NATIONAL RENEWABLE ENERGY LABORATORY

Advances in Solar Measurement and Modeling at NREL

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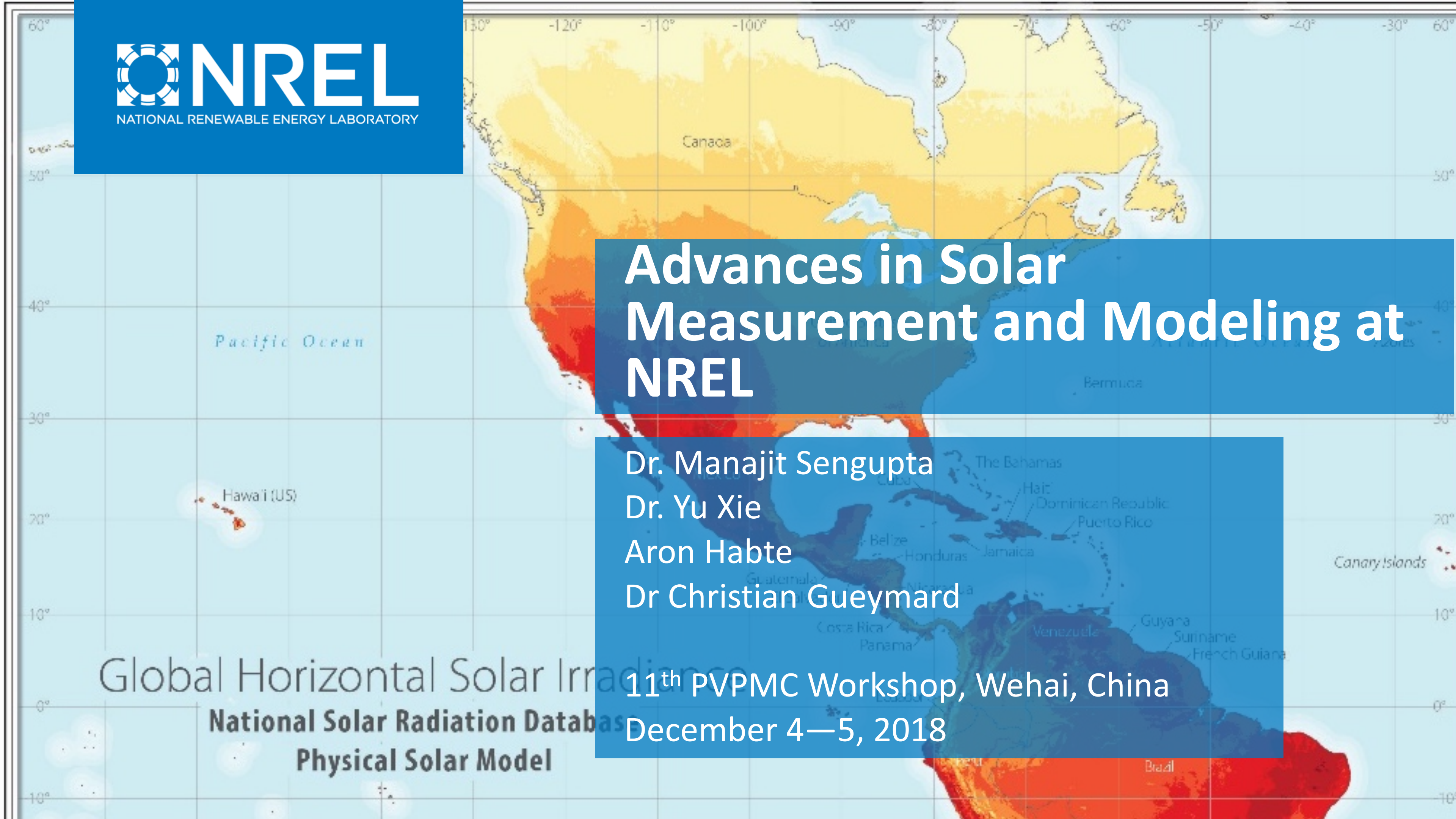
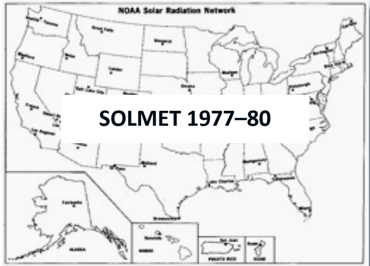
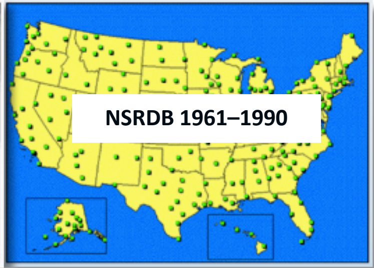
11th PVPMC Workshop, Wehai, China
December 4—5, 2018



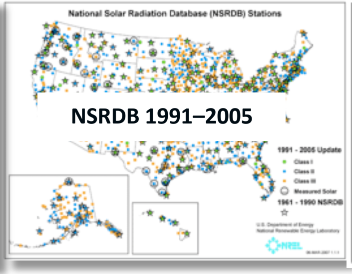
The National Solar Radiation Database



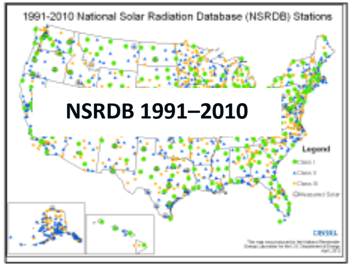
248 weather stations with 26 ***Solar measurement*** stations [ERDA, NOAA, 1979]



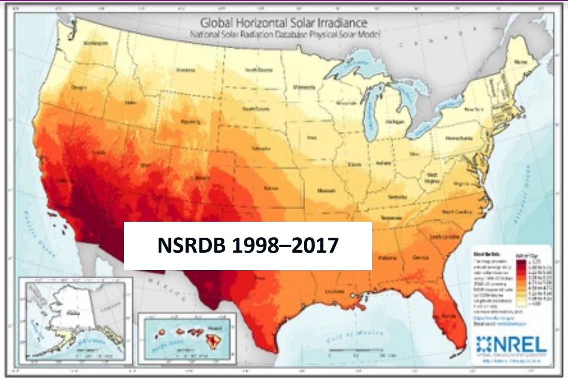
239 ***modeled*** stations with 56 partial measurement stations [DOE, NOAA, 1994]



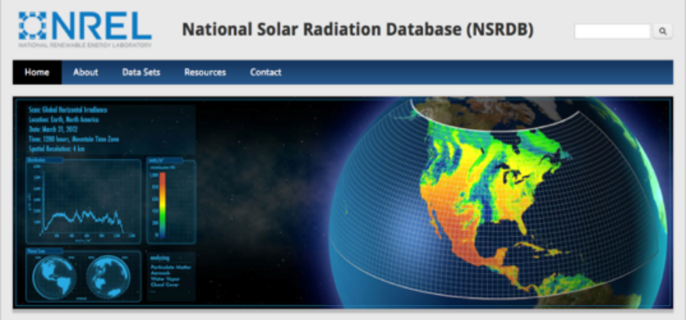
1,454 ***modeled*** locations [DOE, SUNY-A, NOAA, 2007]



1,454 ***modeled*** locations [DOE, CPR, 2012]



