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NREL Pyrheliometer Comparisons (NPC-2001)

September 24 – October 5, 2001

Final Report

By

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NOTICE

NPC 2001 Participants

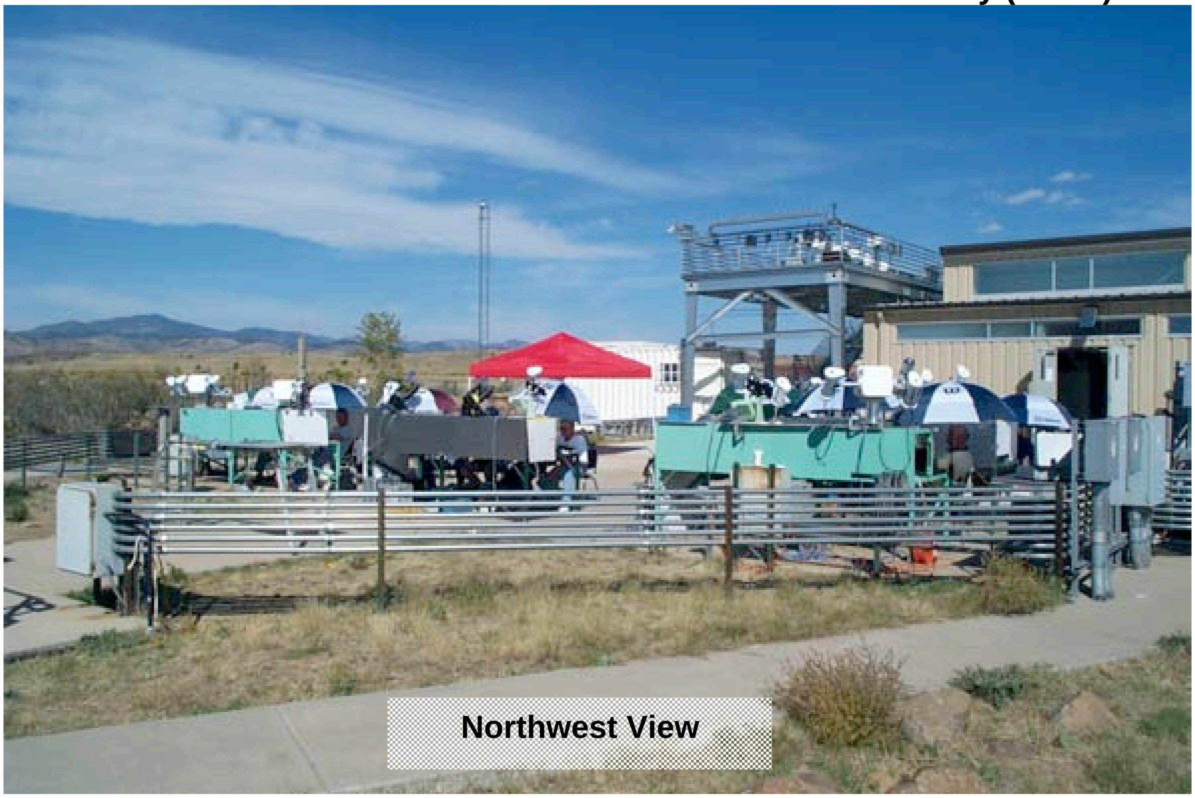
Back Row: Jim Huggins, Don Nelson, Bud Burns, Bryan Fabbri, Ray Decker, Gary Hodges, Mike Edgar, Steve Wilcox, Tom Stoffel
Front Row: Ibrahim Reda, Fred Denn, Wim Zaaiman, Dan Nelson, Bill Boyson, Bill Miller
(Not shown: Chris Cornwall and James Treadwell)

Acknowledgements

We sincerely appreciate the support of Tony Schaffhauser, 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 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 Don Nelson (NOAA's Climate Monitoring & Diagnostics Laboratory), Chris Cornwall and Gary Hodges (NOAA's Surface Radiation Research Branch), and Jerry Maybee and Gene Zerlaut (ATLAS/DSET). 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 PV917401, WU1D5600,WU865600, and 20100010.

NPC-2001 at the NREL Solar Radiation Research Laboratory (SRRL)



Northwest View

Southeast View of Participants on east side of work area

Table of Contents

Abstract

Accurate measurements of solar irradiance place many demands on the operators of commercially available radiometers. Maintaining careful instrument calibrations traceable to an international standard is the first step in establishing research quality solar irradiance measurement capabilities. The World Meteorological Organization (WMO) established the World Radiometric Reference (WRR) as an international standard for solar irradiance measurement in 1977.

The purpose of the annual NREL Pyrheliometer Comparisons (NPC) is to transfer the WRR from a group of reference radiometers to participating absolute cavity radiometers. These instruments are then used as reference or working standards for calibrating radiometers to be deployed in a variety of solar radiation measurement applications.

NPC-2001 was scheduled from September 24 through October 5, 2001 at the Solar Radiation Research Laboratory (SRRL). Favorable weather conditions allowed for the completion of data collection on September 28th. Sixteen participants operated 28 absolute cavity radiometers to simultaneously measure the clear-sky direct normal solar irradiance during this period. More than 2,000 observations were collected by the reference radiometers during the comparison. The NPC-2001 Transfer Standard Group (TSG) consists of five radiometers having direct traceability to the WRR. These electrically self-calibrating absolute cavity radiometers participated in the Ninth International Pyrheliometer Comparisons (IPC-IX), September 25 – October 13, 2000, hosted by the World Radiation Center/Physikalisch-Meteorologisches Observatorium Davos (WRC/PMOD). The NPC-2001 TSG was used to determine the reference irradiance for each 20-second observation at the NPC. Participating radiometers were assigned a new WRR Transfer Factor based on the measured irradiances and the corresponding reference irradiance values determined by the TSG.

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 2,000 reference irradiance measurements for each participating radiometer were collected during NPC-2001. Clear-sky direct normal irradiance levels ranged from less than 700 Wm^{-2} to 980 Wm^{-2}.

The performance of the TSG during NPC-2001 was consistent with previous comparisons, including the latest IPC-IX conducted in September/October 2000. The measurement performance of the TSG allowed the transfer of the WRR to each participating radiometer with an uncertainty of $\pm$ 0.32% with respect to SI units.

After securing adequate data for the WRR transfer, irradiance measurements were collected to characterize the effects of the protective window often provided with absolute cavity radiometers. Windowed cavity radiometers are candidate instruments for meeting Baseline Surface Radiation Network operations per WMO specifications. Two new All-Weather (AWX) cavity radiometers participated in NPC-2001, one of which was also at IPC-IX.

Ancillary broadband irradiance, spectral irradiance and meteorological data collected at SRRL during the comparison by the Baseline Measurement System are also presented in this report.

Future comparisons are planned at SRRL to continue 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 ground-truth, general atmospheric science research, or the myriad of other possibilities, requires traceable measurements 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 ± 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 pyrheliometers) 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 Pyrheliometer 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 Reduction Factor is calculated for each of the participating radiometers [Reda, 1996]. The range of historical WRR Reduction Factors is 1.00000±0.00250. Multiplying the irradiance reading of each radiometer by its assigned WRR Reduction factor will result in measurements that are traceable to WRR and therefore consistent with the international reference of solar radiation measurement.

The 2001 NREL Pyrheliometer Comparisons (NPC-2001) was scheduled from September 24 to October 5, 2001 at the Solar Radiation Research Laboratory (SRRL). Sixteen participants operated 28 absolute cavity radiometers during the comparisons (see Appendix A for list of participants). As a result of exceptionally good weather conditions, the comparisons were concluded on September 28th (see Appendix B for detailed information). The following programs and organizations were represented at NPC-2001:

- Analytical Services and Materials, Inc.
- Atlas Weathering Services, Inc. -DSET Laboratories
- Atmospheric Radiation Measurement Program of the U.S. Department of Energy
- European Commission Directorate General JRC
- Lockheed Martin Technical Operations
- Los Alamos National Laboratory
- NASA Langley Research Center, Atmospheric Sciences Division
- National Oceanic and Atmospheric Administration
    - -Climate Monitoring & Diagnostics Laboratory
    - -Surface Radiation Research Branch
- National Renewable Energy Laboratory
    - -Distributed Energy Resources Center
    - -Metrology Laboratory
    - -Photovoltaic Research Program
- Sandia National Laboratories
    - -Primary Standards Laboratory
    - -Photovoltaic Testing

In addition to computing the latest WRR Transfer Factors for each absolute radiometer, favorable weather conditions allowed us to collect additional measurements for determining the Window Correction Factors (WCF) for a select group of radiometers, including two new All-Weather (AWX) designs. These radiometers are intended to operate with the protective window mounted on the front aperture under all weather conditions. The transmittance of the window and its effects on the thermodynamic balance of the cavity radiometer contribute to the need for a WCF for each instrument. The WCF values are generally on the order of 1.05.

The results presented in this report are based on clear-sky direct normal solar irradiance data collected on five days during NPC-2001.

2. Reference Instruments

Five absolute cavity radiometers that participated in IPC-IX were used as the Transfer Standard Group (TSG) to maintain the WRR for this comparison. Although additional radiometers with IPC-IX history were available, only those instruments within NREL's control were selected for the TSG. This will permit long-term continuity of the TSG while providing adequate statistical representation of the WRR. Table 2.1 is a list of the TSG with their WRR Reduction Factors and Pooled Standard Deviations [WRC/PMOD, 2001].

Table 2.1 IPC-IX Results Summary for the NPC-2001 TSG

Serial Number	**WRR Factor (from IPC-IX)**	**Standard Deviation** (%)	**Number of Readings**
AHF 28553	0.99733	0.049	212
AHF 28968	0.99866	0.062	113
AHF 29220	0.99846	0.063	113
AHF 30713	0.99861	0.059	113
TMI 68018	0.99848	0.053	113
Mean WRR for the TSG	0.99831	**Pooled Std Deviation for the TSG** 0.056%	

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

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

where,

- i = i^{th} cavity
- m = number of reference cavities
- S_i = standard deviation of the i^{th} cavity, from IPC-IX
- n_i = number of readings of the i^{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 Transfer Factors 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.

By consensus, the goal was set to acquire at least 300 observations from each radiometer to determine the WRR Transfer Factor. 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 the individual WRR Transfer Factors.

Data from each radiometer/operator is 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 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-2001:

- Radiation source was the sun, with irradiance levels greater than 700 Wm^{-2}
- 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 ± 0.25˚ slope angle
- Wind speed was low (< 5 m/s) from the direction of the solar azimuth ± 30˚
- Cloud cover was less than 1/8 with an angular distance larger than 15˚ from the sun.

4.2 Determining the Reference Irradiance

Measurements from the five TSG absolute cavity radiometers that participated in IPC-IX were used to compute the reference irradiance for this NPC. The WRR Reduction 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 Reduction Factor for NPC-2001 is recalculated for each of the TSG cavities.

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 Reduction 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 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 an absolute cavity radiometer.

4.4 Measurements

NPC-2001 was scheduled for September 24 - October 5, 2001. The comparisons were completed on September 27th after more than 2,000 data points were collected from 66 runs completed during three days with 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 NPC2001 WRR Reduction 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 Reduction 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 NPC2001 are presented in Table 4.5.2.

Table 4.5.1 Summary Results for the Reference Transfer Standard Group (TSG) Radiometers Used for NPC2001

Serial Number	WRR IPC-IX	WRR NPC2001	St. Dev. % (NPC2001)	Number of Readings
AHF28553	0.99733	0.99704	0.000	2037
AHF28968	0.99866	0.99866	0.057	2037
AHF29220	0.99846	0.99866	0.056	2037
AHF30713	0.99861	0.99864	0.056	2037
TMI68018	0.99848	0.99854	0.068	2037
Mean WRR	0.99831	0.99831		

Table 4.5.2 Results for Radiometers Participating in NPC2001

Serial Number	WRR-TF NPC2001	Std. Dev. (%)	Number of Readings	%U95	
				w.r.t. WRR	w.r.t. SI
17142	0.99820	0.06	1870	0.17	0.34
21182	0.99948	0.10	2006	0.23	0.38
23734	0.99844	0.04	2021	0.14	0.33
28964	0.99845	0.07	1984	0.18	0.35
30495	0.99771	0.04	1966	0.14	0.33
30710	0.99965	0.05	1726	0.16	0.34
31041/34970A	0.99793	0.04	1007	0.14	0.33
31041/406	0.99830	0.07	798	0.18	0.35
31104	1.00035	0.04	2006	0.14	0.33
31105	1.00327	0.06	991	0.16	0.34
31108	0.99792	0.06	1720	0.16	0.34
67502	1.00198	0.14	979	0.30	0.42
67603	1.00083	0.06	1720	0.16	0.34
67811	1.00086	0.10	1621	0.23	0.38
68017	1.00037	0.07	1146	0.19	0.35
68020	0.99950	0.12	1787	0.27	0.41
68022	1.00121	0.14	1700	0.30	0.43
69036	1.00129	0.06	868	0.16	0.34
AWX32448	1.00073	0.07	461	0.18	0.35
AWX32452	0.99942	0.04	638	0.14	0.33
PMO6 81109	0.99997	0.07	529	0.18	0.35
PMO6 911204	1.00035	0.05	538	0.15	0.34

Note: The analyses for absolute cavity serial number 31041 were separated by the use of either an HP-34970A or EPLAB Model 406 control electronics.

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 NPC2001 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 (%) determined at NPC2001 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 (±%) of the WRR scale with respect to SI units.

The statistical analyses of WRR Transfer Factors for all 19 participating radiometers are presented in Figures 4.5.1 through 4.5.19. These graphical summaries indicate the mean, standard deviation, and frequency of occurrence of the WRR Transfer Factors determined during NPC2001.

As a result of equipment changes and/or operational difficulties, not all cavities were functional for the entire comparison. The dates of data collection for each radiometer are shown in Table 4.5.2.

