



Spectral Effects in Performance Ratio Measurement: Comparing PV Reference Devices and Pyranometers

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Non-Confidential Information

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Background

- PV Array Performance Ratio (PR) measurements depend critically on insolation measurements.
- Pyranometers historically described as near-ideal insolation meters due to flat spectral response.
- Large body of historical data from Pyranometer measurements exists.
- Pyranometer response can differ significantly from PV technologies primarily due to long-wavelength response (*i.e.*, >1200 nm).
- Our thinking: the measurement important to PV operation is perceived (*i.e.*, spectrally matched) insolation specific to that PV device.

Summary of Findings

- Pyranometers deviate from PV module perceived irradiances due to spectral effects.
 - Monthly deviations can be $> 3\%$.
 - Annual deviations can be $> 1.5\%$.
- Atmospheric conditions matter
 - Houston: high water vapor \rightarrow larger Pyranometer deviation from PV measurement
 - Phoenix: less water vapor \rightarrow smaller (but still significant) Pyranometer deviation from PV measurement
- C-Si reference devices also show significant mismatch errors with thin film modules.

Reference Devices

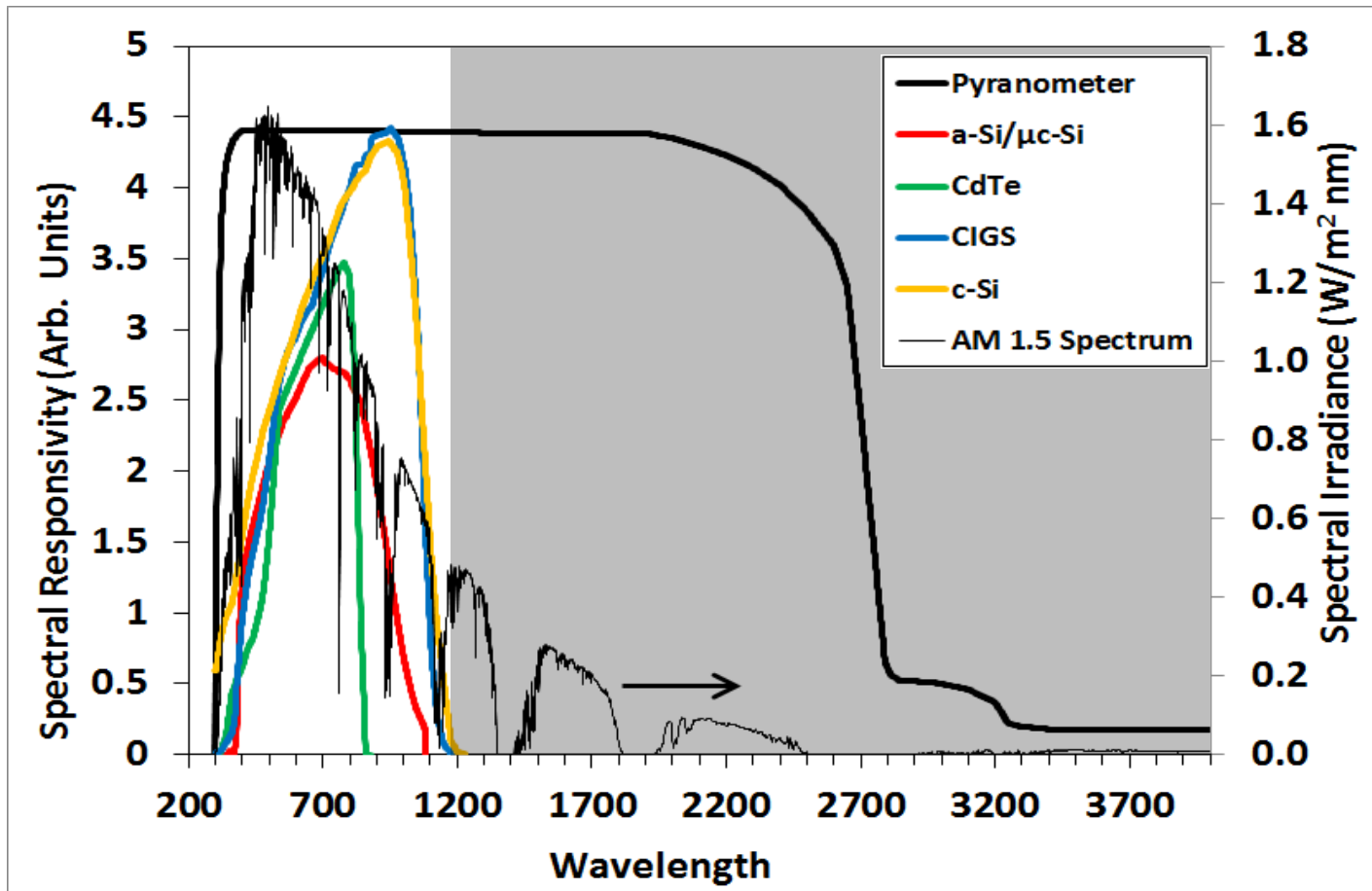
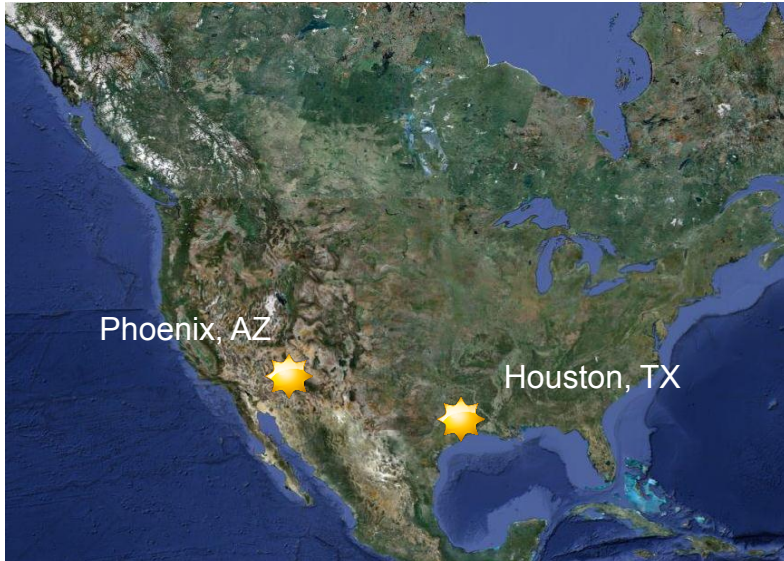