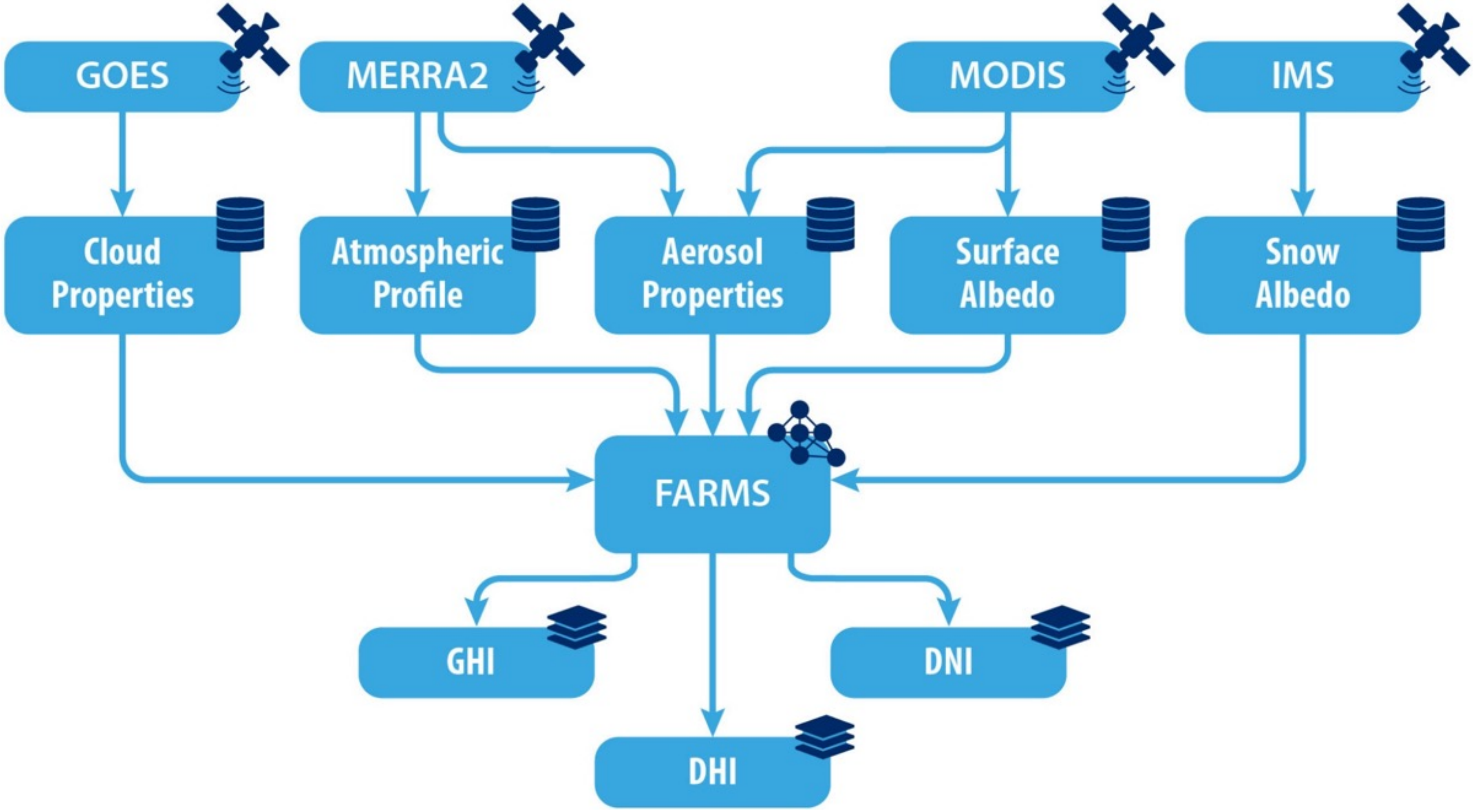
Satellite-based, gridded, 4 km x 4 km, half-hourly [DOE, NOAA, UW, SCS 2016]



http://nsrdb.nrel.gov

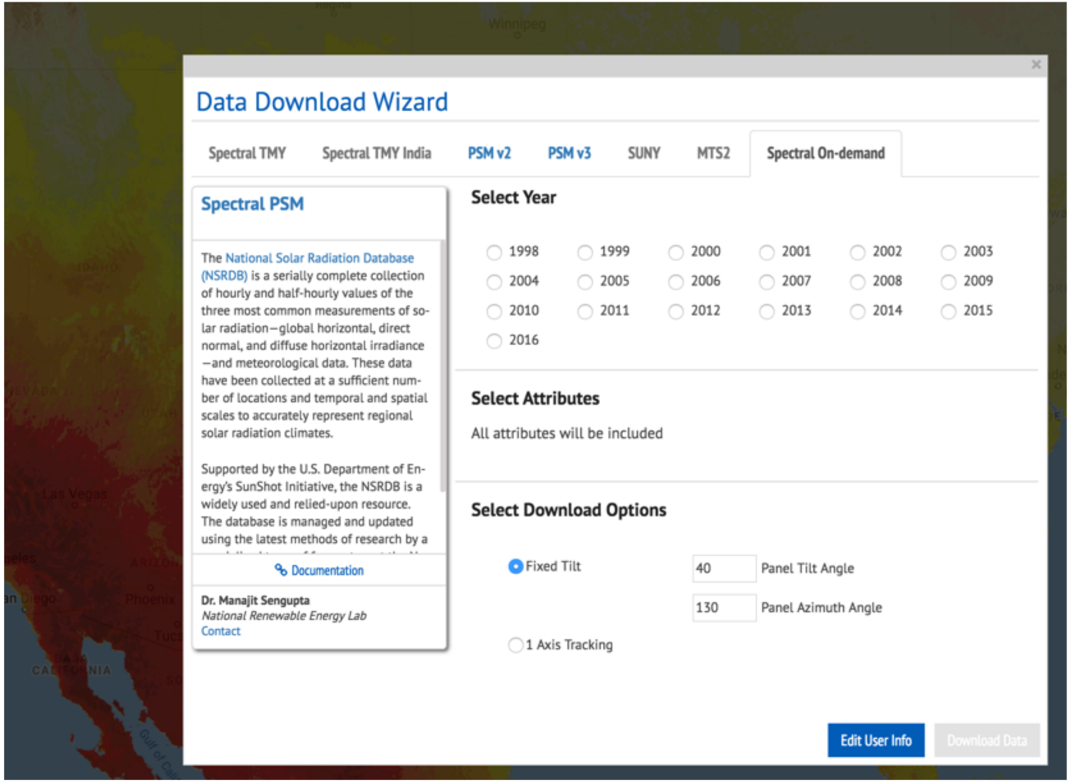
Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby (2018), The National Solar Radiation Data Base (NSRDB), Renew. Sustain. Energy Rev., 89, 51-60. https://doi.org/10.1016/j.rser.2018.03.003

Physical Solar Model (PSM) Framework



Spectral Datasets from the NSRDB

Spectral Data in the Plane-of-Array

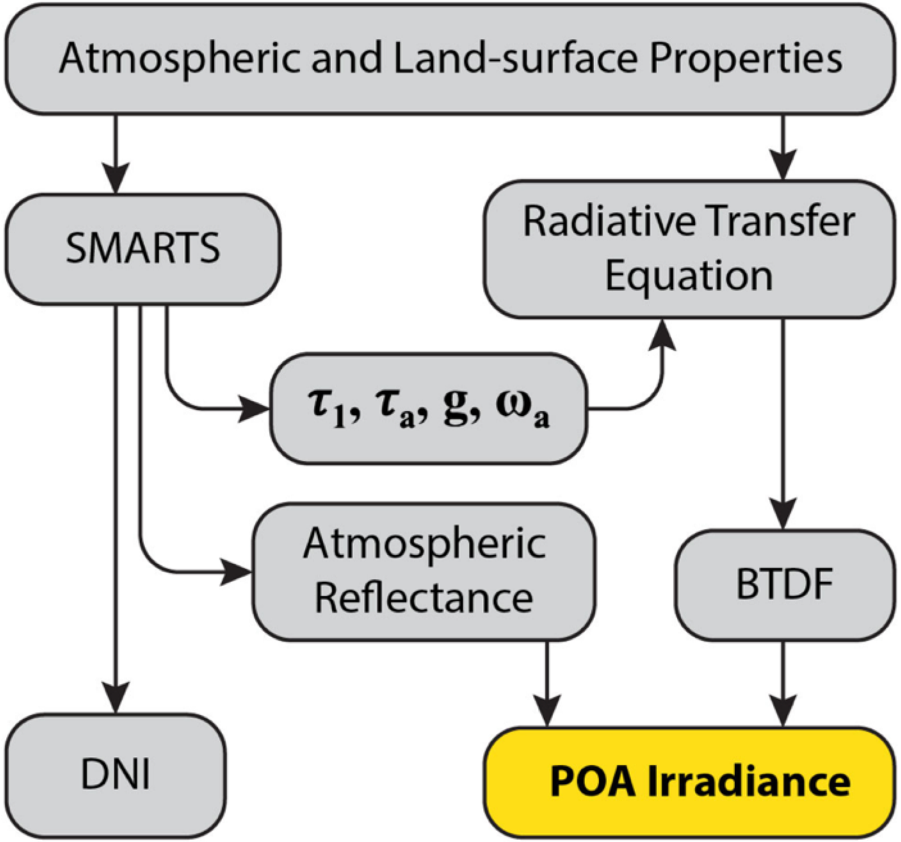


NSRDB Variables:

- Global horizontal irradiance (GHI)
- Direct normal irradiance (DNI)
- Diffuse horizontal irradiance (DHI)
- Clear-sky GHI, DNI, and DHI
- Cloud type
- Dew point**
- Air temperature*
- Atmospheric pressure
- Relative humidity**
- Solar zenith angle
- Precipitable water*
- Wind direction**
- Wind speed.**
- Spectral POA (2002 wavelengths)

