

Equating reference cell and broadband pyranometer data

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Pyranometer vs reference cell



Photo taken at NREL
Part of the SRRL PV resource study
<https://midcdmz.nrel.gov/apps/sitehome.pl?site=PVSSA>

Pyranometers:

- Measure total amount of light
- Spectrally flat
- Little directional response
- Little temperature dependence

Reference cell:

- Measure the light accessible by PV
- Spectrally similar to PV modules
- Angle of incidence similar to PV modules
- Temperature adjusted data

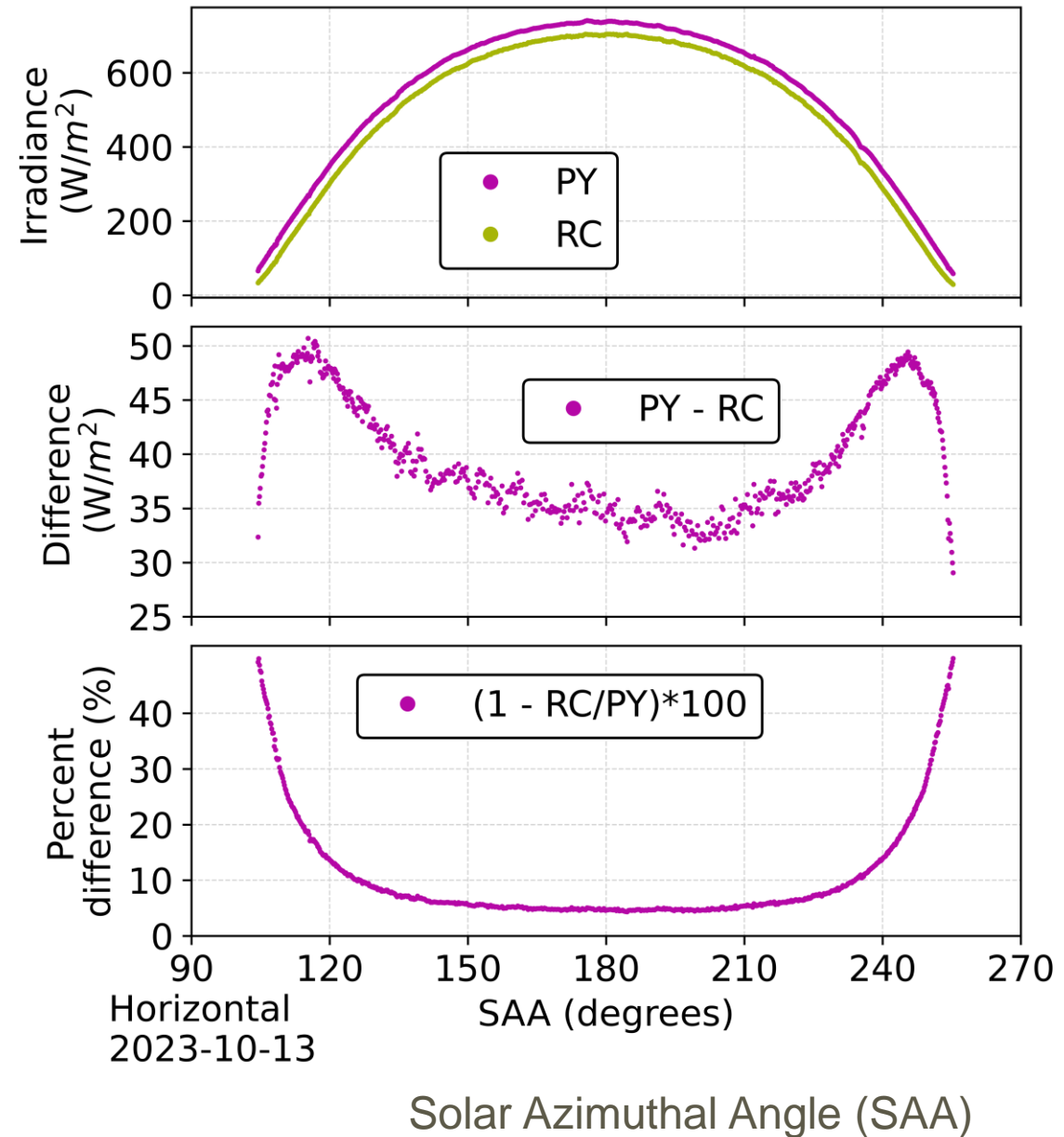
Pyranometer

Reference cells

Pyranometer vs reference cell

Difficult to compare the outputs of these two instruments types with such a large variation throughout the day.

The goal of this talk is to demonstrate an adjustment algorithm that reduces the differences between pyranometer and reference cell data.



Solar Azimuthal Angle (SAA)

Spectral effects

Pyranometer

Spectral response is quite flat over entire wavelength range

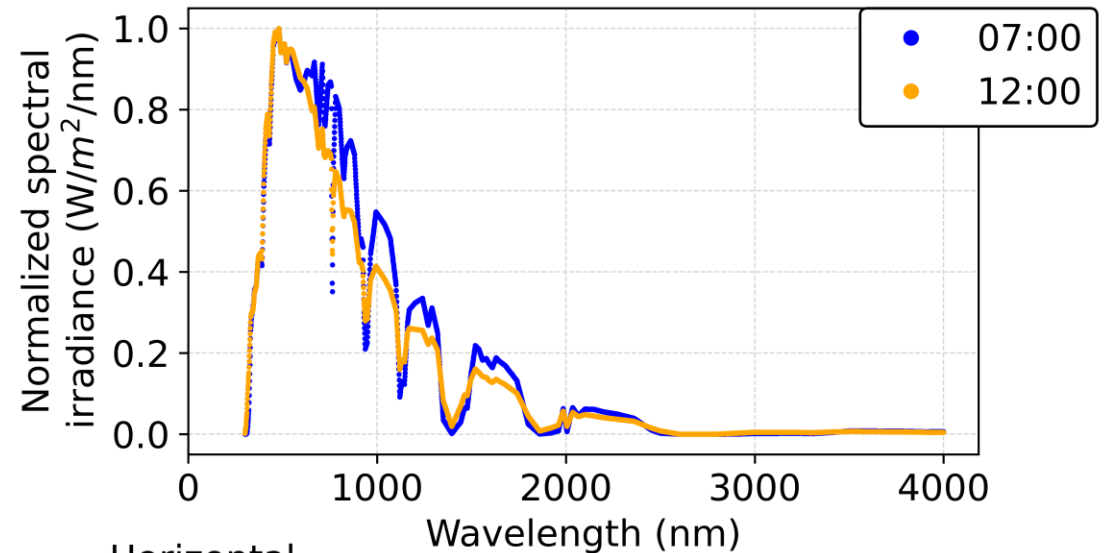
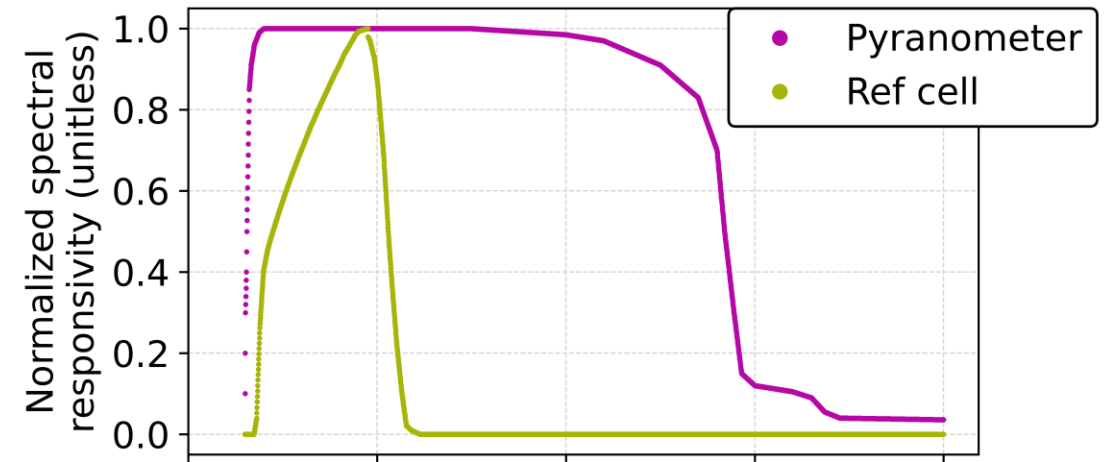
Reference cell

