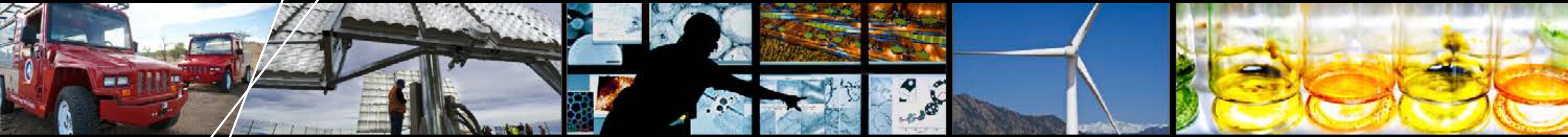
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Comparison of Calibration Methods and Resulting Solar Irradiance Measurement Differences



14th BSRN Scientific Review and Workshop – Canberra, Australia April 26-29, 2016

Presenter: Ibrahim Reda, NREL

Authors: Aron Habte, Manajit Sengupta, Afshin Andreas, Ibrahim Reda
National Renewable Energy Laboratory

Motivation:

- **The accuracy of solar radiation measured by radiometers depends on the specifications of the instrument, calibration procedure, measurement setup, maintenance, location, and environmental conditions.**
  - Understanding and quantifying differences due to different calibration methods (indoor versus outdoor) would assist in:
    - Acquiring accurate ground-based solar irradiance data.
    - Determining accurate measurement uncertainty of the radiometric data.

Key differences between Indoor and outdoor calibration methods

- **Possible differences between outdoor environmental conditions and the laboratory indoor calibration conditions with respect to the spectral and spatial distribution of the source radiation (sun and sky versus lamps or enclosure walls).**

- **Indoor calibration of radiometers Provides:**
  - User control of test conditions.
  - Calibration result independent of outdoor conditions.
  - User convenience.

Quantifying Measurement Uncertainties

- **Sources of uncertainties**
  - Calibration— calibration certificate
    - NREL radiometer calibrations are done outdoor.
    - Most manufacturers' pyranometer calibrations are done indoor.
      - In both cases, calibration certificate reports the calibration results under specific environmental conditions that are different from conditions in the field.
  - Solar Zenith Angle response — radiometer specification sheet
  - Spectral response — user estimate/ radiometer specification sheet
  - Non-linearity — radiometer specification sheet
  - Temperature response — radiometer specification sheet
  - Aging per year — radiometer specification sheet
  - Data logger accuracy — data logger specification sheet
  - Maintenance (e.g., soiling) — user estimate

Methodology

- The data for the comparison was obtained from radiometers deployed at NREL Solar Radiation Research Laboratory
- The Comparison was performed under clear sky conditions (Clearness Index: KN>0.6)
- The reference data was obtained using a CHP1 radiometer for DNI and CM22 radiometer for diffuse irradiance.
- 1-minute data was included in the study from 6/23/2015 to 4/07/2016.

Measurement Equations

NREL Broadband Outdoor Radiometer Calibration Method

$$R = \frac{(V - R_{net} * W_{net})}{N * Cos(Z) + D}$$

where:

R = the pyranometer's responsivity, µV/(Wm^{-2})

V = the pyranometer's sensor output voltage, in µV

N = the beam irradiance measured by a primary or standard reference standard pyrheliometer, measuring the beam irradiance directly from the sun's disk in Wm^{-2}

Z = the solar zenith angle, in degrees

D = the diffuse irradiance, sky irradiance, without the beam irradiance from the sun's disk, measured by a shaded pyranometer, , in Wm^{-2}

R_{net} = the pyranometer's net infrared responsivity, in µV/(Wm^{-2})

W_{net} = the effective net infrared irradiance measured by a collocated pyrgeometer, in Wm^{-2}

General method for indoor Pyranometer calibration

$$R_{test} = \frac{V_{test}}{V_{ref}} R_{ref}$$

where:

R_{test}* = *Responsivity of the radiometer under calibration, µV/(Wm^{-2})

V_{ref}* *and* *V_{test} = the voltages (µV), measured using the reference and the field radiometers, respectively

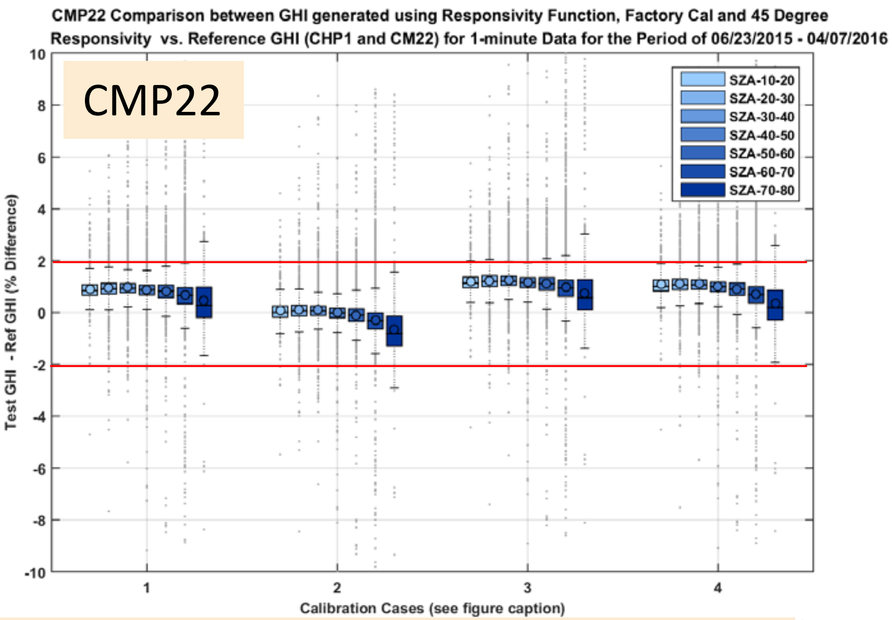
R_{ref} = Responsivity, µV/(Wm^{-2}) of the reference radiometer

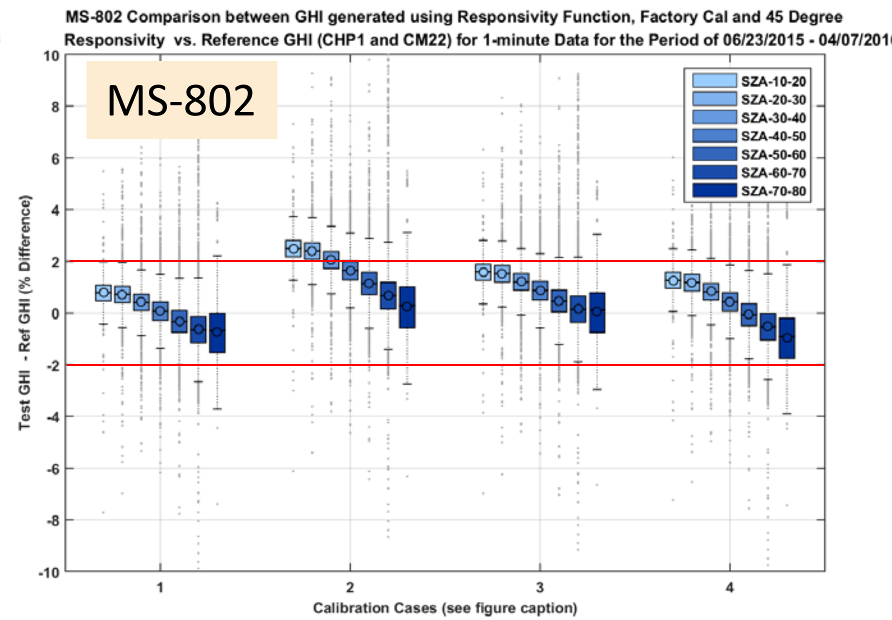
The outdoor responsivity is from responsivity of the reference radiometer corrected by the ratio of measured voltage to the voltage from the reference radiometer. The indoor method has the traceability to the world radiation reference by using a reference radiometer that is traceable to the world radiation reference.

