Simple Photovoltaic Spectral Correction Model Based on FARMS-NIT Modeled Spectra

Alan Curran, Boris Lin
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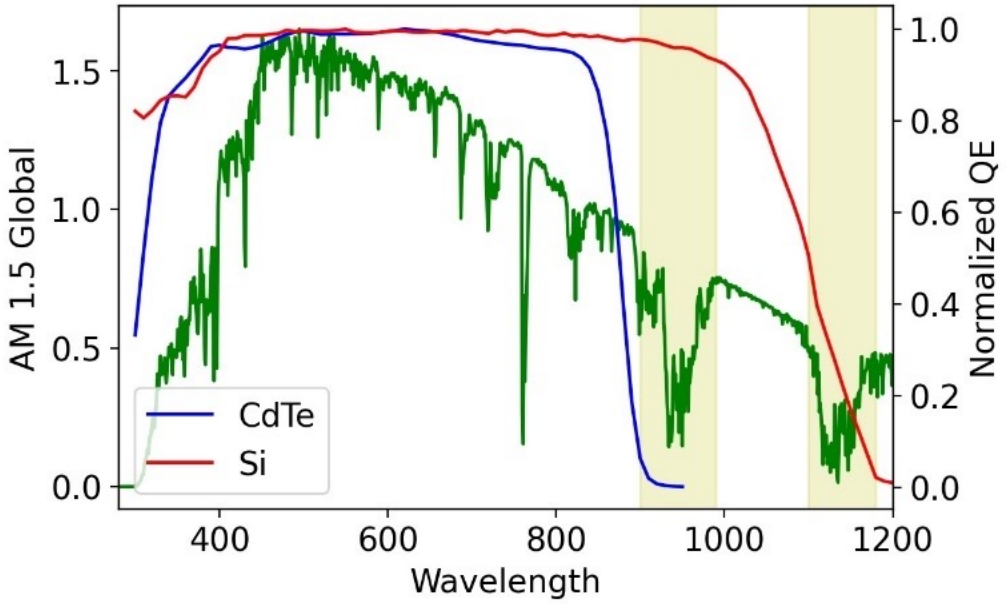
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CdTe Spectral Correction

CdTe shows a stronger spectral mismatch response than silicon

- CdTe narrower QE range falls outside of two significant water absorption bands
  - atmospheric water strongly influences these regions

Higher spectral sensitivity has led to a greater emphasis on accurate modeling of CdTe behavior



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2-Parameter Spectral Model

$$M = a + b \cdot AM + c \cdot p_{wat} + d \cdot \sqrt{AM} + e \cdot \sqrt{p_{wat}} + f \cdot \frac{AM}{\sqrt{p_{wat}}}$$

Available with coefficients for both CdTe and Si

- Primary guidance for CdTe modules

Developed using the SMARTS model to predict a range of spectral correction

- Based on provided range of precipitable water and absolute air mass
  - 37-tilt angle
- Assumes clear-sky conditions for results
  - Pessimistic due to cloud cover benefits

Lee, Mitchell, and Panchula, Alex.
Spectral Correction for Photovoltaic Module Performance Based on Air Mass and Precipitable Water.
IEEE Photovoltaic Specialists Conference, Portland, 2016

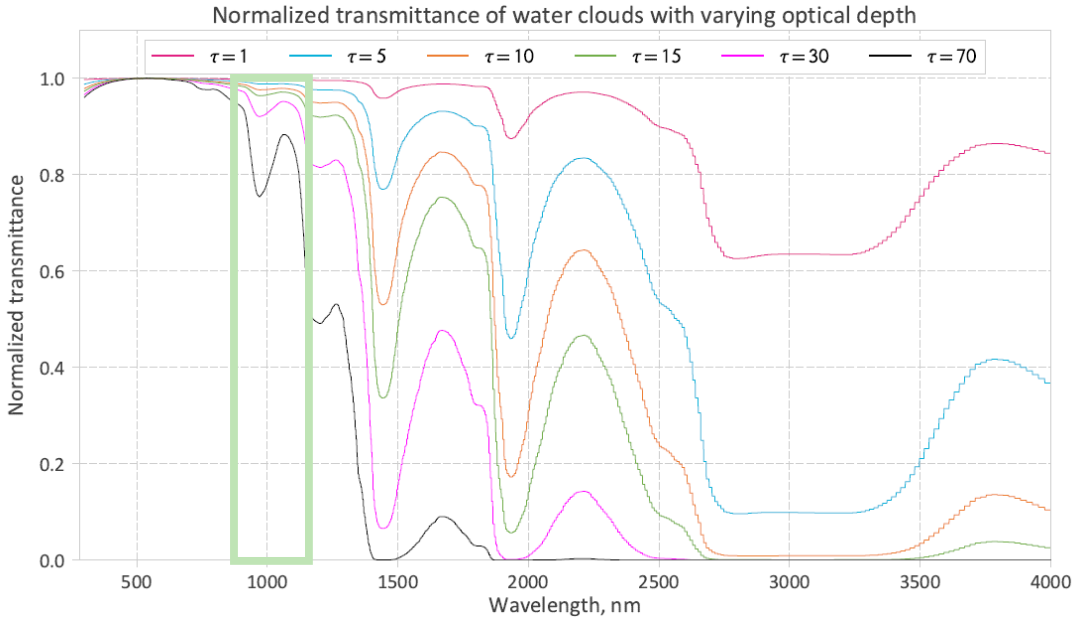
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Cloud Cover Influence