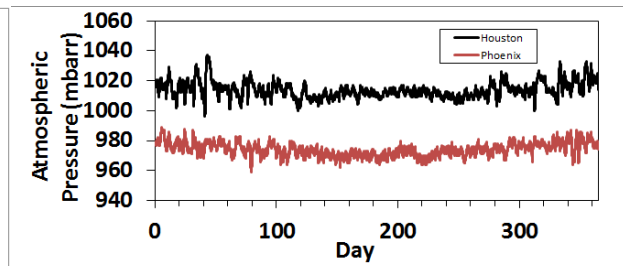
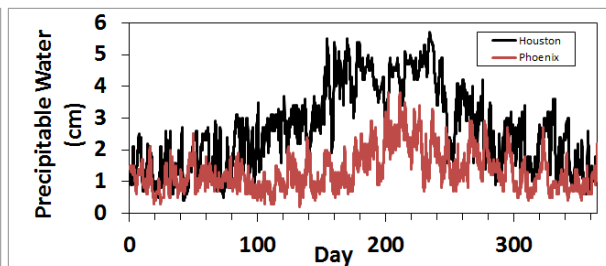
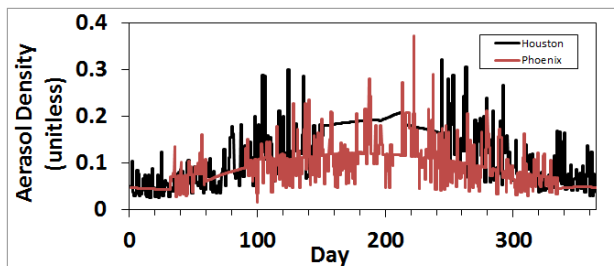
Figure 1: Spectral Response of Pyranometer and PV devices of various technologies, shown with the AM 1.5 Reference Spectrum. Shaded area represents spectral region of Pyranometer response and no PV response. Pyranometer Spectral Response taken from data published by a Pyranometer manufacturer. a-Si/μc-Si, c-Si, CdTe, and CIGS spectral responses taken from NREL calibration reports or from literature. Note Spectral Response is shown on the left y-axis.

Simulating Solar Spectra



- NREL SPECTRL2 worksheet based on Bird's Simple Spectral Model used to generate solar spectra at 5 minute increments.
- Aerosol density (AOD), atmospheric pressure, and precipitable water inputs to spectral model taken from Typical Meteorological Year 3 (TMY3) database hosted by NREL
- Simulations done for clear-sky conditions only
- Houston, TX (sunny, humid) and Phoenix, AZ (sunny, dry) chosen as simulated locations.

TMY3 Weather Data



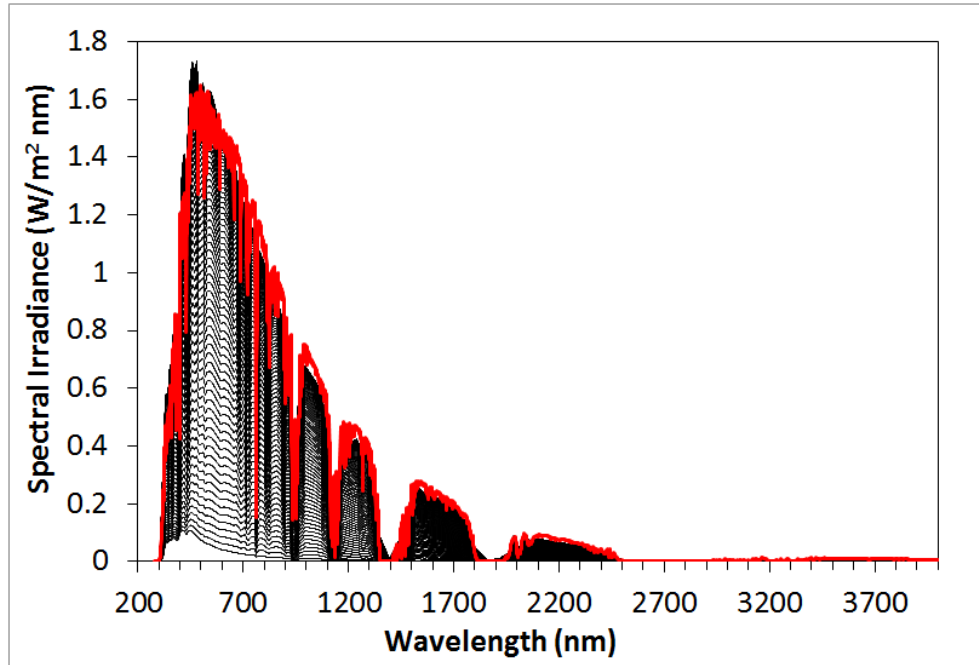


Figure 2: Example simulated spectra at 5 minute increments from 6:30 a.m. to 12:30 p.m. in Phoenix, Arizona on the 152nd day of the year (June 1). The thick red curve is the AM 1.5 reference spectrum.

