

# **NREL Pyrheliometer Comparisons September 22 – October 3, 2003**

## **(NPC-2003)**

### **Final Report**

By

Tom Stoffel  
Ibrahim Reda  
Steve Wilcox

National Renewable Energy Laboratory  
Electric & Hydrogen Technologies & Systems Center  
Resource Integration Group  
Measurement & Instrumentation Team



July 30, 2004

## **NOTICE**

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

## NPC 2003 Participants



Kneeling: John Hickey, Phil Thacher, Bill Boyson, Mike Stein, Craig Webb, Ly Vo, Ray Decker, Steve Wilcox.

Standing: Mike Edgar, Bill Porch, Duncan Maciver, Erik Naranen, Ibrahim Reda, Bev Kay, Tom Stoffel, Fred Denn, Gary Hodges.

[Not Shown: Joe Michalsky & Don Nelson]

## Acknowledgements

We sincerely appreciate the support of Susan Hock, our Center Director, for helping us host these comparisons. Our thanks go to Beverly Kay for her timely administrative and logistical help, Pete Gotseff for his site and instrument preparations, and to Afshin Andreas for providing web-access to Baseline Measurement System data. We are also grateful to Stan Bull and Daryl Myers for their financial support from NREL's Metrology Laboratory Technical Overhead and the DOE/NREL Photovoltaics Research Program. The DOE Atmospheric Radiation Measurement (ARM) Program, funded through Argonne National Laboratory and Pacific Northwest National Laboratory, provided additional support. Solar irradiance measurements from radiometers with direct traceability to the World Radiometric Reference (WRR) were provided by John Hickey and Mike Stein (The Eppley Laboratory, Inc.), Don Nelson (NOAA's Climate Monitoring & Diagnostics Laboratory), Joe Michalsky and Gary Hodges (NOAA's Surface Radiation Research Branch), Duncan Maciver and Erik Naranen (ATLAS Weathering Services Group), and the ARM/NREL reference standard group. These radiometers greatly strengthened our ability to transfer the WRR to the participating radiometers. Our thanks also go to each participant for their patience and cooperation during this weather-dependent exercise.

This work was accomplished under NREL subtasks PV37401, WU1D5600, WU865600, and 20100010.

## NREL Solar Radiation Research Laboratory (SRRL)



North View



South View from Instrument Platform



Absolute Cavity Radiometers on Solar Trackers

## Table of Contents

	Acknowledgements .....	iii
	Abstract .....	vi
1.	Introduction .....	1
2.	Reference Instruments .....	2
3.	Measurement Protocol .....	2
4.	Transferring World Radiometric Reference .....	3
	4.1 Calibration Requirements .....	3
	4.2 Determining the Reference Irradiance .....	3
	4.3 Data Analysis Criteria .....	4
	4.4 Measurements .....	4
	4.5 Results .....	4
	4.6 Recommendations .....	17
5.	Ancillary Data .....	17
6.	References .....	18
7.	Images .....	18
8.	Appendices	
	A. List of Participants and Pyrheliometers .....	A-1
	B. Ancillary Data Summaries .....	B-1
	22 September 2003 .....	B-1
	23 September 2003 .....	B-2
	24 September 2003 .....	B-3
	C. Operational Notes .....	C-1

## Abstract

Providing reliable measurements of solar irradiance places many demands on the operator of commercially available radiometers. Maintaining accurate radiometer calibrations 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 solar irradiance measurement. The WRR is a detector-based measurement standard, subject to instrument performance changes with time. Therefore, every five years, the World Radiation Center/Physikalisch-Meteorologisches Observatorium Davos (WRC/PMOD) in Davos, Switzerland hosts an International Pyrheliometer Comparison (IPC) for transferring the WRR to participating radiometers. Representing the U.S. Department of Energy, NREL has participated in each of the IPCs since 1980. As a result, NREL has developed and maintained a select group of absolute cavity radiometers with direct calibration traceability to the WRR. These instruments are then used to transfer WRR to other radiometers.

NREL Pyrheliometer Comparisons (NPCs) are held annually at the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado. Open to any pyrheliometer owner/operator, the NPC provides an opportunity to determine the unique WRR Transfer Factor (WRR-TF) for each participating pyrheliometer. By adjusting all subsequent solar irradiance measurements by the appropriate WRR-TF, the operator can establish calibration traceability to the WRR.

NPC-2003 was scheduled from September 22 through October 3, 2003. Nineteen participants operated 27 absolute cavity radiometers and one conventional thermopile-based pyrheliometer to simultaneously measure clear-sky direct normal solar irradiance during this period. The Transfer Standard Group (TSG) of reference radiometers for NPC-2003 consisted of seven radiometers with direct traceability to the WRR having participated in IPC-IX 2000. As the result of NPC-2003, each participating absolute cavity radiometer was assigned a new WRR-TF computed as the ratio of observed irradiance to the corresponding reference irradiance as determined by the TSG. The performance of the TSG during NPC-2003 was consistent with previous comparisons, including the latest IPC-IX. The measurement performance of the TSG allowed the transfer of the WRR to each participating radiometer with an estimated uncertainty of  $\pm 0.32\%$  with respect to SI units.

The comparison protocol is based on data collection periods, or *runs*. Each *run* consists of a six-minute electrical self-calibration, a series of 33 solar irradiance measurements at 20-second intervals, and a post-calibration. More than 1,000 reference irradiance measurements for each participating radiometer were collected during NPC-2003. Clear-sky daily maximum direct normal irradiance levels ranged from less than  $967 \text{ Wm}^{-2}$  to  $1026 \text{ Wm}^{-2}$ .

Ancillary environmental parameters (e.g., broadband irradiance, spectral irradiance and other surface meteorological data) collected at SRRL during the comparison are also presented in this report to document the environmental test conditions.

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

## 1. Introduction

Collecting solar irradiance data for applications in renewable energy technology research, global climate change studies, satellite remote sensing validations, general atmospheric science research, or the myriad of other possibilities, requires measurements traceable to a recognized calibration standard. The World Radiometric Reference (WRR) is the internationally recognized standard for solar irradiance measurements [Fröhlich, 1991].

The WRR was established by the World Meteorological Organization (WMO) in 1977 and has been maintained by the World Radiation Center at the Physikalisch-Meteorologisches Observatorium Davos (WRC/PMOD) in Switzerland (<http://www.pmodwrc.ch>). This standard of measurement is maintained for broadband solar irradiance with an absolute uncertainty of better than  $\pm 0.3\%$  with respect to the System International (SI) unit [Romero, et al, 1996]. This standard is widely used for the calibration of shortwave radiometers (pyranometers and pyrhemometers) with a wavelength response range of 280 nm to 3000 nm. Every five years, the WRR is transferred to WMO Regional Centers and other participants in the International Pyrhemometer Comparisons (IPC) held at the WRC/PMOD. The instantaneous measurements from the seven radiometers comprising the World Standard Group (WSG) are compared at 90-second intervals with the data from participating radiometers recorded under clear-sky conditions. Maintaining the mean WRR of the seven WSG radiometers, a WRR Transfer Factor is calculated for each of the participating radiometers [Reda, 1996]. The range of historical WRR Transfer Factors is  $1.00000 \pm 0.00250$ . Multiplying the irradiance reading of each radiometer by its assigned WRR Transfer Factor (WRR-TF) will result in measurements that are traceable to WRR and therefore consistent with the international reference of solar radiation measurement.

The 2003 NREL Pyrhemometer Comparisons (NPC-2003) were scheduled from September 22 to October 3, 2003 at the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado. Nineteen participants operated 27 absolute cavity radiometers during the comparisons (see Appendix A for list of participants). The following organizations were represented at NPC-2003:

- Analytical Services and Materials, Inc.
- Atlas Weathering Services, Inc. -DSET Laboratories
- Atmospheric Radiation Measurement Program of the U.S. Department of Energy
- The Eppley Laboratory, Inc.
- Florida Solar Energy Center
- NASA Langley Research Center, Atmospheric Sciences Division
- National Oceanic and Atmospheric Administration
  - Climate Monitoring & Diagnostics Laboratory
  - Surface Radiation Research Branch
- National Renewable Energy Laboratory
  - Electric & Hydrogen Technologies & Systems Center
  - Metrology Laboratory
  - Photovoltaic Research Program

Weather conditions during the period September 22-24 were adequate for this year's NPC (see Appendix B for more specific meteorological information). The results presented in this report are based on clear-sky direct normal solar irradiance data collected on these three days.

## 2. Reference Instruments

Seven absolute cavity radiometers that participated in IPC-IX were used as the Transfer Standard Group (TSG) to maintain the WRR for this comparison. Table 2.1 is a list of the TSG absolute cavity radiometers with their *WRR Transfer Factors* and *Pooled Standard Deviations* as determined from the latest International Pyrheliometer Comparisons in 2000 [WRC/PMOD, 2001].

**Table 2.1 IPC-IX Results Summary for the NPC-2003 TSG**

Serial Number	WRR Factor (from IPC-IX)	Standard Deviation (%)	Number of Readings
<b>AHF 14915</b>	1.00026	0.08	102
<b>AHF 28553</b>	0.99733	0.05	212
<b>AHF 28968</b>	0.99866	0.06	113
<b>AHF 29220</b>	0.99846	0.06	113
<b>AHF 30713</b>	0.99861	0.06	113
<b>TMI 67502</b>	0.99966	0.07	219
<b>TMI 68018</b>	0.99848	0.05	113
<b>Mean WRR for the TSG</b>	0.99878	<b>Pooled Std Deviation for the TSG</b> 0.06%	

The Pooled Standard Deviation ( $SD_p$ ) for the Transfer Standard Group (TSG) is computed from the following equation:

$$SD_p = \left[ \frac{\sum_{i=0}^m (n_i * S_i^2)}{\sum_{i=0}^m n_i} \right]^{1/2}$$

where,

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

## 3. Measurement Protocol

The decision to deploy instruments for a comparison is made daily. Data are collected only during clear-sky conditions determined visually and from stability of pyrheliometer readings. Simultaneous direct normal solar irradiance measurements were taken by most cavity radiometers in groups of 33 observations at 20-second intervals (PMO6 used 40-second open/closed shutter cycle). Each group of observations is called a *Run*. An electrical self-calibration of each absolute cavity is performed just prior to each Run. Previous WRR-TFs were not applied to the observations. The original manufacturer calibration factor was used according to the standard operating procedure provided by the manufacturer for each radiometer. A timekeeper announced the beginning of calibration periods and gave a 6-minute countdown prior to the start of each Run to facilitate the simultaneous start for each participant (See Appendix C for details).



By consensus, the goal was set to acquire at least 300 observations from each radiometer to determine the WRR-TF. Participants also agreed that ten Runs should be made over a period of at least two days to provide a variety of temperature and spectral irradiance conditions. Our goal was to build a statistically significant data set from which to derive individual WRR TF.

Data from each radiometer/operator system are collected at the end of the day using diskettes. Daily summaries were produced using a spreadsheet analysis tool. Results were distributed to the participants the following day. Additional operational notes can be found in Appendix C.

#### **4. Transferring World Radiometric Reference**

The primary purpose of these absolute cavity comparisons is to transfer the WRR from the NPC Transfer Standard Group (TSG) to each of the participating radiometers. This requires the collection of simultaneous measurements of clear-sky direct normal (or beam) solar irradiance by the participating radiometers and the TSG.

##### 4.1 Calibration Requirements

Using WMO guidelines [Romero, 1995], the following conditions were required before data collection was accomplished during NPC-2003:

- Radiation source was the sun, with irradiance levels greater than 700 Wm<sup>-2</sup>
- Digital multimeters with accuracy better than 0.05% of reading were used to measure the thermopile signals from each radiometer
- Solar trackers were aligned within  $\pm 0.25^\circ$  slope angle
- Wind speed was low ( $< 5$  m/s) from the direction of the solar azimuth  $\pm 30^\circ$
- Cloud cover was less than 1/8 with an angular distance larger than  $15^\circ$  from the sun.

##### 4.2 Determining the Reference Irradiance

Seven absolute cavity radiometers, that participated in IPC-IX, were used as the TSG to transfer the WRR in the comparison. The WRR Transfer Factor for each of the TSG is presented in Table 2.1. The reference irradiance at each reading is calculated using the following summarized steps [Reda, 1996]:

- a. Each irradiance reading of the TSG is divided by the irradiance measured by AHF28553, the instrument with the *lowest* standard deviation with respect to the WRR.
- b. Maintaining the mean of WRR for the TSG, a new WRR Transfer Factor for NPC-2003 is recalculated for each of the TSG cavities [Reda, 1996].
- c. 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 Transfer Factor calculated in step b.

### 4.3 Data Analysis Criteria

The absolute cavity radiometer AHF30713 was used to check irradiance stability at the time of each comparison reading. Stable irradiance readings are defined to be within  $1.0 \text{ Wm}^{-2}$  during an interval of three seconds centered about the comparison reading, 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 less than 10% of the data collected during an NPC.

Additionally, all calculated ratios of the reference irradiance divided by the test instrument irradiance that deviated from their mean by more than 1.0% were rejected [WRC/PMOD, 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.

### 4.4 Measurements

NPC-2003 was scheduled for September 22 - October 4, 2003. The comparisons were completed on September 24<sup>th</sup> after 2082 data points were collected by the reference cavities from 63 runs completed during three days with the requisite clear-sky conditions. The actual number of readings for each participating radiometer compared with the reference irradiance varies according to the data analysis selection criteria described above. Additionally, some instruments experienced minor data loss due to a variety of problems with the measurement systems and operating difficulties.

### 4.5 Results

The results for the TSG are presented in Table 4.5.1. To evaluate the performance of these instruments, the standard deviations of each radiometer are monitored during the comparisons. The results suggest successful performance of the TSG during this NPC:

- The NPC2003 WRR Transfer Factors did not change by more than a fraction of the standard deviation derived during IPC-IX in 2000 (see Table 2.1 for IPC-IX results).
- The standard deviations of the new WRR Transfer Factors are also smaller than the standard deviations observed for these instruments during IPC-IX.

The WRR Transfer Factor for each participating cavity radiometer is derived using the reference irradiance values derived from the TSG. At each reading, the reference irradiance is divided by the irradiance measured by a participating radiometer. The mean of these ratios is the WRR Transfer Factor for each participating radiometer. Results for each radiometer participating in NPC2003 are presented in Table 4.5.2.