* From MERRA-2
** Recalculated from MERRA-2

FARMS-NIT for Clear Sky

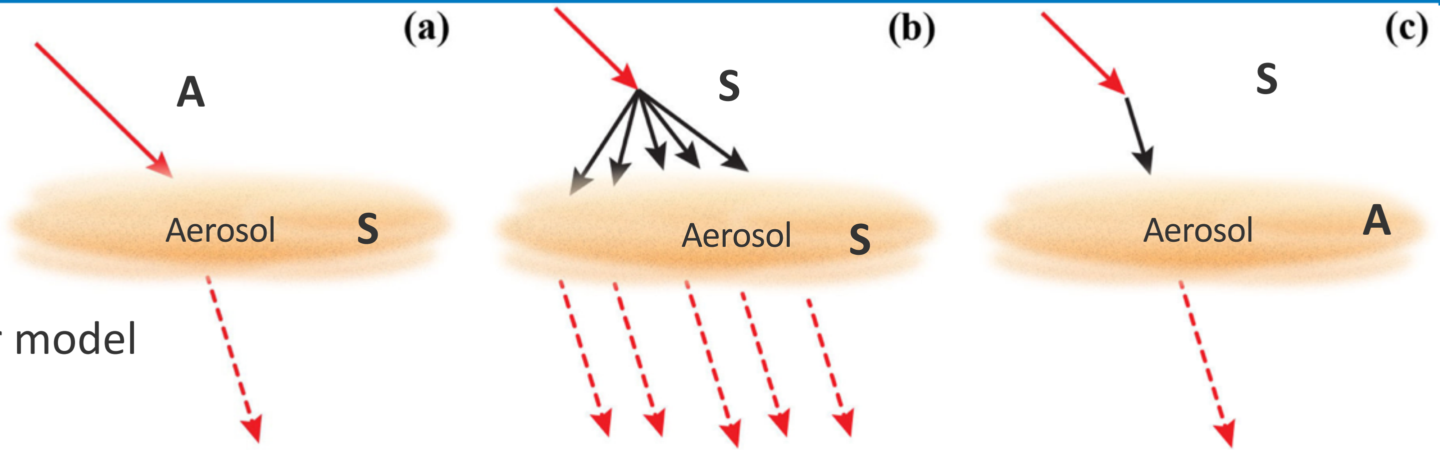


Fast All-Sky Model for Solar Applications – Narrowband Irradiance on Tilted Surfaces (FARMS-NIT)

SMARTS – Simplified Model of Atmospheric Radiative Transfer of Sunshine.

Provides atmospheric properties including atmospheric optical depth, aerosol optical depth, asymmetry parameter and single-scattering albedo

FARMS-NIT for Clear Sky

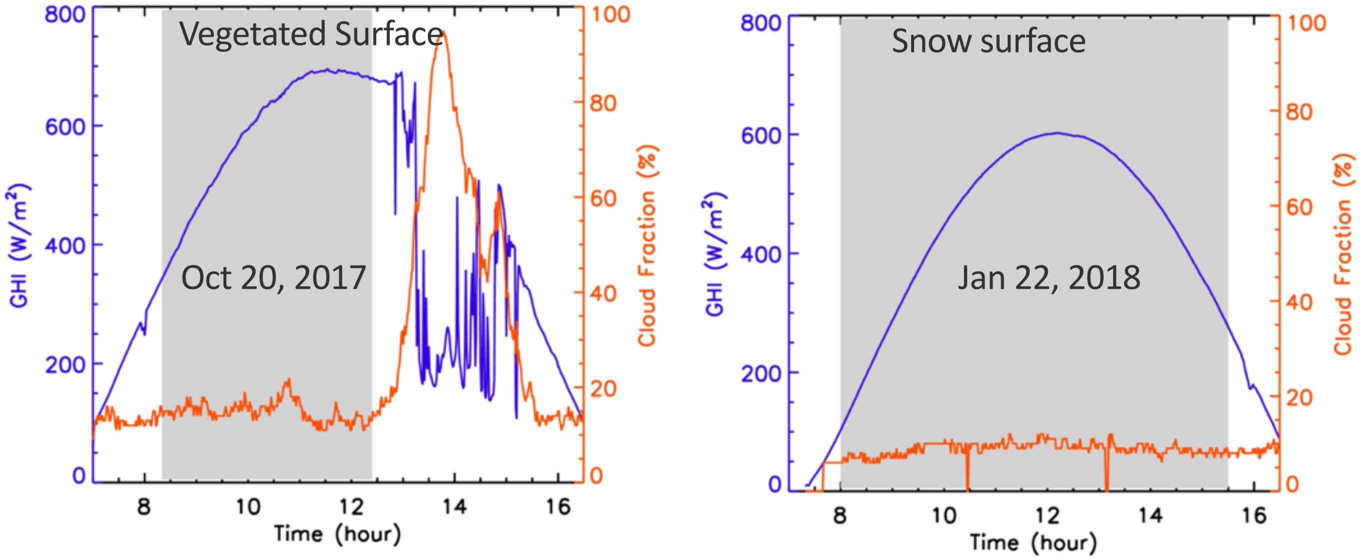


Two-layer model

- Spectral radiances are computed by solving the **radiative transfer equation** with the single-scattering approximation for three individual photon paths.
- The atmospheric radiances are given by radiances related to the three photon paths.
- POA irradiances are efficiently computed for 2002 wavelength bands (0.28-4.0 µm) from the radiances.
- Radiances are computed for 450 sky-view angles that can be integrated for any tilt-geometry

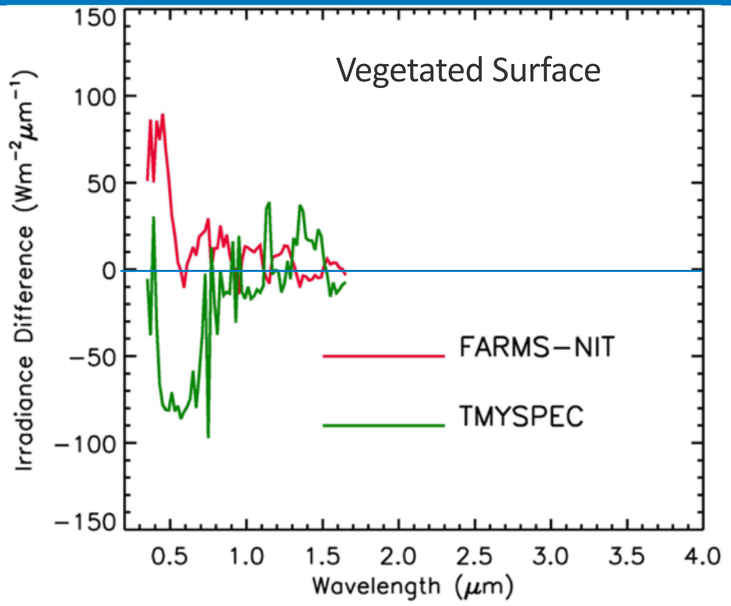
Xie, Y., Sengupta, M., 2018. A Fast All-sky Radiation Model for Solar applications with Narrowband Irradiances on Tilted surfaces (FARMS-NIT): Part I. The clear-sky model. Sol. Energy, 174C, 691-702.

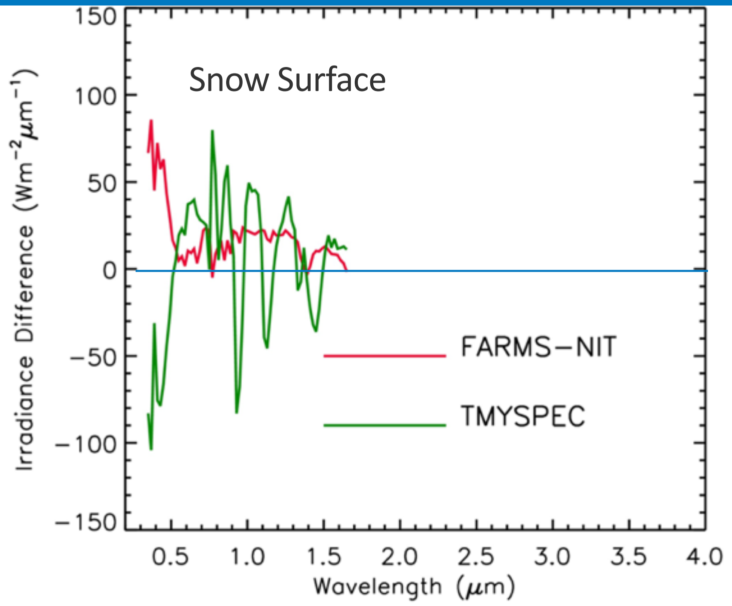
Evaluation of FARMS-NIT for Clear Sky



- To validate FARMS-NIT, we use measurements of GHI and cloud fraction at NREL's SRRL to identify clear-sky conditions (shadows).
- Measurements of precipitable water vapor (PWV), aerosol optical depth (AOD), and surface albedo are used by the models.
- Measurements from EKO-WISER spectroradiometer (MS-711 and MS-712) on a 1-axis tracker is compared with FARMS-NIT and TMYSpec (parameterized model, Myers, 2012).

