Results
Of

NREL Pyrheliometer Comparisons
(NPC1999)

October 4-10, 1999

By

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NOTICE

NPC 1999 Participants

From left to right:

Back Row – Bruce McArthur, Fred Denn, Wynn Christensen, Hamad Al-Fares, Zaid Al-Otaibi, Jim Treadwell, Don Nelson, John Hickey, Craig Webb

Front Row – Steve Wilcox, Tom Stoffel, Wim Zaaiman, Dan Nelson, Herizal, Edmund Wu, Ibrahim Reda

(Not shown: Chris Cornwall & Gary Hodges,)

Acknowledgements

We sincerely appreciate the support of Cecile Warner, our Center Director, for helping us host these comparisons. Our thanks to Beverly Kay for her timely administrative help and to Afshin Andreas for providing the SRRL/BMS data graphics. We are also grateful to Daryl Myers, Dave Renne, and Stan Bull for the financial support from the NREL Photovoltaics Program, the DOE Atmospheric Radiation Measurement Program, and NREL's Metrology Laboratory Technical Overhead. John Hickey from The Eppley Laboratory, Inc., Don Nelson from NOAA's Climate Monitoring & Diagnostics Laboratory, Chris Cornwall and Gary Hodges from NOAA's Solar Radiation Research Branch, and Jerry Maybee and Gene Zerlaut from ATLAS/DSET provided reference radiometers greatly strengthening our ability to transfer the World Radiometric Reference to the participating radiometers. Our thanks also to all the participants for their patience and cooperation during this weather-dependent exercise.

This work was accomplished under NREL subtasks PV907401 and WU865600.

NPC1999 at the NREL Solar Radiation Research Laboratory (SRRL)

West View

(Participants are working under the awnings)

East View

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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.

NPC1999 was conducted at NREL's Solar Radiation Research Laboratory (SRRL) from October 4 through October 10, 1999. Nineteen participants operated 25 absolute cavity radiometers to simultaneously measure the clear-sky direct normal solar irradiance during this period. More than 1,500 observations were collected during the comparison. The NPC1999 Transfer Standard Group (TSG) consists of six radiometers having direct traceability to the WRR. The TSG was used to determine the reference irradiance for each 20-second observation in the comparisons. Participating radiometers were assigned a new WRR Reduction Factor computed by comparing the measured irradiances with the corresponding reference irradiance values.

The comparison protocol is based on data collection periods, or “runs.” Each run consists of a six-minute electrical self-calibration, a series of 31 solar irradiance measurements at 20-second intervals, and a post-calibration. A total of 66 runs were accomplished in NPC1999 providing more than 2,000 irradiance measurements for each participating radiometer. Clear-sky direct normal irradiance levels ranged from less than 700 Wm^{-2} to 1040 Wm^{-2}.

The performance of the TSG during NPC1999 was consistent with previous comparisons, including the latest IPC-VIII conducted in 1995. The measurement performance of the TSG allowed the transfer of the WRR to each participating radiometer with an uncertainty of ± 0.37% 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 WMO specifications for its Baseline Surface Radiation Network operations.

Building on our experiences at NPC1998 with a new control unit for absolute cavity radiometer TMI68017, we also evaluated the performance of similar control unit conversions for other selected NREL-owned radiometers. The new control units provided more stable pre- and post-comparison electrical self-calibrations.

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 international 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 (PMOD) in Switzerland. This standard of measurement is maintained for broadband shortwave solar irradiance, wavelength range of 280 nm to 3000 nm, with an absolute uncertainty of better than ± 0.3% with respect to the System International (SI) unit [Romero, et al, 1996]. 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 of the WRR Reduction Factors 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 1999 NREL Pyrheliometer Comparisons (NPC1999) were held from 4 to 10 October at the Solar Radiation Research Laboratory (SRRL). Twenty participants operated 25 absolute cavity radiometers during the comparisons (see Appendix 9.1 for detailed information). The following programs and organizations were represented at NPC1999:

- Analytical Services and Materials, Inc.
- Atlas Weathering Services, Inc. -DSET Laboratories
- Atmospheric Environment Service of Canada
- Atmospheric Radiation Measurement Program of the U.S. Department of Energy
- The Eppley Laboratory, Inc.
- European Commission Directorate General JRC
- Global Atmospheric Watch Program of the World Meteorological Organization
- King Abdulaziz City for Science and Technology
- Los Alamos National Laboratory
- NASA Langley Research Center, Atmospheric Sciences Division
- National Oceanic and Atmospheric Administration
    - -Climate Monitoring & Diagnostics Laboratory
    - -Solar Radiation Research Branch
- National Renewable Energy Laboratory
    - -Center for Renewable Energy Resources
    - -Metrology Laboratory
    - -Photovoltaic Research Program

In addition to computing the latest WRR Reduction 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. 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 three days during NPC1999. Equipment deployment and tests, technical presentations, and training sessions for selected participants occupied the remainder of the comparison event.

2. Reference Instruments

Six absolute cavity radiometers that participated in IPC VIII were used as the Transfer Standard Group (TSG) to maintain the WRR for this comparison. Table 2.1 is a list of the TSG with their WRR Reduction Factors and Pooled Standard Deviations [WRC/PMOD, 1996].

Table 2.1 IPC-VIII Results Summary for the NPC1999 TSG

Serial Number	WRR Reduction Factor (from IPC-VIII)	Standard Deviation	Number of Readings
HF14915	1.00046	0.118%	426
HF28553	0.99756	0.093%	409
HF28968	0.99827	0.095%	497
HF29220	0.99862	0.107%	401
HF30710	1.00007	0.106%	413
TM68018	0.99888	0.106%	483
Mean WRR for the TSG	0.99898	**Pooled Std Deviation for the TSG**	0.104%

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

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 31 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 Reduction 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 time keeper announces the beginning of calibration periods and gives a 6-minute count-down prior to the start of each Run.

By consensus, the goal was set to acquire at least 300 observations from each radiometer to determine the WRR Reduction Factor. Participants also agree 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 is to build a statistically significant data set from which to derive the individual WRR Reduction Factors.

Data from each radiometer/operator is collected at the end of the day using diskettes. Daily summaries are produced using a spreadsheet analysis tool. Results are distributed to the participants the following day.

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 NPC1999:

- 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

Six absolute cavity radiometers, that participated in IPC-VIII, were used as the TSG to transfer the WRR in the comparison. 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 NPC1999 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 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 reading. Stable irradiance readings are defined to be within 1.0 Wm-2 during an interval of three seconds, 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.

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].

4.4 Measurements

NPC1999 was scheduled for the period October 4-15, 1999. The comparisons were completed on October 10th after more than 2,000 data points were collected from 66 runs completed during three days with clear-sky conditions (8, 9, and 10 October). 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:

- The new (NPC1999) WRR Reduction Factors did not change by more than a fraction of the standard deviation derived during IPC-VIII in 1995.

- The standard deviations of the new WRR Reduction Factors are smaller than the standard deviation derived during IPC-VIII.

Table 4.5.1 NPC1999 Summary Results for the Reference Transfer Standard Group (TSG) Radiometers

Serial Number	WRR IPC-VIII	WRR NPC1999	SD% (1999)	No. Readings
28553	0.99756	0.99741	0*	1500
28968	0.99827	0.99883	0.08	1500
29220	0.99862	0.99867	0.08	1500
68018	0.99888	0.99842	0.07	1500
30710	1.00007	0.99978	0.08	1500
14915	1.00046	1.00074	0.08	1500
MEAN WRR	0.99898	0.99898		

*Radiometer Serial Number 28553 is the basis for pooled standard deviation calculations.

The WRR Reduction 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 Reduction Factor for each participating radiometer. Results are presented in Table 4.5.2.

Table 4.5.2 NPC1999 Results for Participating Radiometers

SN	WRR	SD	SD%	2SD%	N. RDGS	U95%	
						wrt WRR	wrt SI
HF 17142	0.99878	0.0006	0.06	0.11	1369	0.26	0.39
HF 23734	0.99855	0.0004	0.04	0.07	1469	0.24	0.39
AHF 28964	0.99835	0.0006	0.06	0.12	1298	0.26	0.4
AHF 29222	1.0008	0.0004	0.04	0.08	1454	0.24	0.39
AHF 29226	0.99948	0.0005	0.05	0.09	1478	0.25	0.39
AHF 29227	0.99991	0.0005	0.05	0.1	1428	0.25	0.39
AHF 30110	0.99692	0.0004	0.04	0.09	1363	0.25	0.39
AHF 30114	0.99821	0.0005	0.05	0.09	1410	0.25	0.39
AHF 30494	0.99826	0.0006	0.06	0.12	1425	0.26	0.4
AHF 30495	0.99838	0.0004	0.04	0.08	1459	0.24	0.39
AHF 30713	0.99871	0.0004	0.04	0.07	1474	0.24	0.39
AHF 31041	0.99827	0.0005	0.05	0.09	1387	0.25	0.39
AHF 31104	1.00025	0.0004	0.04	0.08	1330	0.25	0.39
TMI 68017	1.00021	0.0003	0.03	0.07	1476	0.24	0.38
AWX32448	1.00086	0.0004	0.04	0.09	774	0.25	0.39
PMO6 81109	0.99991	0.0007	0.07	0.15	476	0.27	0.41
PMO6 911204	1.0005	0.0005	0.05	0.11	525	0.26	0.39
HF 18747	1.00051	0.0018	0.18	0.37	1337	0.43	0.53
HF 20406	1.00217	0.0023	0.23	0.46	1357	0.52	0.6

The uncertainty of the WRR Reduction 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 Reduction Factor (in percent) determined at NPC1999 with 95% confidence level

0.104 = Pooled standard deviation of the six reference radiometers that participated in IPC-VIII

SD = One standard deviation of the WRR Reduction Factor (in percent) determined at NPC1999 for each participating cavity.

The uncertainty of the WRR Reduction 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 Reduction 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 Reduction Factors determined during NPC1999.

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 NPC1999, we recommend the user apply only the manufacturer's calibration factor (CF), not the WRR Reduction Factor nor 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 Reduction 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 31) 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).

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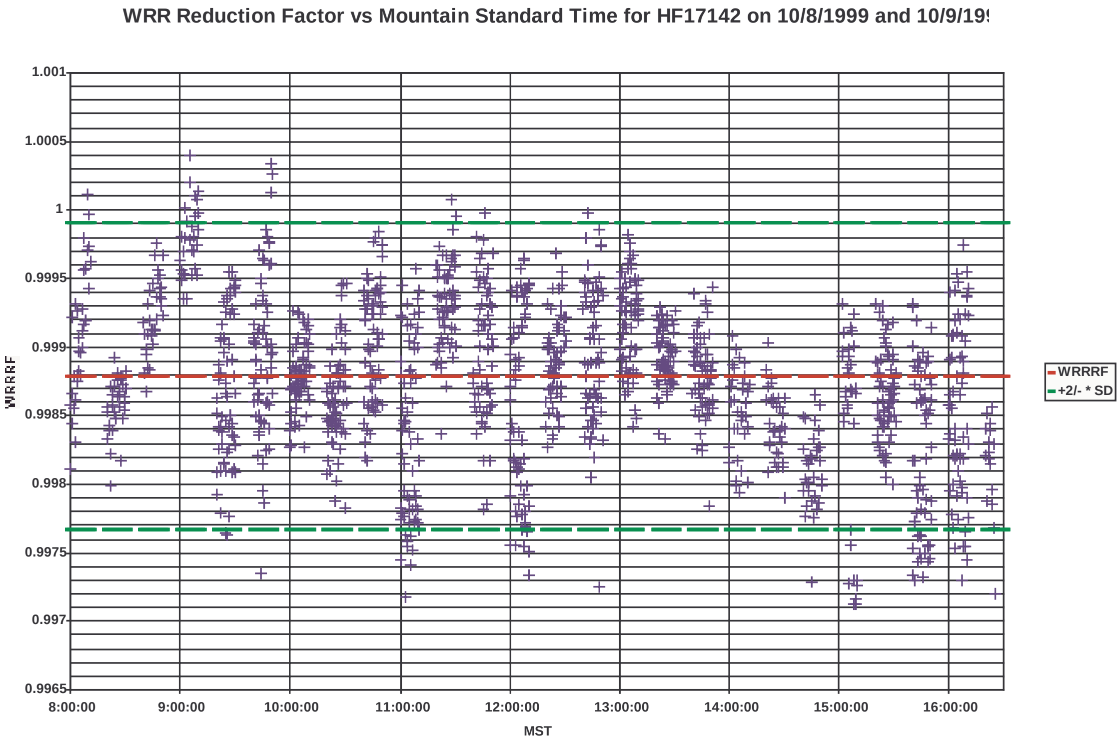


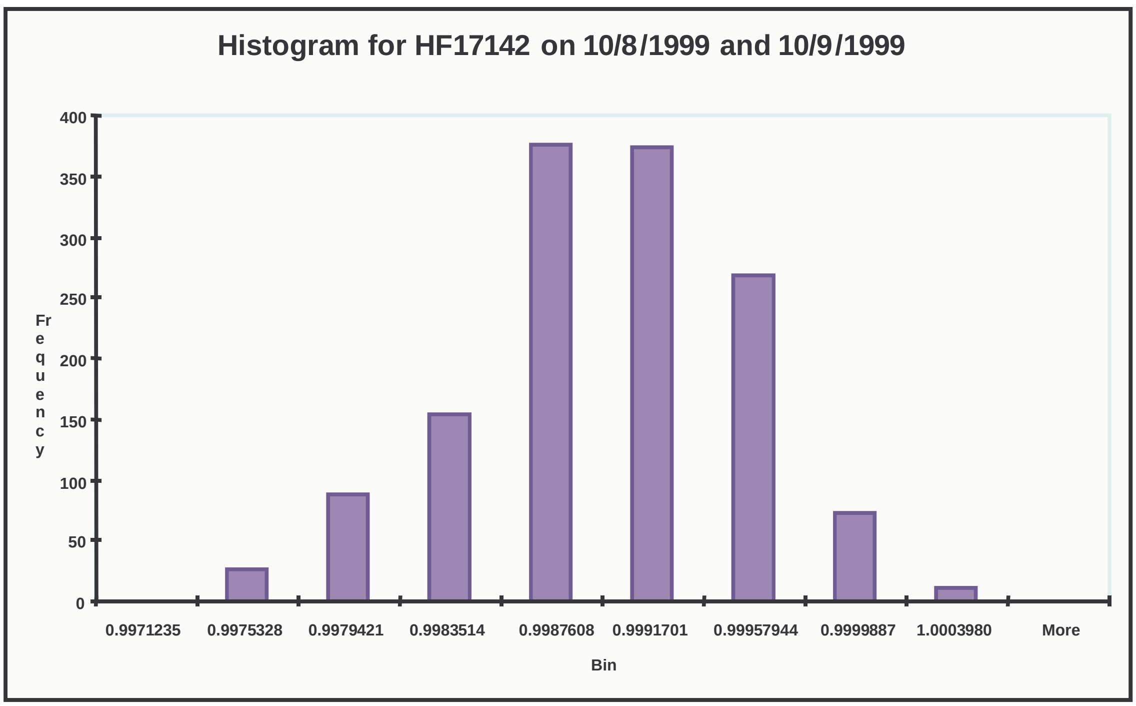
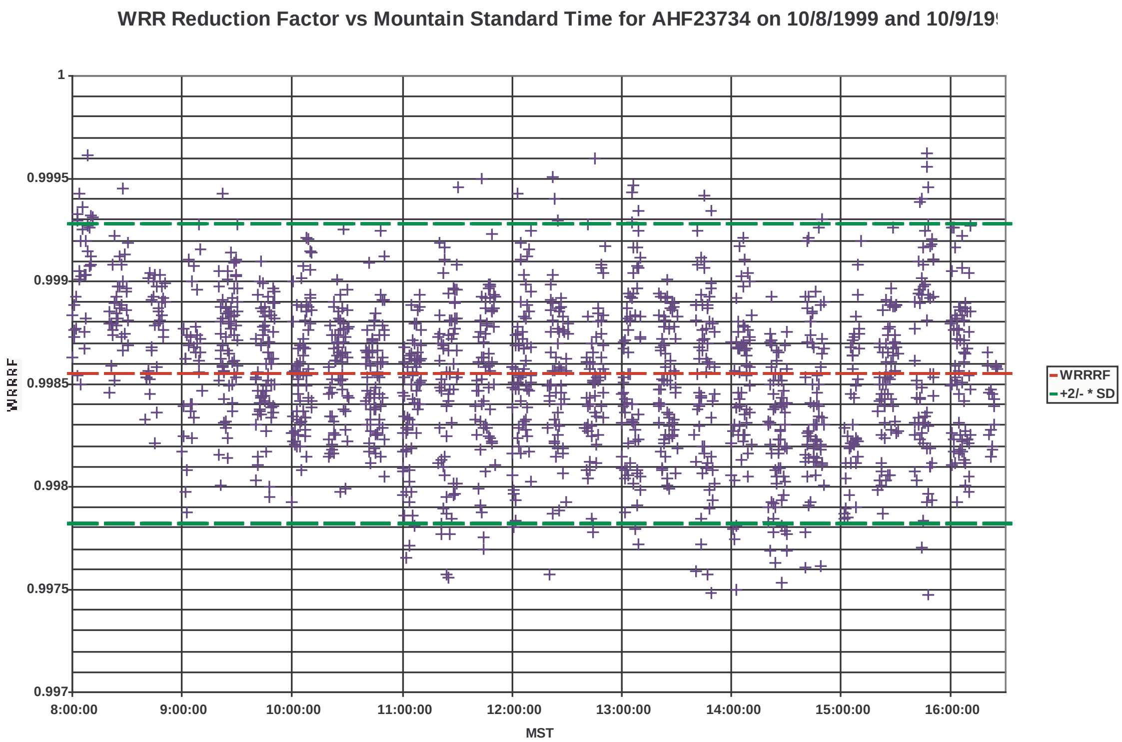


Figure 4.5.1 WRR Reduction Factor Analyses for HF 17142



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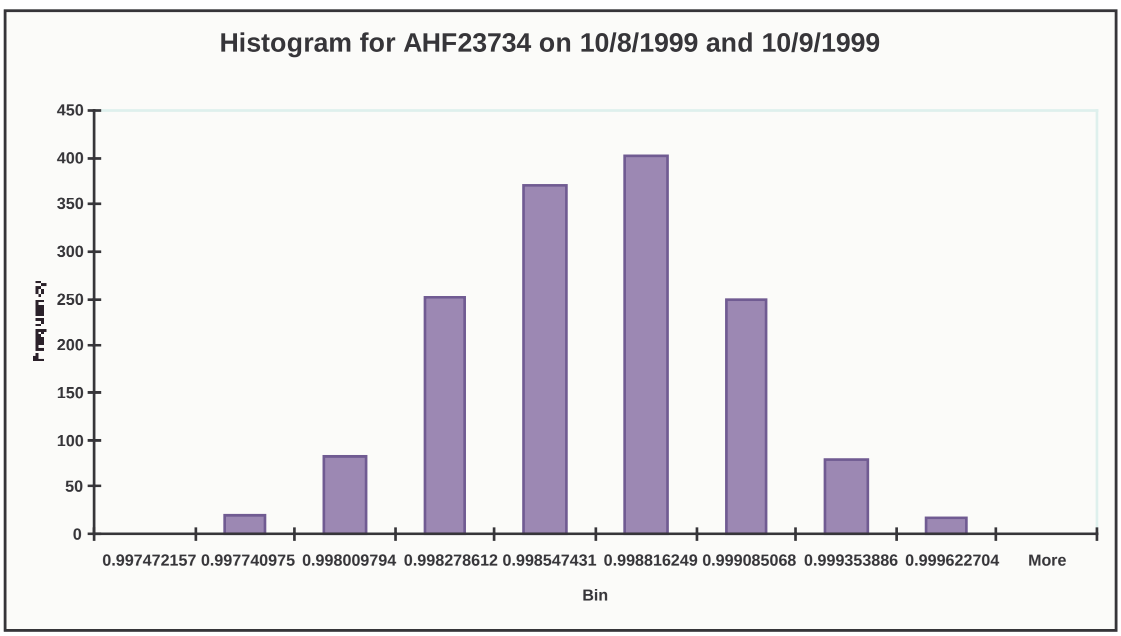