Steps:

1. To analyze the measured data, the radiometric data from the Unit Under Test radiometers were back calculated to determine the raw voltage readings.
2. Five responsivity value cases were applied to the raw voltage readings; these values were obtained from the BORCAL and manufacturers indoor calibration methods.
   I. BORCAL responsivity as a function of SZA with thermal offset correction for thermopile pyranometer and no thermal offset correction for thermopile pyrheliometers and photodiode.
   II. Indoor manufacturer calibration responsivity at zero degree SZA.
   III. BORCAL responsivity at 45 degree with thermal offset correction for thermopile pyranometer and no thermal offset correction for pyrheliometers and photodiode.
   IV. BORCAL responsivity at 45 degree without thermal offset correction for thermopile radiometers and photodiode radiometers.
   V. Indoor manufacturer calibration responsivity at zero degree SZA and with manufacturer supplied measurement equation.

GHI: Calibration Methods and Subsequent Differences



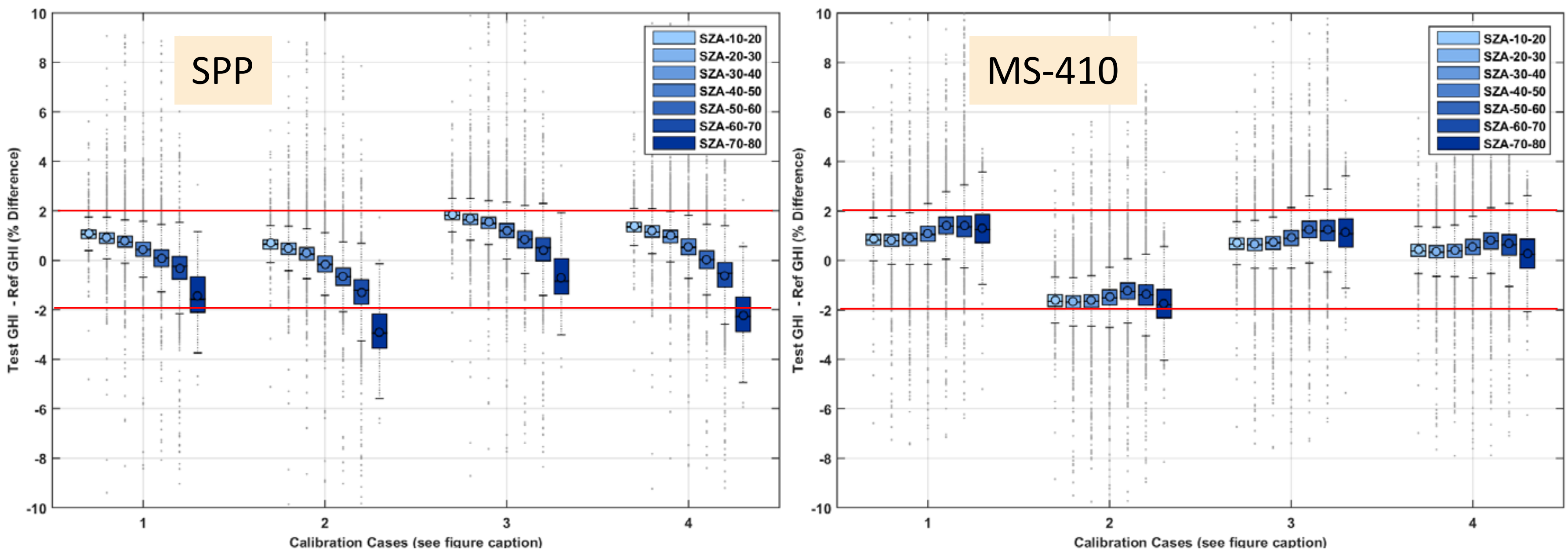


Indoor and Outdoor calibration comparison between the reference GHI irradiance (using CHP1 for DNI and CM22 for DHI) and CMP22 test radiometer irradiance.