Spectral response varies drastically over wavelength range. Only extends to up to 1150 nm.

Spectral irradiance

The composition of the spectral irradiance varies throughout the day. Early morning irradiance is shifted to higher wavelengths.

For this study, spectral data obtained using the Bird clear sky spectral model through pvlib.



Horizontal
2023-10-13

Bird, R, and Riordan, C., 1984, "Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the earth's surface for cloudless atmospheres", NREL Technical Report TR-215-2436 DOI: [10.2172/5986936](https://doi.org/10.2172/5986936).

Anderson, K., Hansen, C., Holmgren, W., Jensen, A., Mikofski, M., and Driesse, A. "pvlib python: 2023 project update." Journal of Open Source Software, 8(92), 5994, (2023). DOI: [10.21105/joss.05994](https://doi.org/10.21105/joss.05994).

Angle of incidence effects

Incident angle modifier (IAM)

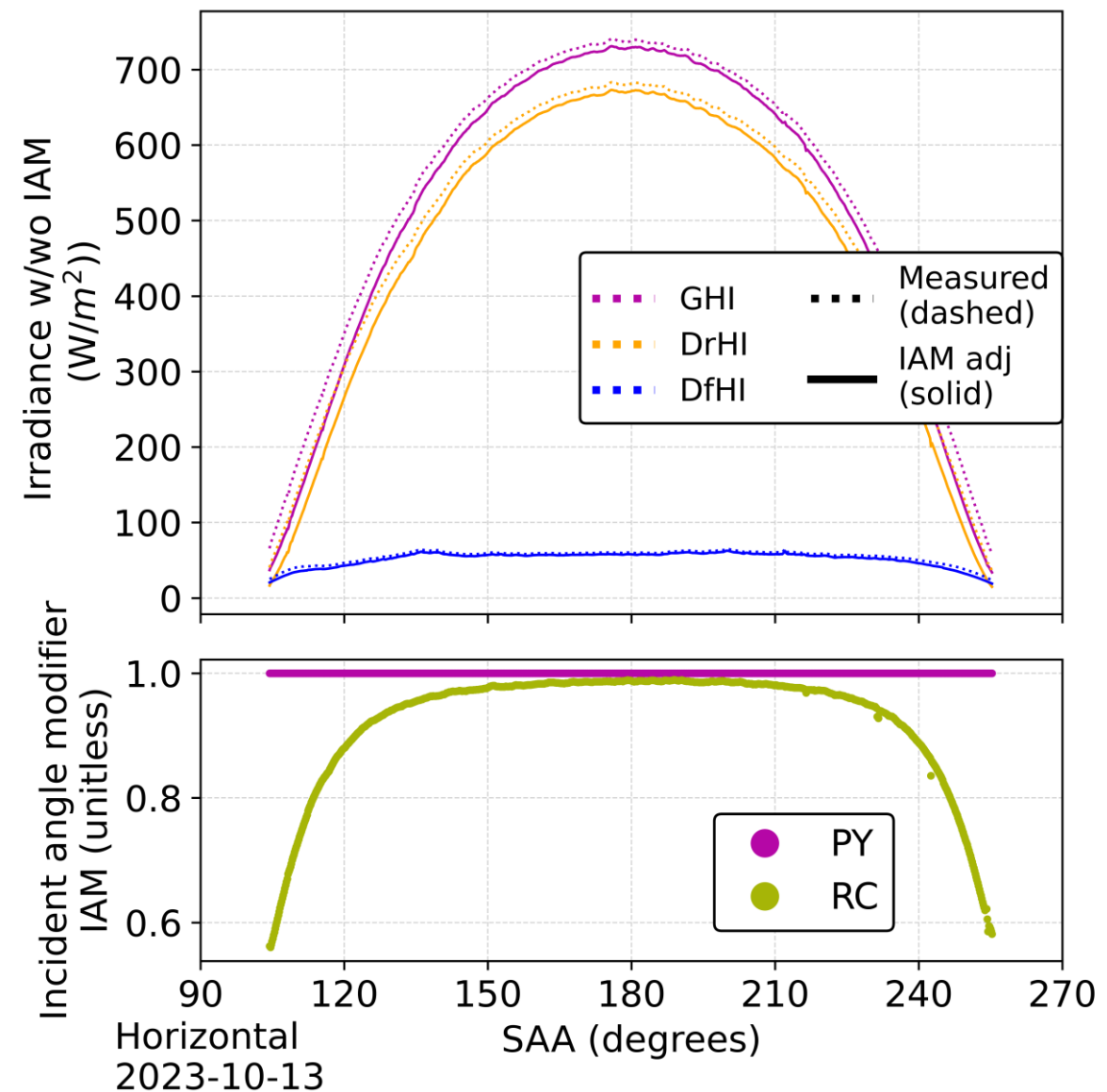
The IAM is a measure of how much light makes it through the glass at various angles.

The light was separated into its components using the Perez model. (Circumsolar, Dome, Horizon)

The Marion IAM model was used to compute the IAM for each component.

The IAM of the reference cell was computed using a weighted average of the various components.

The IAM of a pyranometer is 1.
(little directional response)



W. Marion, Numerical method for angle-of-incidence correction factors for diffuse radiation incident photovoltaic modules, Solar Energy 147 344–348, 2017

R. Perez, et al., Modeling daylight availability and irradiance components from direct and global irradiance, Solar Energy 44, 271–289, 1990

Reference cell model

$$RC_{Model} = \left(\frac{1}{K_{RC}} \right) * \left(IAM_{RC} * \sum_{\lambda=300\text{ nm}}^{4000} R_{RC\lambda}(T) \cdot I_{\lambda} \right)$$

- IAM_{RC} : Average angle of incidence modifier
- $R_{\lambda}(T)$ Reference cell spectral response
 - Temperature adjusted to allow for changes in the bandgap of the PV at different temperatures. The temperature adjustment only affects wavelengths greater than 950 nm
- I_{λ} Spectral irradiance of the incoming irradiance
- K_{RC} : Calibration factor needed to scale the modeled data to the measured data

$R_{\lambda} \cdot I_{\lambda}$ is a measure of how much short circuit current the reference cell will generate at a particular wavelength.