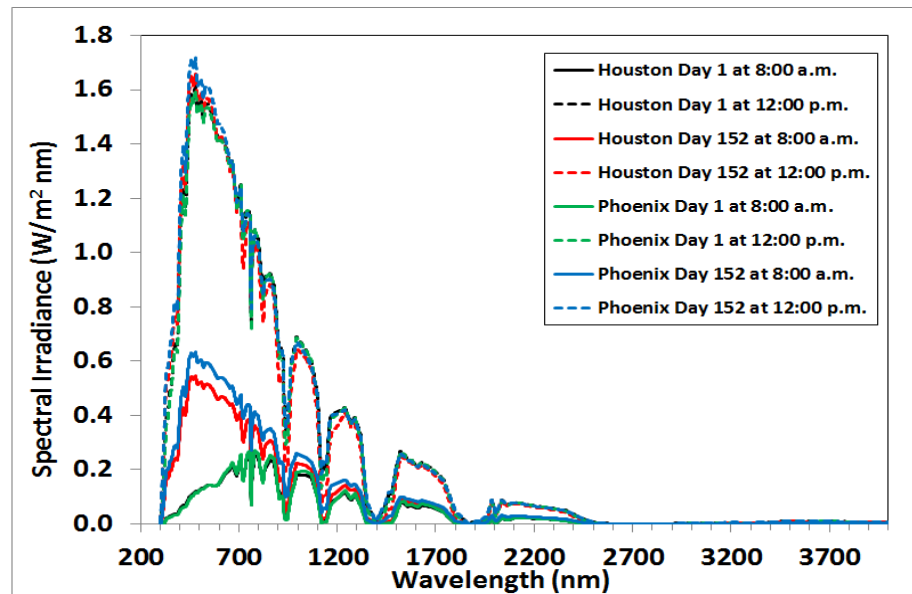
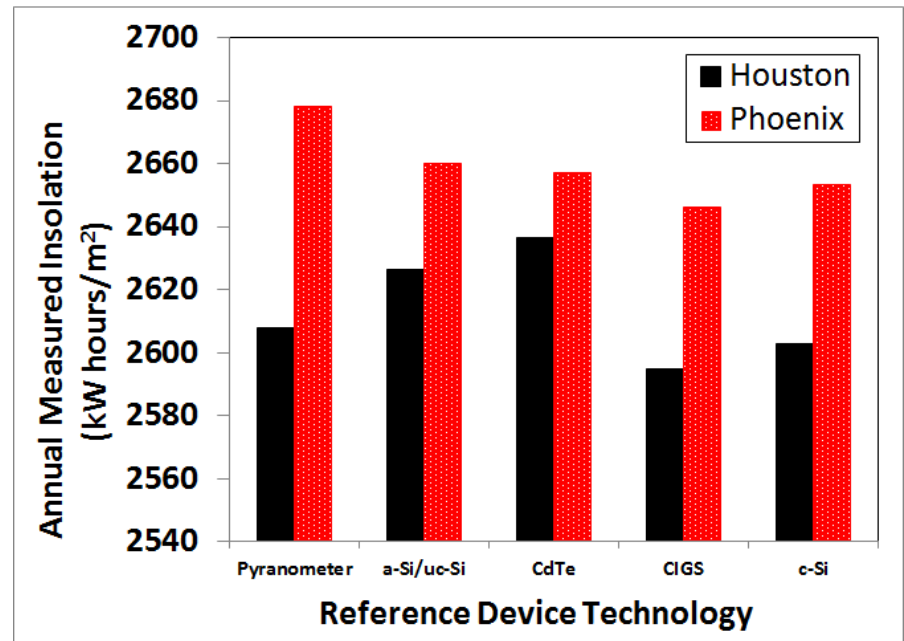
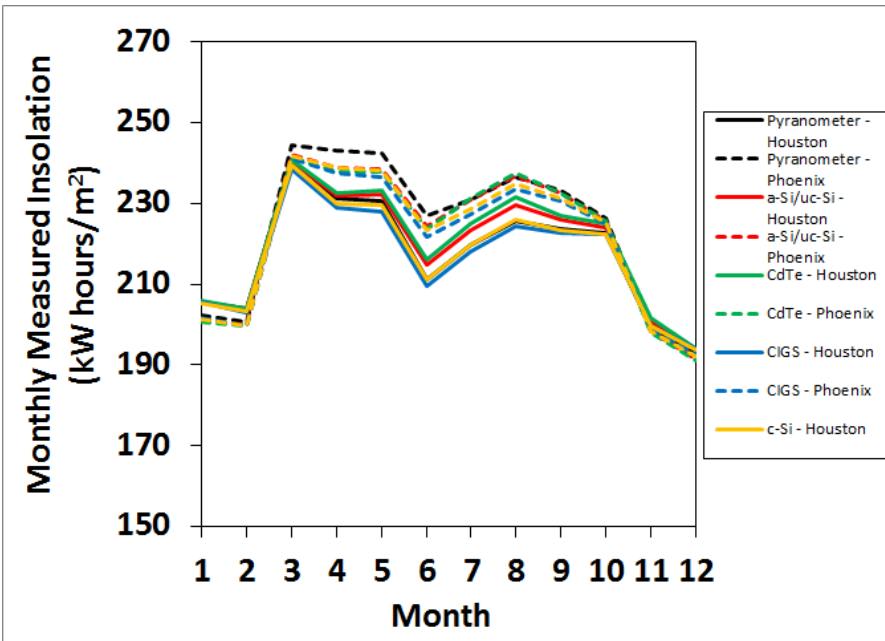
