

Reducing Broadband Shortwave Radiometer Calibration-Bias Caused by Longwave Irradiance in the Reference Direct Beam

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Abstract

Shortwave radiometers such as pyranometers, pyrhemometers, and photovoltaic cells are calibrated with traceability to consensus reference, maintained by Absolute Cavity Radiometers (ACRs). The ACR is an open cavity with no window that measures the extended broadband spectrum of the terrestrial direct solar beam irradiance, unlike shortwave radiometers that cover a limited range of the spectrum. The difference between the two spectral ranges may lead to calibration bias that can exceed 1%. This article describes a method to reduce the calibration bias resulting from using broadband ACRs to calibrate shortwave radiometers by using an ACR with Schott glass window to measure the reference broadband shortwave irradiance in the terrestrial direct solar beam from 0.3 μm to 3 μm . Reducing the calibration bias will result in lowering the historical solar irradiance by at least 0.9%. The published results in this article might raise the awareness of the calibration discrepancy to the users of such radiometers, and open a discussion within the solar and atmospheric science community to define their expectation from such radiometers to the radiometers' manufacturers and calibration providers.

Keywords

Pyranometer, Pyrhemometer, Calibration, Absolute Cavity Pyrhemometer, Photovoltaic Cells, Shortwave

1. Introduction

Shortwave radiometers such as pyranometers, pyrhemometers, and photovoltaic cells are calibrated with traceability to the World Radiometric Reference (WRR) (ISO, 1990) [1]. Photovoltaic cells have two traceability chains: the solar simulator method is traceable through a standard lamp to the National Institute of Standards and Technology (NIST) or other National Metrology Institute (NMI) while the solar irradiance method

is traceable to the WRR [2]. The WRR is maintained by six Absolute Cavity Radiometers (ACR) that form the World Standard Group (WSG), which are located at the Physikalisch-Meteorologisches Observatorium in Davos, Switzerland [3]. The ACR is an open cavity with no windows and was developed to measure the extended broadband spectrum of the terrestrial direct solar beam irradiance that extends beyond the ultraviolet and infrared bands (*i.e.*, below $0.2 \mu\text{m}$ and above $50 \mu\text{m}$, respectively). On the other hand, pyranometers and pyrhemometers measure broadband shortwave irradiance from approximately $0.3 \mu\text{m}$ to $3 \mu\text{m}$ [4] [5] and the silicon-based photovoltaic cells are limited to the spectral range of approximately $0.3 \mu\text{m}$ to $1 \mu\text{m}$. The broadband spectral mismatch of the ACR versus the shortwave radiometers might result in a larger than 1% bias in the radiometers' calibration methods, as shown in Reda, *et al.* 2015 [6]. The method described in Reda, *et al.*, 2015 summarizes using two pyrgeometers: one shaded with a Schott glass shading mechanism to block the spectral range greater than $3 \mu\text{m}$ from the direct solar beam, and the other unshaded with spectral range from approximately $3 \mu\text{m}$ to $50 \mu\text{m}$. The Schott glass shading mechanism is used for broadband shortwave radiometers' dome to transmit spectral range from $0.3 \mu\text{m}$ to $3 \mu\text{m}$, per manufacturer design. The reference broadband longwave irradiance in the direct solar beam (W_{LW}) is then calculated by subtracting the irradiance measured by the shaded pyrgeometer from that measured by the unshaded pyrgeometer.

As will be described in section 2 below, the reference broadband shortwave irradiance (W_{SW}) is calculated by subtracting the measured reference W_{LW} from the broadband irradiance (W_{BB}), measured by broadband ACR (ACR_{BB}) (*i.e.* $W_{SW} = W_{BB} - W_{LW}$). The reference W_{SW} is then used to calibrate an ACR with Schott glass window (ACR_{SW}), which is then used to calibrate a set of shortwave radiometers. The difference between using ACR_{BB} and ACR_{SW} to calibrate the radiometers is shown in Section 3 below.

2. Calibration Procedure

The shaded and unshaded pyrgeometers, the two ACRs (ACR_{BB} and ACR_{SW}), and five-shortwave radiometers, two thermopile pyrhemometers (Eppley Laboratory, Inc., model NIP and Kipp and Zonen model CHP1), two thermopile pyranometers (Eppley Laboratory, Inc., model PSP and Kipp and Zonen model CMP22), and one photodiode pyranometer (Kipp and Zonen model SP Lite2), were set up outdoors at the National Renewable Energy Laboratory's (NREL) Solar Radiation Research Laboratory (SRRL), which is at an elevation of 1828.8 meters above sea level. Data was collected simultaneously from all radiometers under clear sky conditions every 30 seconds, from June 15 to June 18, 2016. The following subsections describe the calibration of the ACR_{SW} . The ACR_{BB} was calibrated with traceability to WRR during NREL Pyrhemometer Comparisons, NPC-2014 [7]. The same outdoor dataset was used to calibrate the shortwave radiometers; their responsivity was calculated using the ACR_{BB} , then re-calculated using the ACR_{SW} . The calibration results of the shortwave radiometers by using ACR_{BB} and ACR_{SW} are compared to show the bias between the two calibration methods.

