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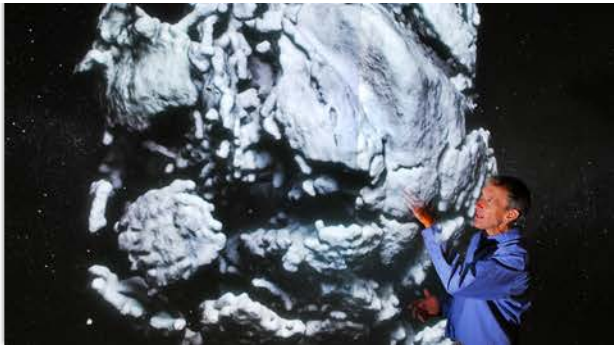

PV Spectral Mismatch: Modeling Options

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Effective Irradiance

- Effective irradiance is the total irradiance "available" to PV modules for power conversion.

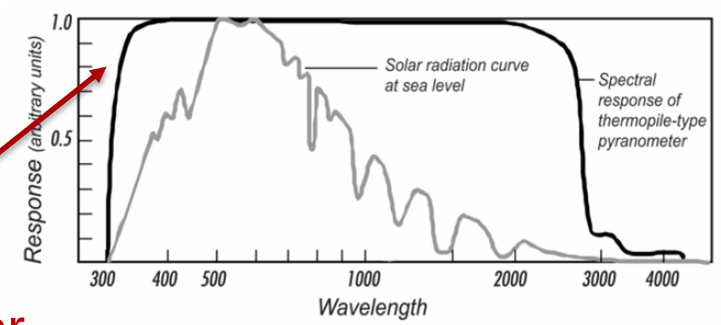
- I_{sc} and I_{mp} are strongly dependent on effective irradiance:
  - $\frac{I_{sc}}{I_{sc0}} = E_e \times [1 + \alpha_{Isc}(T_c - T_0)]$
  - $\frac{I_{mp}}{I_{mp0}} = E_e \times [C_0 \ + C_1 \ ] \times [1 + \alpha_{Imp}(T_c - T_0)]$

- Effective irradiance ≠ pyranometer irradiance
  - Angle of incidence losses.
  - Soiling.
  - **Spectral mismatch.**

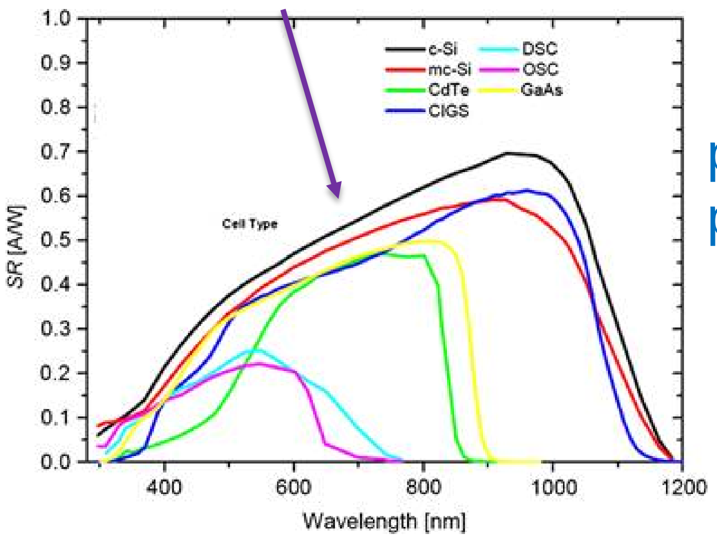
Spectral Mismatch

- PV devices are rated based on a reference spectrum.
- When outdoors, spectrum will vary due to atmospheric content.
- Different spectral response (SR) among different types of PV cells and pyranometers.