Table 4.5.2 Data Collection Periods in September 2001

Serial Number	Data Collection	Serial Number	Data Collection
HF 17142	$24^{th} – 28^{th}$	TMI 67502	$26^{th} – 28^{th}$
AHF 21182	$24^{th} – 28^{th}$	TMI 67603	$24^{th} – 27^{th}$
AHF 23734	$24^{th} – 28^{th}$	TMI 67811	$24^{th} – 27^{th}$
AHF 28964	$24^{th} – 28^{th}$	TMI 68017	26^{th} – 28th
AHF 30495	$24^{th} – 28^{th}$	TMI 68020	$24^{th} – 28^{th}$
AHF 30710	$24^{th} – 28^{th}$	TMI 68022	$24^{th} – 27^{th}$
AHF 31041/3470A	$26^{th} – 28^{th}$	TMI 69036	$24^{th} – 25^{th}$
AHF 31041/406	$24^{th} – 28^{th}$	AWX 32448	$24^{th} – 28^{th}$
AHF 31104	$24^{th} – 28^{th}$	AWX 32452	$27^{th} – 28^{th}$
AHF 31105	$24^{th} – 28^{th}$	PMO6 81109	$24^{th} – 28^{th}$
AHF 31108	$24^{th} – 27^{th}$	PMO6 911204	$24^{th} – 28^{th}$

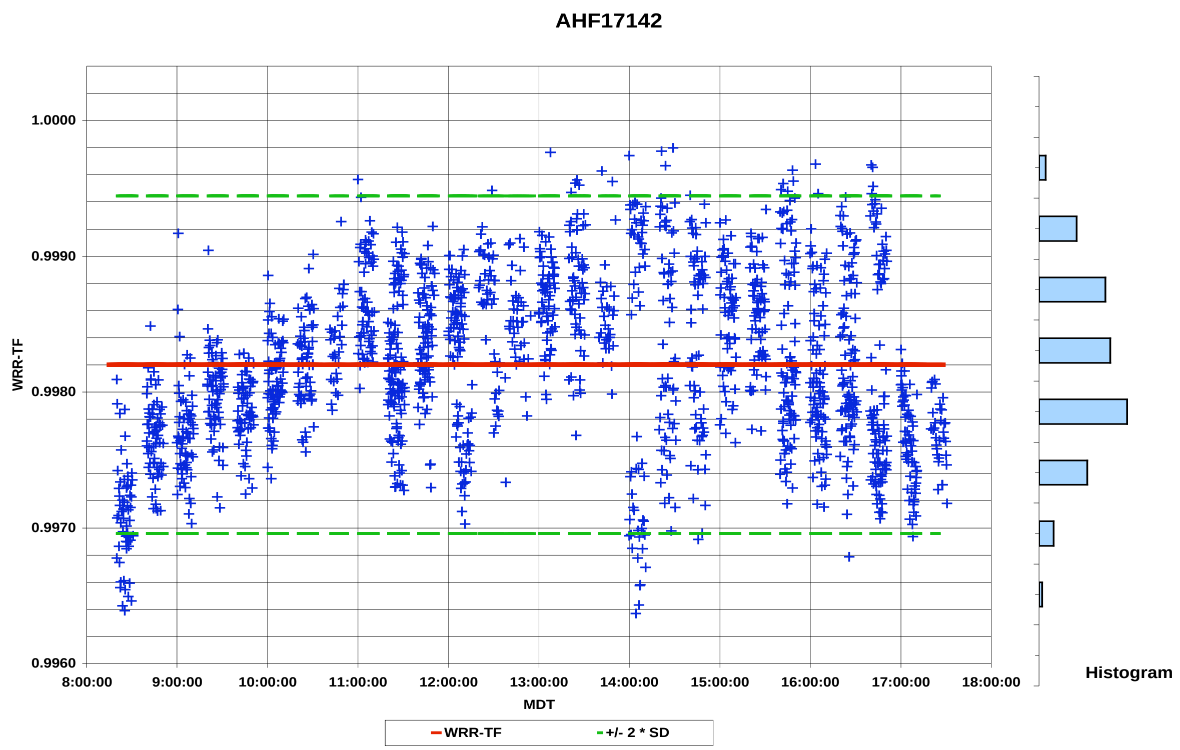


Figure 4.5.1 WRR Transfer Factor vs. Mountain Daylight Time for AHF17142 at NPC2001

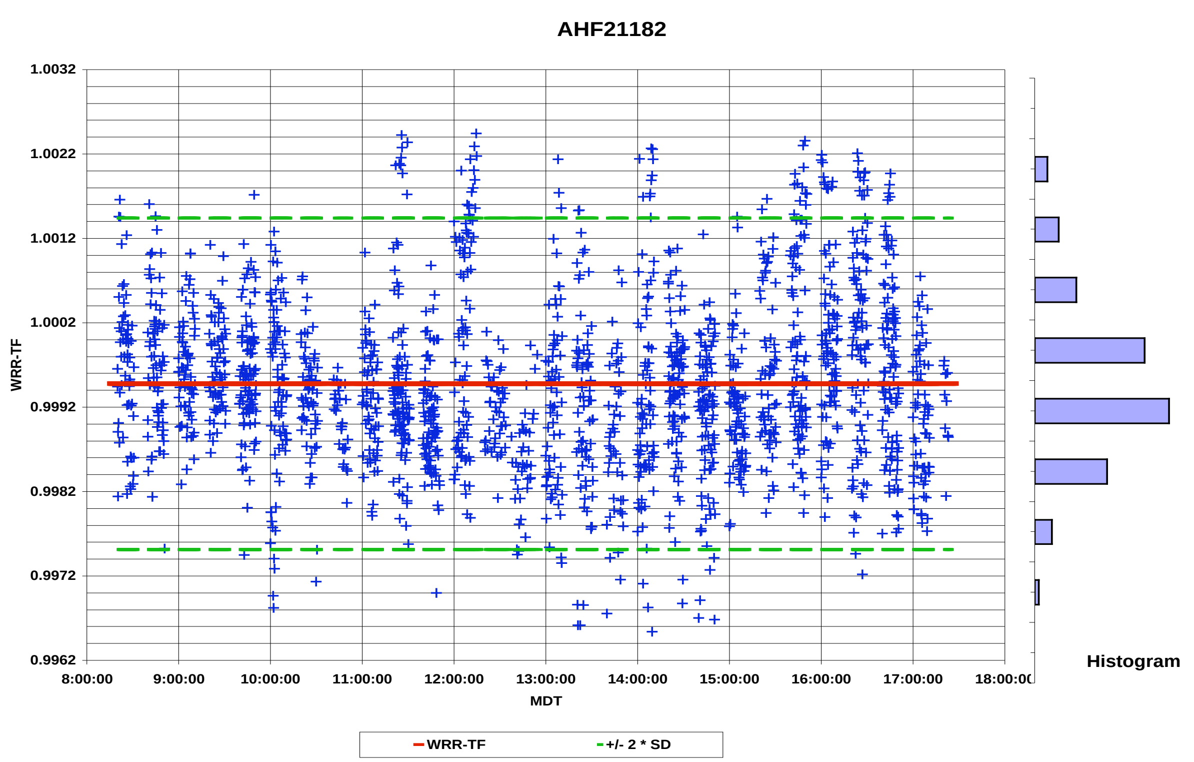


Figure 4.5.2 WRR Transfer Factor vs. Mountain Daylight Time for AHF21182 at NPC2001

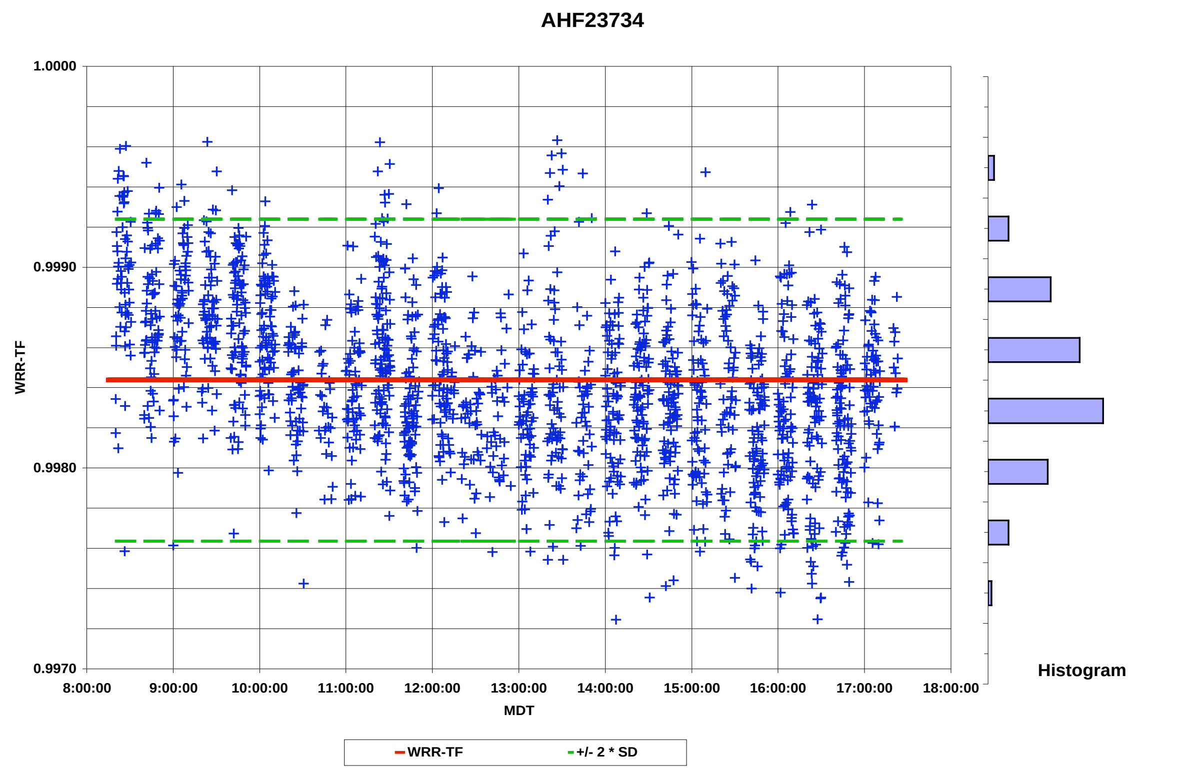


Figure 4.5.3 WRR Transfer Factor vs. Mountain Daylight Time for AHF23734 at NPC2001

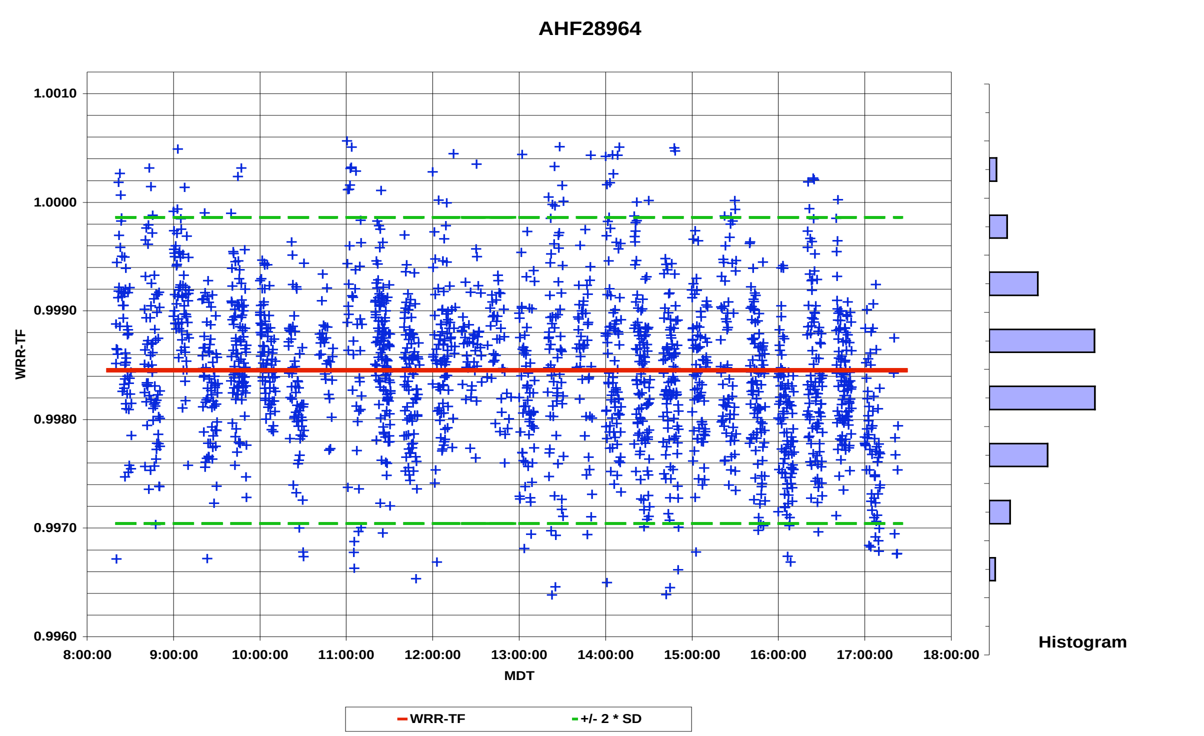


Figure 4.5.4 WRR Transfer Factor vs. Mountain Daylight Time for AHF28964 at NPC2001

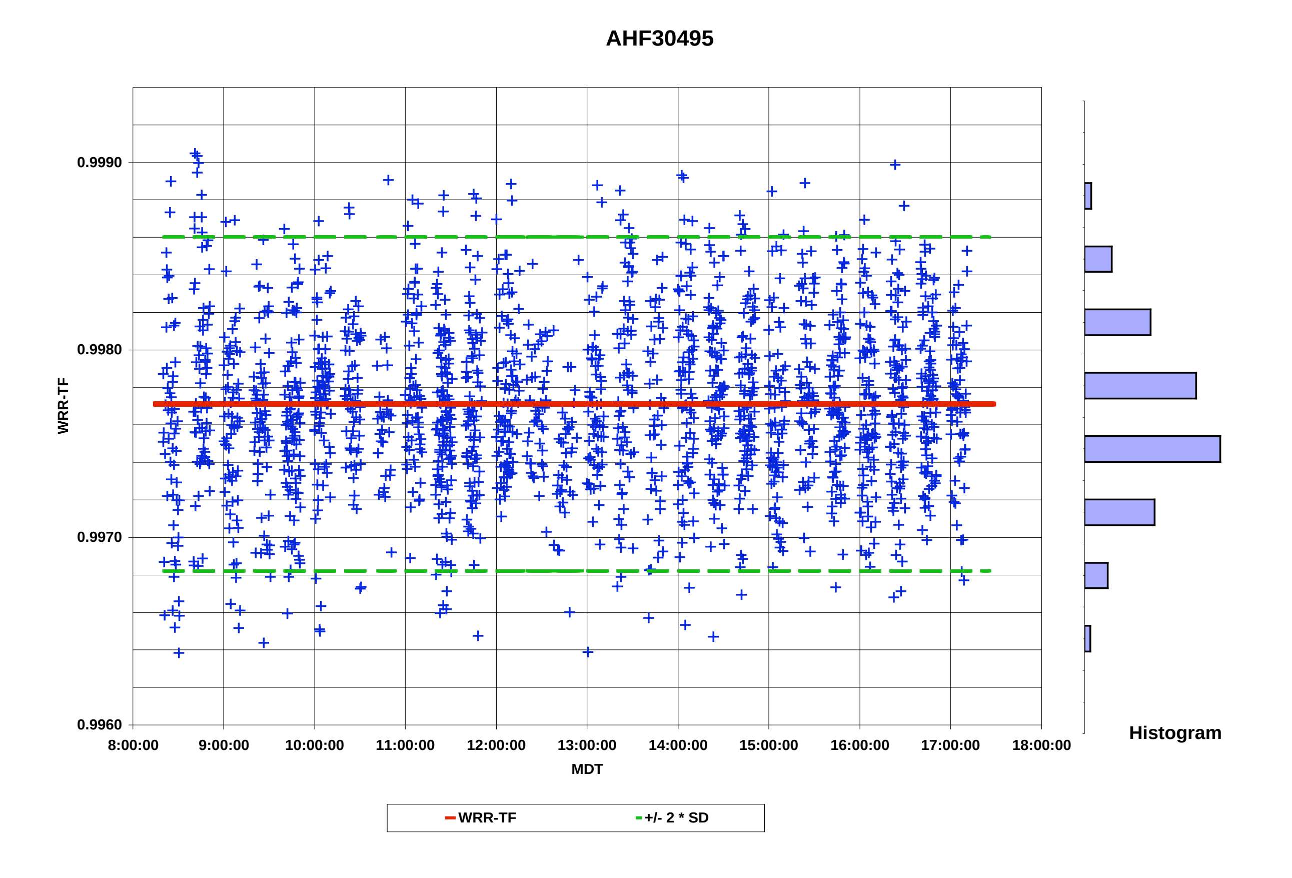


Figure 4.5.5 WRR Transfer Factor vs. Mountain Daylight Time for AHF30495 at NPC2001