The sum adds all these individual wavelength components up to generate a total reference cell short circuit current.

Determining K

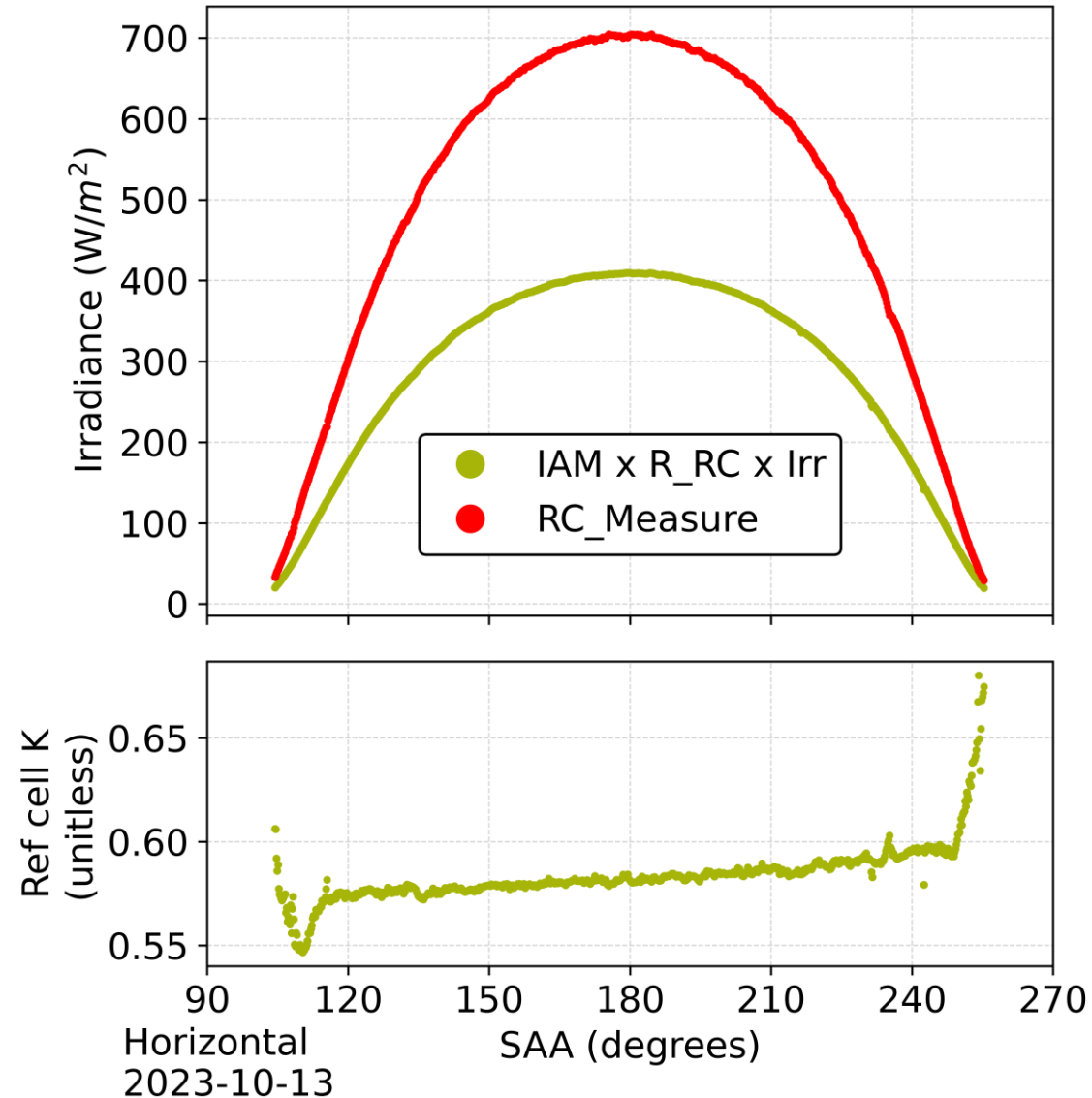
Set the model equal to the measured data.
Solve for K.

$$K_{RC} = \frac{IAM_{RC} * \sum_{\lambda=300\text{ nm}}^{4000} R_{RC\lambda}(T) \cdot I_{\lambda}}{RC_{Measure}}$$

K is the ratio of the computed values over the measured values.

If the model is valid, the value of K should be constant over all conditions.

Do this for all data in the training data set.