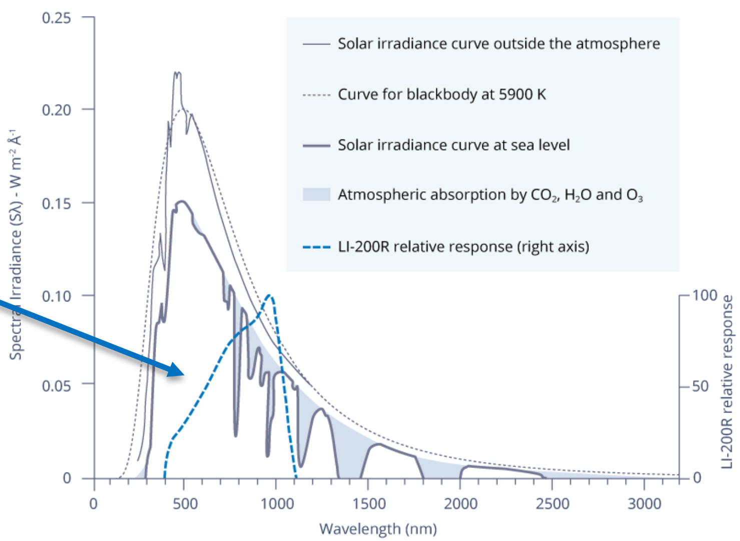
thermopile pyranometer



PV cells



photodiode pyranometer



Images from Kipp and Zonen CM21 Instruction Manual, LICOR Instruction Manual, and pvpmc.sandia.gov

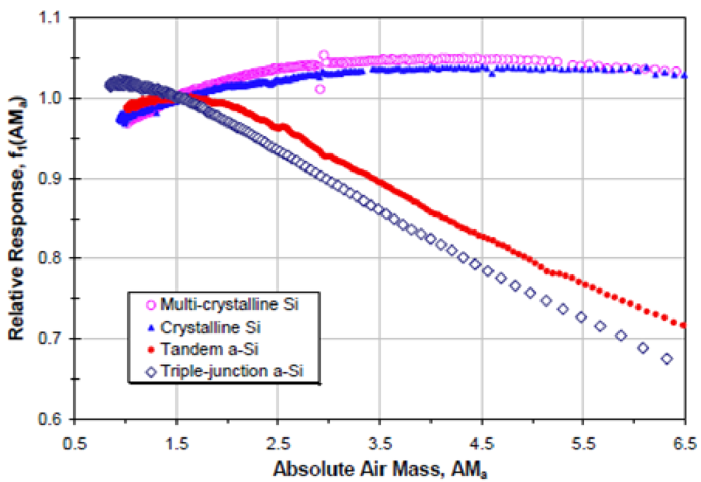
Air Mass Modifier

- In the Sandia Array Performance Model, an empirical function, $f_1(AM_a)$ is used as an air mass modifier when calculating the effective irradiance:

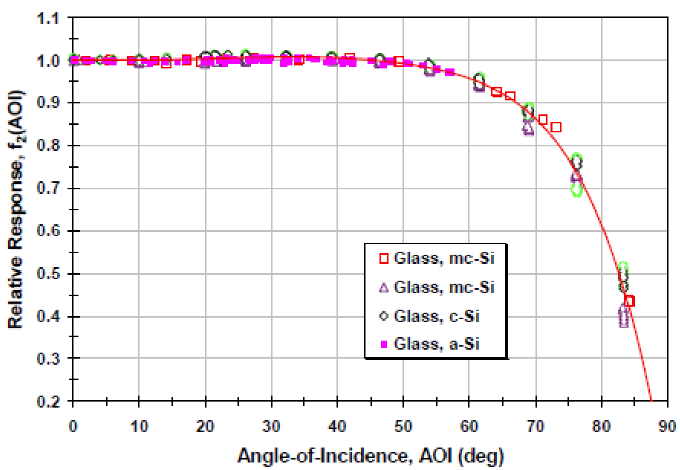
$$E_e = f_1(AM_a) \times \left[\mathrm{E_b} \times f_2(AOI) + f_d E_{diff}\right] / E_o$$

- $f_1(AM_a)$ depends on air mass
  - $f_2(AOI) \approx 1$, when AOI<50˚
  - $f_d = 1$

$f_1(AM_a)$



$f_2(AOI)$



Air Mass vs. Spectral Measurements

- The air mass modifier assumes that spectral content depends *only* on air mass.
- Convenient when few measurements are available: air mass can be calculated from solar zenith.

- But, the makeup of the atmosphere is not constant!
  - Ideally, we would measure the entire spectrum on regular intervals.
    - Cost prohibitive; data intense.

- What if we created low-cost sensors which each measured only one spectral wavelength? Could this be effective to enhance PV performance modeling?