2.1. ACR_{SW} Calibration

Figure 1 show the shaded and unshaded pyrgeometers set up, which was used to



Figure 1. Set up of shaded and unshaded pyrheliometers to measure the longwave irradiance in solar beams.

measure the reference longwave irradiance in the solar beam (W_{LW}) as:

$$W_{LW} = \frac{W_{unsh} - W_{sh}}{\cos \Theta} \tag{1}$$

where,

- W_{unsh} is the longwave irradiance measured by the unshaded pyrheliometer ($W \cdot m^{-2}$)
- W_{sh} is the longwave irradiance measured by the shaded pyrheliometer with the Schott glass shading mechanism, see **Figure 1** ($W \cdot m^{-2}$)
- Θ is the solar zenith angle ($^{\circ}$).

Detailed derivation of the equation is presented in Reda *et al.*, 2015. **Figure 2** shows the measured reference W_{LW} varies from $3 W \cdot m^{-2}$ to $12 W \cdot m^{-2}$ due to time of day, solar irradiance level, and the atmospheric constituents, such as water vapor, aerosol optical depth, ozone, etc.

The broadband direct beam irradiance (W_{BB}) is measured by the ACR_{BB} that was calibrated during NREL Pyrheliometer Comparison (NPC-2014) with traceability to WRR [7]. The ACR_{BB} was self-calibrating every hour to calculate its multiplication factor based on the changing environmental conditions during the outdoor measurement (e.g. temperature, pressure, humidity, irradiance level, and spectral distribution). Details about ACR self-calibration is presented in Reda, 1996 [8]. The reference broadband shortwave irradiance (W_{SW}) is then calculated as:

$$W_{SW} = W_{BB} - W_{LW} \tag{2}$$

Figure 3 shows the W_{BB} and W_{SW} for the four clear days; the reference W_{SW} irradiance is then used to calculate the window factor for the ACR_{SW} at each data point (F_{SW}),

$$F_{SW} = \frac{W_{SW}}{M(V_p - V_0)} \tag{3}$$

where,

- M is the sensitivity reciprocal ($1/Sensitivity$) of the ACR_{SW} ($W/m^2/mV$). Similar to

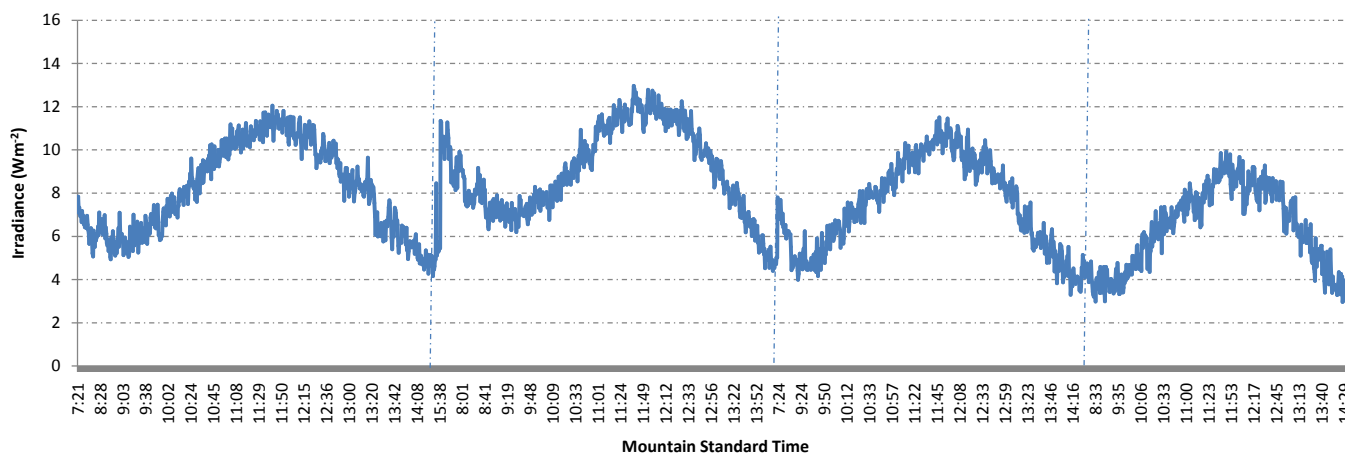


Figure 2. Reference longwave irradiance (Wsh-Wunsh) in solar beam from June 15 to June 18, 2016.

