

# **Traceability and Verification of Radiometer Calibrations at the Southern Great Plains Radiometer Calibration Facility**

*S. M. Wilcox and I. Reda  
National Renewable Energy Laboratory  
Golden, Colorado*

*D. A. Nelson and C. Webb  
Southern Great Plains Central Facility*

## **Introduction**

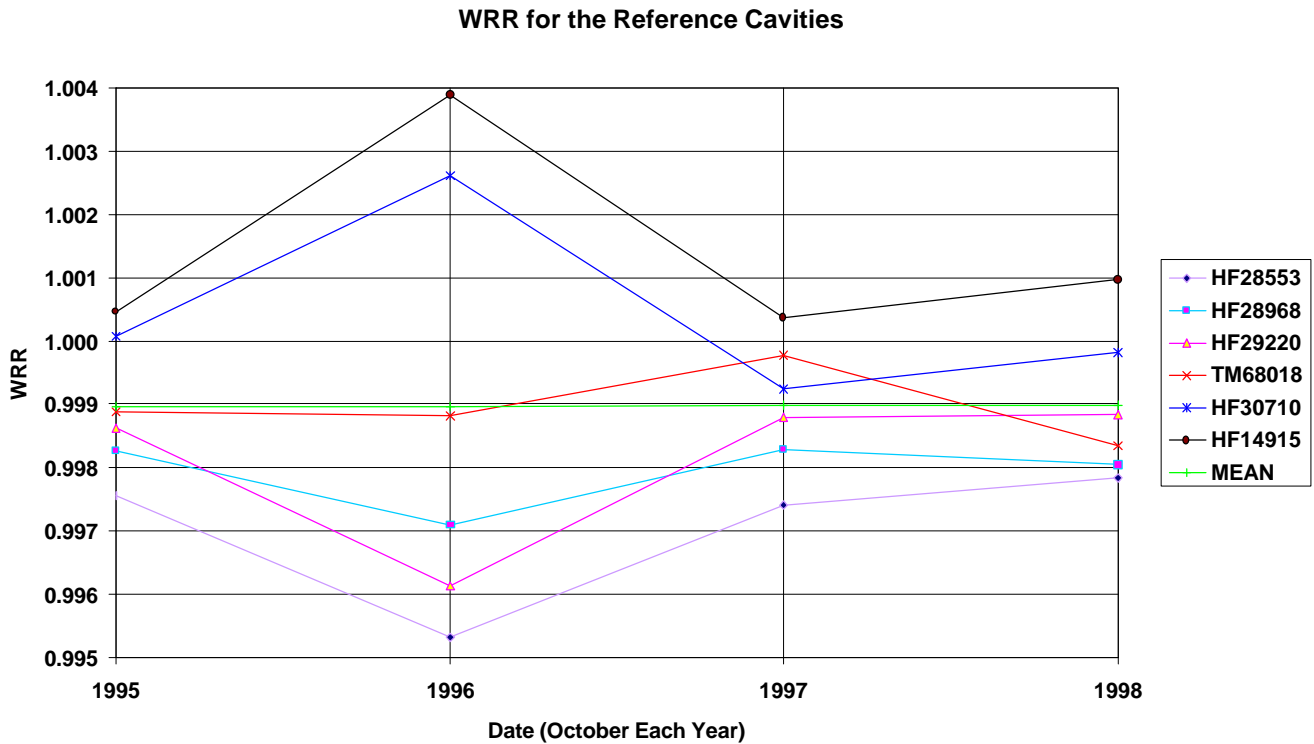
The Radiometer Calibration Facility at the Southern Great Plains (SGP) central facility annually calibrates more than 100 radiometers deployed for routine operations at the 22 SGP measurement sites. Among the factors that affect the reliability of these measurements are traceability of the calibration to the World Radiometric Reference (WRR) and independent verification of calibration results. A series of absolute cavity radiometer intercomparisons establishes and documents the traceability of broadband shortwave radiometers used by the Atmospheric Radiation Measurement (ARM) Program to the WRR. This process also provides values for measurement uncertainty. The Broadband Outdoor CALibrations (BORCALs) at the SGP are independently verified through a set of Measurement Assurance Standard instruments that alternate between calibration events at SGP and the National Renewable Energy Laboratory (NREL).