Determining K

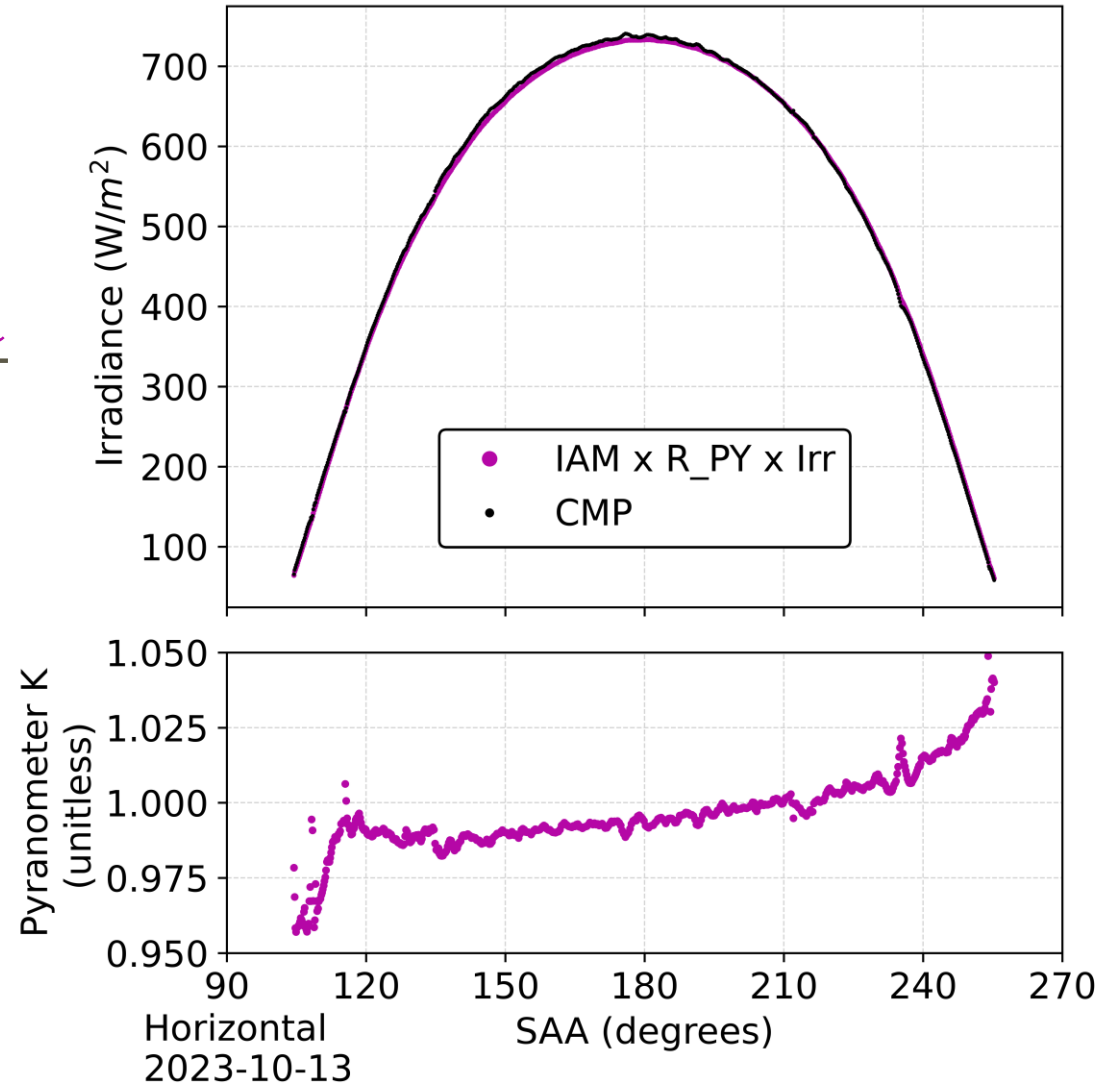
Similar process for the pyranometer

$$K_{PY} = \frac{IAM_{PY} * \sum_{\lambda=300\text{ nm}}^{4000} R_{PY\lambda}(T) \cdot I_{\lambda}}{PY_{Measure}}$$

$K \approx 1$ as we would expect.

The spectral model was computed independently from the measured GHI.

NOTE: the upward trend in K could be due to leveling, temperature, or directional response issues of the pyranometer.



Determining K from training data set

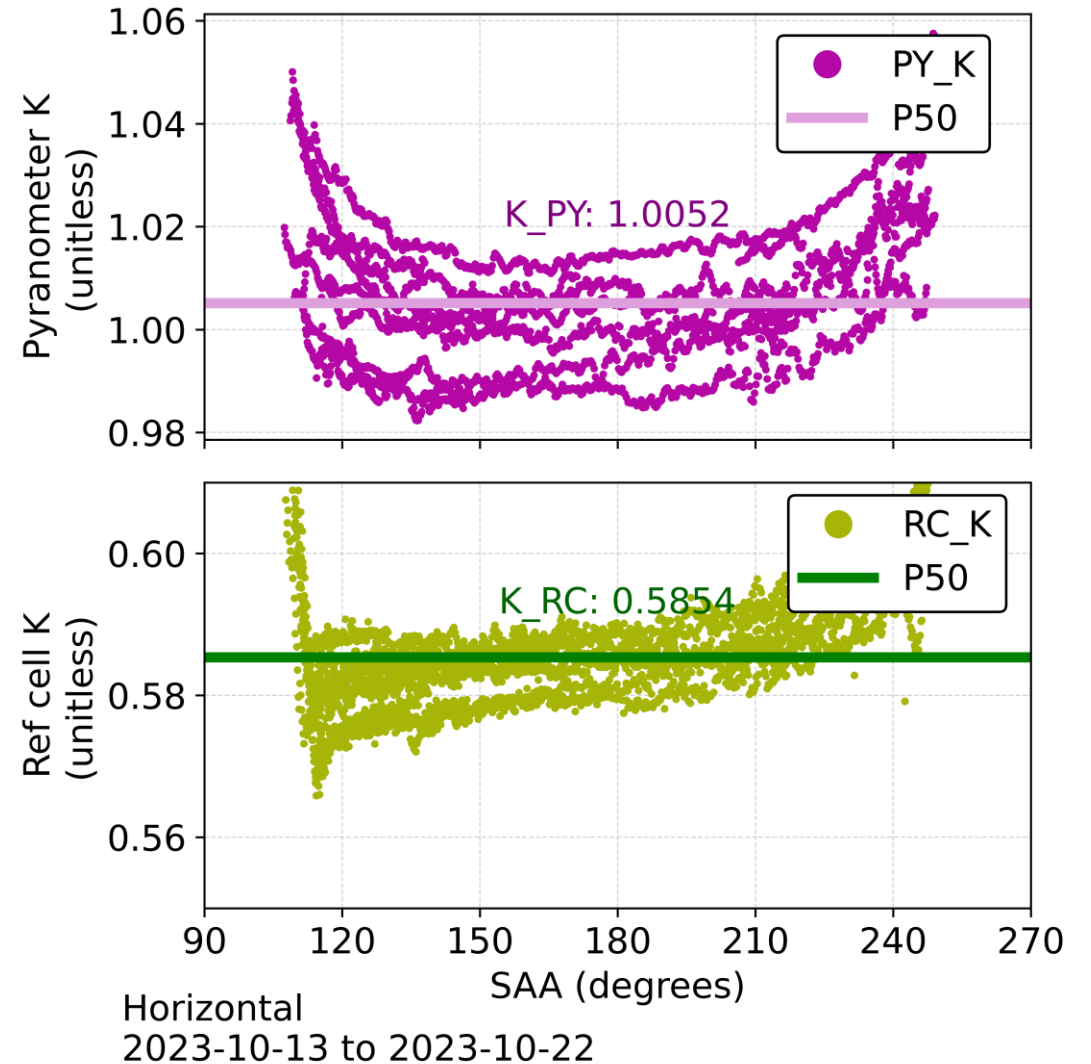
10 days of data in mid October 2023 were selected as a training data set.

Clear sky minutes were selected
Minutes with SZA < 90 were selected.

The median value of K was computed

$$K_{PY} = 1.0052$$

$$K_{RC} = 0.5854$$



Derivation of the pyranometer adjustment algorithm

1. Start with modeled reference cell data

$$RC_{Model} = \frac{IAM_{RC}}{K_{RC}} * \sum_{\lambda=300\text{ nm}}^{4000} R_{RC\lambda}(T) \cdot I_{\lambda}$$

2. Multiply and divide by $PY_{Meausure}$

$$RC_{Model} = \frac{IAM_{RC}}{K_{RC}} * \sum_{\lambda=300\text{ nm}}^{4000} R_{RC\lambda}(T) \cdot I_{\lambda} * \frac{PY_{Meausure}}{PY_{Meausure}}$$

3. Replace $PY_{Meausure}$ with PY_{Model}

$$RC_{Model} = \frac{IAM_{RC}}{K_{RC}} * \sum_{\lambda=300\text{ nm}}^{4000} R_{RC\lambda}(T) \cdot I_{\lambda} * \frac{PY_{Meausure}}{PY_{Model}}$$

4. Replace PY_{Model} with the form $IAM/K (R \cdot I)$

$$RC_{Model} = \left(\frac{IAM_{RC}}{K_{RC}} * \sum_{\lambda=300\text{ nm}}^{4000} R_{RC\lambda}(T) \cdot I_{\lambda} \right) * \left(\frac{PY_{Meausure}}{\frac{IAM_{PY}}{K_{PY}} * \sum_{\lambda=300\text{ nm}}^{4000} R_{PY\lambda}(T) \cdot I_{\lambda}} \right)$$

5. Rearrange terms

$$RC_{Model} = \left(\frac{K_{PY}}{K_{RC}} \right) * \left(\frac{IAM_{RC}}{IAM_{PY}} \right) * \left(\frac{\sum_{\lambda=300\text{ nm}}^{4000} R_{RC\lambda}(T) \cdot I_{\lambda}}{\sum_{\lambda=300\text{ nm}}^{4000} R_{PY\lambda}(T) \cdot I_{\lambda}} \right) * PY_{Meausure}$$

Pyranometer / Reference cell adjustment algorithm

Pyranometer data is adjusted to a data set that mimics that of the corresponding reference cell.

