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Global normal spectral irradiance in Albuquerque: a one-year open dataset for PV research

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ABSTRACT

This report describes the creation process and final content of a spectral irradiance dataset for Albuquerque NM. The spectral irradiance measurements were made using a dual-axis tracker; therefore, they represent global normal irradiance. The dataset combines spectroradiometer and weather measurements from a two-year period into a continuous calendar year. The data files are accompanied by extensive metadata as well as example calculations and graphs to demonstrate the potential uses of this database.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
<i>GHI</i>	Global horizontal irradiance
<i>DHI</i>	Diffuse horizontal irradiance
<i>DNI</i>	Direct normal irradiance
<i>GNI</i>	Global normal irradiance
<i>TMY</i>	Typical Meteorological Year
<i>YAML</i>	YAML Ain't Markup Language
<i>HDF5</i>	Hierarchical Data Format version 5

1. INTRODUCTION

The Photovoltaic Systems Evaluation Laboratory (PSEL) at Sandia National Laboratories (SNL) in Albuquerque, NM has measured global normal spectral irradiance nearly continuously from August 2013 to April 2018. During this time other broadband irradiance measurements (global horizontal, direct normal, diffuse horizontal and global normal) and weather variables were also recorded. For this dataset PV Performance Labs (PVPL) has pulled together data from both sources to assemble a full calendar year spectral dataset for use in photovoltaic research. It is composed of eight continuous segments of different durations taken from the two-year period September 2013 to August 2015.

2. INSTRUMENTS AND MEASUREMENTS

The PSEL facility has a comprehensive set of instruments to record irradiance and other weather parameters. These are located on a building roof at precisely at 35.0545° N, 106.5401° W and elevation 1660 m. These instruments include a pair of spectroradiometers mounted on a dual axis tracker (Figure 1) for the purpose of evaluating spectral mismatch during module tests on two larger trackers (visible in the background in Figure 1).



Figure 1 Two-axis tracker with pair of spectroradiometers (left) at the PSEL facility.

Spectra were recorded at 5-minute intervals from shortly before sunrise to shortly after sunset, whereas the remaining instruments were scanned and recorded at nominally 3-second intervals.

Parameter	Orientation/Position	Manufacturer	Model	Additional details
Spectral irradiance	Global normal (GNI)	Eko instruments	MS710	~350-925 nm
			MS712	~925-1700 nm
Broadband irradiance	Global normal (GNI)	Eppley	PSP	
	Global horizontal (GHI)	Kipp & Zonen	CM21	Using Sandia zenith correction
	Diffuse horizontal (DHI)	Eppley	PSP	On separate shade-disk tracker
	Direct normal (DNI)	Kipp & Zonen	CHP1	Using Sandia temperature correction
Temperature	Inside aspirated shield	Climatronics	100092-2	Accuracy: +/- 0.1°C
Humidity		Climatronics	102273	Accuracy: +/- 1%
Wind speed	10 m height	Climatronics	WM-III	Accuracy: +/- 0.11 m/s
Atmospheric pressure		Climatronics	102270	Accuracy: +/- 0.1%

Table 1: Summary of instruments and parameters

2.1 Calibrations

The pair of spectroradiometers was newly installed in 2013 and calibrated by the manufacturer. They were not recalibrated within the two-year period used for this dataset, which was right after the spectroradiometers were installed.

The pyranometers and pyrhelimeter were calibrated annually at Sandia Labs with traceability to the World Radiation Reference (WRR) through two absolute cavity radiometers (ACR). For the GHI measurements a zenith angle dependent responsivity function was used, and the DNI measurements were corrected for temperature. Both of these adjustments were derived from the calibration procedure at Sandia.

The remaining weather instruments relied on factory calibrations and were not recalibrated during the two-year period used for this dataset.

3. DATA PROCESSING

3.1 Spectrum selection

Despite best efforts, the spectroradiometer data collection was not free of gaps during the measurement period. Sometimes just one or two spectra were missed in a day, whereas other times the instruments were offline for several days in a row. Nevertheless, on the majority of days the availability was 100%, and for every calendar day there exists at least one year in the dataset in which that day has no gaps. Thus it is possible to piece together a complete calendar year.