## **World Radiometric Reference**

The WRR has been maintained by the World Radiation Center (WRC) in Davos, Switzerland, through seven Absolute Cavity Radiometers, known as the World Standard Group (WSG). The WRR is maintained by periodic comparisons of the WSG and maintaining the mean of their WRR reduction factors. An International Pyrheliometer Comparison (IPC) is held every five years to transfer the WRR to cavities from other participating countries. In the period between IPC events, an intercomparison is held annually at NREL to verify and maintain the stability of the WRR scale transferred through the IPC events. This intercomparison also transfers the WRR to other cavities used by other organizations. Six U.S. cavities that participate in the IPC are used to maintain the transferred WRR in the United States. The mean of their transferred WRR reduction factors is maintained through the five-year period using the same method used at the WRC.

Among the six IPC participating cavities used in the NREL intercomparison are the ARM Program reference cavity (AHF 28968) and two NREL radiometric reference cavities (AHF 29220 and TMI 68018). In addition, the ARM SGP Site Reference cavity (AHF 28964), the ARM working standard cavity (AHF 30495) and the ARM all-weather cavity (AHF 29222) all participate in the intercomparison

at NREL to maintain their traceability to the WRR. Cavities AHF 30495 and AHF 29222 are used in the regularly scheduled BORCAL events at the SGP calibration facility. Figure 1 shows the maintained mean of the six cavity radiometers used in the NREL intercomparisons to maintain WRR traceability since the last IPC in 1995.



**Figure 1.** Results of absolute cavity comparisons since IPC-1995.

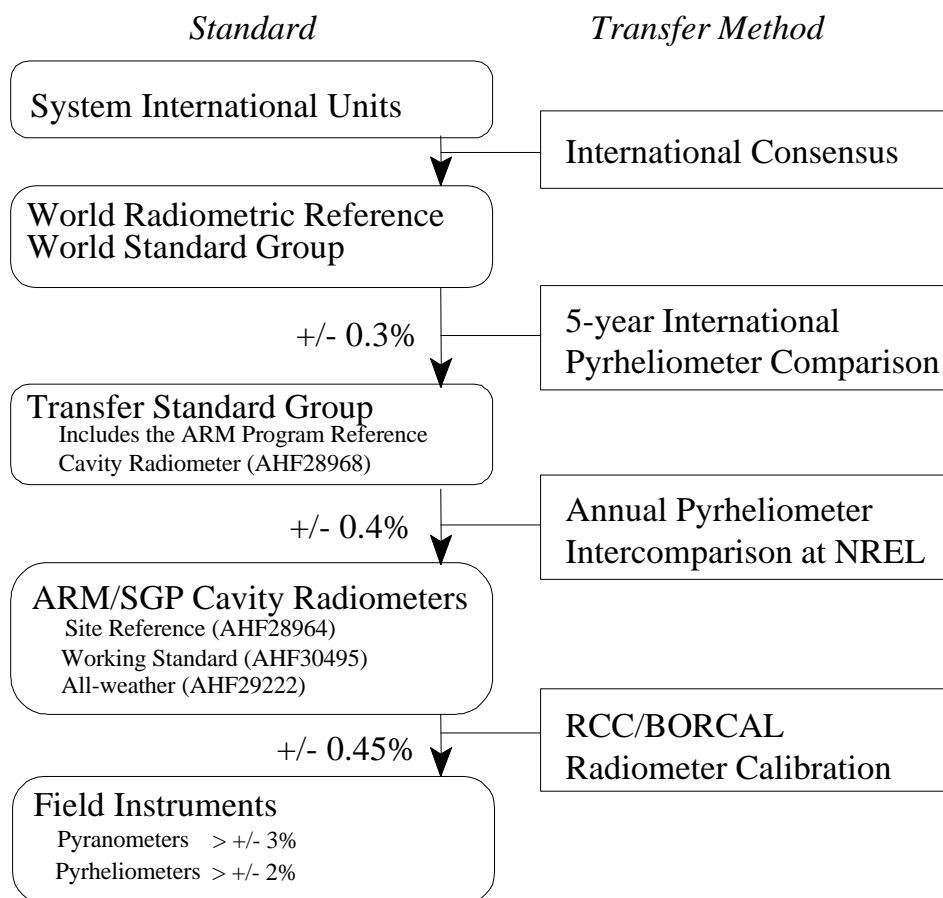
Figure 2 shows the traceability of the ARM cavity radiometers to the WRR.