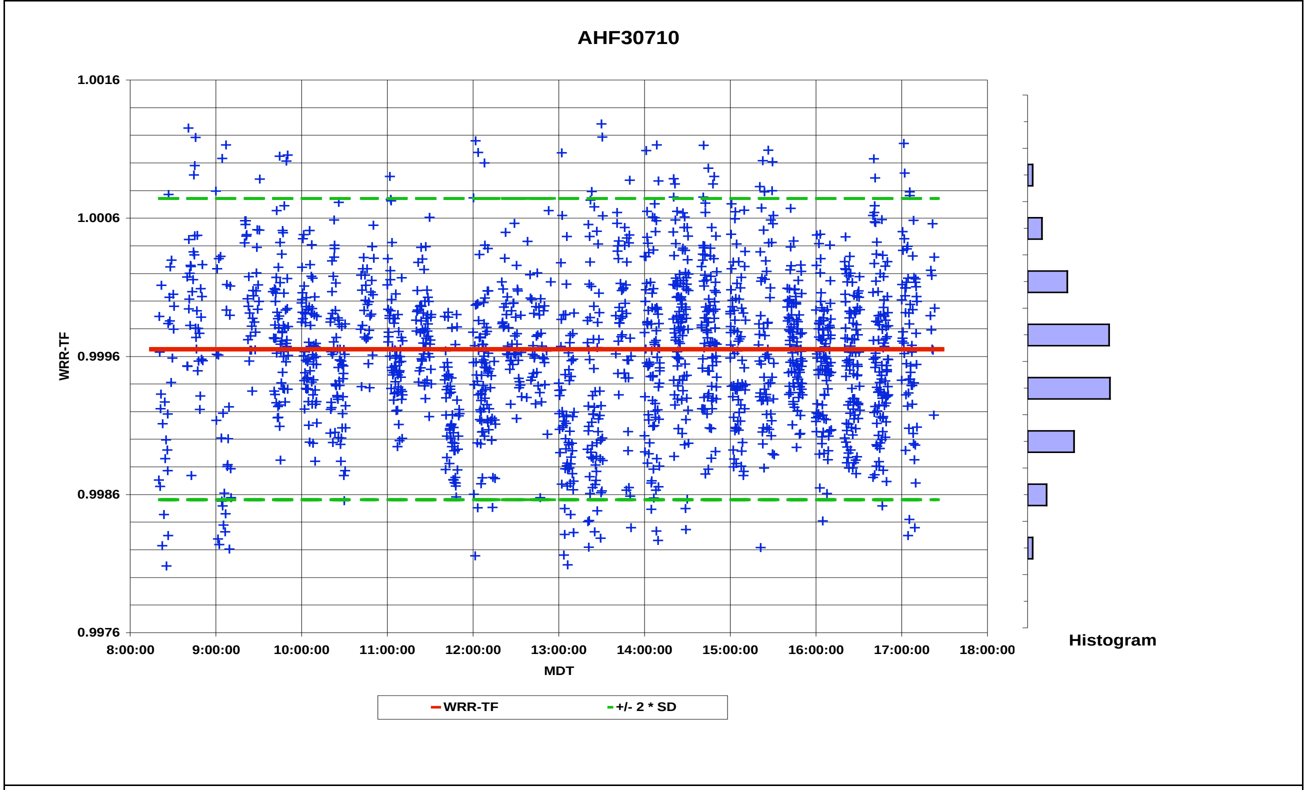


Figure 4.5.6 WRR Transfer Factor vs. Mountain Daylight Time for AHF30710 at NPC2001

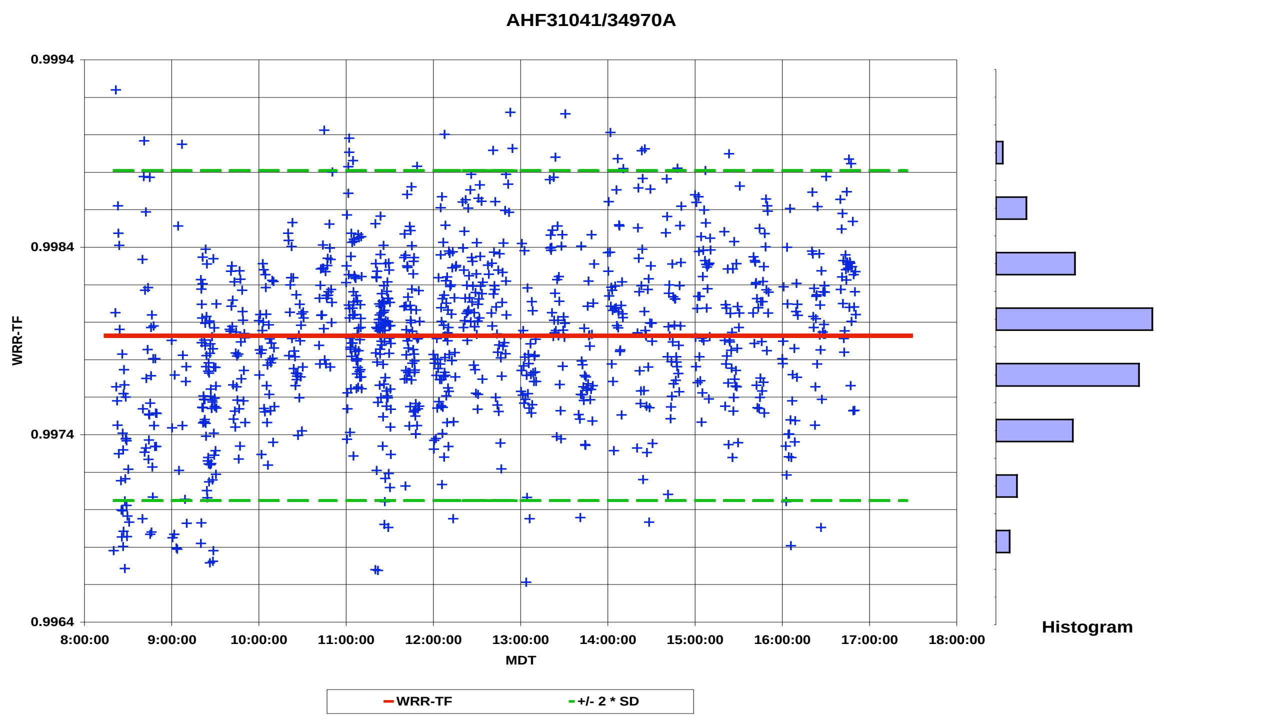


Figure 4.5.7 WRR Transfer Factor vs. Mountain Daylight Time for AHF31041/34970A at NPC2001

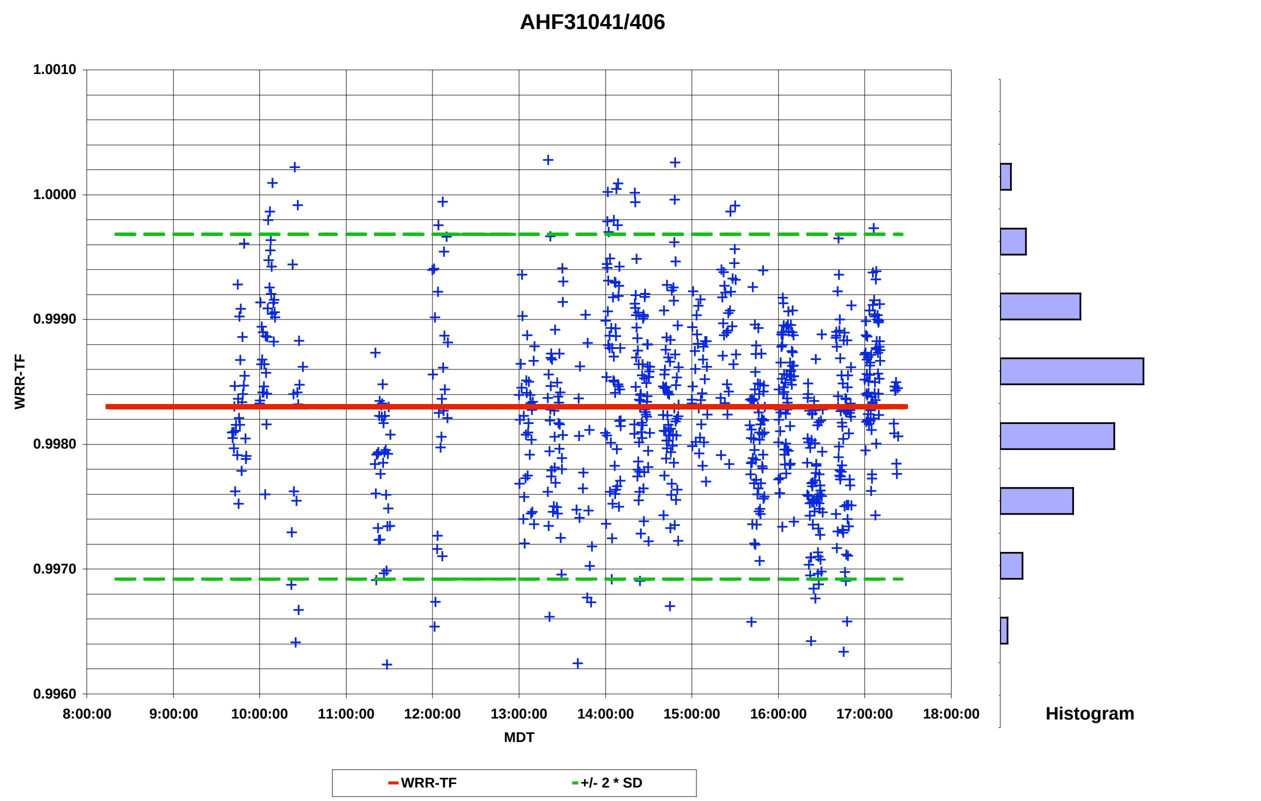


Figure 4.5.8 WRR Transfer Factor vs. Mountain Daylight Time for AHF31041/406 at NPC2001

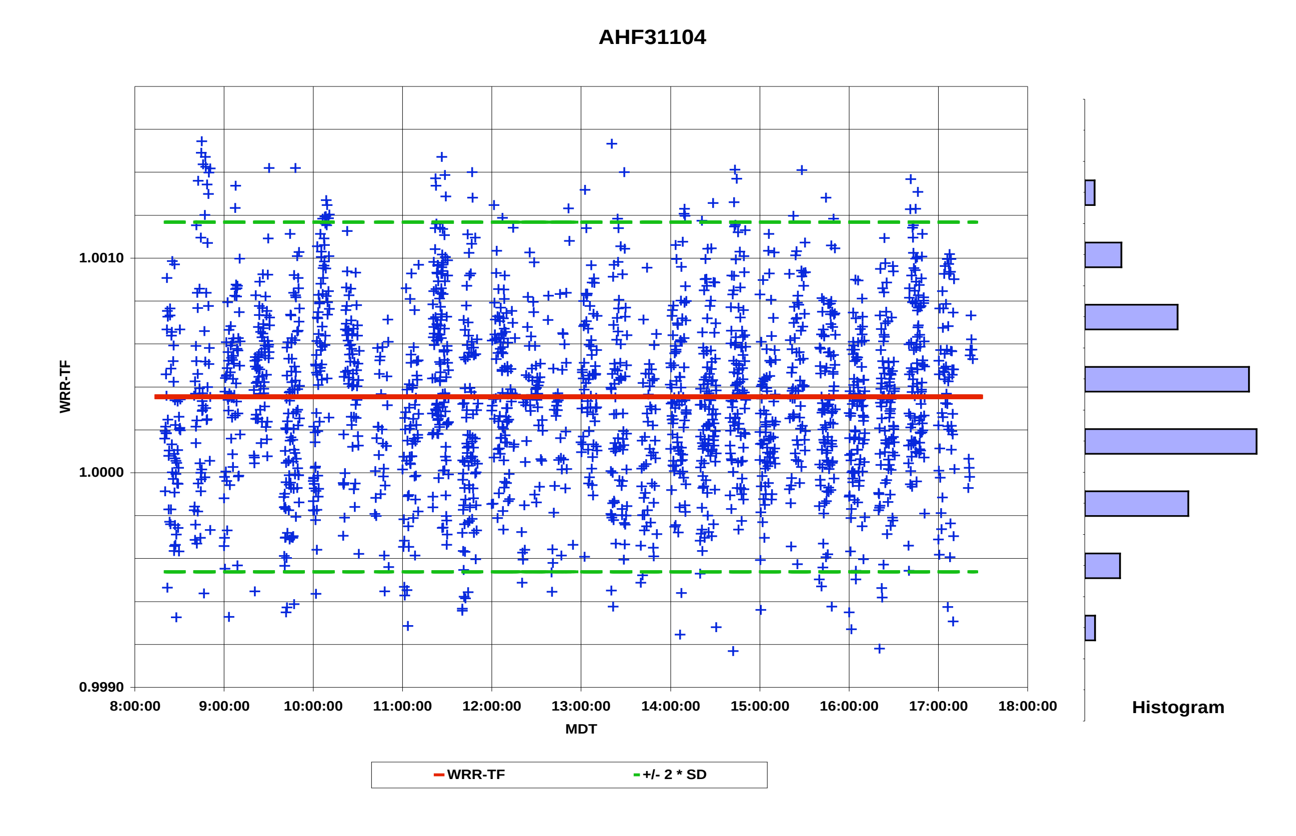


Figure 4.5.9 WRR Transfer Factor vs. Mountain Daylight Time for AHF31104 at NPC2001

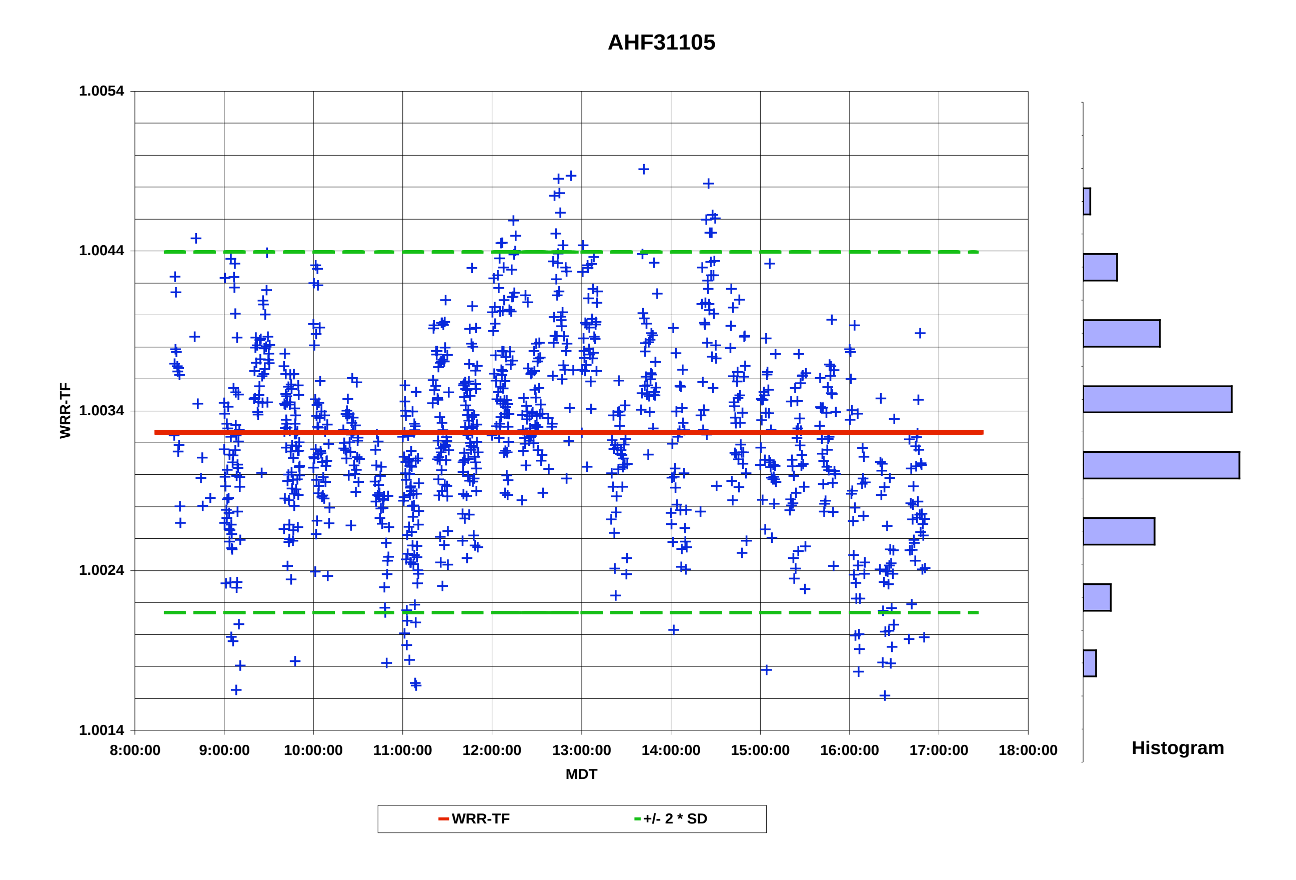


Figure 4.5.10 WRR Transfer Factor vs. Mountain Daylight Time for AHF31105 at NPC2001