Clouds are distinct from precipitable water due to the droplet radii

- Different sizes of droplets have different spectral impacts
- Spectral loss prominent in 900-1100nm range
  - Leads to spectral benefit mostly for CdTe, but Si as well



Tatsiankou, Viktar. *Design Principles and Field Performance of Software-Augmented Solar Sensors for Resolving Spectral Irradiance and Atmospheric Parameters*. Diss. Université d'Ottawa/University of Ottawa, 2020.

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Goals for Modeling Advancement

1. Assess and capture cloud cover influence on spectral performance

2. Easy to integrate into existing pipelines/software
   - No significant additional data or infrastructure

3. Coefficients for different orientations
   - 1-axis, fixed tilt

4. Works well for silicon modules as well

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Spectral 3.0 Model

New proposed Spectral 3.0 model (current iteration):

- M = SCF = Spectral correction factor

$$M = \beta_0 CSI + \beta_1 P_{Wat} + \beta_2 AM + \beta_3$$

Captures cloud based spectral benefit using clear sky index as a simple quantitative value for cloud cover

- 2-parameter model was fit to SMARTS which is a clear sky assumption
- Irradiance weighted regression used to bias fit towards higher production periods

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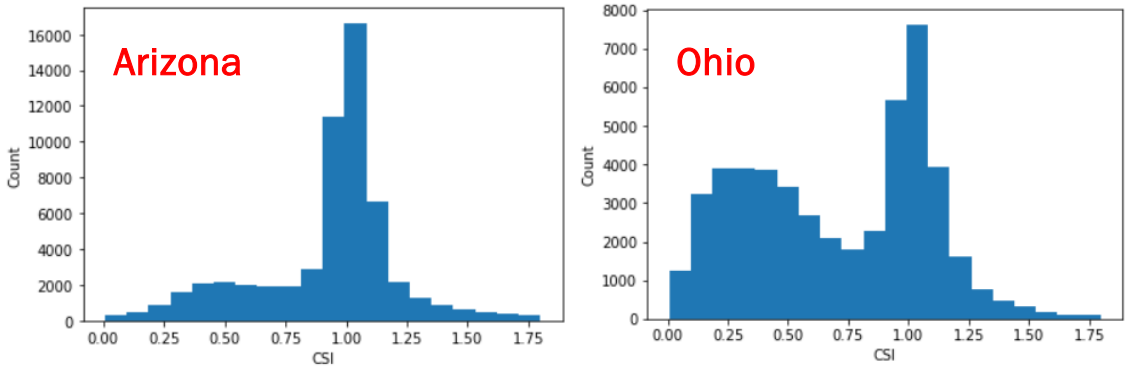
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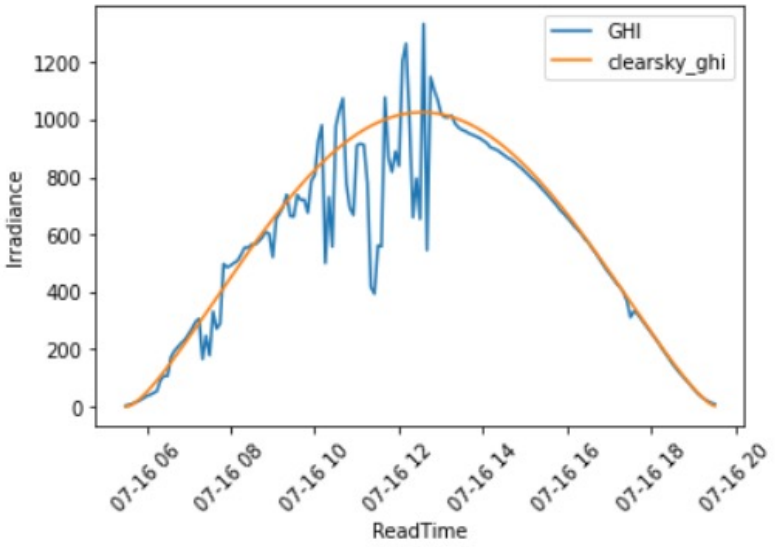
Clear Sky Index: Quantifying Cloud Cover