**Table 4.5.1 Summary Results for the Reference Transfer Standard Group (TSG) Radiometers Used for NPC2003**

Serial Number	WRR (IPC-IX)	WRR (NPC-2003)	St. Dev.	Number of Readings
AHF14915	1.00026	1.00043	0.06	2082
AHF28553	0.99733	0.99713	0.00	2082
AHF28968	0.99866	0.99839	0.05	2082
AHF29220	0.99846	0.99835	0.05	2082
AHF30713	0.99861	0.99829	0.05	2082
TMI67502	0.99966	1.00076	0.08	2082
TMI68018	0.99848	0.99810	0.06	2082
Mean WRR	0.99878	0.99878		

**Table 4.5.2 Results for Radiometers Participating in NPC2003**

Serial Number	WRR-TF (NPC-2003)	%sd	Number of Readings	%U95	
				w.r.t. WRR	w.r.t. SI
AHF17142	0.99868	0.04	1865	0.15	0.34
AHF21182	0.99978	0.09	1935	0.22	0.37
AHF23734	0.99828	0.04	2019	0.15	0.34
AHF28964	0.99828	0.05	1970	0.17	0.34
AHF29222-Window	1.06039	0.06	1952	0.18	0.35
AHF30494-Window	1.05263	0.07	1325	0.19	0.35
AHF30495	0.99749	0.05	1939	0.16	0.34
AHF30710	0.99959	0.05	1260	0.16	0.34
AHF31041	0.99743	0.05	1972	0.16	0.34
AHF31104	0.99984	0.04	2015	0.15	0.34
AHF31105	1.00309	0.05	1968	0.17	0.34
AHF31108	0.99744	0.08	2010	0.20	0.36
AWX32449-Window	1.04521	0.09	1375	0.22	0.37
AWX32452	0.99909	0.05	2002	0.16	0.34
HF30110-Window	1.06718	0.07	1618	0.19	0.35
TMI67603	1.00013	0.04	2018	0.15	0.34
TMI67811	0.99904	0.05	2007	0.17	0.34
TMI68017	1.00001	0.07	851	0.19	0.35
TMI68022	1.00037	0.10	1983	0.23	0.38
TMI69036	1.00111	0.04	1161	0.15	0.33

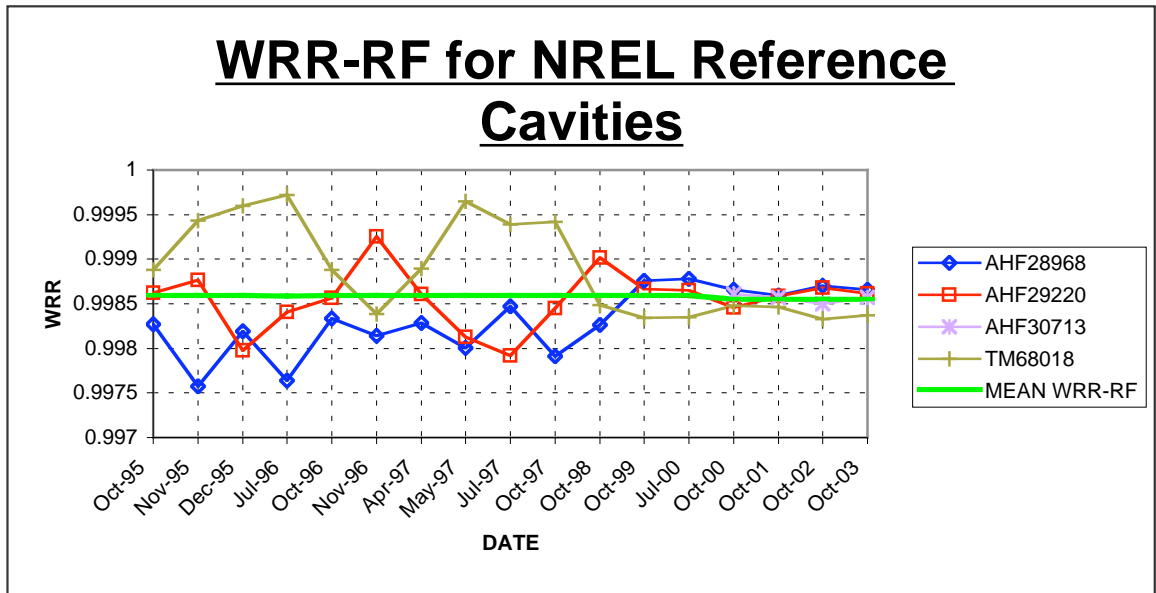


Figure 4.1 – History of WRR Reduction Factors for NREL Reference Cavities.

The uncertainty of the WRR Transfer Factors associated with each participating radiometer with respect to the WRR is calculated using the following formula:

$$U_{95} = \pm [(2 * 0.104)^2 + (2 * SD)^2]^{1/2}$$

where,

- $U_{95}$  = Uncertainty of the WRR Transfer Factor (in percent) determined at NPC2003 with 95% confidence level
- 0.104 = Pooled standard deviation of the six reference radiometers that participated in IPC-IX (September/October 2000).
- SD = One standard deviation of the WRR Transfer Factor (in percent) determined at NPC2003 for each participating cavity.

The uncertainty of the WRR Transfer Factors associated with each participating radiometer with respect to SI units was calculated using the following formula:

$$U_{95} = \pm [(0.3)^2 + (2 * 0.104)^2 + (2 * SD)^2]^{1/2}$$

where,

- 0.3 is the uncertainty ( $\pm\%$ ) of the WRR scale with respect to SI units.

The statistical analyses of WRR Transfer Factors for 20 participating radiometers are presented in Figures 4.5.1 through 4.5.20. These graphical summaries indicate the mean, standard deviation, and frequency of occurrence of the WRR Transfer Factors determined during NPC2003.

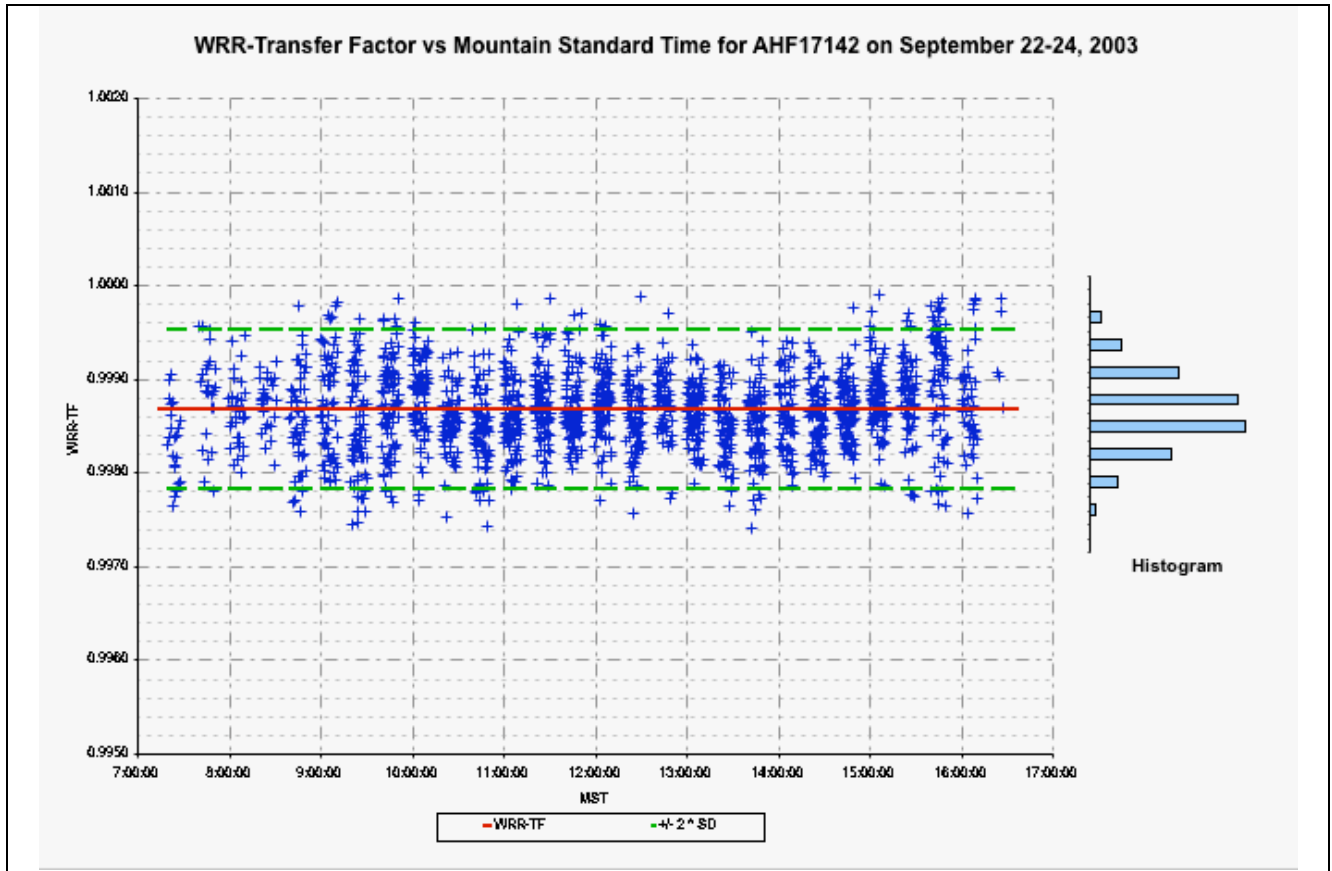


Figure 4.5.1 WRR Transfer Factor vs. Mountain Standard Time for AHF17142 at NPC2003

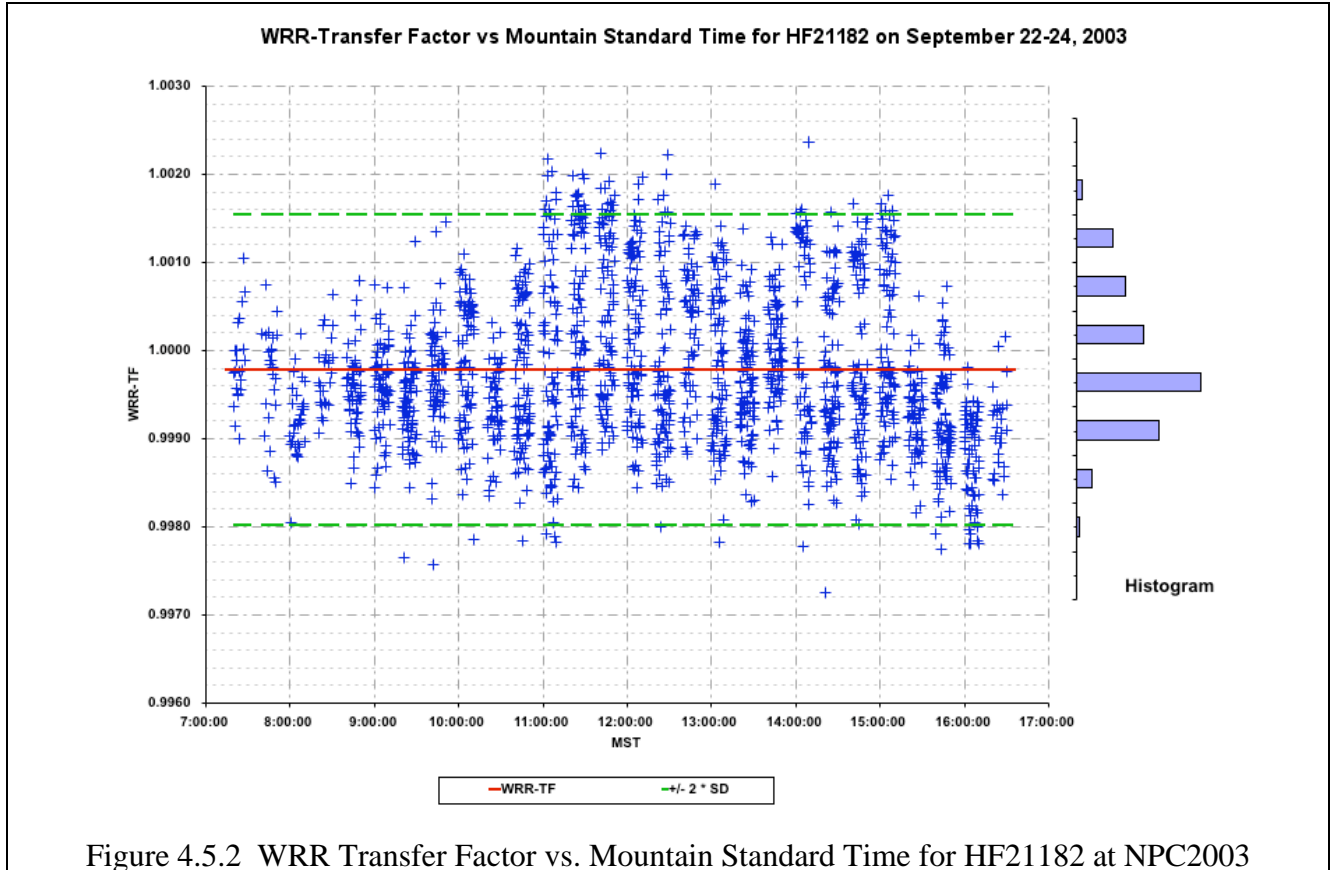


Figure 4.5.2 WRR Transfer Factor vs. Mountain Standard Time for HF21182 at NPC2003

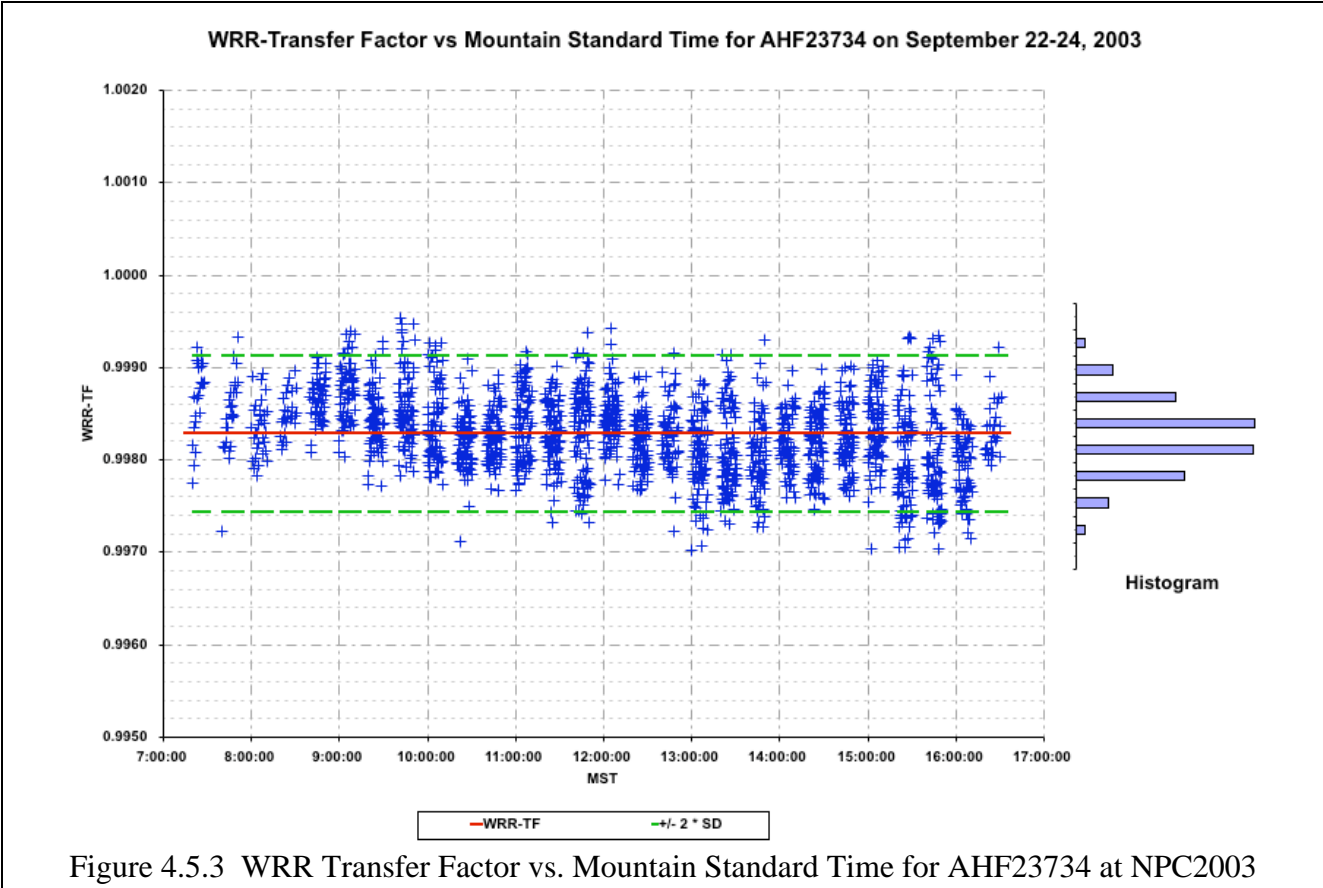


Figure 4.5.3 WRR Transfer Factor vs. Mountain Standard Time for AHF23734 at NPC2003

