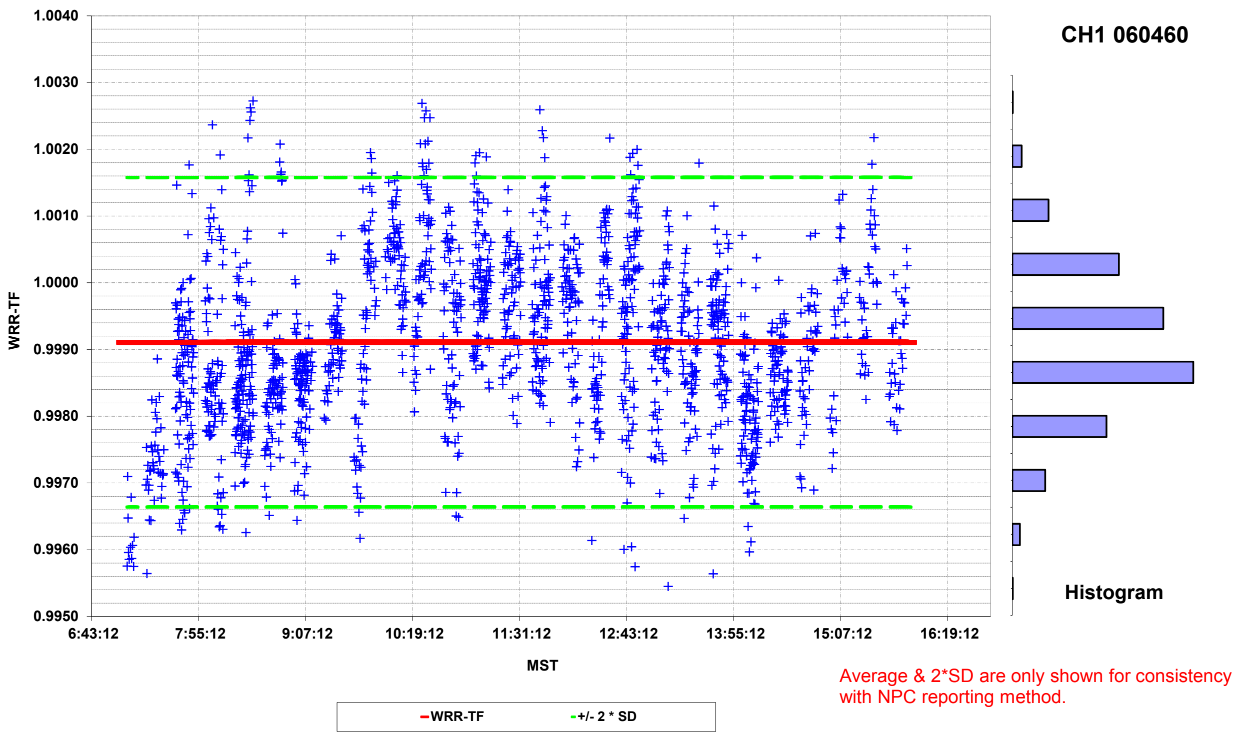
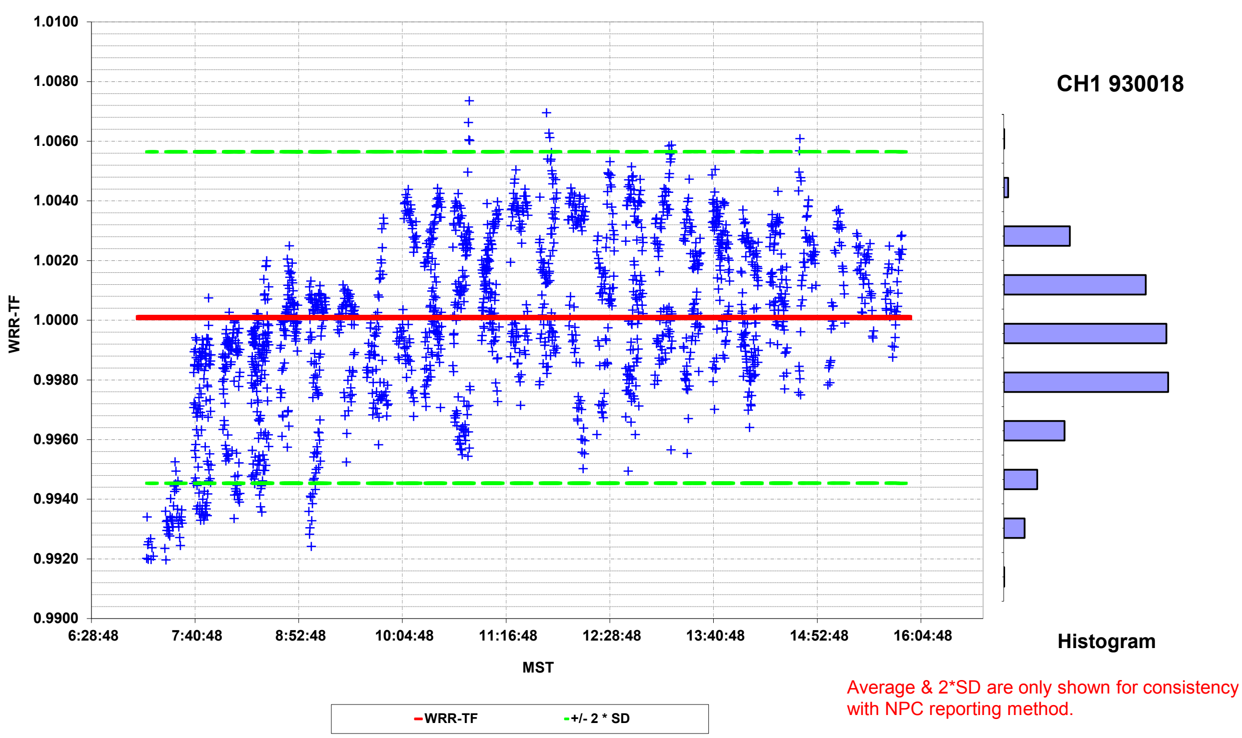
+/- 2 * SD
Average & 2*SD are only shown for consistency with NPC reporting method.

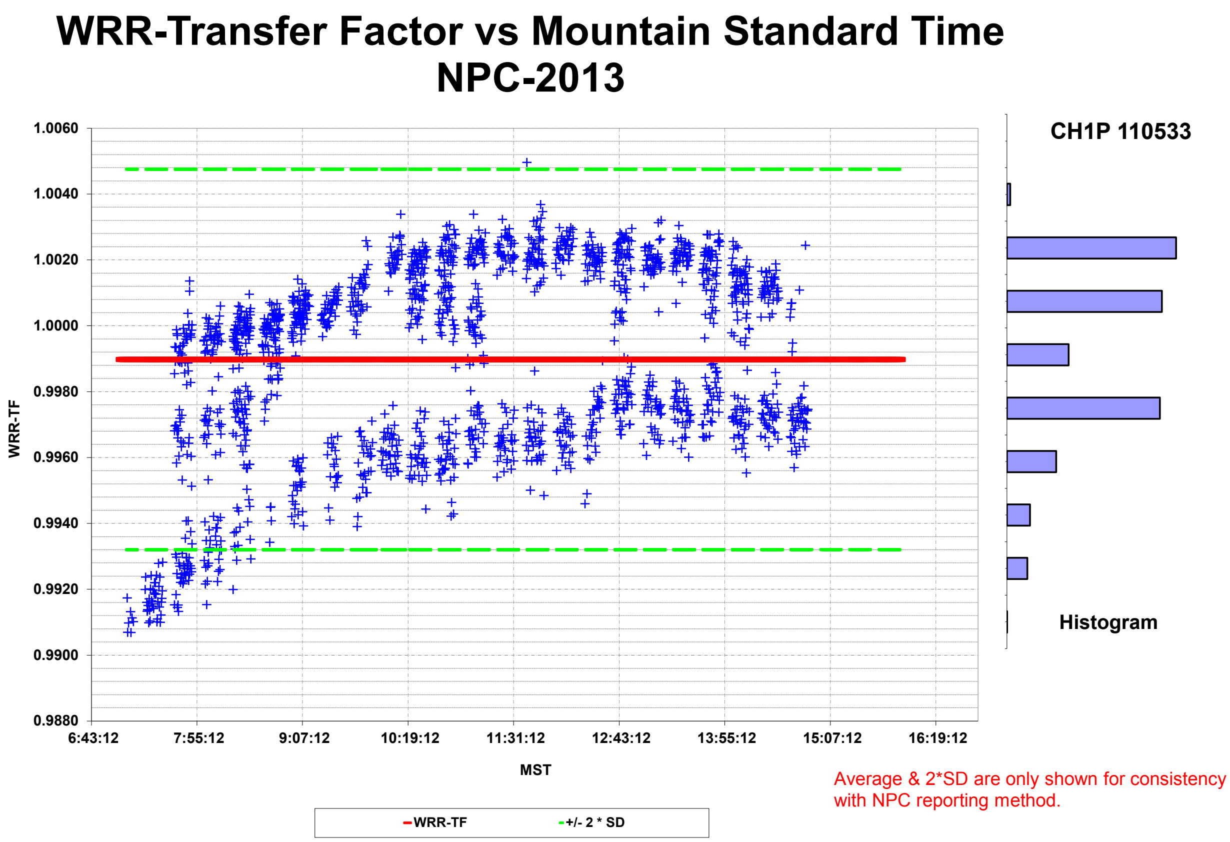

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
CH1 040370
0.9980
0.9960
0.9940
0.9920
0.9900
0.9880
0.9860
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD
Average & 2*SD are only shown for consistency with NPC reporting method.

WRR-Transfer Factor vs Mountain Standard Time NPC-2013

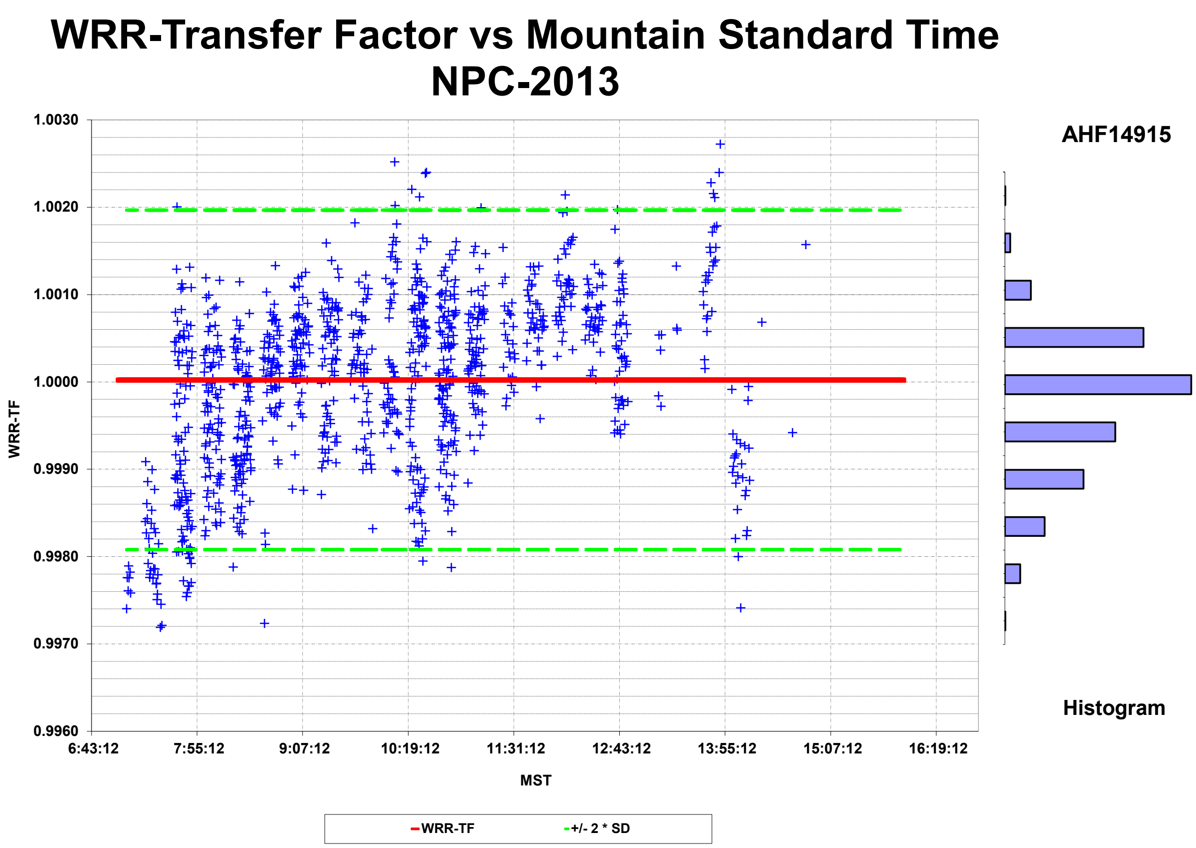


WRR-Transfer Factor vs Mountain Standard Time NPC-2013

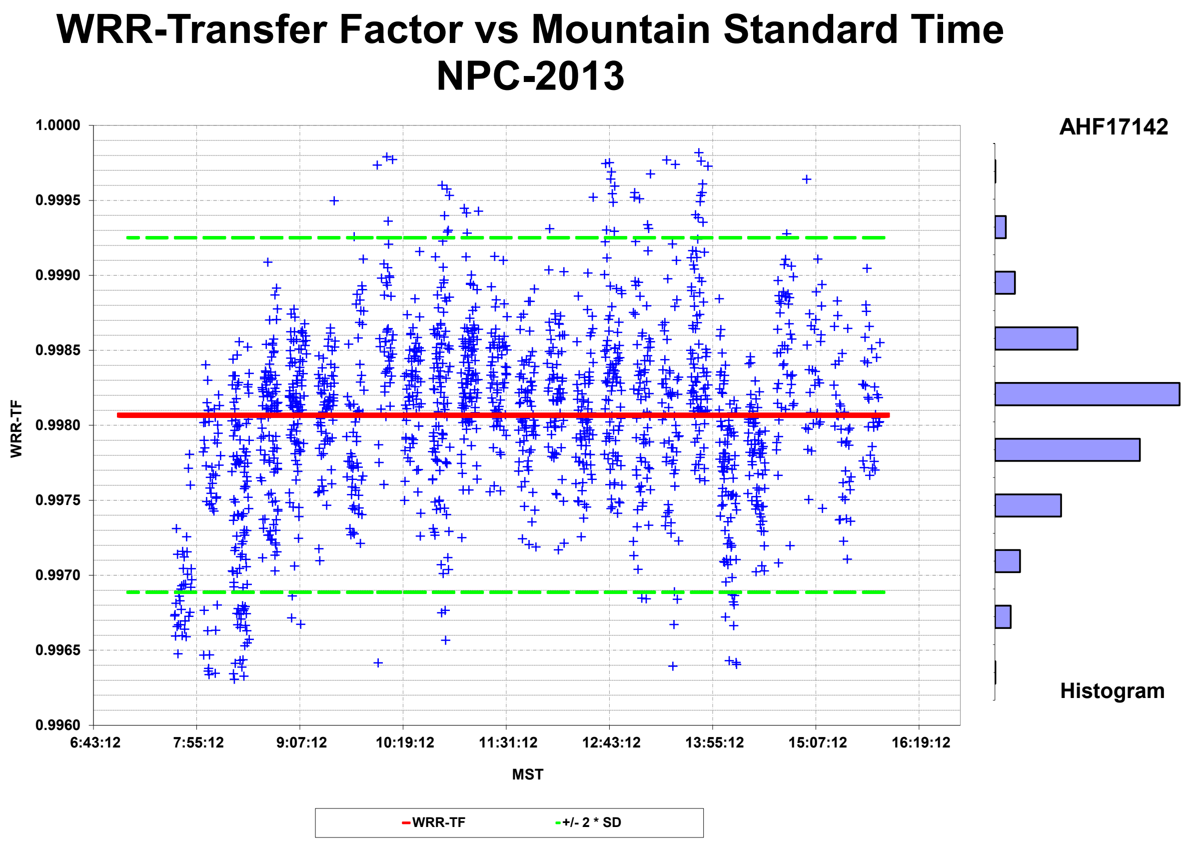


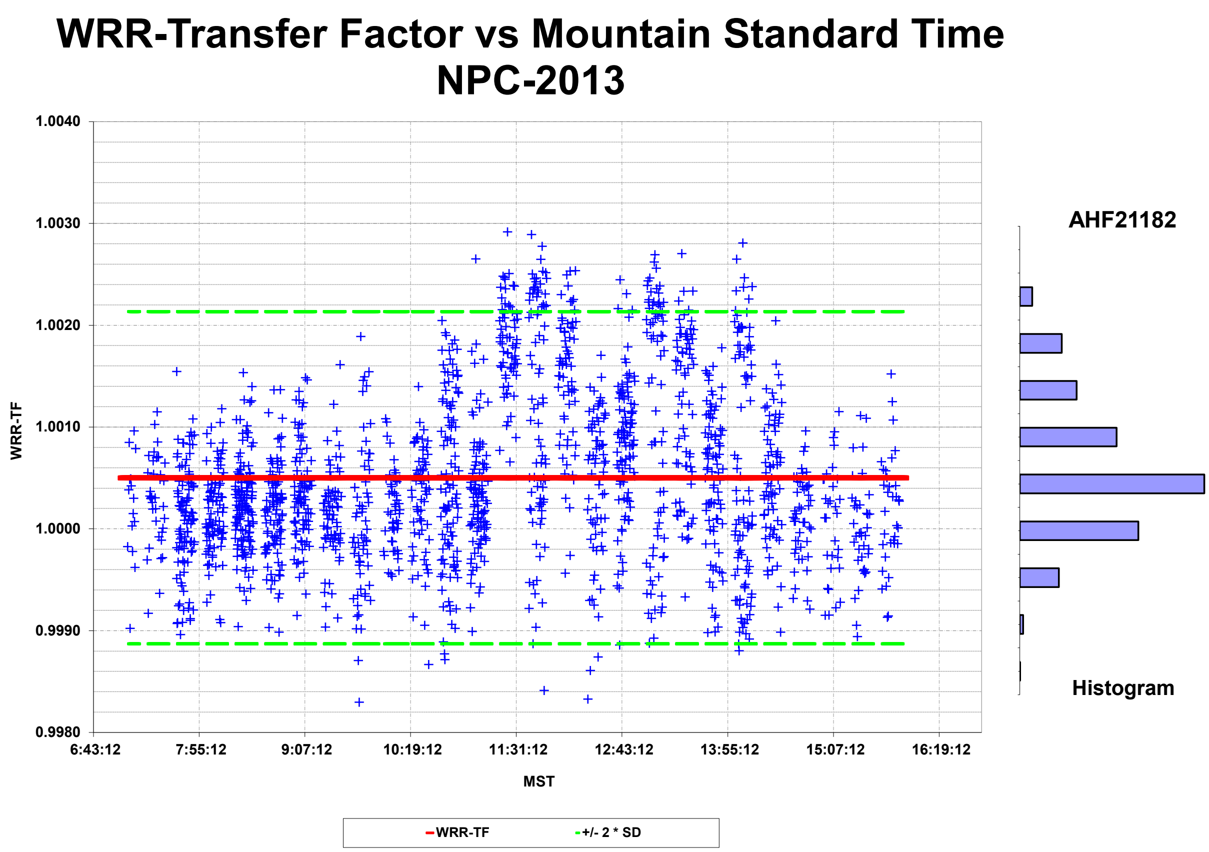


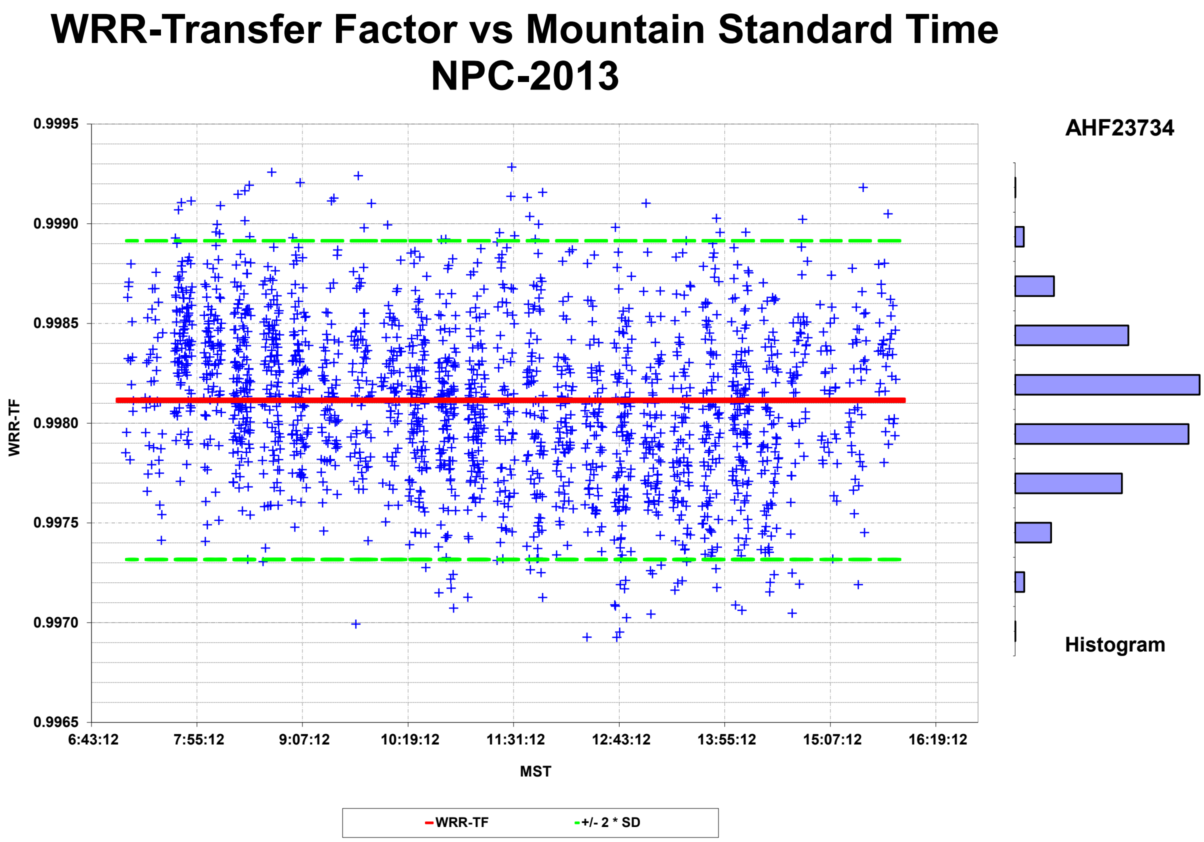
WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
CH1P 110533
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
0.9920
0.9900
0.9880
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
Average & 2*SD are only shown for consistency with NPC reporting method.
WRR-TF
+/- 2 * SD