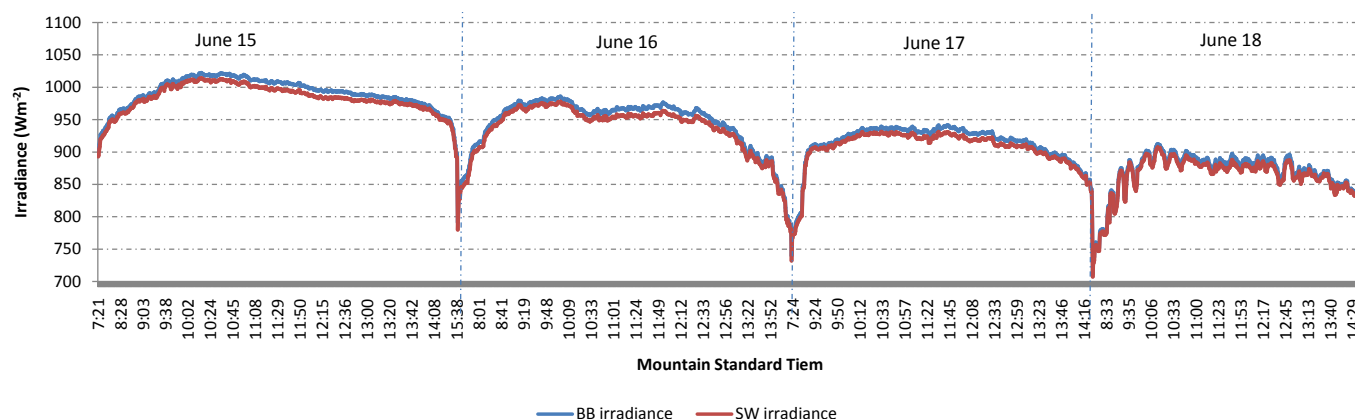


Figure 3. Broadband and shortwave irradiance from June 15 to June 18, 2016.

the ACR_{BB} the ACR_{SW} self-calibrates every hour to calculate M [8].

- V_{ip} is the thermopile output voltage when the shutter of the ACR_{SW} is open (mV) (*i.e.* the direct solar beam is incident on the thermopile's receiving junctions).
- V_0 is the thermopile output voltage when the cavity is self-calibrating and the shutter is closed [*i.e.* no solar irradiance (mV)].

Figure 4 shows the window factor, the average F_{SW} , and its standard deviation (SD). The uncertainty with 95% confidence level ($U_{95,SW}$) for the ACR_{SW} calibration is then calculated using the ISO Guide to the Expression of Uncertainty in Measurement (GUM) [9].

Table 1 shows the results of calibration and its uncertainty, where $u_{95,BB}$ is the standard uncertainty of ACR_{BB} from NPC-2014 [7] and $u_{95,LW}$ is the standard uncertainty of W_{LW} [6]. From the Table, the F_{SW} of the ACR_{SW} equals 1.05655 and $U_{95,SW}$ equals 0.41%.

2.2. Shortwave Radiometer Calibration

During the calibration, each measurement data point consists of simultaneous recording of the following parameters:

- Output voltage from the test radiometer, V (μ V).
- Reference irradiance measured by ACR_{BB} and ACR_{SW} , W_{BB} and W_{SW} ($W \cdot m^{-2}$).

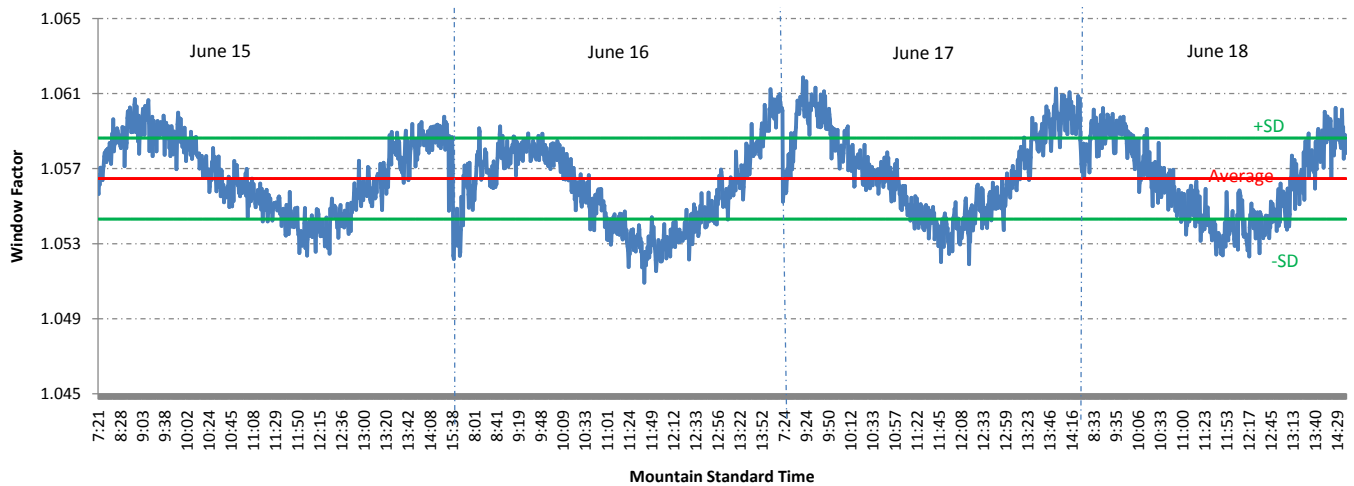


Figure 4. Window factor (FSW) for the absolute cavity radiometer with Schott glass window from June 15 to June 18, 2016.

