Advances in Solar Measurement and Modeling at NREL

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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
Physical Solar Model (PSM) Framework

- GOES
- MERRA2
- MODIS
- IMS

- Cloud Properties
- Atmospheric Profile
- Aerosol Properties
- Surface Albedo
- Snow Albedo

- FARMS

- GHI
- DNI
- DHI
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
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 \( \mu \)m) from the radiances.
- Radiances are computed for 450 sky-view angles that can be integrated for any tilt-geometry.

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).
• 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%.
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

- Spectral radiances are computed by solving the radiative transfer equation.
- Two additional photon paths are considered for Rayleigh scattering under the clouds.
Cloud BTDF for water (left) and ice (right) clouds for $\tau = 5$, $De = 10 \, \mu m$, $\theta_0 = 30^\circ$ at $0.6 \, \mu m$. The viewing zenith angle increases from 0 to 90 degree along the radial direction.
• 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 $\sim$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

\[ UV_m = TS_m (\sum_{i=0}^{4} m_i AM^i) \]

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

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Variability in UV Estimates at Various Locations

UV Estimates for Various Air-masses for all locations

Series 1
Series 2
Series 3
Series 4
Series 5
Series 6

Site Number

R_UV
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.
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/m². There are only a few outliers outside of the range of ±4 W/m², which could be related to unusual combinations of atmospheric conditions or radiometer maintenance issues.
ASTM Work Item: WK57714: Standard estimation of UV irradiance

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

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8529229
Low-Cost Multiparameter Sensor for Solar Resource Applications
Arable Mark Device

- Six-band spectrometer
- Air Temperature
- Humidity
- Pressure
- 4-Way Net Radiometer
- Shortwave (400~700 nm)

Auxiliary Sensing
- Soil moisture, camera

Cellular, Wi-Fi and Bluetooth Internal Antennas

Solar Power
- Rainfall & Hail
  - Drop size distribution

GPS, Tilt, Orientation

Cellular, Wi-Fi and Bluetooth

Longwave radiometer
- Crop and sky Temperature

Six-band spectrometer

Shortwave (400~700 nm)

Cellular, Wi-Fi and Bluetooth
- Rainfall & Hail
- Drop size distribution
- GPS, Tilt, Orientation
- Cellular, Wi-Fi and Bluetooth
- Longwave radiometer
- Crop and sky Temperature
- Six-band spectrometer
- Shortwave (400~700 nm)
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/m² 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
Validation at Various Locations

Kailua Kona, HI

San Diego, CA

Barrow, AK

Palmer, Antarctica

$y = 0.965x + 1.240$

$y = 1.079x - 0.777$

$y = 0.942x - 1.004$

$y = 0.923x - 1.351$

R Squared: 0.97
MBE: 0.4
MAE: 2.6
RMSE: 3.7

R Squared: 0.99
MBE: 1.2
MAE: 2.2
RMSE: 3.0

R Squared: 0.95
MBE: -1.7
MAE: 2.1
RMSE: 2.8

R Squared: 0.96
MBE: 2.1
MAE: 2.3
RMSE: 2.9
Validation

Miami, FL (5 deg. tilt)

- Model: $y = 1.037x - 2.668$
- $R^2 = 0.96$
- MBE: 2.0
- MAE: 3.1
- RMSE: 3.9

Miami, FL (26 deg. tilt)

- Model: $y = 1.077x - 4.324$
- $R^2 = 0.95$
- MBE: 2.6
- MAE: 3.9
- RMSE: 4.8

Phoenix, AZ (5 deg. tilt)

- Model: $y = 0.945x - 1.918$
- $R^2 = 0.98$
- MBE: 3.5
- MAE: 3.1
- RMSE: 4.1

Phoenix, AZ (34 deg. tilt)

- Model: $y = 1.098x - 5.169$
- $R^2 = 6.98$
- MBE: 2.5
- MAE: 3.0
- RMSE: 3.5
Comparison of results using different definitions of UV spectral range

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<th>NREL Model (280–400 nm) MJ/m²</th>
<th>NREL Model (295–400 nm) MJ/m²</th>
<th>Poliskie, 2011 (295–400 nm) MJ/m²</th>
<th>NREL Model (285–385 nm) MJ/m²</th>
<th>NREL Model (295–385 nm) MJ/m²</th>
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* Values are obtained using the NREL TMY data set (PSM V3).
Note: Orientation is south facing