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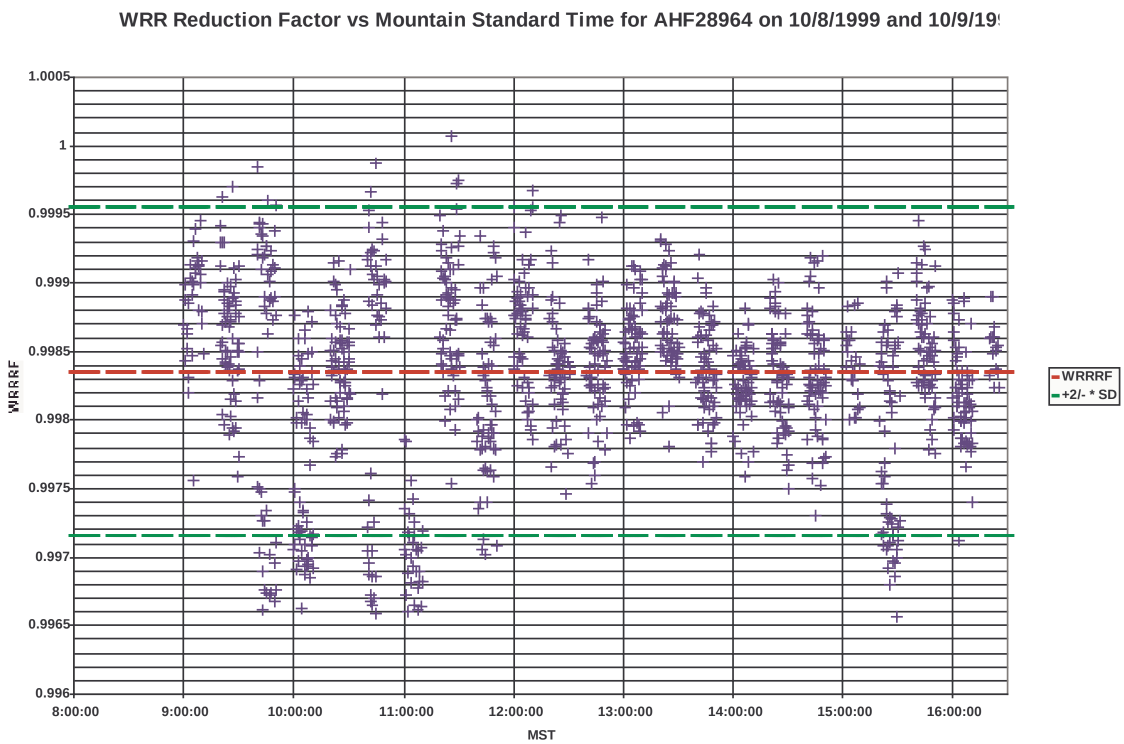
Figure 4.5.2 WRR Reduction Factor Analyses for HF 23734



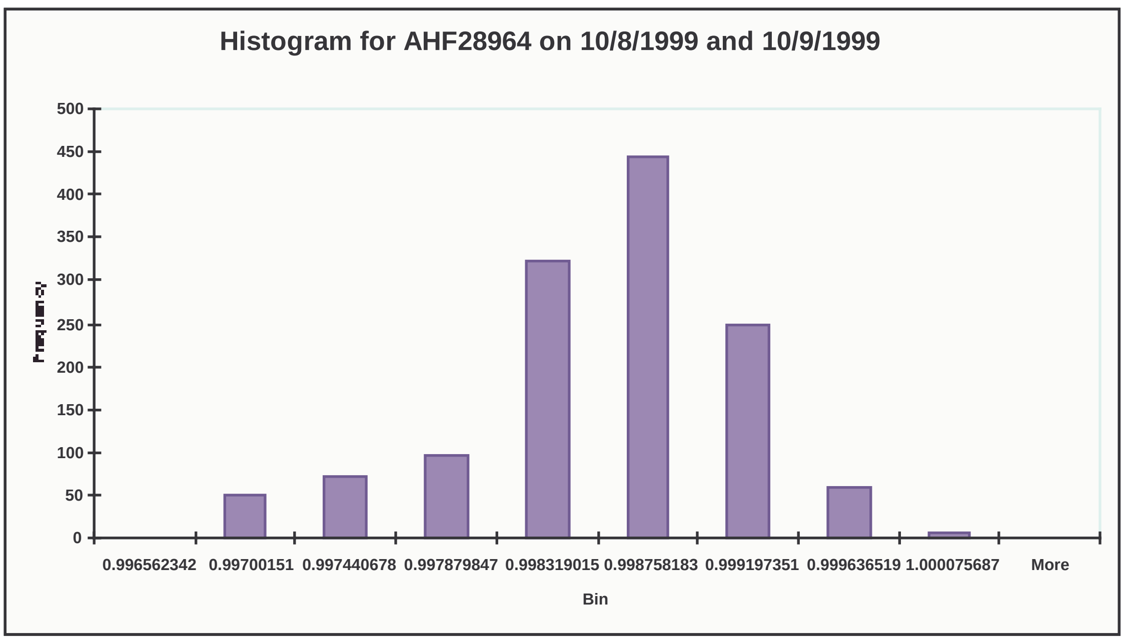


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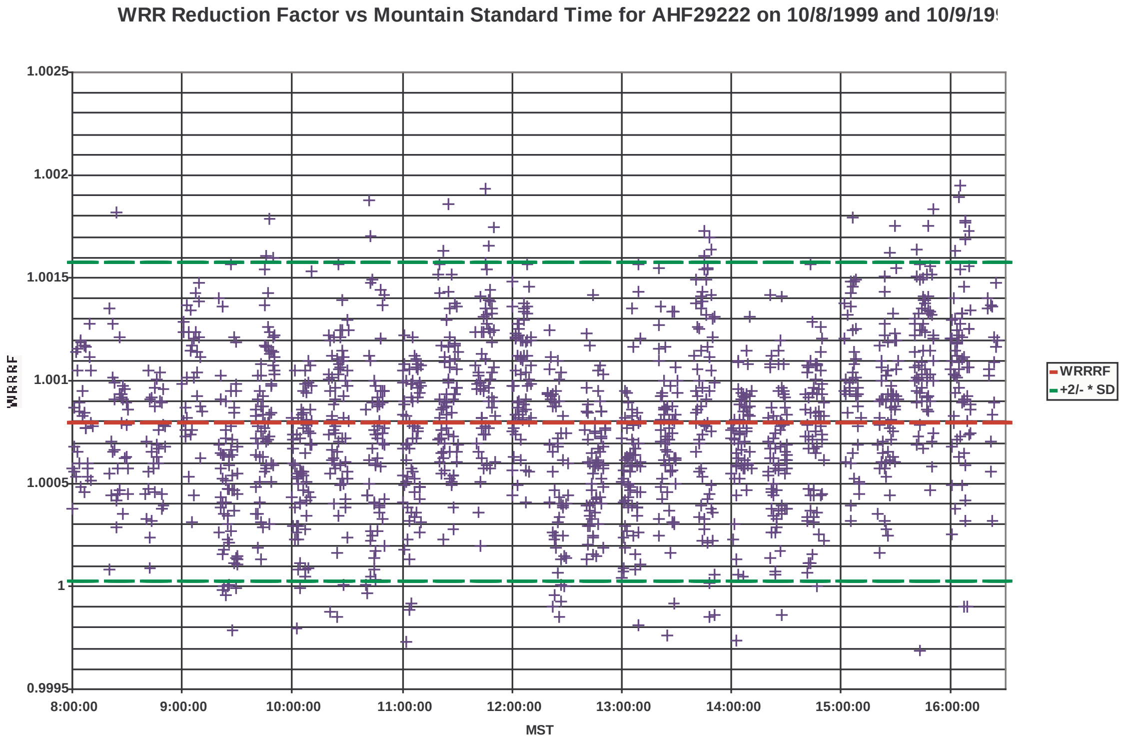
Figure 4.5.3 WRR Reduction Factor Analyses for AHF 28964



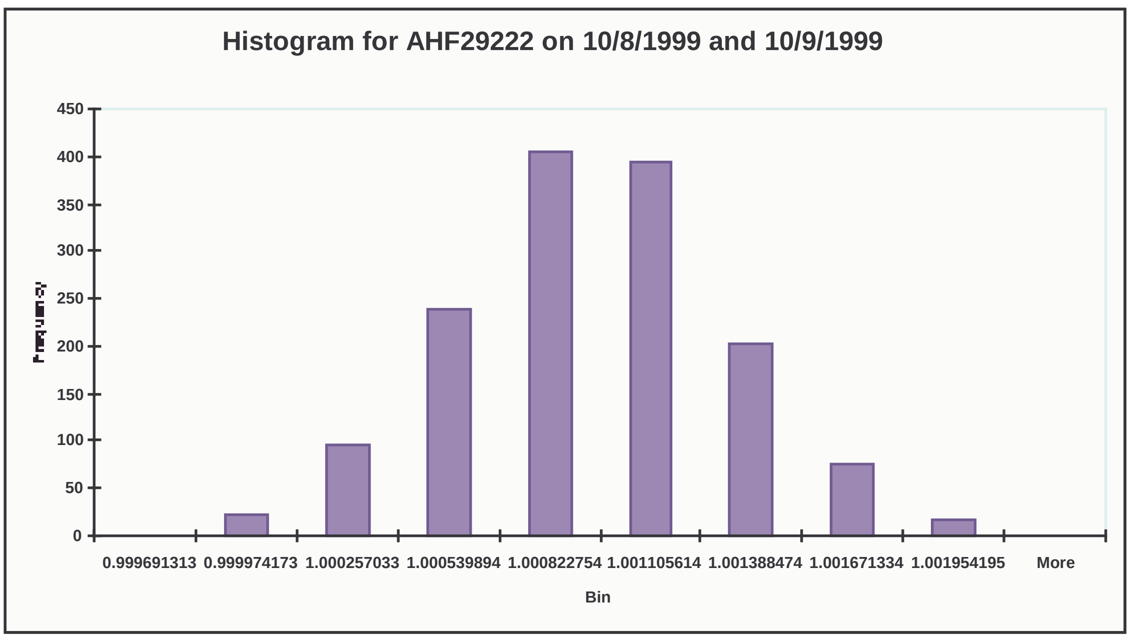
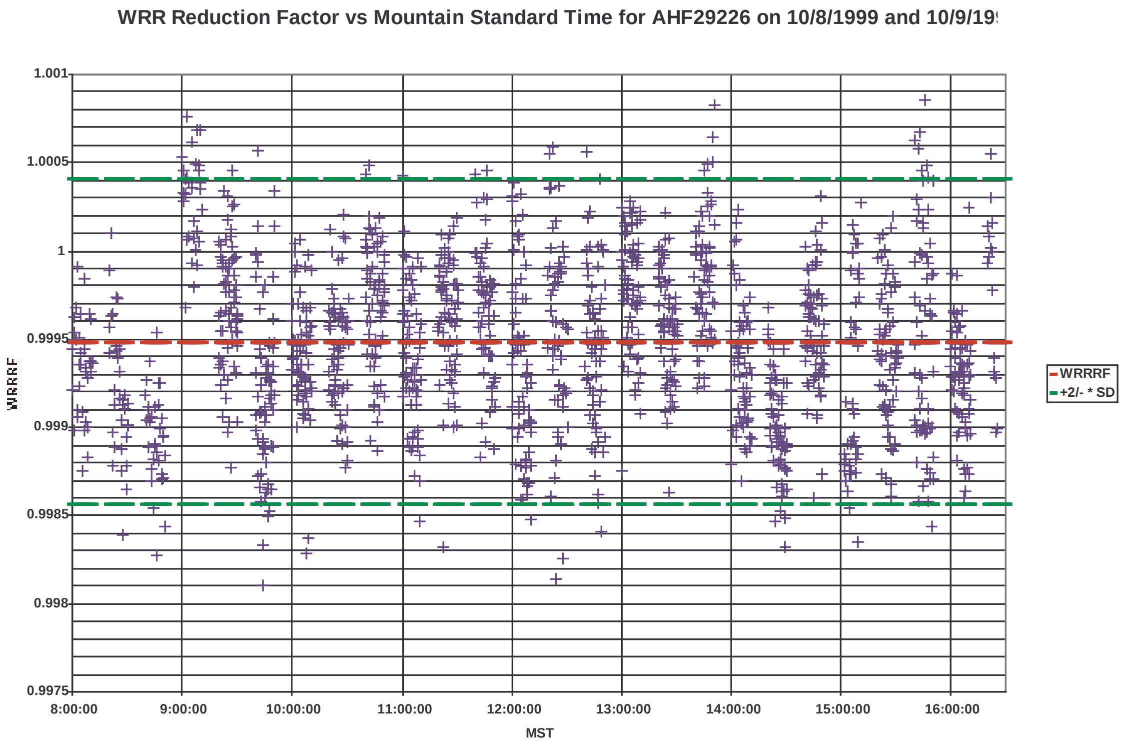


Figure 4.5.4 WRR Reduction Factor Analyses for AHF 29222



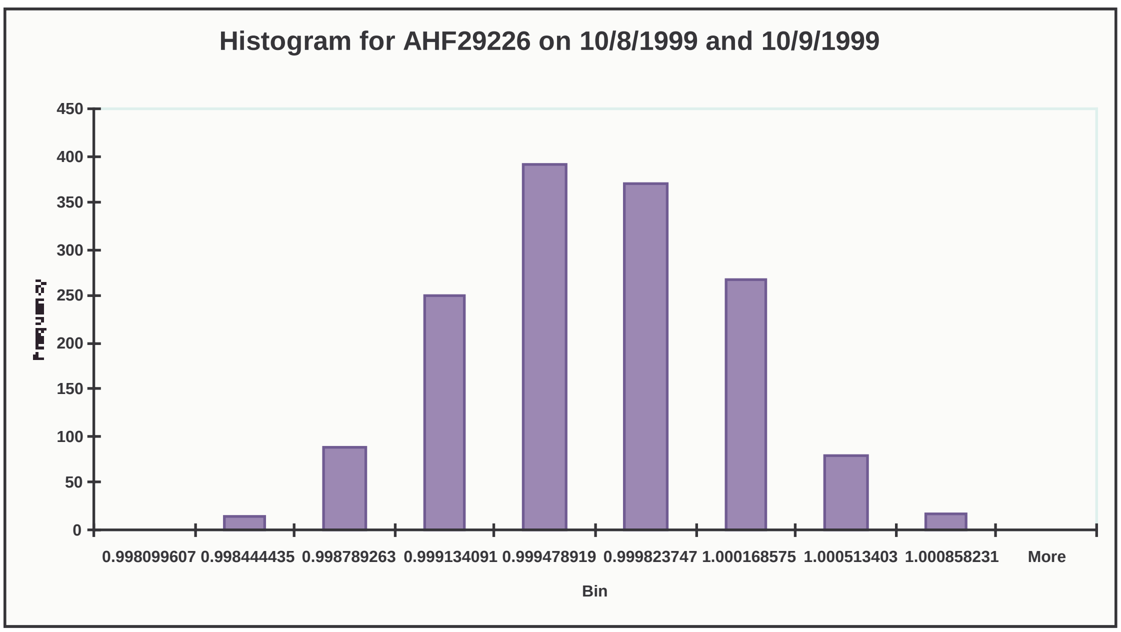


Figure 4.5.5 WRR Reduction Factor Analyses for AHF 29226

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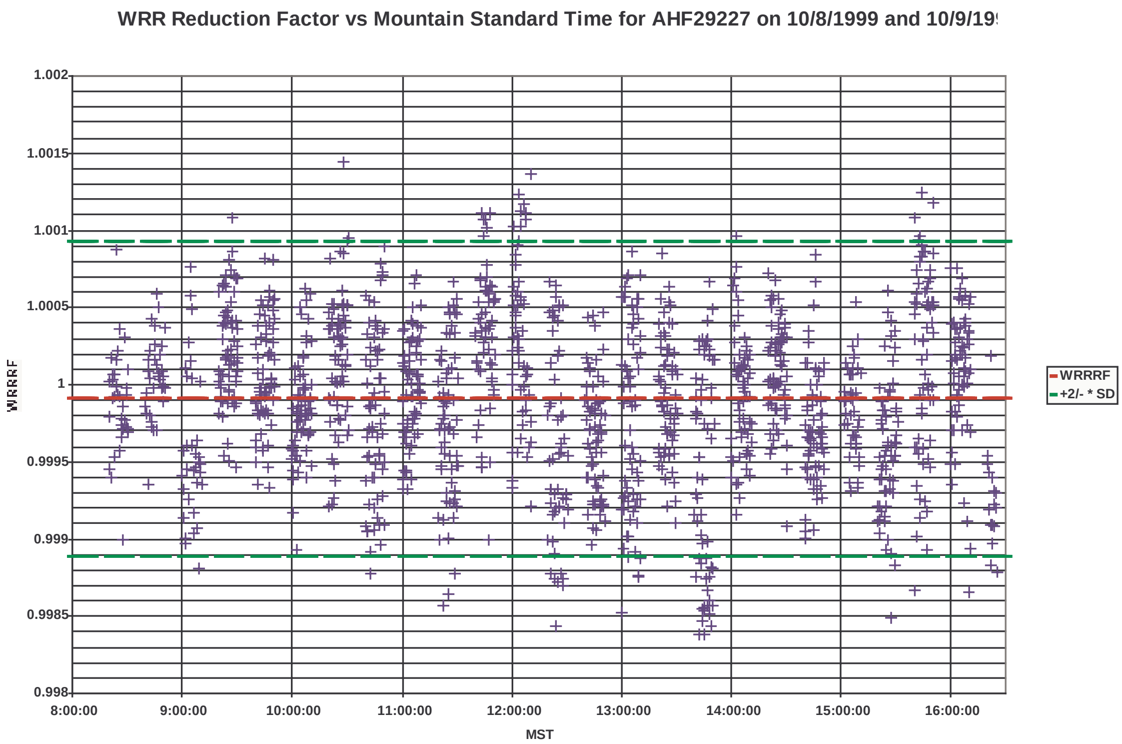

