Improved Methods for Broadband Outdoor Radiometer Calibration (BORCAL)

S. M. Wilcox, A. Andreas, I. Reda, and Daryl Myers
National Renewable Energy Laboratory
Golden, Colorado

Abstract

The Atmospheric Radiation Measurement (ARM) Program deploys approximately 100 radiometers to measure broadband solar radiation at stations in the North Slope of Alaska (NSA), Southern Great Plains (SGP), and Tropical Western Pacific (TWP) Cloud and Radiation Testbed (CART) sites. Two broadband outdoor radiometer calibration (BORCAL) events performed at the SGP radiometer calibration facility (RCF) each year maintain radiometer calibration traceability to the World Radiometric Reference and assure reliable and uniform measurements at each CART site. Calibrations are performed using the radiometer calibration and characterization (RCC) software developed by the National Renewable Energy Laboratory, allowing simultaneous calibrations of up to 200 instruments.

The first generation RCC installed in 1996 was developed and implemented on a DOS computing platform. Subsequent advances in operating systems and connectivity technology outdated the system’s computing environment, and the system became difficult to maintain. These issues and recent improvements in radiometer calibration knowledge led to the upgrade of RCC to a Windows-based product with improved functionality and a more flexible user interface. This poster describes changes and functional improvements in the new system: a more comprehensive basis for calculating calibration uncertainty, accommodation of new state-of-the-art cavity radiometer reference instruments at the RCF, implementation of improved diffuse reference measurements, improved reporting of calibration results, the ability to perform tilt calibrations for increasing pyranometer angular response measurements, improved event configuration, and the capability to correct and document data acquisition or configuration errors.

BORCAL Configuration

Figures 1 and 2 show the enhanced BORCAL event configuration capabilities. In Figure 1, the hierarchical configuration schema is depicted. The operator starts with a configuration overview screen, from which system instruments (such as reference instruments, data logger, etc.) may be selected and test instruments configured. During the selection process, the system allows access to the instrument database, which provides easy access to instrument information. In Figure 2, the configuration is verified by following a set protocol in which operators work as a pair; one identifying the physical instrument at the calibration platform and the other identifying the configured instrument in the system. Ultimately, the instrument and its system configuration are directly related and confirmed by shading the physical instrument and watching the change in instrument voltage in the system.

Twelfth ARM Science Team Meeting Proceedings, St. Petersburg, Florida, April 8-12, 2002
**Event Configuration**

Configuration is accomplished through a hierarchical data base selection process for instruments and system parameters.

Configuration is summarized in the top-level window.

Information is drawn from the underlying Access data tables.

---

**Configuration Verification**

Configuration verification is conducted by a two-person team. For each instrument, the configuration is verified using a prescribed process of visual inspection and data logging.

Step 1: The instrument ID is visually verified and relayed to the computer operator.

Step 2: The instrument ID located in the RCC system and logging commenced.

Step 3: The instrument is shaded for several seconds. The computer operator confirms the telltale drop in instrument voltage.

Step 4: The instrument location and cabling is visually verified and compared to the RCC configuration.

Step 5: The instrument is marked as verified.

Verification Path: Visual ➔ System Configuration ➔ Data Logging

---

Figure 1.

Figure 2.
Data Acquisition

Figure 3 shows an overview of the data acquisition, which includes extensive graphing and real-time error checking. Alarm conditions are identified, alerting the operator to resolve problems and minimize the amount of data collected under error conditions. This improves the quality of the data and reduces the uncertainty of the calibration results.

Database Maintenance

All configuration, instrument, and results are stored in a Microsoft Access database. The system provides a suite of database maintenance tools for viewing data, configuration correction, and results analysis, as shown in Figure 4.

Calibration Calculations

Figures 5 and 6 show the reference irradiance sources for each type of calibration used for calculating instrument responsivity. Depending on the instrument, the reference irradiance comes from the cavity radiometer, the diffuse radiometer, or component summation technique of the two. Additional pyranometer characterizations are shown in Figure 7.
Database Maintenance Tools

- Data Editing Forms
- Data Access
- System Data Tables
  - Instrument Inventory
  - Customer
  - Calibration Results
  - System Configuration
  - Calibration Facility
  - Data Acquisition
- Data Plotting Tools
- Calibration Results

Figure 4.

Responsivity Calculations

During the calibration event, responsivity is calculated at 30-second intervals as:

$$RS = \frac{\text{Thermopile Voltage}}{\text{Reference Irradiance}}$$

Reference Irradiance

- Direct Beam Reference Irradiance
  Measured by the absolute cavity radiometer.