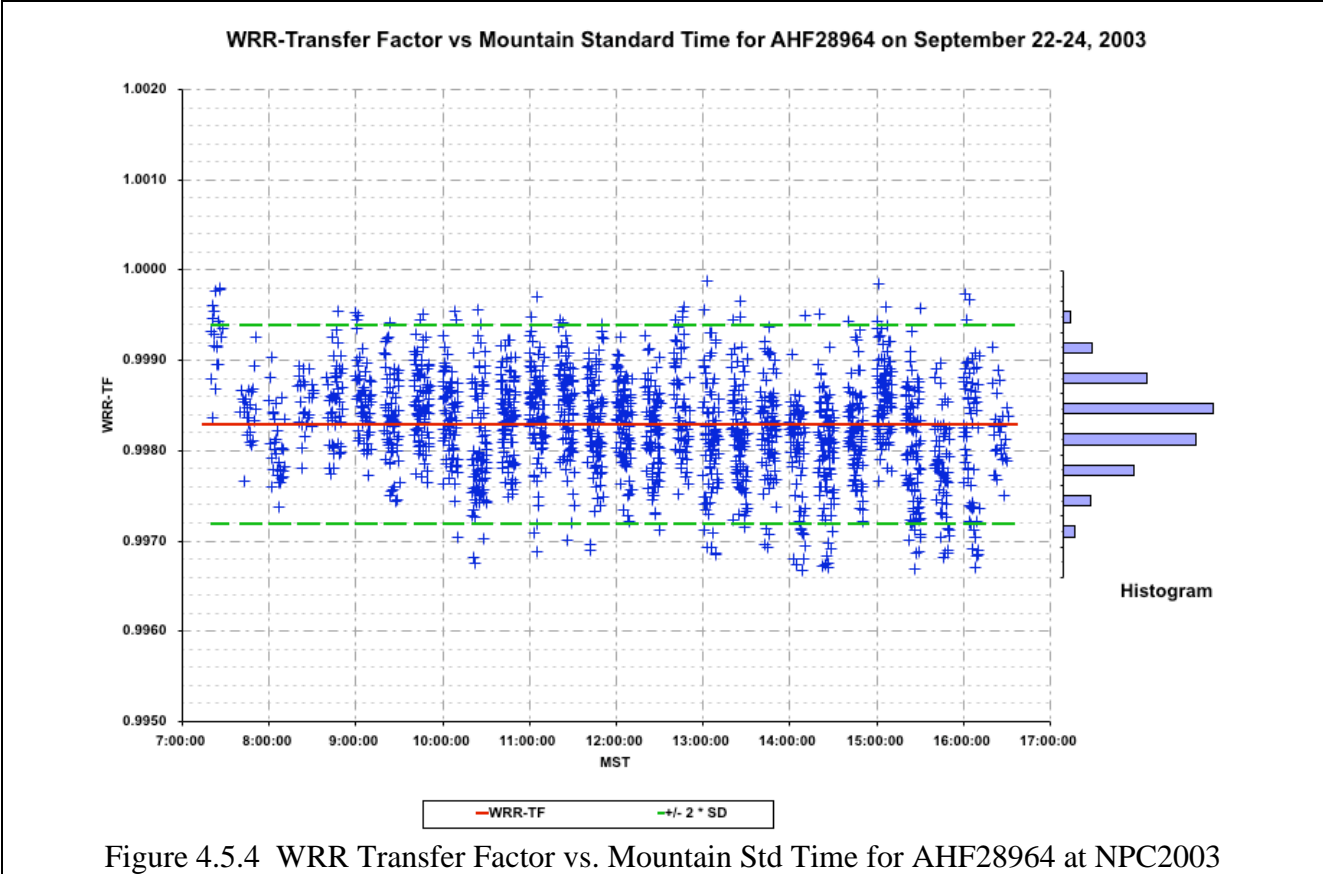


Figure 4.5.4 WRR Transfer Factor vs. Mountain Std Time for AHF28964 at NPC2003

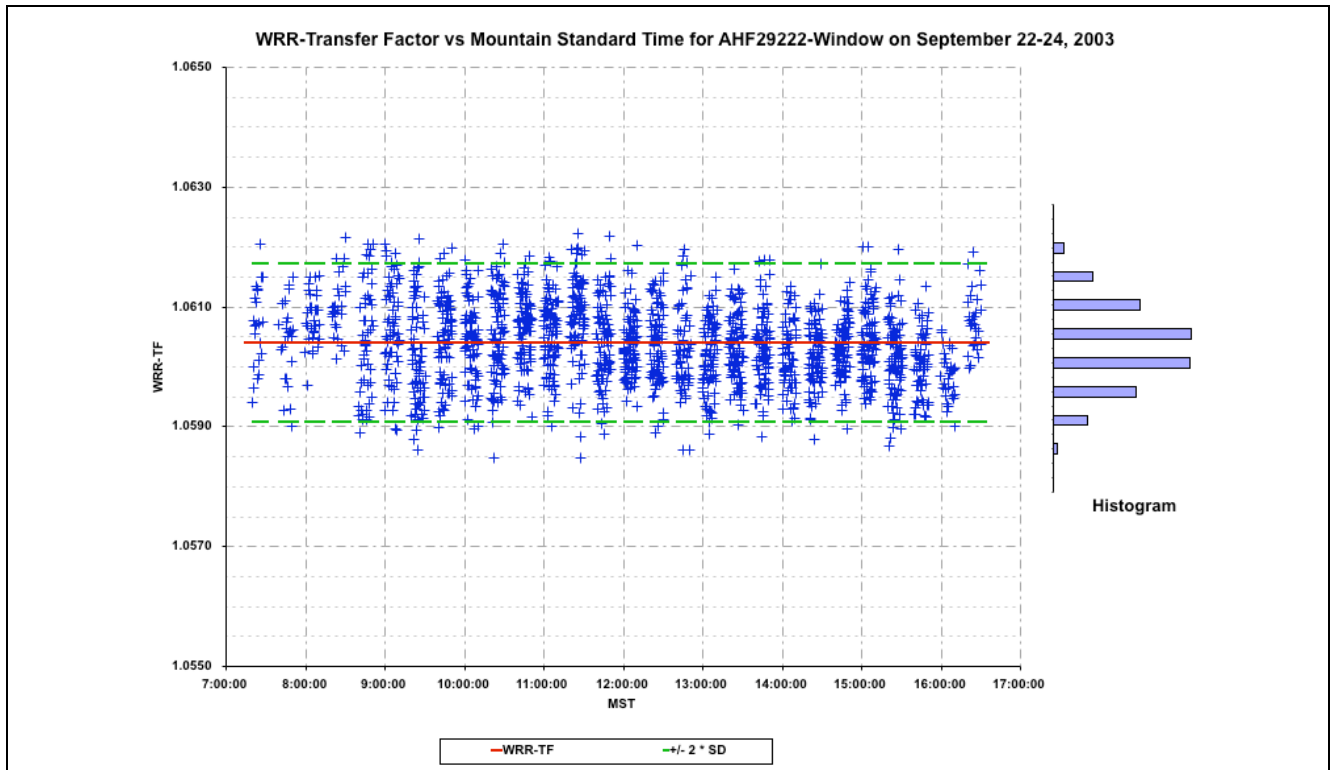


Figure 4.5.5 WRR Transfer Factor vs. Mountain Std Time for AHF29222-Window at NPC2003

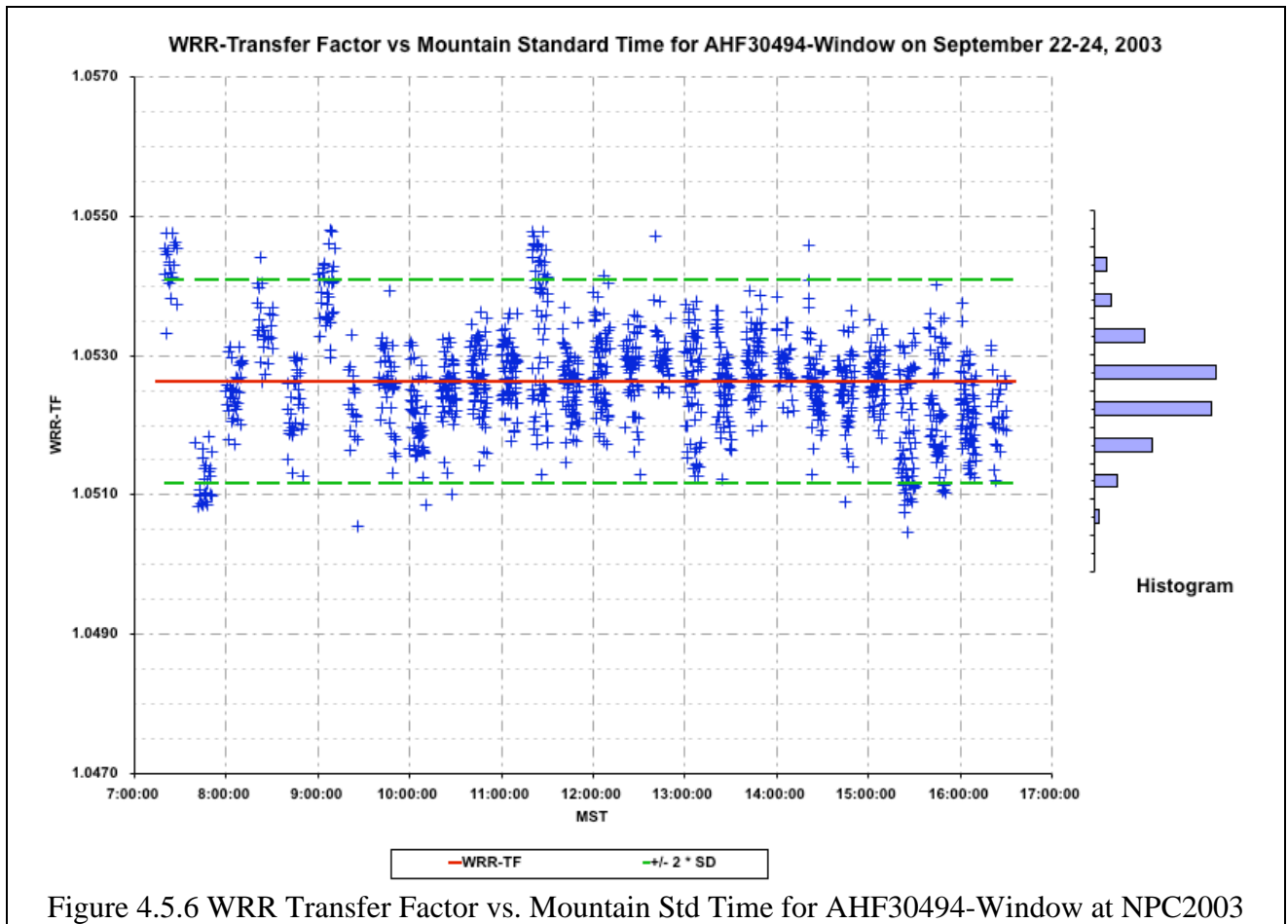


Figure 4.5.6 WRR Transfer Factor vs. Mountain Std Time for AHF30494-Window at NPC2003

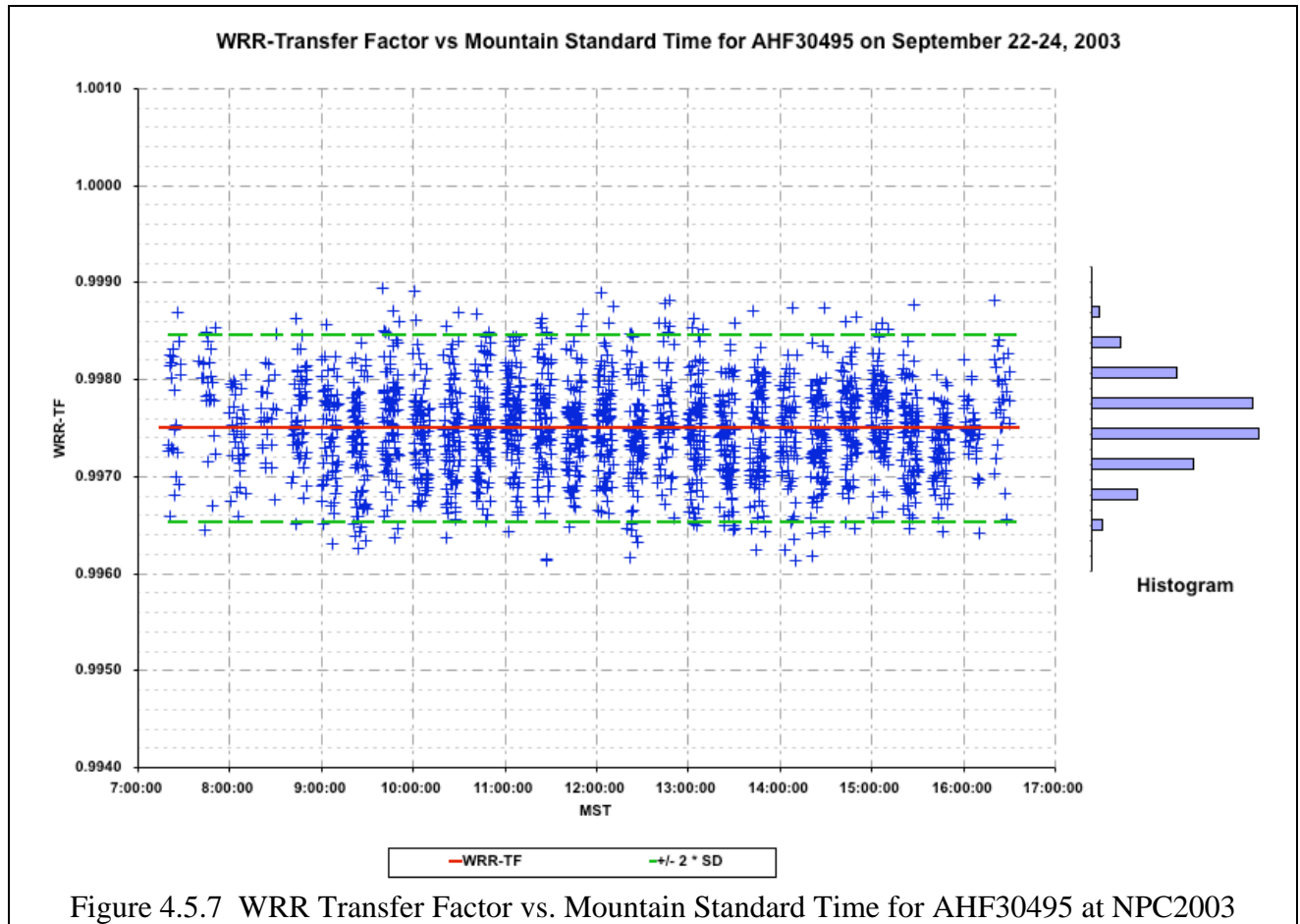


Figure 4.5.7 WRR Transfer Factor vs. Mountain Standard Time for AHF30495 at NPC2003