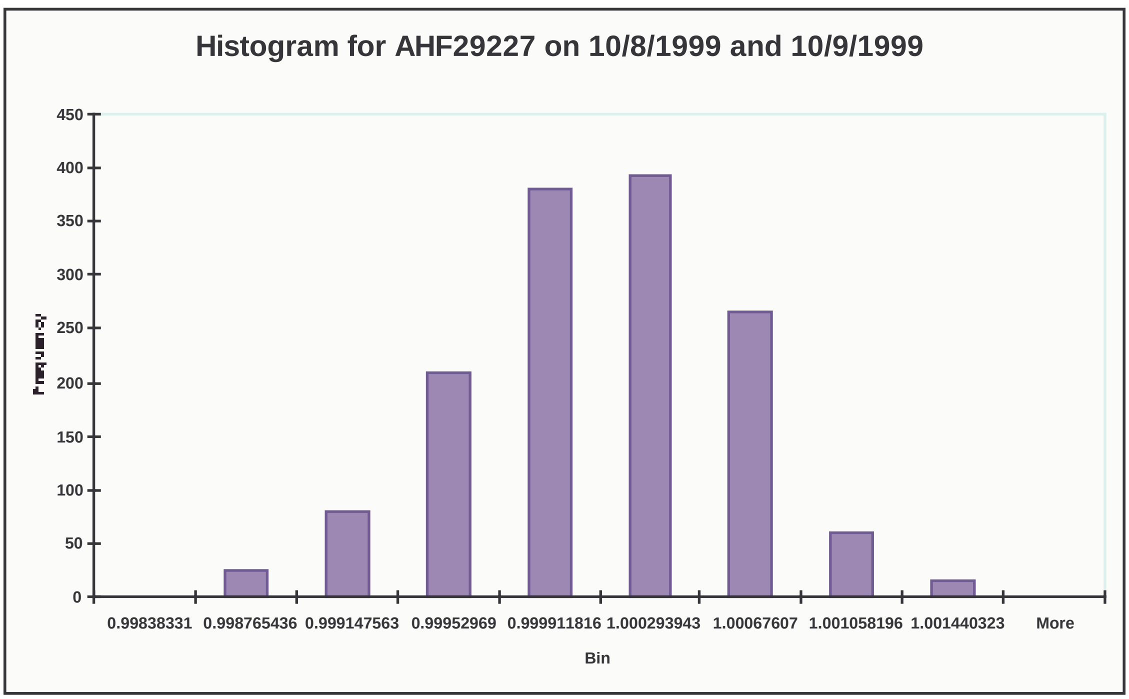

Figure 4.5.6 WRR Reduction Factor Analyses for AHF 29227

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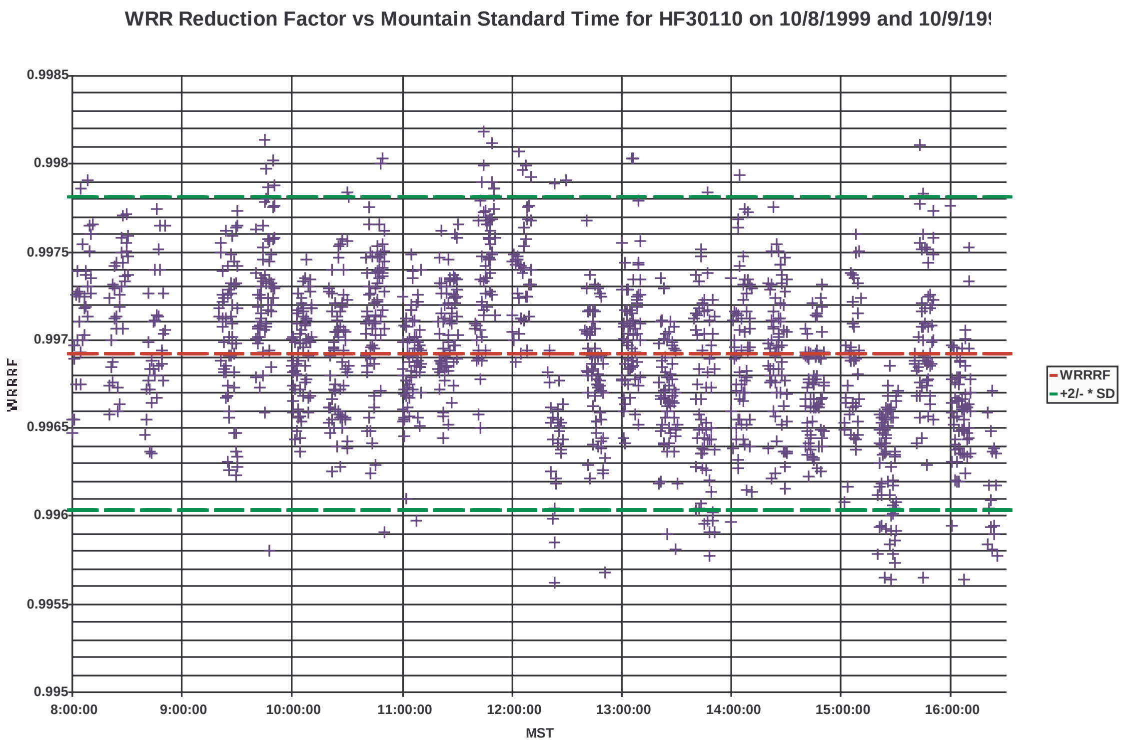

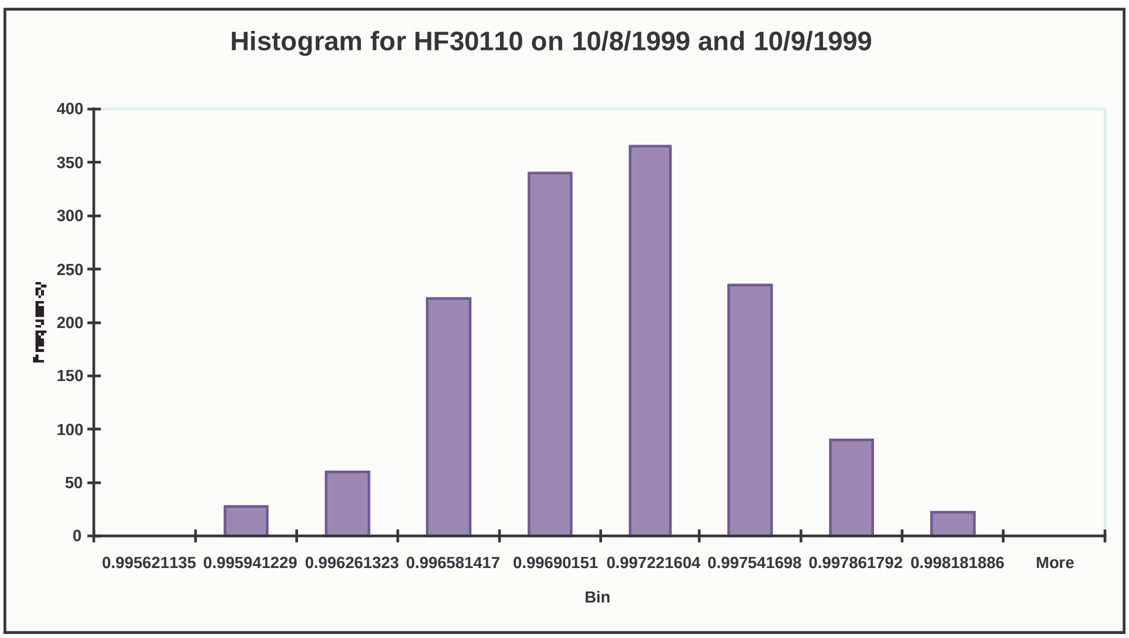

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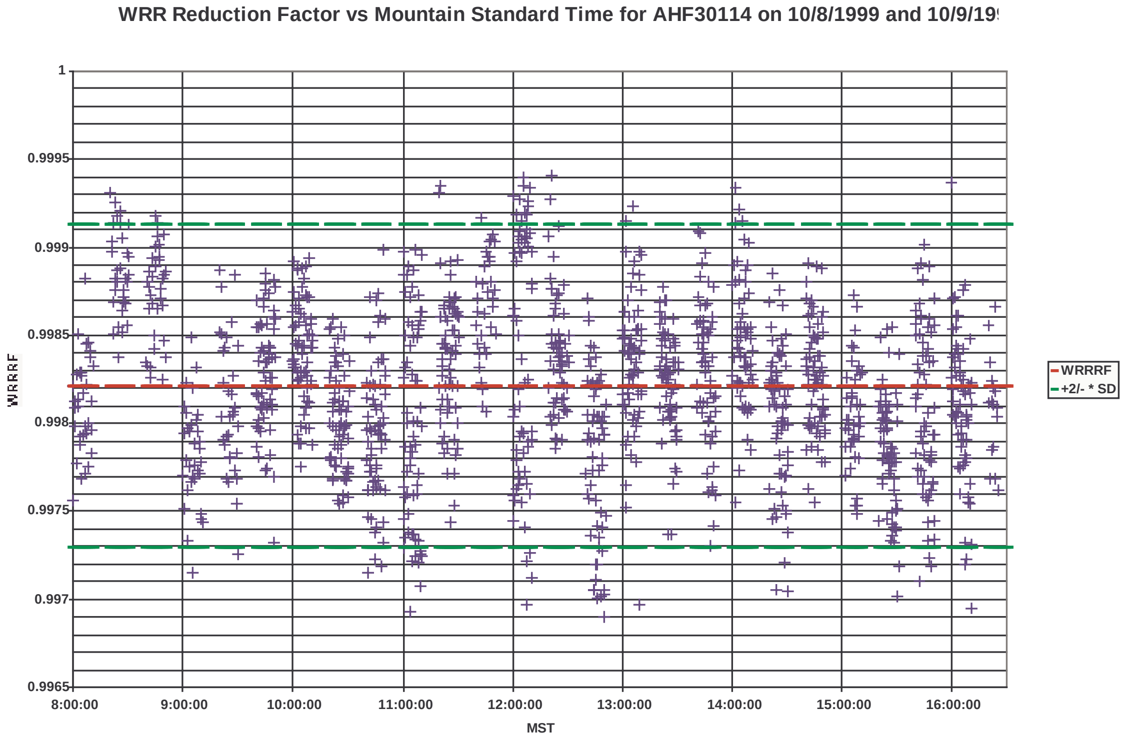
Figure 4.5.7 WRR Reduction Factor Analyses for AHF 30110



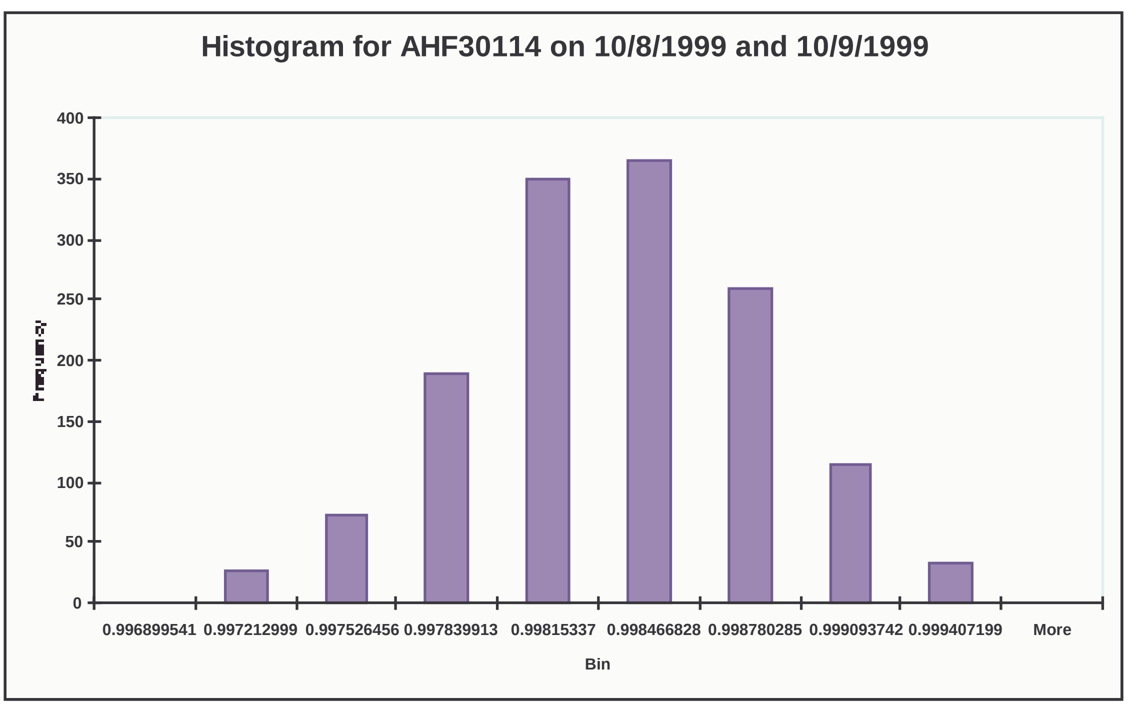


Figure 4.5.8 WRR Reduction Factor Analyses for AHF 30114

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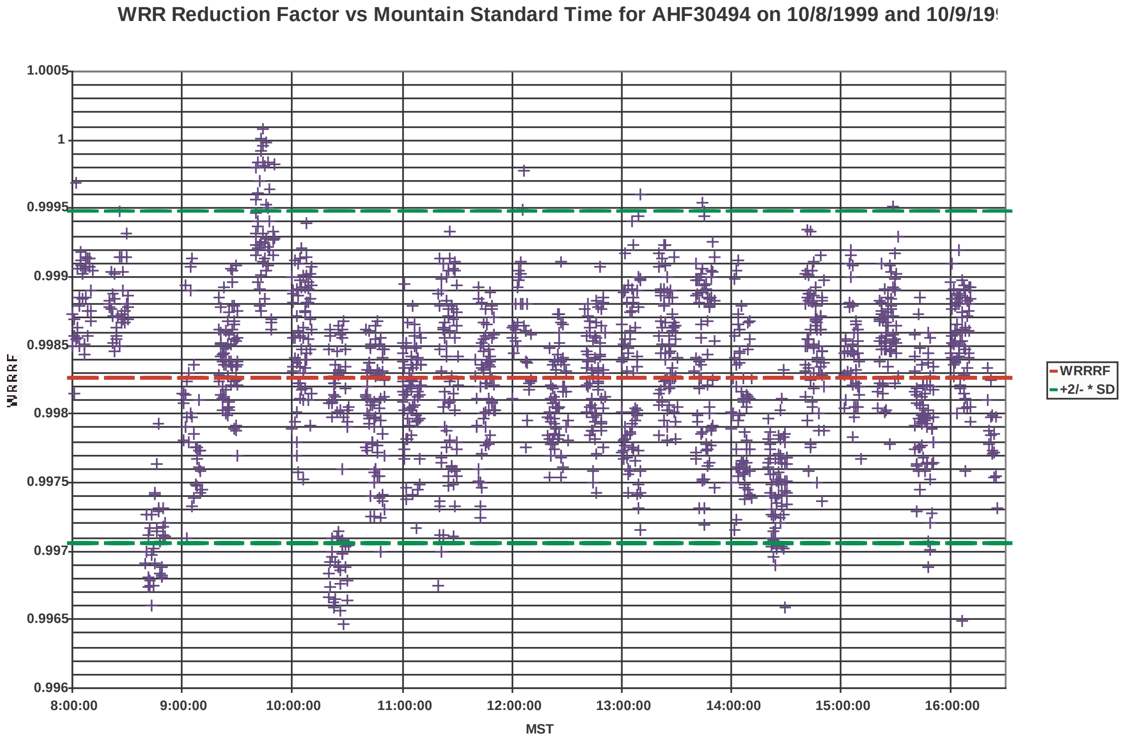

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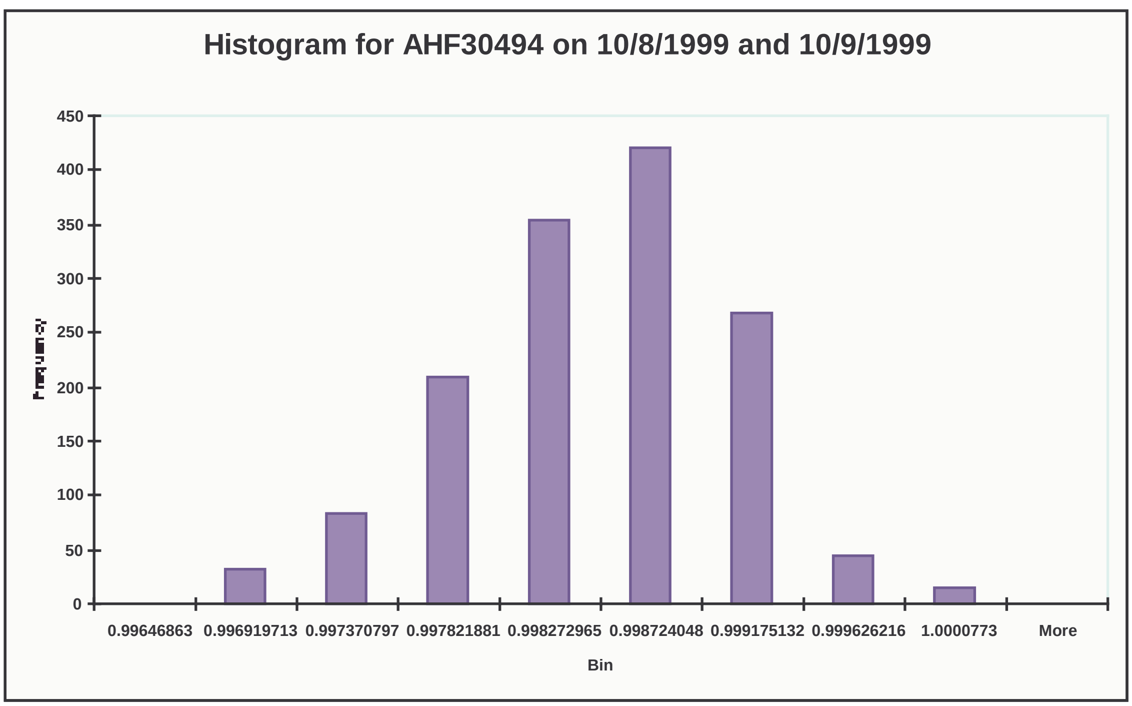

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Figure 4.5.9 WRR Reduction Factor Analyses for AHF 30494