## Process-Monitoring Instruments

As part of the SGP calibration system, two sets of instruments were identified as special groups to monitor the calibration process and validate the results. These sets are:

- Control group
- Measurement Assurance Standard (MAS) groups (two groups).

The control instruments are used only during the calibration events and are never used in the field for measurements. The rationale is that much of the physical changes that cause a shift in a radiometer's responsivity are due to exposure to the elements, particularly ultraviolet light. Thus, by limiting the



**Figure 2.** ARM radiometer calibration traceability to the WRR.

exposure to sunlight to only a few days a year, instruments in this group of seven instruments (six precision spectral pyranometers [PSPs] and one normal incidence pyrheliometer [NIP]) are expected to maintain a constant sensitivity and hence, are expected to show consistent responsivities from one BORCAL to another.

The MAS are similar to Control instruments in that they are used only during a calibration event. The 14 MAS instruments (two groups of six PSPs and one NIP each) are alternately calibrated at the SGP calibration facility and the calibration facility at the NREL Solar Radiation Research Laboratory. In practice, while MAS group 1 is deployed at the SGP, MAS group 2 is deployed at NREL. Then the instrument groups are swapped for a subsequent calibration. The frequency of swaps occurs at intervals of one year or less. This exchange of instruments for calibration should show consistencies among instruments at each calibration facility and also consistencies among calibrations between the two facilities.

## Expected Results from MAS

There are identified variables in the calibration process that contribute to the uncertainty of the results. Among the most dominant are:

- The WRR
- Transfer of WRR to working standards
- Data logger accuracy
- Incidence angle computations.

Contributing to those variables are site-specific factors such as latitude, atmospheric conditions, and physical characteristics of the calibration facility. Hence, in addition to differences that can be attributed to variability from one calibration event to another, additional factors may contribute to differences between calibration sites. Time of year can also be an influential factor because of an inconsistent azimuthal response of many instruments that changes instrument sensitivity as a function of differing solar zenith and azimuth angle combinations.

Because of the inability to control many of these factors, the overall uncertainty assigned to the BORCAL process is a 1.3% base uncertainty *plus* a value based on the scatter of the calibration data that usually equals or exceeds the base uncertainty. Nonetheless, we expect the consistency of results to fall within the estimated uncertainty for each instrument.

## Analysis

Table 1 identifies the 21 instruments by serial number that comprise the Control and MAS groups:

<b>Table 1.</b> Radiometers assigned to MAS and Control groups (by serial number).		
<b>MAS 1</b>	<b>MAS 2</b>	<b>Control</b>
31122E6	31121E6	31120E6
31149F3	31146F3	31099F3
31150F3	31147F3	31100F3
31151F3	31148F3	31101F3
31158F3	31155F3	31152F3
31159F3	31156F3	31153F3
31160F3	31157F3	31154F3

These instruments were calibrated several times during 1997 and 1998 at SGP and NREL. Initially, all instruments were calibrated at both facilities, then the routine was implemented to maintain the Control group at SGP and regular swaps of the MAS groups between NREL and SGP. Table 2 summarizes the calibration histories for these instruments.

Group	NREL9701	SGP9701	SGP9702	SGP9801	NREL9801	SGP9802	NREL9803
MAS 1	✓	✓			✓	✓	
MAS 2	✓	✓	✓	✓			✓
Control	✓	✓	✓	✓		✓	

Because of the recent calibrations at both facilities, the Control group was treated in this analysis as a MAS group to increase the sample size.

To compare the results between the two calibration facilities, the following methodology was used. For each instrument, determine the mean responsivity for all calibrations at both facilities. Then for each instrument, normalize the individual calibration result to the mean for that instrument (divide the instrument's responsivity for that calibration by the mean responsivity for that instrument). This approach allows a ranking of responsivities by BORCAL for each instrument, and when aggregate instrument results are viewed by BORCAL, the data would tend to show any bias in the calibration process.