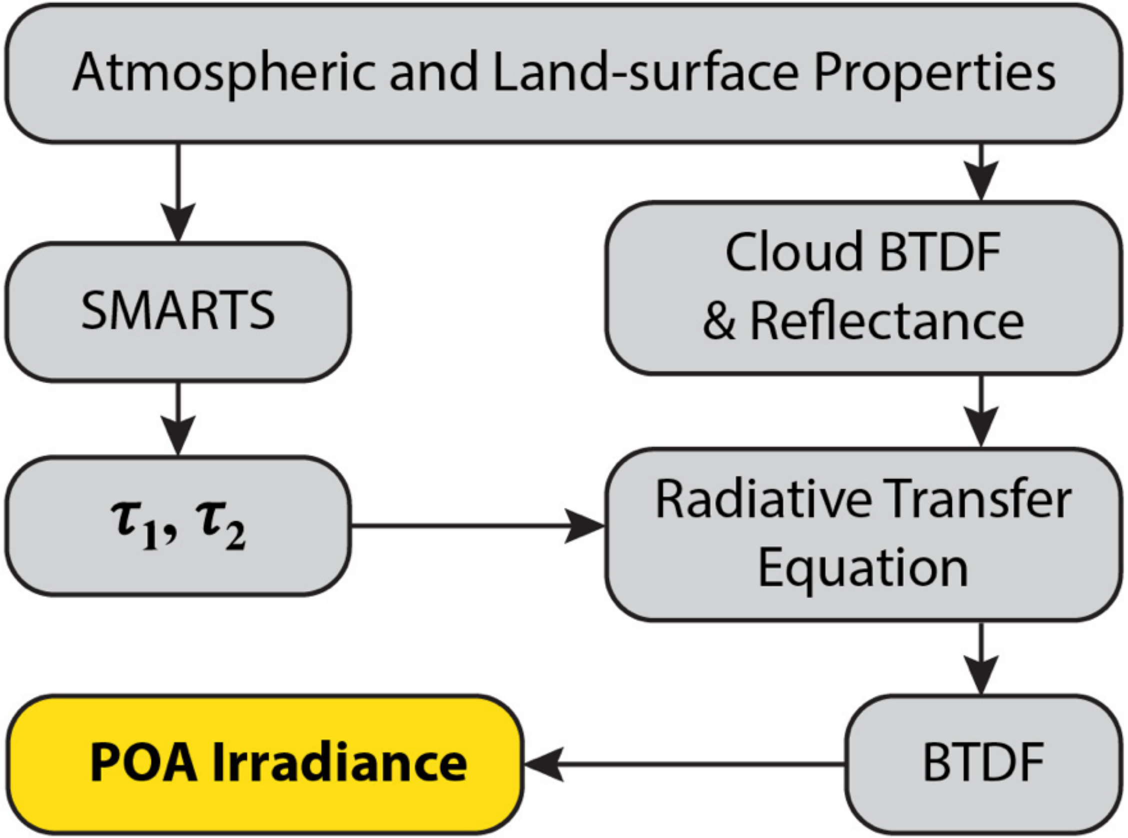
Evaluation of FARMS-NIT





- FARMS-NIT has a much better performance than TMYSPEC, especially on the snow day when validated with spectral measurements from the EKO MS-711 Spectroradiometer.
- FARMS-NIT slightly overestimates spectral radiation in the UV and visible regions while TMYSPEC underestimates it.
- FARMS-NIT Mean Bias Error (MBE) < 1% and Absolute Mean Bias Error <4%.

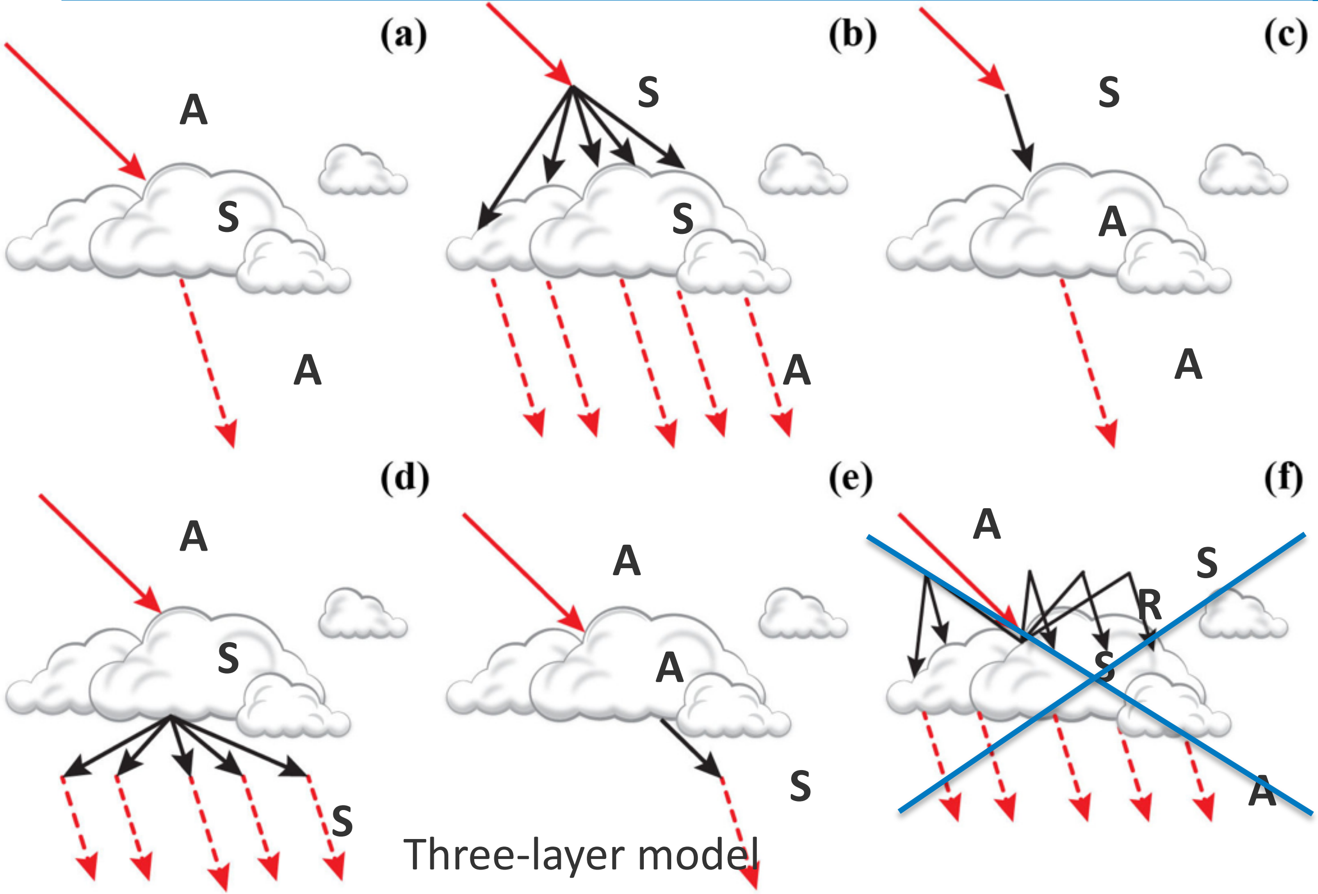
FARMS-NIT for Cloudy-Sky



SMARTS provides atmospheric optical depth for layers below and above cloud.

Aerosols are not important in cloudy sky situation.