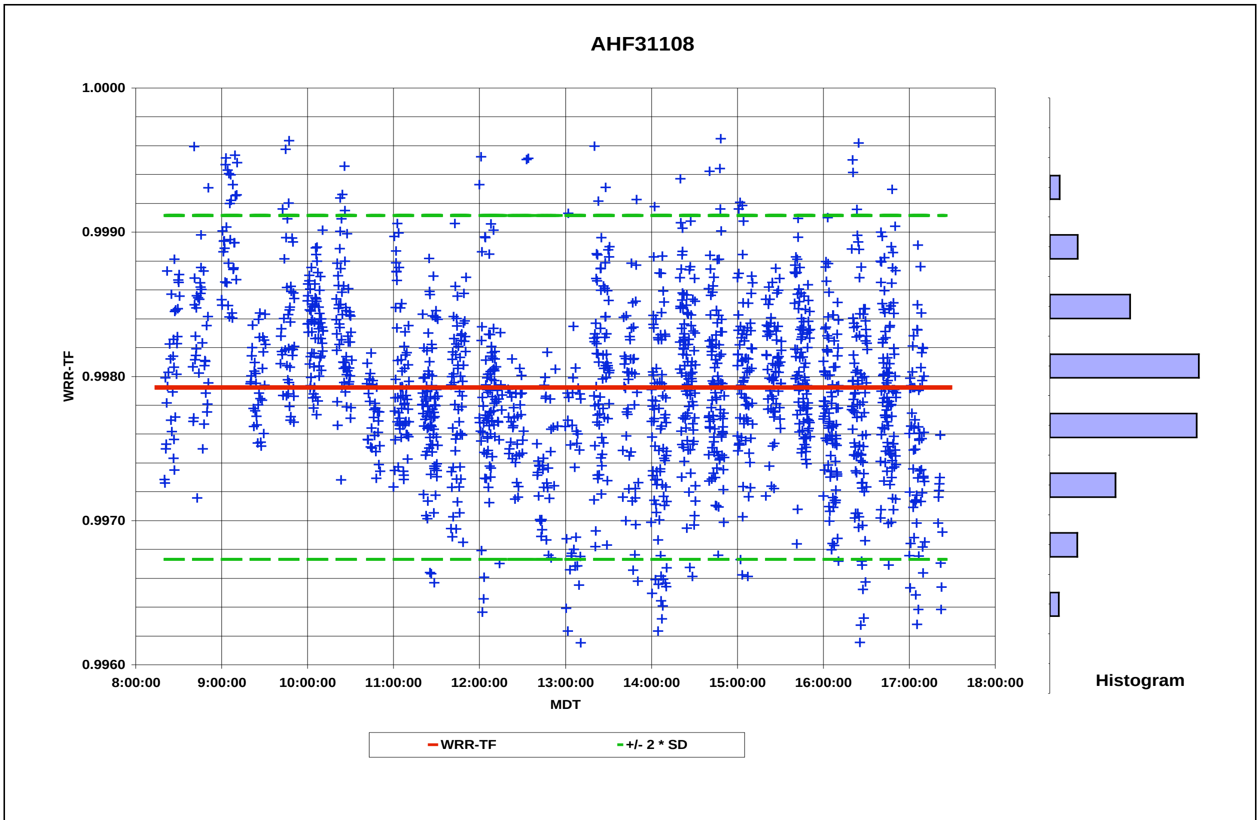


Figure 4.5.11 WRR Transfer Factor vs. Mountain Daylight Time for AHF31108 at NPC2001

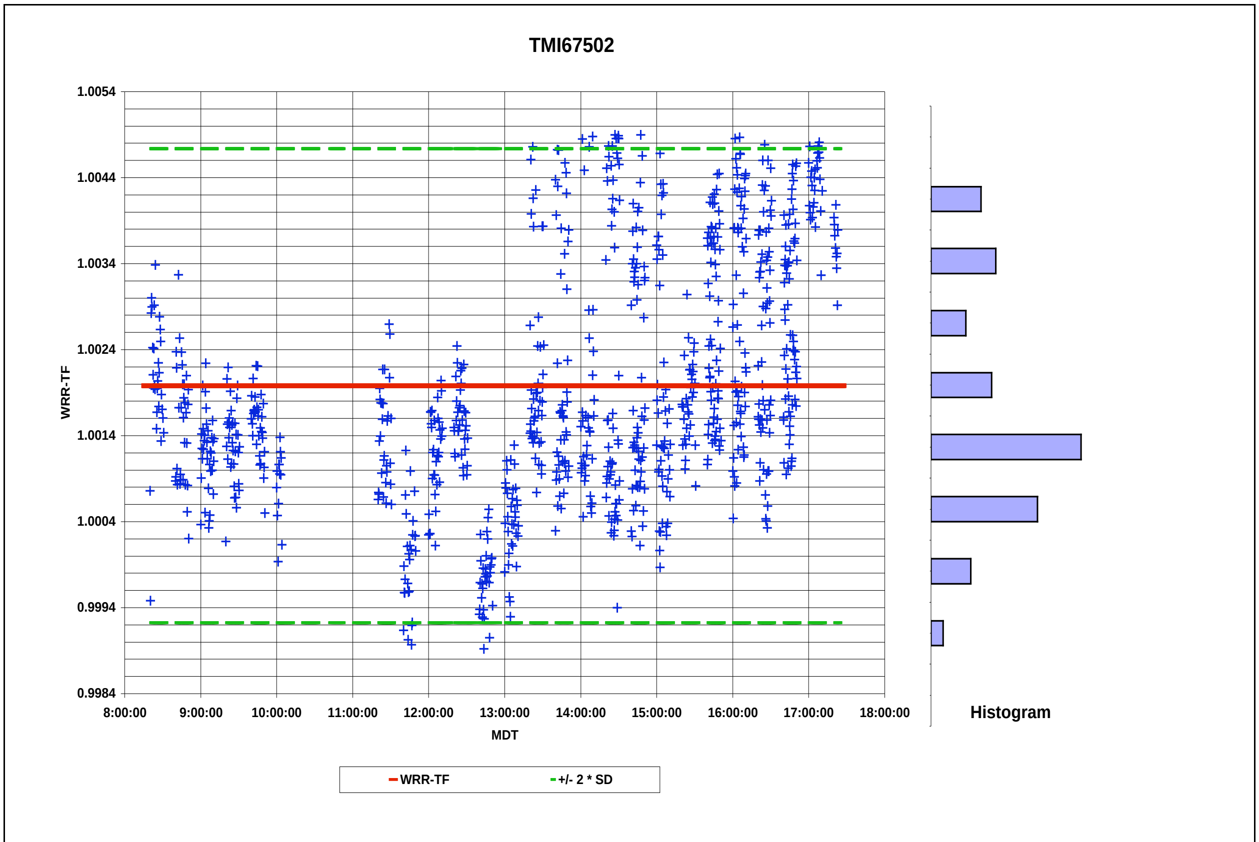


Figure 4.5.12 WRR Transfer Factor vs. Mountain Daylight Time for TMI67502 at NPC2001

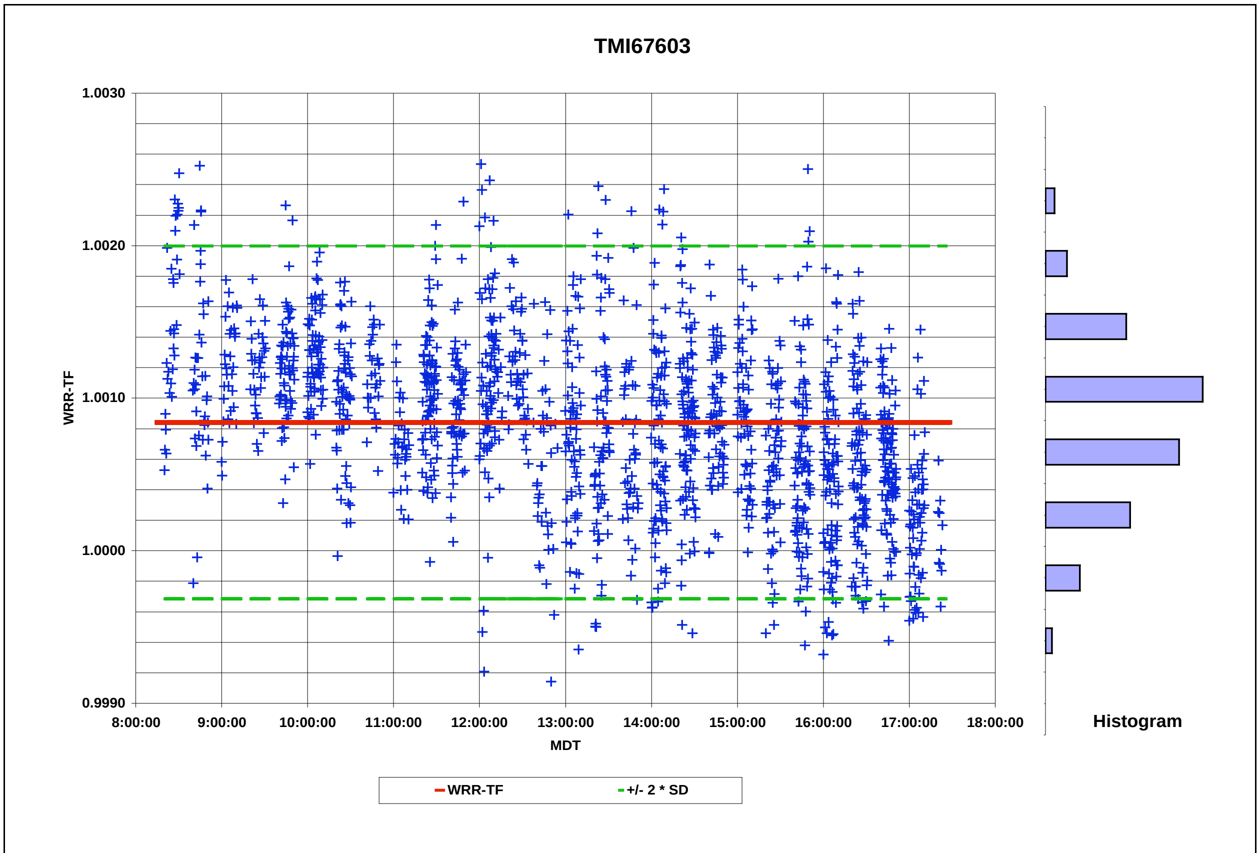


Figure 4.5.13 WRR Transfer Factor vs. Mountain Daylight Time for TMI67603 at NPC2001

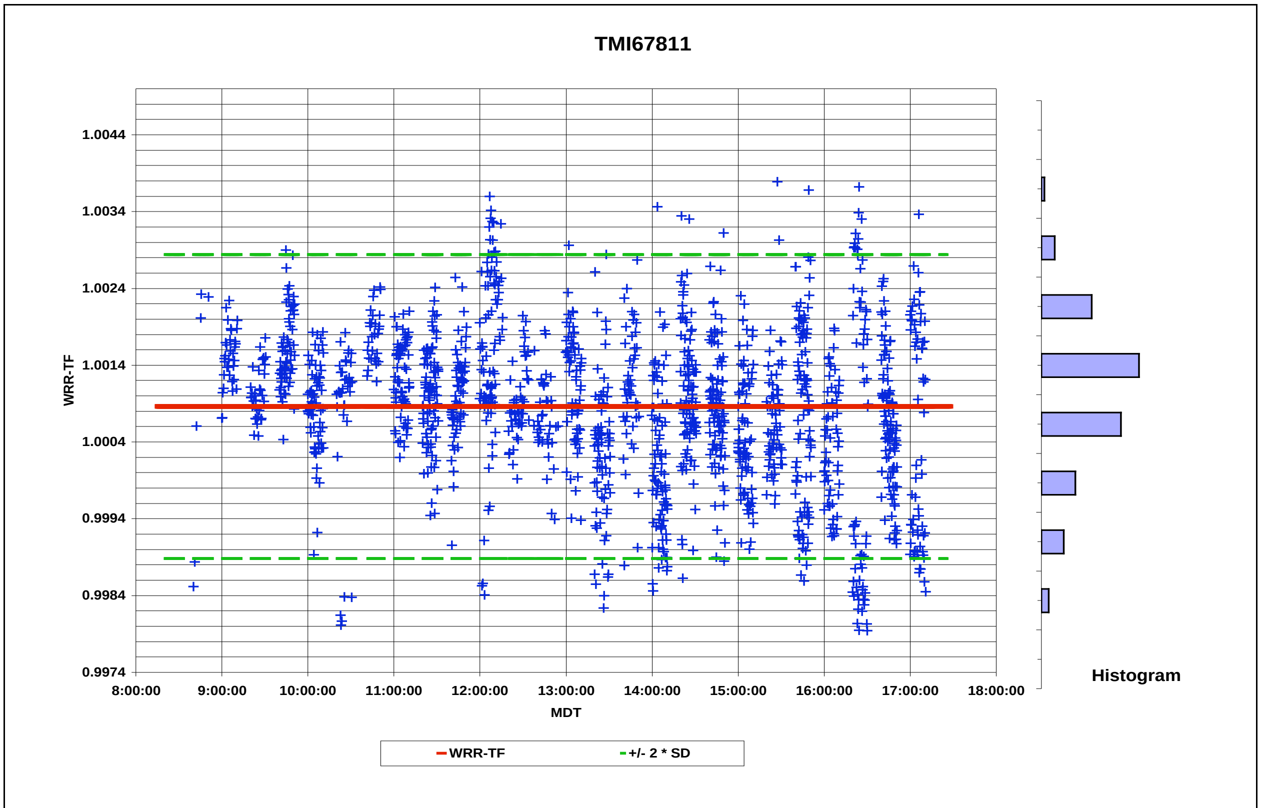


Figure 4.5.14 WRR Transfer Factor vs. Mountain Daylight Time for TMI67811 at NPC2001

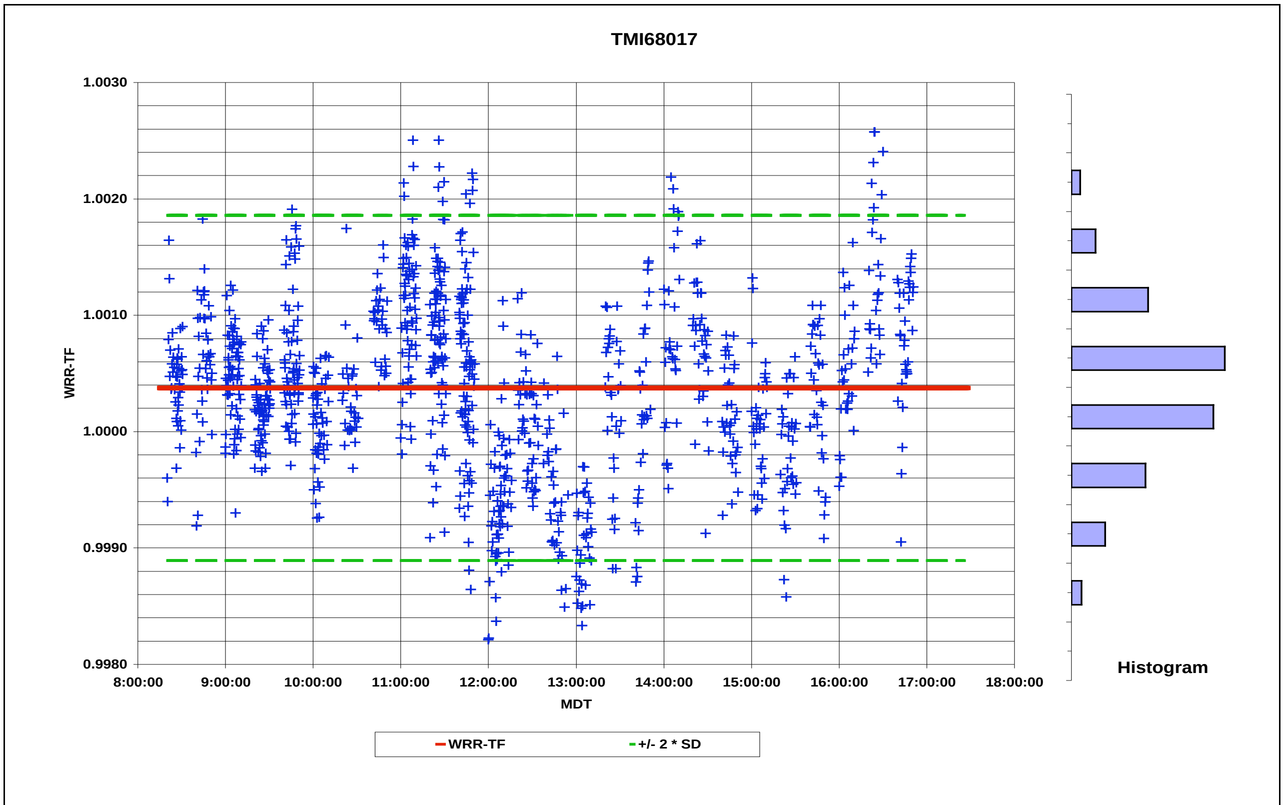


Figure 4.5.15 WRR Transfer Factor vs. Mountain Daylight Time for TMI68017 at NPC2001