Clear sky index (CSI)

- Ratio of measured irradiance and clear sky irradiance
  - Lower CSI = more clouds (inverse)
- Clearness index also being assessed

$$CSI = \frac{TMY\ Irradiance}{Modeled\ Clearsky\ Irradiance}$$





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FARMS-NIT Model

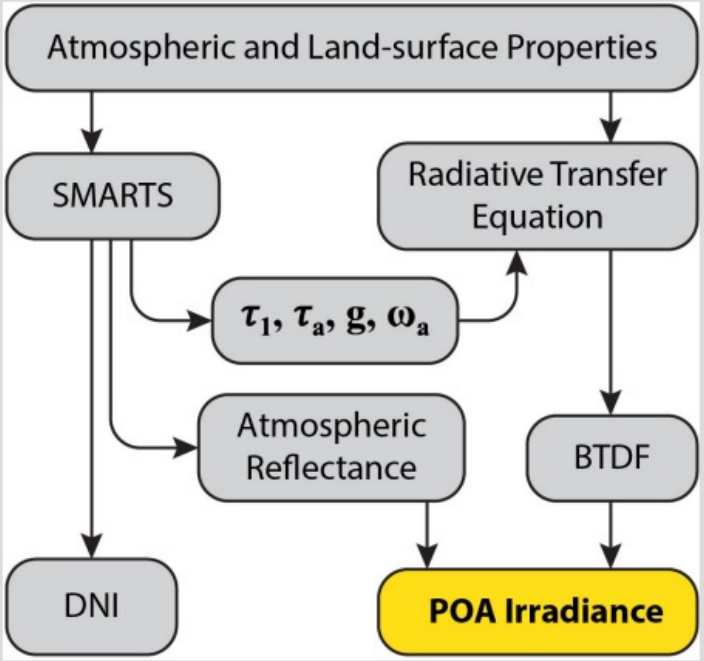
The FARMS-NIT model is an expansion on the SMARTS model to add cloud impact predictions

- Satellite data is used for cloud estimations
- bidirectional transmittance distribution function (BTDF)

Multi-year, orientation tunable spectra

- Across all of US
- Drawbacks: cannot be used for instantaneous measurements (up to 2021)

SMARTS is used to compute atmospheric properties, combined with the solution of radiative transfer equation and BTDF of cloud/aerosol, and compute atmospheric radiances.



https://www.nrel.gov/docs/fy21osti/71722.pdf

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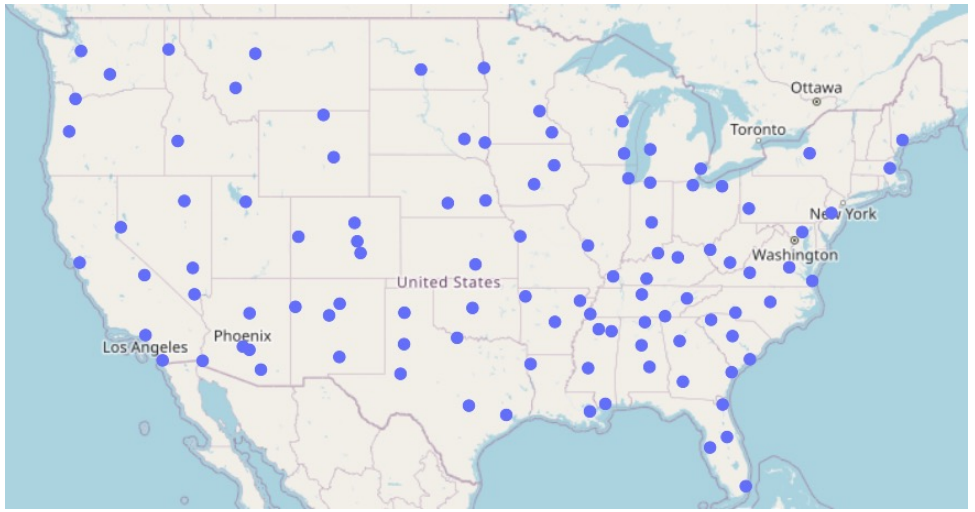
FARMS-NIT Data Set

104 locations across the US selected for fitting/validation

- 2 years at each location, 1-axis orientation (fixed tilt also being modeled)