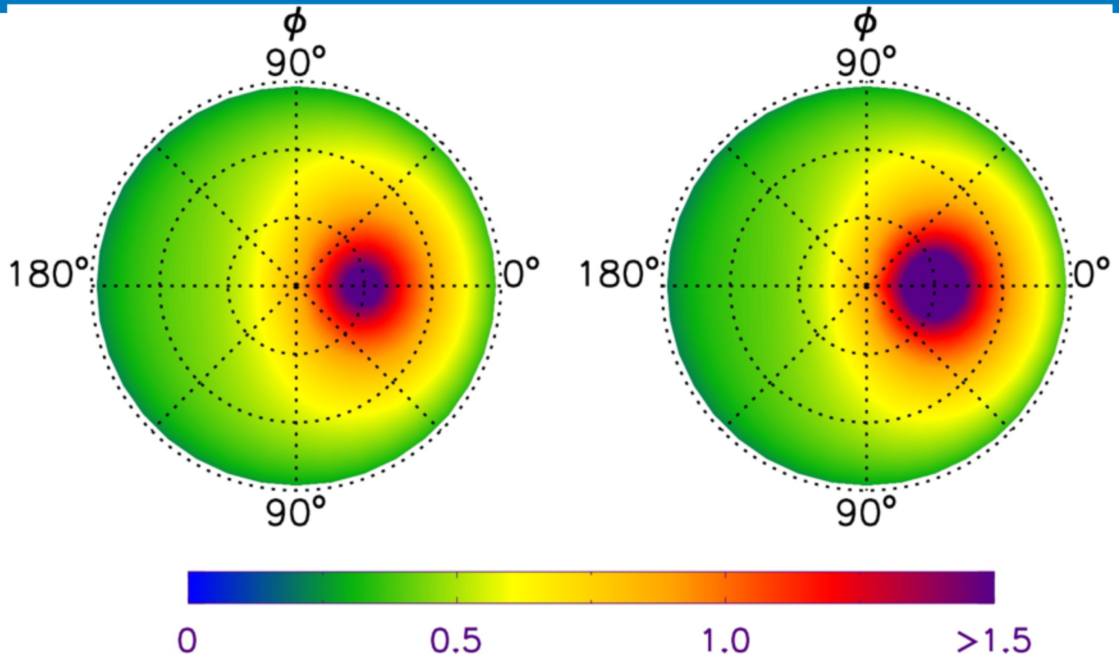
FARMS-NIT for cloudy-sky conditions



Three-layer model

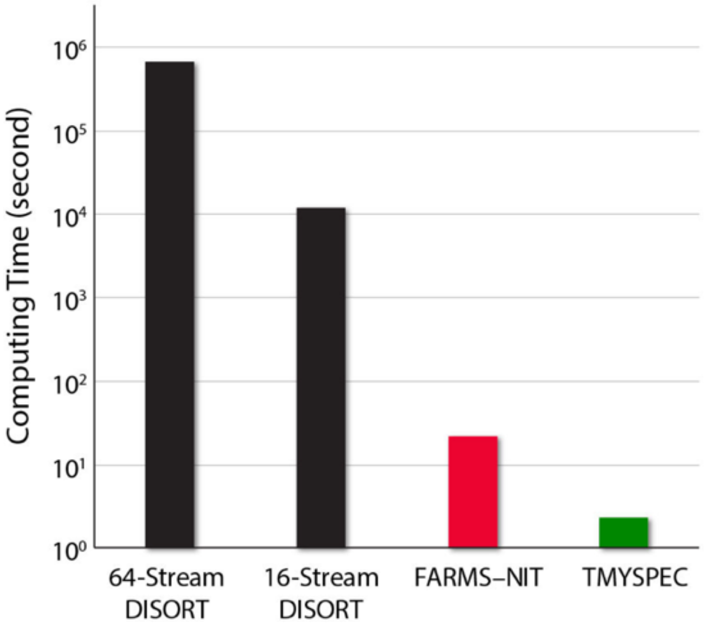
- Spectral radiances are computed by solving the **radiative transfer equation.**
- Two additional photon paths are considered for Rayleigh scattering under the clouds.

FARMS-NIT for cloudy-sky conditions



Cloud BTDF for water (left) and ice (right) clouds for $\tau = 5$, $\mathrm{De} = 10\ \mu m$, $\theta_0 = 30°$ at 0.6 μm. The viewing zenith angle increases from 0 to 90 degree along the radial direction.

Computing time for FARMS-NIT



- For computing hourly spectral POA irradiances for a day, the 64-stream DISORT, 16-stream DISORT, FARMS-NIT, and TMYSPEC consume 180 hours 48 minutes, 3 hours 18 minutes, 21.9 seconds, and 2.31 seconds.
- **Our current server uses multiple-processors and we can compute and deliver spectral data for 1 year in ~2 minutes.**

Estimating Ultraviolet Radiation from Total Radiation

Why UV and How do we Estimate it

Why do we need UV estimates:

- Terrestrial ultraviolet (UV) radiation is a primary factor contributing to degradation and reliability of materials over time.
- There is limited availability of UV measurements.

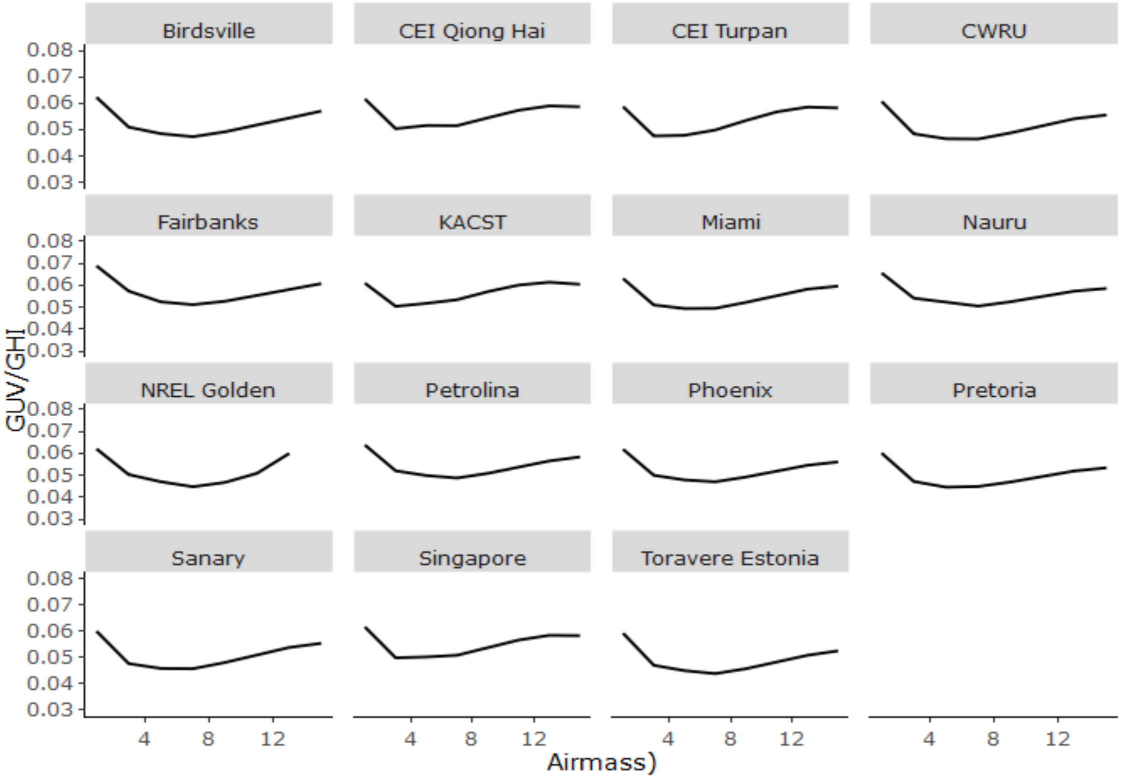
How do we estimate UV

- Measured and/or modeled total solar irradiance (TS) (280–4000 nm) is relatively abundant.
- Estimate the clear-sky terrestrial UV irradiance (~280–400 nm and ~285-385 nm) from TS. **Develop a model of the UV/TS ratio using simulations obtained with the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS).**

Goal: Worldwide Application

- The goal is to make the draft ASTM standard representative of all locations around the world.

R_{uv} as a Function of Airmass



$$R_{uv} = \frac{GUV}{GHI}$$

For mean annual fixed atmospheric conditions (prevailing conditions) at 15 world locations (280–400 nm)

SMARTS v2.9.7 is used

Fourth-Order Polynomial Functions

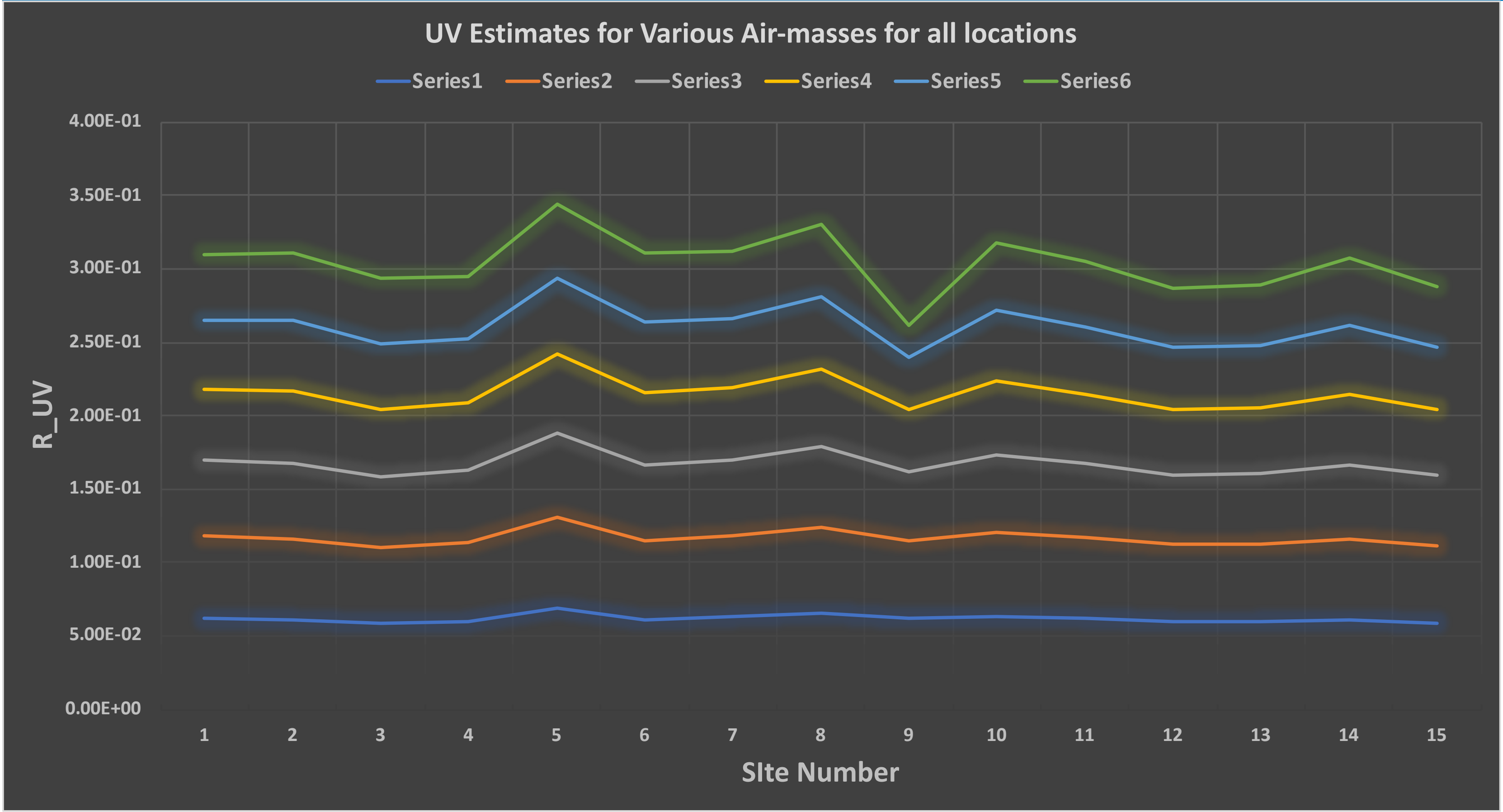
$$UV_m = TS_m\left(\sum_0^4 m_i\, AM^i\right)$$

where AM^i is the airmass, and m_i are numerical coefficients obtained by least-squares fitting.