X-axis:
1) BORCAL using responsivity as a function of SZA
2) Factory calibration responsivity (Mfr. Rs) at zero SZA
3) BORCAL using responsivity at 45 degree with thermal offset correction, and
4) BORCAL using responsivity at 45 degree without thermal offset correction.

Note: Each blue-box represents a 10-degree bin and it also represents the upper quartile and the lower quartile (it is also called as interquartile range) of the data in each bin. The circle in each blue-box is a median of the interquartile range and the black line signifies the mean value of the difference for the interquartile range. The whiskers represent the upper and lower fences of the outliers, beyond the fences is plotted with a symbol (dots).

- The different calibration methods provide different irradiance values
- The different calibration methods also influence uncertainty estimation
- CMP22 has relatively small difference between all the methods compared to the MS-802 radiometer.
- For MS-802, NREL responsivity function method provides better result than the factory responsivity. For CMP22, the factory responsivity is better.

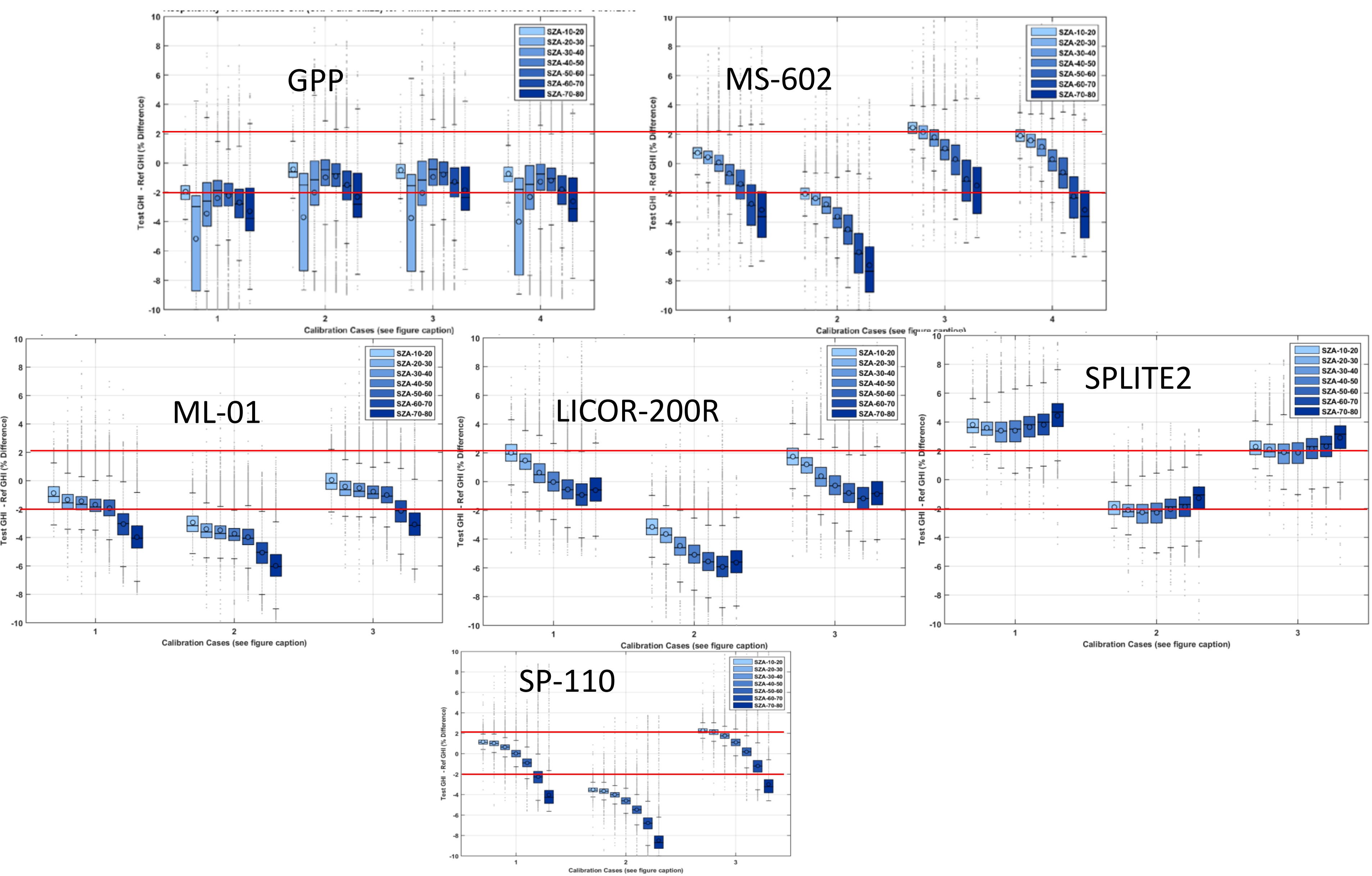
GHI: Calibration Methods and Subsequent Differences