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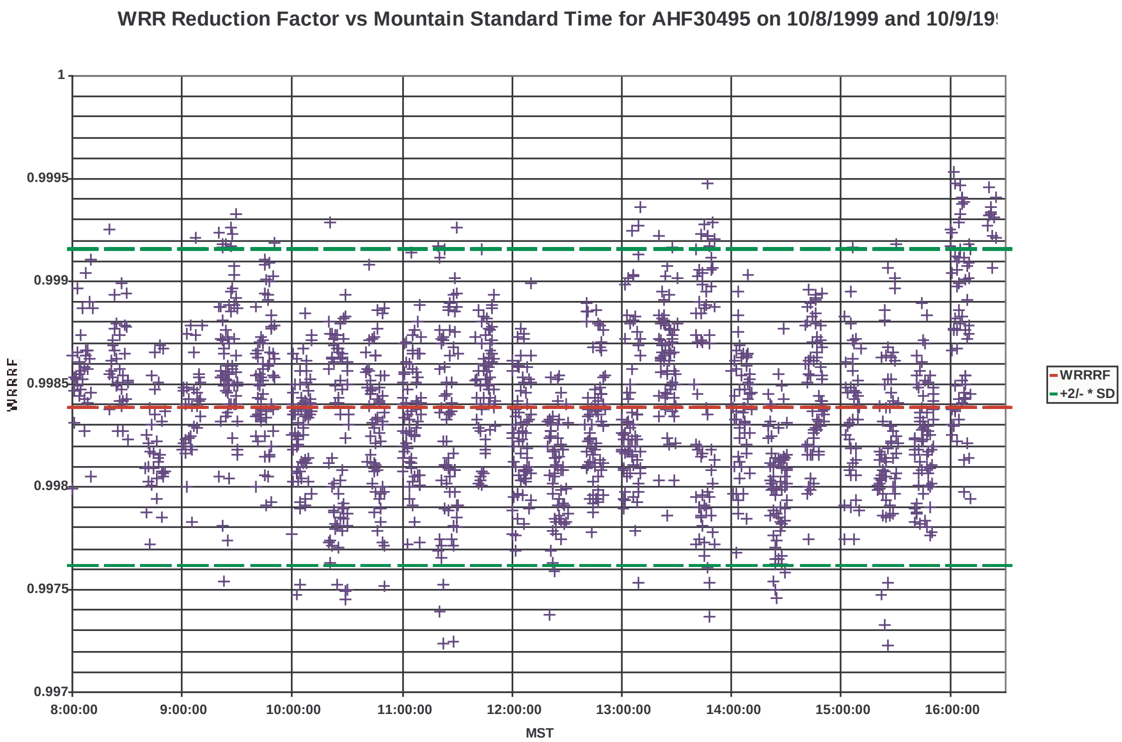

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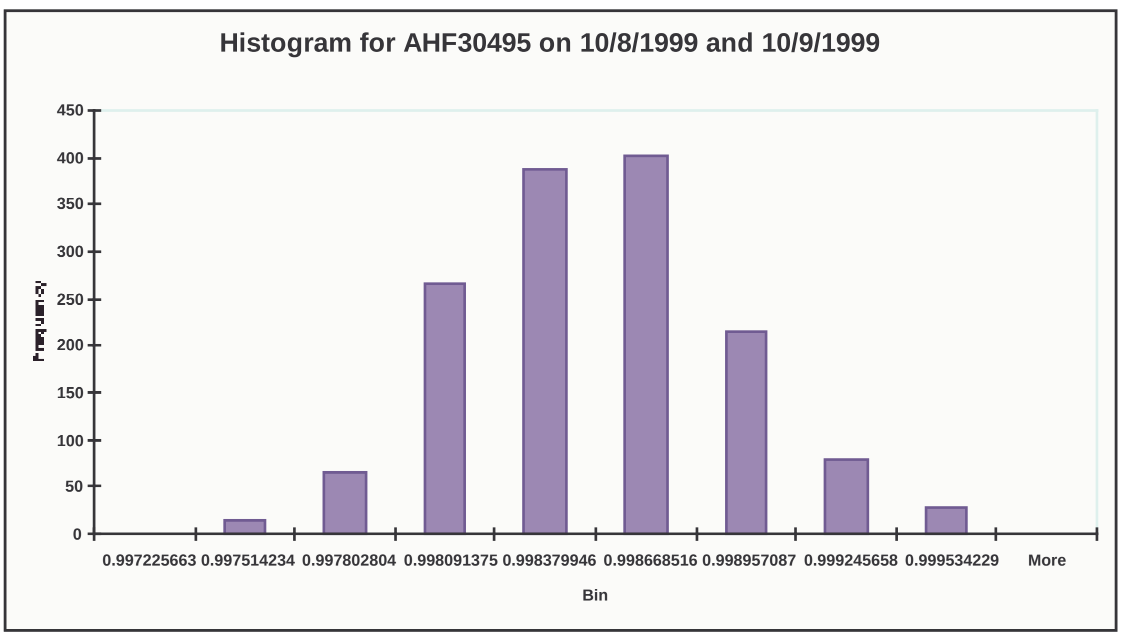

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Figure 4.5.10 WRR Reduction Factor Analyses for AHF 30495

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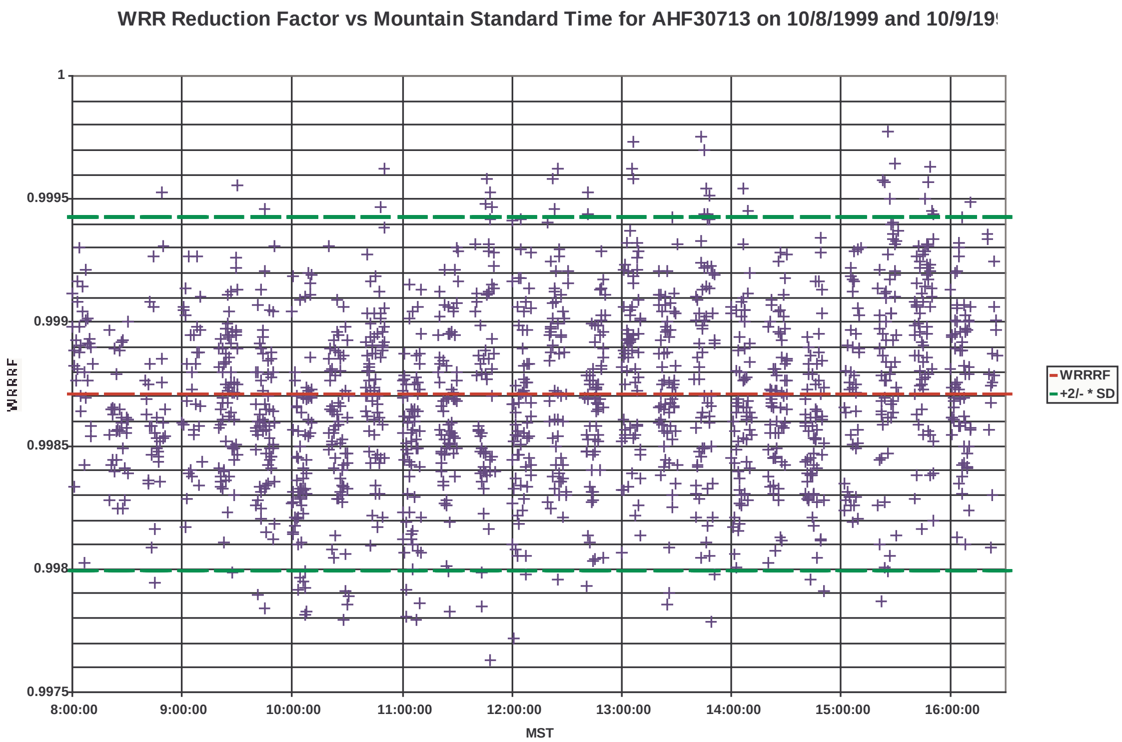

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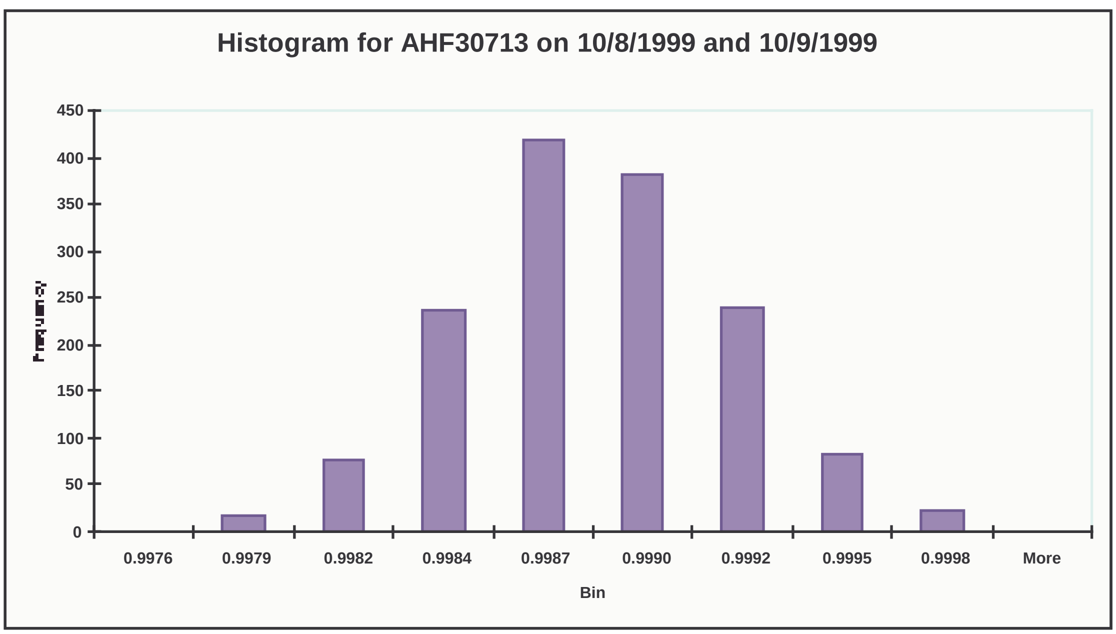

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Figure 4.5.11 WRR Reduction Factor Analyses for AHF 30713

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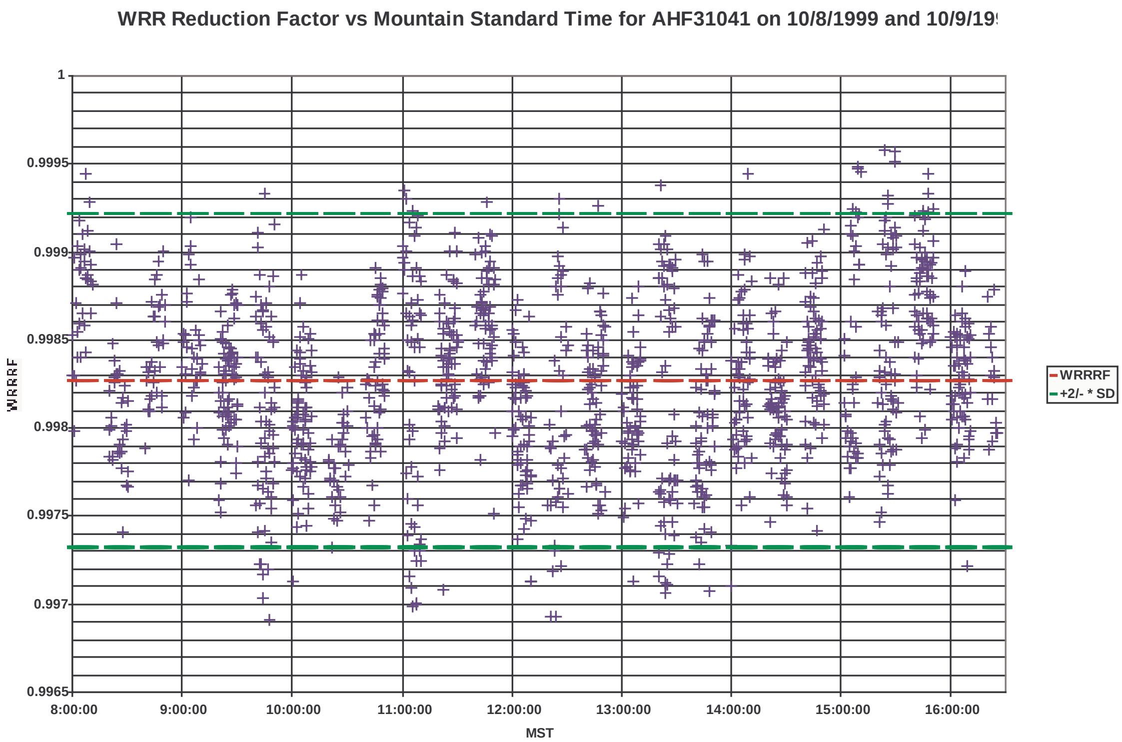

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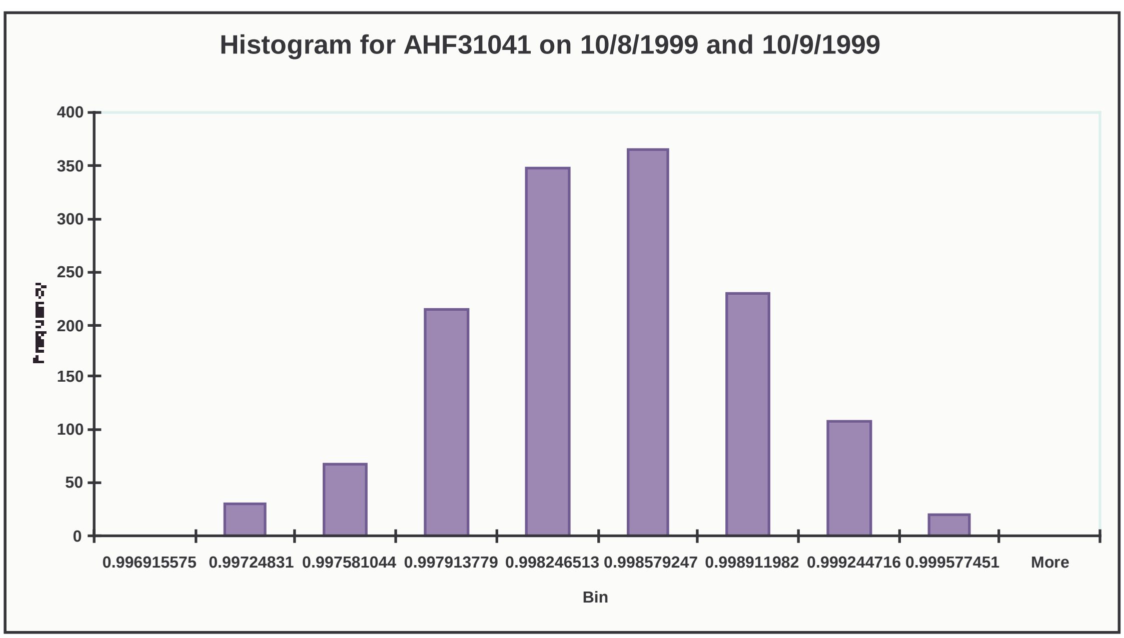

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Figure 4.5.12 WRR Reduction Factor Analyses for AHF 31041

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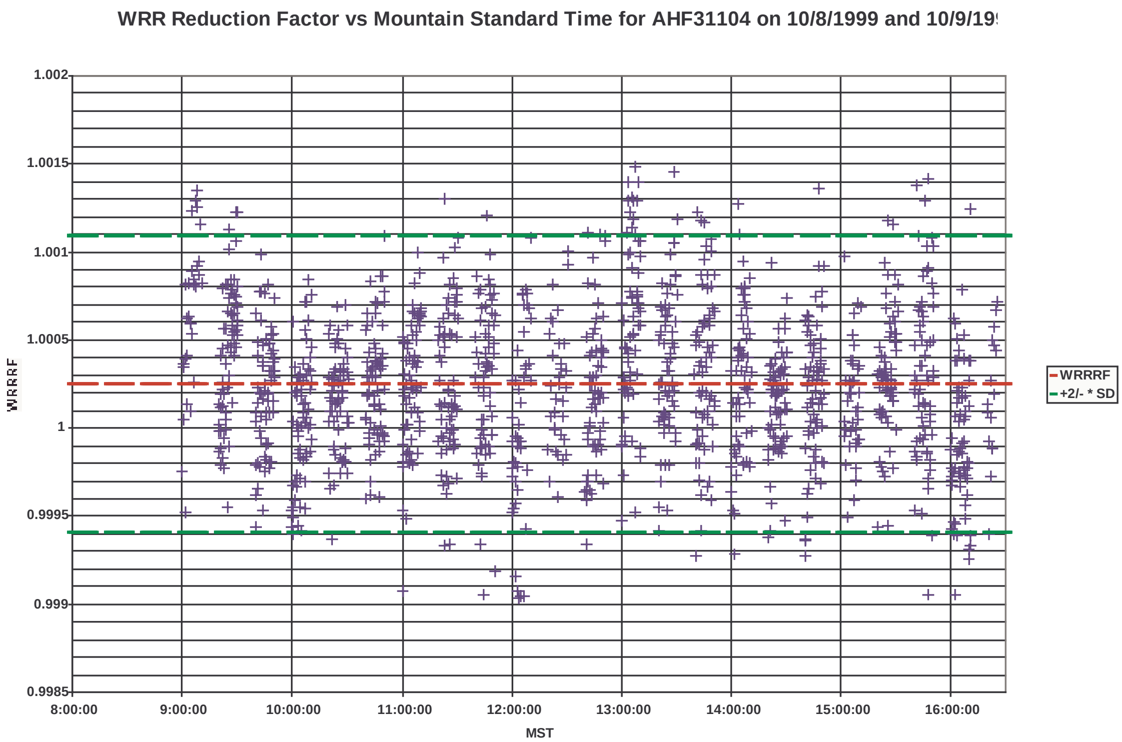

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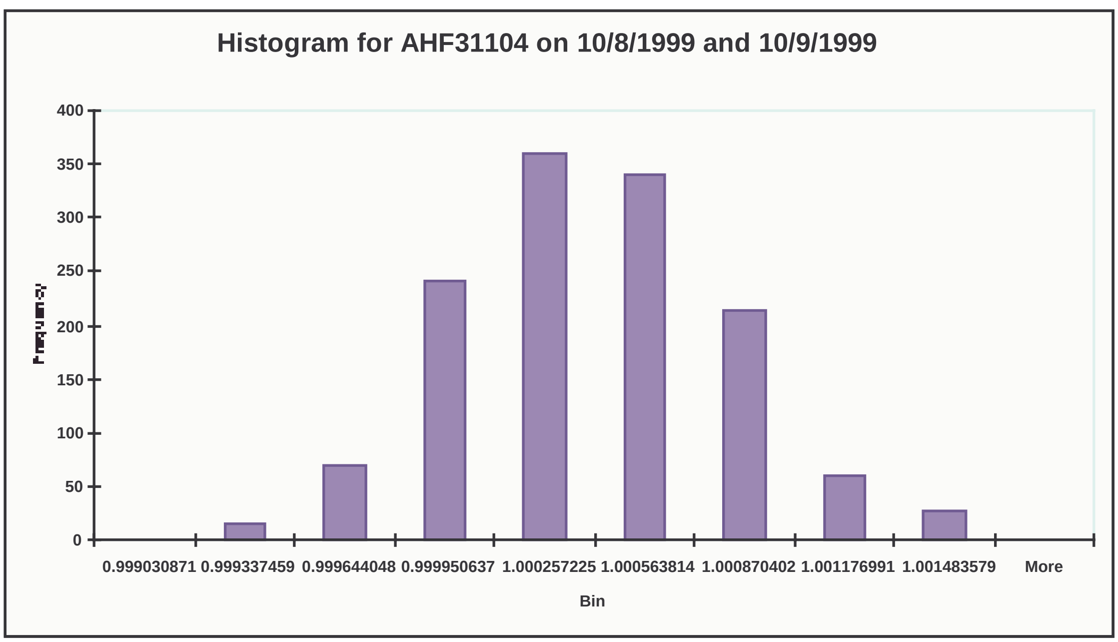