Linear Model of I_{sc}

- Hypothesis: Measurement of only a few spectral wavelengths will be sufficient for significant improvements in PV performance modeling.
- Evaluated match between modeled and measured I_{sc}.
- For simplicity, assumed model form of:

$$I_{sc} = C_1 + C_2 \times POA + \mathrm{C}_3(\mathrm{SP}_1 \,/\, \mathrm{POA}) \ldots \mathrm{C}_{2+\mathrm{n}}\left(\frac{\mathrm{SP}_\mathrm{n}}{POA}\right)$$

  - POA = thermopile irradiance

- Also considered air mass:
  - $\mathrm{I}_{\mathrm{sc}} = \mathrm{C}_1 + \mathrm{C}_2 \times POA + \mathrm{C}_3 \times AM$

Data

Los Alamos, NM

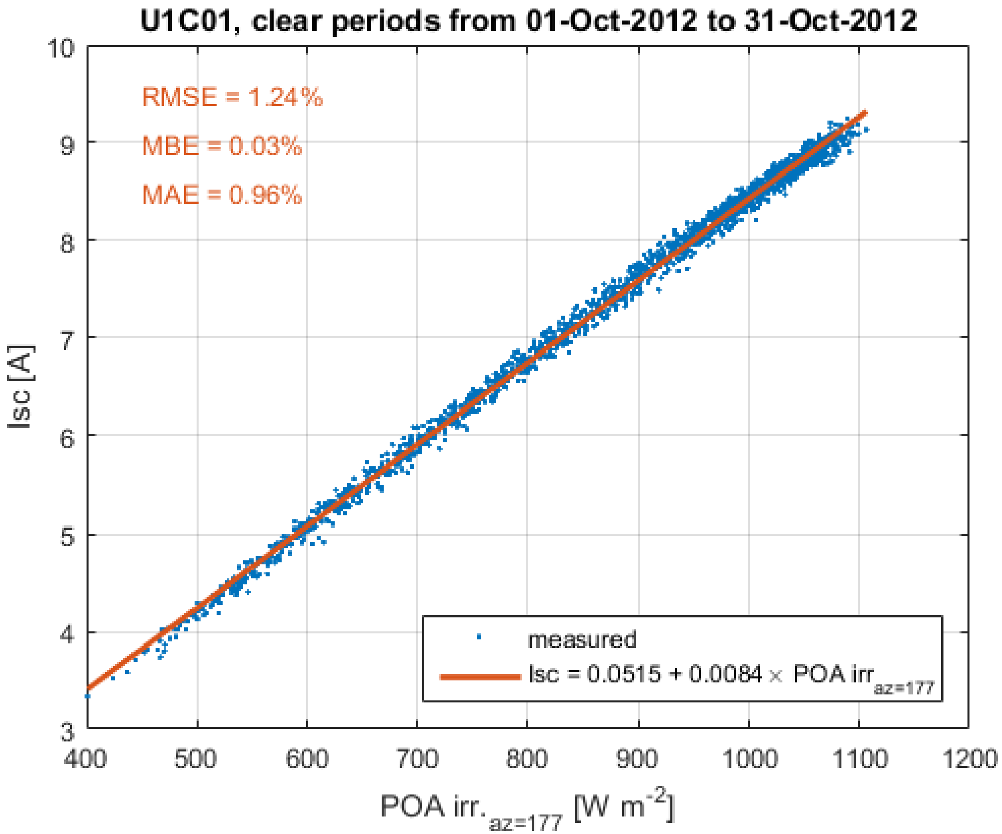
All data collected every 5-min.

- Spectral irradiance (300-1700nm) broadband irradiance (thermopile pyranometer)
  - Latitude tilt
  - Every 5-minutes
- I_{sc} from 10 different types of PV modules
  - Monocrystalline Si (regular and bifacial), Polycrystalline Si, Amorphous Si, CIGS, CdTe
- **Data was collected and graciously shared by the New Energy and Industrial Technology Development Organization (NEDO).**
  - Yuzuru Ueda, Tokyo Institute of Technology, Tokyo, Japan
  - Keiichiro Hakuta, NTT Facilities Inc, Tokyo, Japan

Irradiance Only to Model I_{sc}

- Irradiance only:

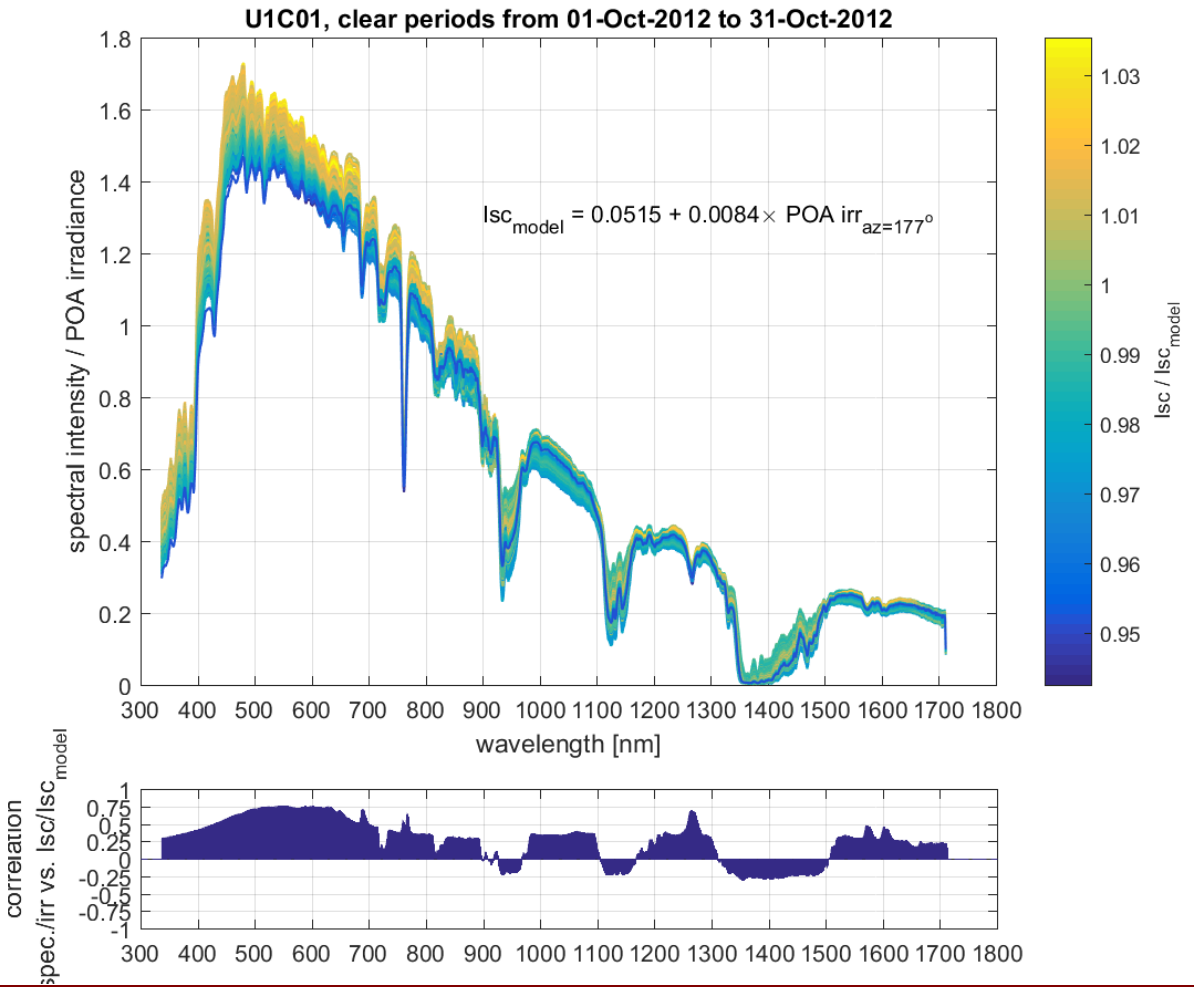
$$I_{sc} = -0.0515 + 0.084 \times \text{POA}$$



- POA highly correlated to I_{sc}, remaining variation expected to be mostly cause by spectral mismatch.