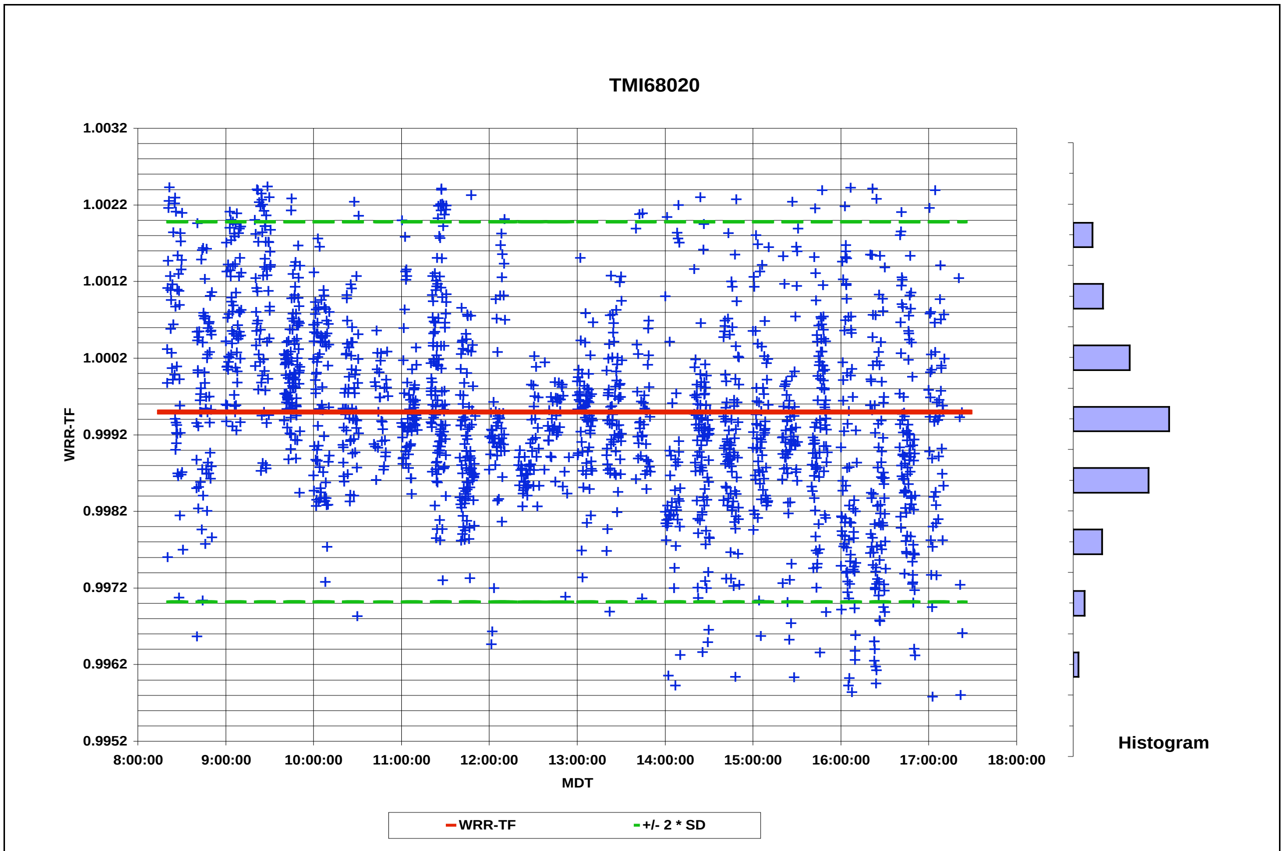


Figure 4.5.16 WRR Transfer Factor vs. Mountain Daylight Time for TMI68020 at NPC2001

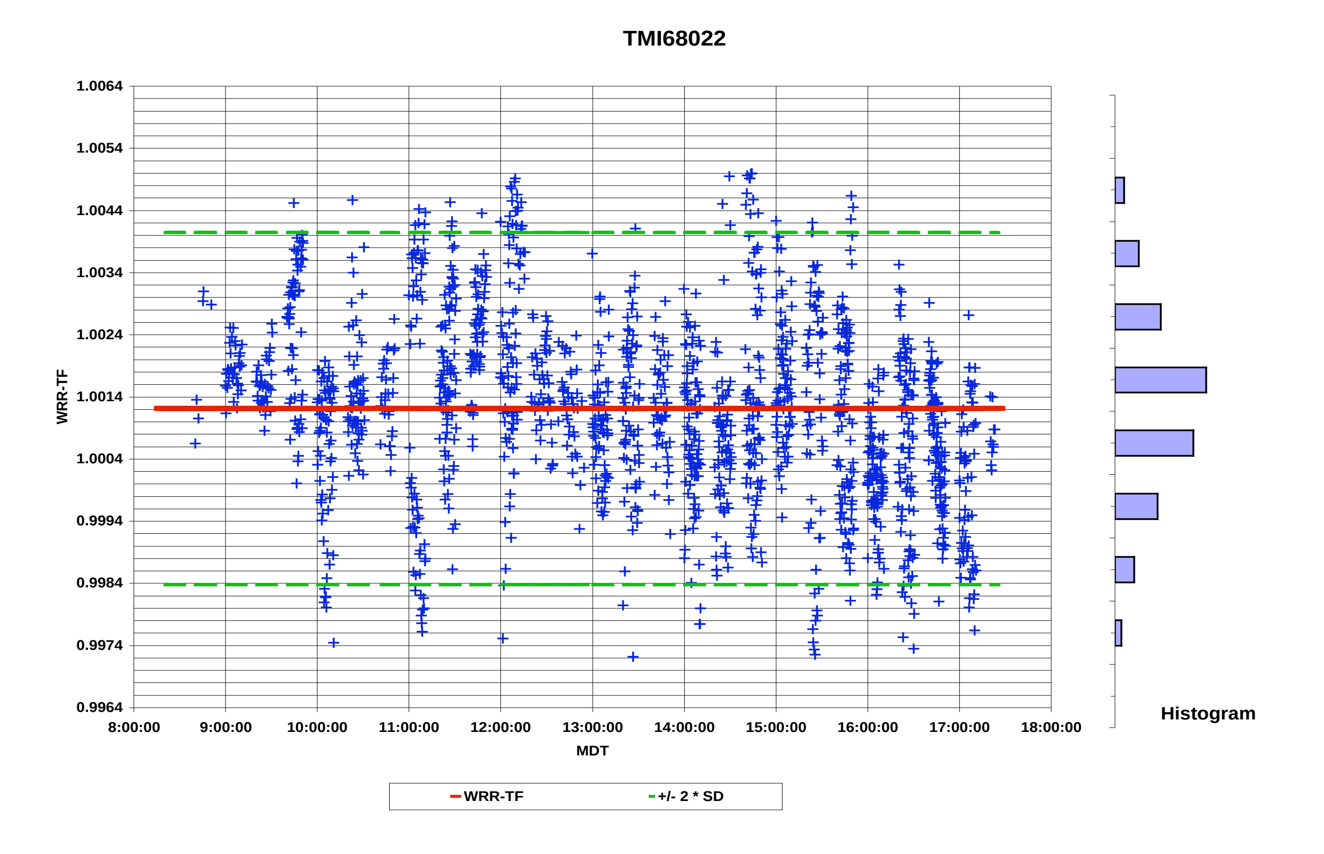


Figure 4.5.17 WRR Transfer Factor vs. Mountain Daylight Time for TMI68022 at NPC2001

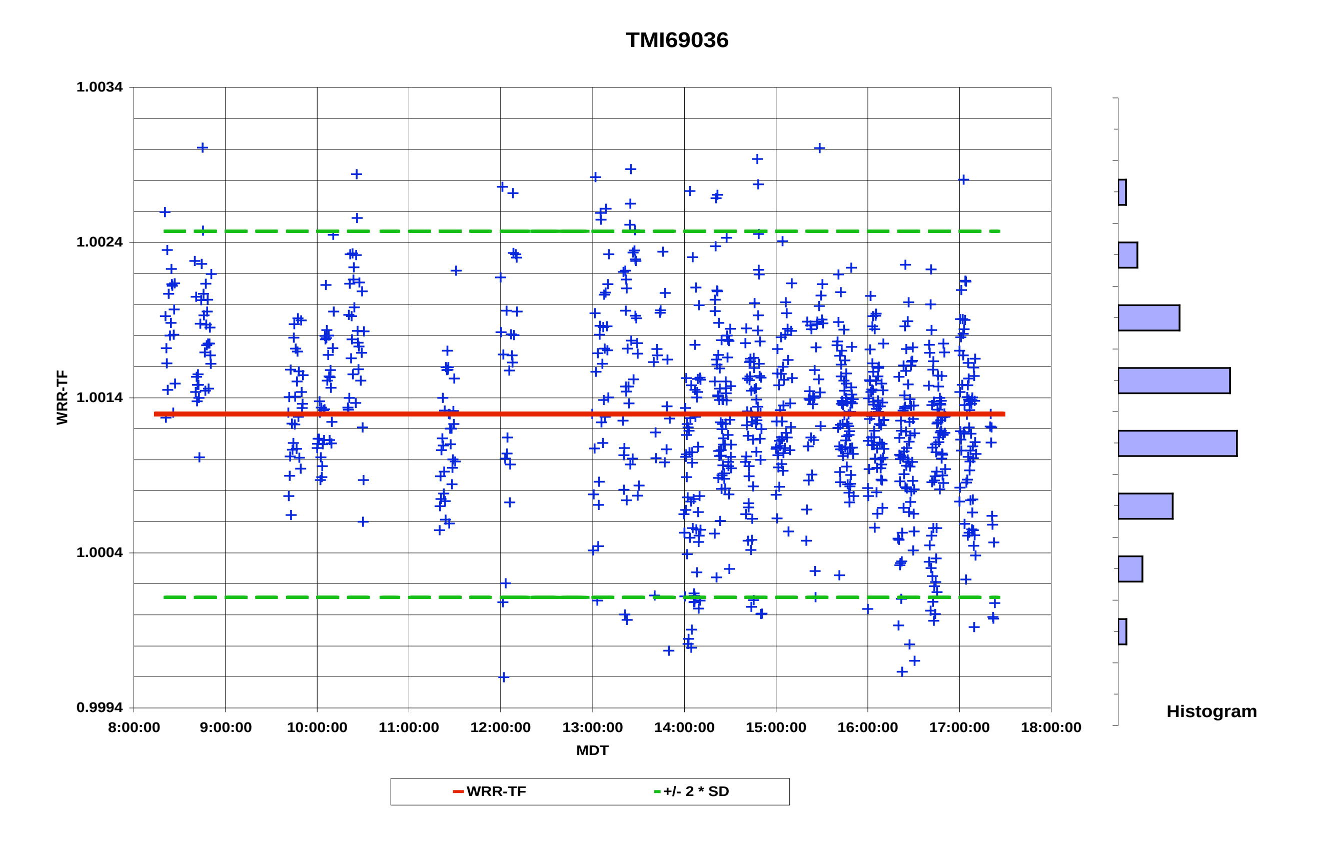


Figure 4.5.18 WRR Transfer Factor vs. Mountain Daylight Time for TMI69036 at NPC2001

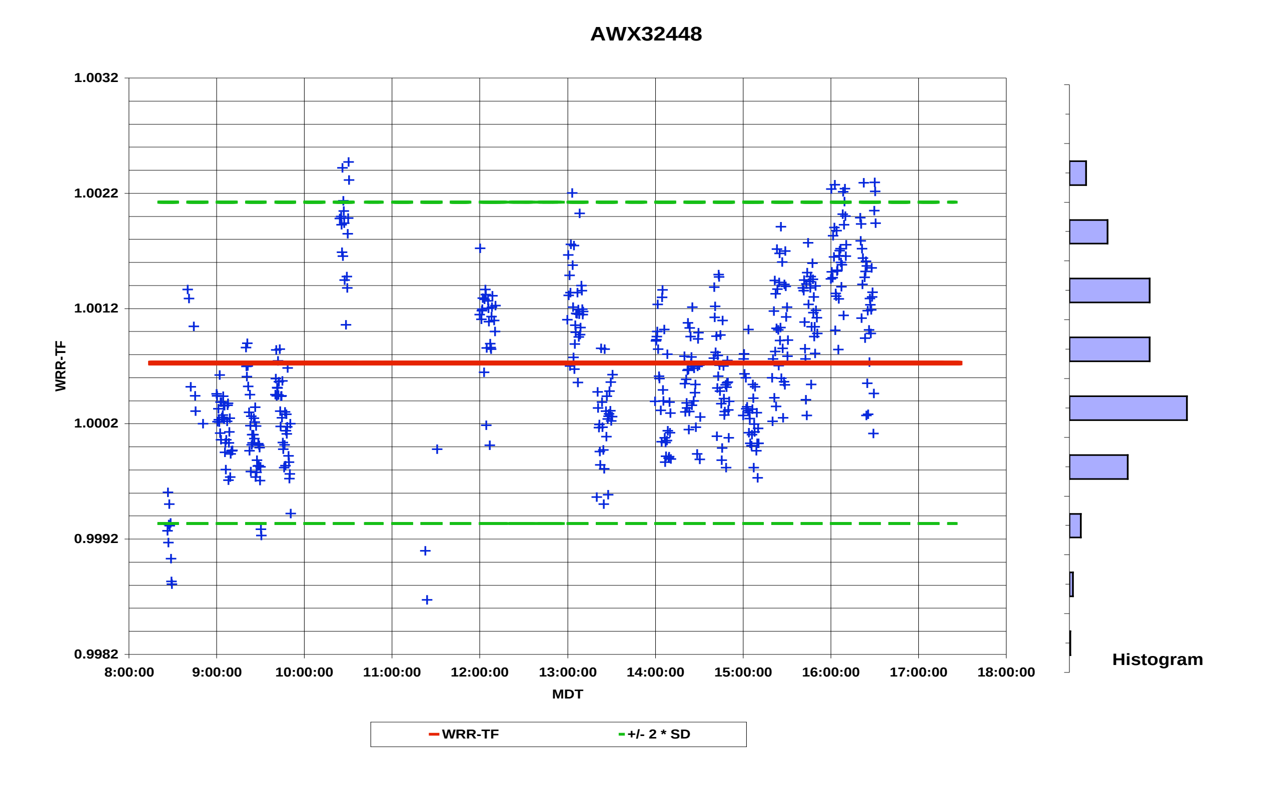


Figure 4.5.19 WRR Transfer Factor vs. Mountain Daylight Time for AWX32448 at NPC2001