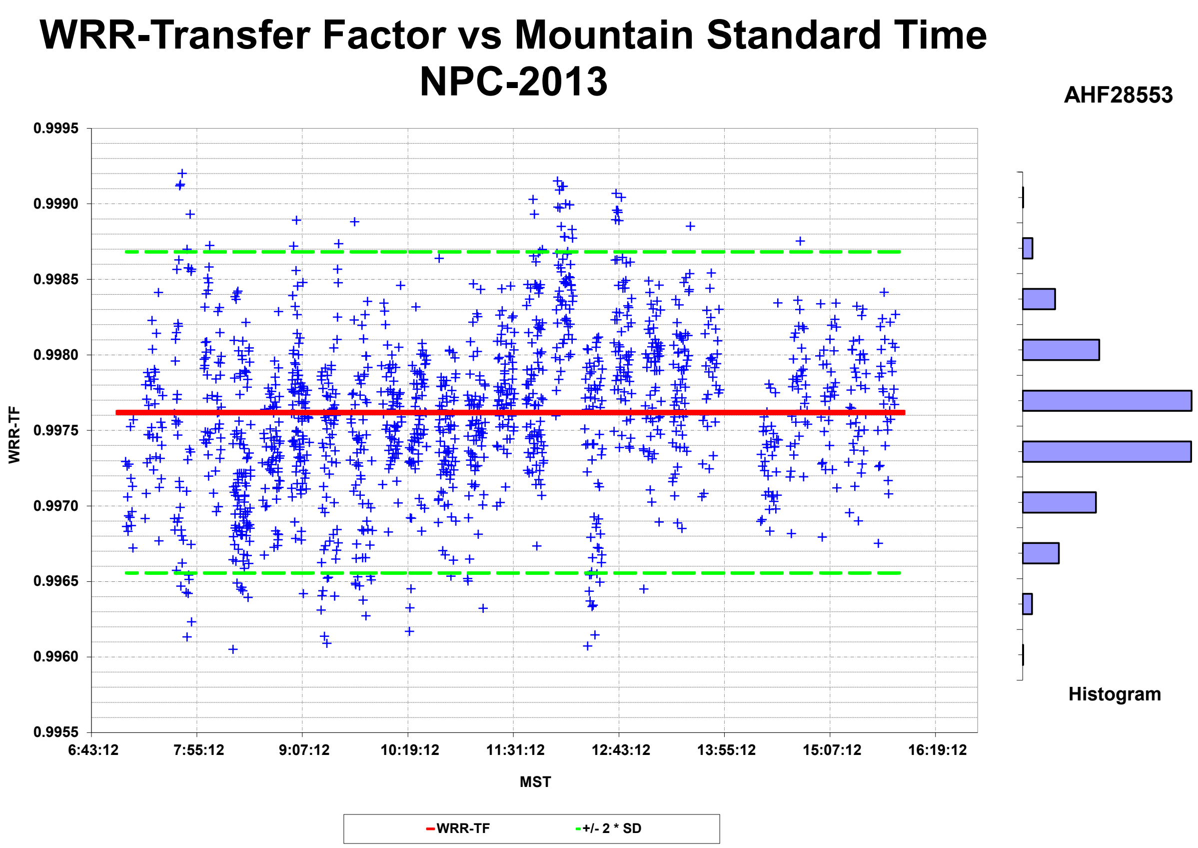


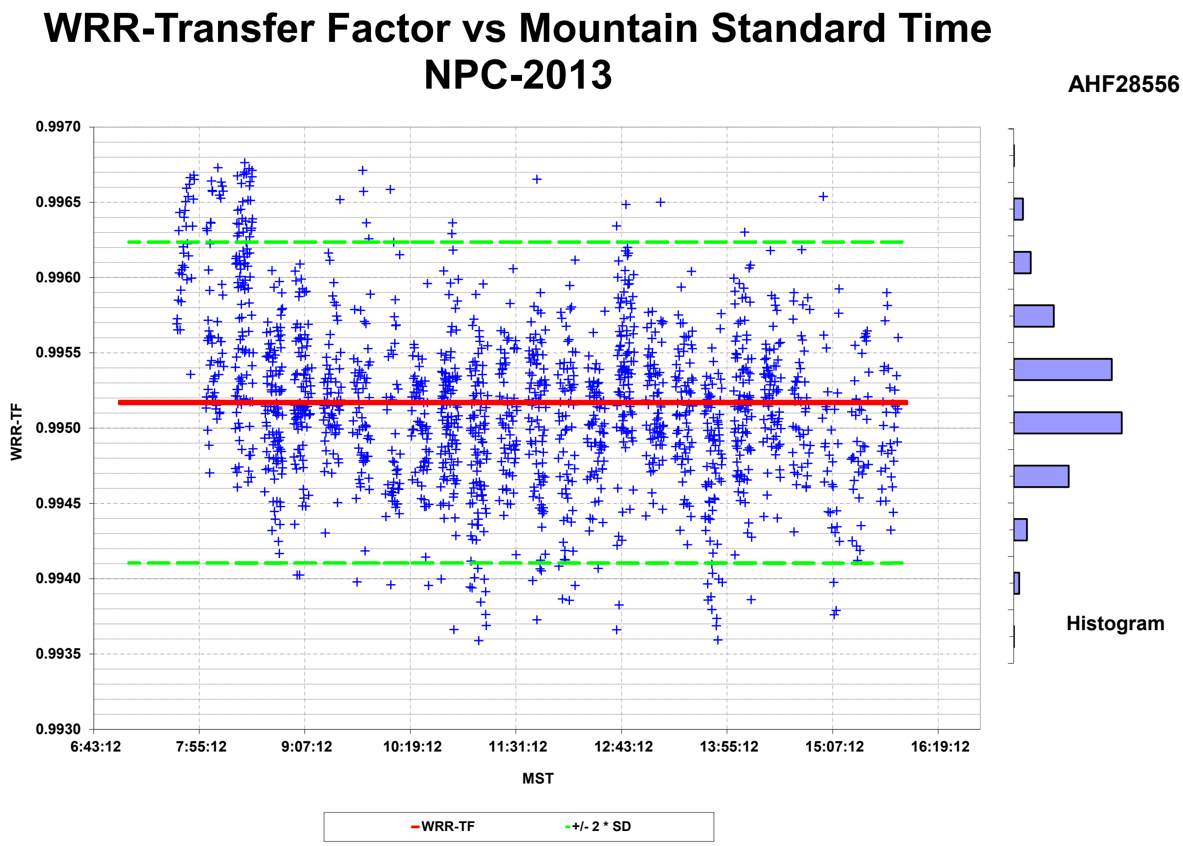
WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF14915
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD

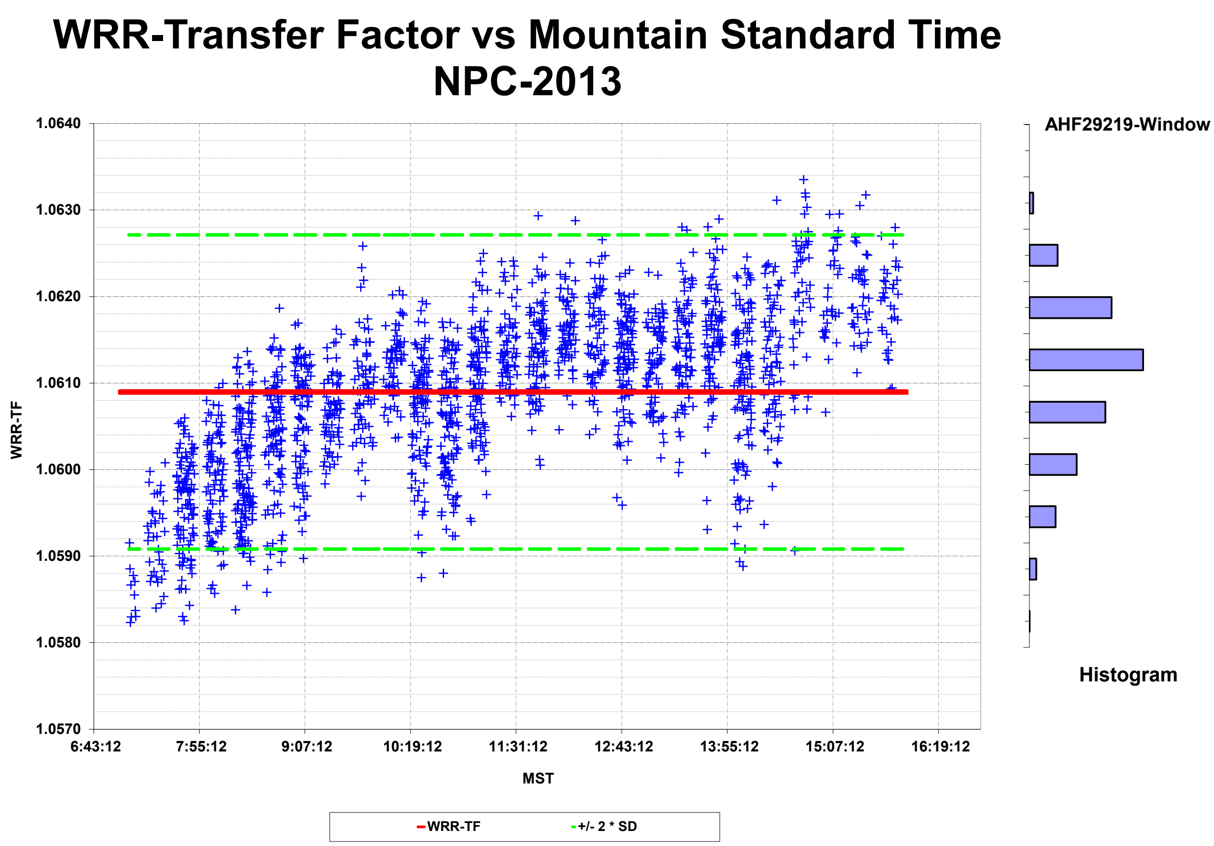

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF17142
Histogram
WRR-TF
MST
1.0000
0.9995
0.9990
0.9985
0.9980
0.9975
0.9970
0.9965
0.9960
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
WRR-TF
+/- 2 * SD

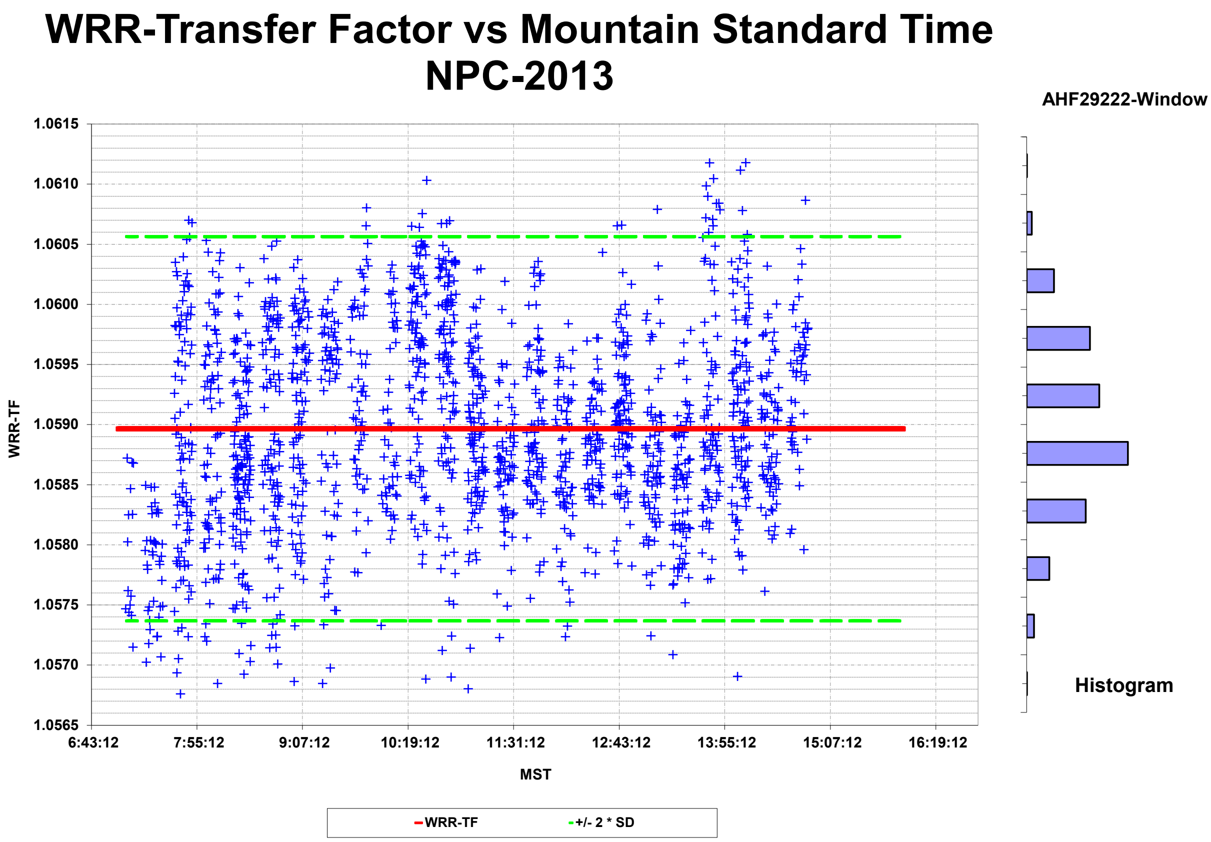

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF21182
Histogram
WRR-TF
MST
1.0040
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
WRR-TF
+/- 2 * SD

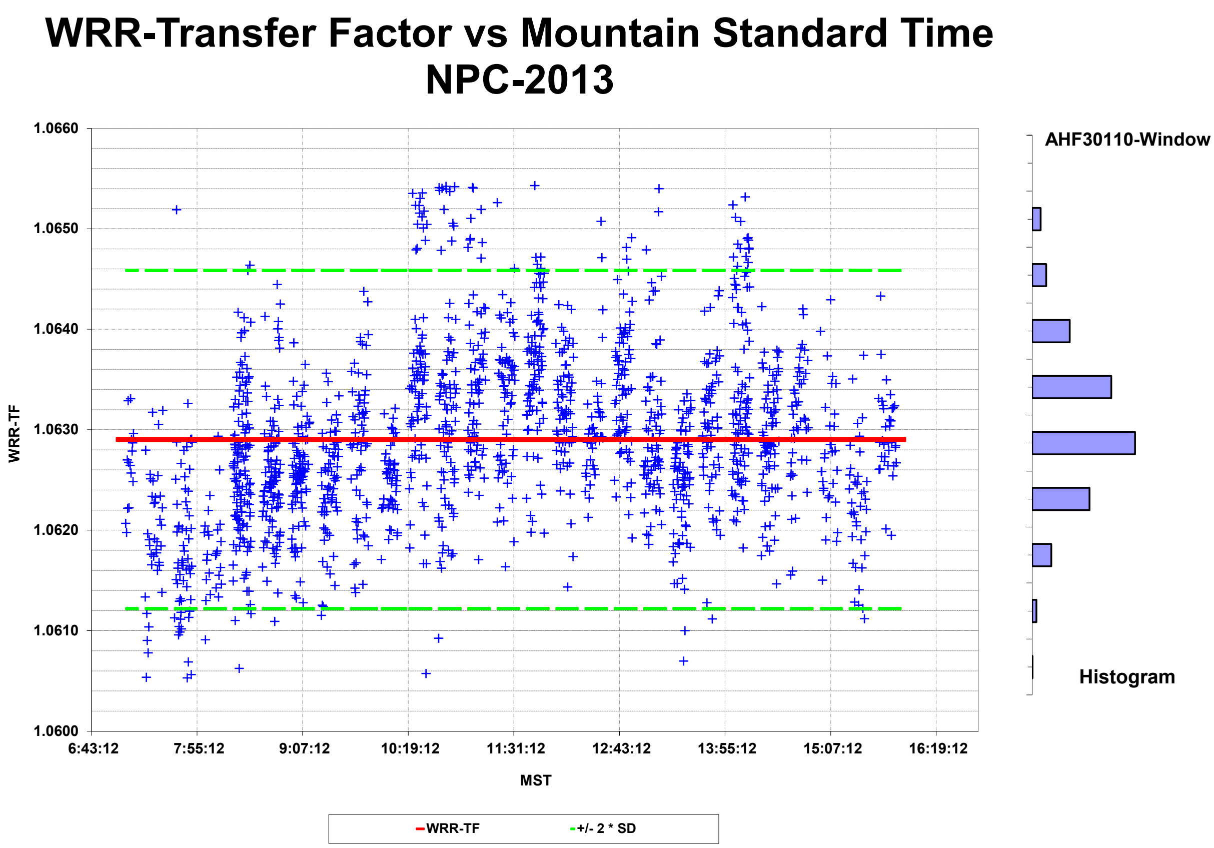

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF23734
0.9995
0.9990
0.9985
0.9980
0.9975
0.9970
0.9965
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD

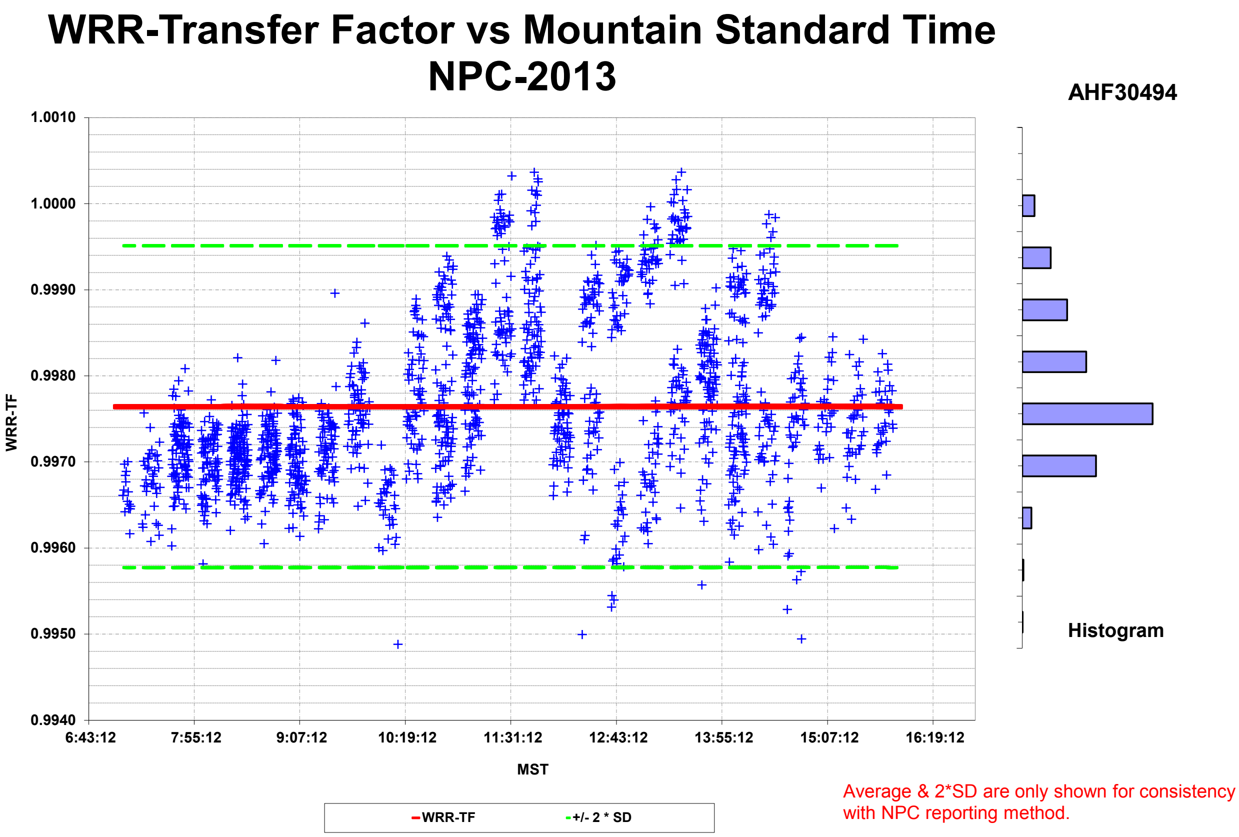

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF28553
0.9995
0.9990
0.9985
0.9980
0.9975
0.9970
0.9965
0.9960
0.9955
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD