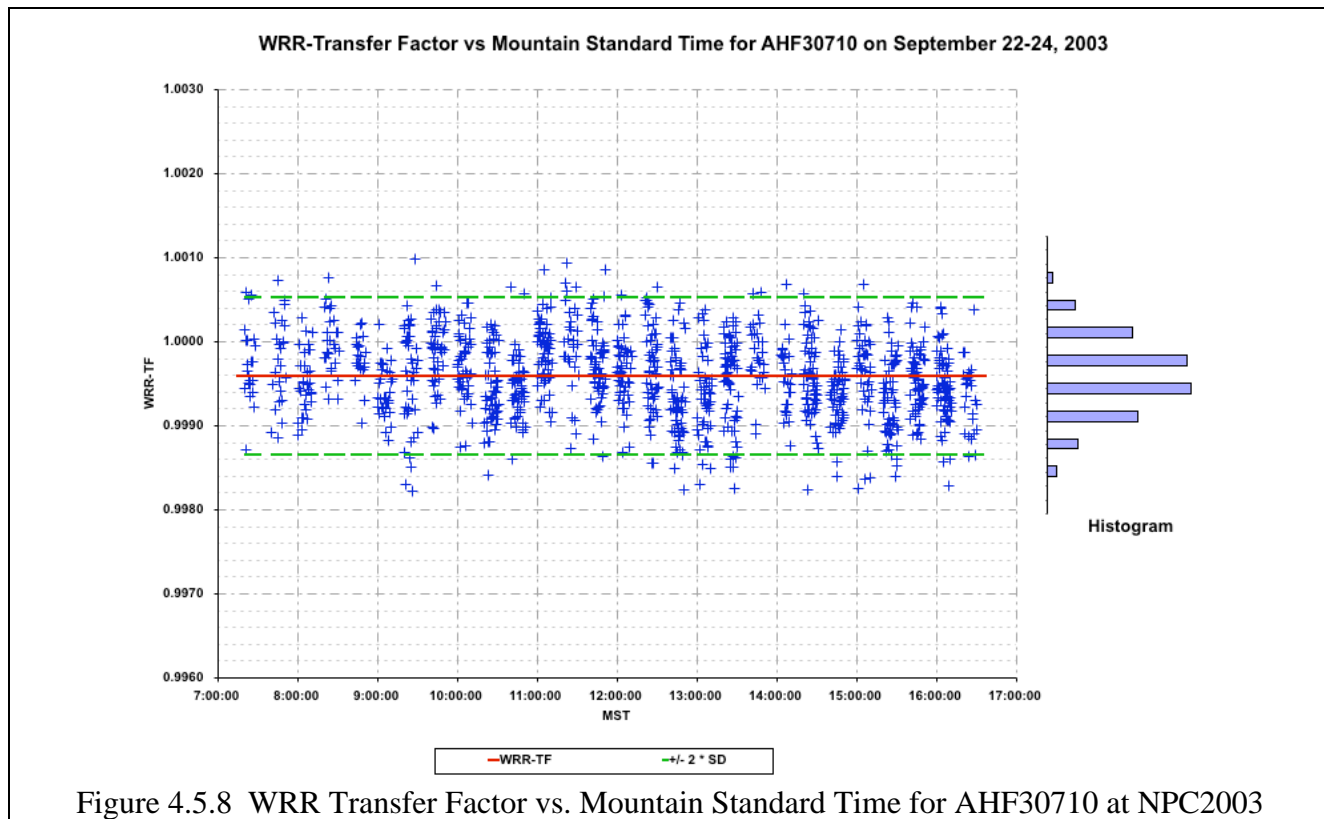
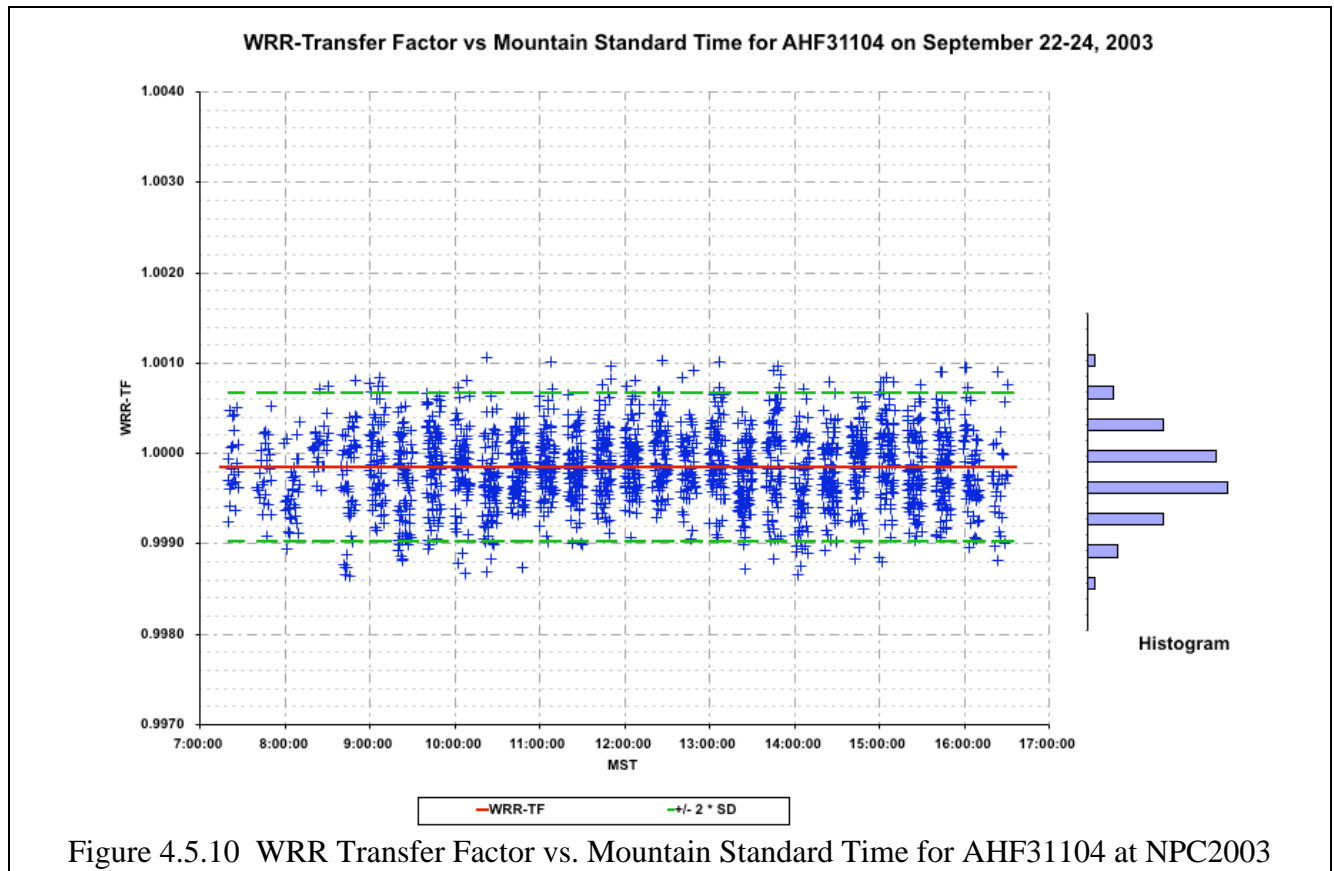
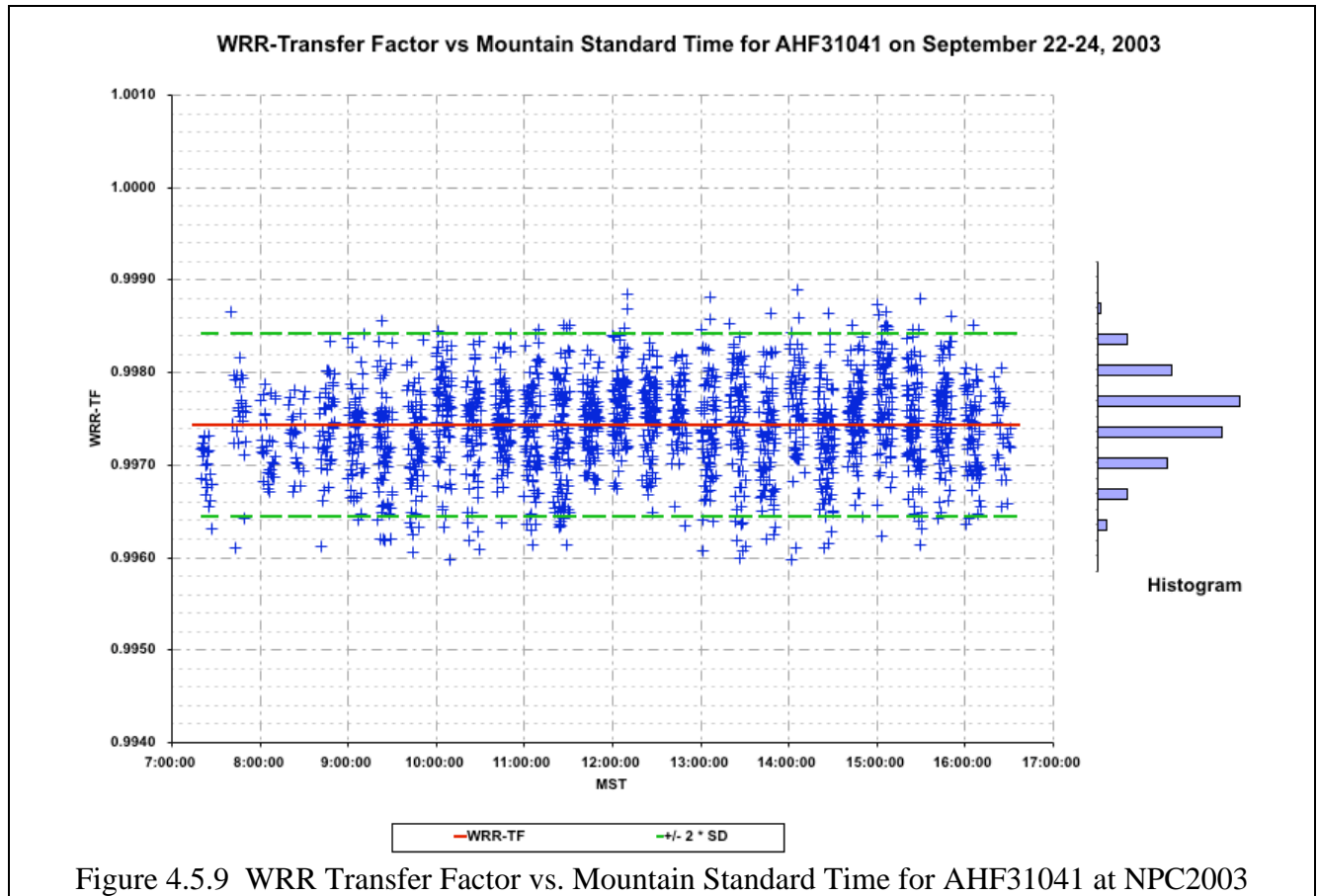
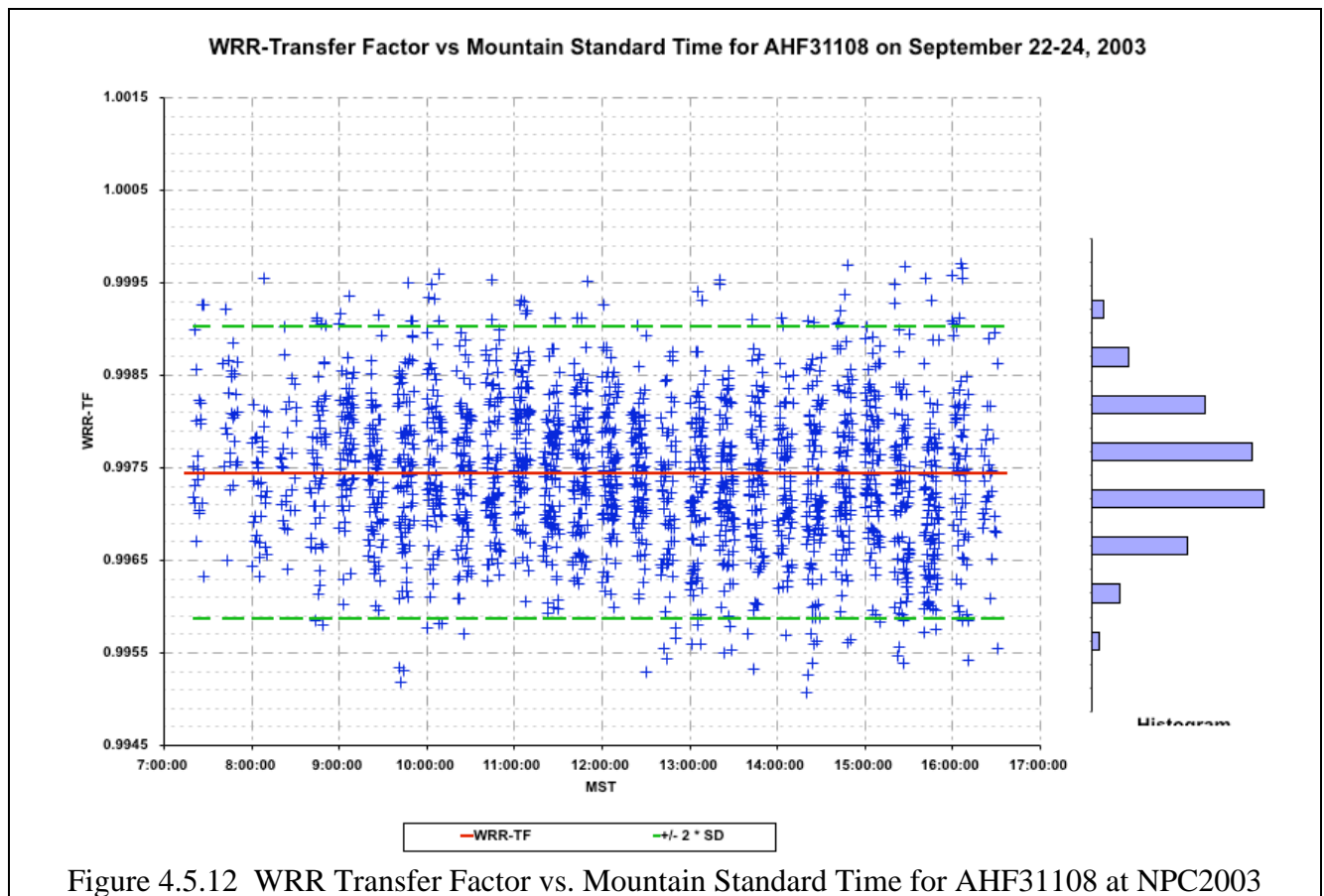
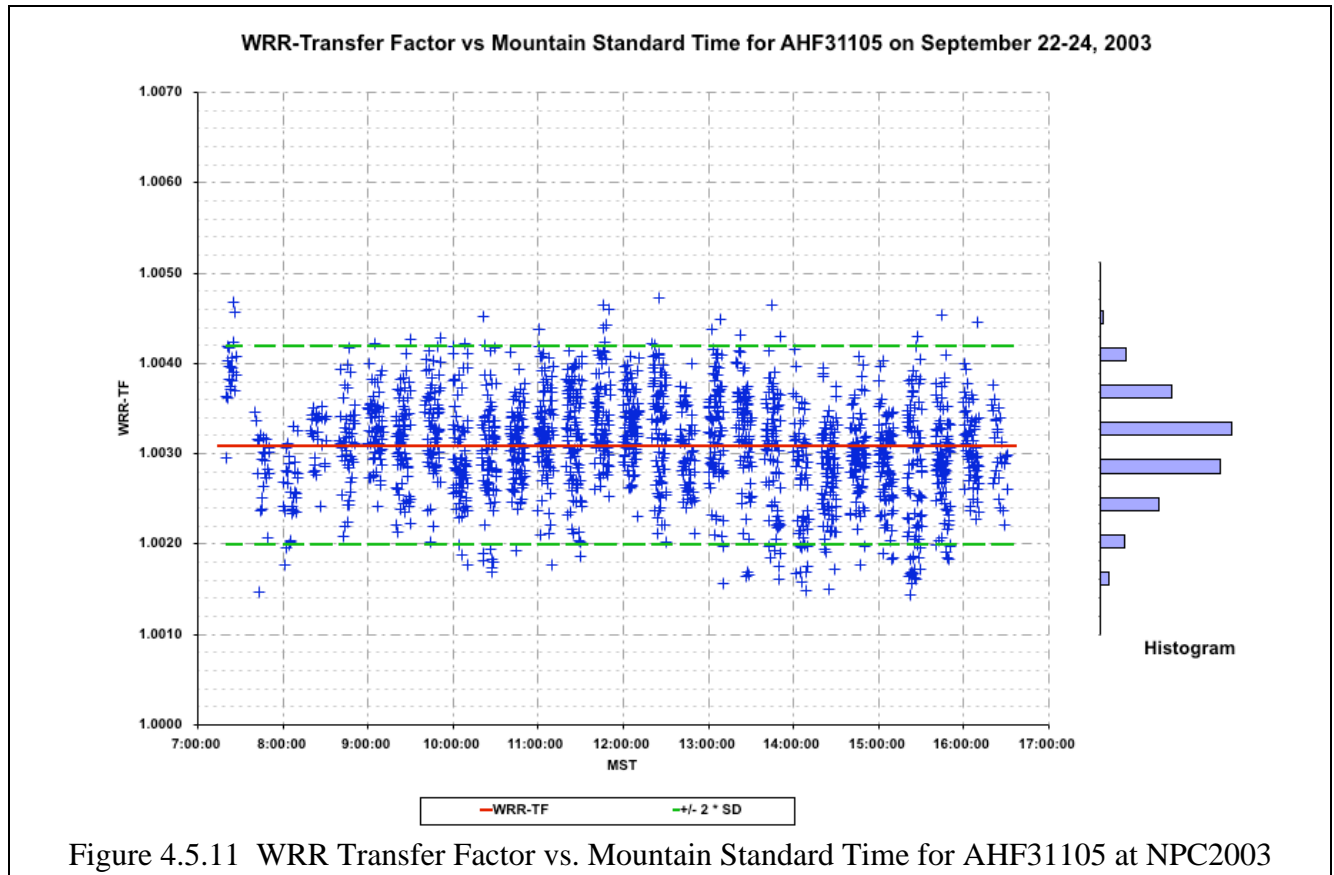