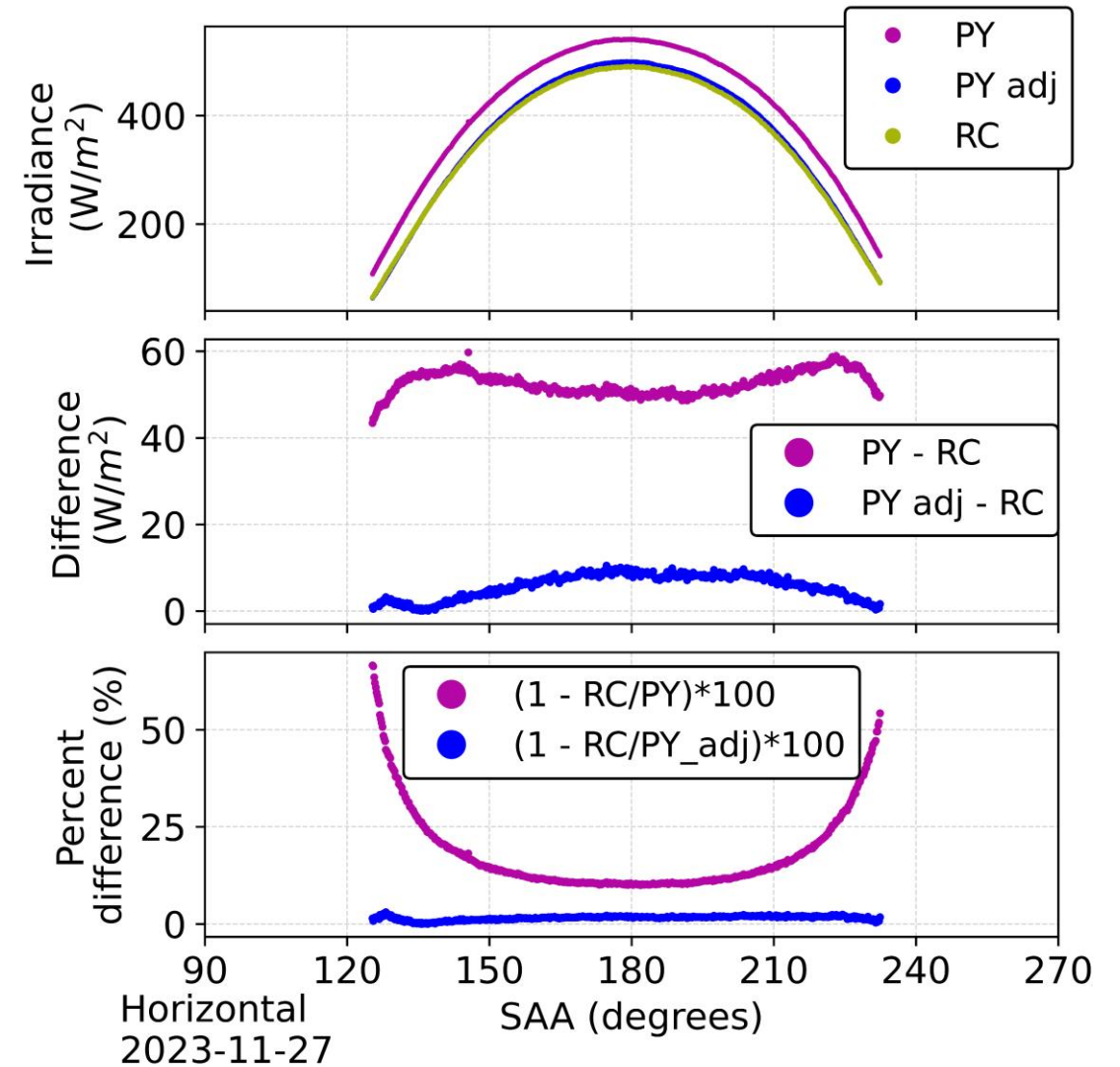
$$RC_{Model} = \left(\frac{K_{PY}}{K_{RC}} \right) * \left(\frac{IAM_{RC}}{IAM_{PY}} \right) * \left(\frac{\sum_{\lambda=300\text{ nm}}^{4000} R_{RC\ \lambda}(T) \cdot I_{\lambda}}{\sum_{\lambda=300\text{ nm}}^{4000} R_{PY\ \lambda}(T) \cdot I_{\lambda}} \right) * PY_{\text{Measurement}}$$

The transformation applies three ratios to the pyranometer data set

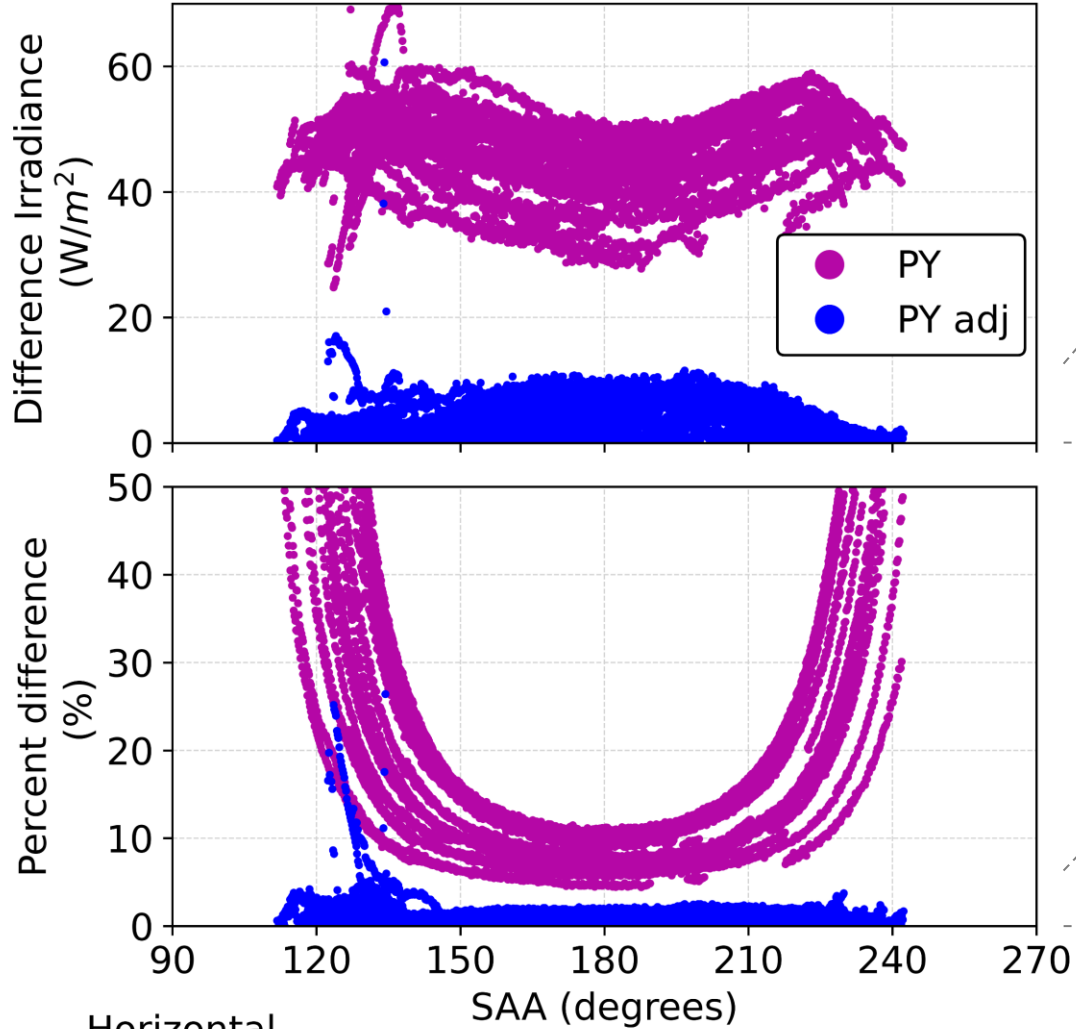
Each ratio unapplies a pyranometer value and applies a corresponding reference cell value.