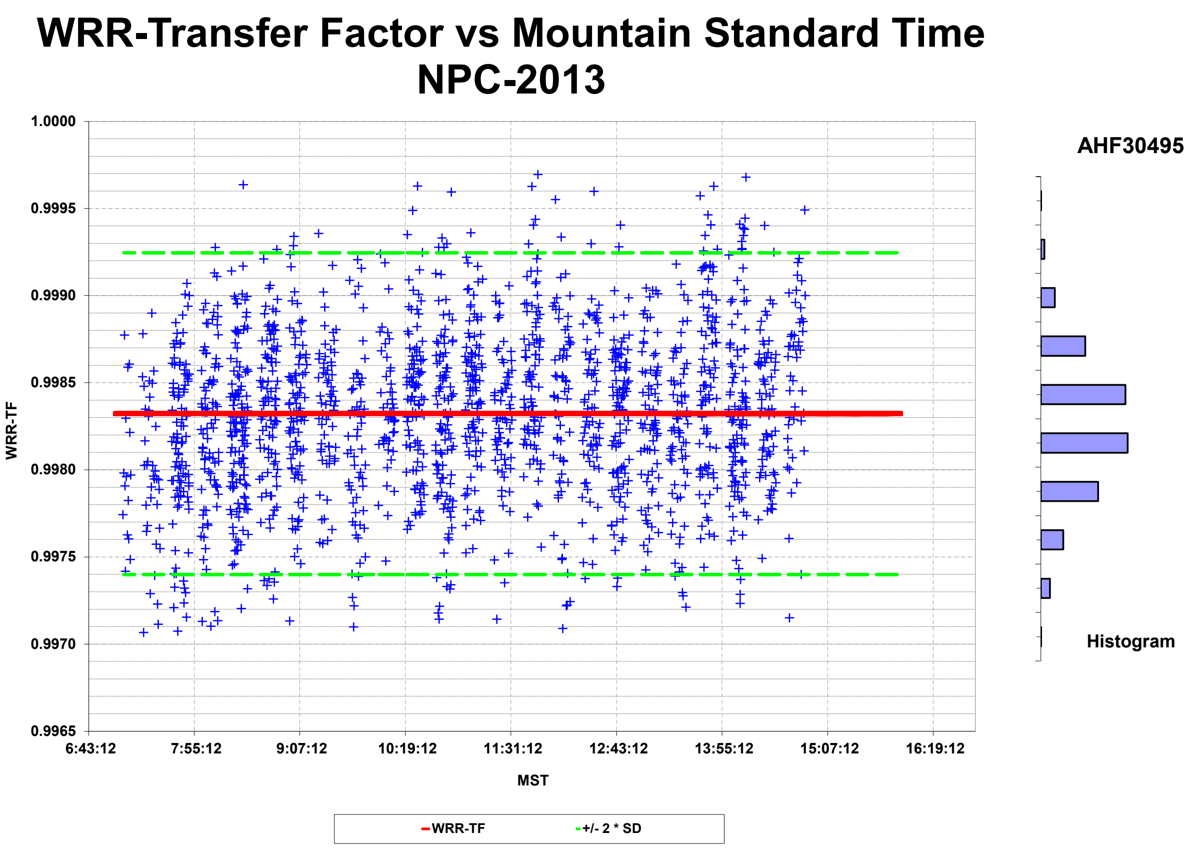

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF28556
0.9970
0.9965
0.9960
0.9955
0.9950
0.9945
0.9940
0.9935
0.9930
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD

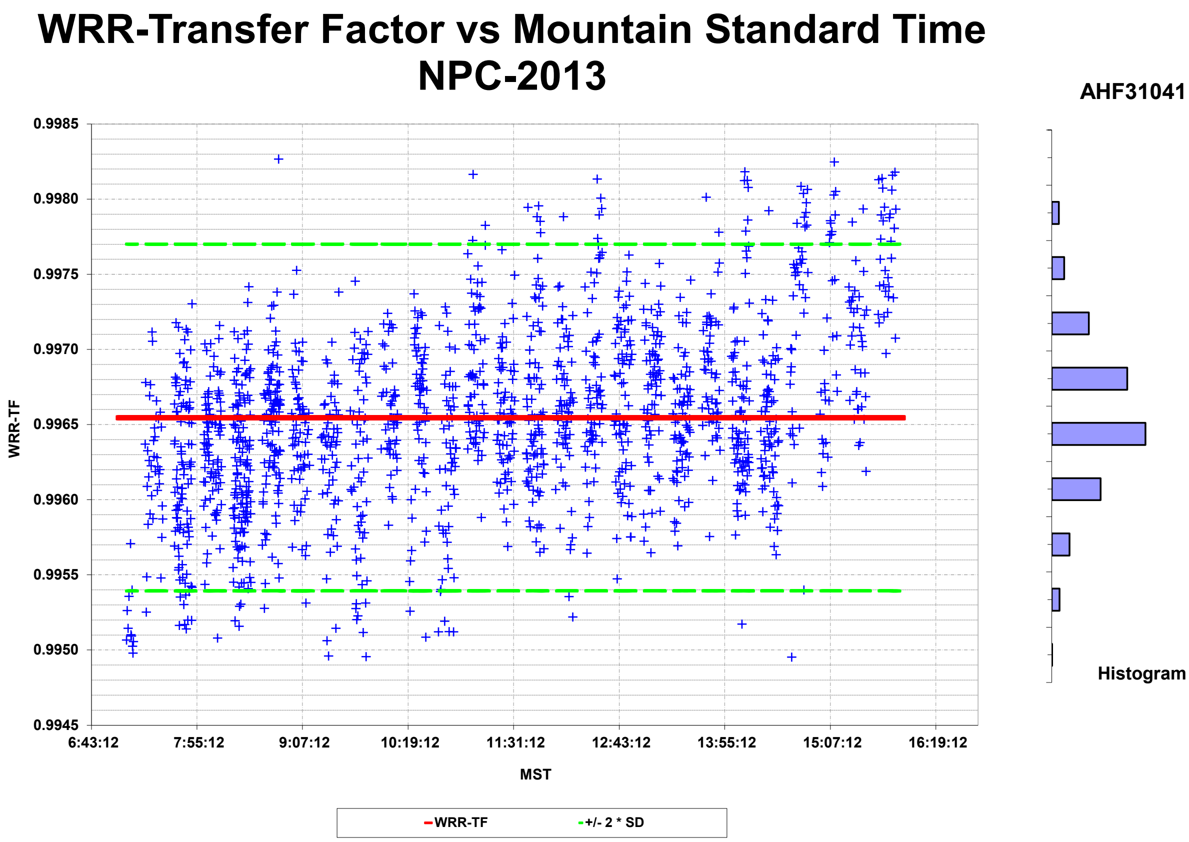

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF29219-Window
1.0640
1.0630
1.0620
1.0610
1.0600
1.0590
1.0580
1.0570
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD

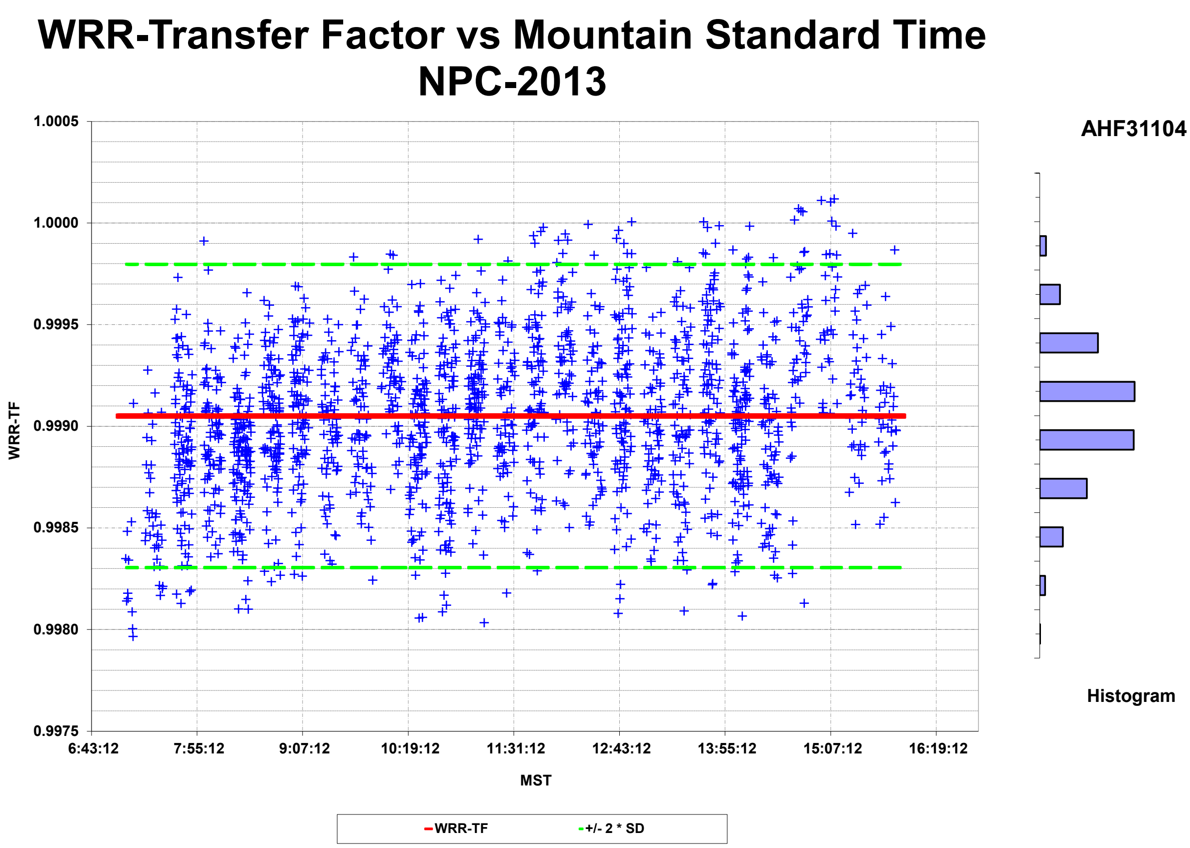

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF29222-Window
1.0615
1.0610
1.0605
1.0600
1.0595
1.0590
1.0585
1.0580
1.0575
1.0570
1.0565
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF30110-Window
1.0660
1.0650
1.0640
1.0630
1.0620
1.0610
1.0600
WRR-TF
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
Histogram
WRR-TF
+/- 2 * SD

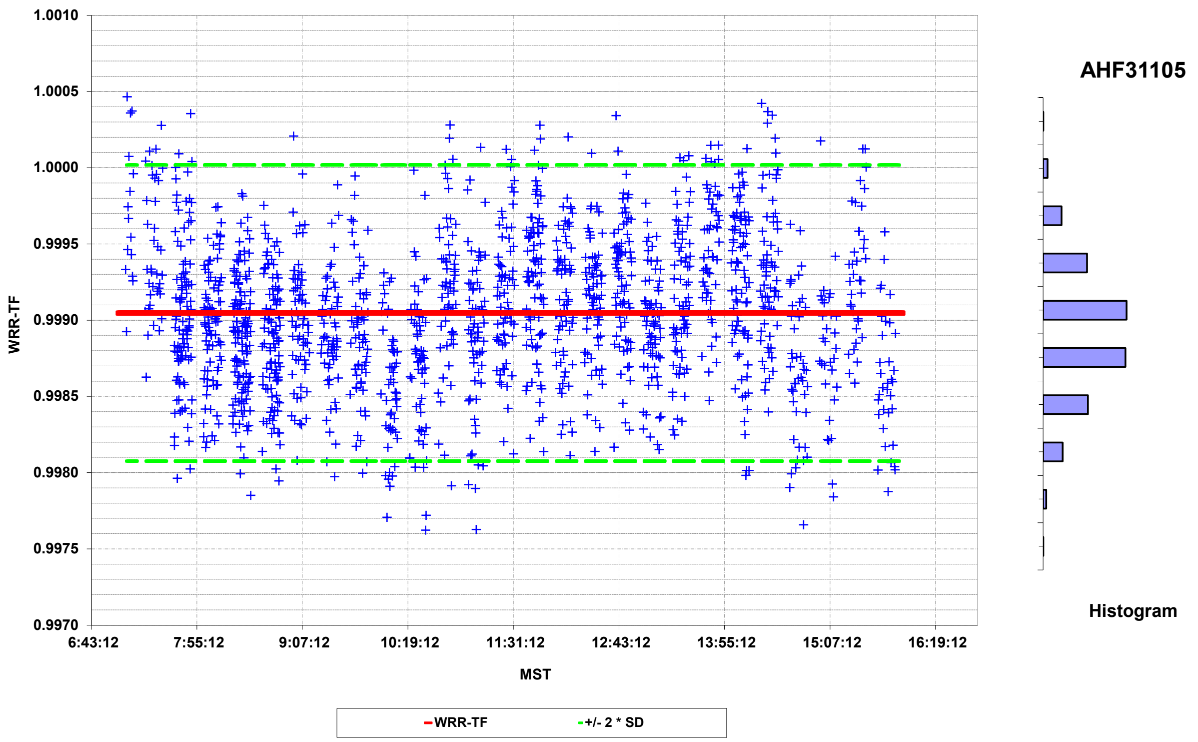

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF30494
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
0.9950
0.9940
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD
Average & 2*SD are only shown for consistency with NPC reporting method.


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF30495
1.0000
0.9995
0.9990
0.9985
0.9980
0.9975
0.9970
0.9965
WRR-TF
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
Histogram
WRR-TF
+/- 2 * SD

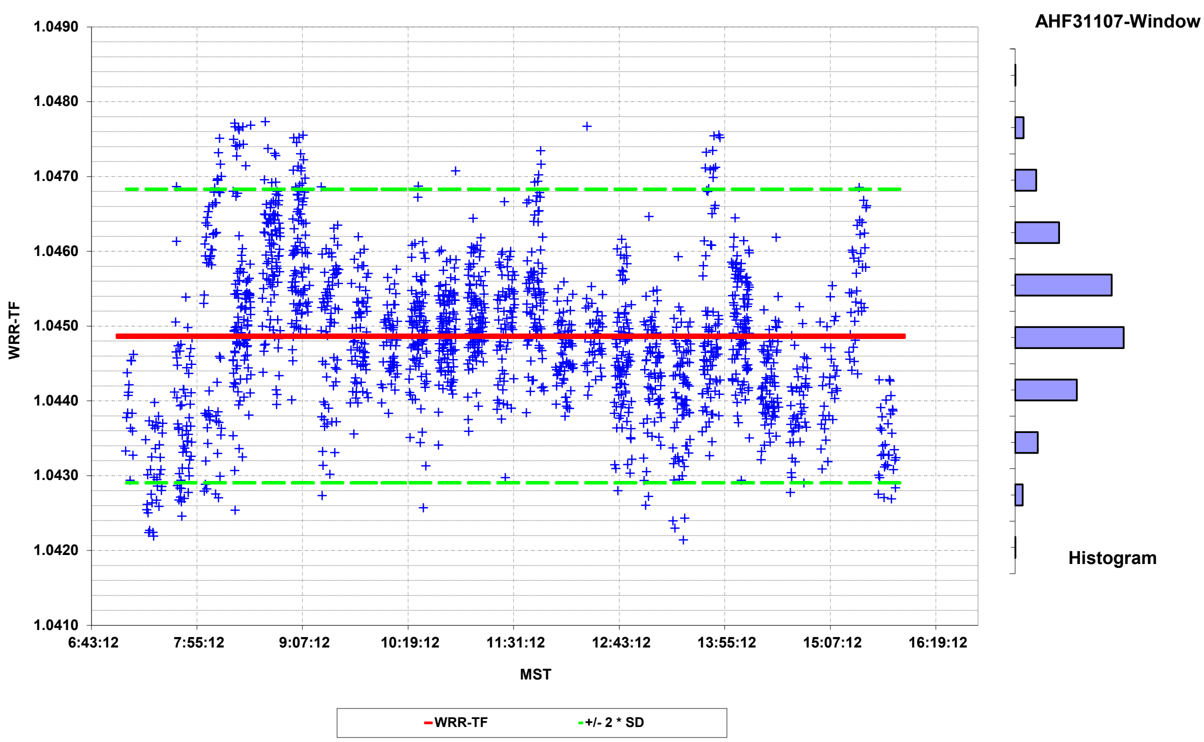

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF31041
0.9985
0.9980
0.9975
0.9970
0.9965
0.9960
0.9955
0.9950
0.9945
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
WRR-TF
+/- 2 * SD
Histogram

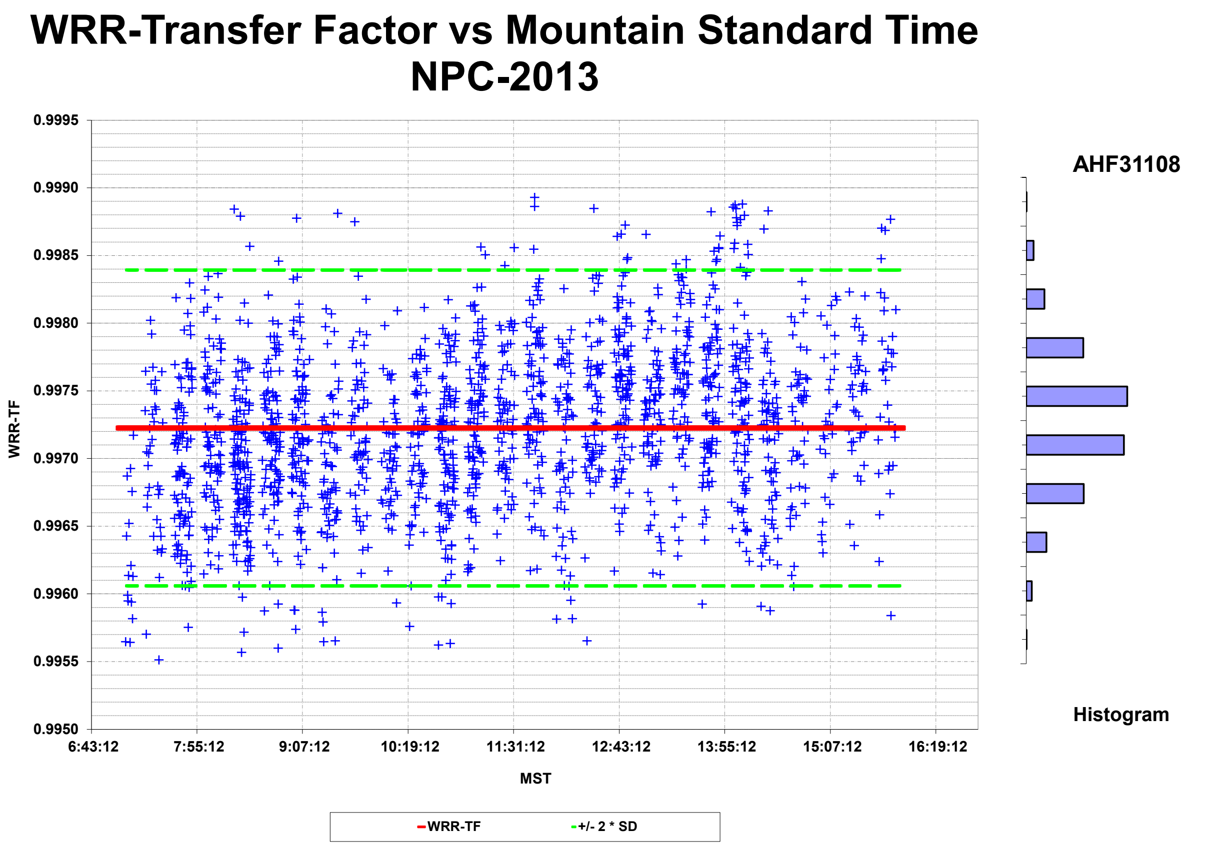

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF31104
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
0.9975
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
WRR-TF
+/- 2 * SD
Histogram