## Results

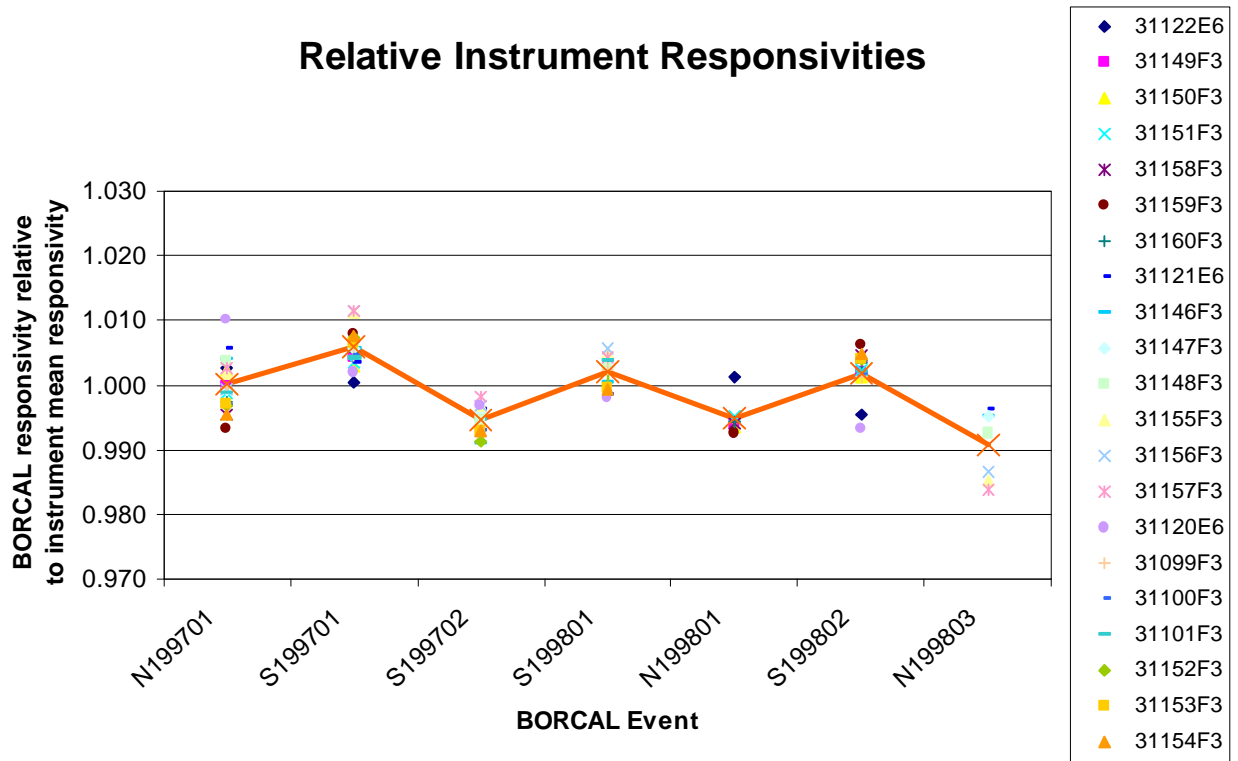
Figure 3 shows normalized results of the individual instruments as a series against the BORCALs (which are in chronological order). The mean for each instrument is superimposed on the scatter of data. Although this plot clearly shows variability among BORCALs, the difference of the means is less than  $\pm 1\%$ , well within the uncertainty of the calibration process (approximately 3% to 5%).

To better compare the differences between the NREL and SGP calibrations, Figure 4 shows the BORCAL events as a series against individual instruments (which are listed in order by serial number within their functional group). The NREL calibration results are shown in bold markers, and the SGP results are shown in narrow markers.