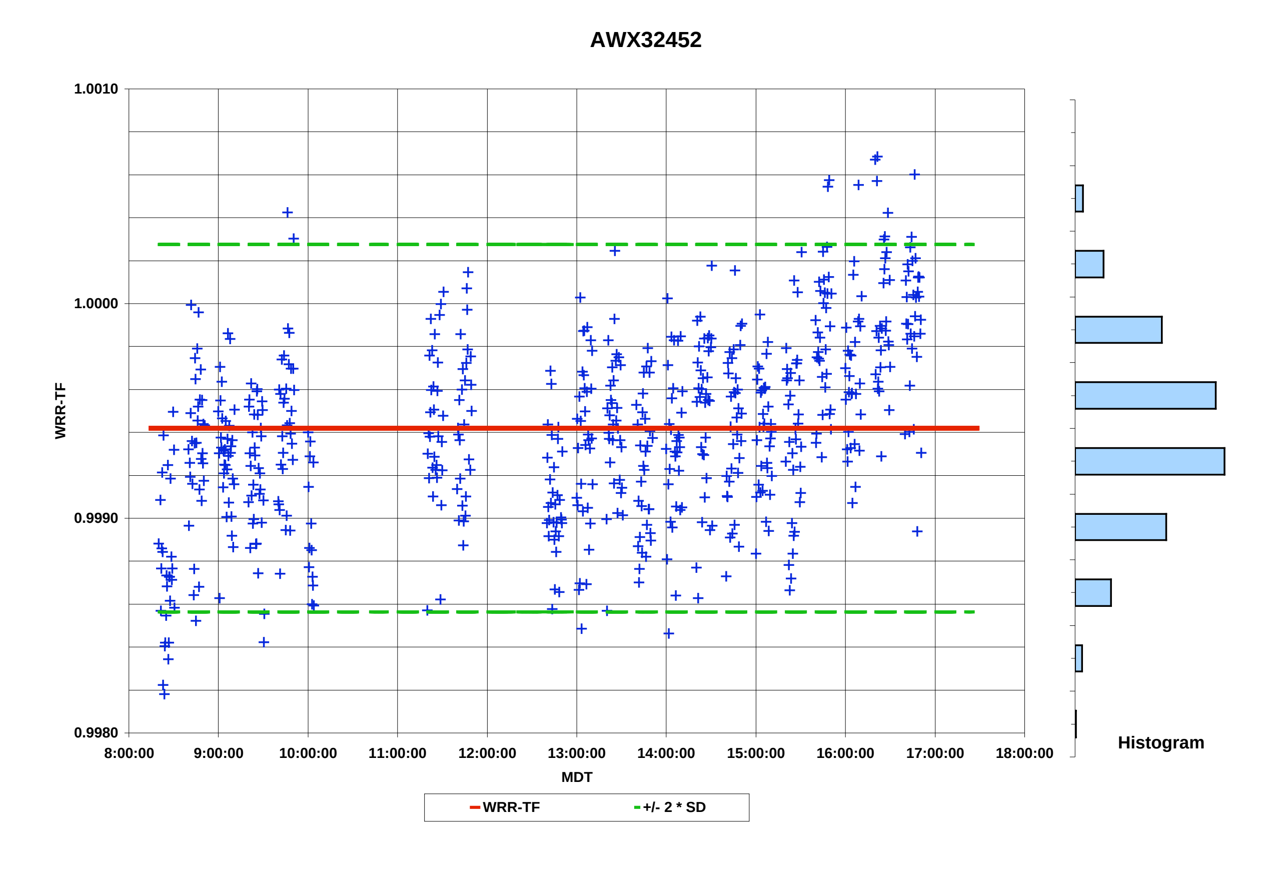


Figure 4.5.20 WRR Transfer Factor vs. Mountain Daylight Time for AWX32452 at NPC2001

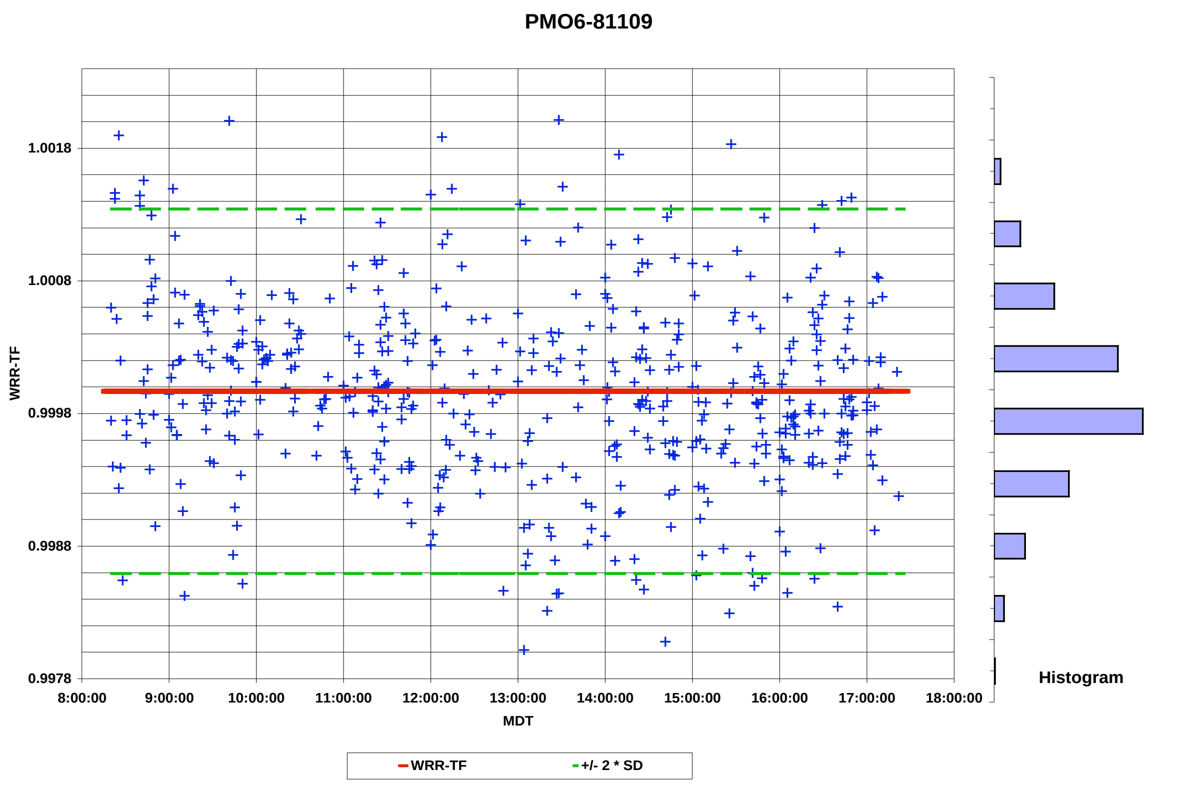


Figure 4.5.21 WRR Transfer Factor vs. Mountain Daylight Time for PMO6 81109 at NPC2001

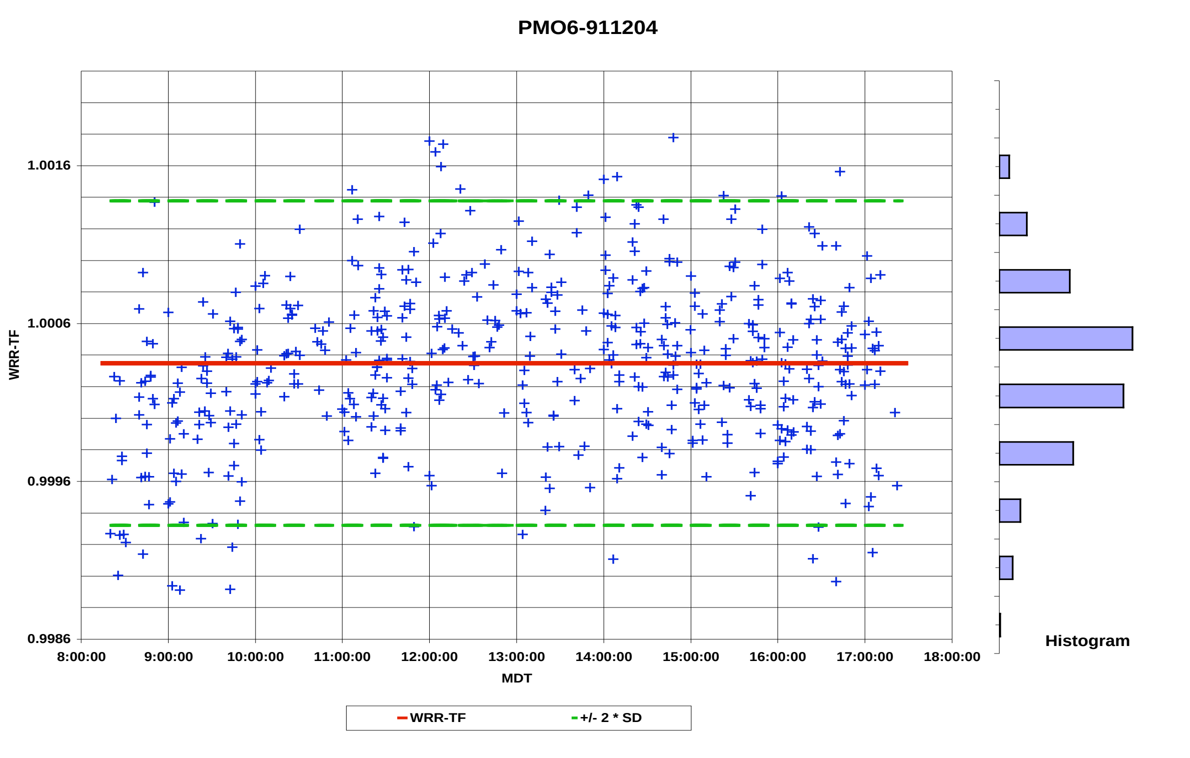


Figure 4.5.22 WRR Transfer Factor vs. Mountain Daylight Time for PMO6 911204 at NPC2001

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 NPC2001, 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^{-2}) 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. Determining the Window Correction Factor

After securing adequate data for the transfer of WRR to all participants, we collected additional irradiance measurements to compute the Window Correction Factor (WCF) for each of the four (4) participating radiometers listed in Table 5.1. Three unwindowed reference cavity radiometers that have direct WRR traceability were used to determine the reference irradiance.

5.1 Background

Absolute cavity radiometers can be fitted with protective windows for all-weather operation. Windowed cavity radiometers are candidate instruments for meeting WMO specifications for its Baseline Surface Radiation Network operations. A correction factor is needed to account for the changes in the thermodynamics of the radiometer and the window transmittance, reflectance, and scattering properties.

Table 5.1 Absolute Cavities Fitted With Windows

No.	Serial No.	Owner / Application
1	AWX 32452[1]	NREL Metrology Laboratory / All-Weather Reference
2	AWX 32448[1]	NOAA Climate Monitoring and Diagnostics Laboratory / Program Reference
3	AHF 30710[2]	NOAA Solar Radiation Research Branch / Program Reference
4	AHF 29222[1]	DOE ARM Southern Great Plains / All-Weather Reference

NOTES:
[1] Calcium Fluoride Window Installed
[2] Corning 7940 Window Installed [Suprasil-W Windows not used in NPC-2001]

5.2 Measurements

A data set of several hundred to a few thousand observations, depending on the radiometer, was used to determine the window correction factor (WCF) for each of the four participating windowed cavity radiometers. For consistency, the window mounting orientation was marked (0˚) for these measurements.

5.3 Results

Using the same analysis technique that was used for determining the WRR Transfer Factors for the participating absolute cavity radiometers, the WCFs were computed for the windowed cavity radiometers. The resulting WRR Transfer Factors for the participating windowed cavity radiometers are presented in Table 5.3.1. Time-series plots of the measurements can be found in Figures 5.3.1 – 5.3.4.

Table 5.3.1 Windowed Cavity Results

Serial Number	Window Factor NPC2001	Std Dev (%)	Number of Readings	%U95	
				w.r.t. WRR	w.r.t. SI
AWX32452	1.03520	0.09188	1349	0.22	0.37
AWX32448	1.06053	0.06384	664	0.17	0.34
AHF 30710	1.07074	0.05765	228	0.16	0.34
AHF 29222	1.06041	0.09186	2003	0.22	0.37

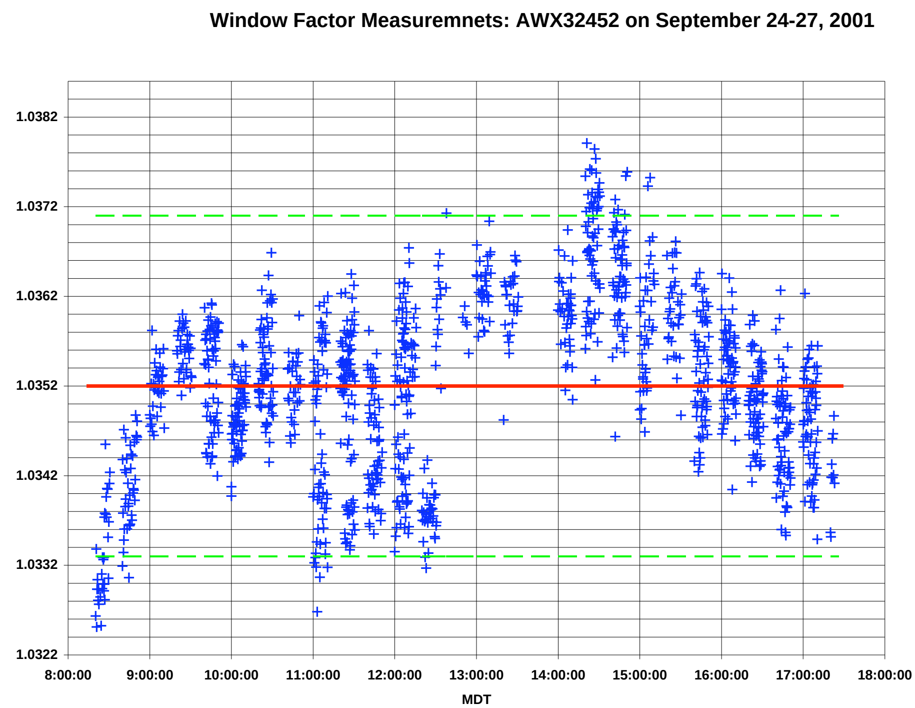


Figure 5.3.1. Window Factor data from All-Weather AWX32452 during NPC2001.

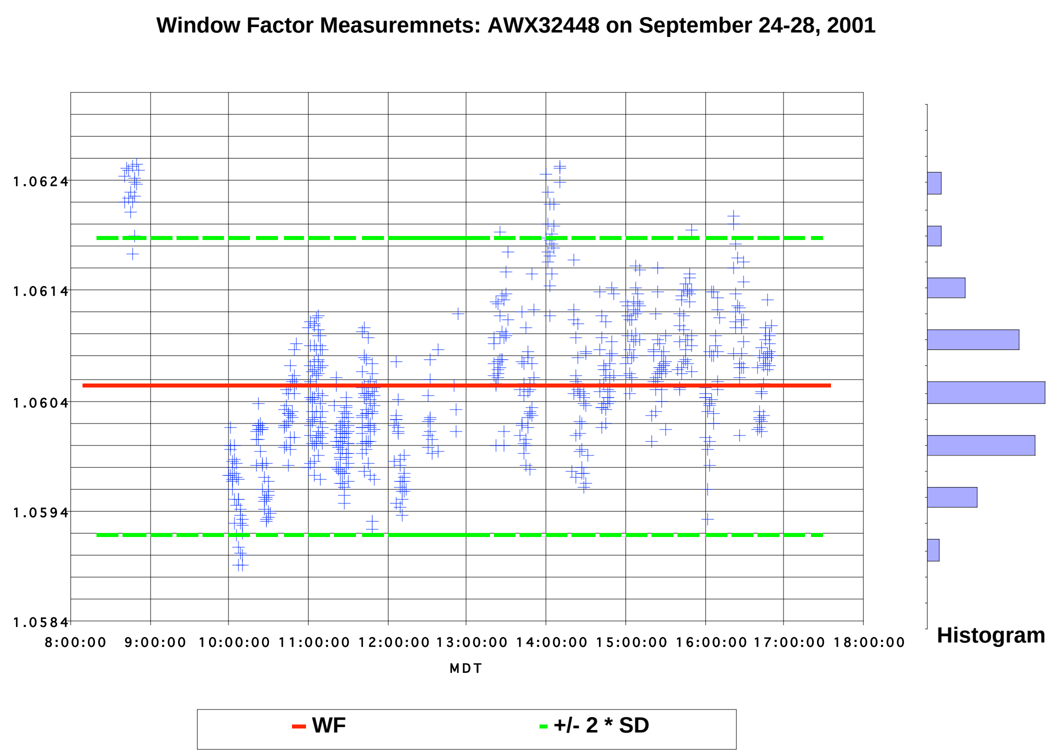


Figure 5.3.2. Window Factor data from All-Weather AWX32448 during NPC2001.