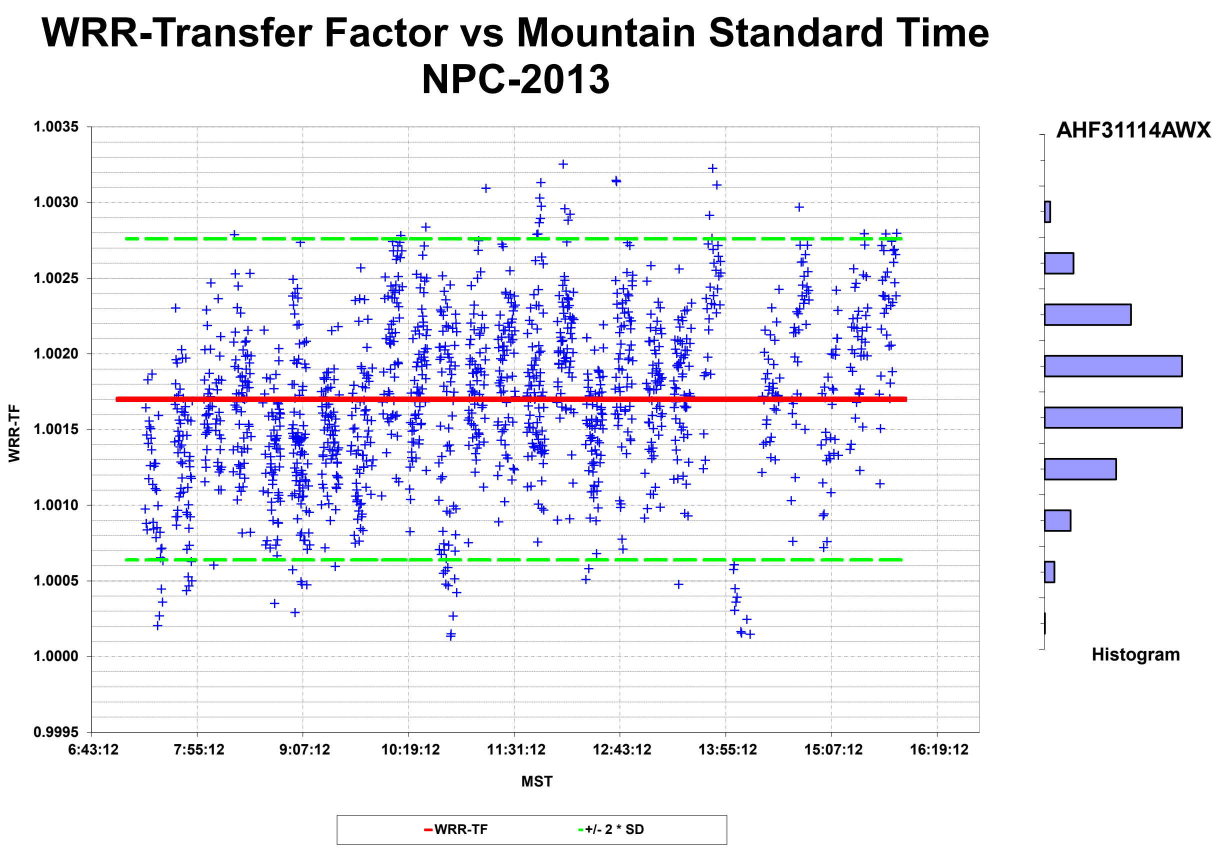
WRR-Transfer Factor vs Mountain Standard Time NPC-2013

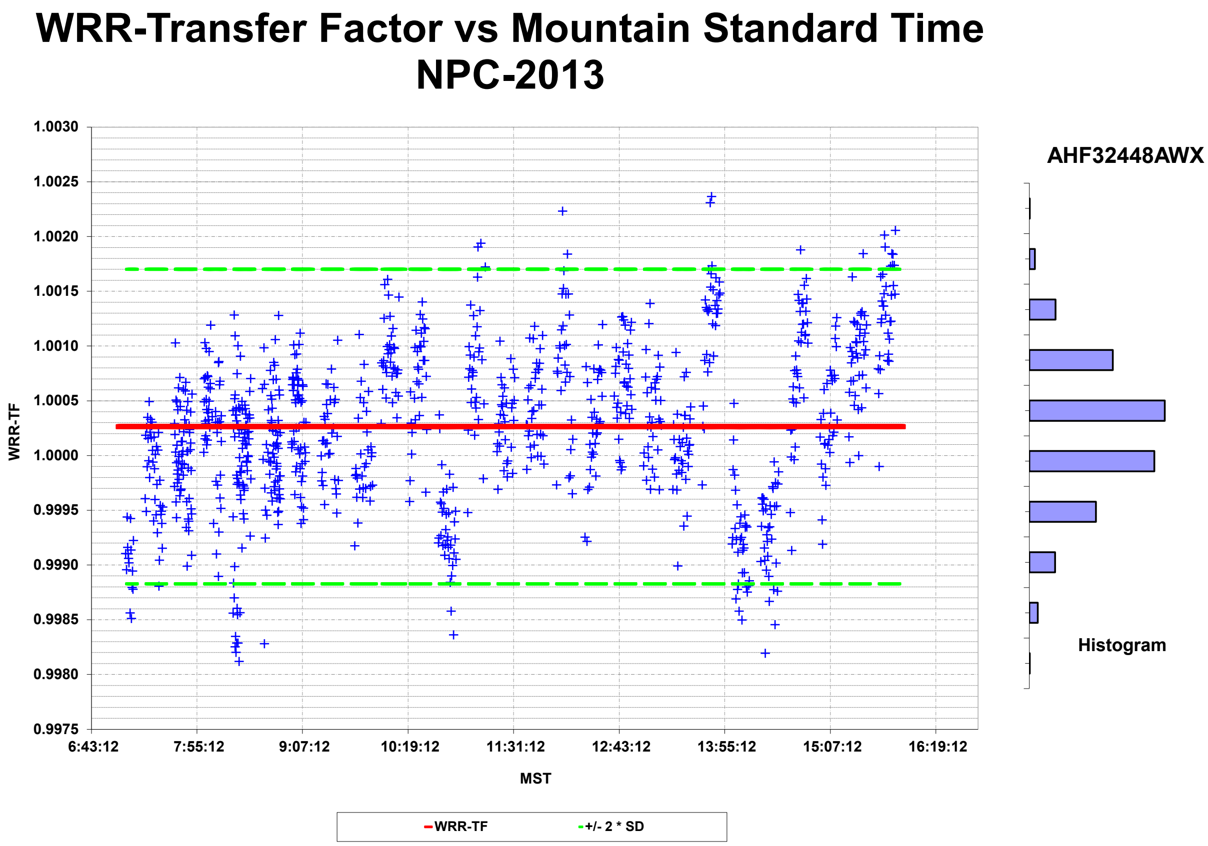


WRR-Transfer Factor vs Mountain Standard Time NPC-2013

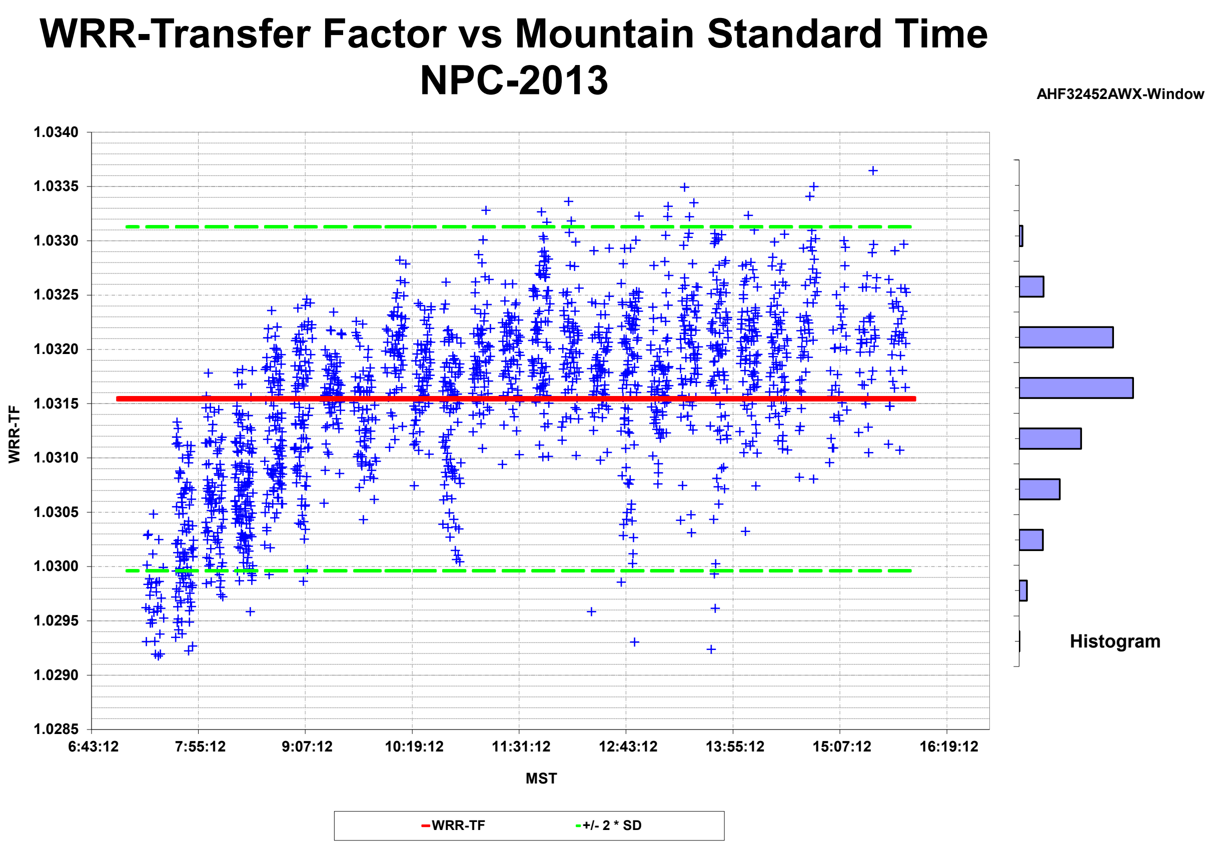



WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF31108
WRR-TF
MST
Histogram
WRR-TF
+/- 2 * SD

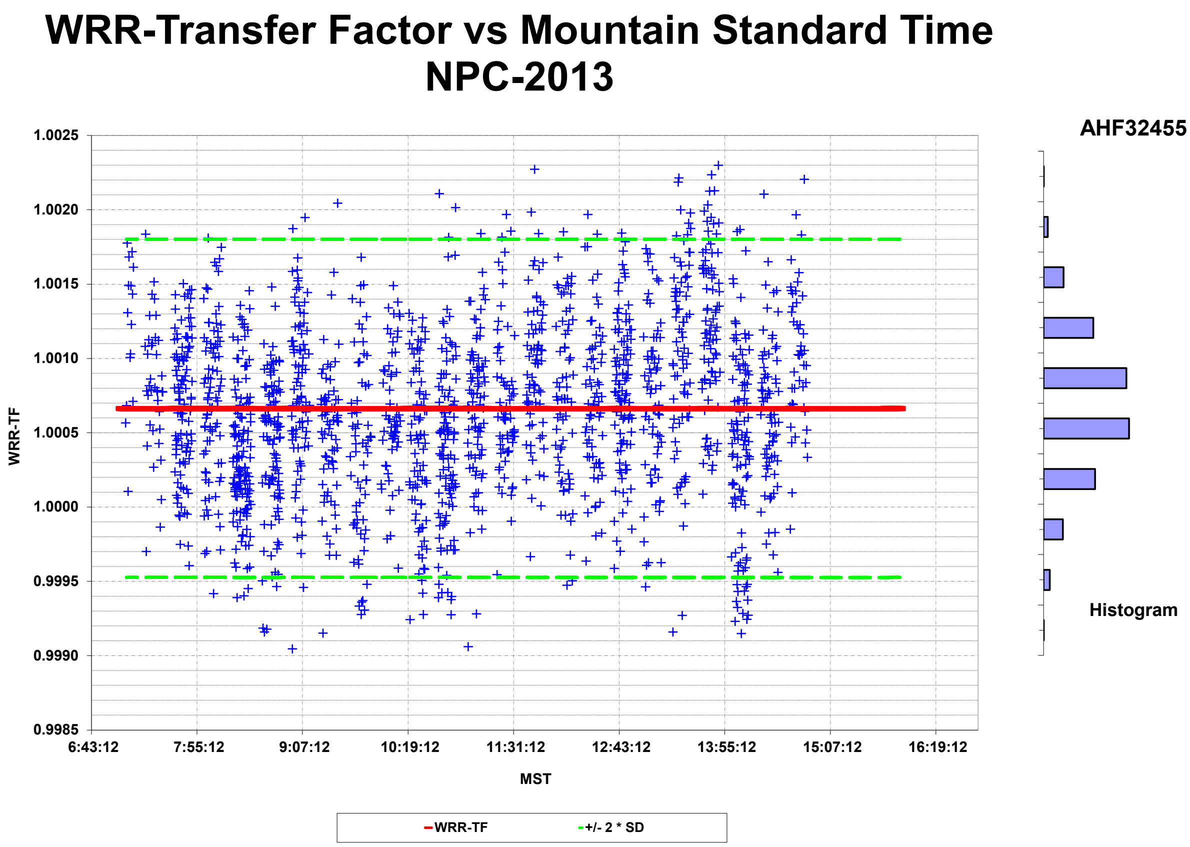

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF31114AWX
WRR-TF
MST
Histogram
WRR-TF
+/- 2 * SD

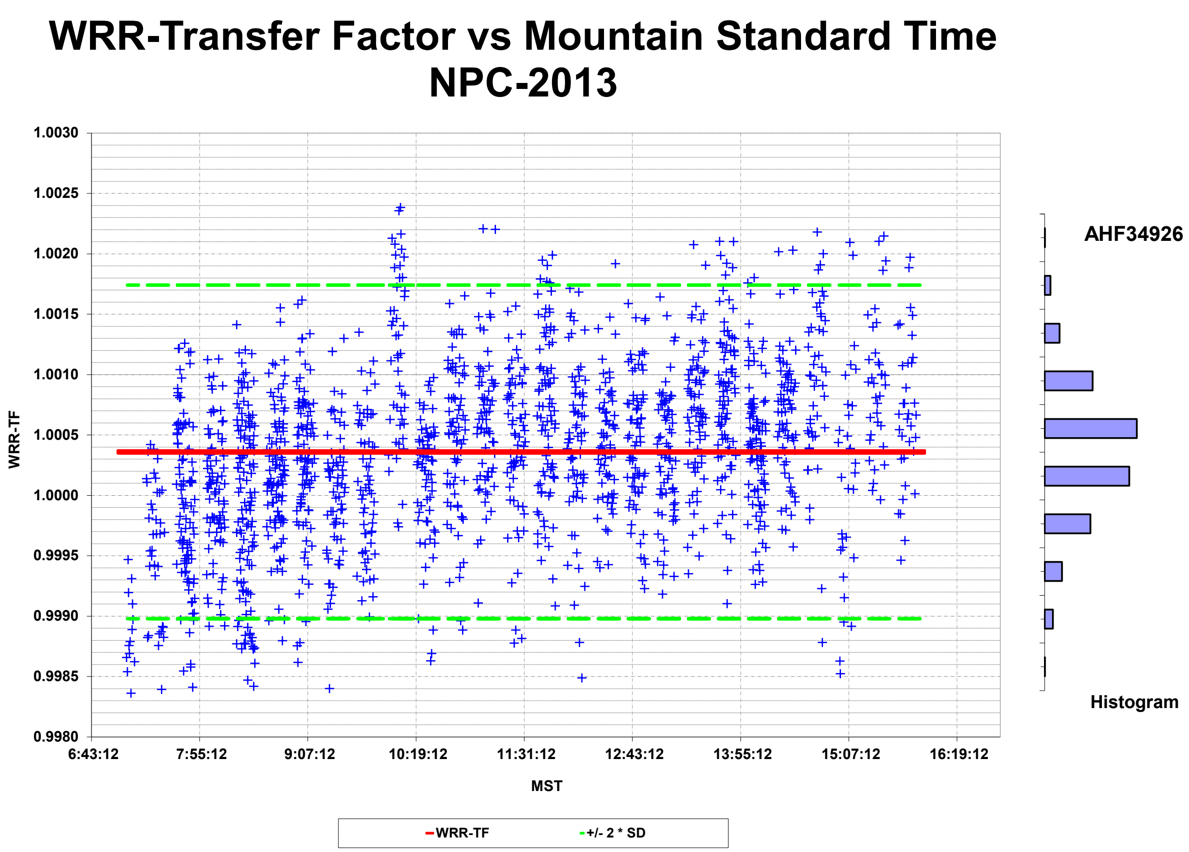


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF32448AWX
WRR-TF
1.0030
1.0025
1.0020
1.0015
1.0010
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
0.9975
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
WRR-TF
+/- 2 * SD
Histogram

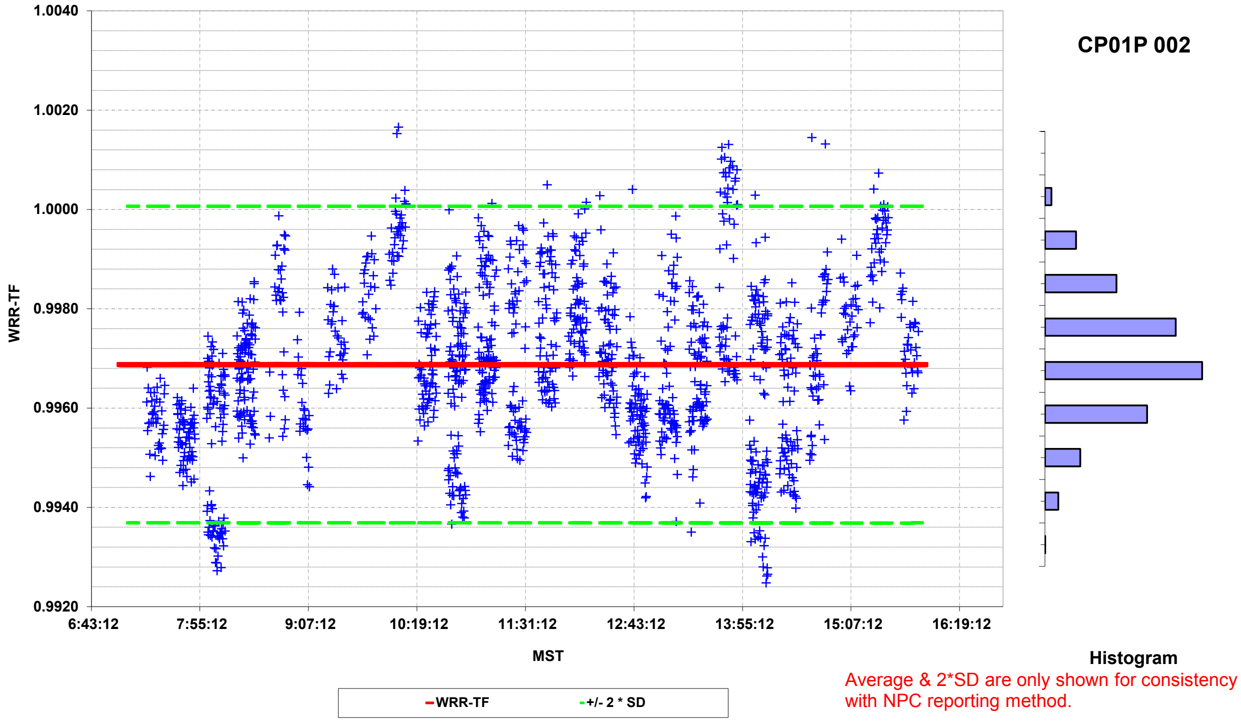


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF32452AWX-Window
WRR-TF
1.0340
1.0335
1.0330
1.0325
1.0320
1.0315
1.0310
1.0305
1.0300
1.0295
1.0290
1.0285
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
WRR-TF
+/- 2 * SD
Histogram


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF32455
1.0025
1.0020
1.0015
1.0010
1.0005
1.0000
0.9995
0.9990
0.9985
WRR-TF
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
Histogram
WRR-TF
+/- 2 * SD