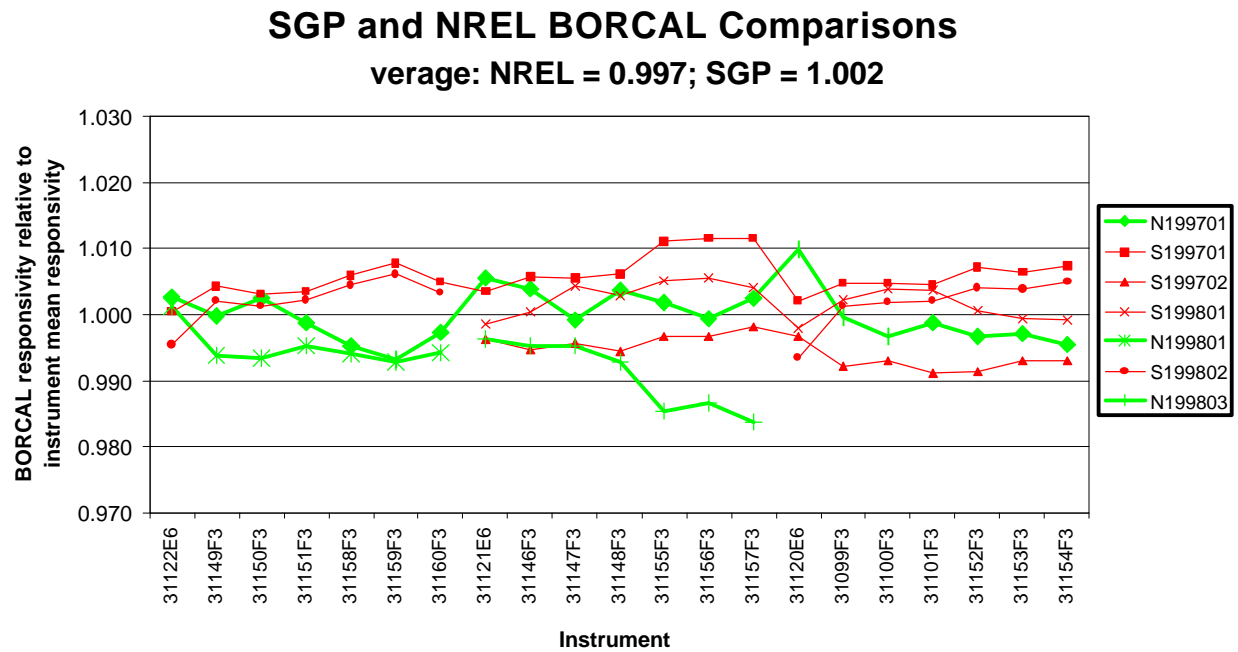
Note that the average results between the two facilities differ by only about half a percent (0.005). Although the sample size is too small to draw statistical conclusions about the significance of these results, it is apparent that the difference in these samples is quite small compared with the overall variability of individual instruments (about 3%).

Some other interesting observations can be made looking at the data. Three instruments (31155F3, 31156F3, and 31157F3) are notable outliers in NREL BORCAL 199803. These instruments, being of adjacent serial numbers, may disclose a contribution of the manufacturing process to the overall uncertainty of a measurement. Although these instruments don't show the same bias in the other calibration events, it may indicate sensitivity to certain conditions present during that calibration event.

Note also that the three NIPs (31122E6, 31121E6, and 31120E6) stand out as high outliers on the plot of NREL BORCAL 199701. This could be attributed to atmospheric conditions or tracker alignment that imposed a bias on the results for NIPs.



**Figure 3.** Summary results for MAS and Control group radiometers as a function of the BORCAL event.



**Figure 4.** Comparison of mean BORCAL results for each MAS and Control instrument.

## **Conclusions**

- The ARM Program maintains the calibration traceability of broadband, shortwave radiometers to the WRR with a group of well characterized reference and working standard absolute cavity radiometers.
- The broadband shortwave radiometer calibrations at SGP are well controlled, providing results that are consistent and verifiable with the Radiometer Calibration and Characterization (RCC)/BORCAL process used by NREL.
- A group of 21 radiometers, identical to the field instruments now in the Solar Infrared Station (SIRS), has been selected as Measurement Assurance and Control standards for monitoring the RCC/BORCAL processes at the SGP and at NREL. The results from seven BORCAL events suggest an inter-laboratory difference of less than 0.5% with no clear bias.
- Comparisons of the BORCAL results for the MAS at the SGP and at NREL will continue to provide annual verifications of the radiometer calibration process sufficient to meet the needs of the ARM Program.
- The BORCAL process has been transferred from its origin at NREL to a successful implementation at the SGP facility. This transfer includes construction of the facility, electrical design and layout, equipment, and training for the staff.