Figure 4.5.8 WRR Transfer Factor vs. Mountain Standard Time for AHF30710 at NPC2003







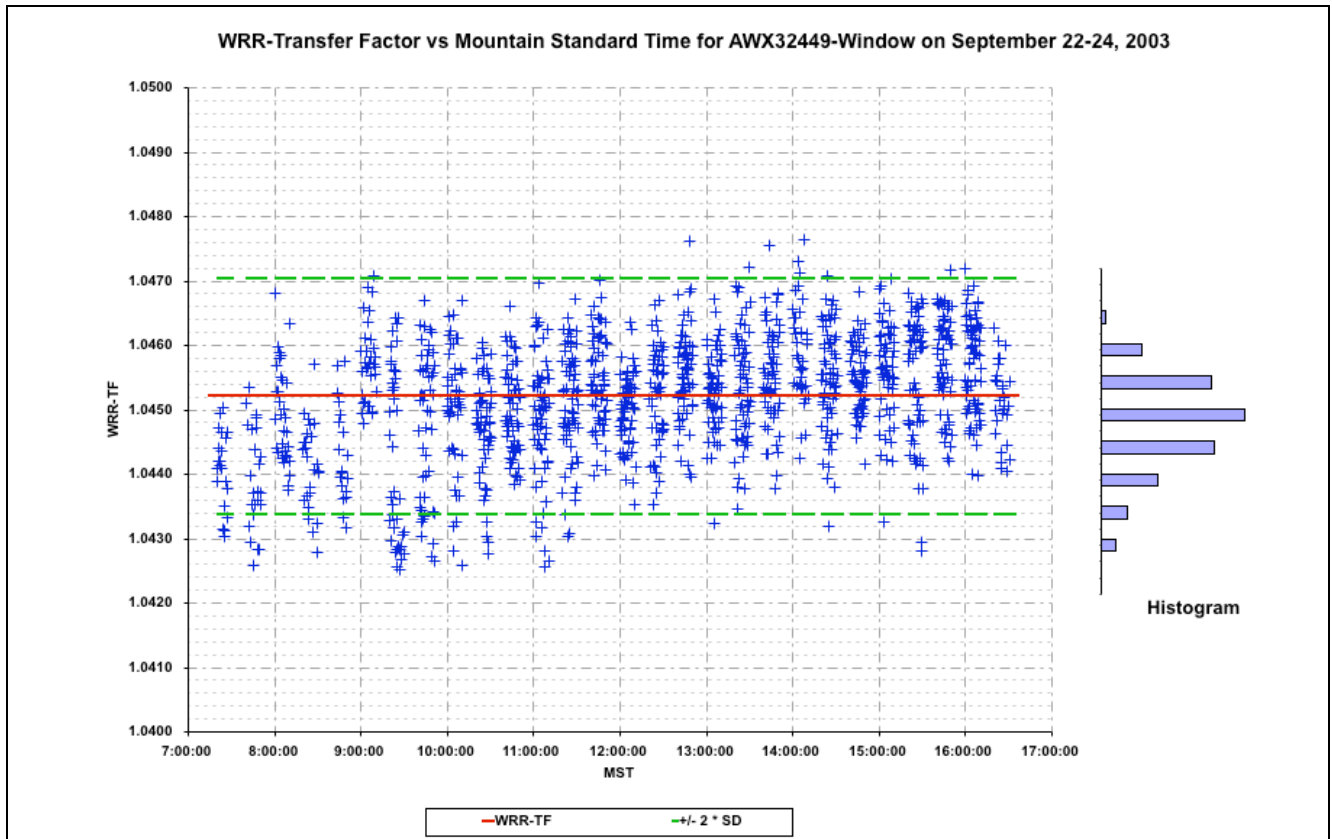


Figure 4.5.13 WRR Transfer Factor vs. Mountain Sdt Time for AHF32449-Window at NPC2003

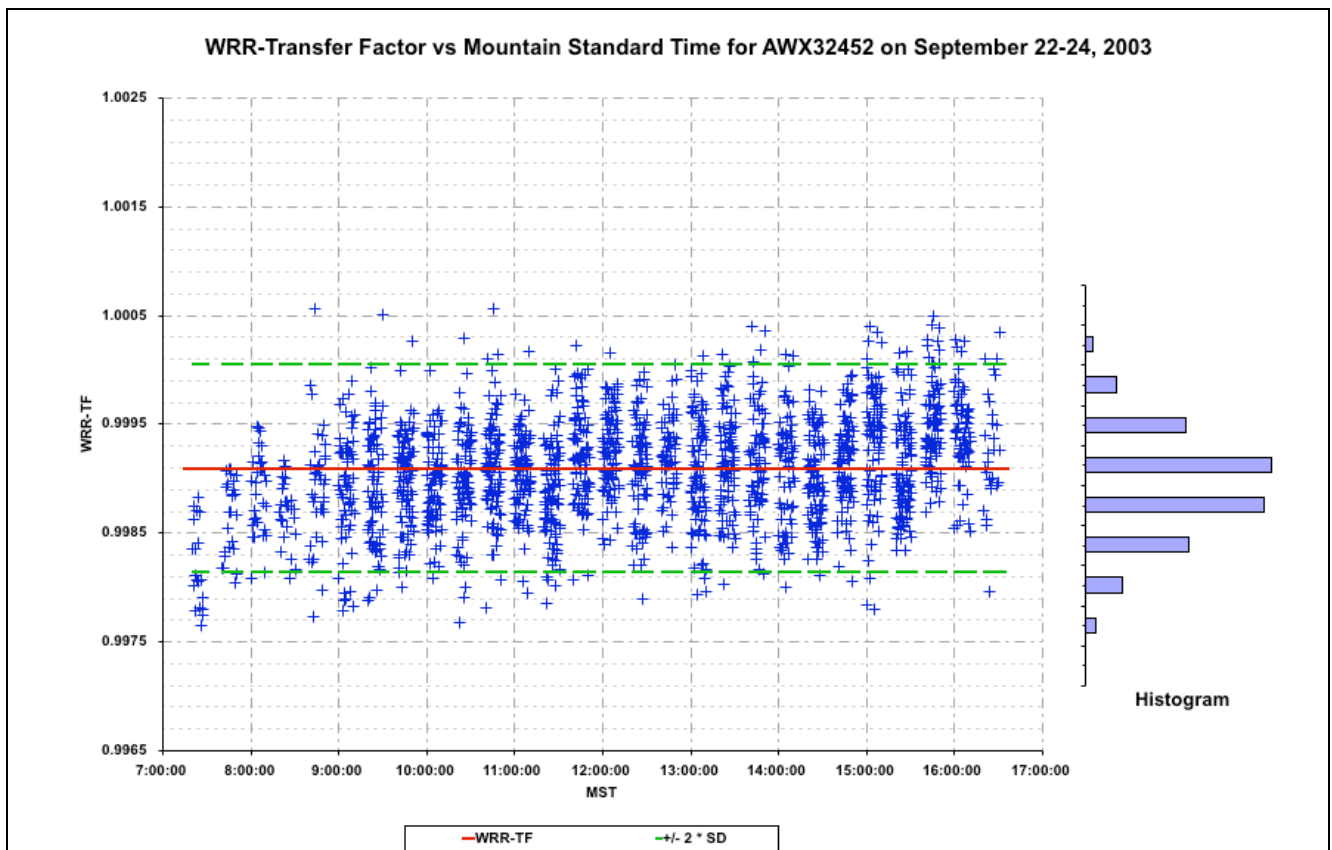


Figure 4.5.14 WRR Transfer Factor vs. Mountain Standard Time for AWX32452 at NPC2003

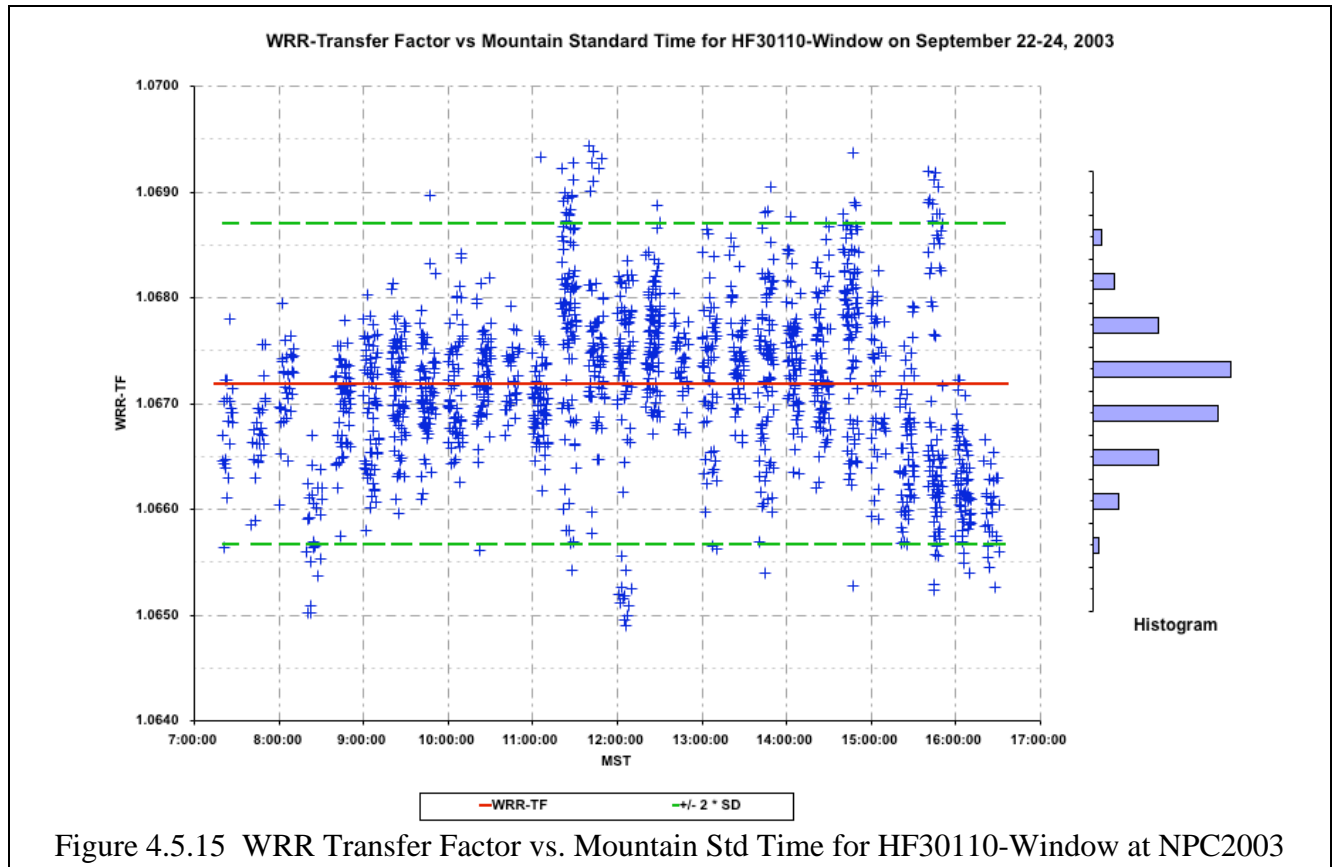


Figure 4.5.15 WRR Transfer Factor vs. Mountain Std Time for HF30110-Window at NPC2003

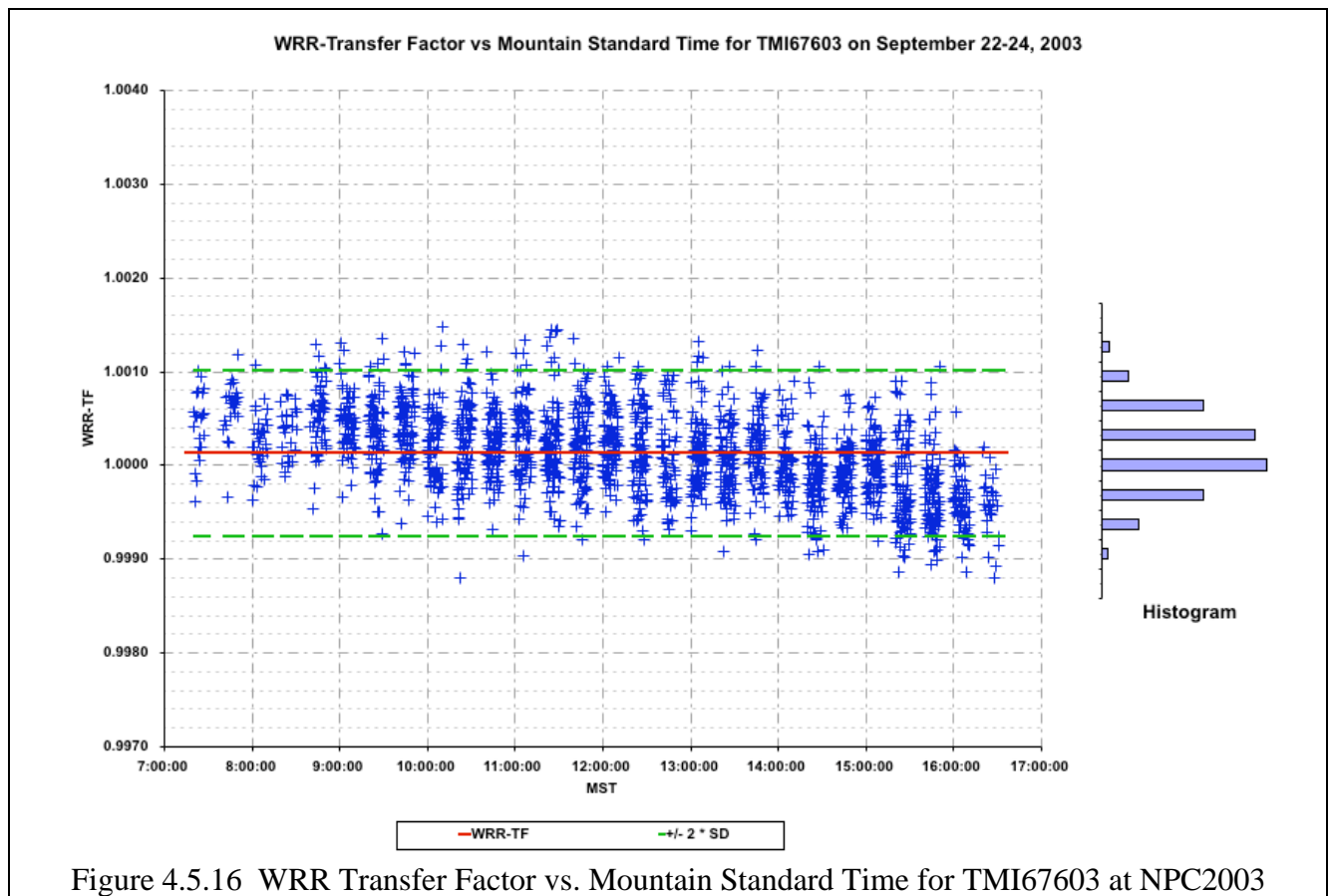


Figure 4.5.16 WRR Transfer Factor vs. Mountain Standard Time for TMI67603 at NPC2003