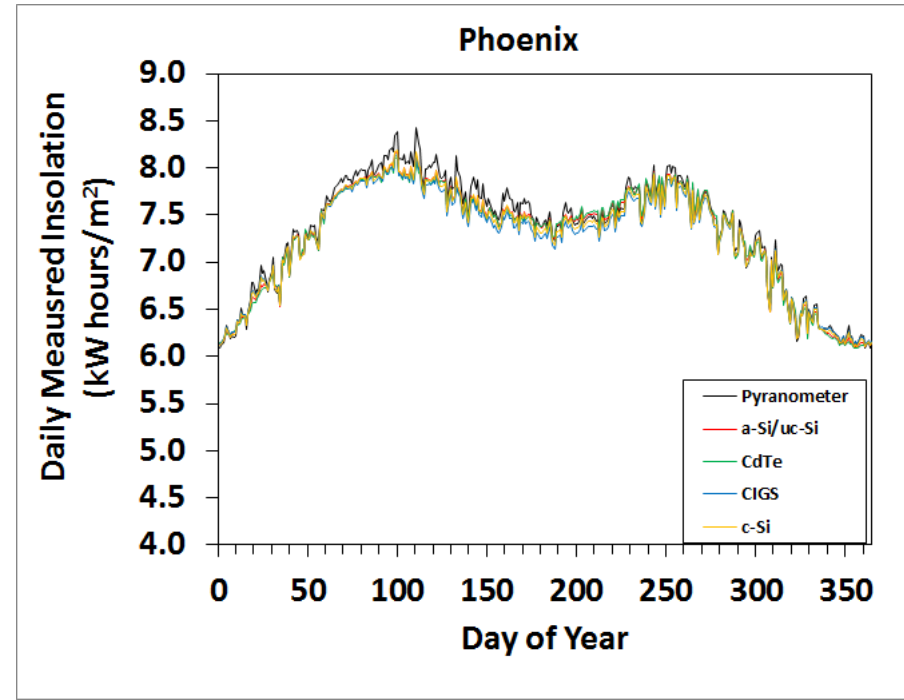
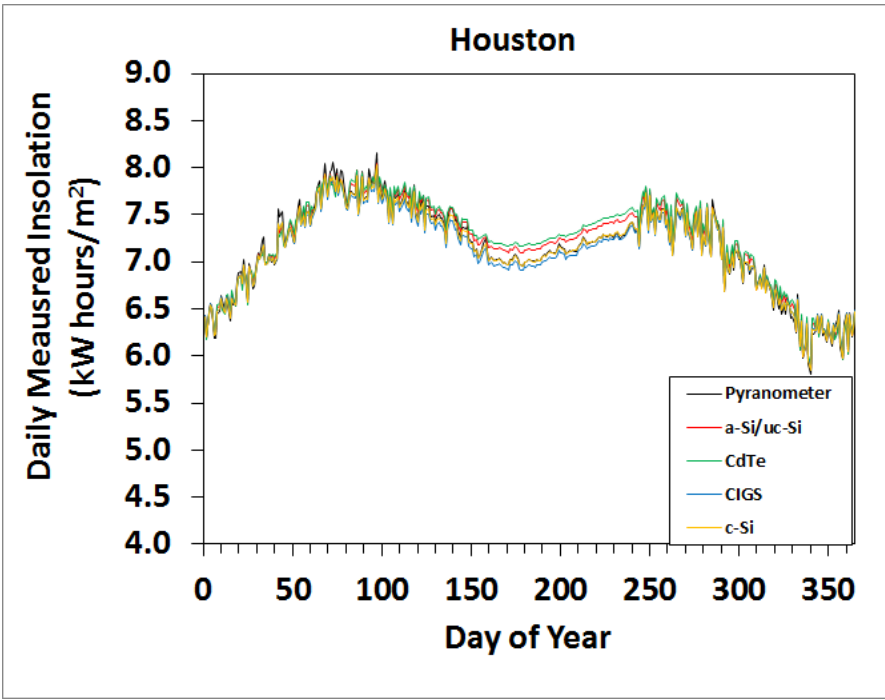