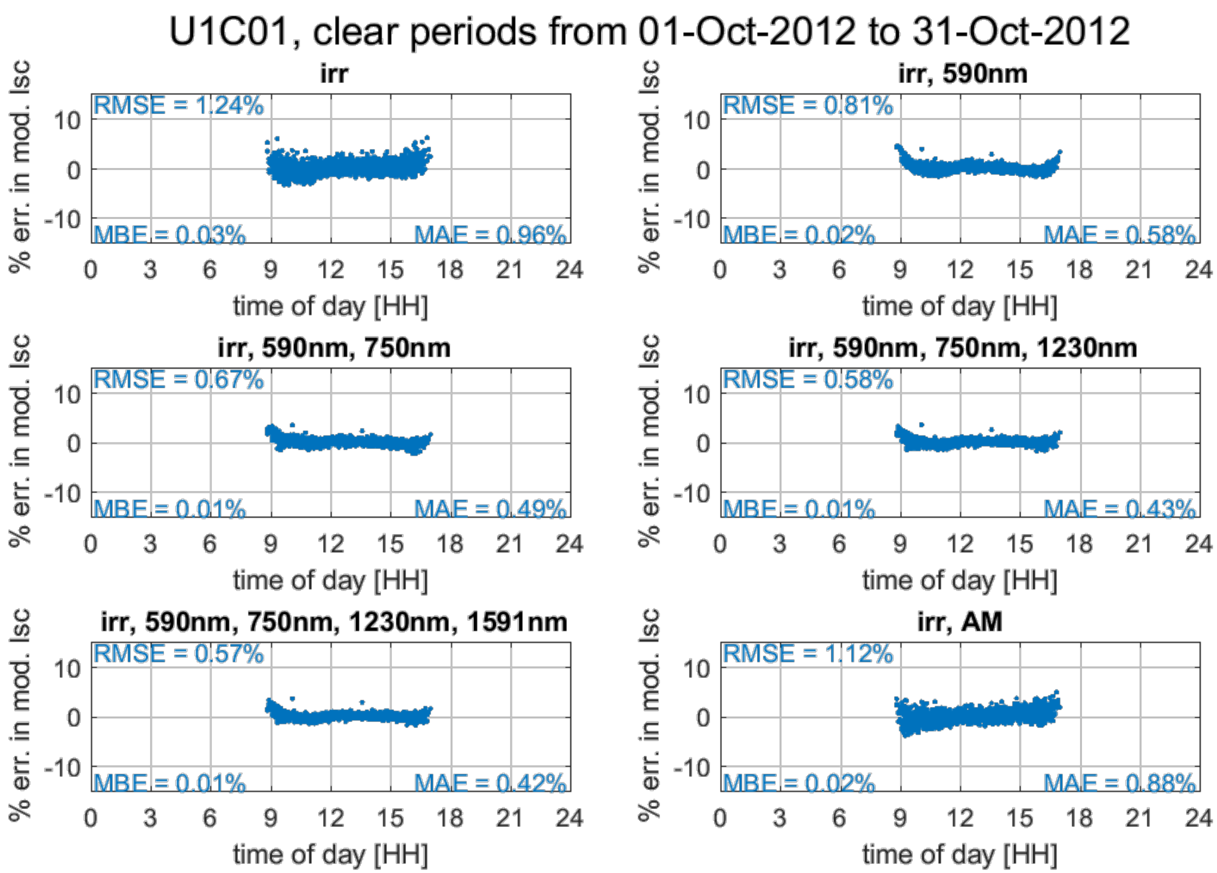
Spectrum and I_{sc} Variation

- Normalized spectral intensity plots show correlation between I_{sc} and certain spectral wavelengths.