Table 1. Calibration results of the ACR_{SW} .

Window Factor	1.05655
%SD = Type A Standard Uncertainty (uA)	0.0002
%Standard Uncertainty ($u_{95, BB}$)	0.19
%Standard Uncertainty ($u_{95, LW}$)	0.21
Coverage Factor	1.96
$\%U_{95, SW}$	0.41

- Net longwave irradiance measured by a pyrgeometer, W_{net} ($W \cdot m^{-2}$).
- Reference diffuse irradiance measured by a shaded pyranometer, D ($W \cdot m^{-2}$).
- The solar zenith angle calculated using the Solar Position Algorithm (SPA), Θ ($^{\circ}$) [10].

The responsivity of each shortwave radiometer is then calculated using two methods: Using the ACR_{BB} as a reference and using the ACR_{SW} as the reference. The following equation is used to calculate the broadband responsivity (RS_{BB}) [11]:

$$RS_{BB} = \frac{V - R_{net} * W_{net}}{W_{BB} * \cos \Theta + D} \quad (4)$$

where R_{net} is the pyranometer's net infrared responsivity calculated using the method described in [12], in $\mu V / (W \cdot m^{-2})$.

The shortwave responsivity (RS_{SW}) is then calculated using Equation (4) by replacing RS_{BB} and W_{BB} by RS_{SW} and W_{SW} , respectively.

3. Results

Figures 5-8 show the difference between the RS_{BB} and RS_{SW} for five radiometers, two thermopile pyrhemometers (Eppley Laboratory, Inc., model NIP and Kipp and Zonen model CHP1), two thermopile pyranometers (Eppley Laboratory, Inc., model PSP and Kipp and Zonen model CMP22), and one photodiode pyranometer (Kipp and Zonen model SP Lite2). From the figures, pyrhemometers RS_{SW} is larger than RS_{BB} by at least 0.75%, and for pyranometers RS_{SW} is larger than RS_{BB} by at least 0.6%. Historically, direct solar beam and global irradiance is calculated using the RS_{BB} for all radiometers.