- Diffuse Reference Irradiance
  Measured by two Eppley 8-48 pyranometers

- Global Reference Irradiance
  Calculated from Direct Beam and Diffuse Reference
  $$\text{Glo} = \text{Dir} \cdot \cos(\text{zenith}) + \text{Dif}$$

Pyrheliometers

Shaded Pyranometers*

Pyranometers

*Experimental

Figure 5.
Instrument Responsivity

Responsivity (RS) is Calculated from the 30-second Individual Instrument Responsivities

Reported Instrument Responsivity

Mean of all 30-second RS at 45° ±0.3°

Additional Pyranometer Characterizations

2-degree
Mean of all 30-second RS ±0.3° at 2° zenith angle increments

Respnsivity Function: RS(z)
Polynomial in cos(z), fitted to all available 2-degree responsivities

45-55 Degree
Mean of responsivities calculated from RS(z) between 45° - 55°

9-degree Bins
Mean of responsivities calculated from RS(z) over 9° wide intervals

Composite
Cosine weighted from z = 0° to 90° of RS(z)

Latitude Optimized
Latitude limited, calculated from RS(z) and latitude
Uncertainty Calculations

Figure 8 shows the sources of calibration uncertainty in the RCC process. These sources are different for pyranometers and pyrheliometers. Figure 9 shows the calibration uncertainty calculations for pyranometers and pyrheliometers respectively.

<table>
<thead>
<tr>
<th>Sources of Calibration Uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRR Transfer of Direct Beam Irradiance</td>
<td>~ 0.4%</td>
</tr>
<tr>
<td>Data Logger</td>
<td>~ 0.12%</td>
</tr>
<tr>
<td>Zenith Angle Calculations (&lt; 75°)</td>
<td>~ 0.06%</td>
</tr>
<tr>
<td>Diffuse Sky Irradiance (w.r.t. reference global)</td>
<td>~ 0.25% - 2.5%</td>
</tr>
</tbody>
</table>

**Base Uncertainty** for each data point as Root Sum Square of Sources of Uncertainty (with respect to reference irradiance)

Pyrheliometers

- ~ 0.5%
  - Excludes zenith angle and diffuse irradiance uncertainties

Pyranometers

- ~ 0.8% – 3.0%
  - Includes zenith angle and diffuse irradiance uncertainties

Figure 8.

Results and Reporting

The RCC system produces calibration certificates that conform to intraseasonal oscillations (ISO) guidelines. Sample certificates are shown in Figure 10. In addition to the calibration certificates, the RCC system produces suggested methods of applying the calibration results. The different methods are shown in Figure 11. As part of the need to distribute calibration results, the system has several built-in data exporting functions, including a customizable export that is compatible with common data format conventions. Examples of RCC exports are shown in Figure 12.

Results and Reporting

The RCC system produces calibration certificates that conform to ISO guidelines. Sample certificates are shown in Figure 10. In addition to the calibration certificates, the RCC system produces suggested methods of applying the calibration results. The different methods are shown in Figure 11. As part of the need to distribute calibration results, the system has several built-in data exporting functions, including a customizable export that is compatible with common data format conventions. Examples of RCC exports are shown in Figure 12.
**Calibration Uncertainty**

Calculated from 30-second data points

### Terms
- \( U_{avg} \) = Mean of base uncertainties (%)
- \( U_{std} \) = Standard deviation, base uncertainties
- \( RS_{max} \) = Highest responsivity (within Z range)
- \( RS_{min} \) = Lowest responsivity (within Z range)
- \( RS \) = Mean responsivity @ 45°

### Intermediate Calculations
- \( U_{rad} = \left[ U_{avg}^2 + (2 \cdot U_{avg})^2 \right]^{1/2} \)
- \( E_+ = 100 \cdot (RS_{max} - RS) / RS \)
- \( E_- = 100 \cdot (RS - RS_{min}) / RS \)

\[ U_{95+} = +(U_{rad} + E_+) \]
\[ U_{95-} = -(U_{rad} + E_-) \]

**Figure 9.**

**Calibration Certificates**

Figure 10.
Suggested Methods of Applying Results

- 45-55 Degree Responsivity
- Composite Responsivity
- Calibration History
- Responsivity Function
- Latitude-Optimized Responsivity
- 9-Degree Responsivities

Figure 11.

Data Exporting and Distribution

- Custom Exports with Selectable Parameters and Output Format
- Dedicated Export Format (AIM Database, Calibration Stickers)
- Responsivity Data Export for Transferring Calibration Results

Figure 12.
Conclusions

The updated version of the Radiometer Calibration and Characterization System provides significant improvements over the DOS version:

- Calibration certificates using ISO guidelines
- Easier, more reliable configuration and error correction
- Greater capabilities for monitoring and control during data acquisition
- Improved calibration characterization and uncertainty analysis
- More flexibility in data reports, exports, and distribution.

Corresponding Author

S. M. Wilcox, Stephen_Wilcox@nrel.gov, (303) 275-4061

References