Results (one day)

- The adjustment was applied to the pyranometer data set.
- Significant improvements were obtained
 - Differences reduced to less than 10 W/m².
 - Percent differences reduced to less than 2%.

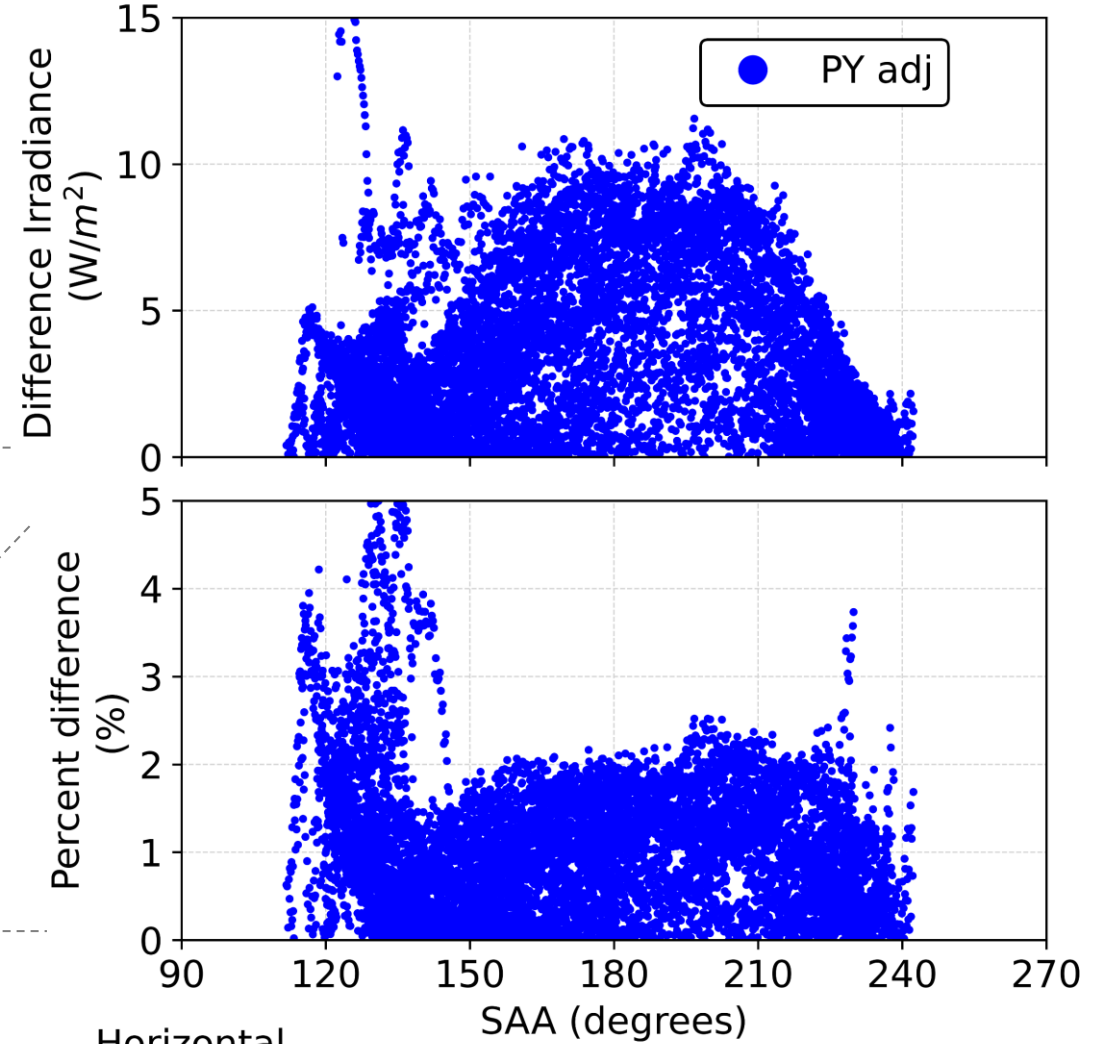


Results (2 ½ months)



Horizontal
2023-10-23 to 2023-12-30
Clear sky minutes

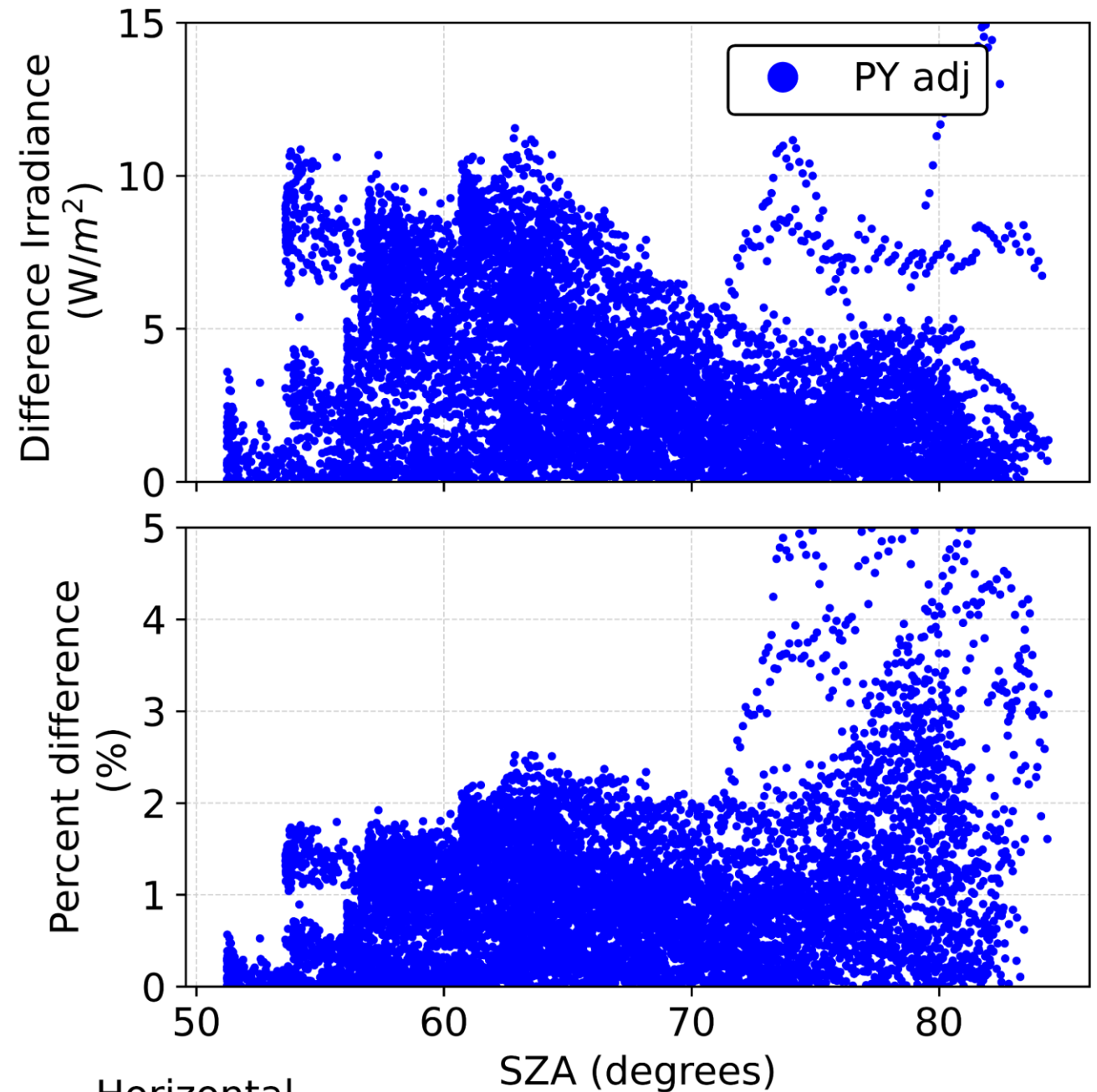
Zoomed in view of just
the adjusted differences