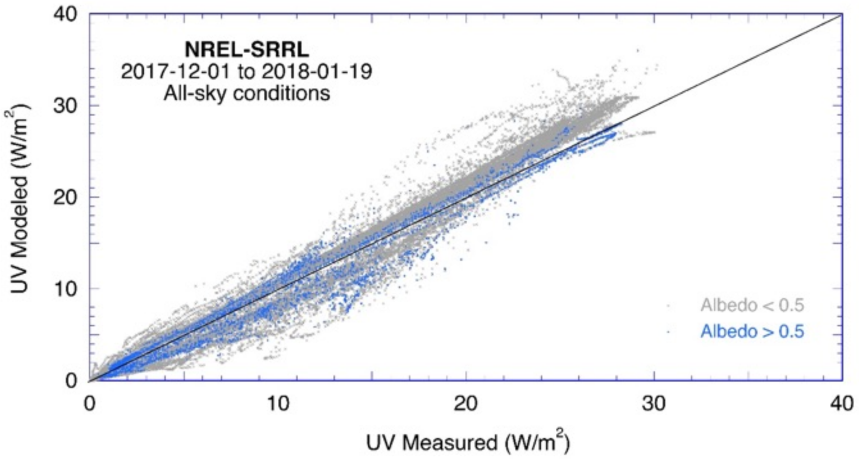
LOCATION INFORMATION AND ASSOCIATED NUMERICAL COEFFICIENTS OBTAINED BY LEAST-SQUARES FITTING (280–400 nm)

Station	Lat	Long	Elevation (m)	Numerical Coefficients				
				m4	m3	m2	m1	m0
Birdsville, Australia	-25.9	139.3	46	1.79E-06	-8.39E-05	1.47E-03	-1.01E-02	7.09E-02
CEI Qiong Hai, HaiNan province, China	19.2	110.5	62	2.84E-06	-1.27E-04	1.95E-03	-1.11E-02	7.05E-02
CEI Turpan, XinJiang province, China	42.9	89.8	10	3.25E-06	-1.45E-04	2.22E-03	-1.22E-02	6.86E-02
Case Western Reserve University (CWRU), Ohio, USA	41.5	-81.6	200	2.53E-06	-1.15E-04	1.87E-03	-1.18E-02	7.05E-02
Fairbanks, AK, USA	64.8	-147.7	136	1.04E-06	-6.01E-05	1.26E-03	-9.98E-03	7.76E-02
KACST Riyadh, Saudi Arabia	24.9	46.4	740	3.30E-06	-1.46E-04	2.17E-03	-1.16E-02	7.02E-02
Miami, Florida, USA	25.6	-80.5	30	2.30E-06	-1.09E-04	1.82E-03	-1.15E-02	7.26E-02
Nauru	-0.5	166.9	7	1.46E-06	-7.52E-05	1.38E-03	-9.76E-03	7.38E-02
NREL-Golden, Colorado, USA	39.7	-105.2	1790	1.97E-05	-5.39E-04	5.26E-03	-2.18E-02	7.96E-02
Petrolina, Brazil	-9.4	-40.5	370	1.73E-06	-8.53E-05	1.52E-03	-1.04E-02	7.26E-02
Phoenix, Arizona, USA	33.9	-112.2	395	1.97E-06	-9.41E-05	1.62E-03	-1.08E-02	7.09E-02
Pretoria, South Africa	-25.8	28.3	1449	2.91E-06	-1.28E-04	2.04E-03	-1.27E-02	7.07E-02
Sanary, France	43.1	5.8	110	2.50E-06	-1.14E-04	1.86E-03	-1.18E-02	6.97E-02
Singapore	1.3	103.8	30	3.10E-06	-1.37E-04	2.09E-03	-1.19E-02	7.12E-02
Toravere, Estonia	58.3	26.5	70	2.16E-06	-9.92E-05	1.67E-03	-1.10E-02	6.84E-02

Variability in UV Estimates at Various Locations

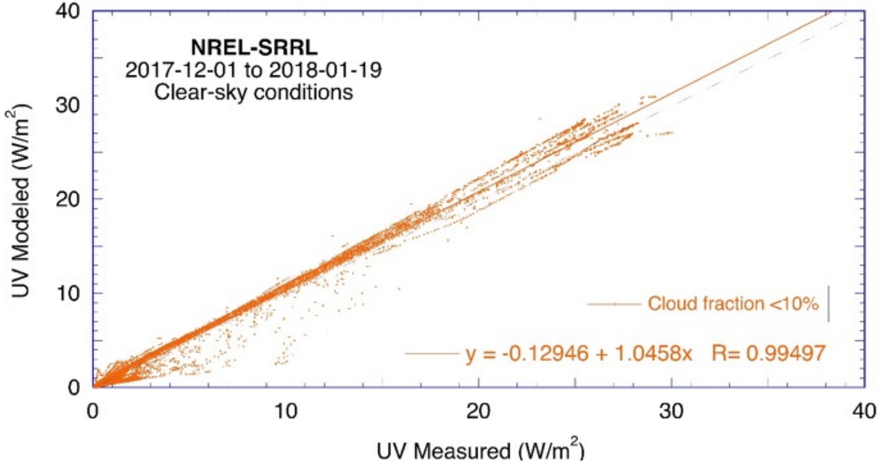


Validation using 1-minute Measurements



UV radiometers (Eppley Lab TUVR and Kipp & Zonen CUV4)

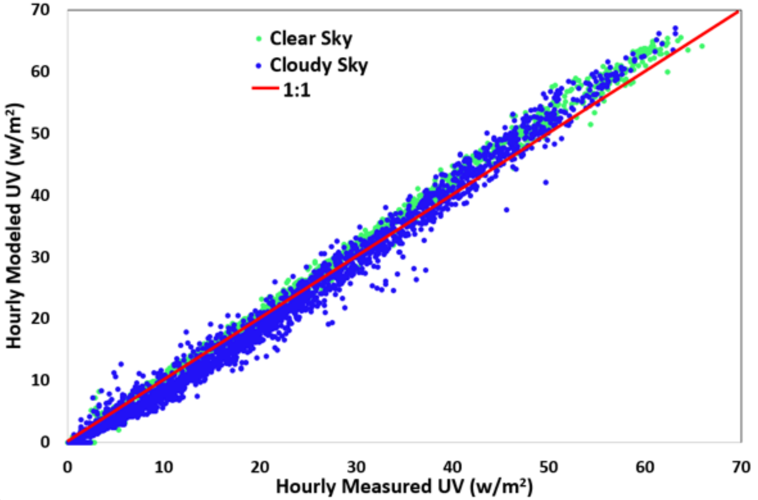
Modeled vs. measured 1-min UV global irradiance under all sky conditions at SRRL for low and high surface albedo conditions.

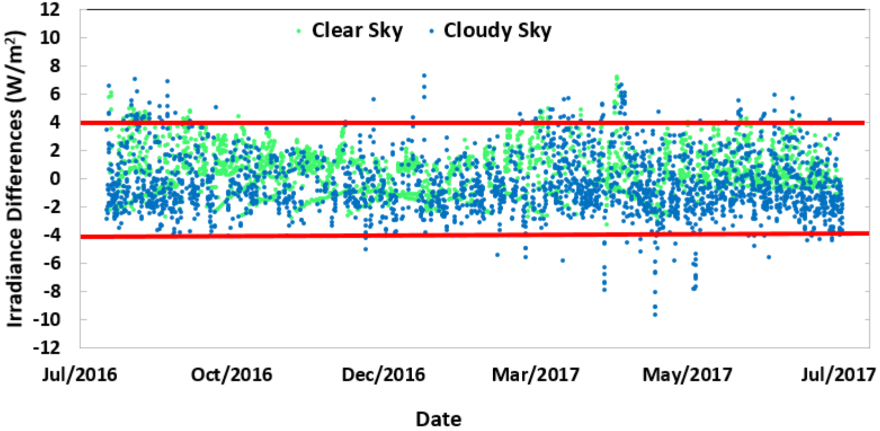


Modeled vs. measured 1-min UV global irradiance under clear-sky winter conditions at SRRL.

The correlation between the modeled and measured UV irradiance is highly significant (R^2 = 0.995), which provides confidence in the model developed here.