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Figure 4.5.13 WRR Reduction Factor Analyses for AHF 31104

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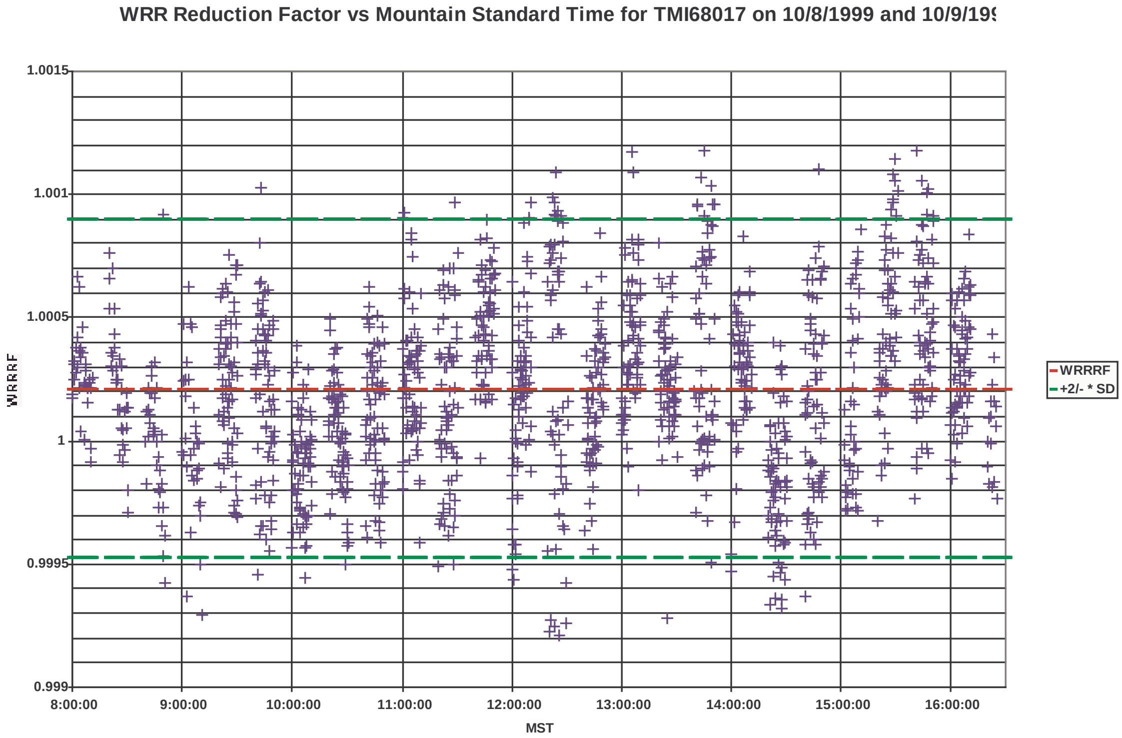

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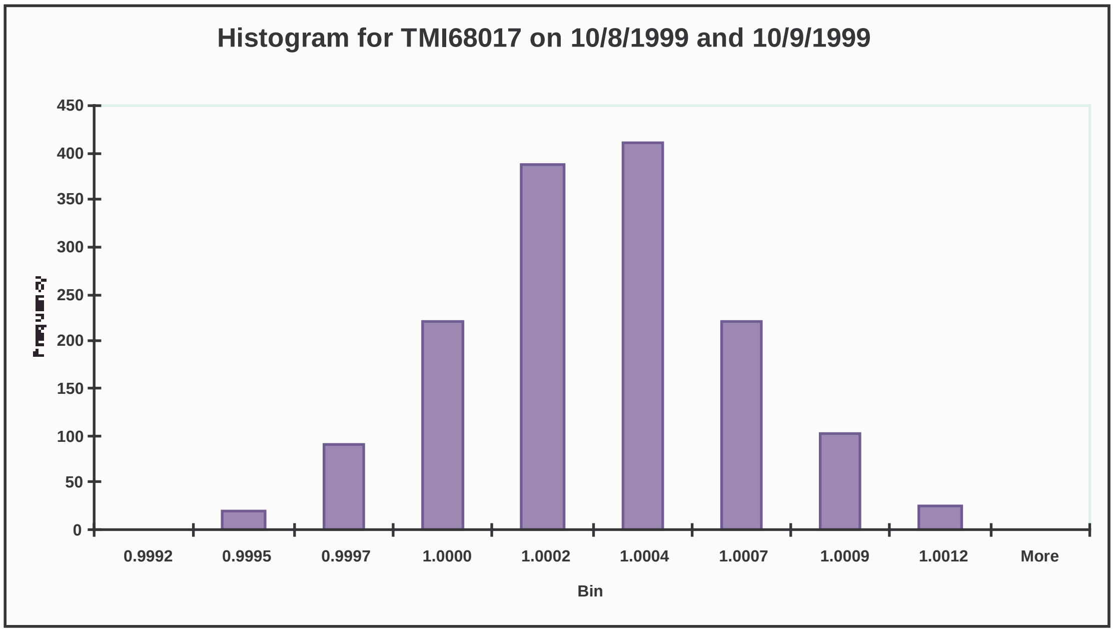
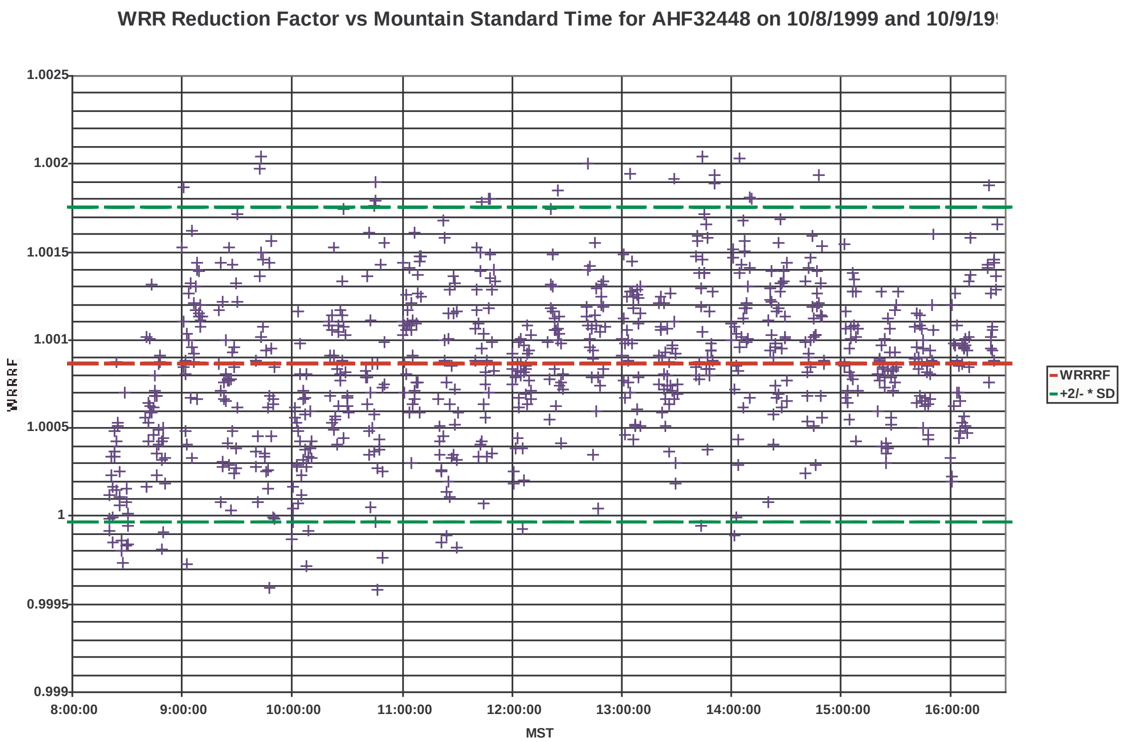


..

Figure 4.5.14 WRR Reduction Factor Analyses for TMI 68017

..



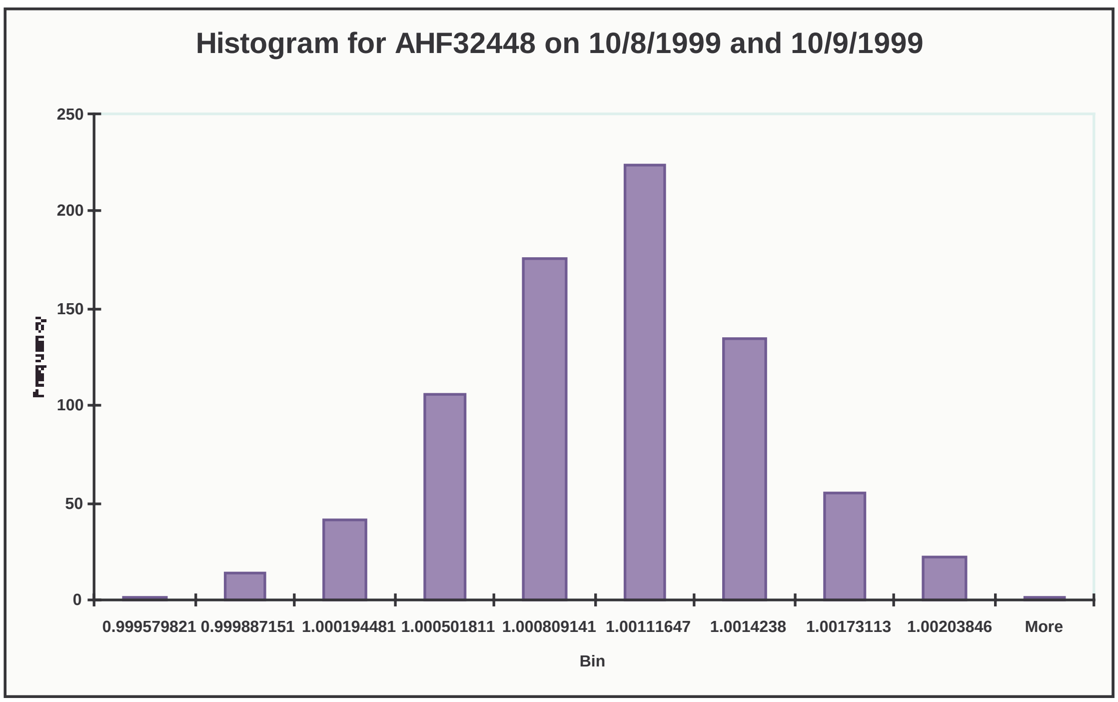
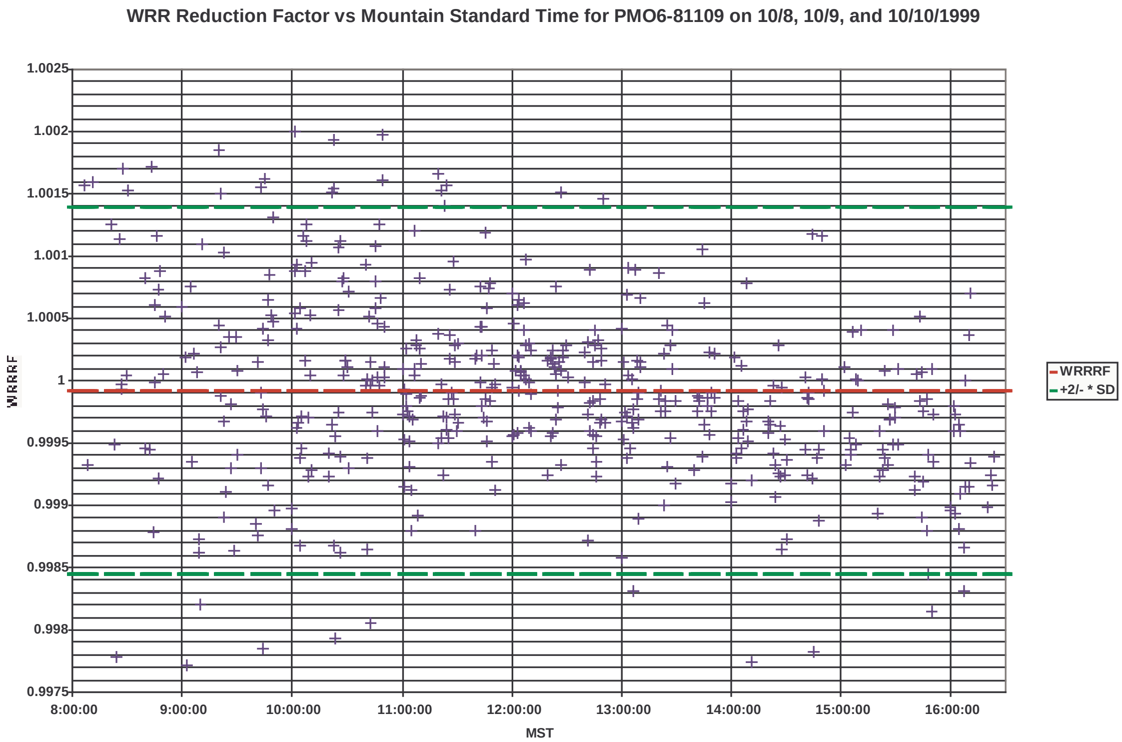


Figure 4.5.15 WRR Reduction Factor Analyses for AHF 32448

..



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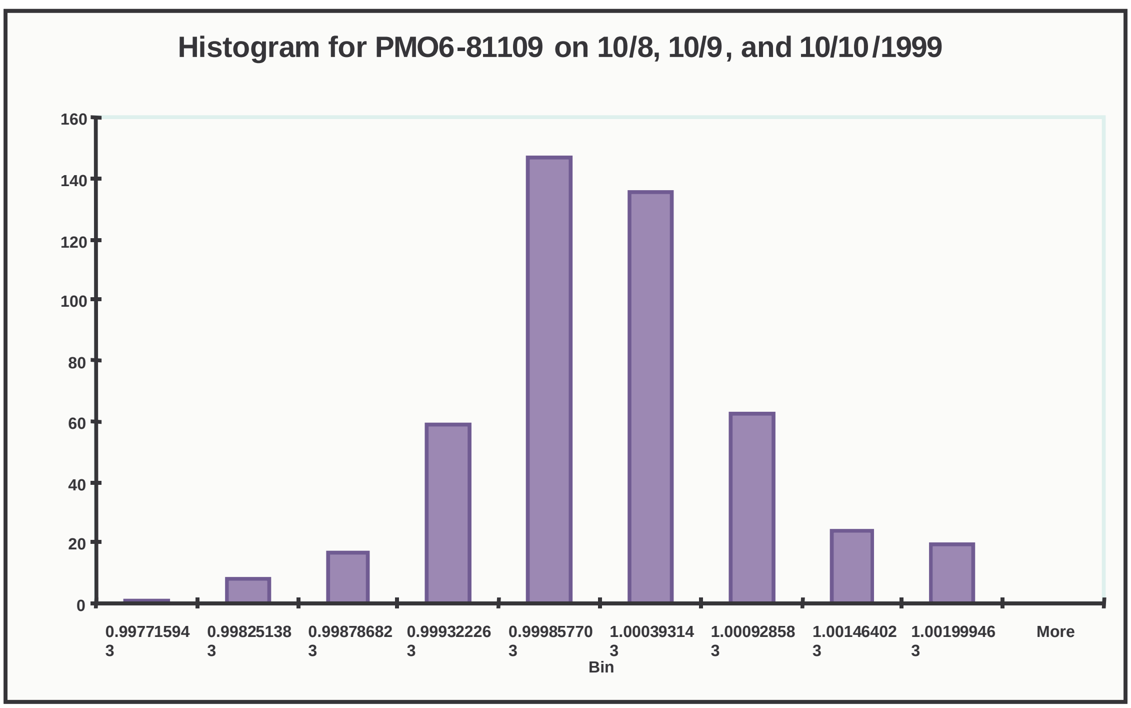
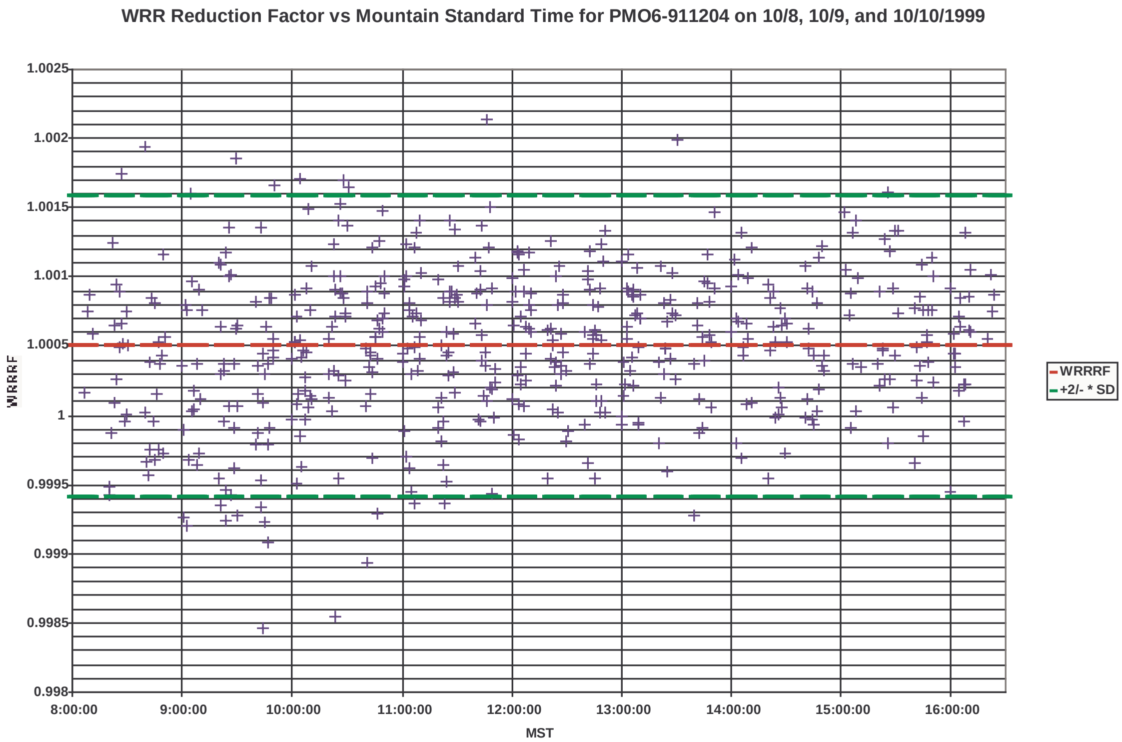


Figure 4.5.16 WRR Reduction Factor Analyses for PMO6-81109

..



