Assessing the Performance of the Fast All-sky Radiation Model for Solar Applications with Narrowband Irradiances on Tilted Surfaces (FARMS-NIT)

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Assessing the Performance of the Fast All-sky Radiation Model for Solar Applications with Narrowband Irradiances on Tilted Surfaces (FARMS-NIT)

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***Abstract*—This study evaluates the performance of a new radiative transfer model, Fast All-sky Radiation Model for Solar Applications with Narrowband Irradiances on Tilted surfaces (FARMS-NIT), that efficiently computes spectral irradiances on inclined photovoltaic (PV) panels. FARMS-NIT numerically solves the spatial distribution of solar radiation in 2,002 wavelength bands, and thereby accurately provides plane-of-array (POA) irradiances by integrating radiances over inclined surfaces. The FARMS-NIT for clear- and cloudy-sky conditions are used to compute POA irradiances for TMY3 sites and compared with the simulation by TMYSPEC. Our results indicate that FARMS-NIT leads to ~5% greater spectral irradiances compared to TMYSPEC. The difference in POA irradiance with a latitude tilt angle is slightly larger than global horizontal irradiance (GHI).**

I. Introduction

Radiative transfer models numerically solve atmospheric radiation by considering the light scattering and absorption by atmospheric constituents and land surface [1]. During the last decades, a number of radiative transfer models have been developed and employed in a broad range of applications, such as solar energy, and weather and climate studies [2-15]. Conventional radiative transfer models only compute solar radiation on horizontal surfaces. Thus, they need to be coupled with parametric transposition models, such as that developed by Perez et al. [16], to estimate solar radiation in the plane of array (POA).

To extend the capability of the current radiative transfer models for advancing solar energy studies, Xie and Sengupta [11] developed the Fast All-sky Radiation Model for Solar applications with Narrowband Irradiances on Tilted surfaces (FARMS-NIT) to efficiently provide physics-based solutions of solar irradiances on inclined surfaces. This model can simultaneously compute POA irradiances in 2,002 wavelength bands from 0.28-4.0 µm, and it can be used in understanding the spectral response of photovoltaic (PV) panels.

The operational application of a radiative transfer model requires validation studies under various conditions to understand the magnitude of its uncertainties and the possible sources [17]. This study uses FARMS-NIT and the satellitee-based observations from the National Oceanic and Atmospheric Administration's (NOAA's) Geostationary Operational Environmental Satellite (GOES) to numerically simulate global horizontal irradiance (GHI) and POA irradiance in the 2,002 wavelength bands from 0.28-4.0 µm. The GHI and POA irradiance are compared with those computed by TMYSPEC [18] in 151 wavelength bands where GHI, direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) from the National Solar Radiation Data Base (NSRDB) [17] are used as input. The rest of the paper is organized as follows. Section 2 briefly reviews the conventional computation of POA irradiances and the development of FARMS-NIT. Section 3 validates FARMS-NIT in clear-sky and cloudy-sky conditions. Section 4 further discusses the results and the possible sources of the model uncertainties.

II. Computation of POA Irradiance by FARMS-NIT

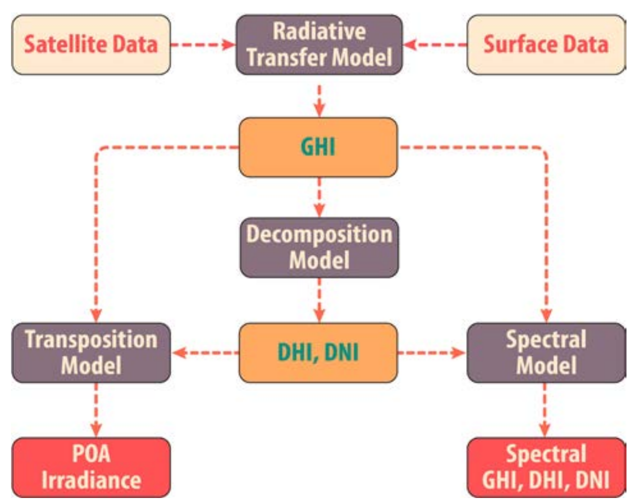

Figure 1 Flowchart of the conventional computation of POA irradiance and radiation in spectral bands.