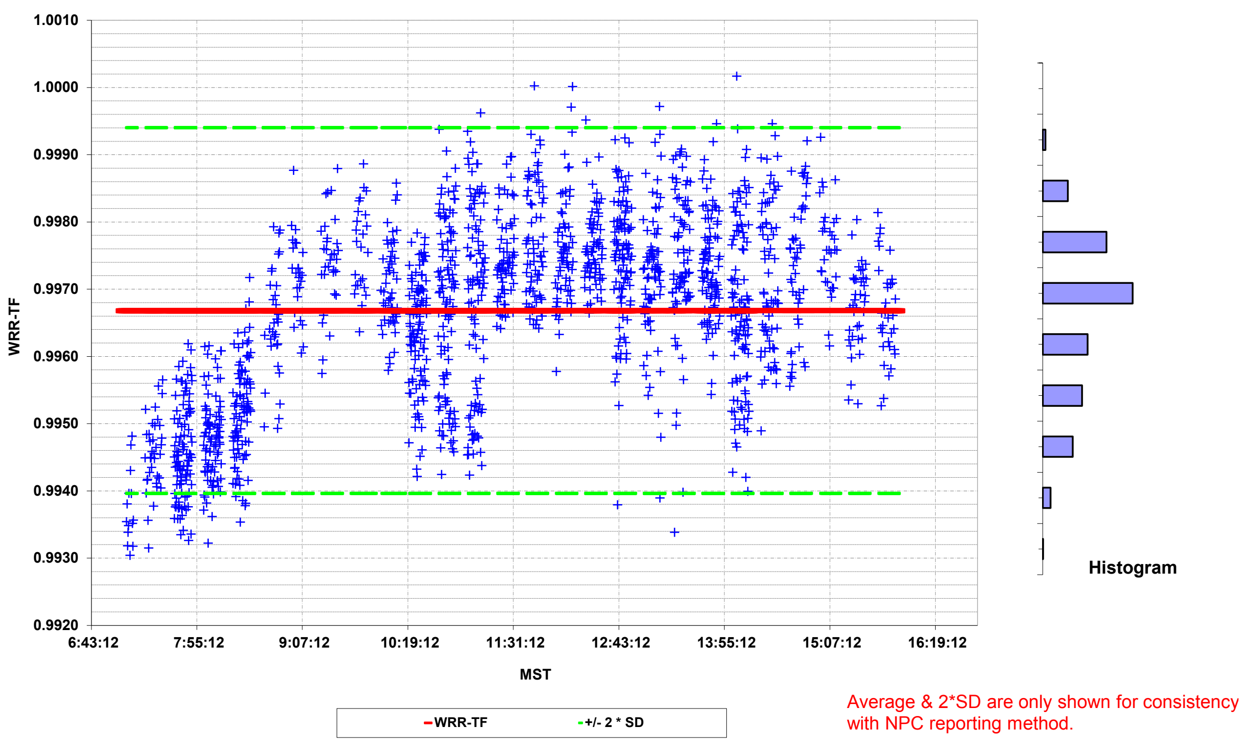

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
AHF34926
1.0030
1.0025
1.0020
1.0015
1.0010
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD

WRR-Transfer Factor vs Mountain Standard Time NPC-2013

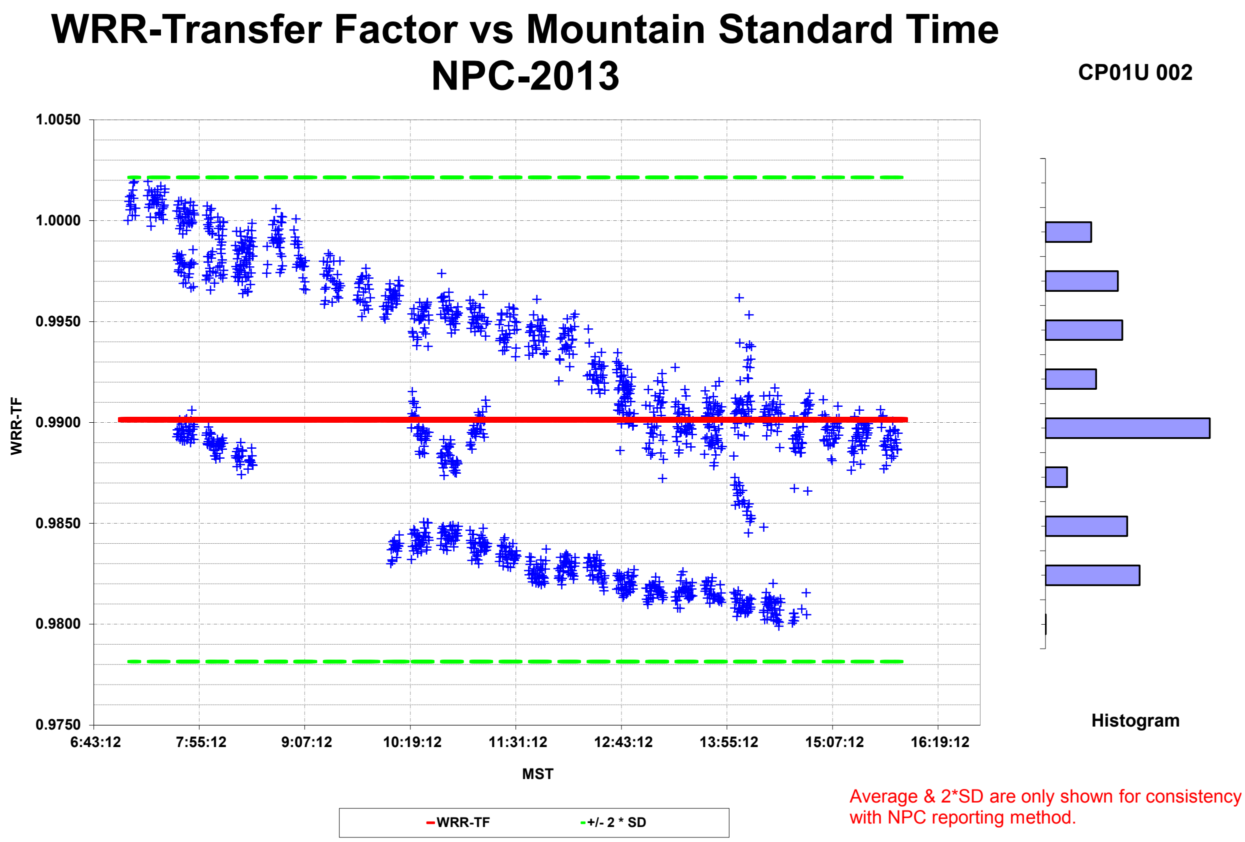


Average & 2*SD are only shown for consistency with NPC reporting method.

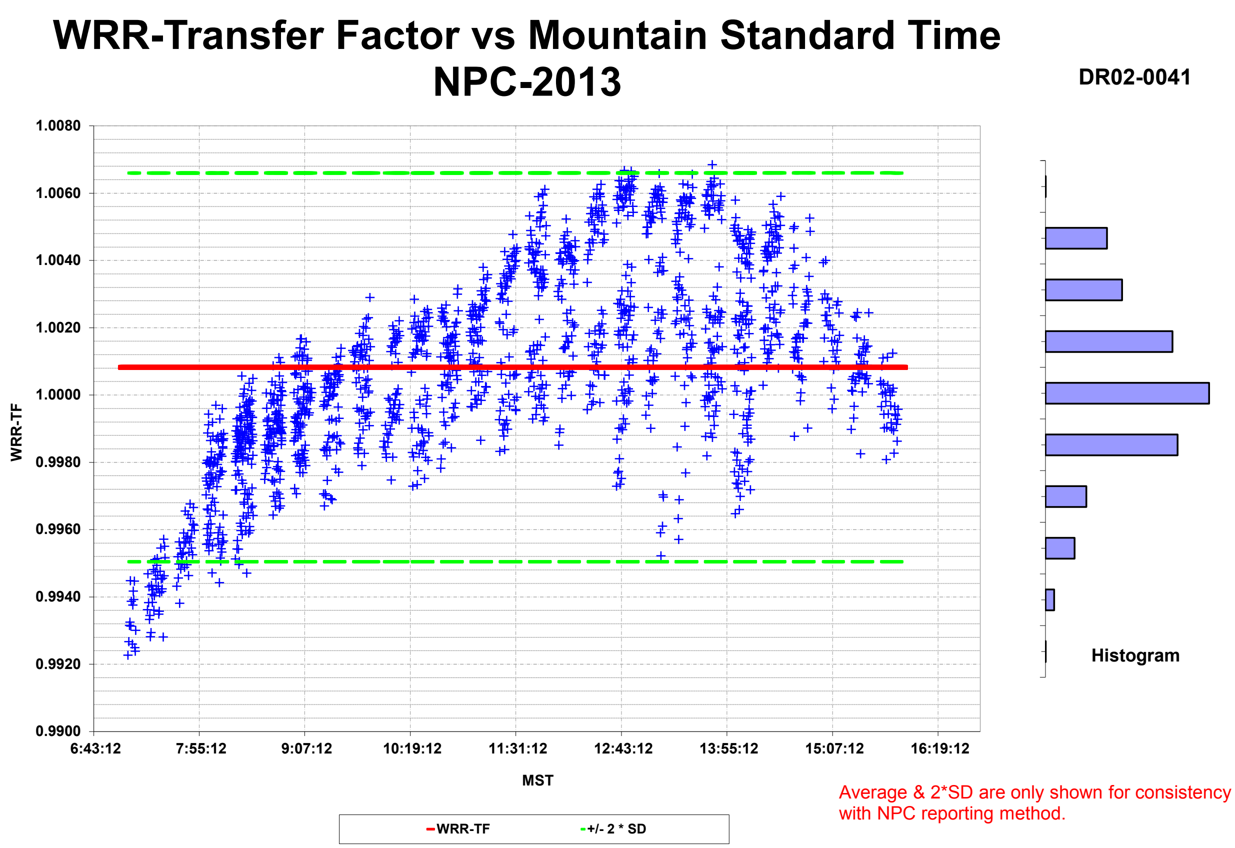
WRR-Transfer Factor vs Mountain Standard Time NPC-2013



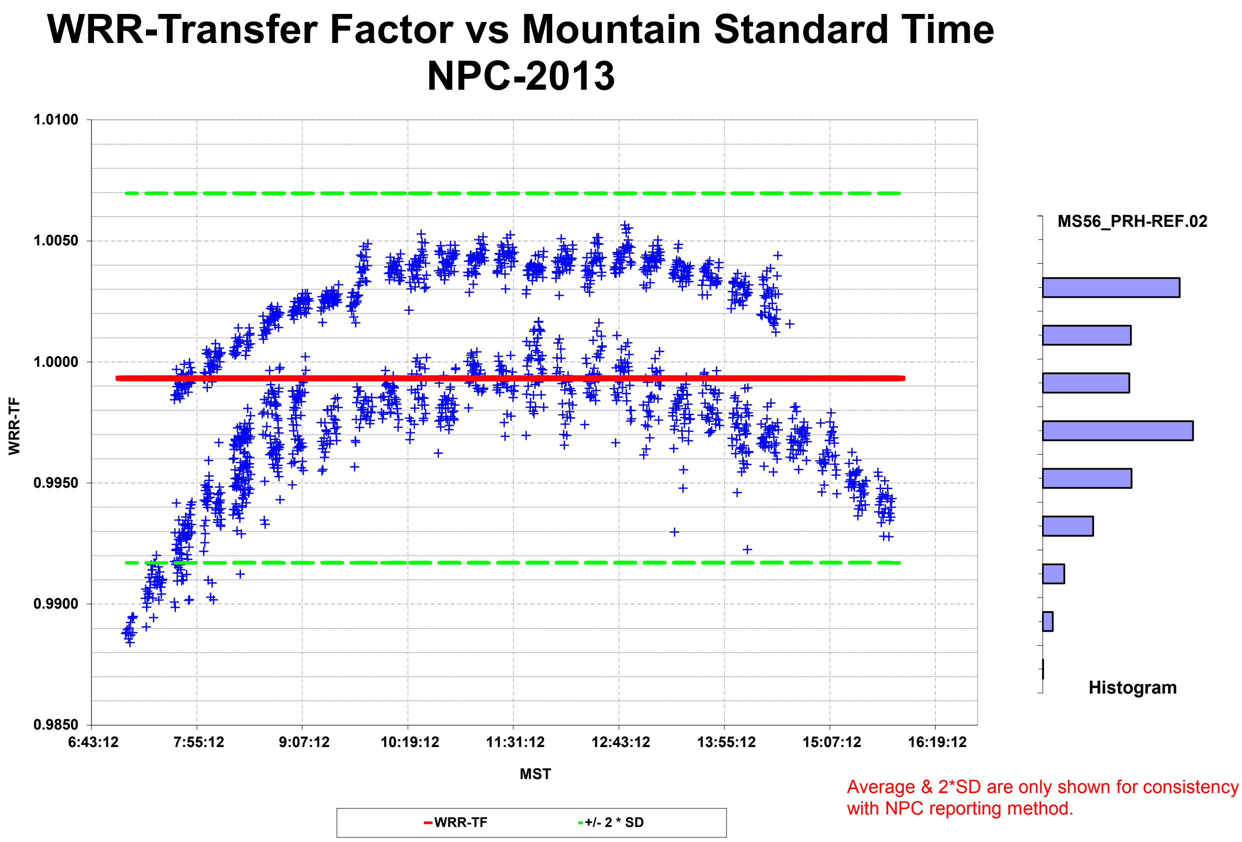
Average & 2*SD are only shown for consistency with NPC reporting method.

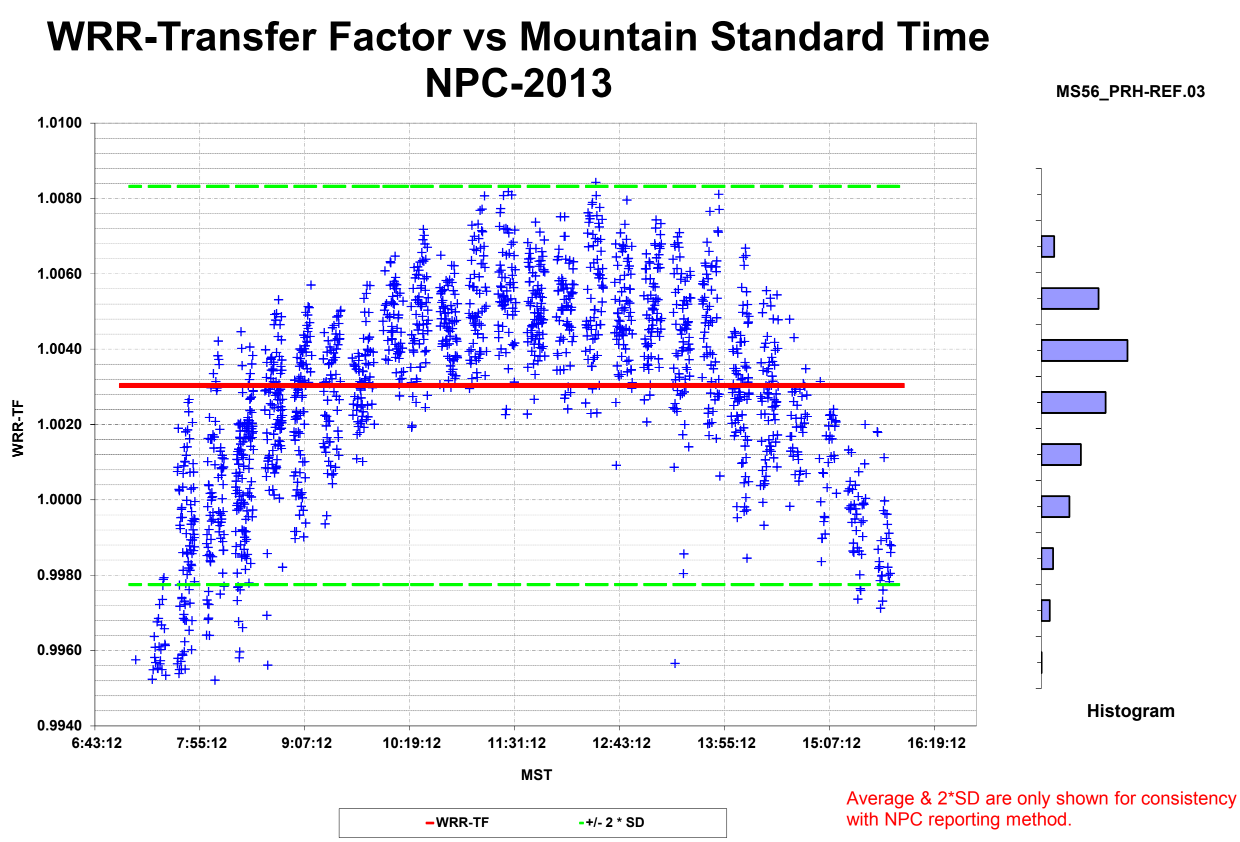


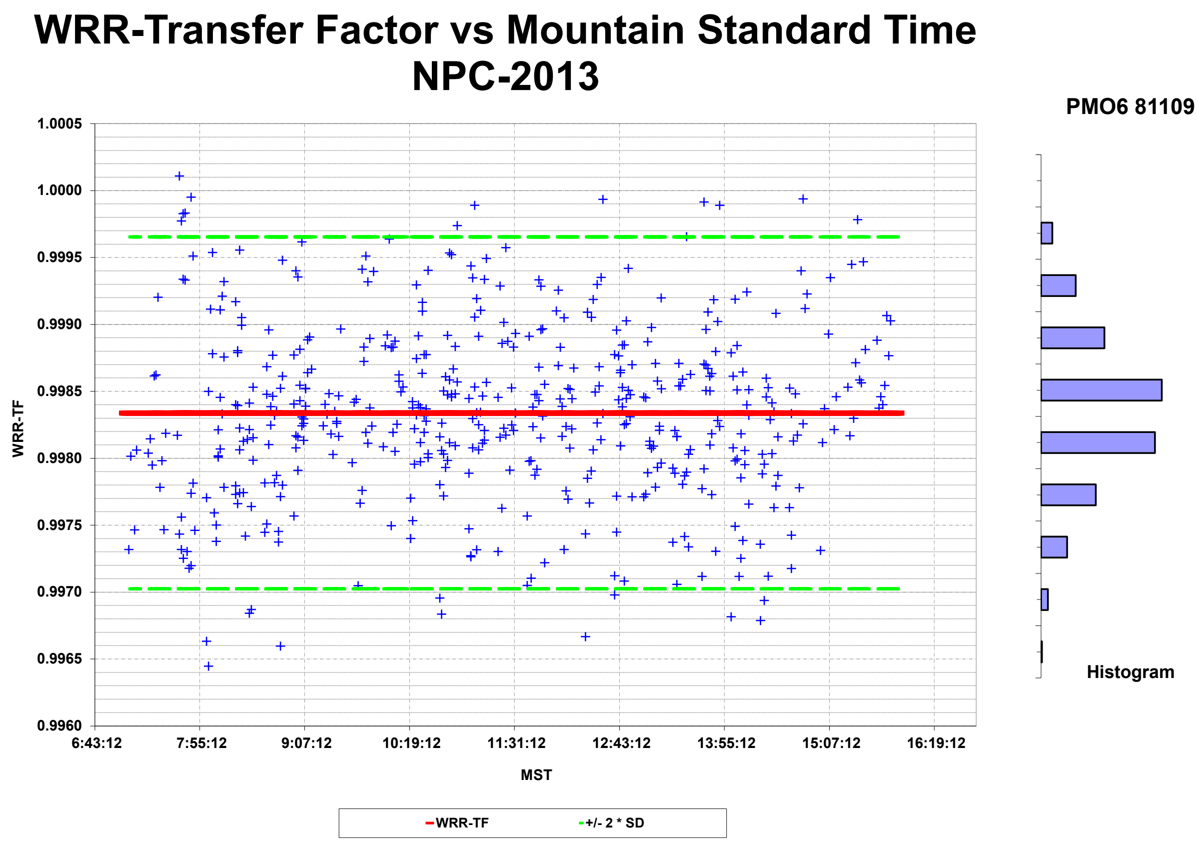
WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
CP01U 002
1.0050
1.0000
0.9950
0.9900
0.9850
0.9800
0.9750
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD
Average & 2*SD are only shown for consistency with NPC reporting method.