Figure 3: Example simulated spectra in Houston, TX and Phoenix, AZ on the first (January 1) and 152nd (June 1) days of the year at 8:00 a.m. and noon.

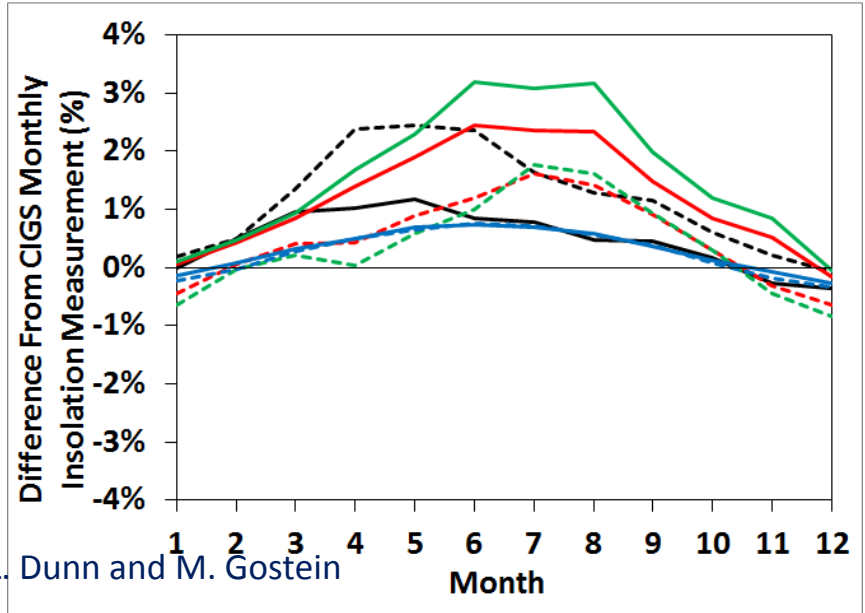
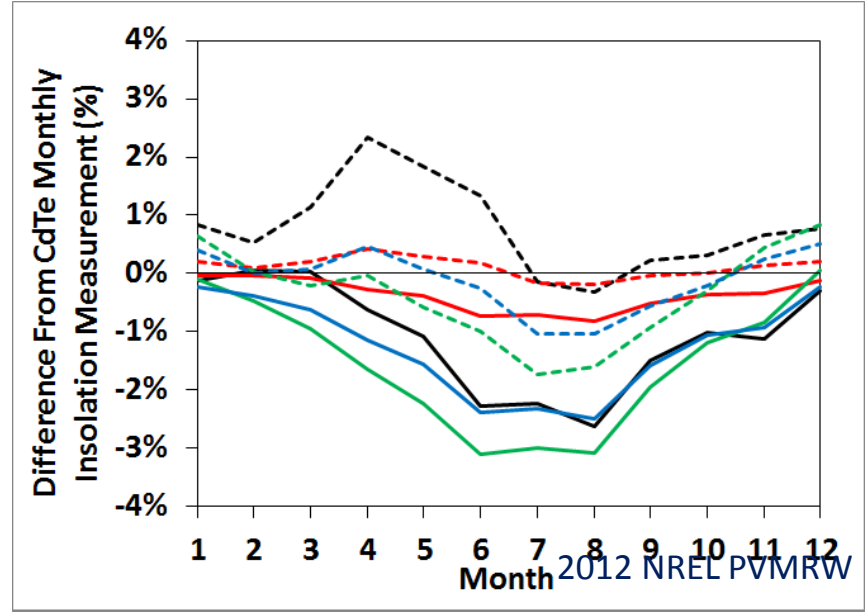
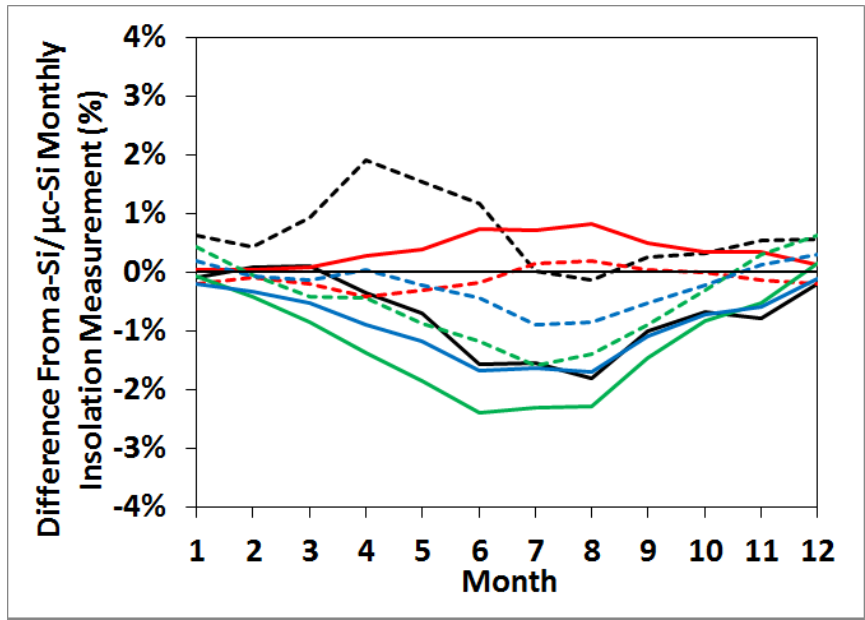
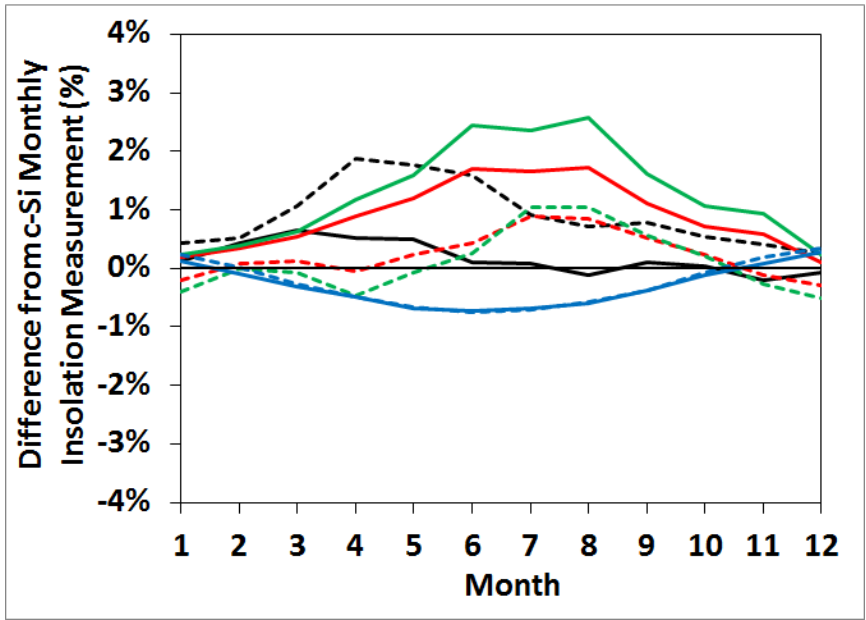
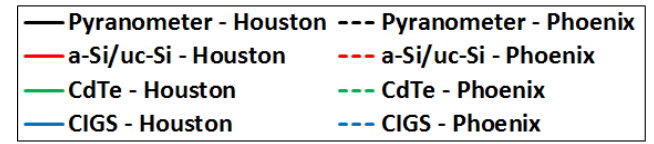
Methodology

- Response of each reference device under AM 1.5 Spectrum calculated to perform a simulated calibration.
 - Thermopile Pyranometer
 - a-Si/ μ c-Si
 - CdTe
 - CIGS
 - Crystalline Si
- Thousands of simulated spectra generated from TMY3 data using the SPECTRAL2 model for each location.
- Each device's calibrated response calculated for all spectra and compiled.
- Simulated daily, monthly, and annual insolation measurements for each technology were calculated.
 - Errors between perceived irradiances by power generating PV modules and reference devices calculated.