Modeling was done on a subset of locations

- Found to be a better fit to field measured data
- All sites still used for validation



Note: this presentation will not cover magnitude impacts due to unfinished nature of model

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1-Axis Fitting Results: 104 FARMS-NIT Systems

Spectral 3.0 shows the best fitting in all cases for both technologies (G > 100)

- Silicon 2-parameter model shows minor improvements to no correction
- Silicon has overall lower error than CdTe
  - Lower magnitude of spectral impact

	CdTe				Si			
Model	**RMSE**	**Weighted RMSE**	**MAE**	**Weighted MAE**	**RMSE**	**Weighted RMSE**	**MAE**	**Weighted MAE**
Spectral 3.0	0.038	13.820	0.021	8.706	0.026	8.317	0.013	5.274
2-parameter	0.055	17.514	0.034	12.441	0.035	11.292	0.020	7.693
SAPM AM	-	-	-	-	0.035	12.044	0.021	8.656
No Correction	0.064	24.607	0.044	19.219	0.036	12.703	0.024	9.929

RMSE – Root Mean Square Error
MAE – Mean Absolute Error
Weighted terms are irradiance weighted to bias towards higher irradiance predictions, (Predicted – Actual) * Irradiance

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22° Tilt Fitting Results: 104 FARMS-NIT Systems

Spectral 3.0 maintains best fit compared to other models

- CdTe error increases vs. 1-axis, Si error decreases compared to 1-axis
- CdTe spectral correction increases with greater diffuse light
  - GHI best case for CdTe, 2-axis best case for Si

	CdTe				Si			
Model	**RMSE**	**Weighted RMSE**	**MAE**	**Weighted MAE**	**RMSE**	**Weighted RMSE**	**MAE**	**Weighted MAE**
Spectral 3.0	0.044	14.506	0.022	7.810	0.025	7.862	0.012	4.202
2-parameter	0.063	18.323	0.037	11.878	0.036	11.149	0.021	7.181
SAPM AM	-	-	-	-	0.036	11.917	0.021	8.120
No Correction	0.069	23.562	0.045	17.100	0.036	11.603	0.022	8.067

RMSE – Root Mean Square Error
MAE – Mean Absolute Error
Weighted terms are irradiance weighted to bias towards higher irradiance predictions, (Predicted – Actual) * Irradiance

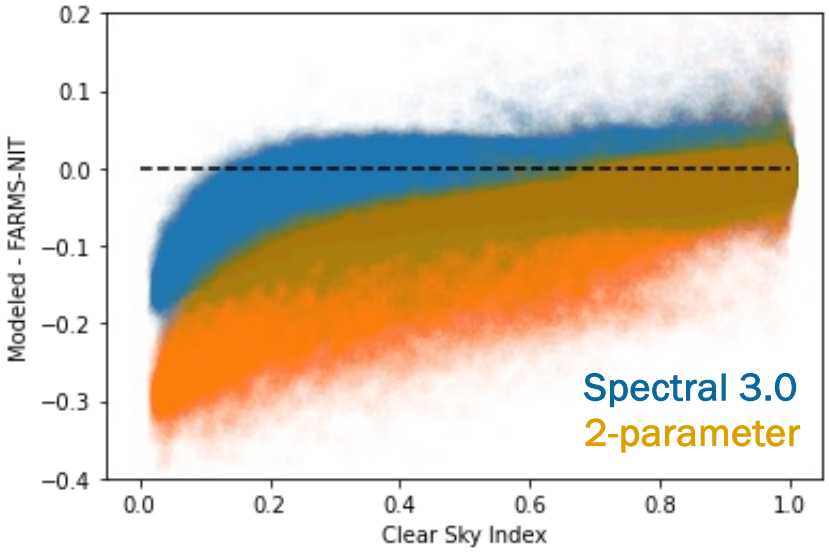
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FARMS-NIT Trend with Cloud Cover

2-parameter underprediction to FARMS-NIT increases with decreasing CSI

- Spectral 3.0 also beings to underpredict at very low CSI
  - partial result of weighted irradiance
- Models converge at clear sky periods, predictions are similar



* CSI = 1 excluded from plot for clarity

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Field Study: 1-Axis Tripod Spectrometers

SolarSIM-Gs & ST-5 tracker systems sent to partner sites

- Arizona, Ohio, Florida (UCF), Louisiana (ULL), Northern California (RETC)
  - Installations Aug-Sept 2023, nearing full year of data
- 1-axis tracking orientation spectral measurements
  - 5-minute interval, precipitable water collection as well
  - 280-4000nm range, irradiance calculated from spectra to avoid potential offsets to pyranometers
- CSI evaluated from GHI data at each location
  - 1-axis data more difficult to align to clear sky model