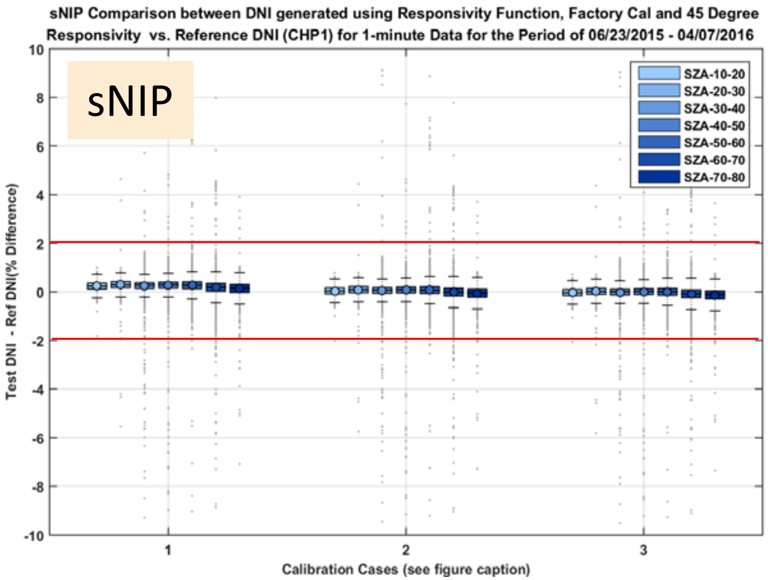
Indoor and Outdoor calibration comparison between the reference GHI irradiance (using CHP1 for DNI and CM22 for DHI) and CMP22 test radiometer irradiance.
X-axis:
1) BORCAL using responsivity as a function of SZA
2) Factory calibration responsivity (Mfr. Rs) at zero SZA
3) BORCAL using responsivity at 45 degree with thermal offset correction, and
4) BORCAL using responsivity at 45 degree without thermal offset correction.

- SPP radiometer shows relatively higher cosine dependence
- For SPP, both factory calibration and NREL responsivity function calibration show better results
- NREL 45 degree responsivity without thermal offset method provides better result for MS-410 (~2% improvement) than factory calibration.