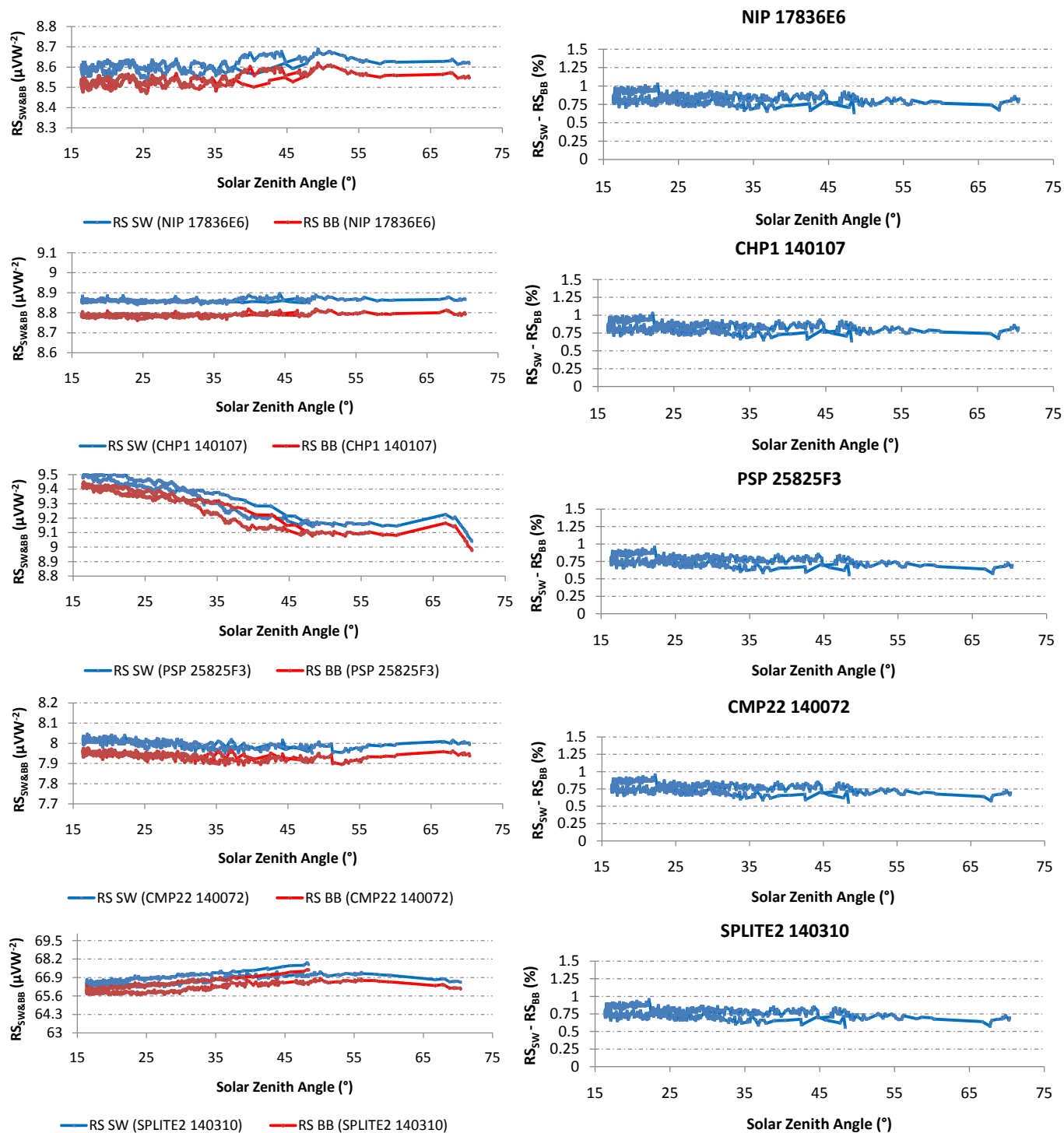


Figure 5. Shortwave and broadband responsivities and percentage differences on June 15, 2016.

This implies that when the radiometers are deployed in the field after being calibrated using ACR_{SW} , the measured direct broadband shortwave beam solar irradiance might be lower than the historical irradiance by at least 0.75%, and that the global broadband shortwave solar irradiance might be lower than the historical global irradiance by 0.6%.

The same calibration method was repeated at the USA-Department of Energy (DOE), Atmospheric Radiation Measurement (ARM) program at the Southern Great