Figure 1 shows a flowchart of the conventional computation of POA irradiance and radiation in spectral bands. As shown, a radiative transfer model is used to compute GHI that is seperated into DHI and DNI using a decomposition model. The POA irradiance is then computed using the horizontal irradiances and a transposition model based on surface observations and empirical equations. An individual spectral model is required to compute GHI, DHI, and DNI in spectral wavelength bands. The transposition and spectral models have been developed using observations from a limited number of locations, so there are significant uncertainties when using those models in locations that are not adequately represented in the available choice of parameters.

Compared to the conventional computation, FARMS-NIT combines all individual models shown in Fig. 1 to a physics-based model efficiently computing spectral radiances in 2,002 wavelength bands from 0.28-4.0 µm. The atmosphere is divided into three layers: a cloud/aerosol layer and clear-sky layers above and below the cloud layer. We consider all possible photon paths in each layer that are related to direct transmission through a layer or the scattering by air molecules/aerosols/clouds. The solar radiance at the land surface is given by the total values of the radiances from the photon paths. The POA irradiances are then accurately computed by integrating the radiances on horizontal or inclined surfaces. More details in the development of FARMS-NIT can be found in [11].

III. Assessing the Performance of FARMS-NIT

To understand the performance of FARMS-NIT, we investigate the typical meteorological year (TMY) data from satellite-based observations by NOAA’s GOES over TMY3 locations. Figure 2 illustrates the 942 TMY3 locations where four sites are selected for this study to represent a diverse distribution of geographical and climatological features in the United States: Pullman, WA; Rapid City, SD; Mobile, AL; and Alcoa, TN.

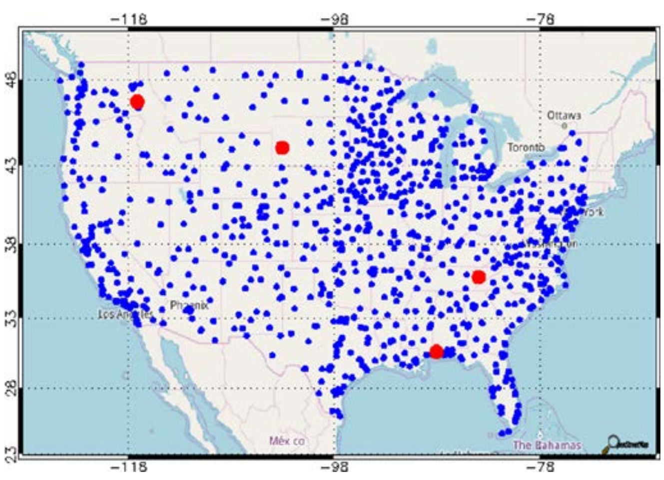

Figure 2 The four sites (red dots) selected from 942 TMY3 locations (blue dots) in the United States.

The 1-year satellite products at the selected TMY3 sites—including solar zenith and azimuth angles, land-surface albedo and pressure, aerosol optical depth (AOD), cloud thermodynamic phase, cloud top pressure, cloud optical thickness and effective particle size—are used by FARMS-NIT to efficiently compute GHI and POA irradiance on a PV panel facing south with a latitude tilt angle.

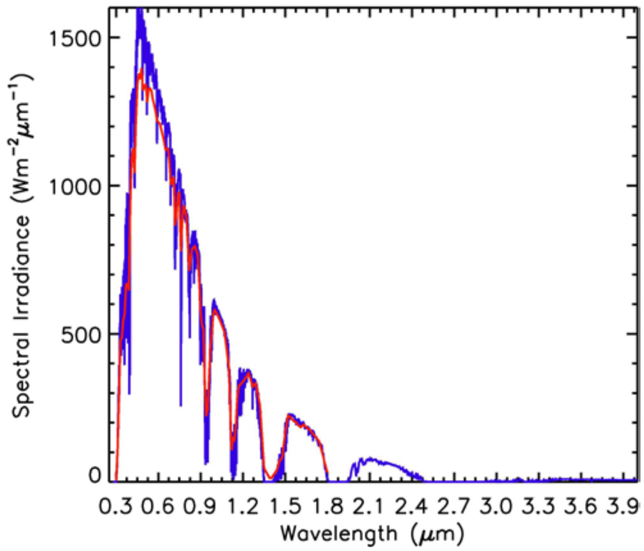

Figure 3 Comparison of POA irradiances at Rapid City, SD. The POA irradiances are computed for a latitude tilt angle at 12:00 pm on June 29. The blue and red line represent the simulations by FARMS-NIT and TMYSPEC, respectively.