Validation using Hourly Averaged Measurements





Hourly modeled vs. measured UV global irradiance under clear- and cloudy-sky conditions at SRRL for one year (August 2016 to August 2017) .

Most of the hourly differences are within ±2 W/m^2. There are only a few outliers outside of the range of ±4 W/m^2, which could be related to unusual combinations of atmospheric conditions or radiometer maintenance issues.

Development of ASTM Standard

ASTM Work Item: WK57714: Standard estimation of UV irradiance

Collaboration Area

Collaboration on WK57714

New Standard estimation of UV irradiance received by samples a

location, orientation and tilt

Created: Target Date: 2019-06-01 Technical Contact : Olivier Rosseler

Drafts File Repository Members History

Thank you for creating an ASTM Collaboration Area.

The next couple screens will guide you through setting up your new Collaboration Area.

If you are ready to upload a standard draft, please click below.

UPLOAD DRAFT

Drafts Members Complete

1 2 3

https://www.astm.org/DATABASE.CART/WORKITEMS/WK57714.htm

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

IEEE JOURNAL OF PHOTOVOLTAICS 1

Estimating Ultraviolet Radiation From Global Horizontal Irradiance

Aron Habte, Manajit Sengupta, Christian A. Gueymard, Ranganath Narasappa, Olivier Rosseler, and David M. Burns

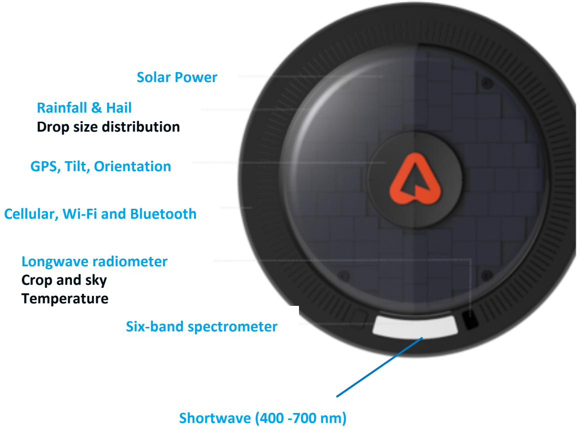
Abstract—**Terrestrial ultraviolet radiation (UV) radiation is a primary factor contributing to the degradation of photovoltaic (PV) modules' efficiency and reliability over time. Therefore, accurate knowledge of terrestrial UV incident on the surface of the PV materials is essential to understand the degradation of PV modules and provide reliable assessment of their service life. As PV is deployed in various climate zones, it is crucial that terrestrial UV information is available at various locations. However, the availability of terrestrial UV data—measured or modeled—is extremely**

occur because of exposure to solar radiation in combination with heat and various states of water [1], [2]. Solar radiation—specifically ultraviolet (UV) radiation, as one of the major stress factors—plays a significant role in the dissociation of polymer bonds in coatings, and discoloring of pigments [2], [3]. Therefore, obtaining accurate solar radiation data is important to accurately predict the service life and durability of the materials

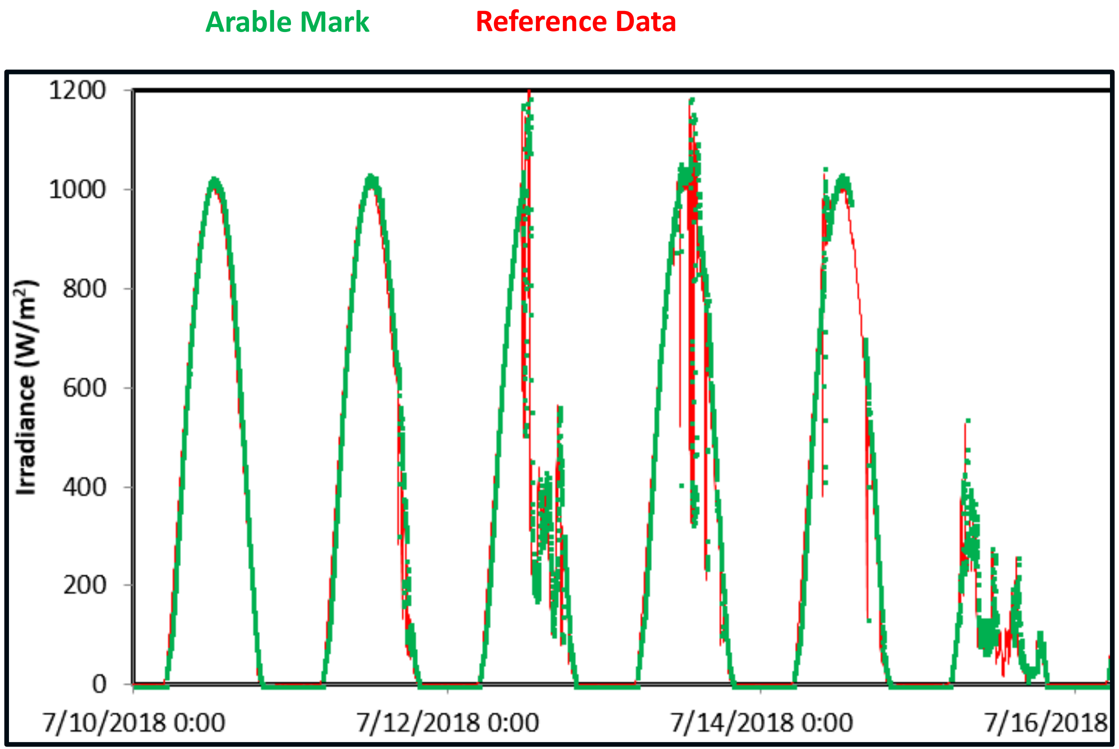
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8529229

Low-Cost Multiparameter Sensor for Solar Resource Applications

Arable Mark Device



Characterization Results



All-sky comparison at 1-minute resolution—shows good agreement compared with reference data.

Conclusions and Future Work

- A fast spectral POA model was built, validated and implemented to provide on demand spectral radiation from the NSRDB.
- A model was developed to estimate the GUV irradiance in two different wavebands (280–400 nm and 285–385 nm) using the total broadband solar irradiance.
- The atmospheric airmass was found to be the primary driver of the GUV/TS ratio, at least under “typical” atmospheric conditions.
- The model does not appear to be significantly affected by cloudiness.
- The model typically under- or overestimates the measured UV irradiance by only ±2 W/m^2 on an hourly basis during the course of one year.
- We characterized a low cost device for irradiance measurement and showed that it held significant promise for PV applications.

Thank You

www.nrel.gov

Contact: Manajit.Sengupta@nrel.gov

This work was authored by Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Solar Energy Technology Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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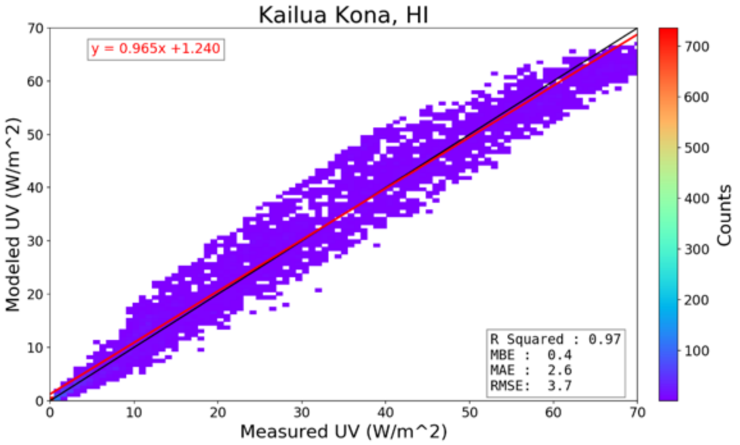
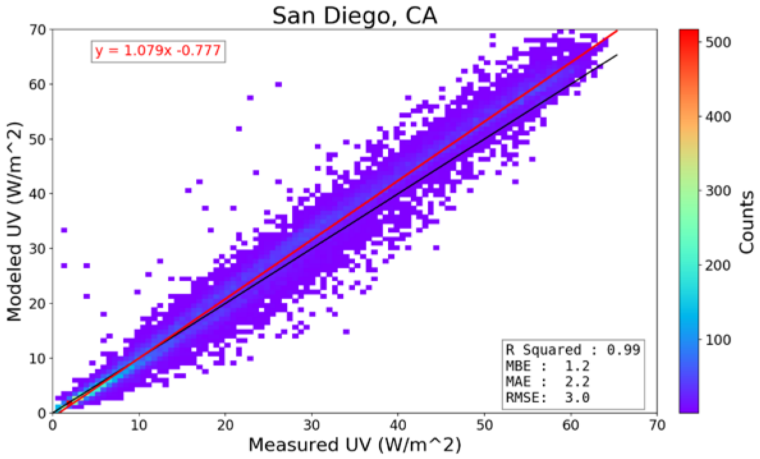
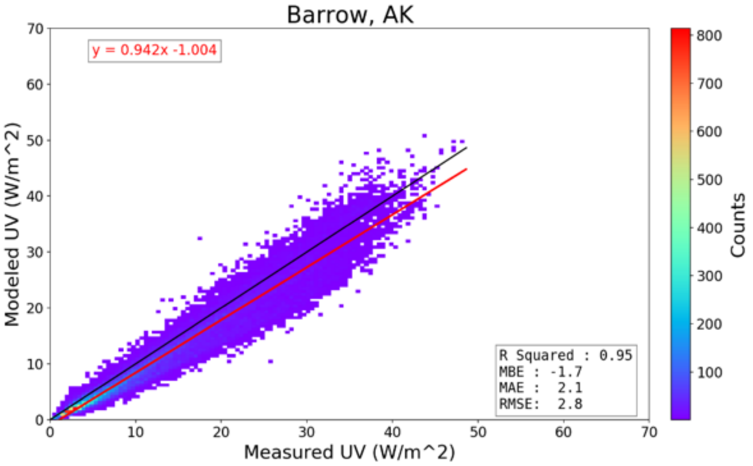
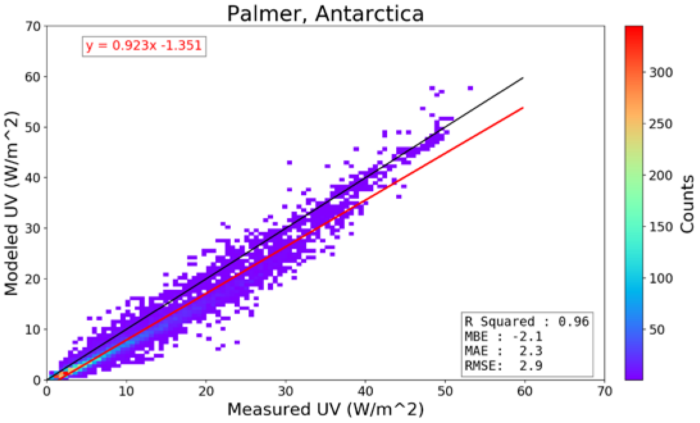
Validation at Various Locations