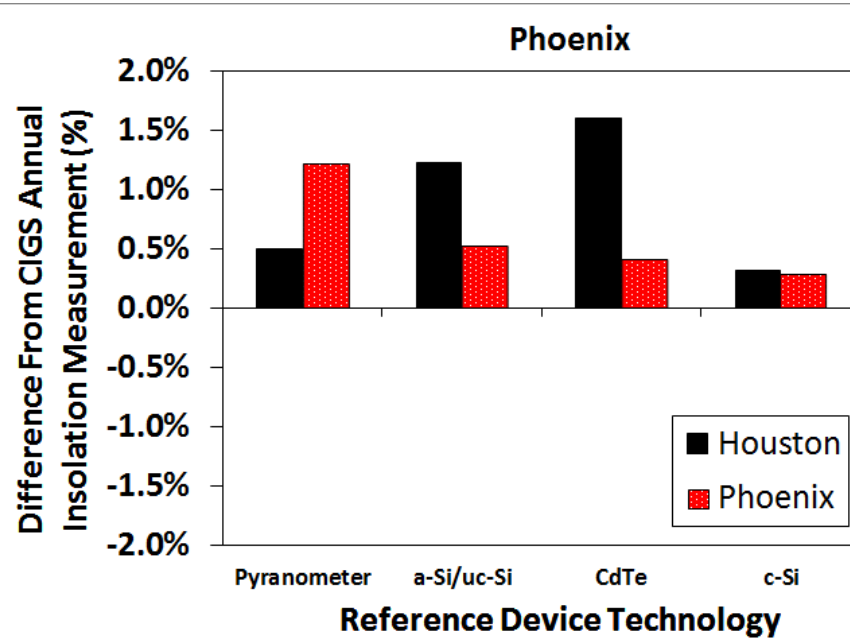
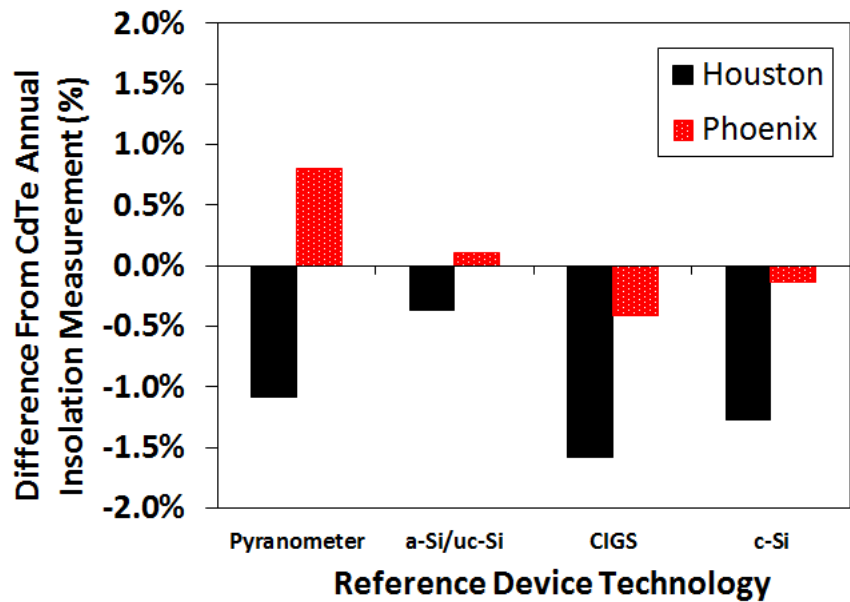
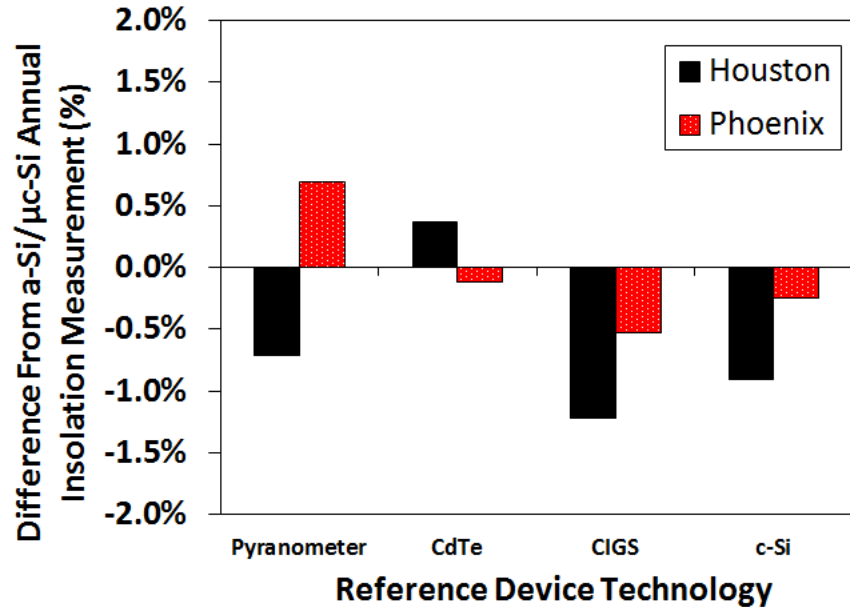
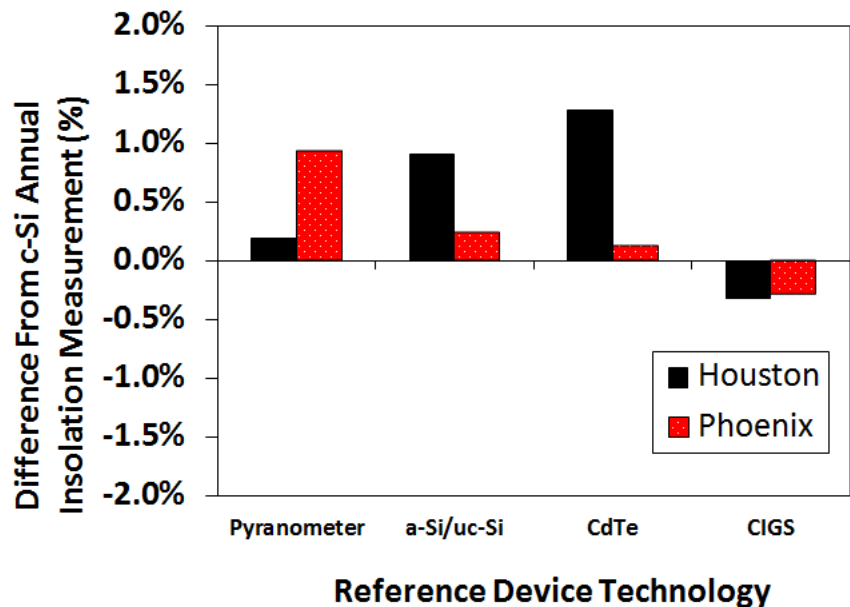
Daily, Monthly, and Annually Simulated Insolation Values