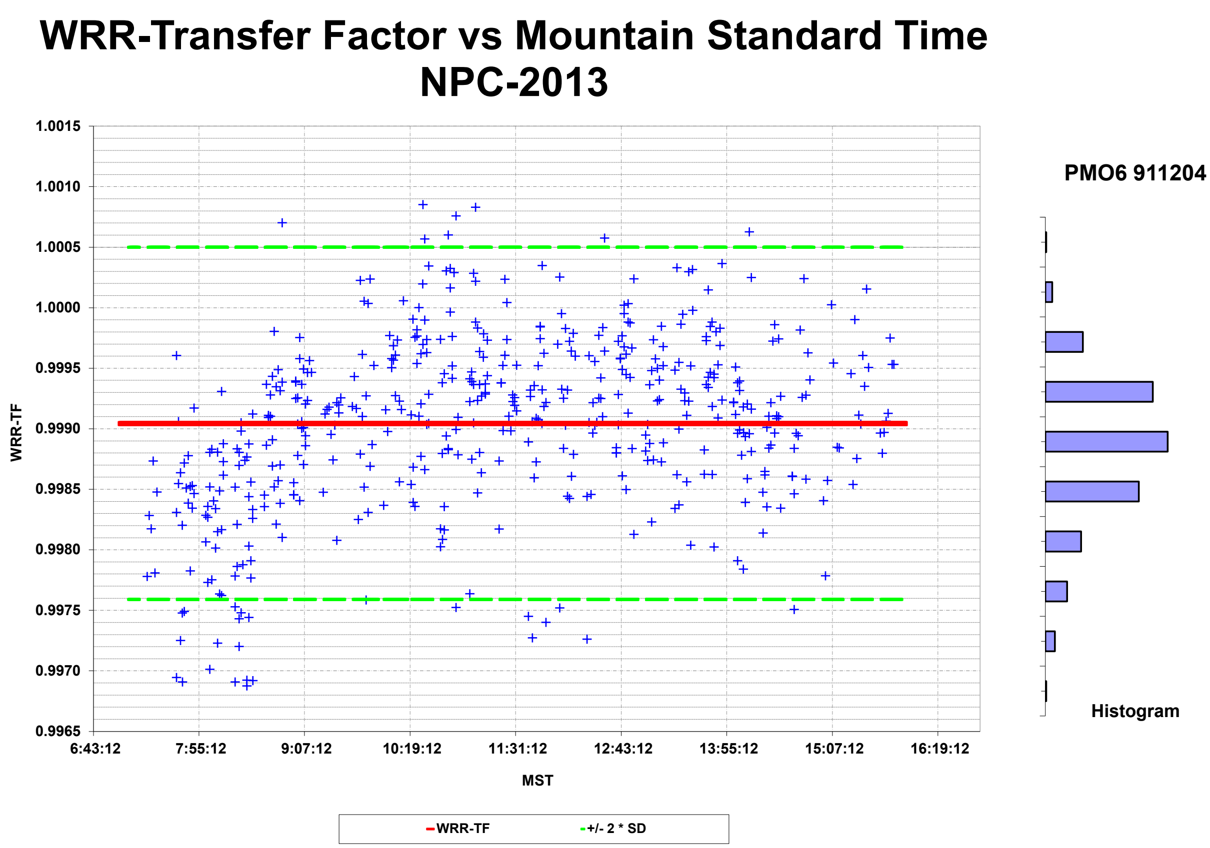


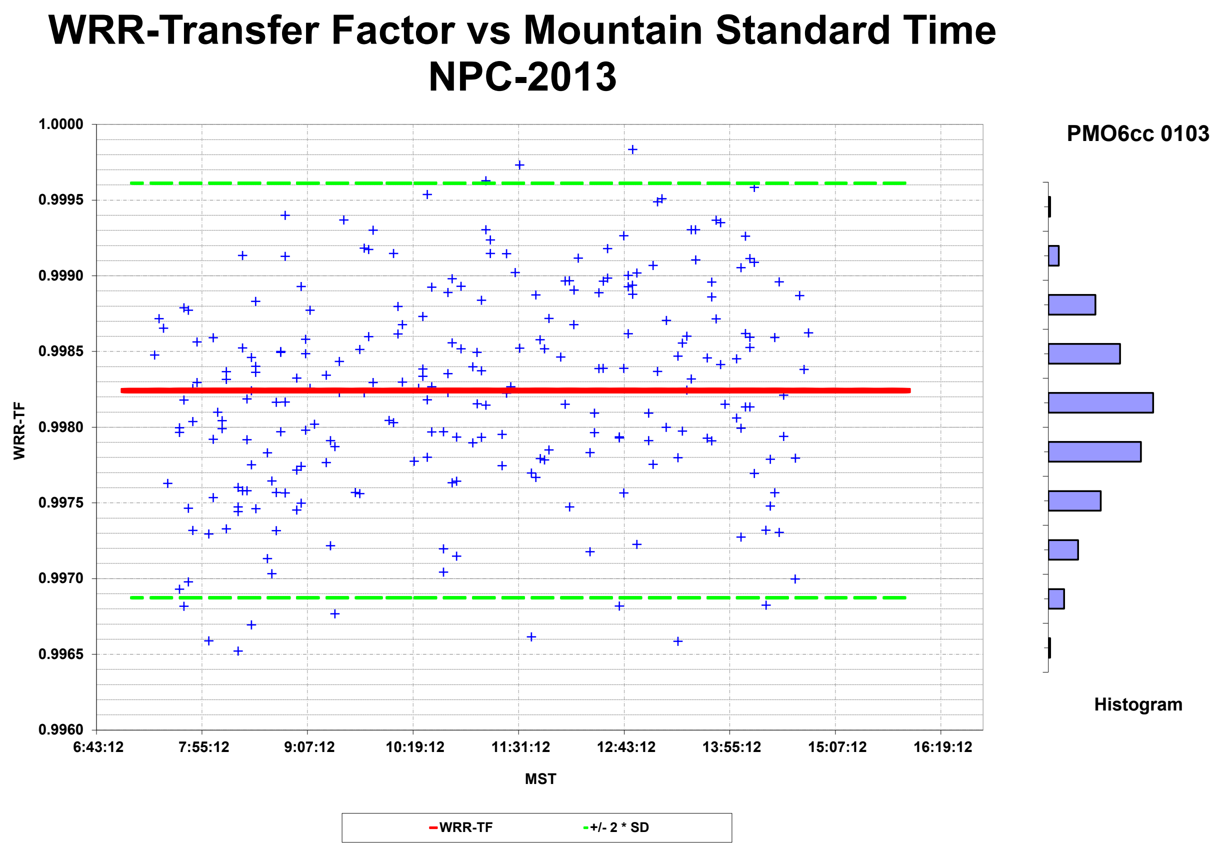
WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
DR02-0041
1.0080
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
0.9920
0.9900
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD
Average & 2*SD are only shown for consistency with NPC reporting method.

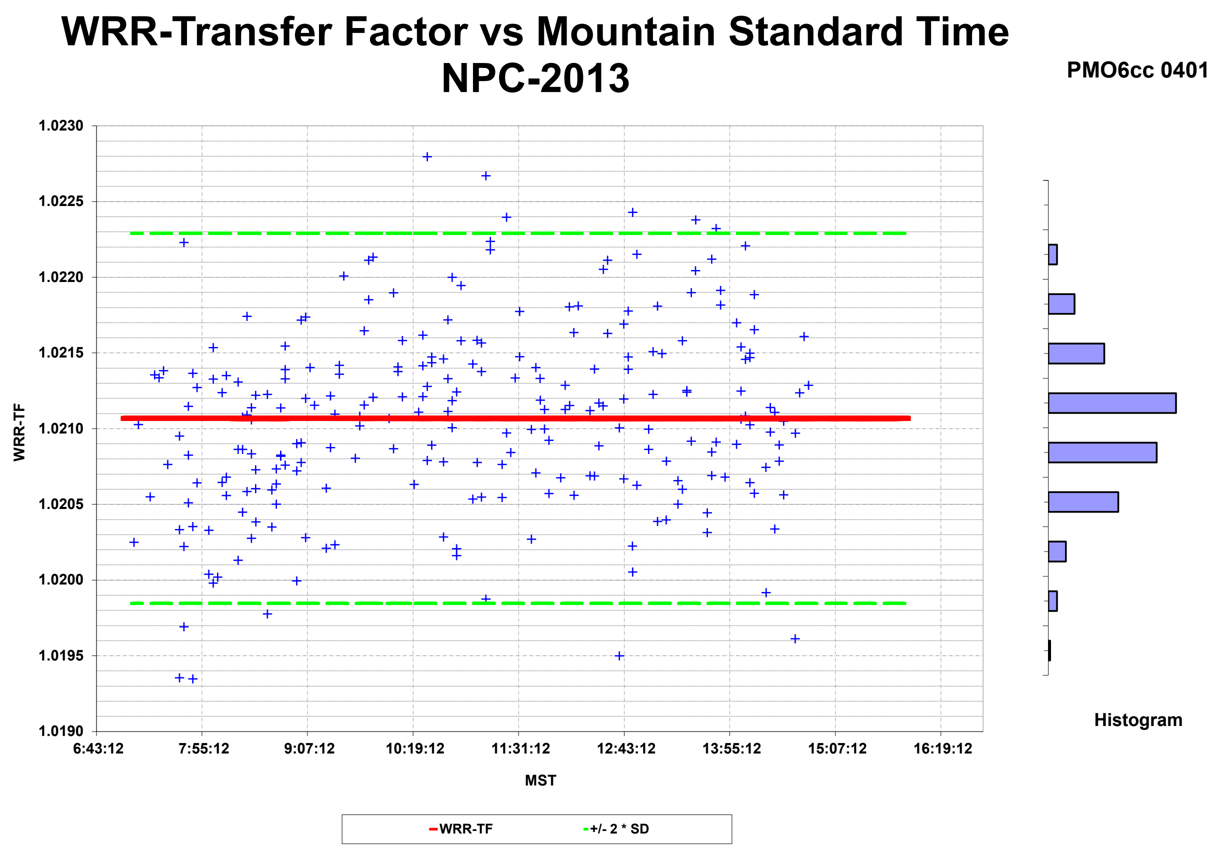

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
1.0100
1.0050
1.0000
0.9950
0.9900
0.9850
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
WRR-TF
+/- 2 * SD
MS56_PRH-REF.02
Histogram
Average & 2*SD are only shown for consistency with NPC reporting method.

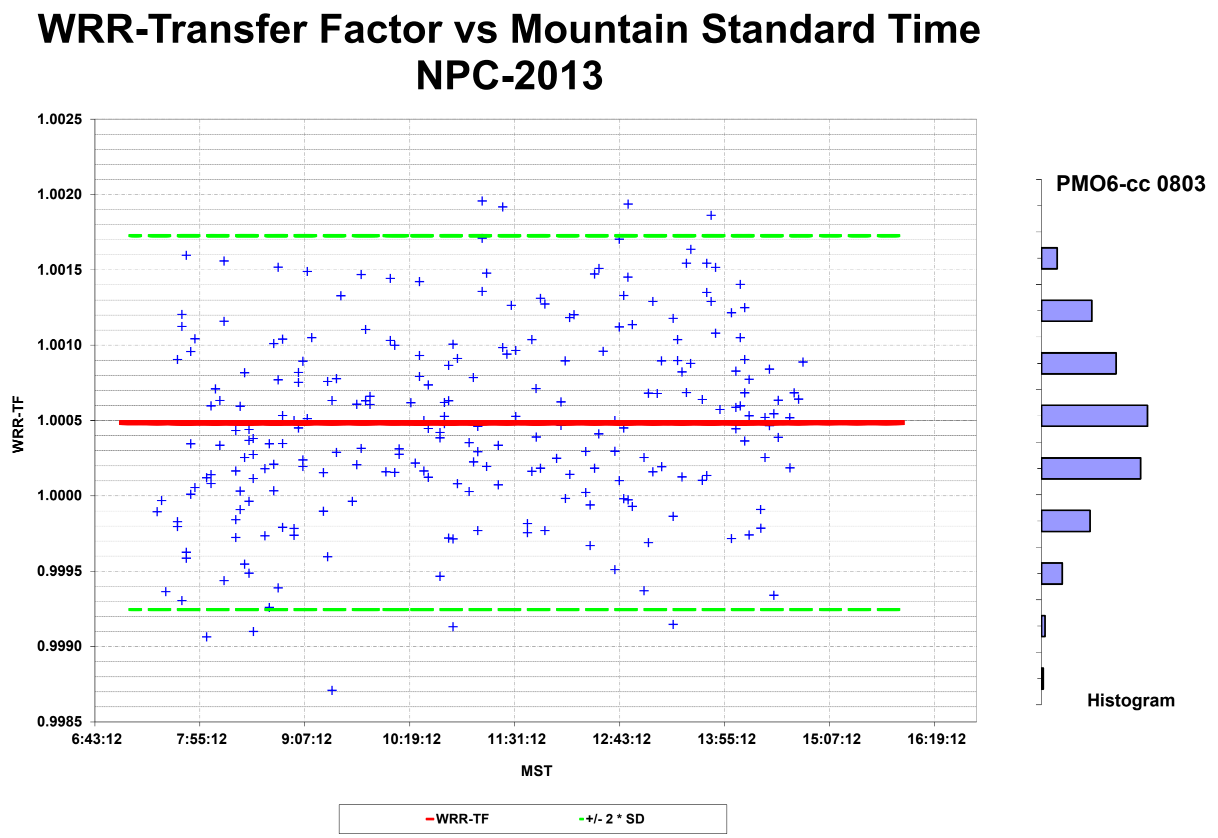

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
MS56_PRH-REF.03
1.0100
1.0080
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
WRR-TF
+/- 2 * SD
Histogram
Average & 2*SD are only shown for consistency with NPC reporting method.

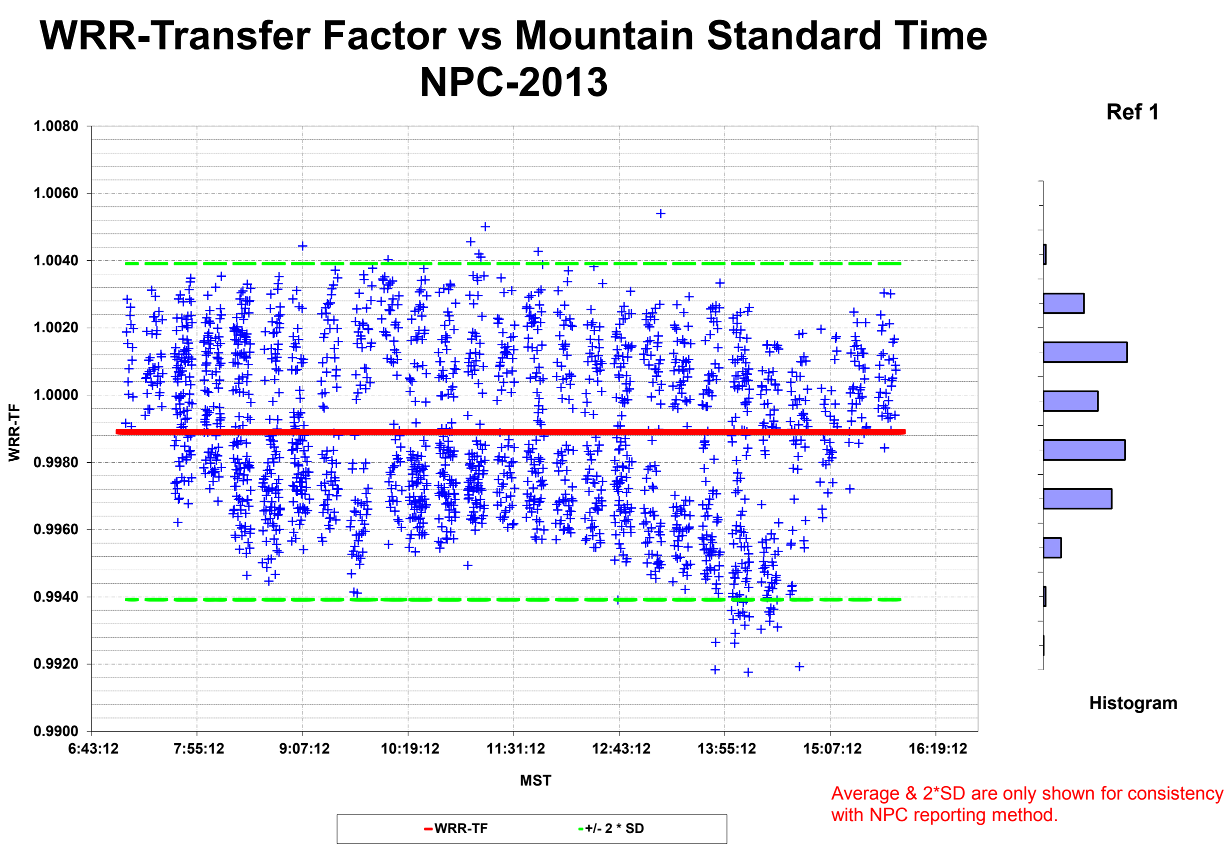

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
PMO6 81109
WRR-TF
MST
Histogram
WRR-TF
+/- 2 * SD


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
PMO6 911204
WRR-TF
MST
Histogram
WRR-TF
+/- 2 * SD


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
PMO6cc 0103
WRR-TF
MST
Histogram
WRR-TF
+/- 2 * SD

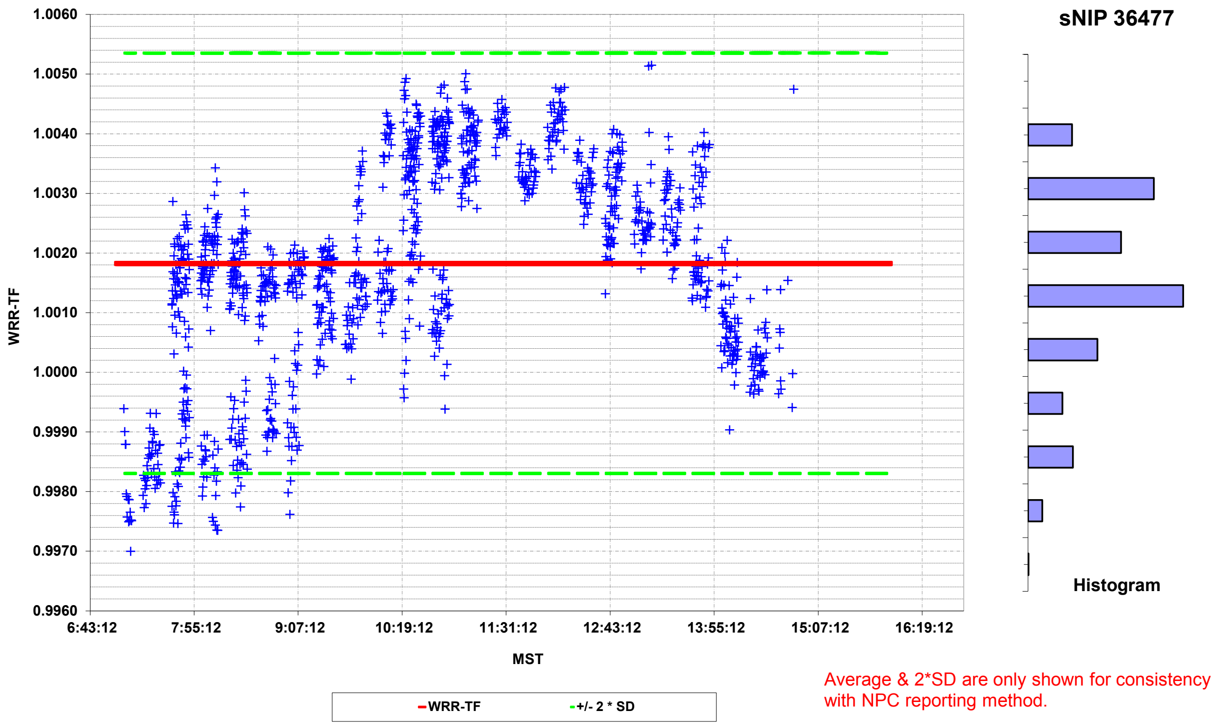

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
PMO6cc 0401
WRR-TF
MST
Histogram
WRR-TF
+/- 2 * SD