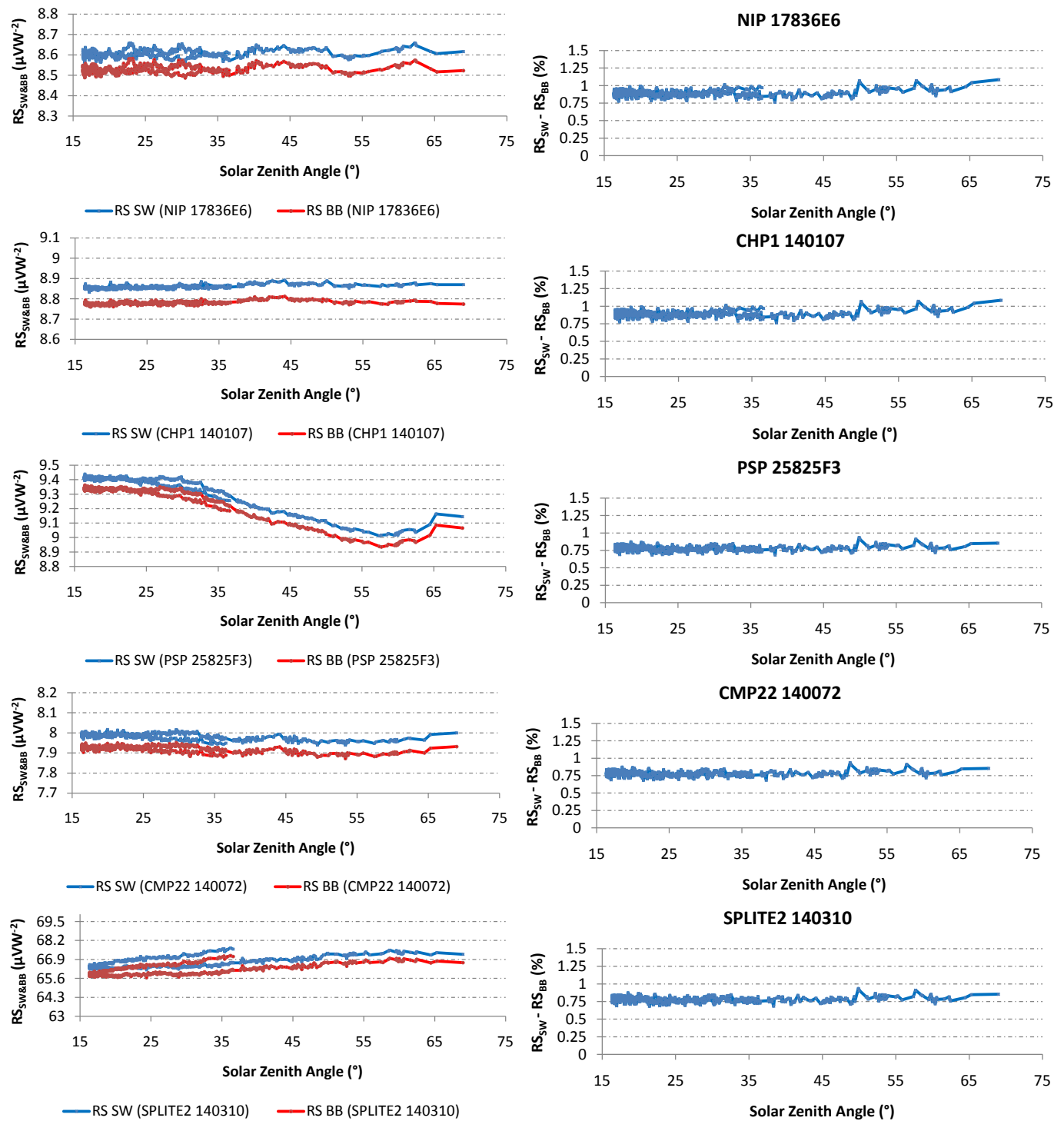


Figure 6. Shortwave and broadband responsivities and percentage differences on June 16, 2016.

Plains (SGP) site, which is at an elevation of 318 meters above sea level. Figure 9 shows the difference between the RS_{BB} and RS_{SW} for the same five radiometers. From the figure it is noted that for pyrhemometers RS_{SW} is larger than RS_{BB} by at least 1.1%, and for pyranometers RS_{SW} is consistently larger than RS_{BB} by at least 0.9%. Again, historical direct beam and global irradiance is calculated using the RS_{BB} for all radiometers, which implies that when the radiometers are deployed in the field after being calibrated using

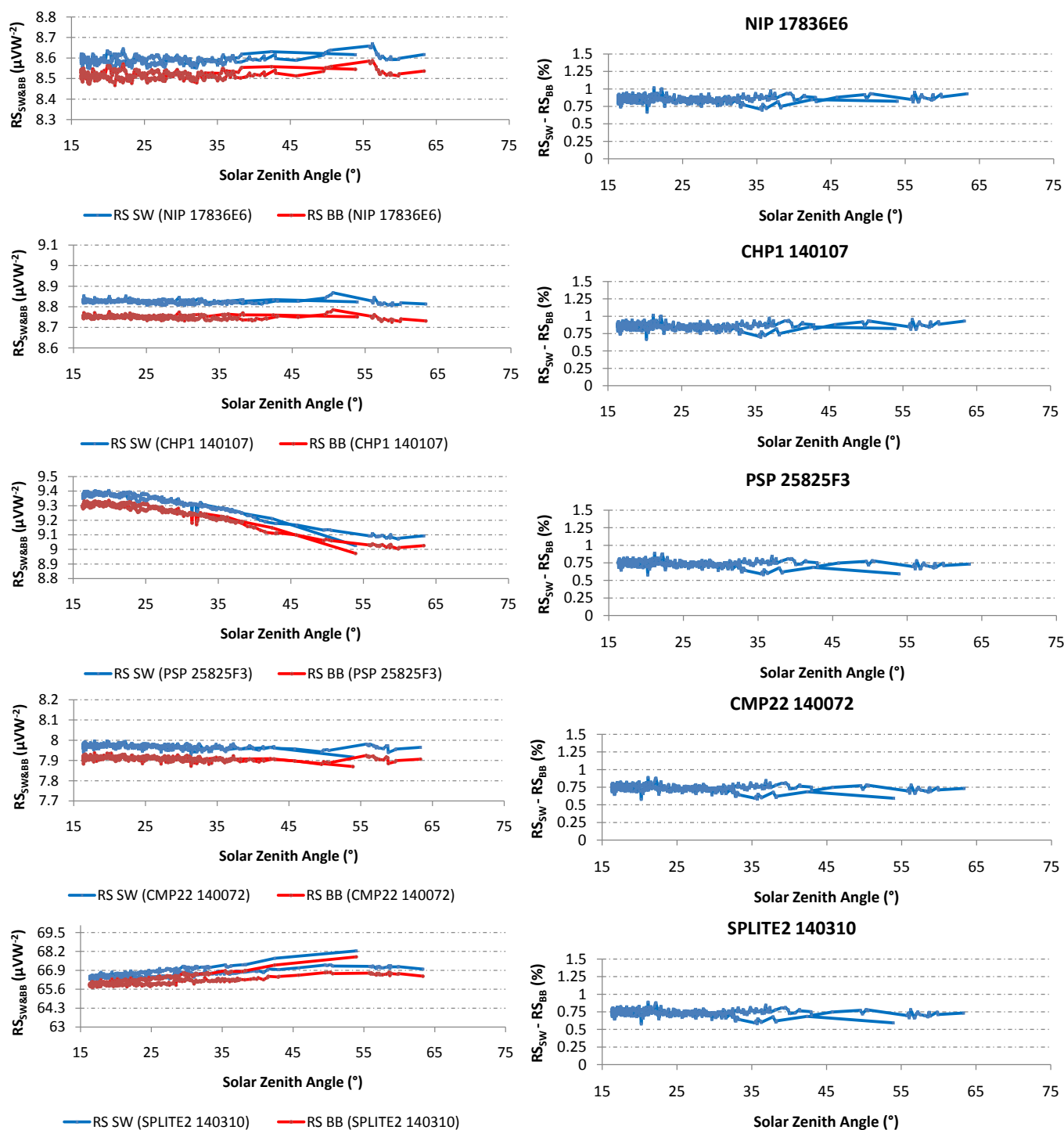


Figure 7. Shortwave and broadband responsivities and percentage differences on June 17, 2016.