Discrepancies in Monthly Insolation Measurements for Various PV Technologies



Discrepancies in Annual Insolation Measurements



Results Summary Table

| Annual Data | | Reference Device Technology | | | | | | | | | |
|----------------------|------------------|-----------------------------|---------|---------|---------|------------------|---------|---------|---------|---------|---------|
| | | Pyranometer | | c-Si | | a-Si/ μ c-Si | | CdTe | | CIGS | |
| | | Houston | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston | Phoenix |
| PV Module Technology | c-Si | 0.2% | 0.9% | 0.0% | 0.0% | 0.9% | 0.2% | 1.3% | 0.1% | -0.3% | -0.3% |
| | a-Si/ μ c-Si | -0.7% | 0.7% | -0.9% | -0.2% | 0.0% | 0.0% | 0.4% | -0.1% | -1.2% | -0.5% |
| | CdTe | -1.1% | 0.8% | -1.3% | -0.1% | -0.4% | 0.1% | 0.0% | 0.0% | -1.6% | -0.4% |
| | CIGS | 0.5% | 1.2% | 0.3% | 0.3% | 1.2% | 0.5% | 1.6% | 0.4% | 0.0% | 0.0% |

| Legend | |
|--|--|
| Error = 0.0% | |
| $0\% < \text{Error} \leq 0.5\%$ | |
| $0.5\% \leq \text{Error} \leq 1.5\%$ | |
| $1.5\% \leq \text{Error} \leq 2.5\%$ | |
| $ \text{Error} < 2.5\%$ | |

| | Difference from c-Si Monthly Measured Insolation | | | | | | | | | | |
|--------|--|---------|---------|---------|------------------|---------|---------|---------|---------|---------|--|
| | Reference Device Technology | | | | | | | | | | |
| | Pyranometer | | c-Si | | a-Si/ μ c-Si | | CdTe | | CIGS | | |
| | Houston | Phoenix | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston | |
| Jan | 0.1% | 0.4% | 0.0% | 0.0% | 0.2% | -0.2% | 0.2% | -0.4% | 0.1% | 0.2% | |
| Feb | 0.4% | 0.5% | 0.0% | 0.0% | 0.3% | 0.1% | 0.4% | 0.0% | -0.1% | 0.0% | |
| March | 0.6% | 1.1% | 0.0% | 0.0% | 0.5% | 0.1% | 0.6% | -0.1% | -0.3% | -0.3% | |
| April | 0.5% | 1.9% | 0.0% | 0.0% | 0.9% | 0.0% | 1.2% | -0.5% | -0.5% | -0.5% | |
| May | 0.5% | 1.8% | 0.0% | 0.0% | 1.2% | 0.2% | 1.6% | -0.1% | -0.7% | -0.7% | |
| June | 0.1% | 1.6% | 0.0% | 0.0% | 1.7% | 0.4% | 2.4% | 0.3% | -0.7% | -0.7% | |
| July | 0.1% | 0.9% | 0.0% | 0.0% | 1.6% | 0.9% | 2.4% | 1.0% | -0.7% | -0.7% | |
| August | -0.1% | 0.7% | 0.0% | 0.0% | 1.7% | 0.8% | 2.6% | 1.0% | -0.6% | -0.6% | |
| Sept | 0.1% | 0.8% | 0.0% | 0.0% | 1.1% | 0.5% | 1.6% | 0.6% | -0.4% | -0.4% | |
| Oct | 0.0% | 0.5% | 0.0% | 0.0% | 0.7% | 0.2% | 1.1% | 0.2% | -0.1% | -0.1% | |
| Nov | -0.2% | 0.4% | 0.0% | 0.0% | 0.6% | -0.1% | 0.9% | -0.3% | 0.1% | 0.2% | |
| Dec | -0.1% | 0.3% | 0.0% | 0.0% | 0.1% | -0.3% | 0.2% | -0.5% | 0.3% | 0.3% | |

Monthly Results for a-Si/ μ c-Si Modules

| | Difference from a-Si/ μ c-Si Monthly Measured Insolation | | | | | | | | | |
|--------|--|---------|---------|---------|------------------|---------|---------|---------|---------|---------|
| | Reference Device Technology | | | | | | | | | |
| | Pyranometer | | c-Si | | a-Si/ μ c-Si | | CdTe | | CIGS | |
| | Houston | Phoenix | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston |
| Jan | -0.1% | 0.6% | -0.2% | 0.2% | 0.0% | 0.0% | 0.0% | -0.2% | -0.1% | 0.4% |
| Feb | 0.1% | 0.4% | -0.3% | -0.1% | 0.0% | 0.0% | 0.0% | -0.1% | -0.4% | -0.1% |
| March | 0.1% | 0.9% | -0.5% | -0.1% | 0.0% | 0.0% | 0.1% | -0.2% | -0.9% | -0.4% |
| April | -0.4% | 1.9% | -0.9% | 0.0% | 0.0% | 0.0% | 0.3% | -0.4% | -1.4% | -0.4% |
| May | -0.7% | 1.5% | -1.2% | -0.2% | 0.0% | 0.0% | 0.4% | -0.3% | -1.9% | -0.9% |
| June | -1.6% | 1.2% | -1.7% | -0.4% | 0.0% | 0.0% | 0.7% | -0.2% | -2.4% | -1.2% |
| July | -1.5% | 0.0% | -1.6% | -0.9% | 0.0% | 0.0% | 0.7% | 0.2% | -2.3% | -1.6% |
| August | -1.8% | -0.1% | -1.7% | -0.8% | 0.0% | 0.0% | 0.8% | 0.2% | -2.3% | -1.4% |
| Sept | -1.0% | 0.3% | -1.1% | -0.5% | 0.0% | 0.0% | 0.5% | 0.0% | -1.5% | -0.9% |
| Oct | -0.7% | 0.3% | -0.7% | -0.2% | 0.0% | 0.0% | 0.4% | 0.0% | -0.8% | -0.3% |
| Nov | -0.8% | 0.5% | -0.6% | 0.1% | 0.0% | 0.0% | 0.3% | -0.1% | -0.5% | 0.3% |
| Dec | -0.2% | 0.6% | -0.1% | 0.3% | 0.0% | 0.0% | 0.1% | -0.2% | 0.2% | 0.6% |