Horizontal
2023-10-23 to 2023-12-30

Results vs SZA

- At all zenith angles, the differences are less than 10 W/m² (5%)
- At zenith angles less than 70° the percent difference decreases to 2%.



Horizontal
2023-10-23 to 2023-12-30 Clear sky minutes

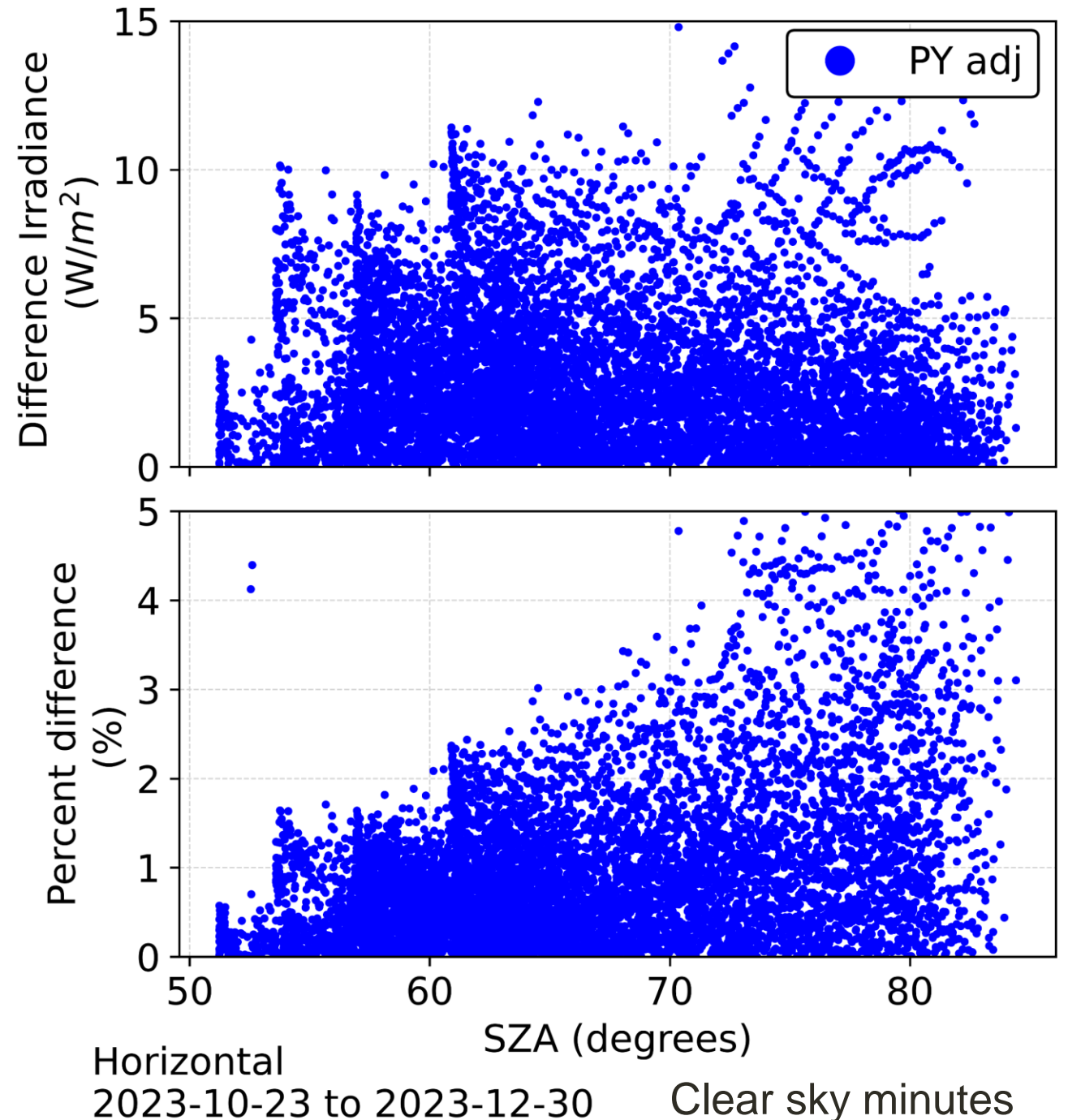
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Atonometrics reference cell

- Method works on different reference cells

(Previous plots were for an IMT reference cell)

- The plot on the right is for an Atonometrics 18 reference cell.