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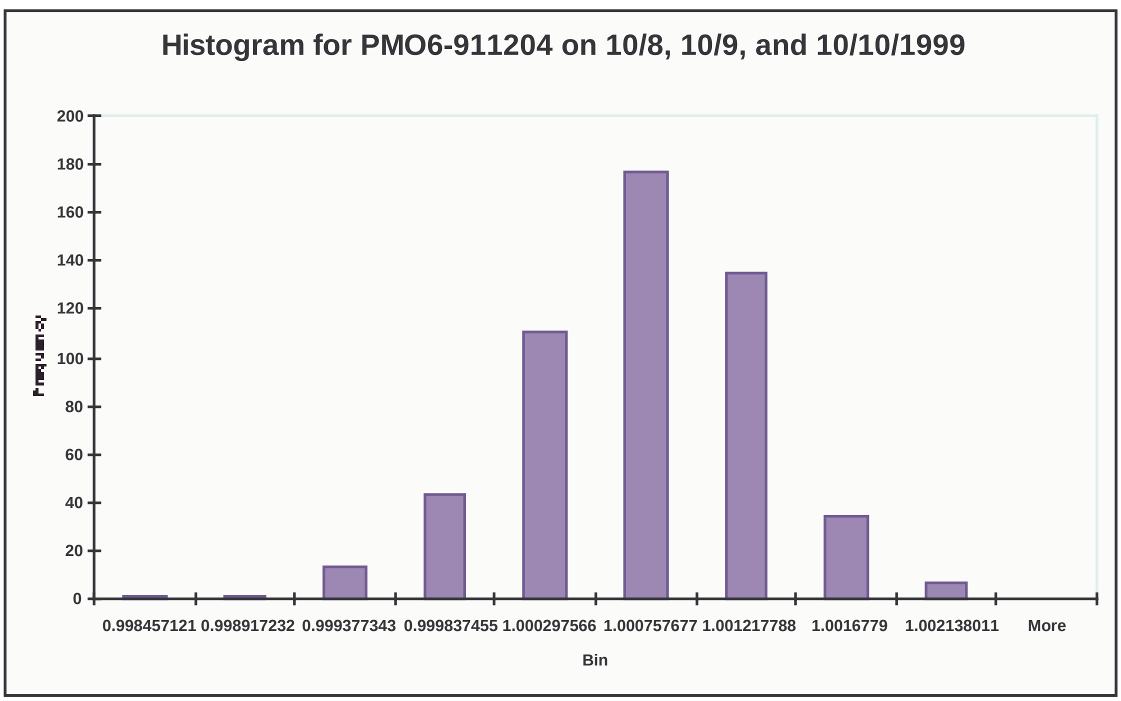
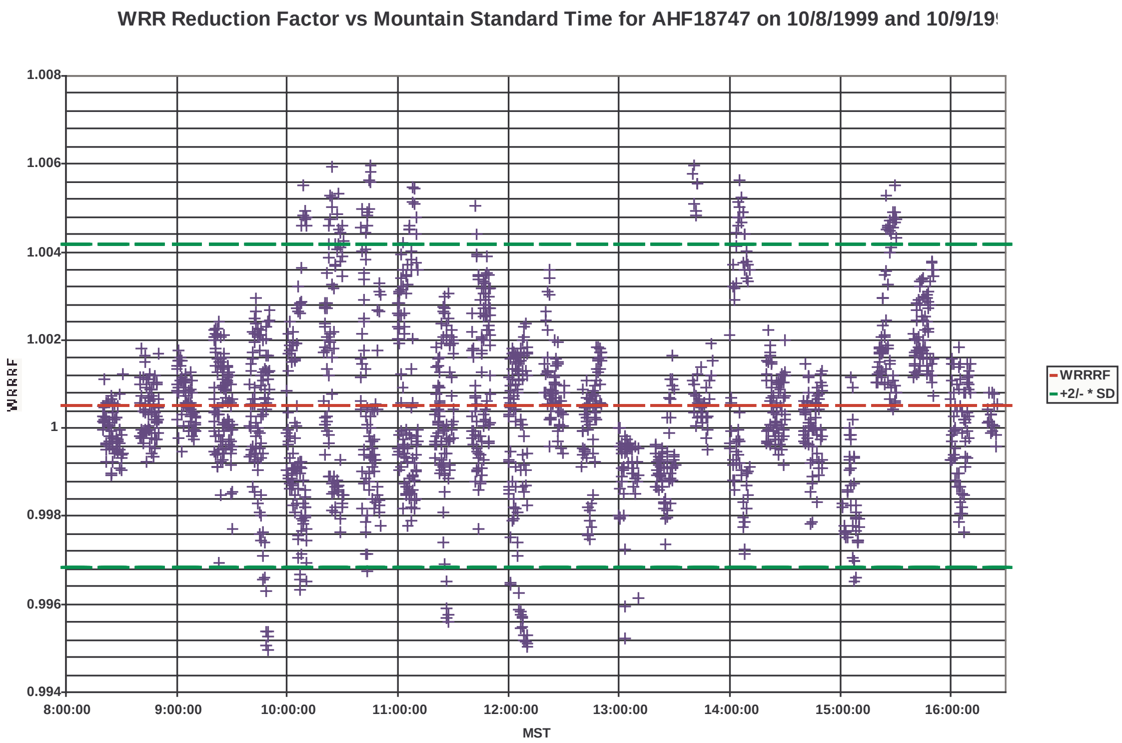


Figure 4.5.17 WRR Reduction Factor Analyses for PMO6-911204

..



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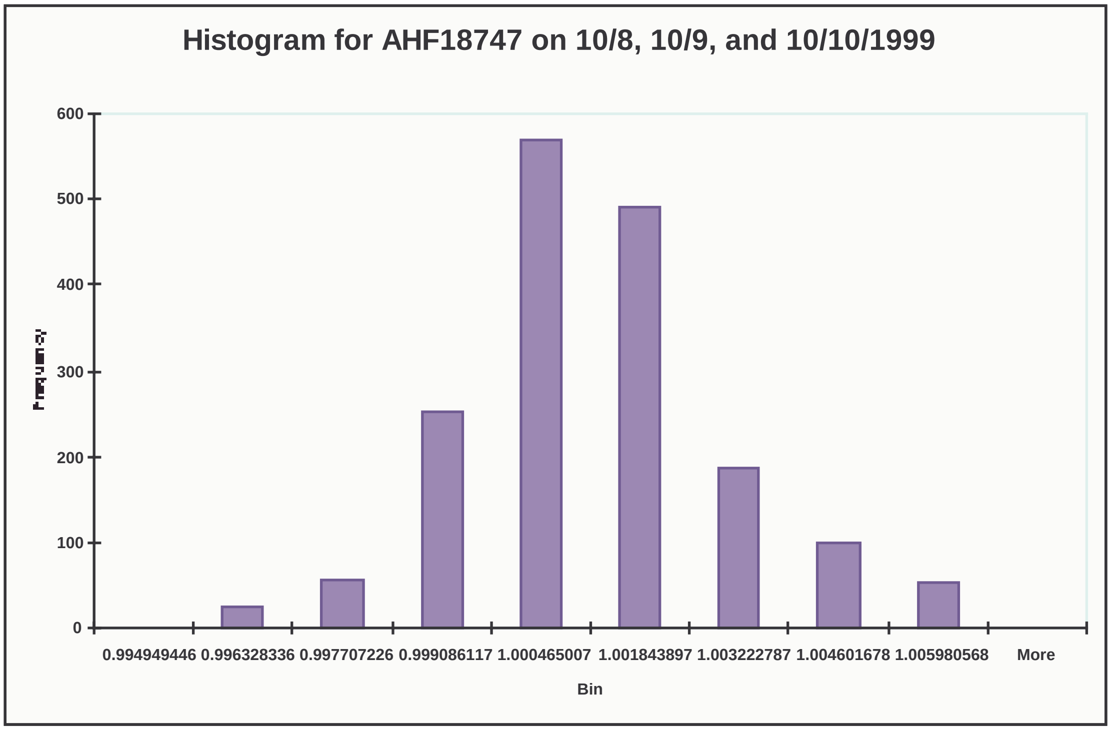
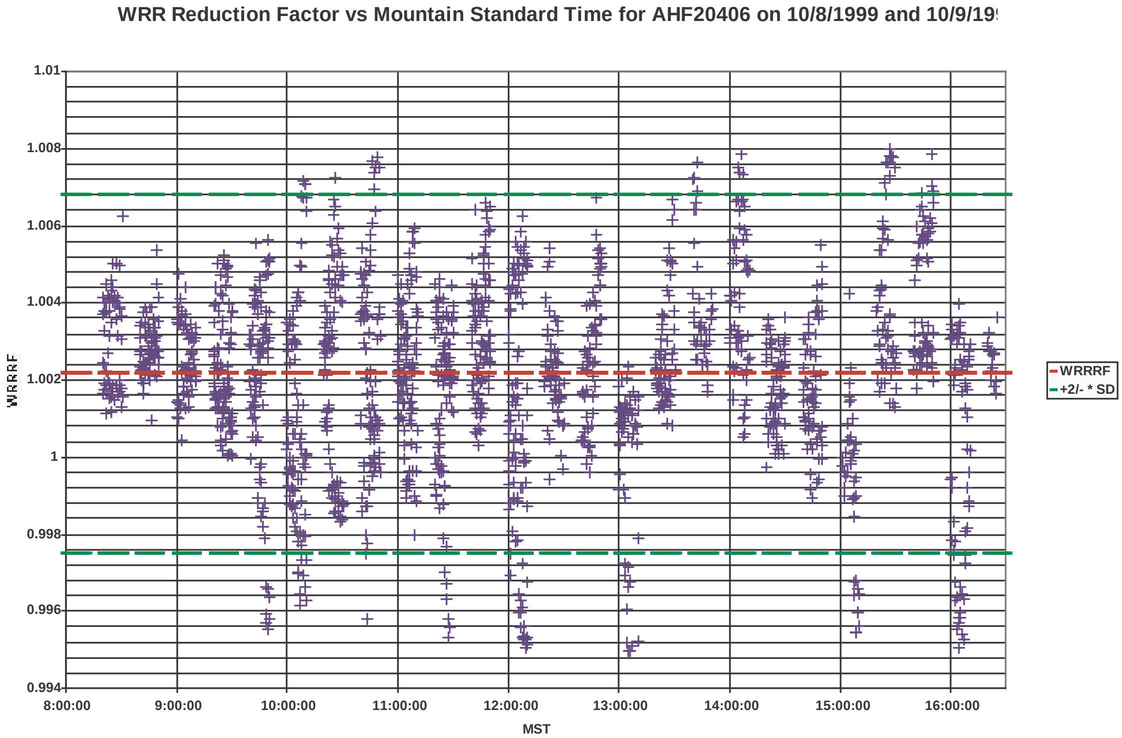


Figure 4.5.18 WRR Reduction Factor Analyses for AHF 18747

..



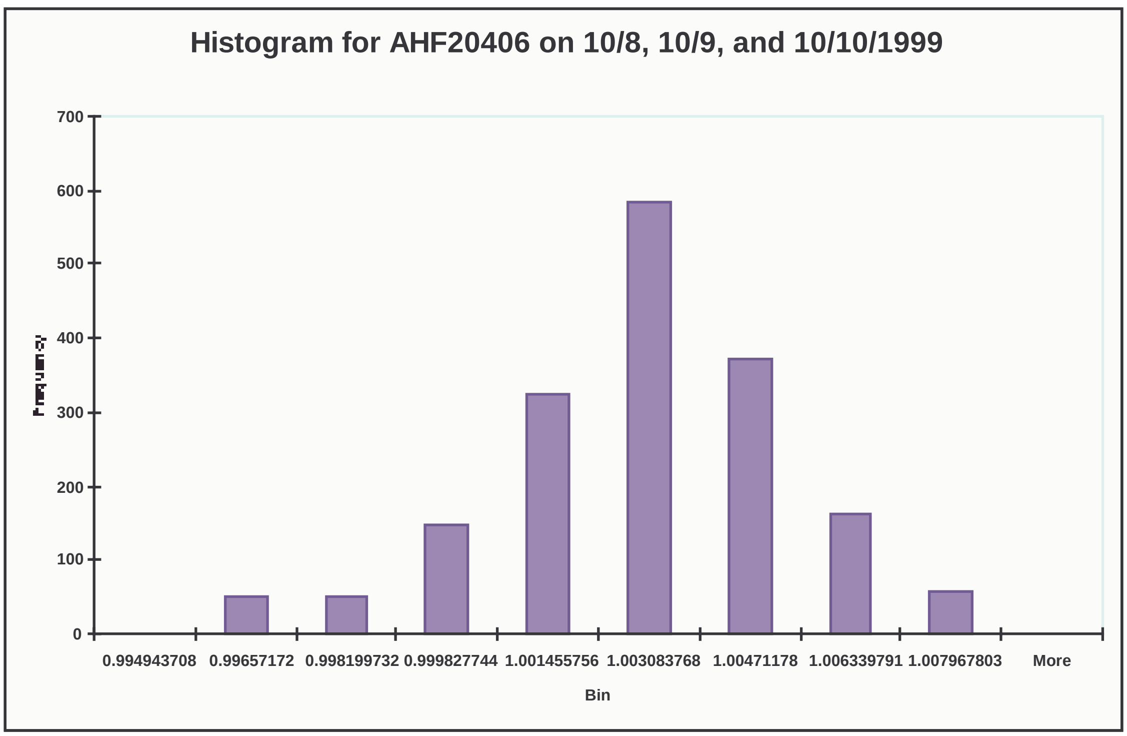


Figure 4.5.19 WRR Reduction Factor Analyses for AHF 20406

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 eight (8) participating radiometers listed in Table 5.1. Three unwindowed reference cavity radiometers that have direct WRR traceability were used to determine the reference irradiance.

Table 5.1 Absolute Cavities Fitted With Windows on 10 October 1999

No.	Serial No.	Owner / Application
1	AHF 29222[1]	DOE ARM Southern Great Plains / All-Weather Reference
2	AHF 29226[2]	Los Alamos National Laboratory / ARM-Unmanned Aerospace Vehicle Reference
3	AHF 29227[2]	Los Alamos National Laboratory / ARM-Unmanned Aerospace Vehicle Reference
4	AHF 31041[3]	NASA/Clouds and the Earth's Radiation Energy System (CERES) Reference
5	HF 30110[2]	King Abdulaziz City for Science and Technology / Program Reference
6	AHF 30494[2]	DOE ARM / Tropical Western Pacific Site Reference
7	AHF 30495[2]	DOE ARM / Southern Great Plains Working Standard
8	AHF 32448[1]	NOAA Climate Monitoring and Diagnostics Laboratory / All-Weather Reference.

NOTES:

[1] Calcium Fluoride Window Installed
[2] Corning 7940 Window Installed
[3] Suprasil-W Window Installed

Rotating the window from its original position may cause the WCF to change due to the following possible reasons:

- Sunlight polarization caused by the presence of the window

- When the window is rotated, the window plane may not be parallel to the same plane before rotation (i.e., the window may not be as perpendicular to the incoming radiation as it was before rotation).

The window orientations for the eight cavities were the same as in NPC1998 or, if new to the comparisons, the orientation for NPC1999 was marked on the window holder with respect to the outer case.

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.

5.2 Measurements

A data set of more than 450 observations, on 10 October 1999, was used to determine the window correction factor (WCF) for each of the seven participating windowed cavity radiometers. 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 Reduction Factors for the participating absolute cavity radiometers, the WCFs were computed for the windowed cavity radiometers. The resulting WRR Reduction Factors for the participating windowed cavity radiometers are presented in Table 5.3.1.

Table 5.3.1 Windowed Cavity Results

SN	WCF	SD	SD%	2SD%	N. RDGS	U95%	
						wrt WRR	wrt SI
29226	1.06373	0.00125	0.12	0.23	493	0.33	0.45
29227	1.06469	0.00093	0.09	0.17	492	0.29	0.42
30494	1.05059	0.00079	0.07	0.15	494	0.28	0.41
30110	1.06089	0.00056	0.05	0.11	458	0.25	0.39
30495	1.05083	0.00051	0.05	0.10	401	0.25	0.39
29222	1.05959	0.00063	0.06	0.12	401	0.26	0.40
31041	1.05602	0.00063	0.06	0.12	396	0.26	0.40

Note: No data were available from All-Weather AHF 32448 due to technical difficulties.

5.4 Recommendations

- The WRR Reduction 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

The meteorological elements of temperature, relative humidity and barometric pressure were measured during the comparisons using the meteorological station at SRRL. Direct, global, and difuse irradiances were measured by a NIP, PSP, and Model 8-48 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 **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.

Appendix A: List of Participants and Radiometer Inventory
NREL Pyrheliometer Comparisons (NPC1999)
4-10 October 1999

Participants Name / Address / Phone / Fax / Internet	Radiometer(s)*
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Zaid S. Al-Otaibi King Abdulaziz City for Science and Technology The Energy Research Institute P. O. Box 6086 Riyadh 11442 Saudi Arabia Phone: 966-1-488-3555 ext 1404 Fax: 966-1-481-3880 E-mail: zalotaibi@kacst.edu.sa	HF 30110
Wynn Christensen Los Alamos National Laboratory MS C323 Los Alamos, NM 87545 Phone: (505) 665-3249 Fax: (505) 667-3815 E-mail: christensen@lanl.gov	AHF 29226 AHF 29227
Chris Cornwall NOAA/ARL/SRRB 325 Broadway R/E/ARx1 Boulder, CO 80303 Phone: (303) 497-7316 Fax: (303) 497-6546 cornwall@srrb.noaa.gov	AHF 30494
Fred Denn	AHF 31041

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Fax: ___
E-mail: F.M.Denn@Larc.NASA.GOV

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CANADA
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European Commission Directorate General JRC PMO6-911204
Environment Institute
Renewable Energies Unit NIP-25738E6 <control pyrheliometer>
Building 45, TP450 CH1-930018 <control pyrheliometer>
Via Fermi, 1
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Fax: +39 0 332 789 628
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NREL Pyrheliometer Comparisons (NPC1999)
Solar Radiation Research Laboratory
4-10 October 1999

List of Absolute Cavities

No.	Serial No.	Owner / Application
1	AHF 14915*	The Eppley Laboratory, Inc. / Reference Standard
2	HF 17142*	Atlas Weathering Services-DSET Laboratories / Reference Standard
3	HF 18747*	Atmospheric Environment Service-Environment Canada / Reference Standard
4	HF 20406*	Atmospheric Environment Service-Environment Canada / Reference Standard
5	AHF 23734	NREL/Photovoltaics Program Reference
6	AHF 28553*	NOAA/Climate Monitoring & Diagnostics Laboratory (CMDL) / Reference
7	AHF 28964	U.S. Deptartment of Energy(DOE) / Atmospheric Radiation Measurement (ARM) Program / Southern Great Plains Site Reference
8	AHF 28968*	DOE/ARM Program Reference
9	AHF 29220*	NREL/SRRL Traveling Cavity Reference System
10	AHF 29222	DOE/ARM-Southern Great Plains / All-Weather
11	AHF 29226	Los Alamos National Laboratory / ARM-Unmanned Aerospace Vehicle
12	AHF 29227	Los Alamos National Laboratory/ARM-Unmanned Aerospace Vehicle
13	HF 30110*	King Abdulaziz City for Science and Technology/Program Reference
14	AHF 30114	Bukit Kototabang WMO Global Atmospheric Watch Station / Indonesian Reference
15	AHF 30494	DOE/ARM-Tropical Western Pacific Site Reference
16	AHF 30495	DOE/ARM-Southern Great Plains Working Standard