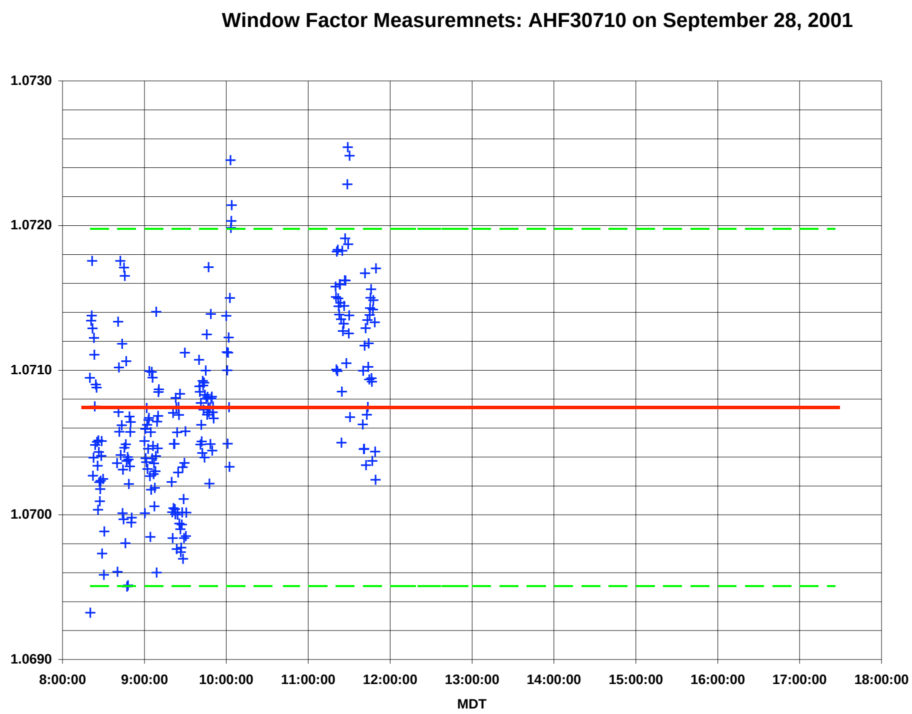


Figure 5.3.3. Window Factor data from AHF30710 during NPC2001.

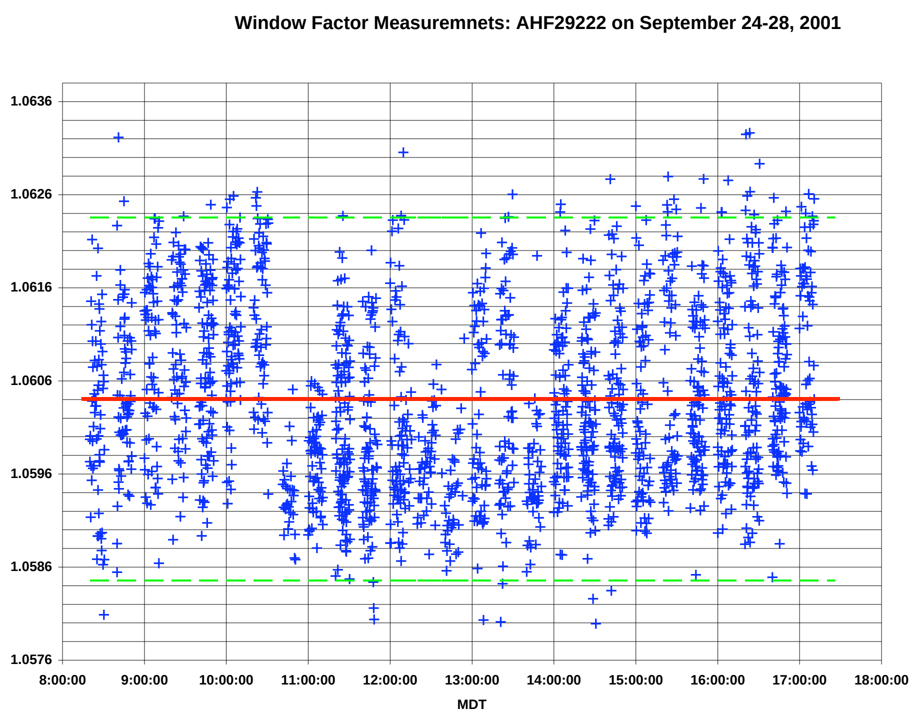


Figure 5.3.4. Window Factor data from AHF29222 during NPC2001.

5.4 Recommendations

- The WRR Transfer Factor must not be used when operating a windowed cavity radiometer. Traceability to the WRR is maintained by using *only* the Window Correction Factor (WCF).
- Always mount the window in the same orientation used during the transfer of WCF. This recommendation is based on a very limited data set to evaluate the possible sun light polarization due to the window.
- Always mount the same window on the same cavity radiometer that was used to determine the WCF.

Based on our very limited data sets for determining the WCFs, further window characterization is needed to evaluate the spectral dependency(s) and orientation with respect to the receiving cavity.

6. Ancillary Data

Air Temperature, relative humidity and barometric pressure and other surface meteorological parameters were measured during this NPC. Additionally, continuous measurements of direct normal, diffuse horizontal, and global irradiances are available from the SRRL Baseline Measurement System (BMS) as 1-minute averages of 3-second samples. These and other data including graphical summaries, can be found at the Measurement and Instrumentation Data Center:

http://www.nrel.gov/midc/srrl_bms.

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

7. 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.

8. Images

Digital images taken during NPC-2001 are available from the SRRL web site:

http://www.nrel.gov/srrl/npc2001

Appendix A: List of Participants and Radiometer Inventory
NREL Pyrheliometer Comparisons (NPC2001)

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PMO6-81109
PMO6-911204

NIP-25738E6 <control
CH1-930018 <control

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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)
Steve Wilcox	Computer Issues, Trackers, Cavity Operations

NREL Pyrheliometer Comparisons (NPC-2001)

List of Absolute Cavities

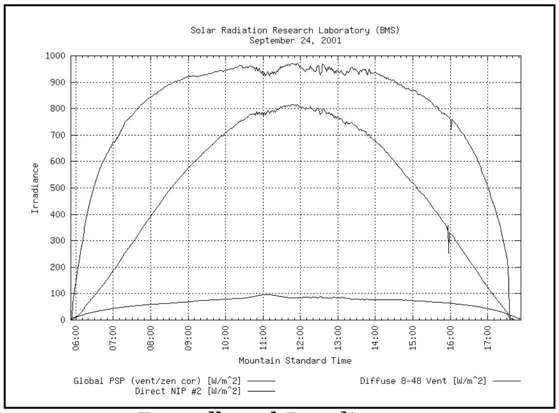
No.	Serial No.	Owner / Application
1	AHF 17142	Atlas Weathering Services-DSET Labs / Reference Standard
2	AHF 23734	NREL / Photovoltaics Program Reference
3	AHF 28553	NOAA Climate Monitoring & Diagnostics Laboratory (CMDL) / Reference
4	AHF 28964	U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program / Southern Great Plains Site Reference
5	AHF 28968	DOE ARM/ Program Reference
6	AHF 29220	NREL / Metrology Lab Reference Standard #2
7	AHF 29222	DOE ARM-Southern Great Plains / All-Weather
8	AHF 30494	DOE ARM-Tropical Western Pacific Site Reference
9	AHF 30495	DOE ARM-Southern Great Plains Working Standard
10	AHF 30710	NOAA / Surface Radiation Research Branch Reference
11	AHF 30713	NREL / Metrology Lab Working Standard #1
12	AHF 31041	NASA Clouds and the Earth's Radiant Energy System (CERES) / Reference 1
13	AHF 31104	NREL / Metrology Lab Working Standard #2
14	AHF 31105	NASA Clouds and the Earth's Radiant Energy System (CERES) / Reference 2
15	AHF 31108	Sandia National Labs / PV Reference Standard
16	AWX 32448	NOAA / CMDL All-Weather Standard
17	AWX 32452	NREL / All-Weather Standard
18	HF 21182	Florida Solar Energy Center / Reference Standard
19	PMO6-81109	European Commission Directorate General / Reference Standard
20	PMO6-911204	European Commission Directorate General / Reference Standard
21	TMI 67502	NOAA CMDL / Reference Standard
22	TMI 67603	Sandia National Labs / Reference Standard
23	TMI 67811	Sandia National Labs / Reference Standard
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 Labs / Reference Standard
27	TMI 69036	NREL Metrology Lab / BORCAL Working Standard #3
28	TMI 68020	Lockheed-Martin Technical Services / Reference Standard

Appendix B: Ancillary Data Summaries

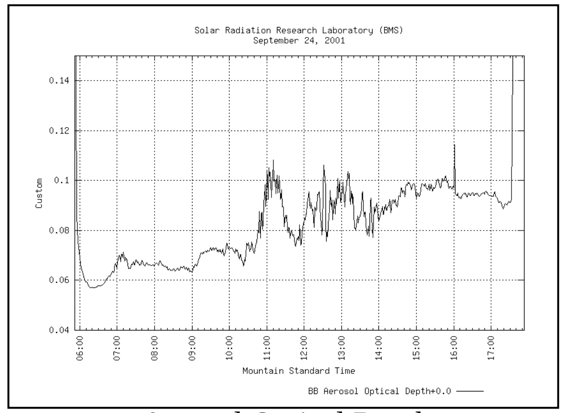
The measurement performance of an absolute cavity can be affected by several environmental parameters. Potentially relevant meteorological data collected during the NPC are presented in this appendix. The Baseline Measurement System (BMS) has been in continuous operation at the Solar Radiation Research 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.

Time-series plots and other graphical presentations of these data acquired during the NPC-2001 measurements are presented here.

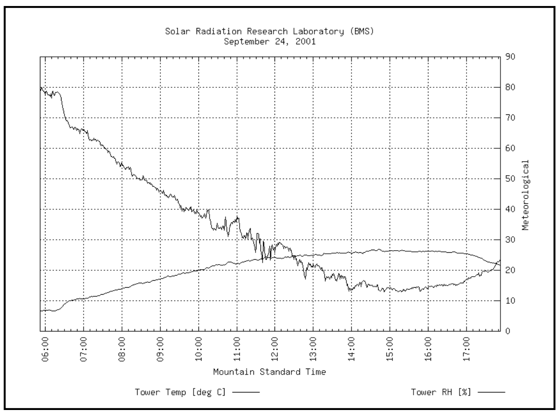
Baseline Measurement System Data for September 24, 2001