Monthly Results for CdTe Modules

| | Difference from CdTe Monthly Measured Insolation | | | | | | | | | |
|--------|--|---------|---------|---------|------------------|---------|---------|---------|---------|---------|
| | Reference Device Technology | | | | | | | | | |
| | Pyranometer | | c-Si | | a-Si/ μ c-Si | | CdTe | | CIGS | |
| | Houston | Phoenix | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston |
| Jan | -0.1% | 0.8% | -0.2% | 0.4% | 0.0% | 0.2% | 0.0% | 0.0% | -0.1% | 0.6% |
| Feb | 0.0% | 0.5% | -0.4% | 0.0% | 0.0% | 0.1% | 0.0% | 0.0% | -0.5% | 0.0% |
| March | 0.0% | 1.1% | -0.6% | 0.1% | -0.1% | 0.2% | 0.0% | 0.0% | -0.9% | -0.2% |
| April | -0.6% | 2.3% | -1.2% | 0.5% | -0.3% | 0.4% | 0.0% | 0.0% | -1.6% | 0.0% |
| May | -1.1% | 1.8% | -1.6% | 0.1% | -0.4% | 0.3% | 0.0% | 0.0% | -2.2% | -0.6% |
| June | -2.3% | 1.3% | -2.4% | -0.3% | -0.7% | 0.2% | 0.0% | 0.0% | -3.1% | -1.0% |
| July | -2.2% | -0.1% | -2.3% | -1.0% | -0.7% | -0.2% | 0.0% | 0.0% | -3.0% | -1.7% |
| August | -2.6% | -0.3% | -2.5% | -1.0% | -0.8% | -0.2% | 0.0% | 0.0% | -3.1% | -1.6% |
| Sept | -1.5% | 0.2% | -1.6% | -0.5% | -0.5% | 0.0% | 0.0% | 0.0% | -1.9% | -0.9% |
| Oct | -1.0% | 0.3% | -1.1% | -0.2% | -0.4% | 0.0% | 0.0% | 0.0% | -1.2% | -0.3% |
| Nov | -1.1% | 0.7% | -0.9% | 0.3% | -0.3% | 0.1% | 0.0% | 0.0% | -0.8% | 0.4% |
| Dec | -0.3% | 0.8% | -0.2% | 0.5% | -0.1% | 0.2% | 0.0% | 0.0% | 0.0% | 0.8% |

Monthly Results for CIGS Modules

| | Difference from CIGS Monthly Measured Insolation | | | | | | | | | |
|--------|--|---------|---------|---------|------------------|---------|---------|---------|---------|---------|
| | Reference Device Technology | | | | | | | | | |
| | Pyranometer | | c-Si | | a-Si/ μ c-Si | | CdTe | | CIGS | |
| | Houston | Phoenix | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston | Phoenix | Houston |
| Jan | 0.0% | 0.2% | -0.1% | -0.2% | 0.1% | -0.4% | 0.1% | -0.6% | 0.0% | 0.0% |
| Feb | 0.5% | 0.5% | 0.1% | 0.0% | 0.4% | 0.1% | 0.5% | 0.0% | 0.0% | 0.0% |
| March | 1.0% | 1.3% | 0.3% | 0.3% | 0.9% | 0.4% | 0.9% | 0.2% | 0.0% | 0.0% |
| April | 1.0% | 2.4% | 0.5% | 0.5% | 1.4% | 0.4% | 1.7% | 0.0% | 0.0% | 0.0% |
| May | 1.2% | 2.4% | 0.7% | 0.7% | 1.9% | 0.9% | 2.3% | 0.6% | 0.0% | 0.0% |
| June | 0.8% | 2.4% | 0.7% | 0.8% | 2.5% | 1.2% | 3.2% | 1.0% | 0.0% | 0.0% |
| July | 0.8% | 1.6% | 0.7% | 0.7% | 2.4% | 1.6% | 3.1% | 1.8% | 0.0% | 0.0% |
| August | 0.5% | 1.3% | 0.6% | 0.6% | 2.3% | 1.4% | 3.2% | 1.6% | 0.0% | 0.0% |
| Sept | 0.5% | 1.2% | 0.4% | 0.4% | 1.5% | 0.9% | 2.0% | 0.9% | 0.0% | 0.0% |
| Oct | 0.2% | 0.6% | 0.1% | 0.1% | 0.8% | 0.3% | 1.2% | 0.3% | 0.0% | 0.0% |
| Nov | -0.3% | 0.2% | -0.1% | -0.2% | 0.5% | -0.3% | 0.9% | -0.4% | 0.0% | 0.0% |
| Dec | -0.3% | -0.1% | -0.3% | -0.3% | -0.2% | -0.6% | 0.0% | -0.8% | 0.0% | 0.0% |