17	AHF 30710	NOAA/Solar Radiation Research Branch Reference
18	AHF 30713	NREL/Metrology Lab Reference Standard #1
19	AHF 31041	NASA/Clouds and the Earth's Radiant Energy System (CERES)
20	AHF 31104	NREL/Metrology Lab Working Standard
21	AHF 32448	NOAA/CMDL All-Weather
22	PMO6-811109*	European Commission Directorate General
23	PMO6-911204*	European Commission Directorate General
24	TMI 68017	NREL/SRRL All-Weather
25	TMI 68018*	NREL/Metrology Lab Reference Standard #2

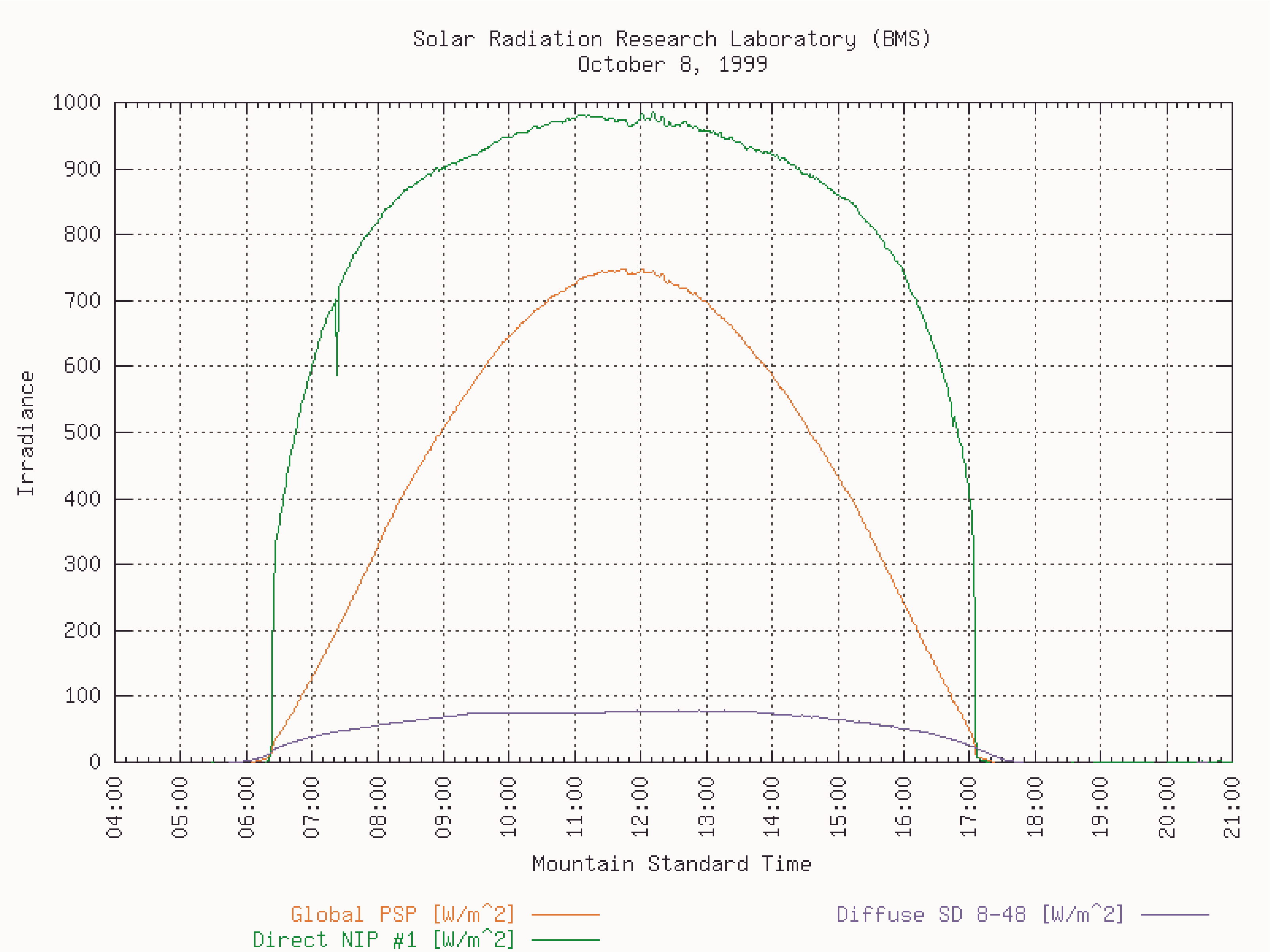
* Radiometer participated in International Pyrheliometer Comparison(s) or has direct traceability to the WRR.

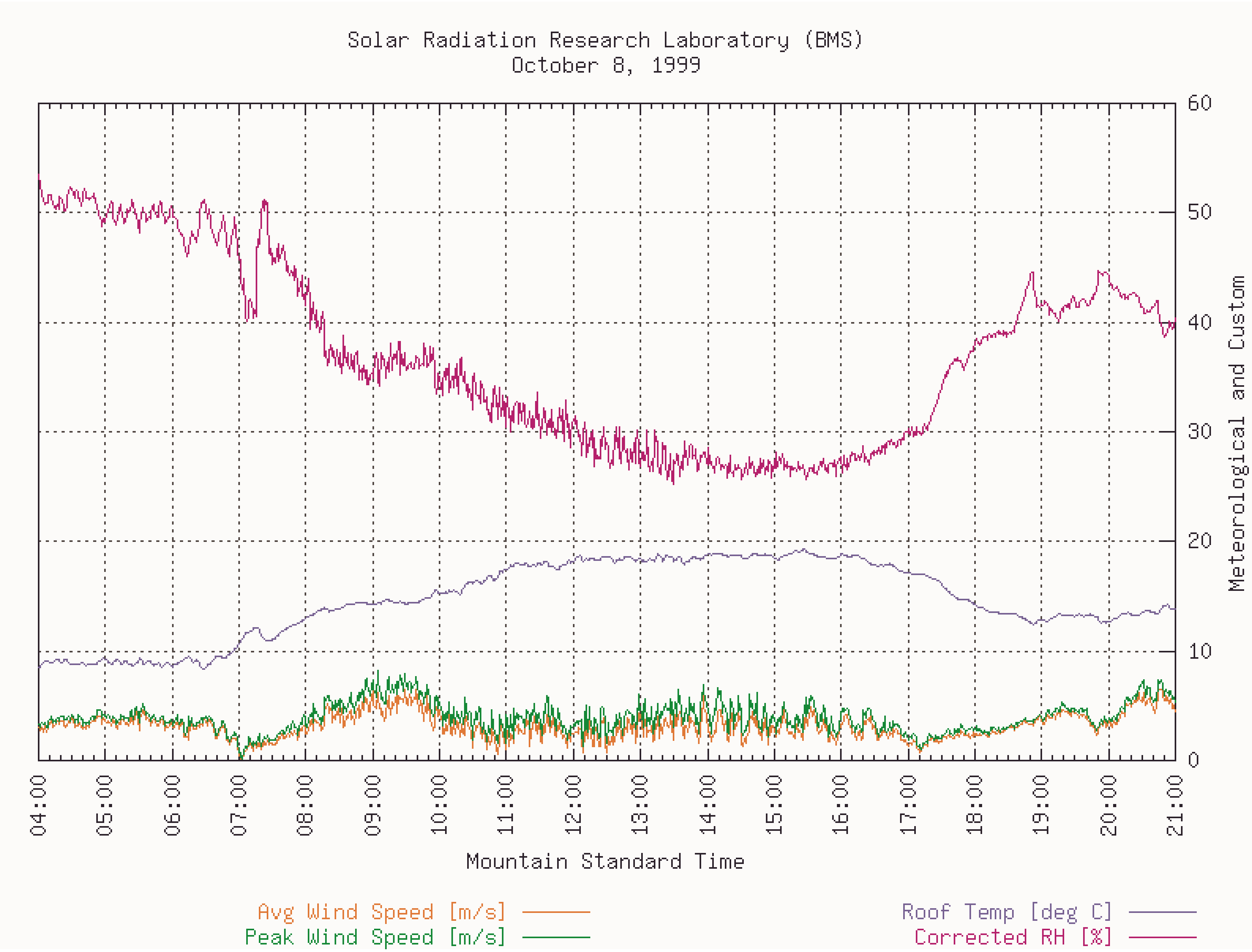
Appendix B: Ancillary Data Summaries

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 Renewable Resource Data Center: http://rredc.nrel.gov.

Time-series plots and other graphical presentations of these data acquired during the three days of NPC1999 measurements are presented here.

SRRL Baseline Measurement System Data for October 8, 1999

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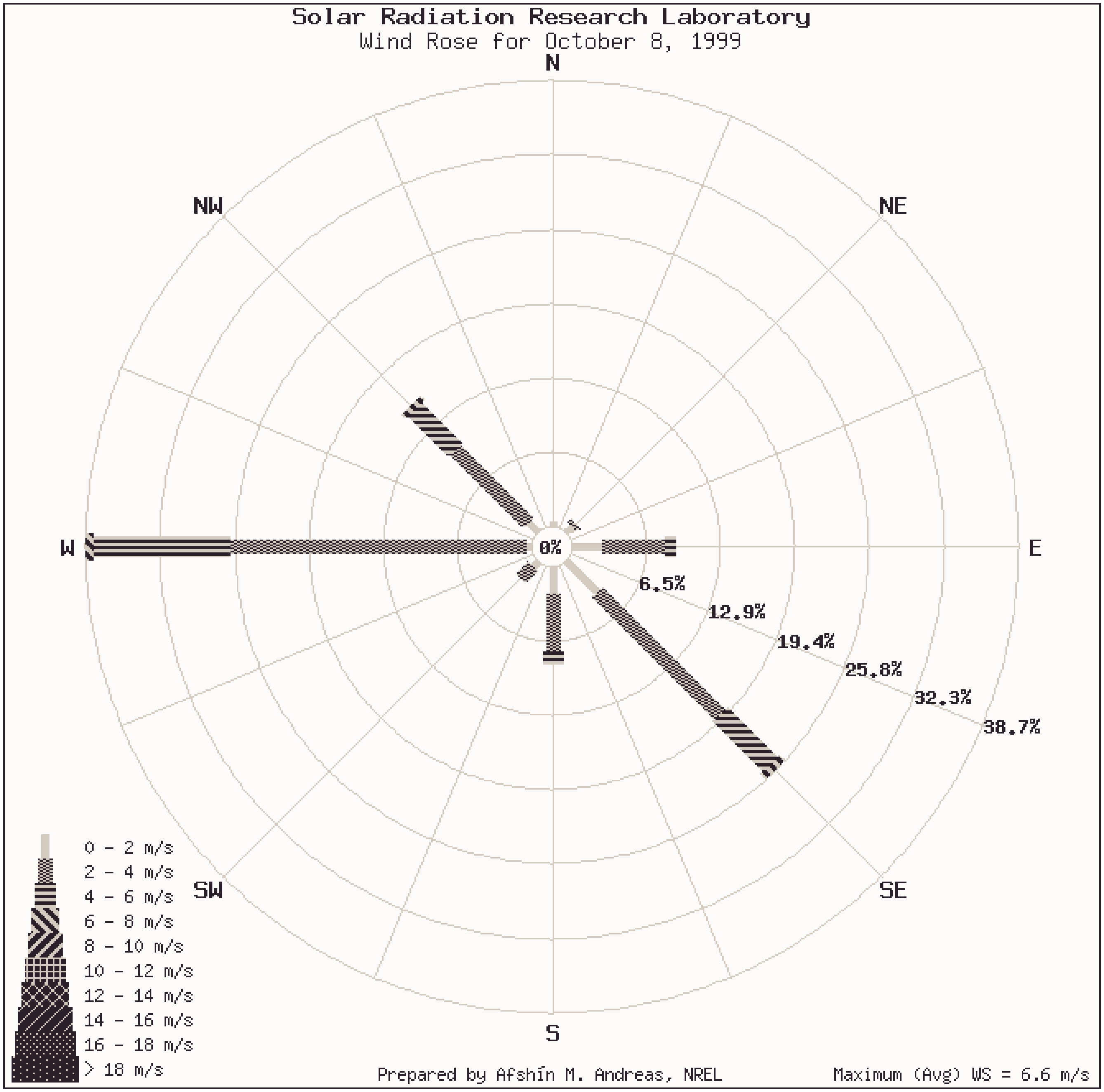
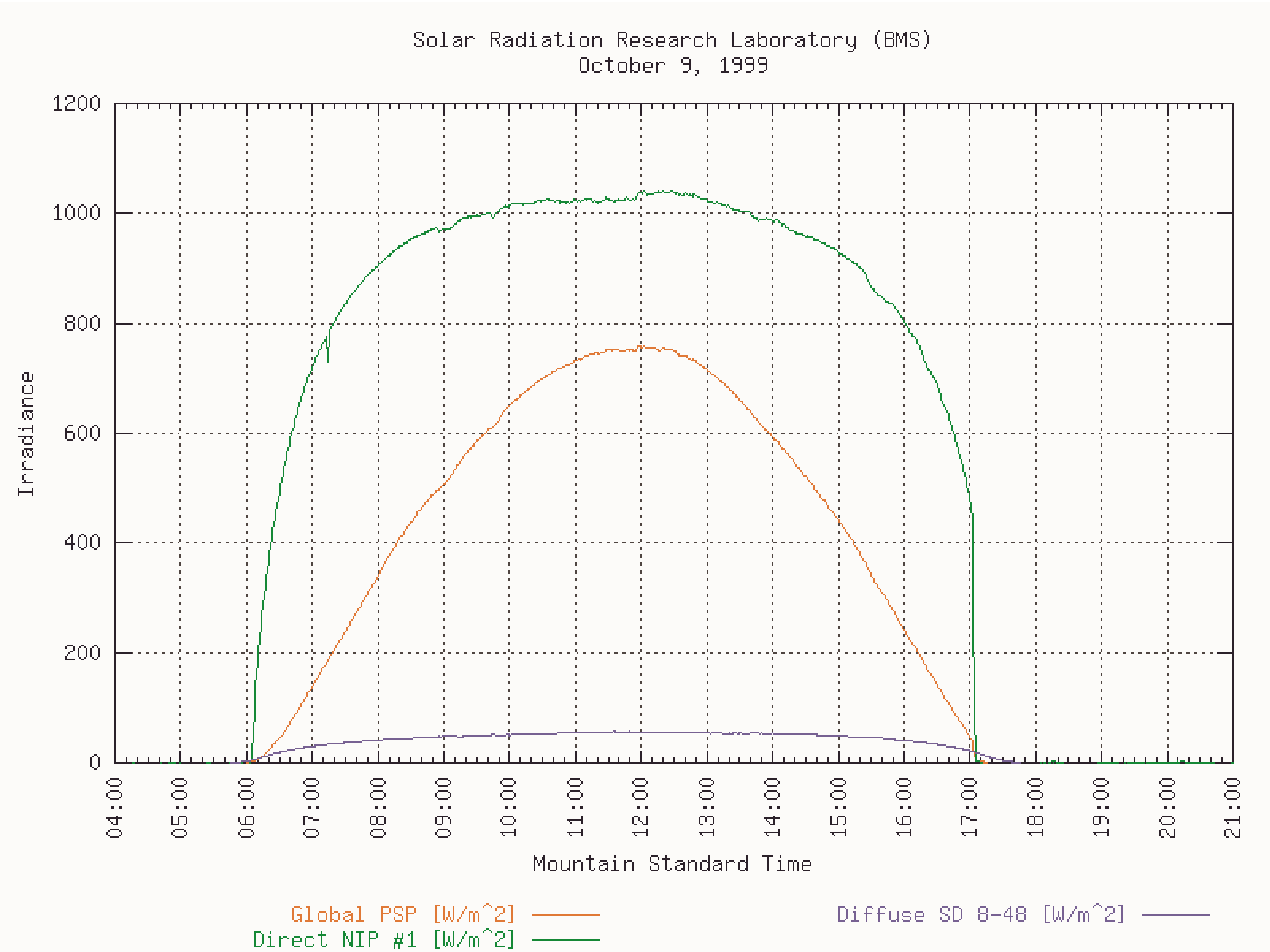
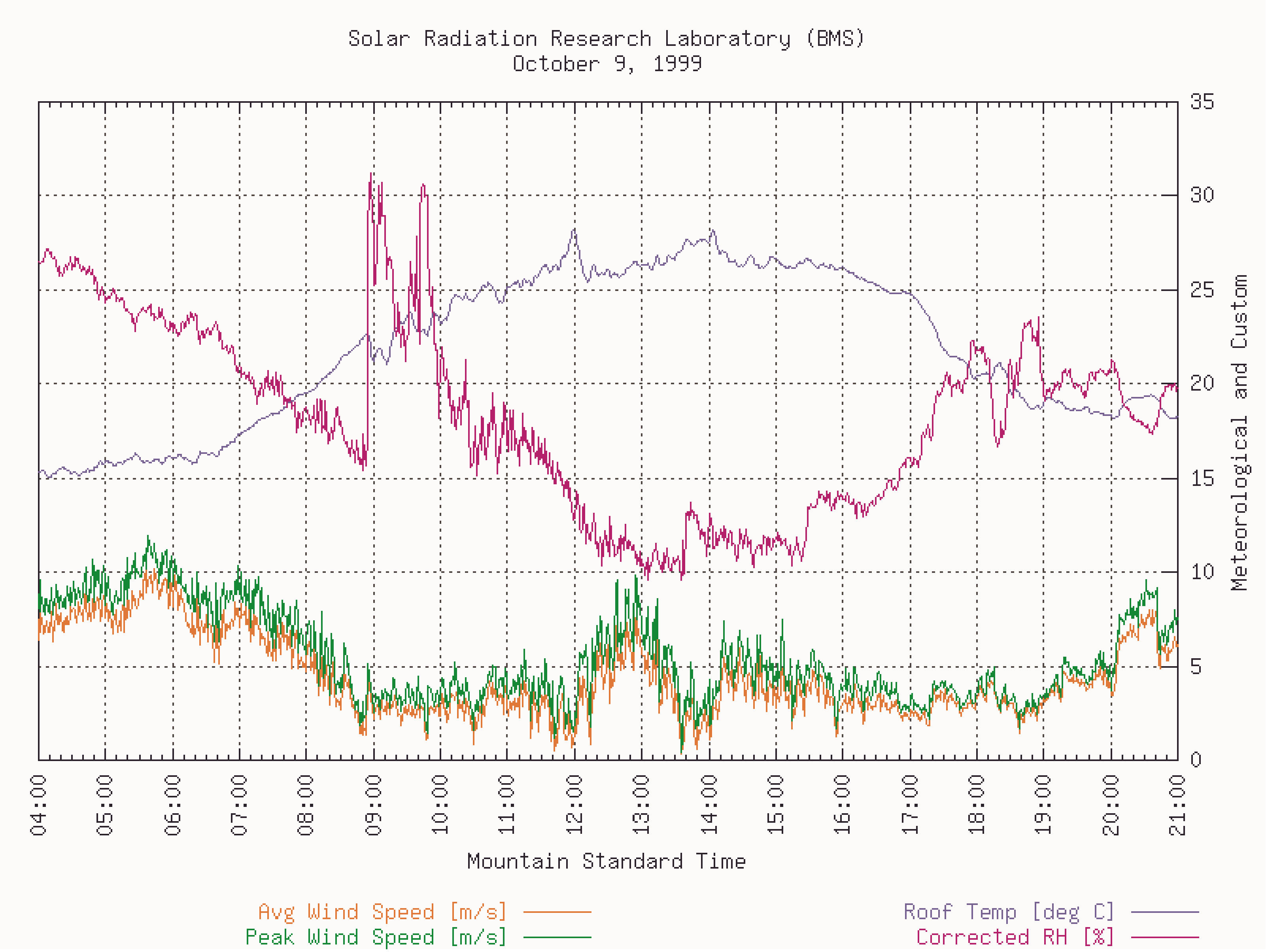
October 8, 1999
Meteorological and Custom
0
10
20
30
40
50
60
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Mountain Standard Time
Avg Wind Speed [m/s]
Peak Wind Speed [m/s]
Roof Temp [deg C]
Corrected RH [%]