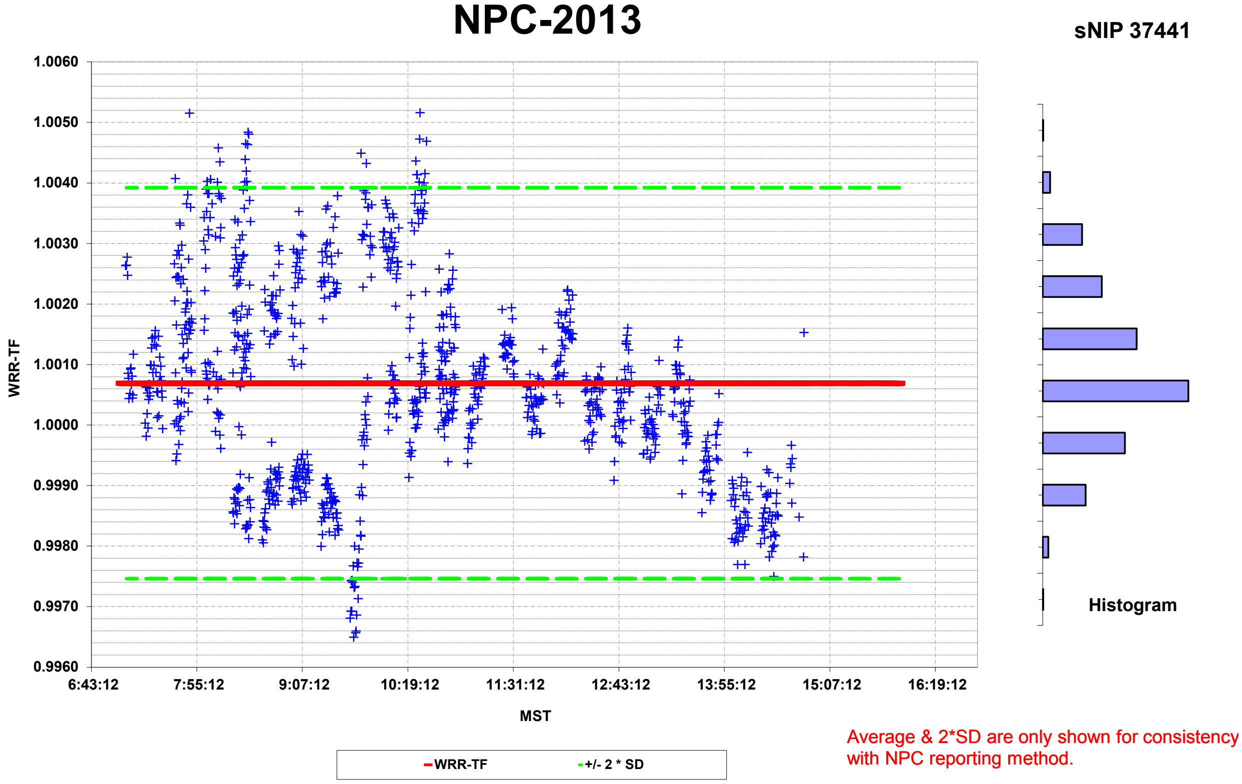


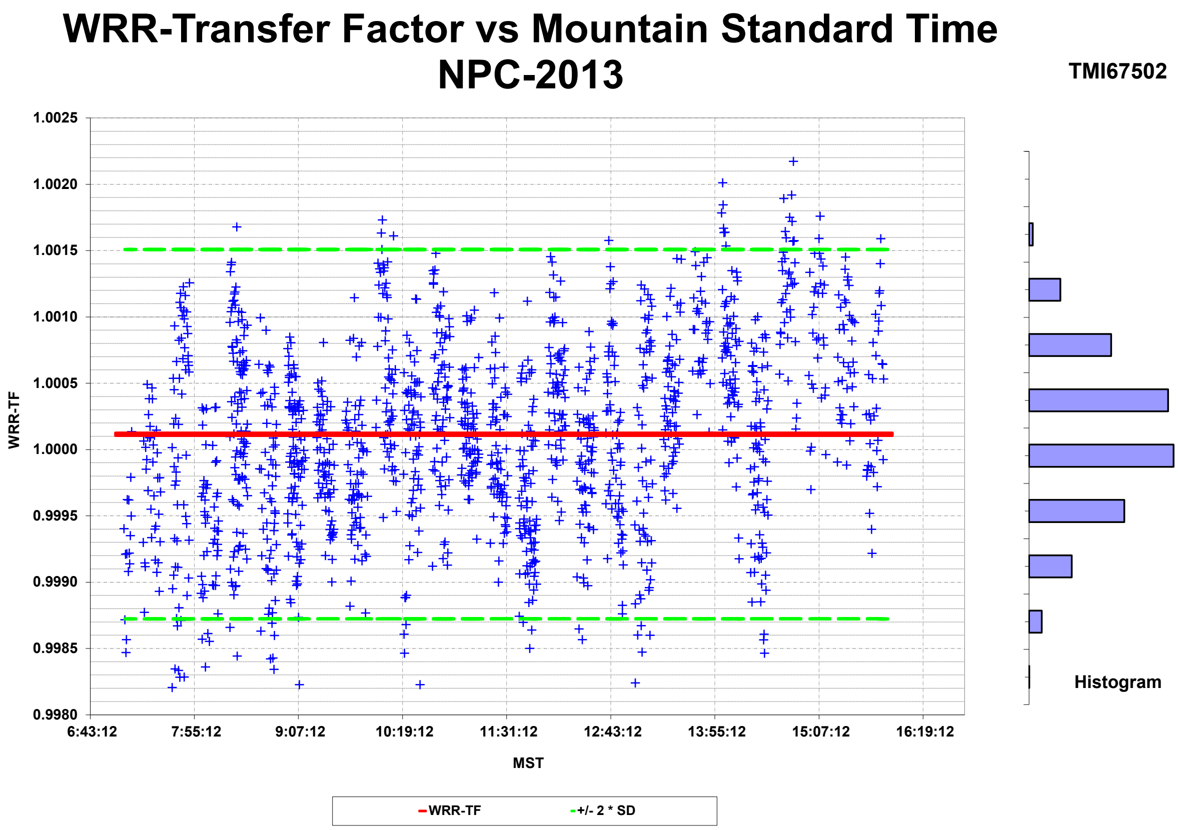
Average & 2*SD are only shown for consistency with NPC reporting method.

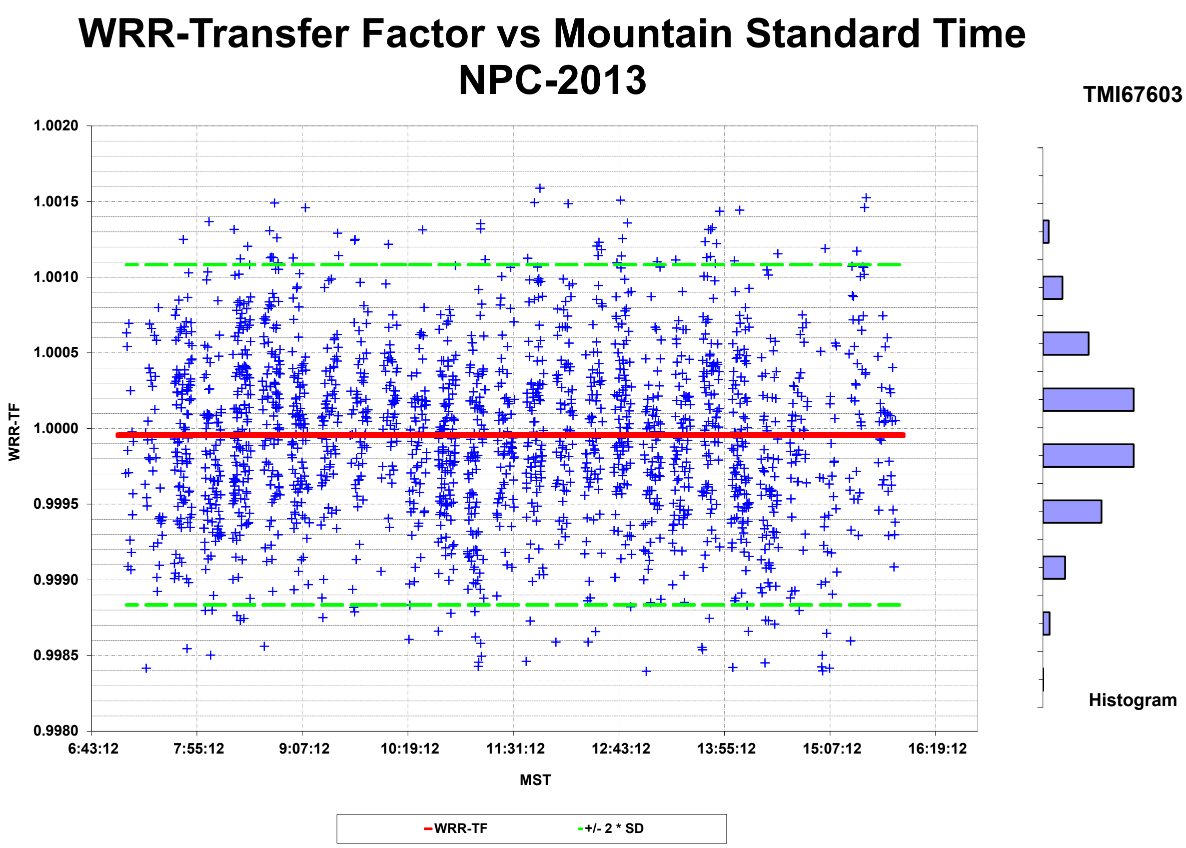
WRR-Transfer Factor vs Mountain Standard Time
NPC-2013

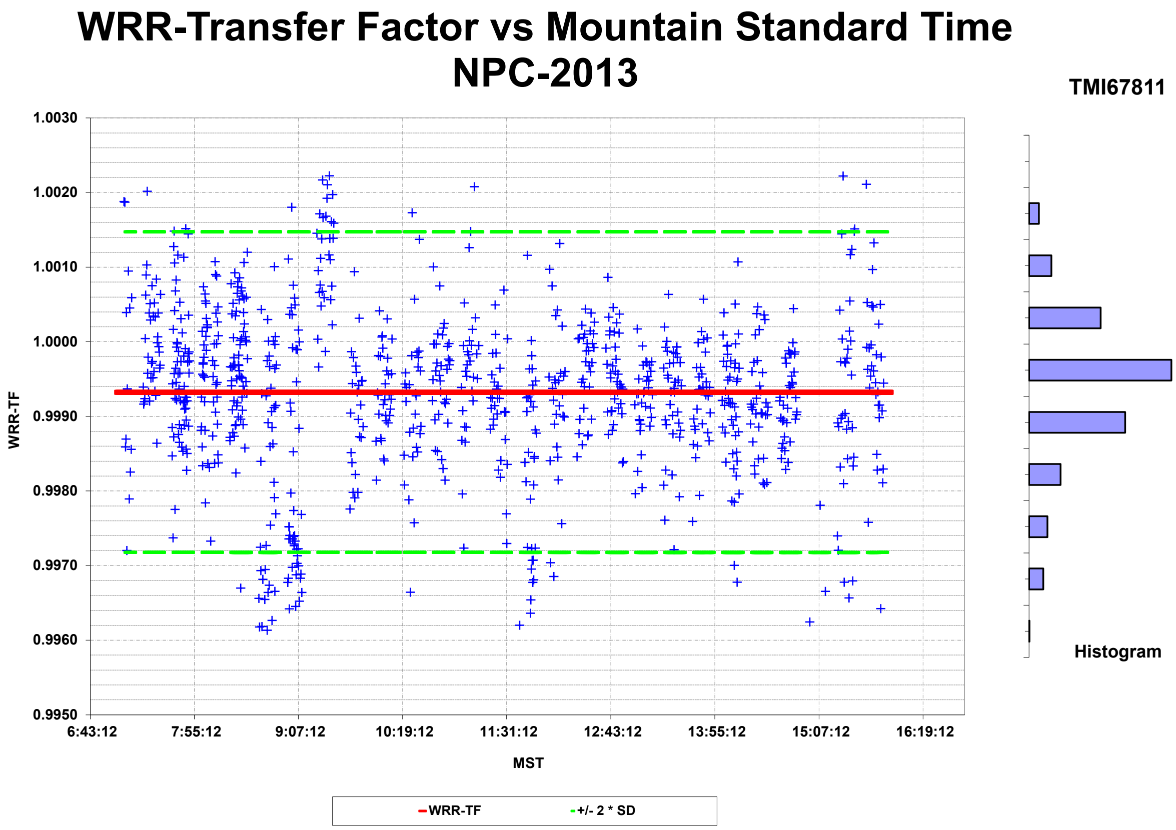


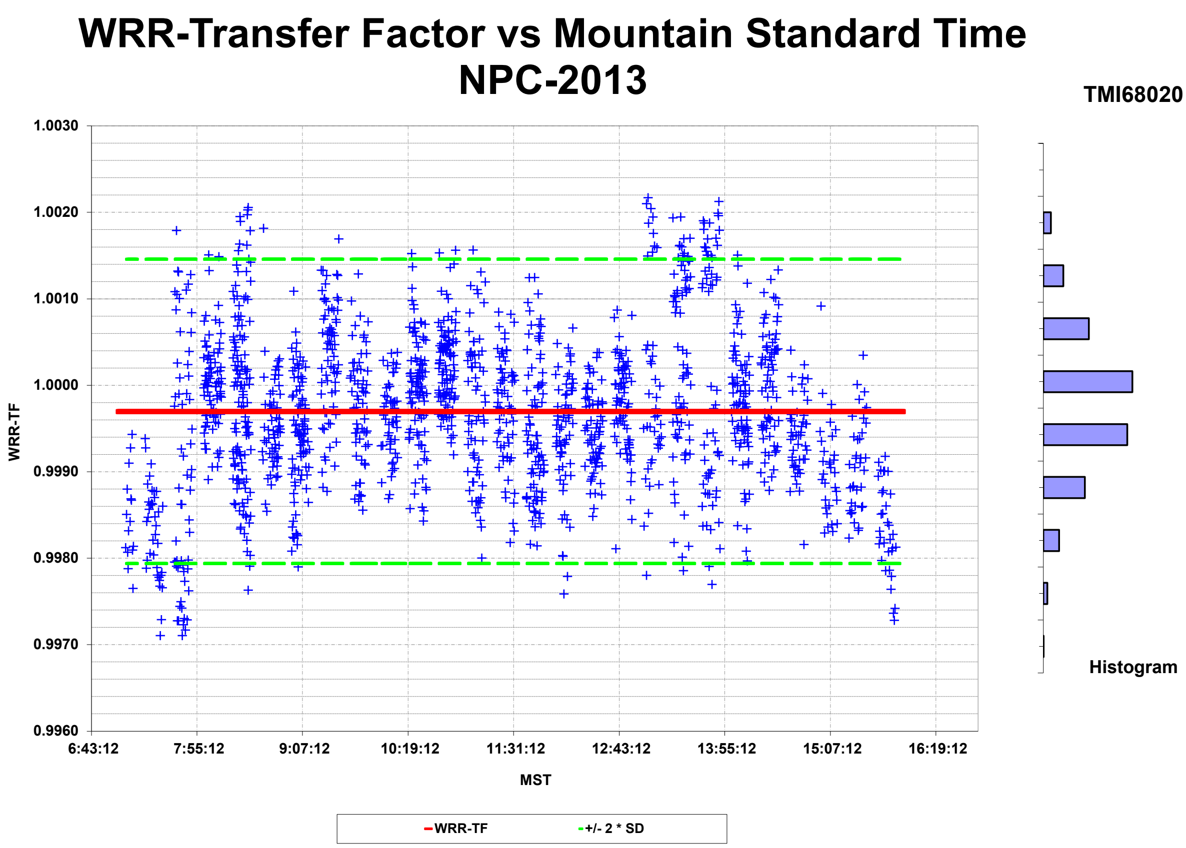
WRR-Transfer Factor vs Mountain Standard Time
NPC-2013

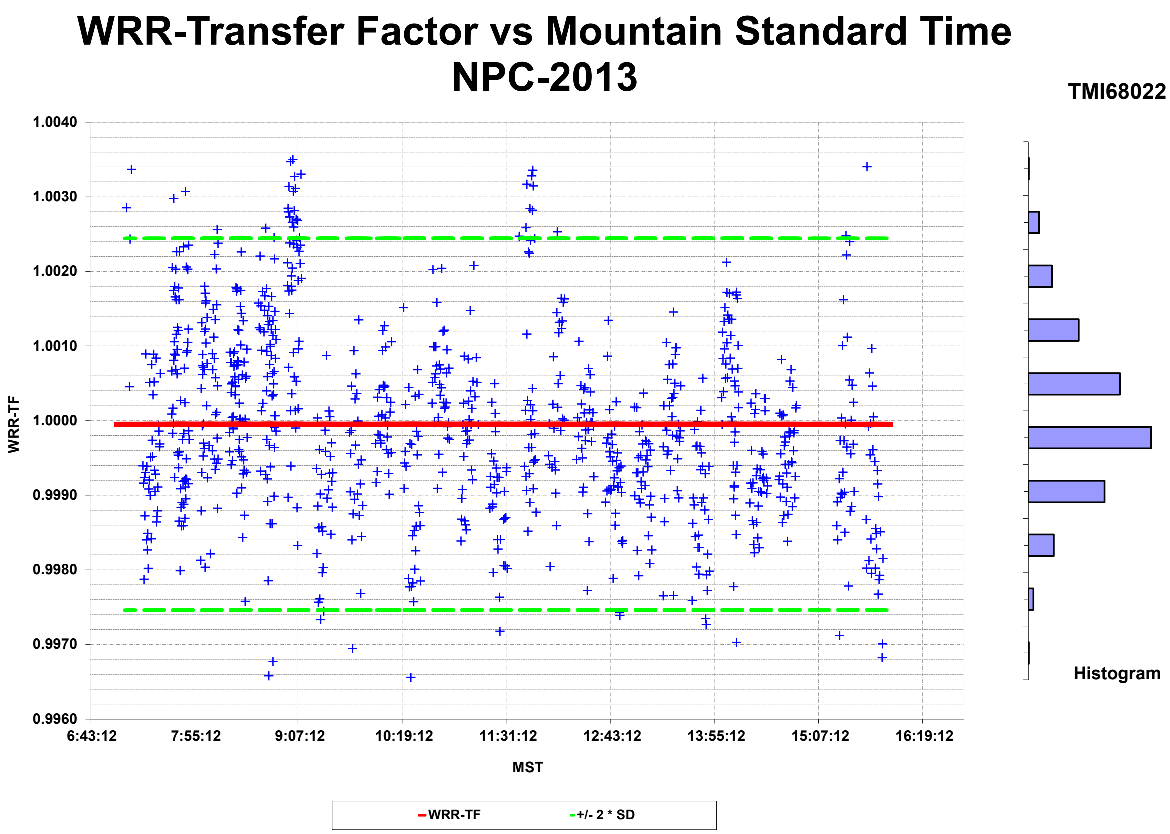


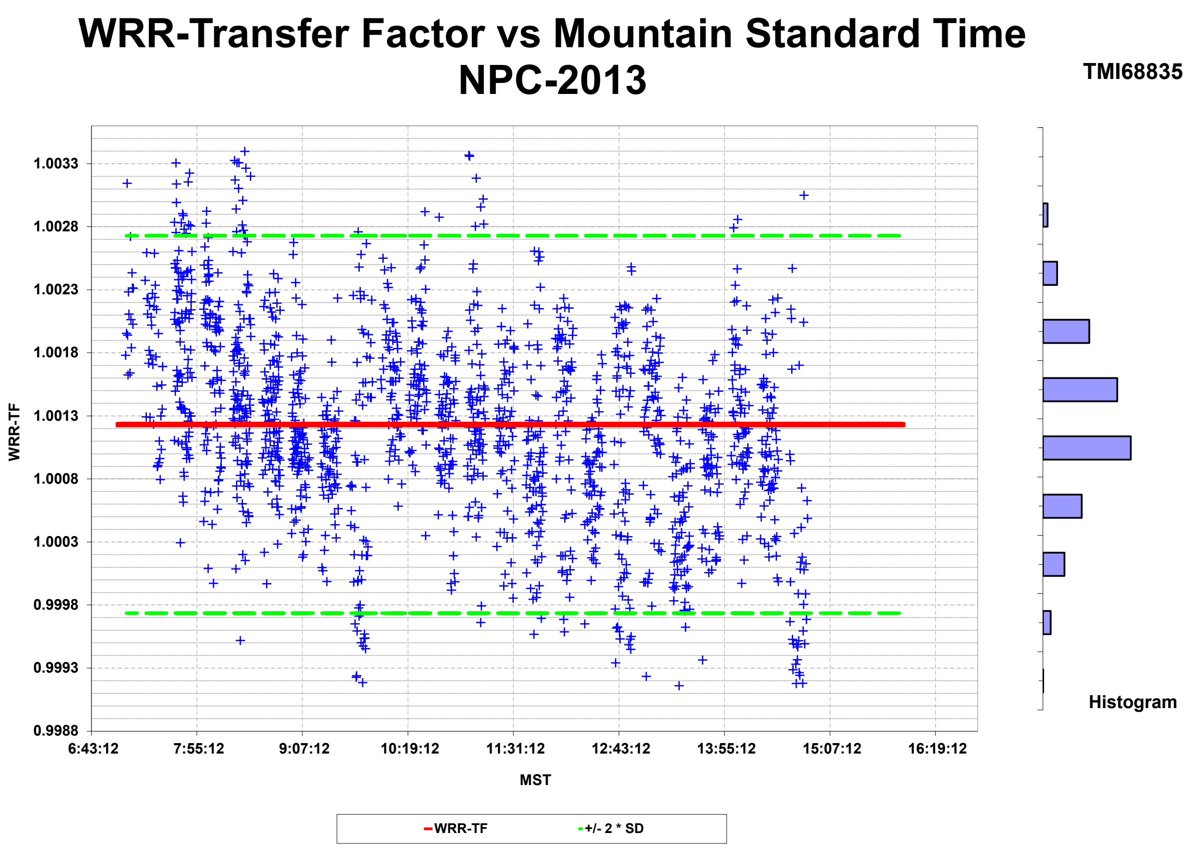

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
TMI67502
1.0025
1.0020
1.0015
1.0010
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
TMI67603
1.0020
1.0015
1.0010
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
WRR-TF
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
Histogram
WRR-TF
+/- 2 * SD