GHI: Calibration Methods and Subsequent Differences

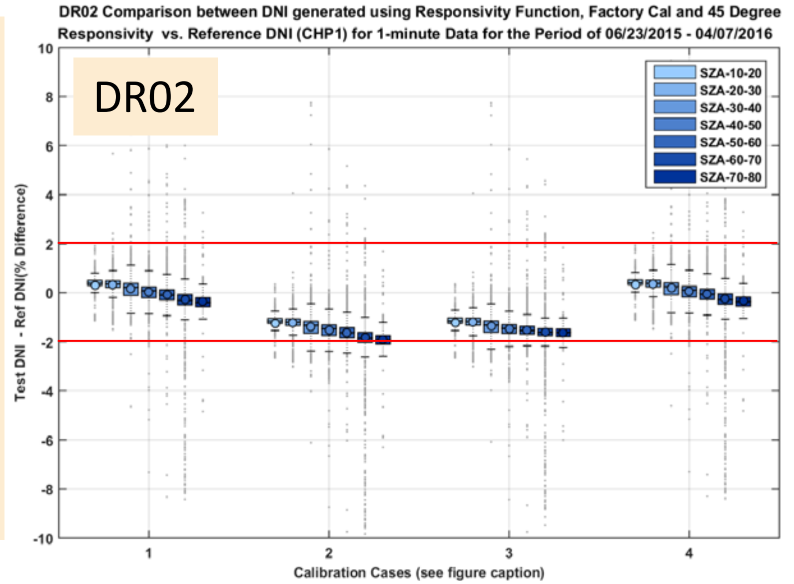


DNI: Calibration Methods and Subsequent Differences

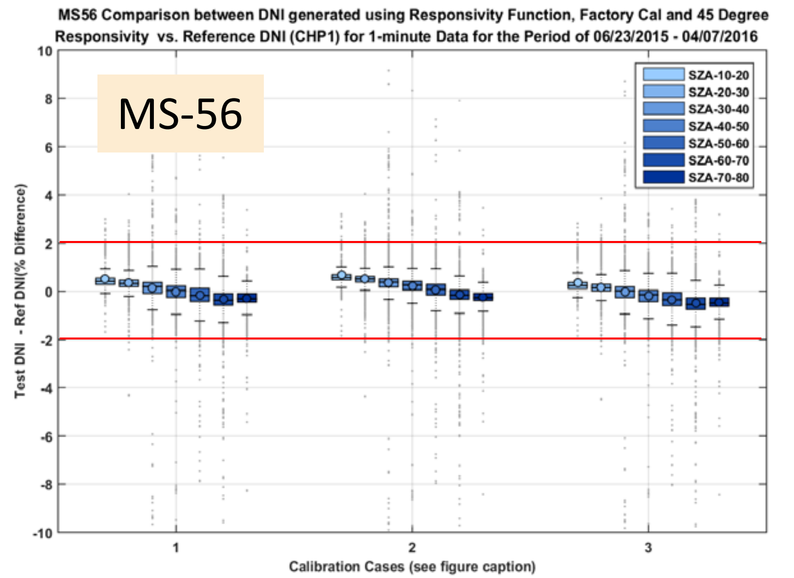


X-axis:

1) *BORCAL using responsivity as a function of SZA,*
2) *Factory calibration responsivity at zero SZA (sNIP) and manufacturer supplied equation (MS-56 & DR02),*
3) *BORCAL using responsivity at 45 degree*



- The sNIP radiometer data shows a better agreement to the reference DNI (CHP1) data than the DR02 radiometer data.
- NREL responsivity function method provides better results for the DR02 radiometer than the factory responsivity method.



Summary

- NREL made no effort to ensure that the radiometers presented here are representative units; therefore, this work does not guarantee the same result for all radiometers from the same manufacturer or model.
- The difference obtained in this study appears to be specific to the test radiometer under the study. There was no trend seen from one manufacturer to another.
- Understanding and quantifying the difference between the different calibration methodology would provide valuable information in acquiring accurate solar radiation data set.
- Both methods are traceable to world radiation reference (WRR).
- Outdoor calibrations are useful for cosine response correction which ultimately assists in reducing measurement uncertainty.

Thank You!

Questions?