Solar Radiation Research Laboratory
Wind Rose for October 8, 1999
N
NW
NE
W
0%
E
6.5%
12.9%
19.4%
25.8%
32.3%
38.7%
SW
SE
S
0 - 2 m/s
2 - 4 m/s
4 - 6 m/s
6 - 8 m/s
8 - 10 m/s
10 - 12 m/s
12 - 14 m/s
14 - 16 m/s
16 - 18 m/s
> 18 m/s
Prepared by Afshin M. Andreas, NREL
Maximum (Avg) WS = 6.6 m/s

SRRL Baseline Measurement System Data for October 9, 1999




Solar Radiation Research Laboratory (BMS)
October 9, 1999
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30
25
20
15
10
5
0
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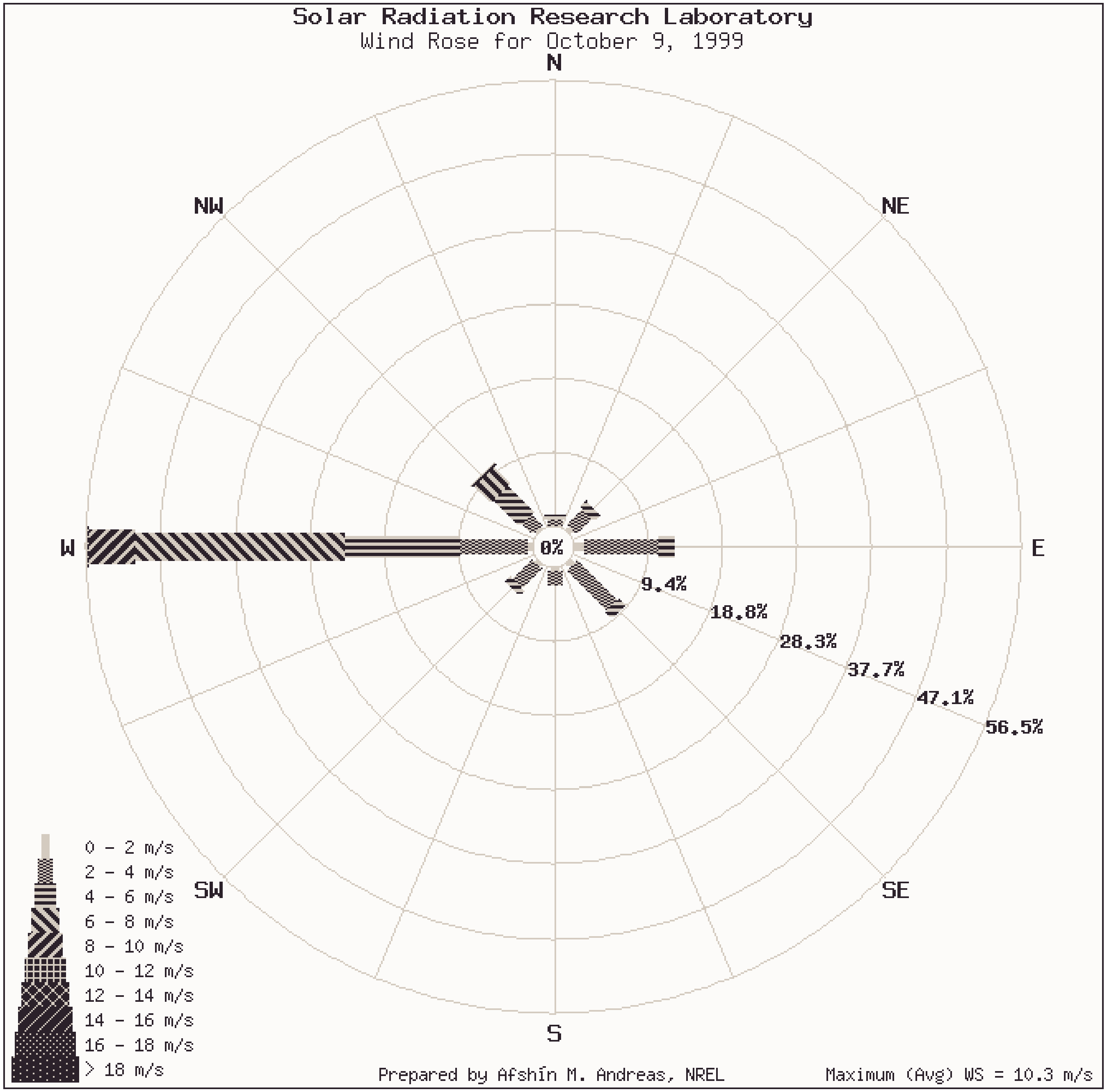
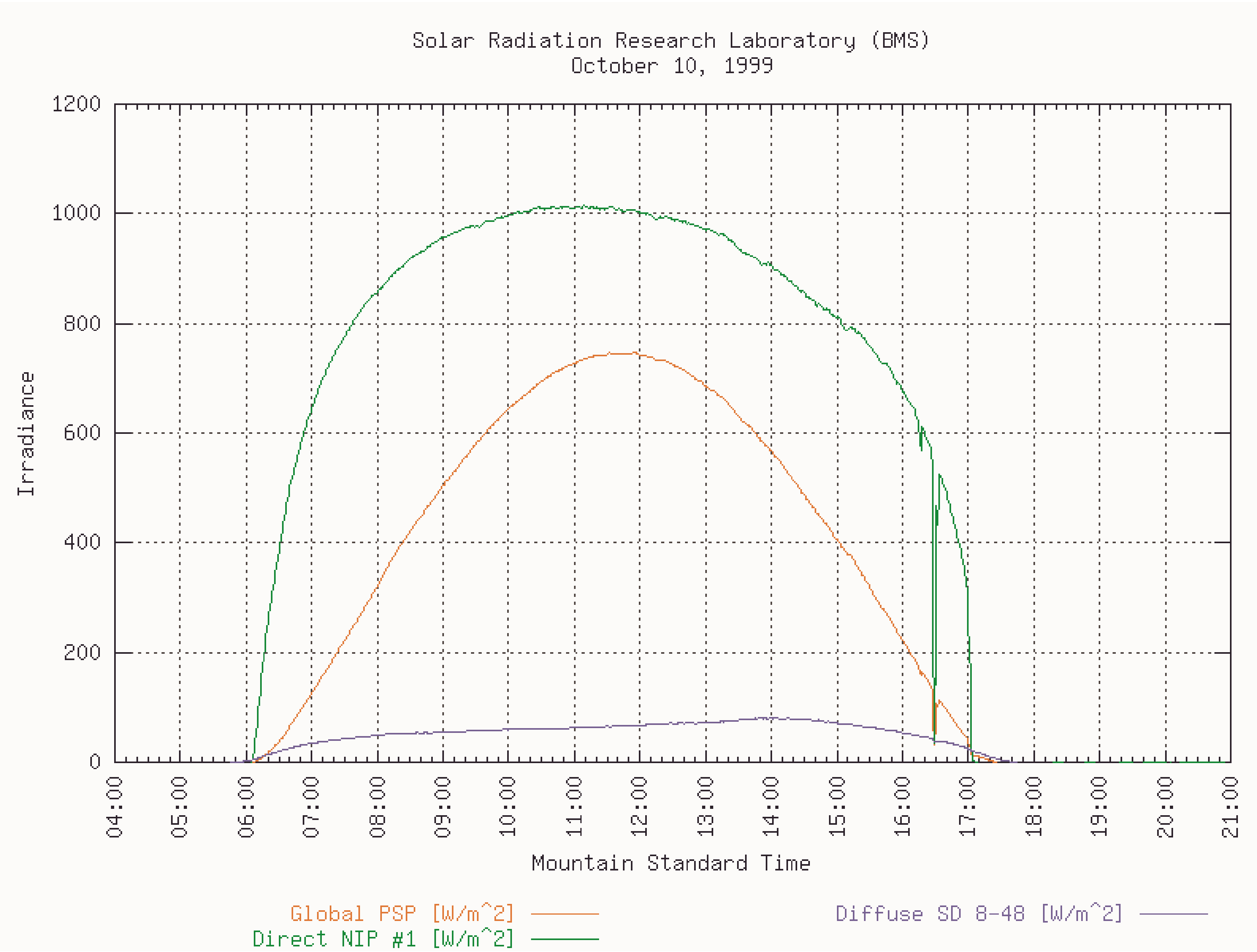
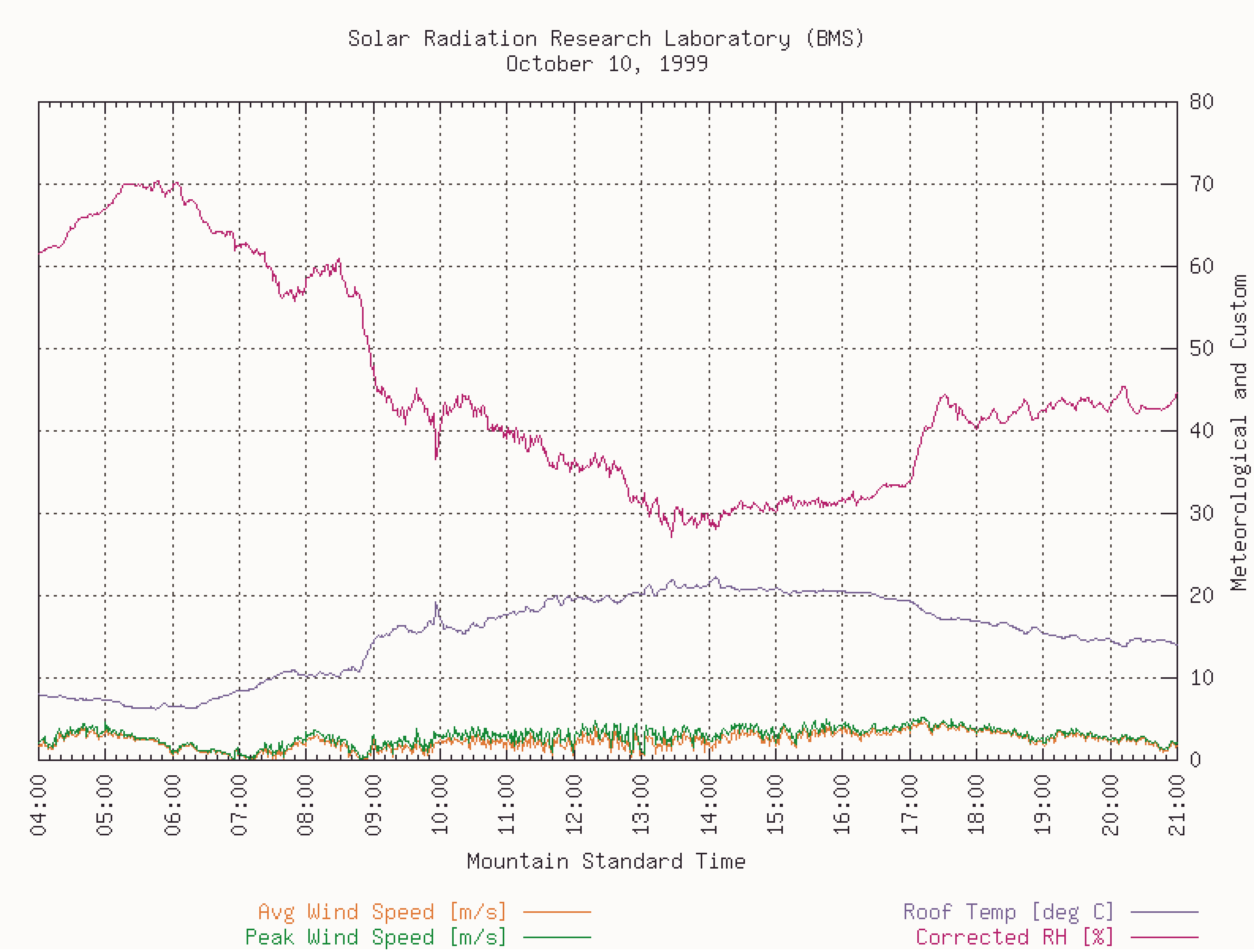
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Mountain Standard Time
Avg Wind Speed [m/s]
Peak Wind Speed [m/s]
Roof Temp [deg C]
Corrected RH [%]


Solar Radiation Research Laboratory
Wind Rose for October 9, 1999
N
NE
E
SE
S
SW
W
NW
0%
9.4%
18.8%
28.3%
37.7%
47.1%
56.5%
0 - 2 m/s
2 - 4 m/s
4 - 6 m/s
6 - 8 m/s
8 - 10 m/s
10 - 12 m/s
12 - 14 m/s
14 - 16 m/s
16 - 18 m/s
> 18 m/s
Prepared by Afshin M. Andreas, NREL
Maximum (Avg) WS = 10.3 m/s

SRRL Baseline Measurement System Data for October 10, 1999




Solar Radiation Research Laboratory (BMS)
October 10, 1999
80
70
60
50
40
30
20
10
0
Meteorological and Custom
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
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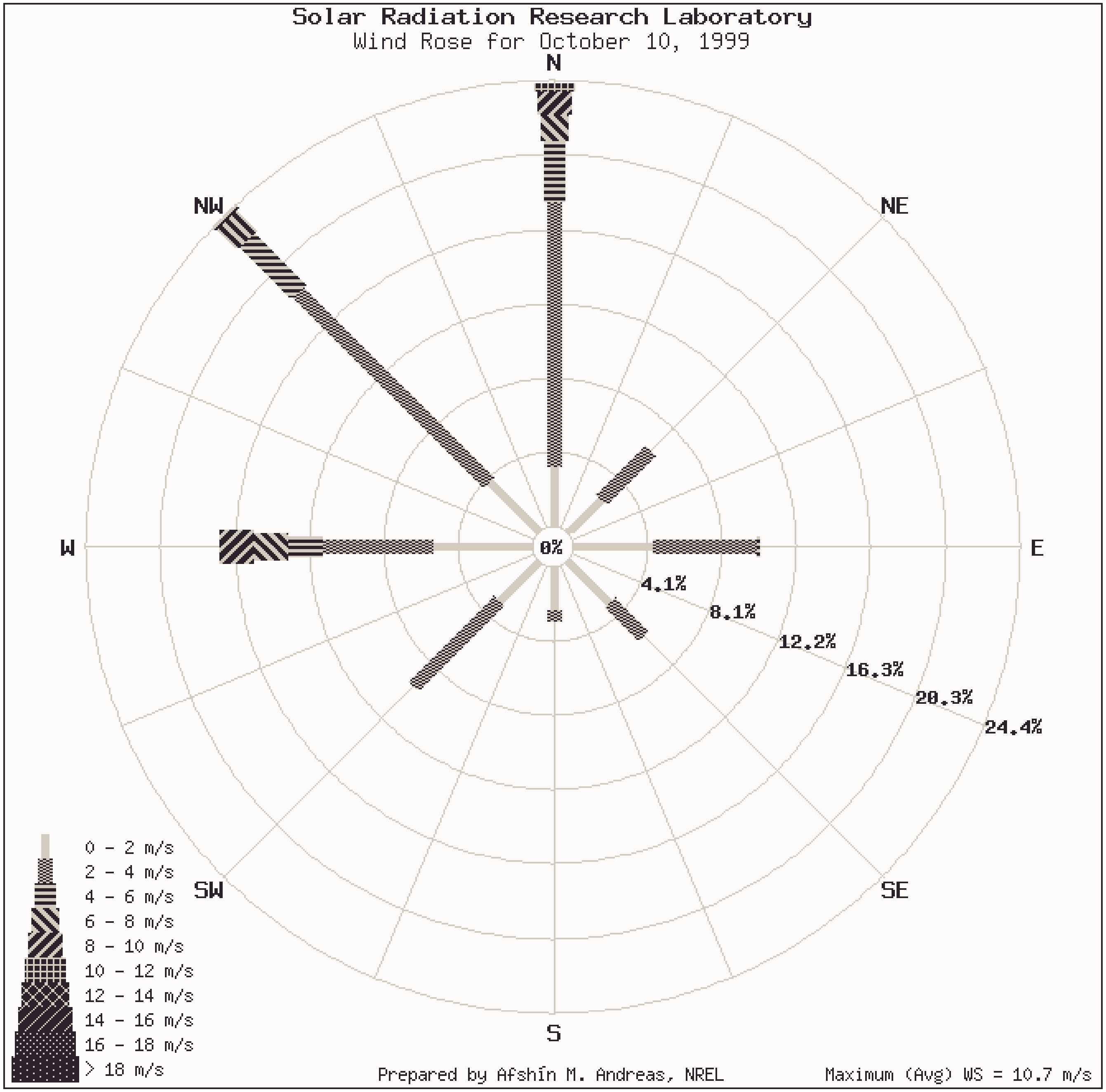
21:00
Mountain Standard Time
Avg Wind Speed [m/s]
Peak Wind Speed [m/s]
Roof Temp [deg C]
Corrected RH [%]


Solar Radiation Research Laboratory
Wind Rose for October 10, 1999
N
NE
E
SE
S
SW
W
NW
0%
4.1%
8.1%
12.2%
16.3%
20.3%
24.4%
0 - 2 m/s
2 - 4 m/s
4 - 6 m/s
6 - 8 m/s
8 - 10 m/s
10 - 12 m/s
12 - 14 m/s
14 - 16 m/s
16 - 18 m/s
> 18 m/s
Prepared by Afshin M. Andreas, NREL
Maximum (Avg) WS = 10.7 m/s

For more information go to: http://www.nrel.gov/midc/srrl_bms/

Appendix C: Operational Notes

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

1999 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 *NPC1999* (NREL Pyrheliometer Comparisons 1999).

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.

October 4th:

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.We will have a seating diagram to accommodate 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.

October 5-15 (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.

- 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 time keeper 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 31 readings taken in sequence.
Shade & Calibrate	=	Perform electrical calibration after each run.

The time keeper 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 31 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 tear-down, 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
NPC1999 will conclude after all items are returned to the proper storage locations.
(See Jim for details)

13. Contacts

Daily Voice Mail Announcement:

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>
JimTreadwell ....(303) 275-4690 <Voice Mail ONLY>
Bev Kay..........................(303) 384-6388 <Real Person>

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

NREL EMERGENCY................. 1 2 3 4