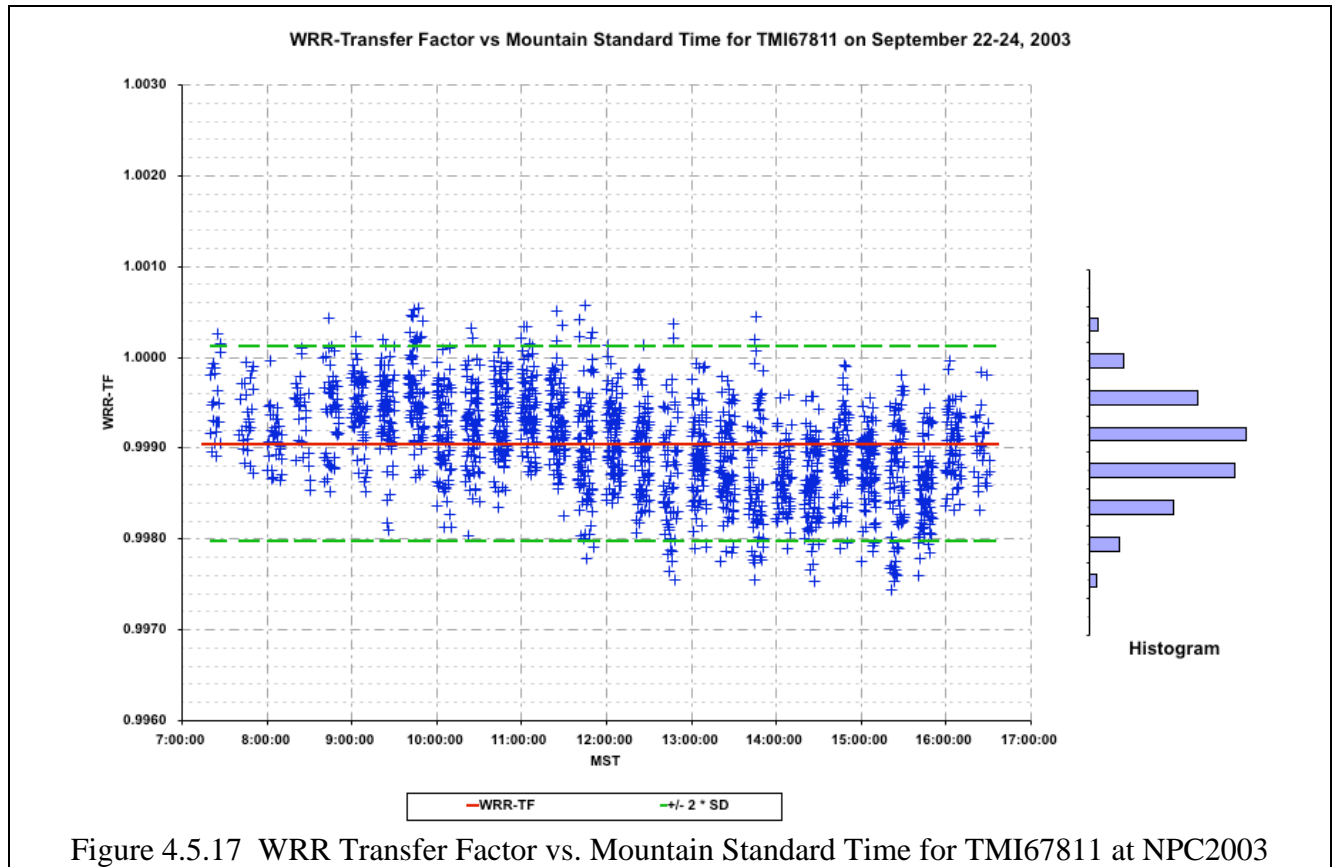


Figure 4.5.17 WRR Transfer Factor vs. Mountain Standard Time for TMI67811 at NPC2003

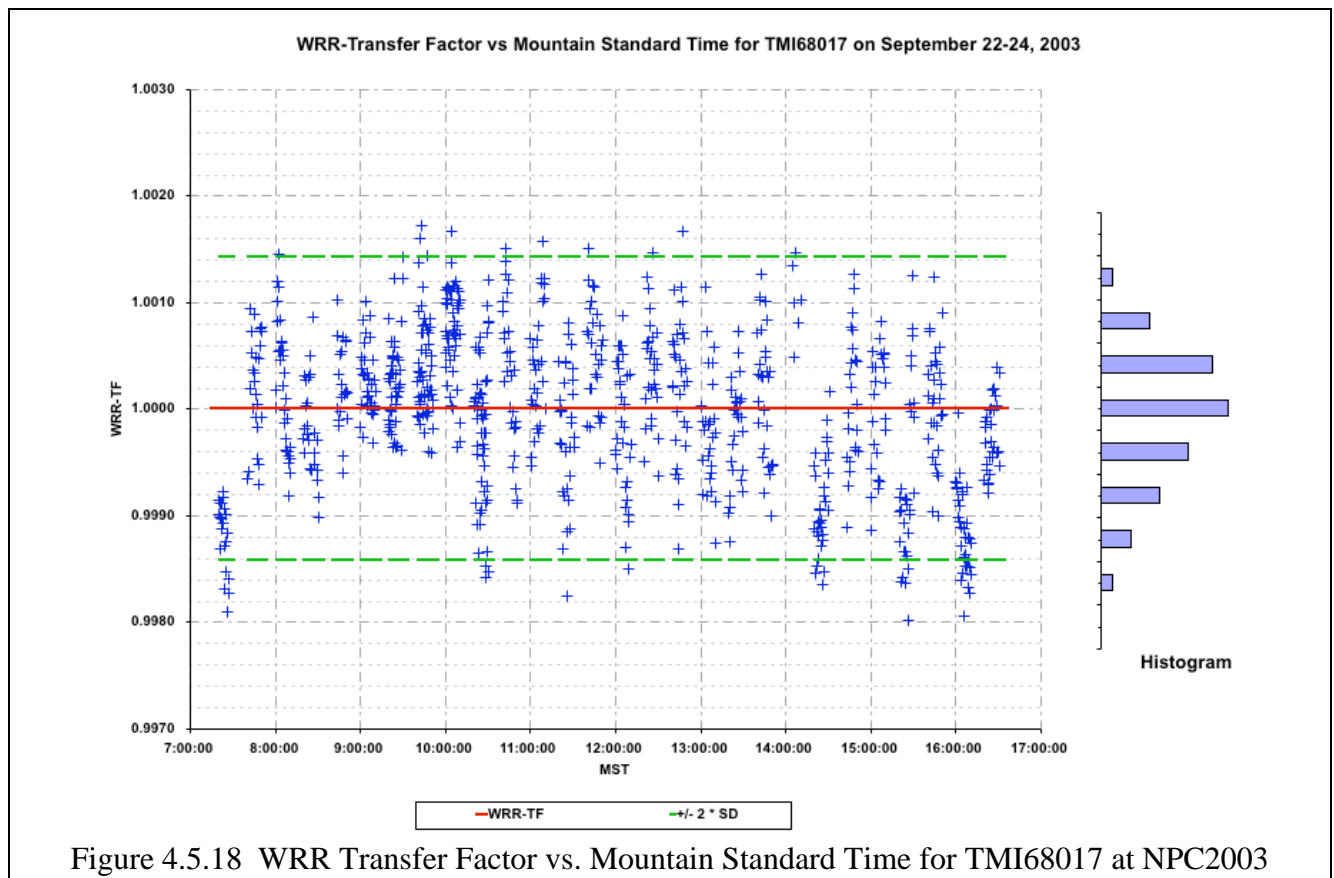


Figure 4.5.18 WRR Transfer Factor vs. Mountain Standard Time for TMI68017 at NPC2003

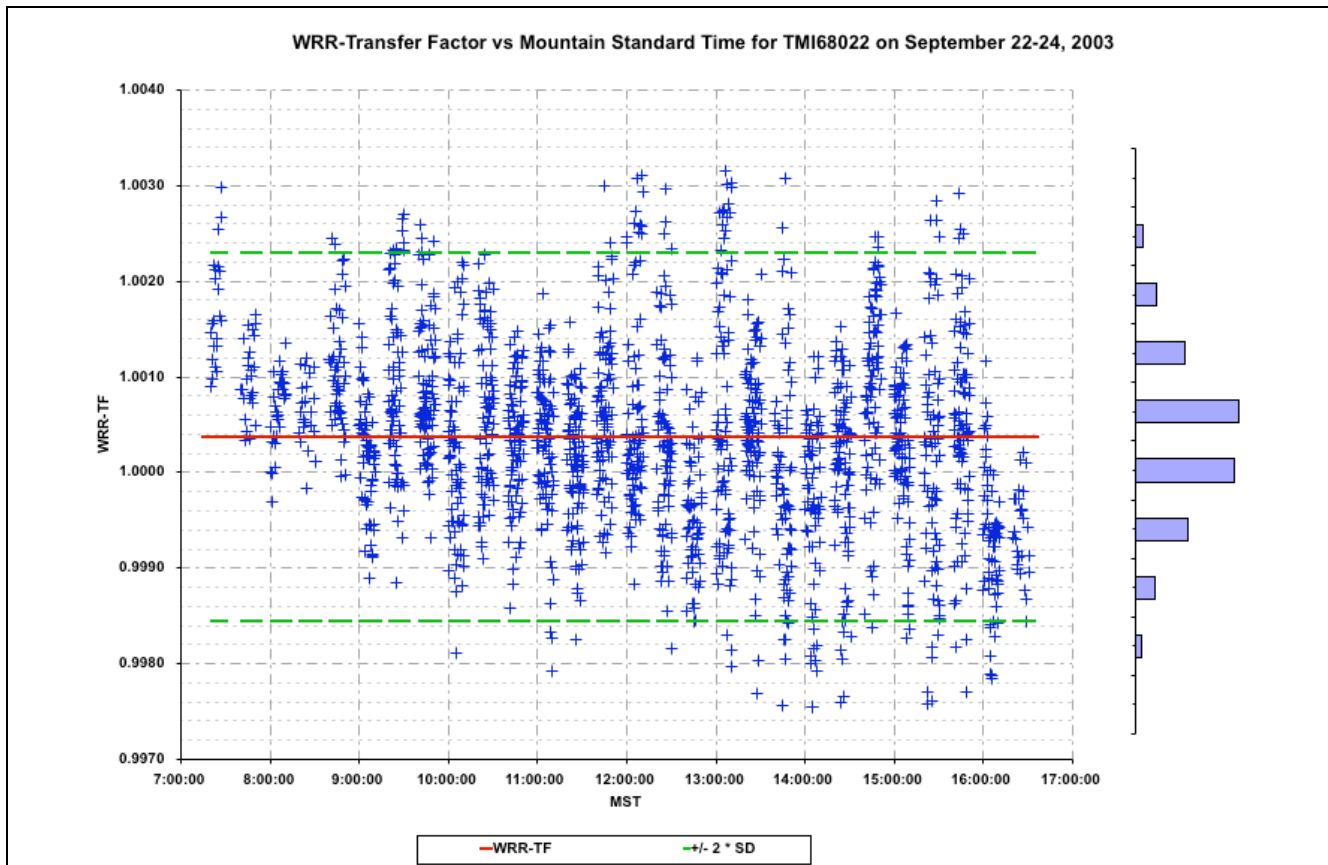


Figure 4.5.19 WRR Transfer Factor vs. Mountain Standard Time for TMI68022 at NPC2003

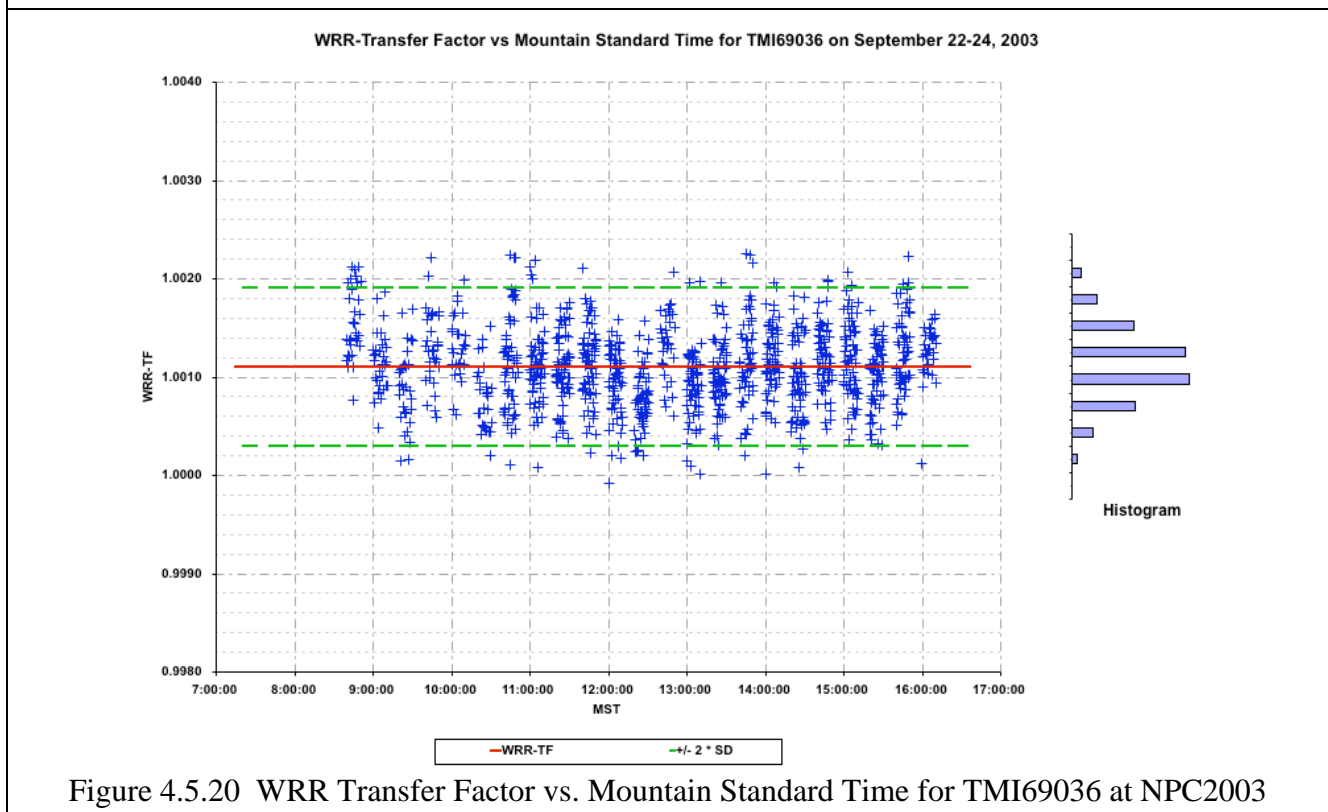


Figure 4.5.20 WRR Transfer Factor vs. Mountain Standard Time for TMI69036 at NPC2003

## 4.6 Recommendations

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

- For the purpose of pyrheliometer comparisons, such as NPC2003, we recommend the user apply only the manufacturer's calibration factor (CF), not the WRR Transfer Factor or the new calibration factor, to report his/her absolute cavity radiometer's irradiance readings. This eliminates the possibility of compounding WRR factors from previous comparisons.
- For data collection purposes, the manufacturer's CF is used to calculate the cavity responsivity. Each irradiance reading is then *multiplied* by the appropriate WRR Transfer Factor.

For future comparisons, we strongly urge the participants to provide their irradiance readings in the following format:

Serial Number  
##, HH:MM:SS, TPs, IRR

where,

Serial Number	=	Instrument serial number (first line only)
##	=	Reading number (1 to 33) within the Run
HH:MM:SS	=	Hour, minute and second of the reading (Local Standard Time, 24-hour clock)
TPs	=	Measured thermopile signal (mV) with resolution of X.XXXXX
IRR	=	Computed irradiance (Wm <sup>-2</sup> ) with resolution of XXXX.X

The file naming convention is suggested to include the radiometer serial number and date of observations (e.g., *AHF307131009.99* would correspond to data from AHF30713 on 10/9/99).

## 5. **Ancillary Data**

The meteorological elements of temperature, relative humidity and barometric pressure were measured during the comparisons using the meteorological station at SRRL. A NIP, PSP, and Model 8-48 measured direct, global, and diffuse irradiances respectively. These radiometers are used in SRRL's Baseline Measurement System (BMS). The BMS provides 1-minute averages of 3-second samples. Additional information, including data and graphical summaries, can be found at the Measurements and Instrumentation Data Center:

**[http://www.nrel.gov/midc/srri\\_bms](http://www.nrel.gov/midc/srri_bms).**

Time-series plots and other graphical presentations of these data are presented in Appendix B.