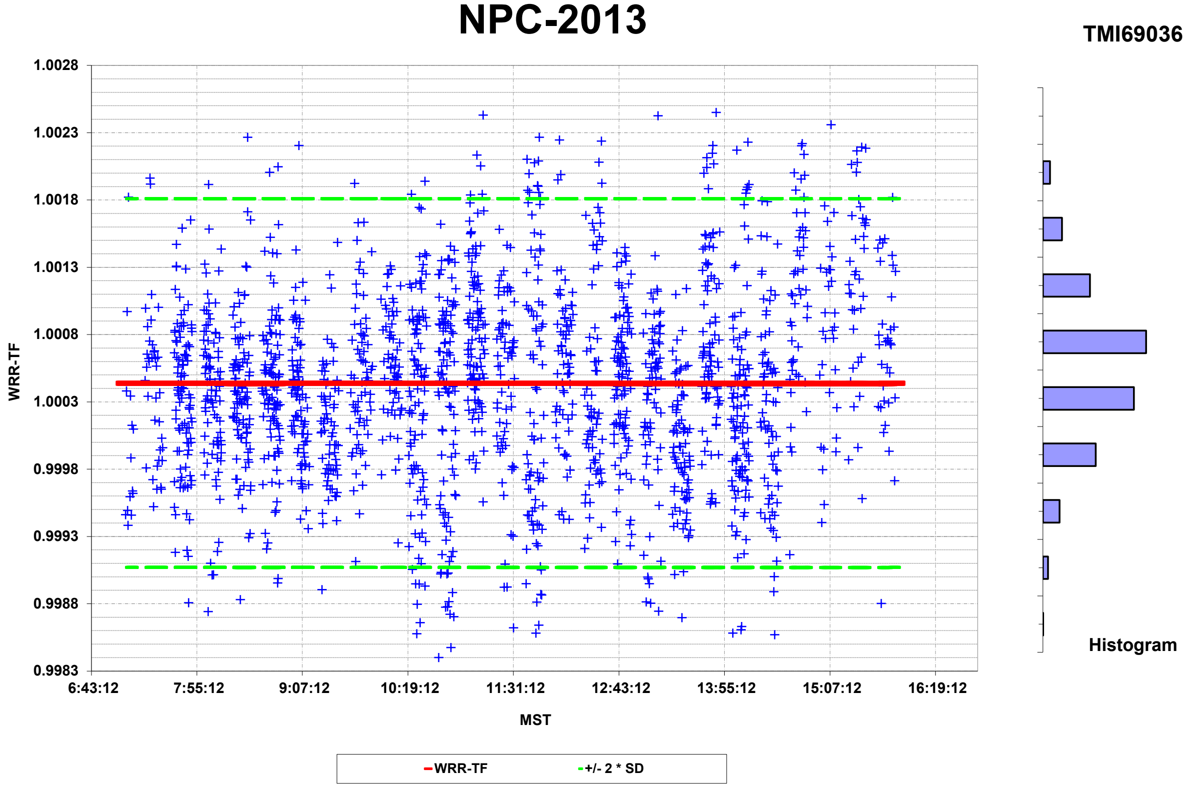

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
TMI67811
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
0.9950
WRR-TF
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST
Histogram
WRR-TF
+/- 2 * SD


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
TMI68020
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
WRR-TF
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
Histogram
WRR-TF
+/- 2 * SD


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
TMI68022
1.0040
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
WRR-TF
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
WRR-TF
+/- 2 * SD
Histogram


WRR-Transfer Factor vs Mountain Standard Time
NPC-2013
TMI68835
1.0033
1.0028
1.0023
1.0018
1.0013
1.0008
1.0003
0.9998
0.9993
0.9988
WRR-TF
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
WRR-TF
+/- 2 * SD
Histogram

WRR-Transfer Factor vs Mountain Standard Time
NPC-2013



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-2013, 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, and vertical wind sheer, 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. (2011). *WMO International Pyrheliometer Comparison, IPC-XI, 27 September – 15 October 2010: Final Report.* WMO IOM Report No. 108. Davos, Switzerland. 86 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. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure* (NCSLI Journal of Measurement Science) (3:4), December 2008; pp. 58–66. NREL/JA-581-41370.

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

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

NPC-2013 Participants and Affiliations

S/N	Operator 1	Operator 2	Affiliation
AHF17142	Erik Naranen		Atlas Weathering Services Group
AHF28556	Erik Naranen		Atlas Weathering Services Group
00347	Scott Smith		Brookhaven National Laboratory
AHF29222-Window	Craig Webb		DOE Atmospheric Radiation Measurement (ARM) Program
AHF30495	Craig Webb		DOE Atmospheric Radiation Measurement (ARM) Program
MS56_PRH-REF.02	Tsukasa Kobashi		EKO Instruments USA, Inc
MS56_PRH-REF.03	Tsukasa Kobashi		EKO Instruments USA, Inc
CH1 930018	Wim Zaaiman		European Commission Directorate General JRC
CH1 060460	Wim Zaaiman		European Commission Directorate General JRC
CH1 040370	Wim Zaaiman		European Commission Directorate General JRC
CH1P 110533	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
TMI68835	Wim Zaaiman		European Commission Directorate General JRC
AHF21182	John Del Mar		Florida Solar Energy Center
90062	Justin Robinson		GroundWorks
110620	Justin Robinson		GroundWorks
DR02-0041	Robert Dolce		HukseefluxUSA, Inc.
CP01U 002	Robert Dolce		HukseefluxUSA, Inc.
CP01P 002	Robert Dolce		HukseefluxUSA, Inc.
CP01T 002	Robert Dolce		HukseefluxUSA, Inc.
AHF30110-Window	Hussain Shibli	Naif Al Sahell	King Abdullah City of Atomic and Renewable Energy
AHF31107-Window	Hussain Shibli	Naif Al Sahell	King Abdullah City of Atomic and Renewable Energy
PMO6cc 0103	Victor Cassella		Kipp & Zonen USA, Inc
Ref 1	Victor Cassella		Kipp & Zonen USA, Inc
090127	Victor Cassella		Kipp & Zonen USA, Inc
070541	Victor Cassella		Kipp & Zonen USA, Inc
TMI68020	Cary Thompson		Lockheed Martin

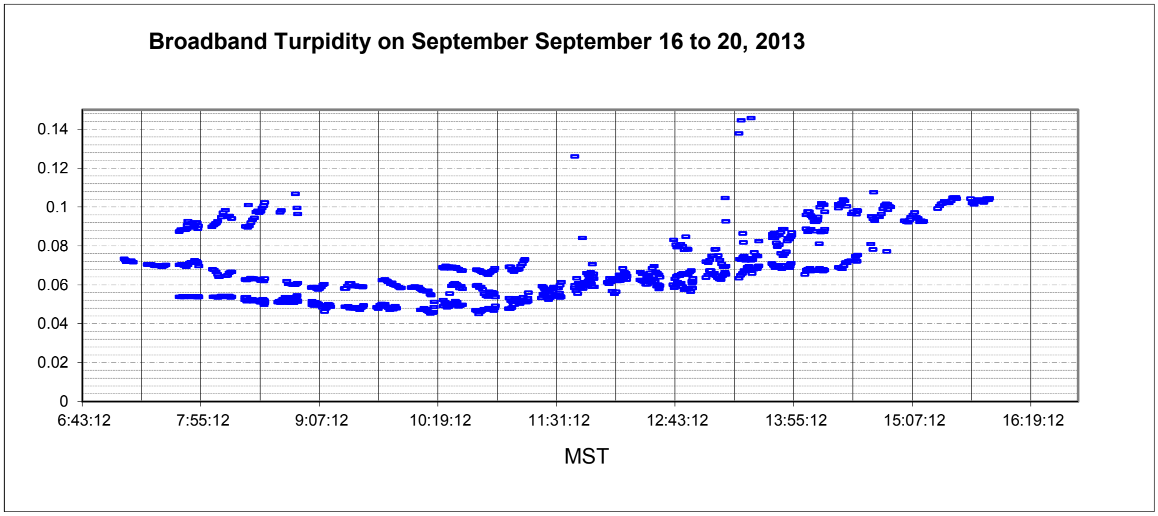
S/N	Operator 1	Operator 2	Affiliation
TMI67502	Don Nelson		National Oceanic & Atmospheric Administration
AHF28553	Don Nelson		National Oceanic & Atmospheric Administration
AHF32448AWX	Don Nelson		National Oceanic & Atmospheric Administration
AHF31114AWX	Don Nelson		National Oceanic & Atmospheric Administration
AHF29219-Window	Ibrahim Reda	Preston Morse	National Renewable Energy Laboratory
AHF31104	Ibrahim Reda	Preston Morse	National Renewable Energy Laboratory
AHF32452AWX-Window	Ibrahim Reda	Preston Morse	National Renewable Energy Laboratory
TMI69036	Ibrahim Reda	Preston Morse	National Renewable Energy Laboratory
AHF23734	Ibrahim Reda	Preston Morse	National Renewable Energy Laboratory
AHF30494	Ibrahim Reda	Preston Morse	National Renewable Energy Laboratory
AHF32455	Wolfgang Finsterle		Physikalisch-Meteorologisches Observatorium Davos (PMOD)
PMO6cc 0401	Wolfgang Finsterle		Physikalisch-Meteorologisches Observatorium Davos (PMOD)
PMO6-cc 0803	Wolfgang Finsterle		Physikalisch-Meteorologisches Observatorium Davos (PMOD)
TMI67603	Bill Boyson		Sandia National Laboratories
AHF31108	Bill Boyson		Sandia National Laboratories
TMI67811	Timothy Moss		Sandia National Laboratories
TMI68022	Timothy Moss		Sandia National Laboratories
AHF31041	Fred Denn		Science Systems & Applications, Inc.
AHF31105	Fred Denn		Science Systems & Applications, Inc.
AHF14915	Tom Kirk		Eppley Laboratory, Inc
sNIP 37441	Tom Kirk		Eppley Laboratory, Inc
sNIP 36477	Tom Kirk		Eppley Laboratory, Inc
AHF34926	Josh Peterson		University of Oregon

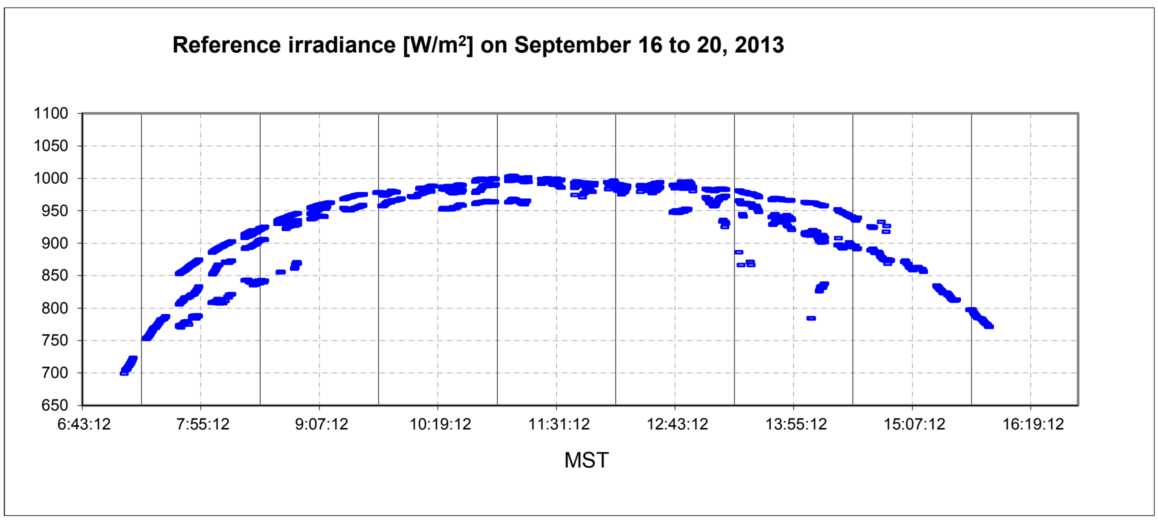
Summary: Absolute cavity radiometers = 33 and Thermopile pyrheliometers = 18

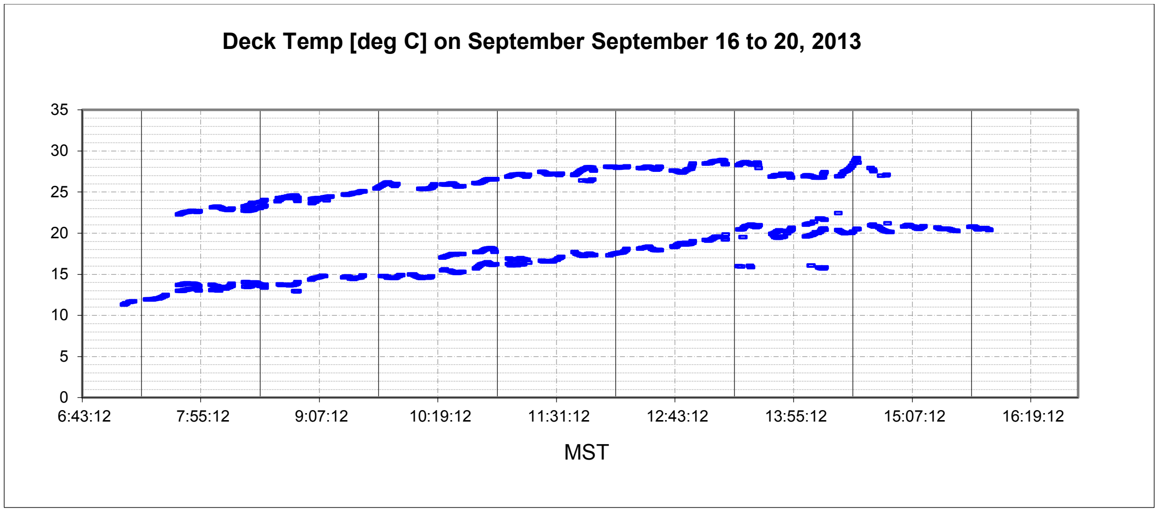
Appendix B: Ancillary Data Summaries

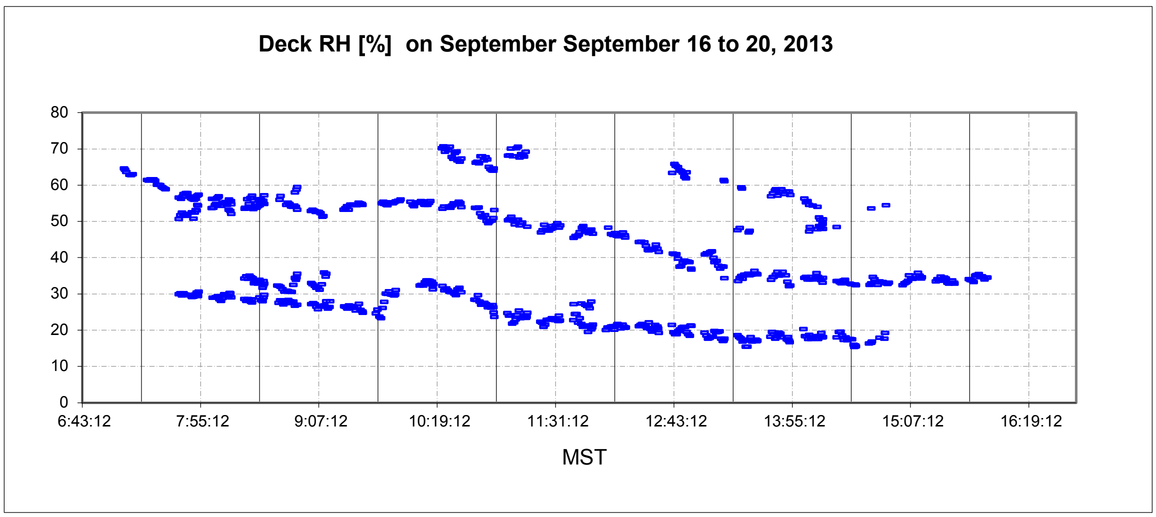
The measurement performance of an absolute cavity can be affected by several environmental parameters. Potentially relevant meteorological data collected during the NPC are presented in this appendix. The BMS has been in continuous operation at the SRRL since 1985. BMS data are recorded as 1-minute averages 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/aim/npc.html)

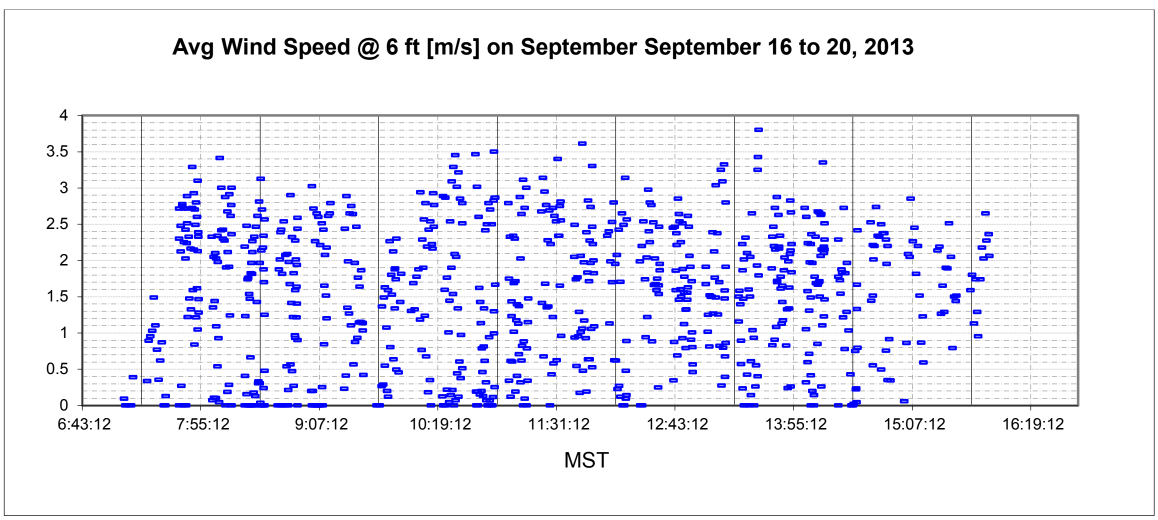
Time-series plots and other graphical presentations of these data acquired during the NPC-2013 measurements are presented here.

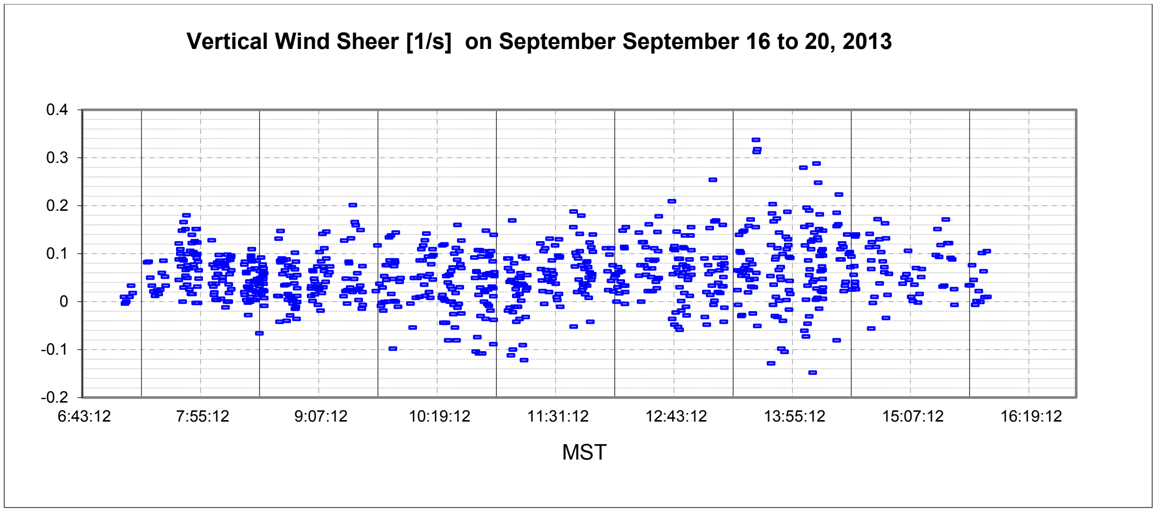





Deck Temp [deg C] on September September 16 to 20, 2013
35
30
25
20
15
10
5
0
6:43:12
7:55:12
9:07:12
10:19:12
11:31:12
12:43:12
13:55:12
15:07:12
16:19:12
MST


Deck RH [%] on September September 16 to 20, 2013
80
70
60
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] on September September 16 to 20, 2013
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] on September September 16 to 20, 2013
0.4
0.3
0.2
0.1
0
-0.1
-0.2
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