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Fitting Results: Fielded 1-Axis Data

Spectral 3.0 continues to show the best performance

- One exception of better irradiance weighted RMSE
- ~8 months of available spectral data

	CdTe				Si			
Model	**RMSE**	**Weighted RMSE**	**MAE**	**Weighted MAE**	**RMSE**	**Weighted RMSE**	**MAE**	**Weighted MAE**
Spectral 3.0	0.034	16.221	0.024	11.957	0.026	10.047	0.016	7.183
2-parameter	0.048	16.103	0.032	12.784	0.034	10.782	0.021	8.218
SAPM AM	-	-	-	-	0.034	11.770	0.022	9.250
No Correction	0.054	19.766	0.038	16.128	0.036	12.341	0.024	10.037

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Conclusions

Spectral 3.0 model using Clear Sky Index shows improved prediction of spectral performance

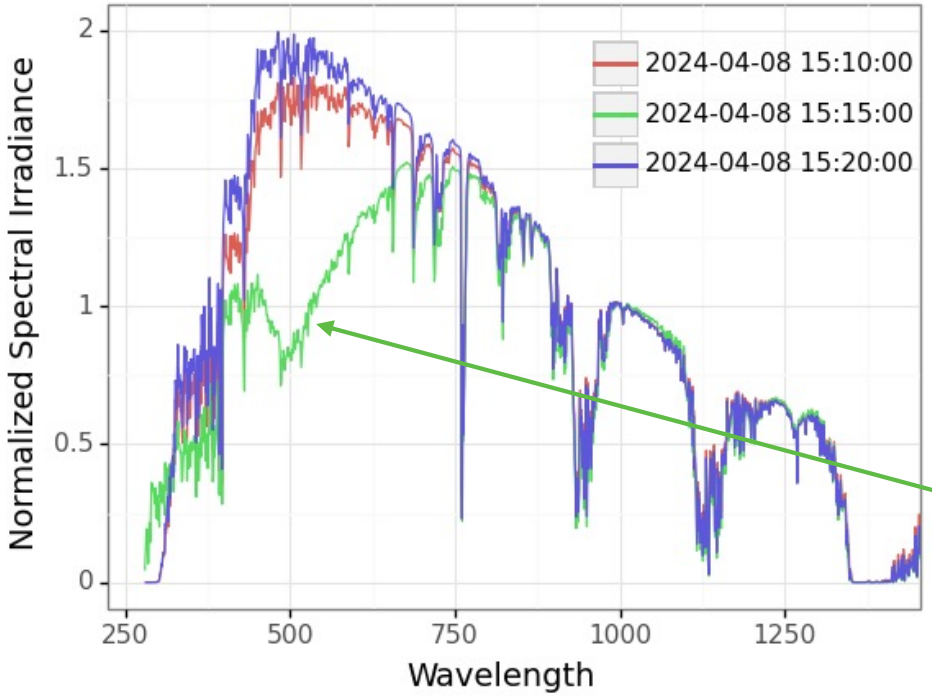
- Both against FARMS-NIT and measured spectral data
  - For both Si and CdTe modules
- Successful fitting improvement for 1-axis and fixed tilt scenarios
- Can be integrated into existing workflows, no new data to chase

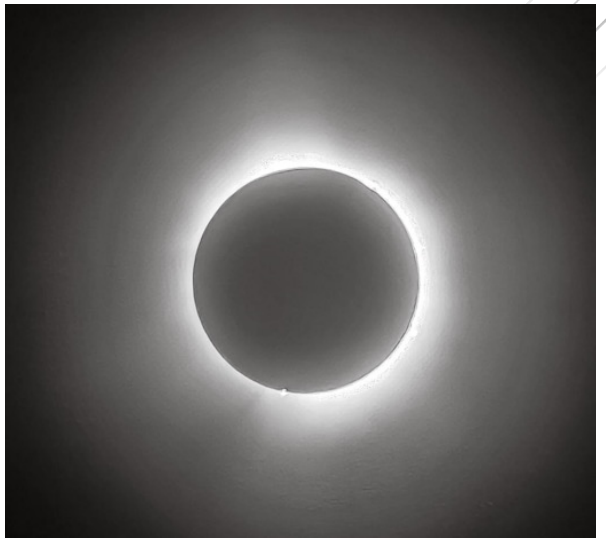
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Bonus: Totality Spectral Correction

Significant visible region losses during totality





CdTe spectral correction during totality = -11%

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Thank You

Alan.Curran@firstsolar.com



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