## 6. References

- Fröhlich, C., 1991. History of Solar Radiometry and the World Radiometric Reference. *Metrologia*, Vol. 28, Issue 3.
- Reda, I., 1996. Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. NREL/TP-463-20619. The National Renewable Energy Laboratory, Golden, Colorado.
- Romero, J., 1995. Direct Solar Irradiance Measurements with Pyrheliometers: Instruments and Calibrations. IPC-VIII, Davos, Switzerland; 16p.
- Romero, J; N.P. Fox and C. Fröhlich, 1996. Improved Comparison of the World Radiometric Reference and the SI Radiometric Scale. *Metrologia*, Vol. 32, Issue 6 (May), p523-524.
- WRC/PMOD, 1996. International Pyrheliometer Comparison, IPC VIII, 25 September - 13 October 1995, Results and Symposium. Working Report No. 188, Swiss Meteorological Institute, Dorfstrasse 33, CH-7260 Davos Dorf, Switzerland. 115 pp.

## 7. Images

Digital images taken during NPC-2003 are available from the SRRL web site:  
<http://www.nrel.gov/srrl/npc2003>



## Appendix A: List of Participants and Pyrheliometers

<u>Name / Address / Phone / Fax / E-mail</u>	<u>Pyrheliometer(s)</u>
<b>1. Naif M. Al-Abbadi</b> (Sending Radiometer) Energy Research Institute KACST, Building 17-E, 4th floor Prince Abdullah Road P. O. Box 6086 Riyadh, 11442 Saudi Arabia Phone: 481-3487 Fax: 4813880 E-mail: nabbadi@kacst.edu.sa	HF 30110
<b>2. Bill Boyson</b> Sandia National Laboratories Photovoltaic Systems Evaluation Lab P.O.Box 5800 Albuquerque, NM 87185-0752 Phone: 505-844-5979 Fax: 505-844-4566 E-mail: weboyso@sandia.gov	TMI 67603 AHF 31108
<b>3. Raymond (Ray) Decker</b> Sandia National Laboratories Primary Standards Laboratory P.O.Box 5800 Albuquerque, NM 87185-0665 MS 0665 Phone: 505-844-1357 Fax: 505-844-7699 E-mail: rddecke@sandia.gov	TMI 67603 AHF 31108
<b>4. Fred Denn</b> Analytical Services & Materials, Inc. Atmospheric Sciences Group 1 Enterprise Parkway, Suite 300 Hampton, VA 23666-5845 Phone: 757 827 4622 Fax: 757-825-8659 E-mail: F.M.Denn@Larc.NASA.GOV	AHF 31041 AHF 31105

**5. Robert M. (Mike) Edgar**  
Sandia National Laboratories  
PO Box 5800 MS 1127  
Albuquerque, NM 87185-1127  
Phone: 505-845-3441  
Fax: 505-845-3366  
E-mail: rmedgar@sandia.gov

TMI 67811  
TMI 68022

**6. John Hickey**  
The Eppley Laboratory, Inc.  
12 Sheffield Ave  
Newport, RI 02840  
Phone: 401-847-1020  
Fax: 401-847-1031  
E-mail: jhickeyeplab@ids.net

AHF 14915  
AWX 32449

**7. Gary Hodges**  
NOAA/OAR/ARL/SRRB  
325 Broadway  
Boulder, CO 80305  
Phone: 303-497-6460  
Fax: 303-497-6546  
E-mail: gary.hodges@noaa.gov

AHF 30710

**8. Duncan Maciver**  
DSET Laboratories  
45601 North 47th Ave.  
Phoenix, AZ 85087  
Phone: 623-465-7356  
Fax: 623-465-9409  
E-mail: dmaciver@atlaswsg.com

AHF 17142

**9. Joe Michalsky**  
NOAA/OAR/ARL/SRRB  
325 Broadway R/ARL  
Boulder, CO 80305  
Phone: 303-497-6360  
Fax: 303-497-6546  
E-mail: Joseph.Michalsky@noaa.gov

5° CaF2 NIP  
26356E6

<p><b>10. Keith Emery</b>  National Renewable Energy Laboratory  1617 Cole Blvd.  Golden, CO 80401-3393  Phone: 303-384-6768  Fax: 303-384-6391  E-mail: myersd@tcplink.nrel.gov</p>	<p>(Sending Radiometer)</p>	<p>AHF 23734</p>
<p><b>11. Erik Naranen</b>  DSET Laboratories  45601 North 47<sup>th</sup> Ave.  Phoenix, AZ 85087  Phone: 623-465-7356  Fax: 623-465-9409  E-mail: Enaranen@atlaswsg.com</p>		<p>AHF 17142</p>
<p><b>12. Don Nelson</b>  NOAA/CMDL  Climate Monitoring &amp; Diagnostics Laboratory  M/5 R/CMDL1  325 Broadway  Boulder, CO 80305  Phone: 303-497-6662  Fax: 303-497-6290  E-mail: donald.w.nelson@noaa.gov</p>		<p>AHF 28553  TMI 67502</p>
<p><b>13. Bill Porch</b>  Los Alamos National Laboratory  Group EES-8, MS J577  P.O. Box 1663  Los Alamos, NM 87545  Phone: 505-667-0971  Fax: 505-667-9122  E-mail: wporch@lanl.gov</p>		<p>AHF 30494</p>
<p><b>14. Ibrahim Reda</b>  National Renewable Energy Laboratory  1617 Cole Blvd.  Golden, CO 80401-3393  Phone: 303-384-6385  Fax: 303-384-6391  E-mail: ireda@tcplink.nrel.gov</p>		<p>AHF 23734  AHF 28968  AHF 29220  AHF 30713  AHF 31104  AWX 32452</p>

- 15. Michael Stein** AHF 14915  
 The Eppley Laboratory, Inc. AWX 32449  
 12 Sheffield Ave  
 Newport, RI 02840  
 Phone: 401-847-1020  
 Fax: 401-847-1031  
 E-mail: mikes@eppleylab.com
- 16. Tom Stoffel** TMI 68017  
 National Renewable Energy Laboratory TMI 68018  
 1617 Cole Blvd. TMI 69036  
 Golden, CO 80401-3393  
 Phone: 303-384-6395  
 Fax: 303-384-6391  
 E-mail: Tom\_Stoffel@nrel.gov
- 17. Phil Thacher** TMI 67603  
 Sandia National Laboratories AHF 31108  
 MS 0665  
 Primary Standards Laboratory  
 P.O.Box 5800  
 Albuquerque, NM 87185-0665  
 Phone: 505-898-4345  
 or 505-844-7599  
 Email: apthach@swcp.com or pdthach@sandia.gov
- 18. Ly Vo** HF 21182  
 Florida Solar Energy Center  
 1679 Clearlake Road  
 Cocoa, FL 32922  
 Phone: 321-638-1438  
 Fax: 321-638-1010  
 E-mail: Lvo@FSEC.UCF.EDU
- 19. Craig Webb** AHF 28964  
 Atmospheric Radiation Measurement Program AHF 29222  
 ARM Program Site Office AHF 30495  
 309600 EW 28  
 Billings, OK 74630-2045  
 Phone: 580-388-4053  
 Fax: 580-388-4052  
 E-mail: craigw@ops.sgp.arm.gov

**20. Steve Wilcox**

AHF 30110

National Renewable Energy Laboratory

1617 Cole Blvd.

Golden, CO 80401-3393

Phone: 303-275-4061

Fax: 303-384-6391

E-mail: [stephen\\_wilcox@nrel.gov](mailto:stephen_wilcox@nrel.gov)

**NREL Staff**

**Afshin Andreas**

Computer Issues (Virus scan, E-mail, Web Site)

**Pete Gotseff**

Tools, Parts (Electronics and Hardware), Trackers

**Bev Kay**

Facilities and services (Phone, Mail, FOOD)

**Ibrahim Reda**

NPC Data Collection & Processing, Cavity Operations

**Tom Stoffel**

Host (Security, Safety, Logistics, FOOD)

**Steve Wilcox**

Computer Issues, Trackers, Cavity Operations

**Appendix A (concluded):  
List of Pyrheliometers**

<u>No.</u>	<u>Serial No.</u>	<u>Owner / Application</u>
1	AHF 14915*	EPLAB / Reference Standard
2	AHF 17142	Atlas Weathering Services-DSET Labs / Reference Standard
3	AHF 23734	NREL / Photovoltaics Program Reference
4	AHF 28553*	NOAA Climate Monitoring & Diagnostics Laboratory (CMDL) / Reference
5	AHF 28964	DOE ARM / Southern Great Plains Site Reference
6	AHF 28968*	DOE ARM / Program Reference
7	AHF 29220*	NREL / Metrology Lab Reference Standard #2
8	AHF 29222	DOE ARM-Southern Great Plains / All-Weather
9	AHF 30494	DOE ARM Tropical Western Pacific Working Standard
10	AHF 30495	DOE ARM-Southern Great Plains Working Standard
11	AHF 30710	NOAA / Surface Radiation Research Branch Reference
12	AHF 30713*	NREL / Metrology Lab Working Standard #1
13	AHF 31041	NASA Clouds and the Earth's Radiant Energy System (CERES) / Reference 1
14	AHF 31104	NREL / Metrology Lab Working Standard #2
15	AHF 31105	NASA Clouds and the Earth's Radiant Energy System (CERES) / Reference 2
16	AHF 31108	Sandia National Laboratories / PV Reference Standard
17	AWX 32449	EPLAB / All-Weather Standard
18	AWX 32452	NREL / All-Weather Standard
19	HF 21182	FSEC / Primary Standard
20	HF 30110	KACST Site Reference & Working Standard
21	TMI 67502*	NOAA CMDL / Reference Standard
22	TMI 67603	Sandia National Laboratories / PSL Reference Standard
23	TMI 67811	Sandia National Laboratories / CRTF Standard #1
24	TMI 68017	NREL / SRRL All-Weather BORCAL Working Standard #2
25	TMI 68018*	NREL / Metrology Lab Reference Standard #1
26	TMI 68022	Sandia National Laboratories / CRTF Standard #2
27	TMI 69036	NREL Metrology Lab / BORCAL Working Standard #3
28	26356E6	NOAA/ARL/SRRB / Research Instrument (5° fov, CaF2 window)

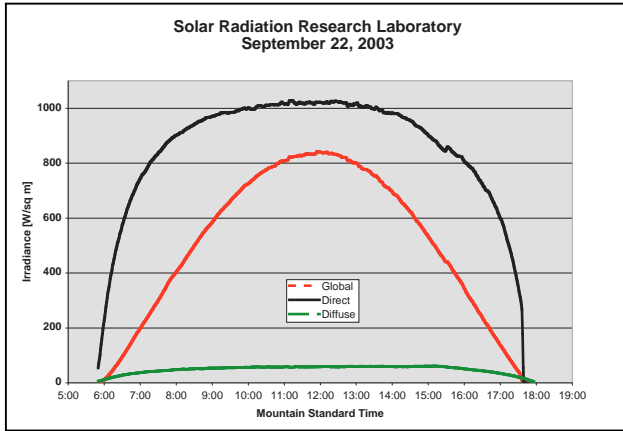
\* One of seven radiometers in NPC-2003 Transfer Standard Group

## **Appendix B: Ancillary Data Summaries**

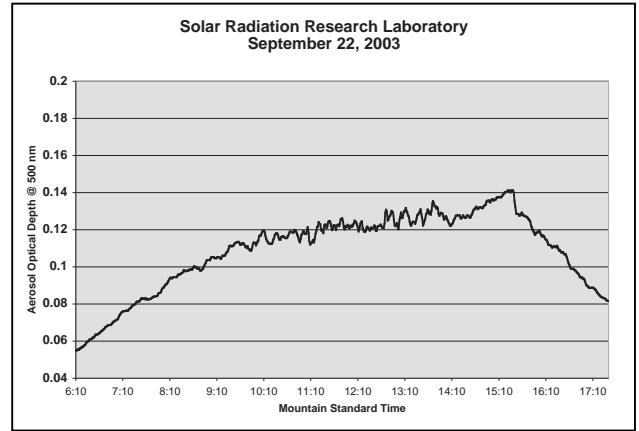
The measurement performance of an absolute cavity can be affected by several environmental parameters. Potentially relevant meteorological data collected during the NPC are presented in this appendix. The Baseline Measurement System (BMS) has been in continuous operation at the Solar Radiation Research Lab (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 our Measurement & Instrumentation Data Center: [http://www.nrel.gov/midc/srrl\\_bms](http://www.nrel.gov/midc/srrl_bms).

Time-series plots and other graphical presentations of these data acquired during the NPC-2003 measurements are presented here.

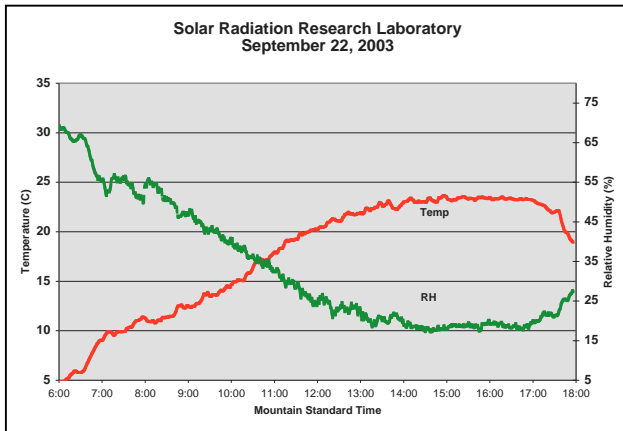
# Baseline Measurement System Data for September 22, 2003