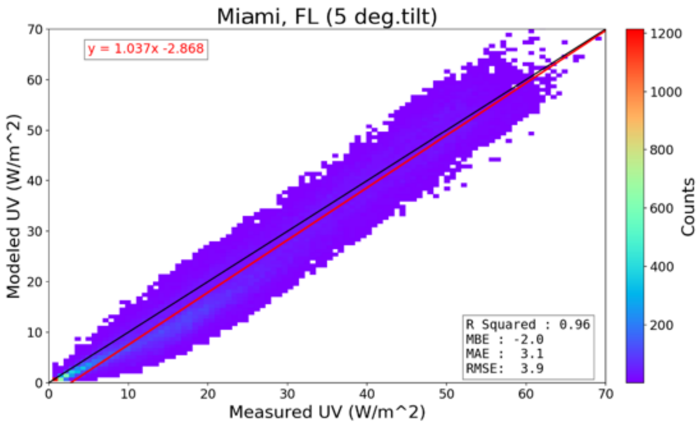




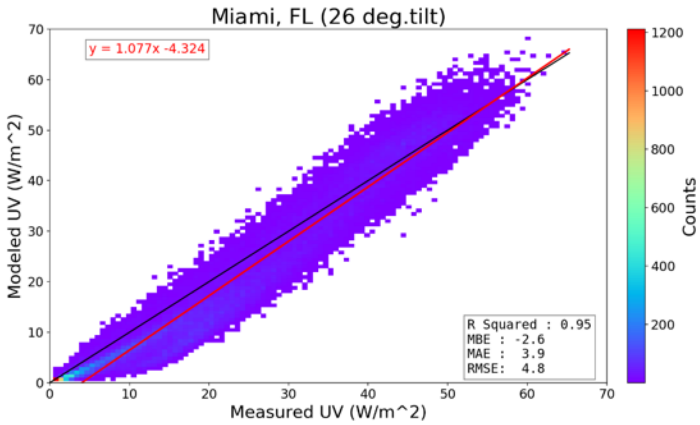




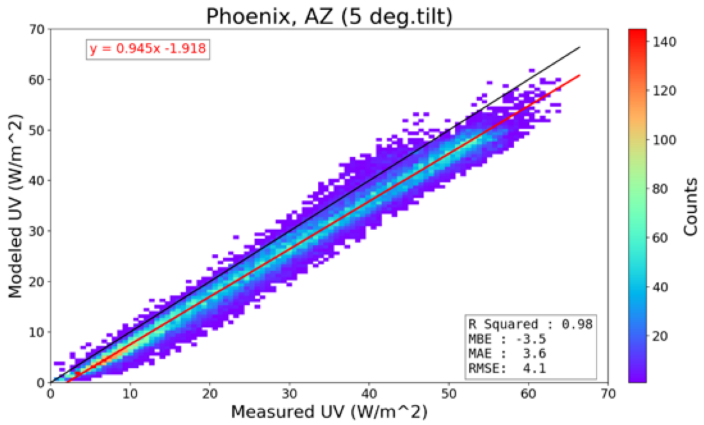
Validation



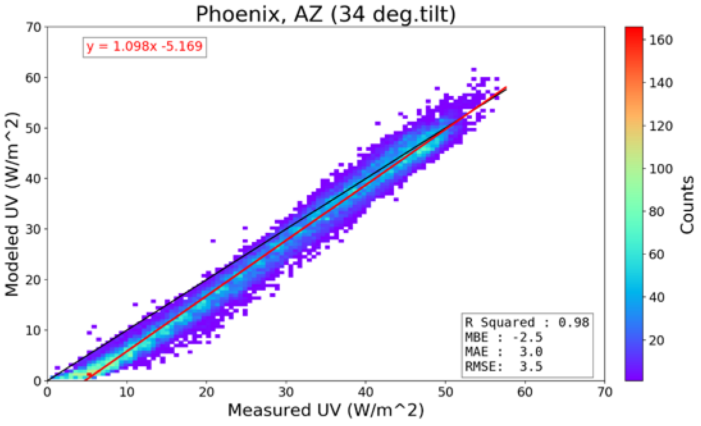
Miami, FL (5 deg.tilt)
y = 1.037x -2.868
R Squared : 0.96
MBE : -2.0
MAE : 3.1
RMSE: 3.9
Modeled UV (W/m^2)
Measured UV (W/m^2)
Counts



Miami, FL (26 deg.tilt)
y = 1.077x -4.324
R Squared : 0.95
MBE : -2.6
MAE : 3.9
RMSE: 4.8
Modeled UV (W/m^2)
Measured UV (W/m^2)
Counts



Phoenix, AZ (5 deg.tilt)
y = 0.945x -1.918
R Squared : 0.98
MBE : -3.5
MAE : 3.6
RMSE: 4.1
Modeled UV (W/m^2)
Measured UV (W/m^2)
Counts



Phoenix, AZ (34 deg.tilt)
y = 1.098x -5.169
R Squared : 0.98
MBE : -2.5
MAE : 3.0
RMSE: 3.5
Modeled UV (W/m^2)
Measured UV (W/m^2)
Counts

Comparison Under Different UV Spectral Ranges

Comparison of results using different definitions of UV spectral range						
Station	NREL Model (280–400 nm) MJ/m^2 *	NREL Model (295–400 nm) MJ/m^2 *	Poliskie, 2011 (295–400 nm) MJ/m^2	NREL Model (285–385 nm) MJ/m^2	NREL Model (295–385 nm) MJ/m^2 *	White et al., 2011 (295–385 nm) MJ/m^2
Case Western Reserve Univ. (CWRU), Ohio, USA	291(0° tilt) 285(5° tilt) 269(41° tilt)	288(0°tilt) 285(5°tilt) 269(41°tilt)	—	227(0°tilt) 221(5°tilt) 208(41°tilt)	224(0°tilt) 221(5°tilt) 208(41°tilt)	—
Miami, Florida, USA	422(0° tilt) 410(5° tilt) 400(26° tilt) 369(45° tilt)	416(0°tilt) 410(5°tilt) 400(26°tilt) 369(45°tilt)	390 (26°tilt)	330(0°tilt) 320(5°tilt) 304(26°tilt) 295(45°tilt)	325(0°tilt) 320(5°tilt) 311(26°tilt) 288(45°tilt)	338 (5°tilt) 320 (45°tilt)
NREL, Golden, Colorado, USA	341(0° tilt) 341(5° tilt) 337(40° tilt)	339(0°tilt) 341(5°tilt) 337(40°tilt)	—	266(0°tilt) 265(5°tilt) 260(40°tilt)	264(0°tilt) 265(5°tilt) 260(40°tilt)	—
Phoenix, Arizona, USA	439 (0° tilt) 435 (5° tilt) 432 (34° tilt)	436 (0°tilt) 435 (5°tilt) 432 (34°tilt)	440(34°tilt)	343 (0°tilt) 339 (5°tilt) 361 (34°tilt)	340 (0°tilt) 339 (5°tilt) 336 (34°tilt)	359 (5°tilt) 363 (34°tilt)

*** Values are obtained using the NREL TMY data set (PSM V3).**
Note: Orientation is south facing