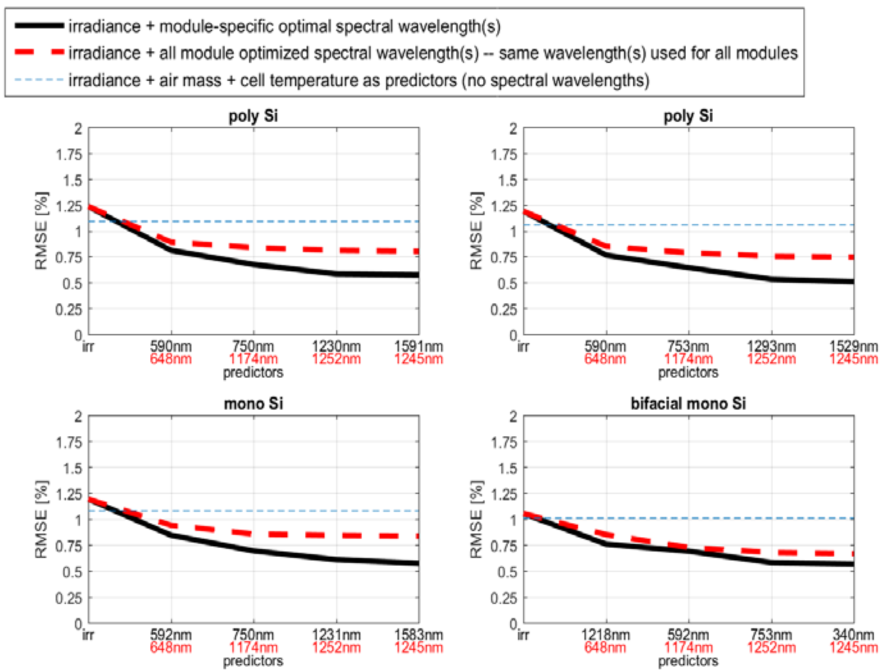
A Few Spectral Wavelengths/AM

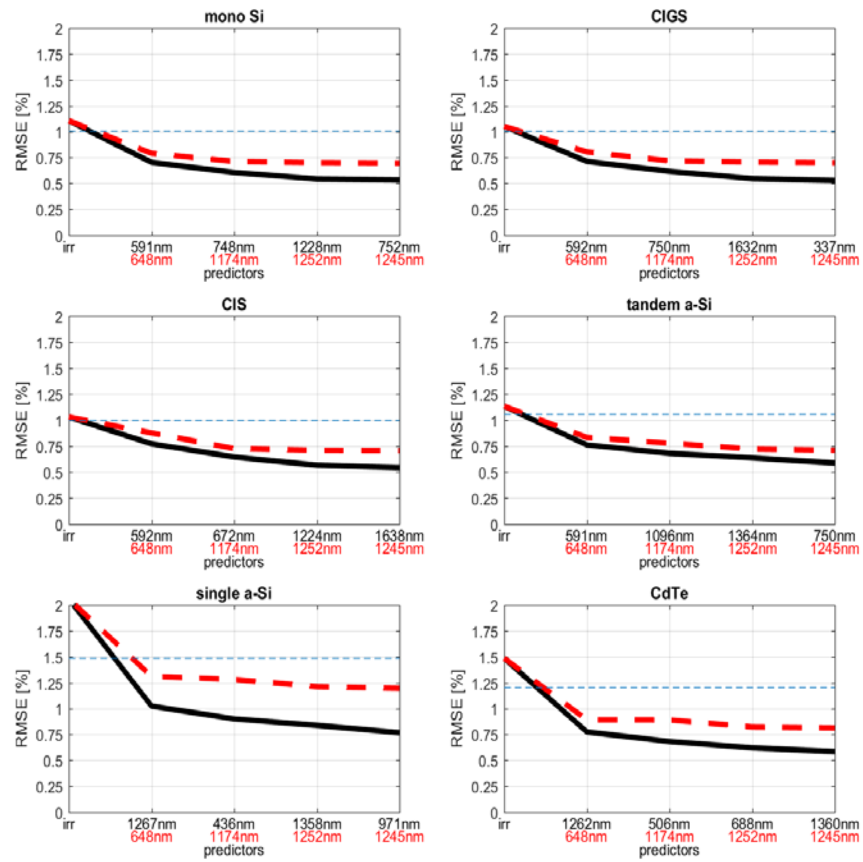
- Using 1, 2, or 3 spectral wavelengths found to reduce error in I_{sc}.
  - RMSE and MAE halved when using 3 wavelengths.
- Little error reduction when using AM.



Different PV Technologies

- Even when using same wavelength predictors for different PV technologies (red lines), I_{sc} model is noticeably improved.
- Spectral inputs outperform AM + Temperature inputs for all technologies.