ACR_{SW} , the measured direct beam solar irradiance might be lower than the historical irradiance by at least 1.1%, and the global solar irradiance might be lower than the historical global irradiance by 0.9%.

4. Conclusion

We find that by using the historical calibration method of broadband shortwave radi-

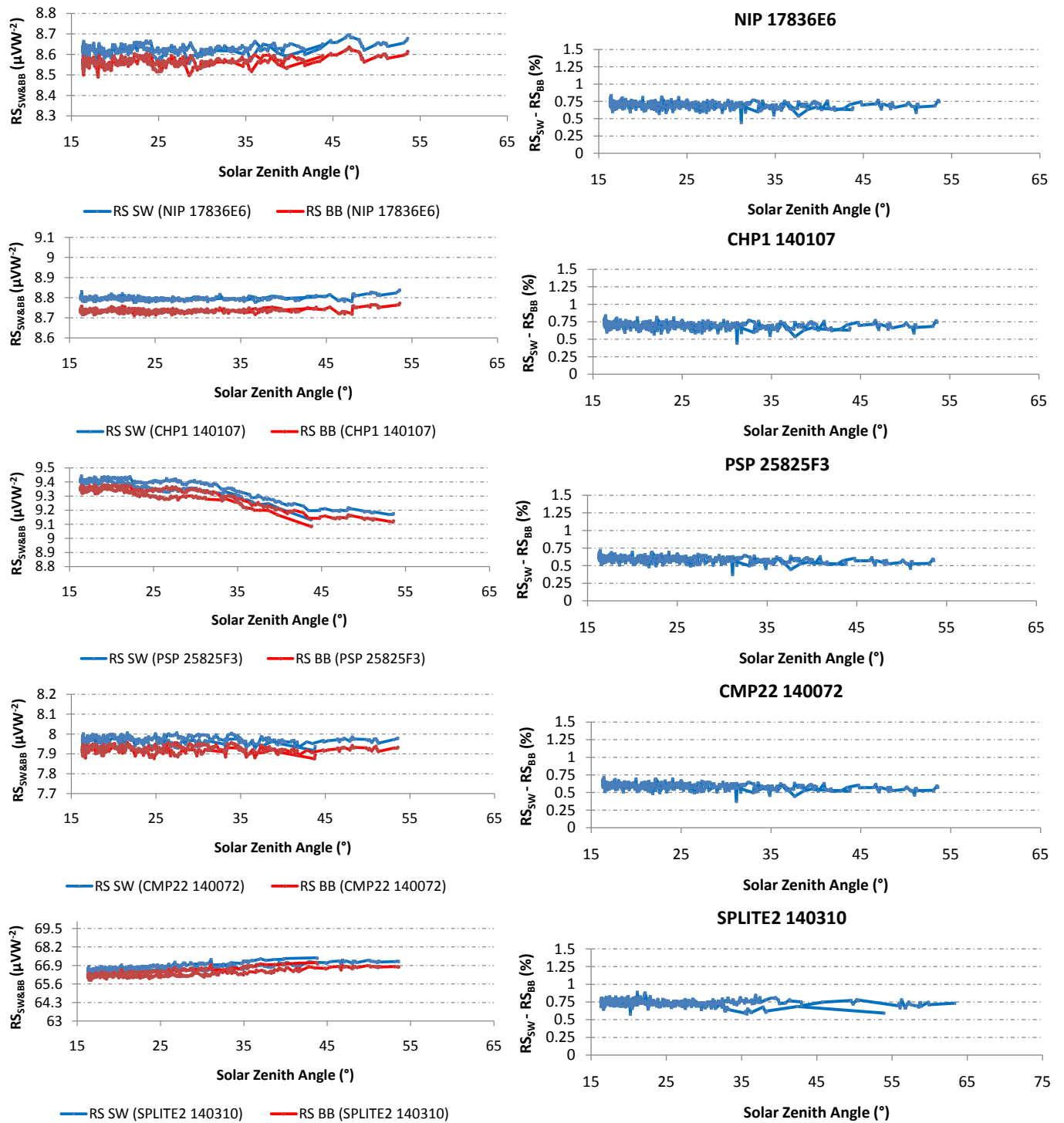


Figure 8. Shortwave and broadband responsivities and percentage differences on June 18, 2016.