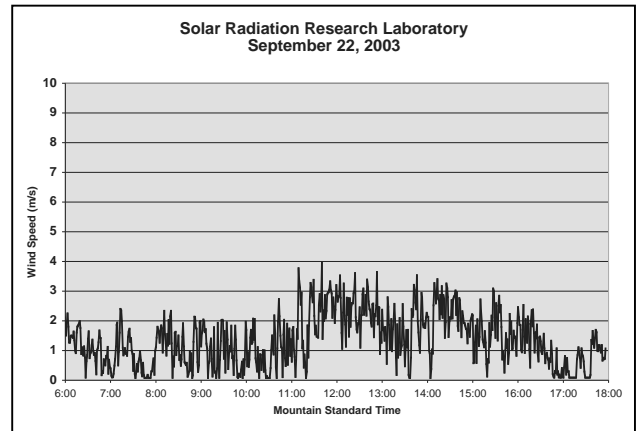
Broadband Irradiance



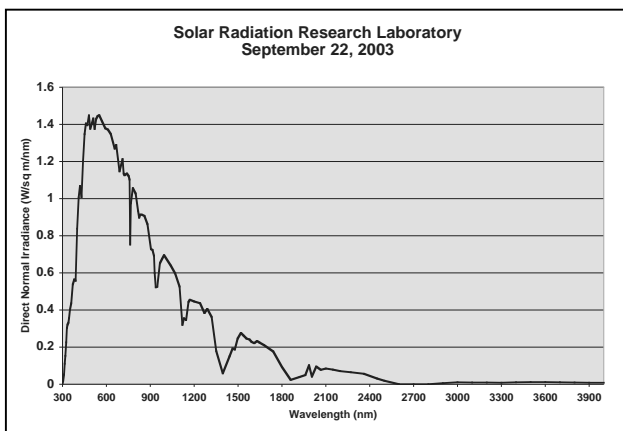
Aerosol Optical Depth



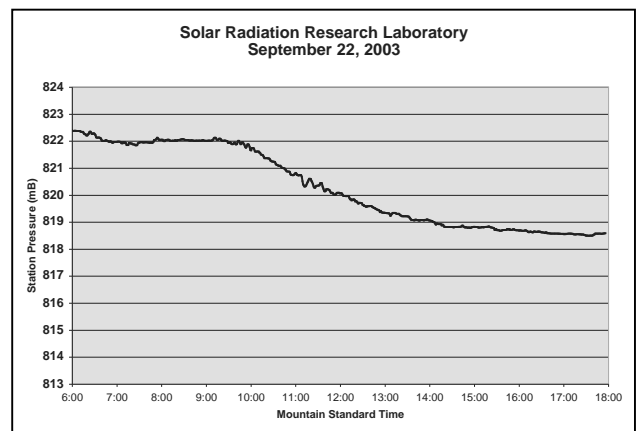
Temperature & Relative Humidity



Wind Speed at 10 m AGL



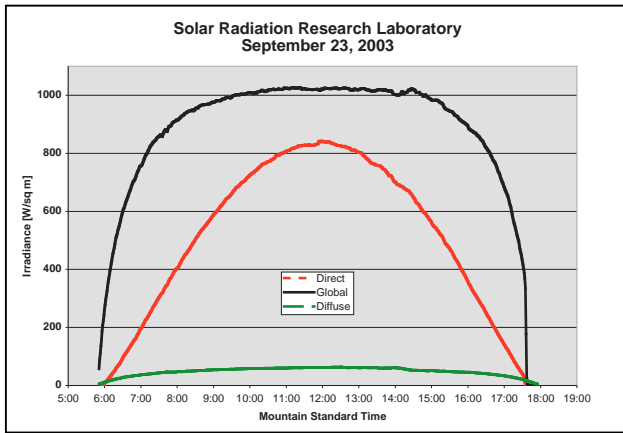
Direct Normal Spectra



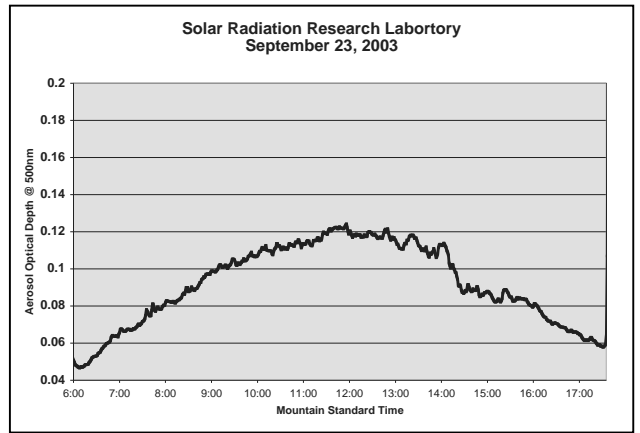
Station Pressure



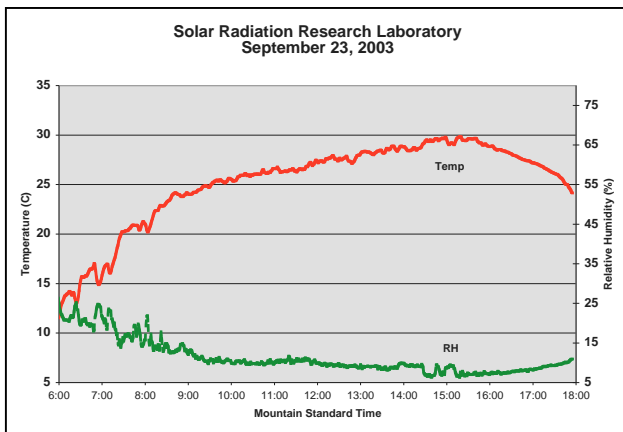
# Baseline Measurement System Data for September 23, 2003



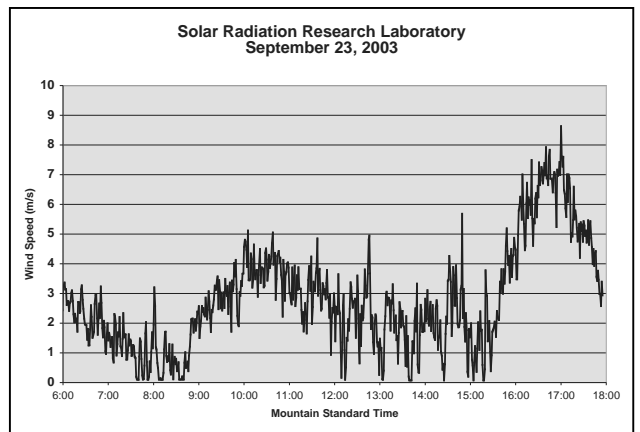
Broadband Irradiance



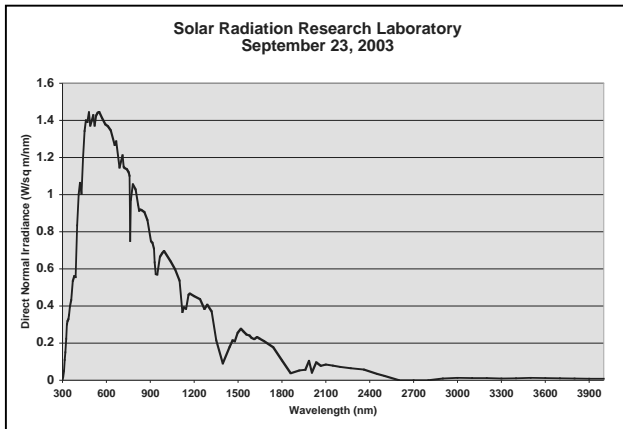
Aerosol Optical Depth



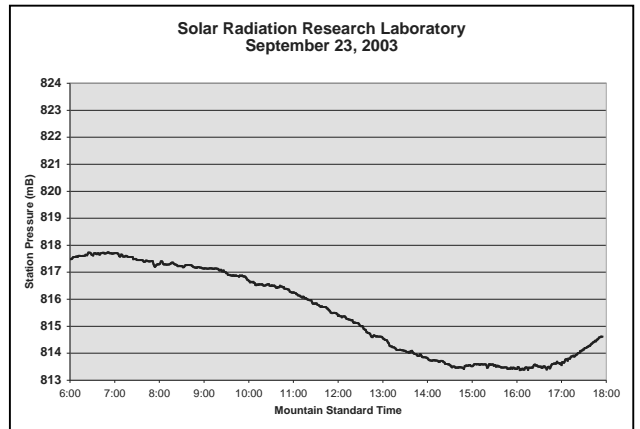
Temperature & Relative Humidity



Wind Speed at 10 m AGL

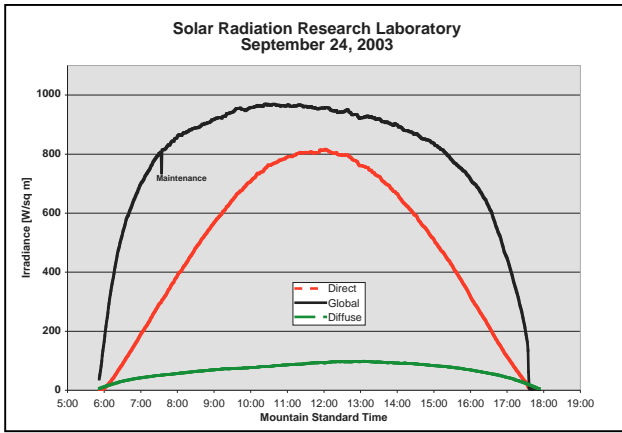


Direct Normal Spectra

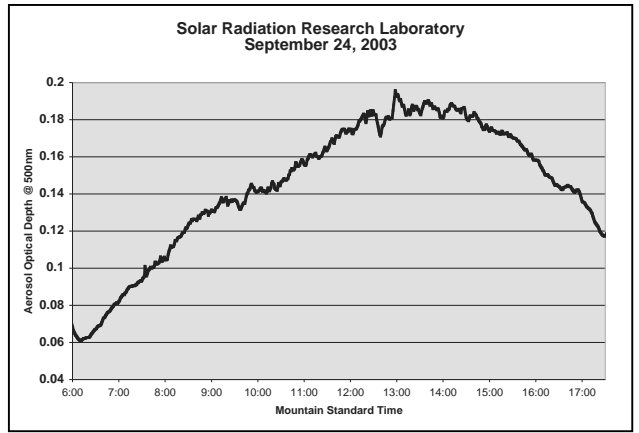


Station Pressure

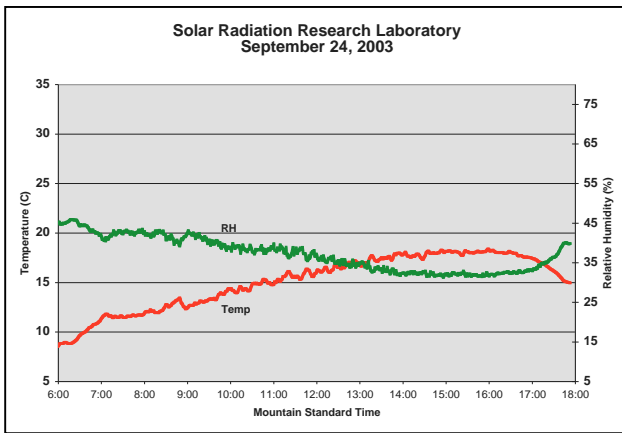
# Baseline Measurement System Data for September 24, 2003



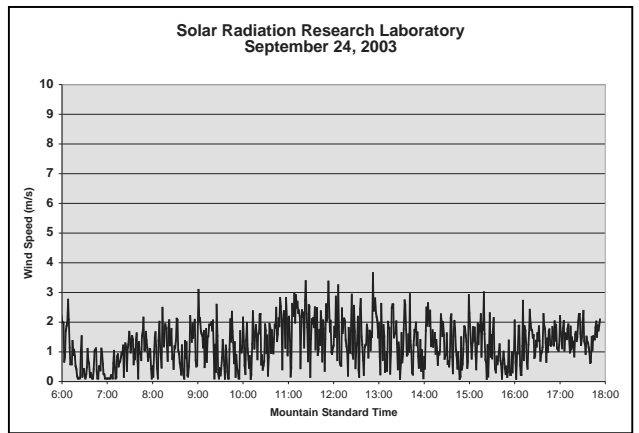
Broadband Irradiance



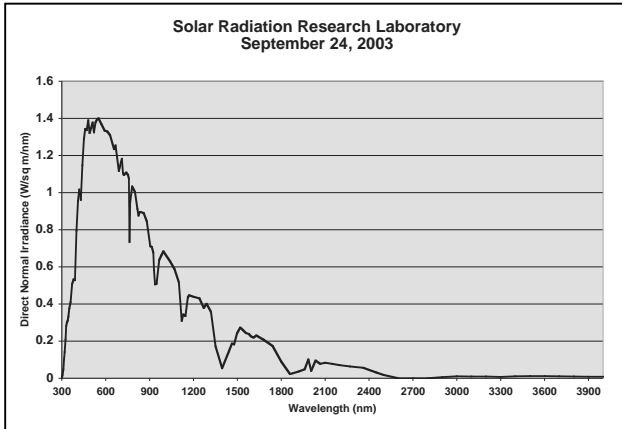
Aerosol Optical Depth



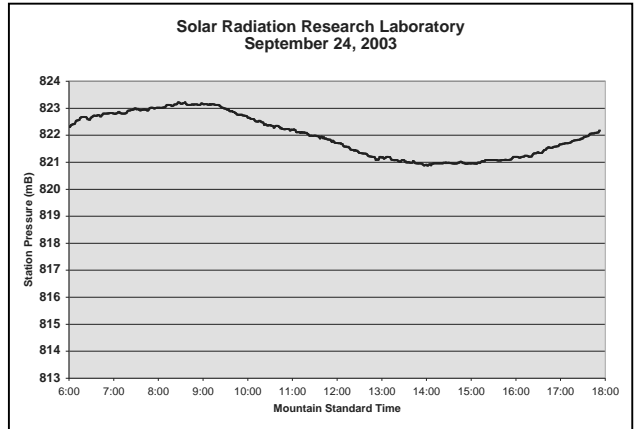
Temperature & Relative Humidity



Wind Speed at 10 m AGL



Direct Normal Spectra



Station Pressure

## Appendix C: Operational Notes

The following text was distributed to the participants at the opening of the NPC for discussion to achieve consensus.

### 2003 Absolute Cavity Radiometer Comparisons at NREL Protocol Issues Summary

Based on past experiences, we need to agree on the following issues before we begin the comparisons.

1. Title - We will refer to this effort as *NPC-2003* (NREL Pyrheliometer Comparisons 2003).

2. Schedule -

Please call Tom's voice mail (303-384-6395) after 06:30 MDT for recorded announcement of daily plan:

**Clear** sky forecast = Data!                      **Cloudy** = Conference Room FTLB 153.

September 23<sup>rd</sup> :

07:30 - 08:30-Visitor check-in at Site Entrance Building.

08:00 - 12:00-Transport equipment to SRRL.

-Equipment Installation & tests.

-ALL personal computers will be scanned for viruses prior to their use at SRRL.NREL will provide this service. A seating diagram is available to indicate operator/solar tracker assignments, but we'll see how this works once every one's there.

12:00 - 13:00-Lunch

13:00 - 17:00-Continue equipment tests as needed

-Review measurement protocol, data format and procedures.

-Dry-run(s) of comparison measurements (weather permitting)

-Update Attendance List Information.

September 23<sup>rd</sup> - October 4<sup>th</sup> (including weekends):

• **Clear sky** => Measurements!

08:00                      -Arrive at SRRL

08:00 - 08:30-Deploy instruments

08:30 - 09:00-Equipment warm-up for at least 30-minutes

09:00 - 17:30-Comparison Data Collection

-Measurements until sundown or clouds.

September 23<sup>rd</sup> - October 4<sup>th</sup> (including weekends):

- **Cloudy sky** => No Measurements, but optionally...

Conference Room 153 in Building "FTLB" is reserved daily for our use:

- Review of previous day's data analyses
- Technical Briefings on Radiometry
- Equipment Tests
- NREL Tours
- Office Time (limited e-mail connections at SRRL)

We will determine the need for more measurements at the end of each day.  
(see item 5 below)

3. SRRL Coordinates

Program your solar tracker using:

- LAT = 39.7425 N
- LON = 105.1778 W
- ELEV = 1828.8 m AMSL (6,000 ft)
- BARO = 820 mBar (average station pressure)

4. Time Keeping

- A timekeeper will be identified.
- All time records will be Mountain Standard Time (MST)
- The NIST atomic clock is a local call:  
303-499-7111
- A GPS time source is also available.
- Set your system clock at the daily start-up or as often as needed for 2 sec accuracy.

5. Minimum Data Set

A subject for discussion, but 300 data points (your instrument/Reference) could be our goal for a minimum data set for these comparisons.

6. Measurements

- Do NOT apply any previous WRR correction factors to your measurements.
- Use only the factory calibration factor to adjust your data beyond any other adjustments you feel are needed to correct your data (e.g., pre- and post-calibration drifts in sensitivity are OK).As in the past, we will use the following terms:

<i>Calibrate</i>	=	Perform electrical calibration and wait for next measurement period to begin
<i>Reading</i>	=	A measurement of direct irradiance within 1 sec of announcement at 20-sec intervals.
<i>Run</i>	=	Collection of 31 readings taken in sequence.
<i>Shade &amp; Calibrate</i>	=	Perform electrical calibration after each run.

The timekeeper will make the following announcements for each Run:

- Next Run Begins at HH:MM (MST)
- T minus 6 minutes. Begin calibration
- T minus 3 minutes
- T minus 2 minutes
- T minus 1 minute
- T minus 30 sec
- T minus 10 sec
- T minus 5 - 4 - 3 - 2 - 1 - READ!
- READ! (at T plus 20 sec intervals for 33 readings in a *Run*)

7. Data Transfer

The data format will be discussed on the first day. After the last daily RUN, but before equipment teardown, our Data Keeper (TBD) will circulate a master diskette for you to copy all of your corrected data. Calibration files will not be collected.

8. Data Processing

Reda has developed an Excel spreadsheet system for reducing the data.

9. Data Reporting

Our goal is to provide each participant with next-day analyses. A final report will be published by NREL within two months of the comparisons.

10. Equipment Storage

Each participant will be given space to store systems at SRRL. Please let us know if you wish to have any electronics connected to AC power while in storage.

11. Common Sense & Courtesy

Please get permission of owner/operator before touching someone else's equipment!  
(Turn on/off power strips, move cables, etc.)

12. Clean-up

NPC2003 will conclude after all items are returned to the proper storage locations.

13. Contacts

Daily Voice Mail Announcement: **NREL EMERGENCY Press 1234**  
Tom Stoffel .....(303) 384-6395

Questions after normal business hours:  
Tom Stoffel .....(303) 666-9719

Other friendly NREL staff:

- Reda .....(303) 384-6385 <Metrology Lab>
- Pete Gotseff .....(303) 384-6327 <Electronics Lab>
- Bev Kay.....(303) 384-6388 <Solar Radiation Research Lab>

SRRL.....(303) 384-6326 <Let it RING!>