The GHI, DHI, and DNI for TMY are provided by the NSRDB and used as input data to TMYSPEC which computes spectral irradiances on the horizontal and tilted surfaces in 151 wavelength bands from 0.3-1.8 µm. Figure 3 compares the POA irradiances at Rapid City, SD. The POA irradiances are computed by FARMS-NIT and TMYSPEC for a latitude tilt angle at 12:00 pm on June 29. As shown, the results from FARMS-NIT better represent the absorption lines of various trace gases from ultraviolet (UV) through the near-infrared regions. The results from TMYSPEC are generally smaller than FARMS-NIT in the visible region though their averaged values over the UV and near-infrerad regions demonstrate very good agreement.

Table I summarizes the difference between FARMS-NIT and TMYSPEC using the 1-year TMY data at the selected TMY sites. Mean bias error (MBE), mean absolute error (MAE), and mean percentage error (MPE) are used to assess the difference between the models. Their definitions are given as follows:

$$MBE = \frac{1}{N}\sum_{n=1}^{N}(F_F - F_T) \quad (1)$$

$$MAE = \frac{1}{N}\sum_{n=1}^{N}|F_F - F_T| \quad (2)$$

$$MPE = \frac{\sum_{n=1}^{N}(F_F - F_T)}{\sum_{n=1}^{N}F_T} \quad (3)$$

where N is the total number of data points, and F_F and F_T represent irradiances computed by FARMS-NIT and TMYSPEC, respectively. It can be concluded from Table I that the spectral GHI and POA irradiance computed by FARMS-NIT are approximately 5% greater than those computed by TMYSPEC. The differences in POA irradiance are larger on average than GHI.

TABLE I
DIFFERENCE BETWEEN FARMS-NIT AND TMYSPEC

	MBE ($W/m^2/nm$)	MAE ($W/m^2/nm$)	MPE (%)
Pullman, WA			
GHI	0.0129	0.0333	5.1687
POA Irradiance	0.0149	0.0515	4.8839
Rapid City, SD			
GHI	0.0142	0.0354	5.2682
POA Irradiance	0.0173	0.0571	4.9761
Mobile, AL			
GHI	0.0129	0.0331	4.702
POA Irradiance	0.0216	0.048	6.6561
Alcoa, TN			
GHI	0.0127	0.0376	4.1187
POA Irradiance	0.0208	0.0486	6.0443

IV. Conclusions

Conventional models use separate steps to compute POA irradiance in the solar wavelength band or spectral irradiances on horizontal surfaces. We extended the capability of the current radiative transfer models and developed a physics-based model, FARMS-NIT, to simultaneously compute spectral irradiance on horizontal or inclined surfaces. To understand the uncertainty of FARMS-NIT, we employed satellite-based observations of atmospheric and land surface properties at TMY3 locations from NOAA's GOES, computed GHI and POA irradiances in 2,002 wavelength bands from 0.28-4.0 µm, and compared them to simulations of TMYSPEC using GHI, DNI, and DHI from the NSRDB. Our results show that FARMS-NIT differs from the TMYSPEC in both clear-sky and cloudy-sky conditions for parts of the spectrum and agree with others. Both GHI and POA irradiance computed by FARMS-NIT are greater in the visible region than those computed by TMYSPEC. The overall difference from the 1-year data over the selected TMY3 locations are approximately 5%. We also concluded that the difference in POA irradiance is slightly greater than GHI.

Note that the difference discovered in the validation study could come from multiple sources. FARMS-NIT assumes clear-sky conditions when observed cloud fractions are smaller than 10%; however, the partially cloudy sky might affect the accuracy of FARMS-NIT. We used broadband surface albedo to represent all wavelengths from 0.28-4.0 µm. For grass land surfaces, the surface albedo tends to be overestimated at visible wavelengths and underestimated at near-infrared wavelengths. Finally, the availability and uncertainty in AOD measurements substantially affect the performance of FARMS-NIT. Thus, further studies and surface observations are needed to better understand the difference between models and accurately quantify the uncertainty of FARMS-NIT.

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References

[1] K. N. Liou, *An introduction to atmospheric radiation*, 2nd ed. (International geophysics series v. 84). Amsterdam; Boston: Academic Press, 2002, pp. xiv, 583 p.