ometers recommended by ISO 9059:1990 results in an overestimation in the field measurement of the direct broadband shortwave beam solar irradiance by at least 0.75% and the global broadband shortwave solar irradiance by at least 0.6%. This overestimation might exceed 1% based on the atmospheric conditions during the calibration, primarily water vapor and aerosols. Since shortwave radiometers are designed to measure the broadband shortwave solar irradiance in the spectral range from 0.3 μm to 3 μm ,

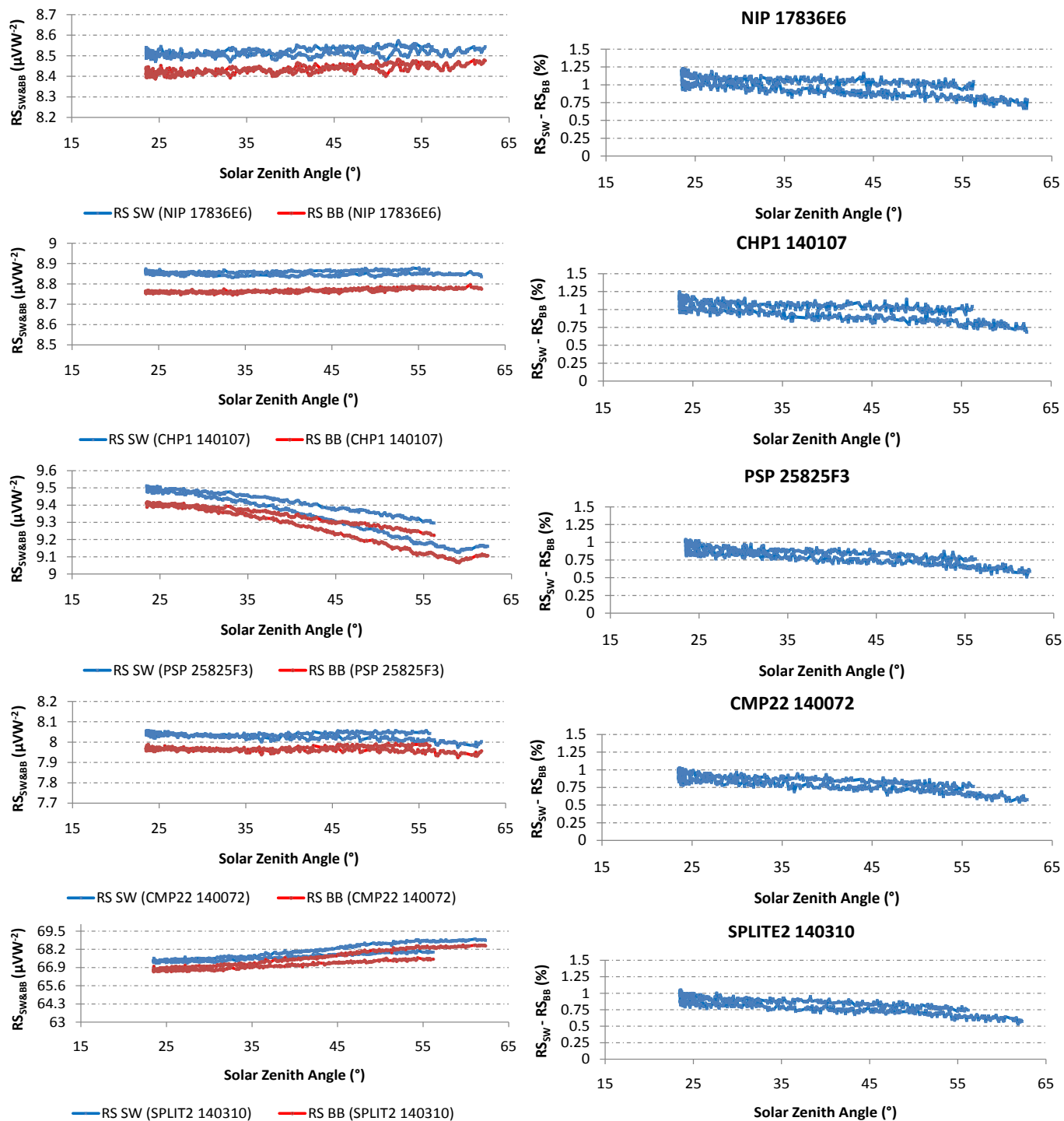


Figure 9. Shortwave and broadband responsivities and percentage differences at SGP on August 17, 2016.

per ISO 9060:1990, the recommended calibration method by ISO 9059-1990 would result in biases in the calibration results. These biases might be significant in atmospheric science and solar energy applications.

5. Discussion

While most users of such radiometers are interested in measuring the broadband short-

wave irradiance, some users are interested in measuring the broadband solar irradiance (W_{BB}). For the latter, it is recommended that radiometers be designed with domes or windows that transmit the broadband spectral range to avoid such calibration discrepancy. The purpose of this article is to raise the awareness of the calibration discrepancy to the users of such radiometers, and open a discussion within the solar and atmospheric science community to define their expectation from such radiometers to the radiometers' manufacturers and calibration providers.

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