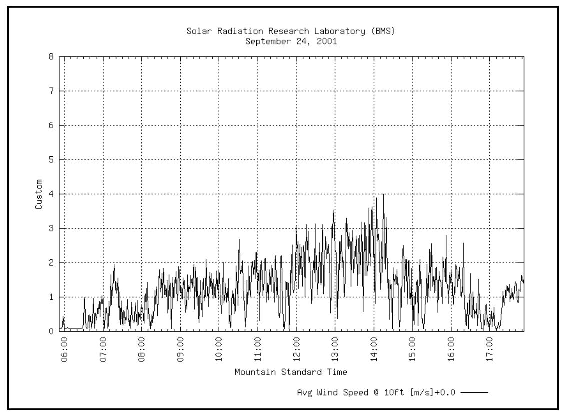
Broadband Irradiance



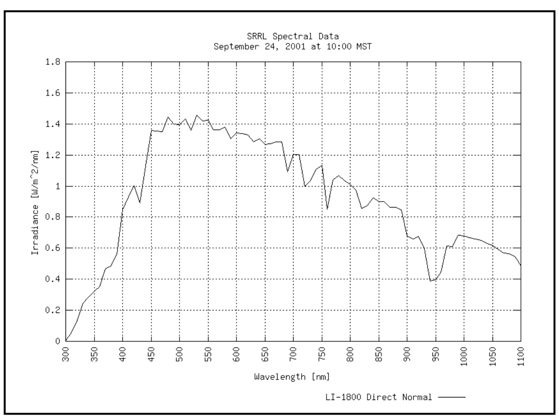
Aerosol Optical Depth



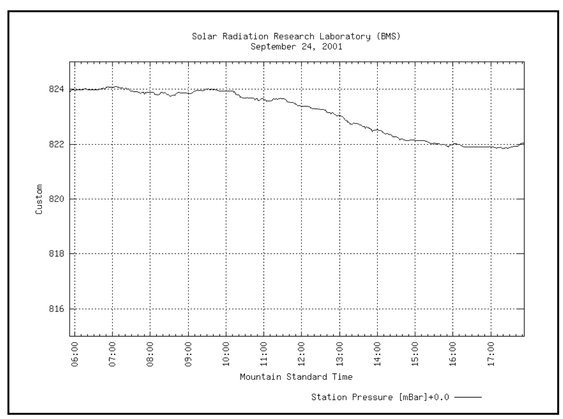
Temperature & Relative Humidity



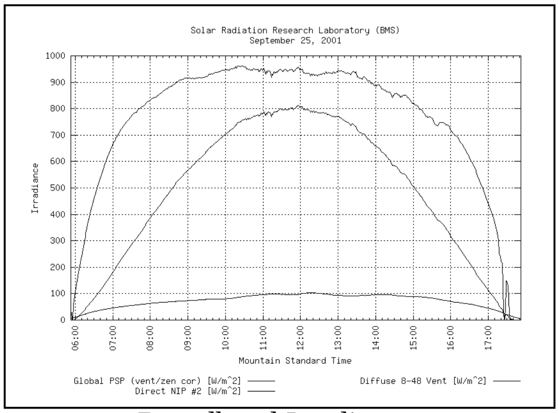
Wind Speed at 10 m AGL



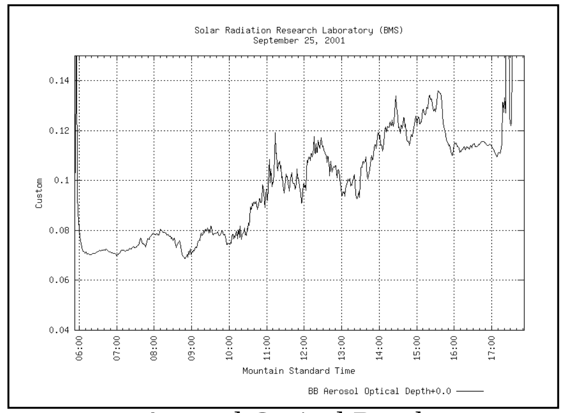
Direct Normal Spectra



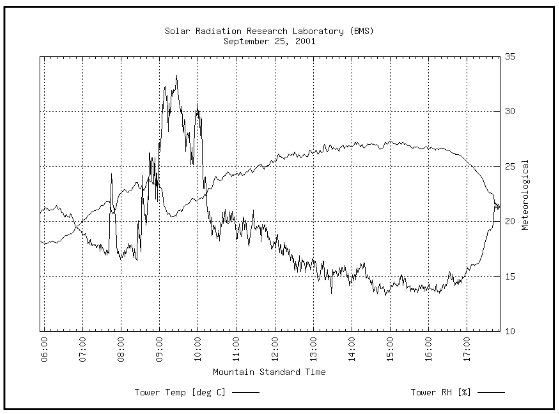
Station Pressure



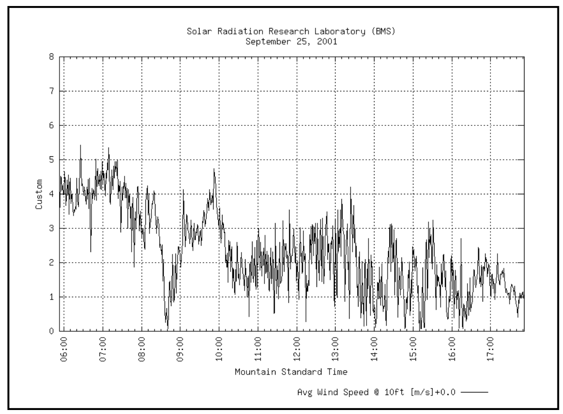
Broadband Irradiance



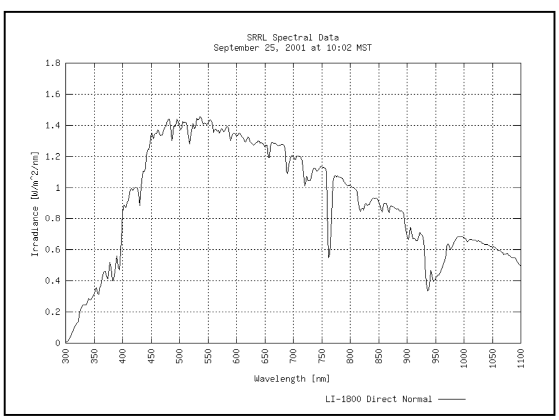
Aerosol Optical Depth



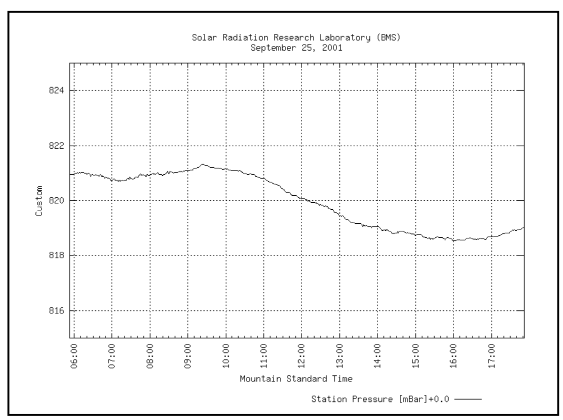
Temperature & Relative Humidity



Wind Speed at 10 m AGL

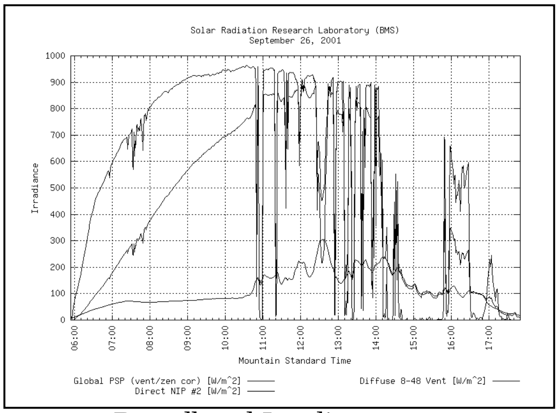


Direct Normal Spectra

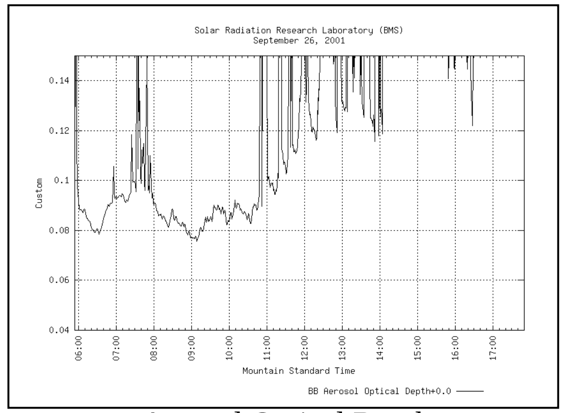


Station Pressure

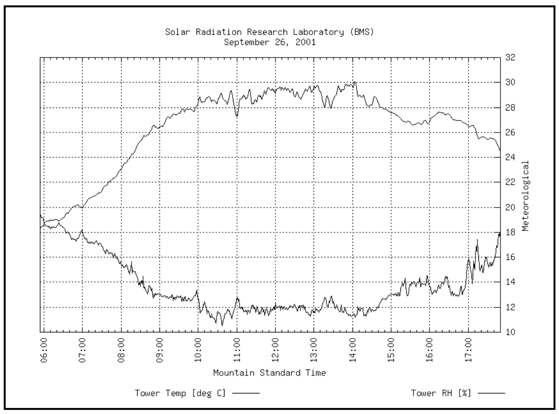
Baseline Measurement System Data for September 26, 2001



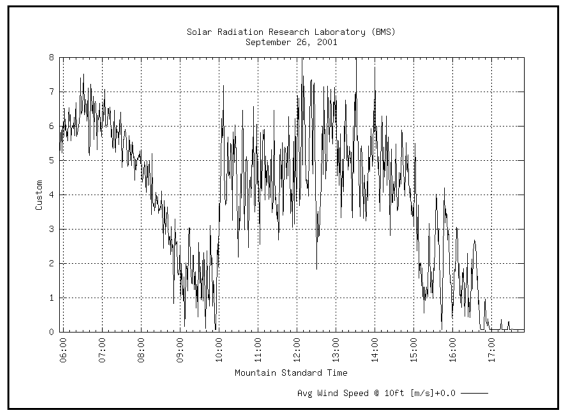
Broadband Irradiance



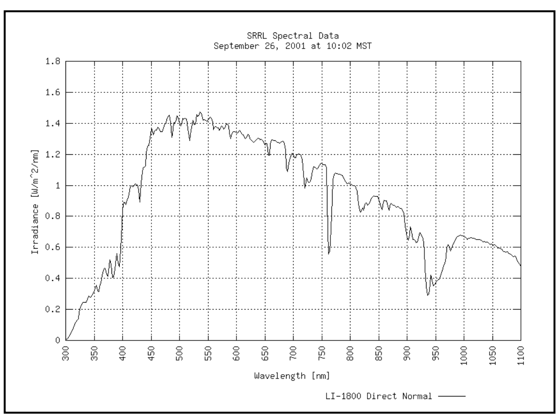
Aerosol Optical Depth



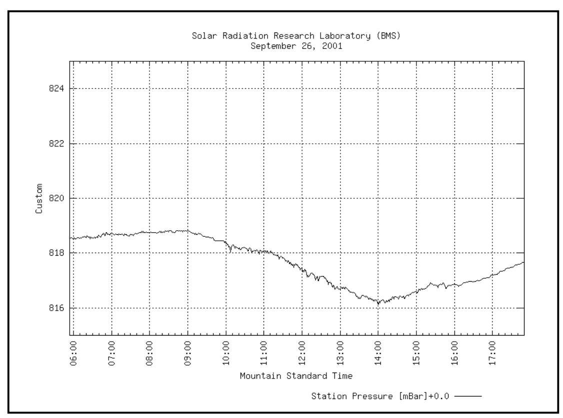
Temperature & Relative Humidity



Wind Speed at 10 m AGL

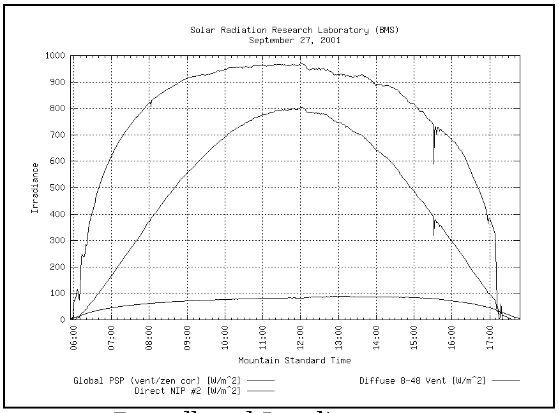


Direct Normal Spectra

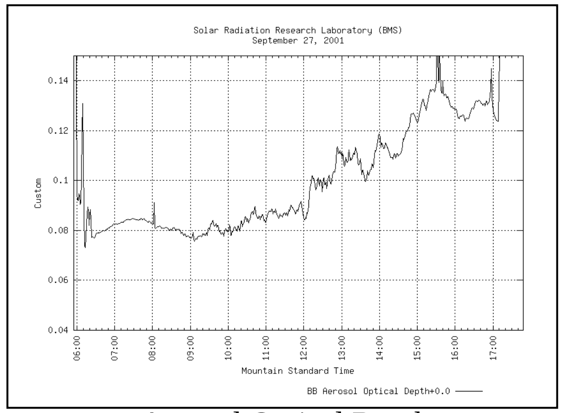


Station Pressure

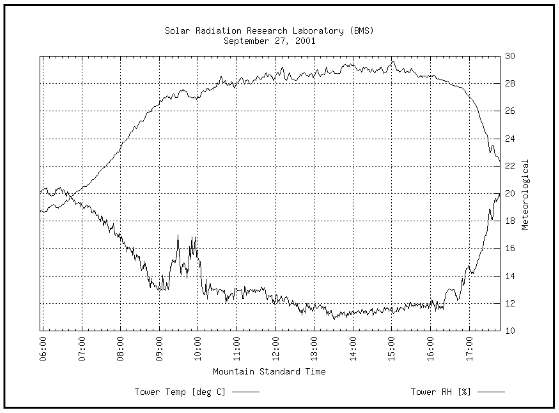
Baseline Measurement System Data for September 27, 2001



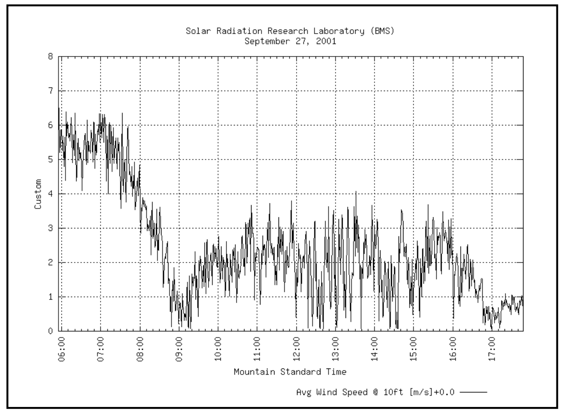
Broadband Irradiance



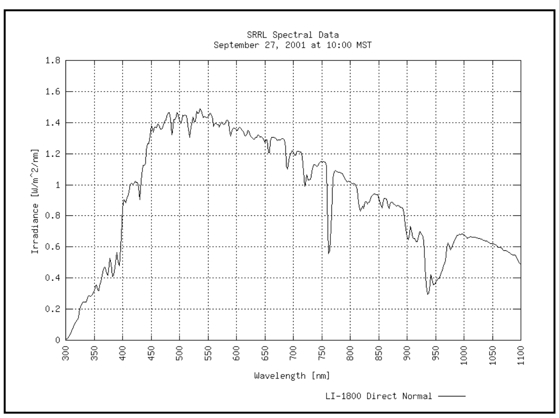
Aerosol Optical Depth



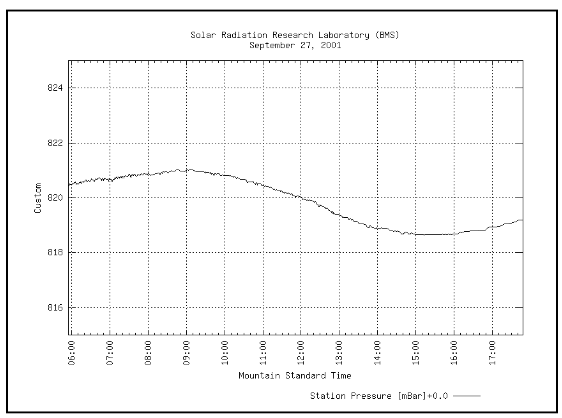
Temperature & Relative Humidity



Wind Speed at 10 m AGL

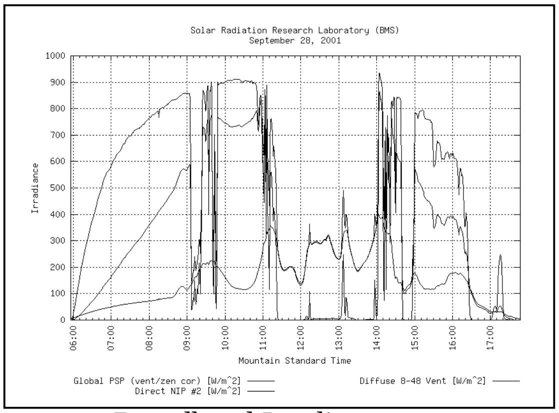


Direct Normal Spectra

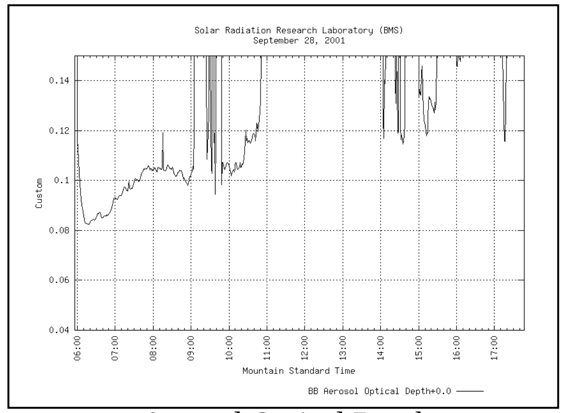


Station Pressure

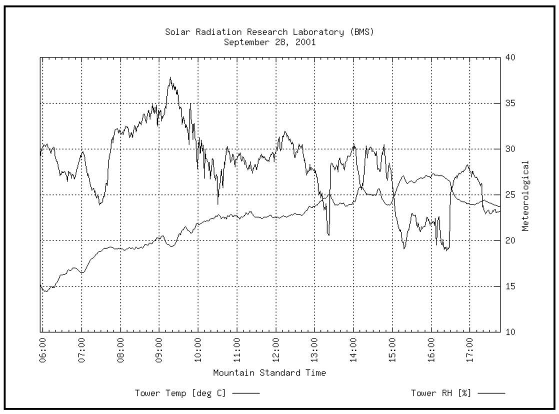
Baseline Measurement System Data for September 28, 2001



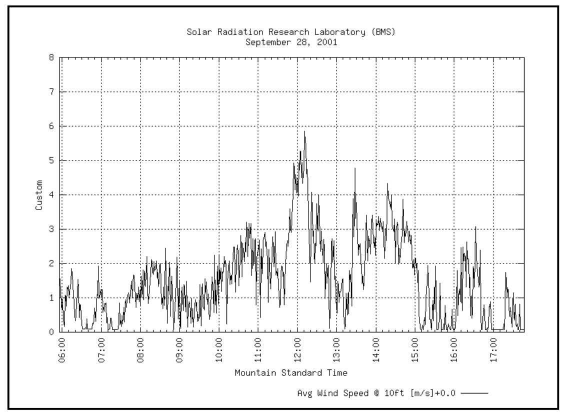
Broadband Irradiance



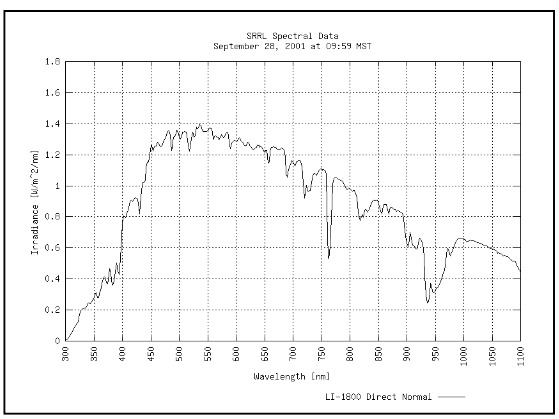
Aerosol Optical Depth



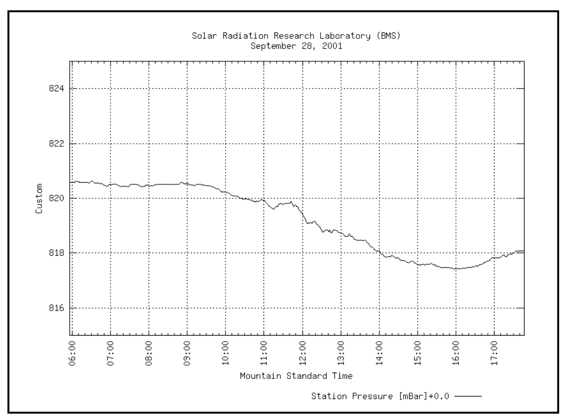
Temperature & Relative Humidity



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.

2001 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 *NPC2001* (NREL Pyrheliometer Comparisons 2001).

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 24th :

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 25th - October 5 (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 25th - October 5 (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:

Calibrate	=	Perform electrical calibration and wait for next measurement period to begin
Reading	=	A measurement of direct irradiance within 1 sec of announcement at 20-sec intervals.
Run	=	Collection of 33 readings taken in sequence.
Shade & Calibrate	=	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!
-T + 20 sec - READ! [Repeat for a total of 33 readings = "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
NPC2001 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!>