[2] K. Stamnes, S. C. Tsay, W. Wiscombe, and K. Jayaweera, "Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media," *Appl. Opt.*, vol. 27, no. 12, pp. 2502-2509, Jun 15 1988.

[3] S. Kotchenova, E. Vermote, R. Matarrese, and F. Klemm, "Validation of a vector version of the 6S radiative transfer code for atmospheric correction of satellite data. Part I: Path radiance," *Appl. Opt.*, vol. 45, no. 26, pp. 6762-6774, Sep 10 2006.

[4] Q. Fu and K. N. Liou, "Parameterization of the radiative properties of cirrus clouds," *J. Atmos. Sci.*, vol. 50, pp. 2008-2025, 1993.

[5] E. J. Mlawer, S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, "RRTM, a validated correlated-k model for the longwave," *J. Geophys. Res.*, vol. 102, pp. 16663-16682, 1997.

[6] Y. Xie, M. Sengupta, and J. Dudhia, "A Fast All-sky Radiation Model for Solar applications (FARMS): Algorithm and performance evaluation," *Sol. Energy*, vol. 135, pp. 435-445, 2016.

[7] C. Gueymard, "REST2: High-performance solar radiation model for cloudless-sky irradiance, illuminance, and photosynthetically active radiation - Validation with a benchmark dataset," *Sol. Energy*, vol. 82, no. 3, pp. 272-285, 2008.

[8] Y. Xie, "Study of ice cloud properties from synergetic use of satellite observations and modeling capabilities," Ph. D., Department of Atmospheric Sciences, Texas A&M University, College Station, TX, 2010.

[9] Y. Xie and Y. G. Liu, "A new approach for simultaneously retrieving cloud albedo and cloud fraction from surface-based shortwave radiation measurements," *Environ. Res. Lett.*, vol. 8, pp. doi:10.1088/1748-9326/8/4/044023, 2013.

[10] Y. Xie, Y. G. Liu, C. N. Long, and Q. L. Min, "Retrievals of cloud fraction and cloud albedo from surface-based shortwave radiation measurements: A comparison of 16 year measurements," *J. Geophys. Res. Atmos.*, vol. 119, no. 14, pp. 8925-8940, Jul 27 2014.

[11] Y. Xie, M. Sengupta, and M. Dooraghi, "Assessment of uncertainty in the numerical simulation of solar irradiance over inclined PV panels: New algorithms using measurements and modeling tools," *Sol. Energy*, vol. 165, pp. 55-64, 2018.

[12] Y. Xie, P. Yang, B. C. Gao, G. W. Kattawar, and M. I. Mishchenko, "Effect of ice crystal shape and effective size on snow bidirectional reflectance," *J. Quant. Specrtrosc. Radiat. Transfer* vol. 100, no. 1-3, pp. 457-469, Jul-Aug 2006.

[13] Y. Xie, P. Yang, G. W. Kattawar, P. Minnis, and Y. X. Hu, "Effect of the inhomogeneity of ice crystals on retrieving ice cloud optical thickness and effective particle size," *J. Geophys. Res.*, vol. 114, pp. D11203, doi:10.1029/2008JD011216, Jun 5 2009.

[14] Y. Xie, P. Yang, G. W. Kattawar, P. Minnis, Y. X. Hu, and D. Wu, "Determination of ice cloud models using MODIS and MISR data," *Int. Remote Sens.*, vol. 33, pp. 4219-4253, 2012.

[15] R. Lawless, Y. Xie, and P. Yang, "Polarization and effective Mueller matrix for multiple scattering of light by nonspherical ice crystals," *Opt. Express*, vol. 14, no. 14, pp. 6381-6393, Jul 10 2006.

[16] R. Perez, R. Seals, P. Ineichen, R. Stewart, and D. Menicucci, "A new simplified version of the Perez diffuse irradiance model for tilted surfaces," *Sol. Energy*, vol. 39, no. 3, pp. 221-231, 1987.

[17] M. Sengupta, Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby, "The National Solar Radiation Data Base (NSRDB)," *Renew. Sustain. Energy Rev.*, vol. 89, pp. 51-60, 2018.

[18] D. Mayeer, "Direct beam and hemispherical terrestrial solar spectral distributions derived from broadband hourly solar radiation data," *Sol. Energy*, vol. 86, no. 9, pp. 2771-2782, 2012.