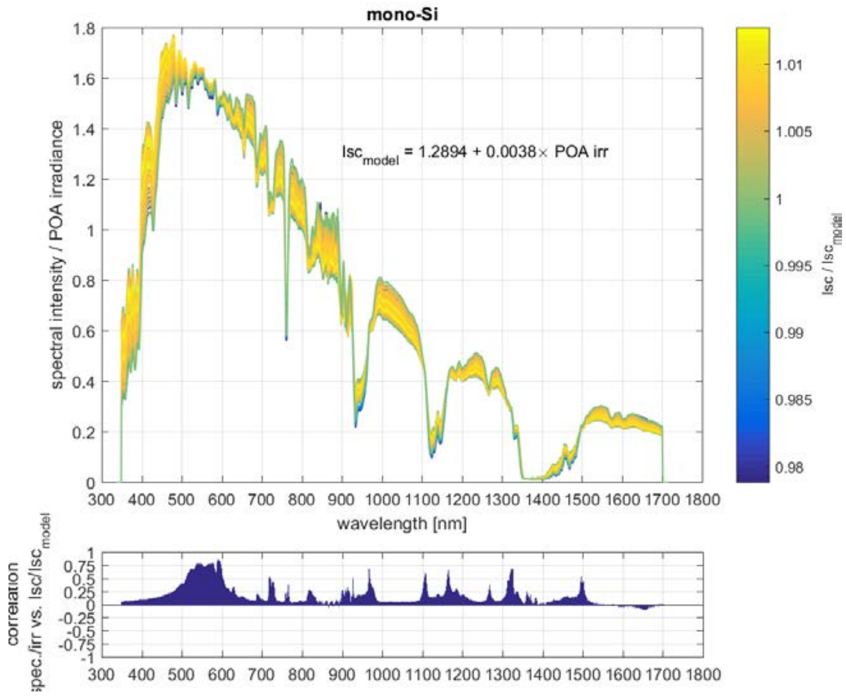




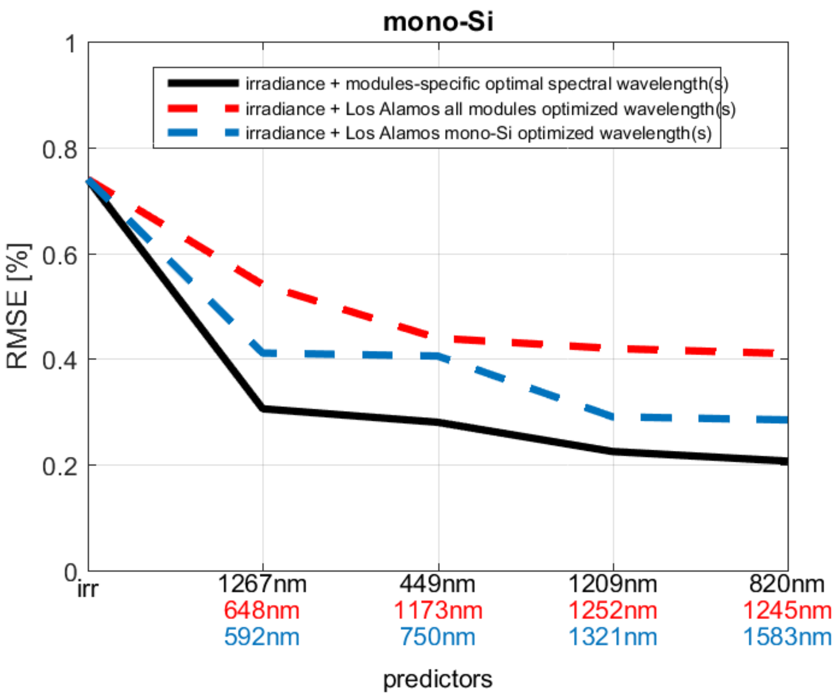
Different Location

- Improvement seen in I_{sc} model, even when using set wavelengths determined at another location.

spectra from Albuquerque, NM



RMSE reduction in Albuquerque, NM



Conclusion

- I_{sc} is strongly correlated to pyranometer irradiance. Errors for a linear irradiance model are order 1% RMSE.
- A few spectral wavelengths seem to be better additional predictors of I_{sc} than air mass.
- The same set of 3 spectral wavelengths (648nm, 1173nm, 1252nm) was found to be effective at reducing I_{sc} model error for various PV technologies and at two different locations.
- This work suggests that a few sensors (e.g., 3), each measuring a single spectral wavelength could be an effective way to improve PV performance models.