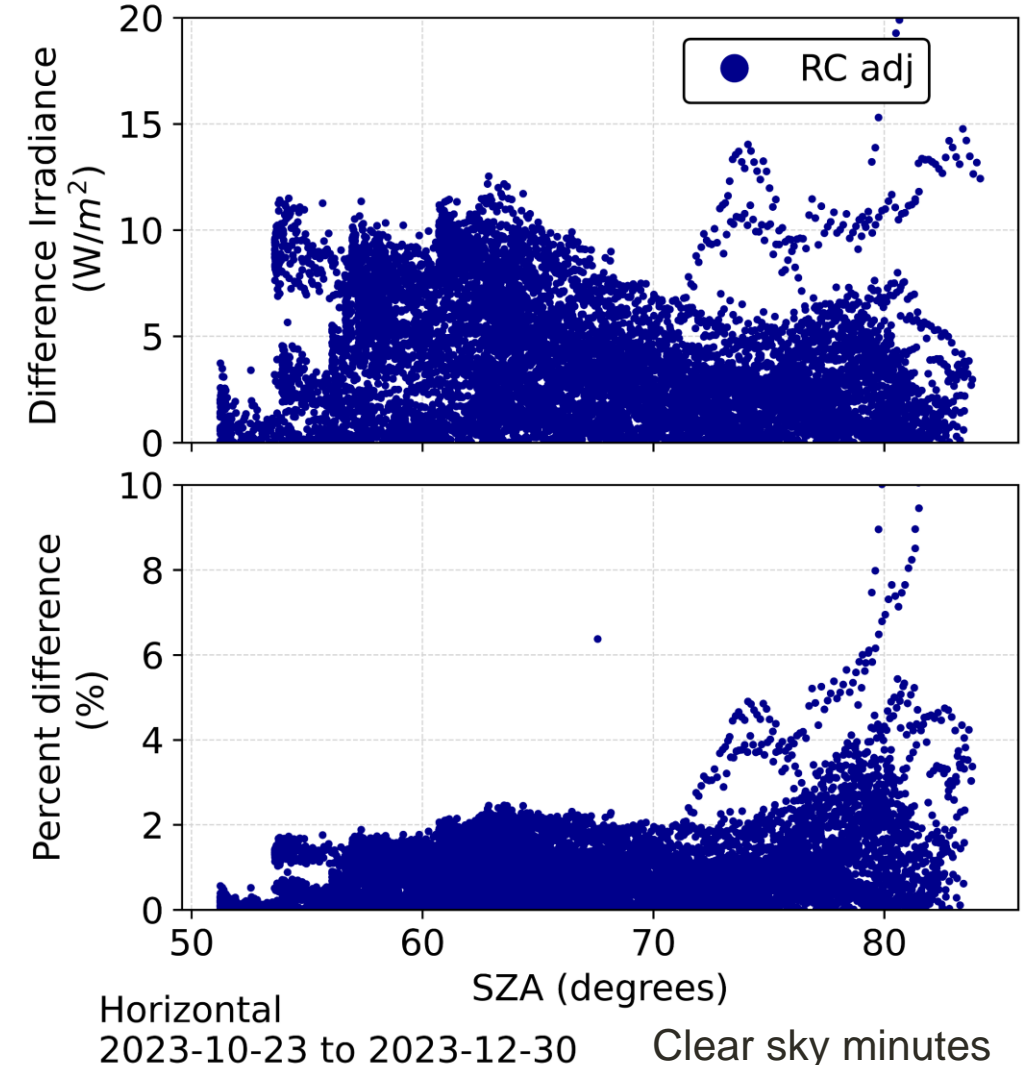
Reference cell adjusted to pyranometer data

- Rearranging the adjustment equation to solve for PY_{model}
 - That is, given a RC data set, what would the corresponding PY data be

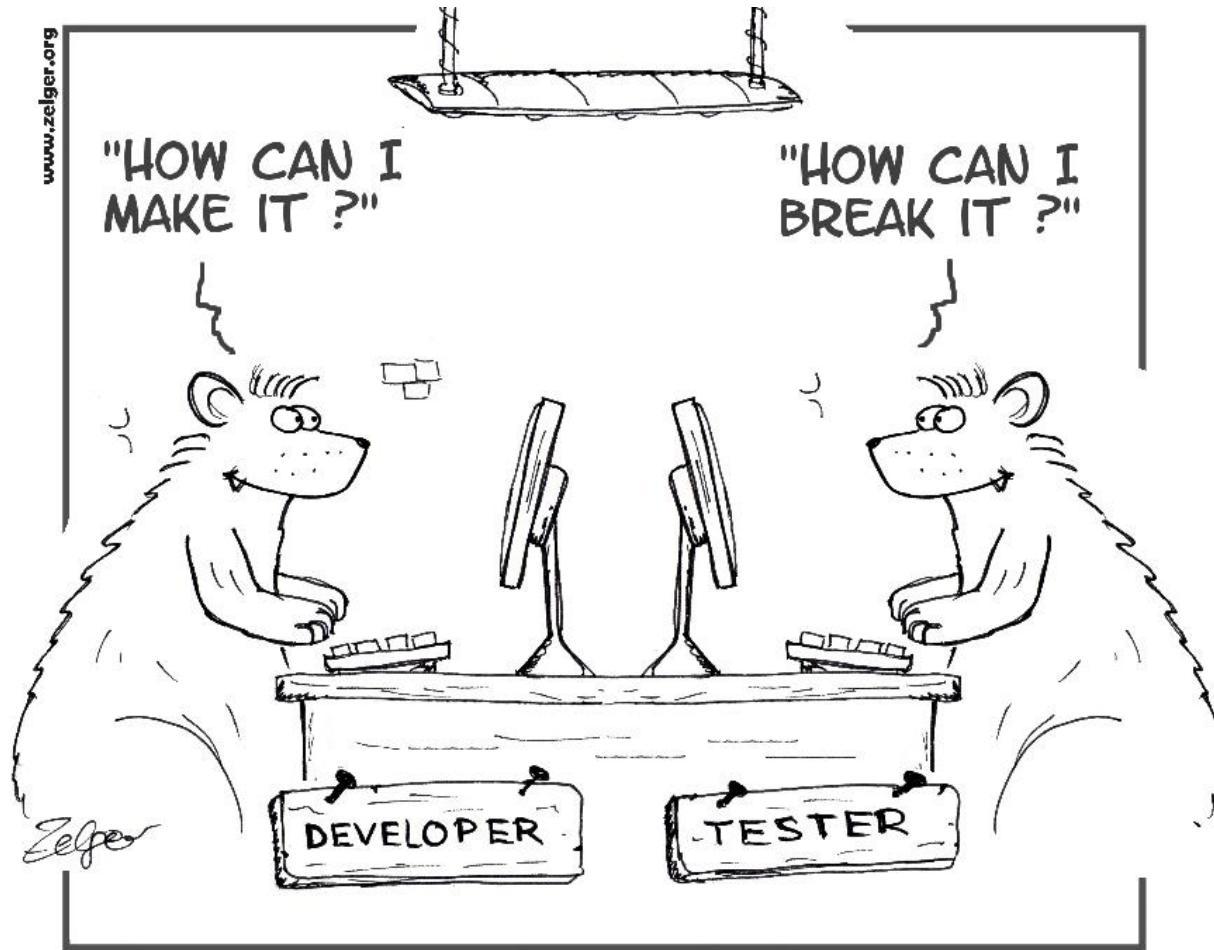
$$PY_{\text{Model}} = \left(\frac{K_{RC}}{K_{PY}} \right) * \left(\frac{IAM_{PY}}{IAM_{RC}} \right) * \left(\frac{\sum_{\lambda=300 \text{ nm}}^{4000} R_{PY \lambda}(T) \cdot I_{\lambda}}{\sum_{\lambda=300 \text{ nm}}^{4000} R_{RC \lambda}(T) \cdot I_{\lambda}} \right) * RC_{\text{Measure}}$$

- Results show similar differences.

Comparison of RC adjusted data with measured pyranometer data



Next steps ... further validation



They weren't so much different, but they had different goals

- Test the results over a longer data set
- Test K from one site to another
- Test other spectral models
- Test the results over non-clear sky days
- Test K from one instrument to another
- Apply this method to PV modules.
- Improve the flatness of K

Conclusions

- Pyranometer data has been transformed to corresponding reference cell data.
- Reference cell data has been transformed to corresponding pyranometer data.
- Since reference cells are very similar to PV modules, this algorithm should for work for PV modules.



Comments Questions

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