The main criterion for composing the year-long dataset was to use the fewest and longest segments from different years. By tolerating one or two missed spectra occasionally it was possible to achieve this with eight segments of differing durations. In addition, the time span between the oldest and newest spectra in the dataset was minimized to avoid the potential influence of calibration drifts. The eight chosen segments span the first 24 months of operation and are missing only 11 spectra for solar zenith angles less than 95° for a total availability of 99.98%.

The availability of the additional weather measurements was not taken into account as there are very few data gaps. Nevertheless 15 of the chosen spectra did not have corresponding weather measurements and were consequently also dropped from the dataset. The final number of records stands at 54221.

This assembly of segments resembles a TMY, which uses 12 fixed duration segments (calendar months). However, unlike the TMY, the actual weather conditions did not influence the selection process, therefore this spectral year cannot be deemed typical. In fact, the only claim that can be made is that the observations are real (not simulated).

3.2 Spectrum reduction

The raw spectral measurements are recorded at 1246 unevenly spaced wavelengths beginning with 349.419 nm and ending with 1700.3093 nm. With spacing between 0.7 and 1.9 nm the recorded spectra are somewhat oversampled with respect to optical resolution, which can be represented by a Gaussian window with a full-width-half maximum (FWHM) specification of 7 to 8 nm. (See Figure 2.) Thus the spectra could be resampled with fewer points without losing information.

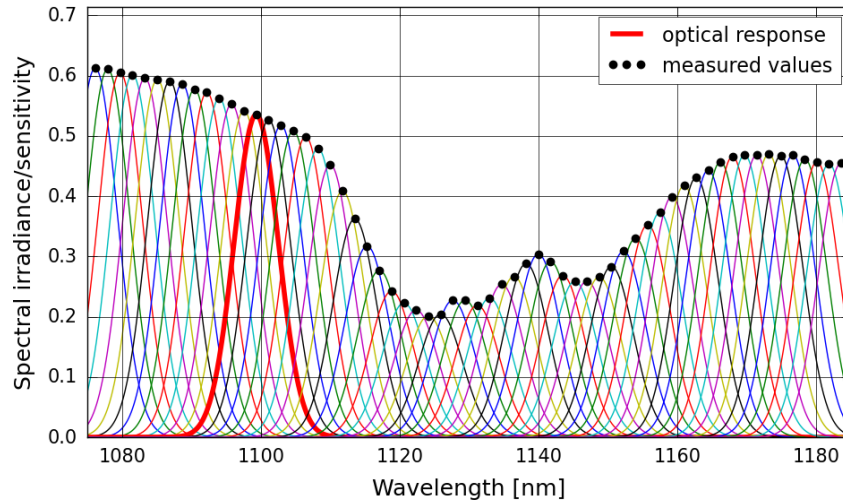


Figure 2 Illustration of the optical resolution of the spectroradiometer in relation to the wavelength interval of the measurements

A second observation is that there are some fluctuations between adjacent wavelengths in the measurements especially near the lower end of the range of each instrument. Since these are beyond the resolution of the optics, they are clearly measurement noise. This should be filtered out, if possible.

The potential choices for resampling and filtering are many, but we must also consider the intended application: photovoltaic studies (as opposed to analysis of atmospheric conditions). This means that the spectral irradiance will be multiplied by the spectral response of photovoltaic devices and integrated over wavelength in order to calculate total photo-current or spectral mismatch factors. Random noise is automatically attenuated in this process; and since spectral response of PV devices have few if any high-resolution features and are typically measured at lower wavelength resolutions, high-resolution features of the spectral irradiance do not influence the integrated values either. The most important feature of the spectral response is the rapid drop around the band-gap energy, which is still gradual enough that it spans a range of 100 to 300 nm.

Thus, it is possible to reduce the wavelength resolution without undermining the objectives for the dataset, but is it necessary? The motivation for creating this dataset is to make spectral irradiance data more widely accessible. Accessibility includes ease of use; therefore both resampling to uniformly spaced wavelengths and reduction of file size are desirable.

The chosen wavelength interval is 5 nm, which corresponds to the highest resolution photovoltaic cell spectral response measurements that we are aware of, from PTB in Germany. The final spectra thus have 271 wavelengths from 350 to 1700 nm. In the process of down sampling a Gaussian smoothing kernel with FWHM 6.6 nm was used so that the final data correspond to what would have been measured with an instrument having an optical resolution of 10 nm and sampling interval of 5 nm. (See Figure 3) **Figure 4** shows the processed spectra over the course of a clear day.

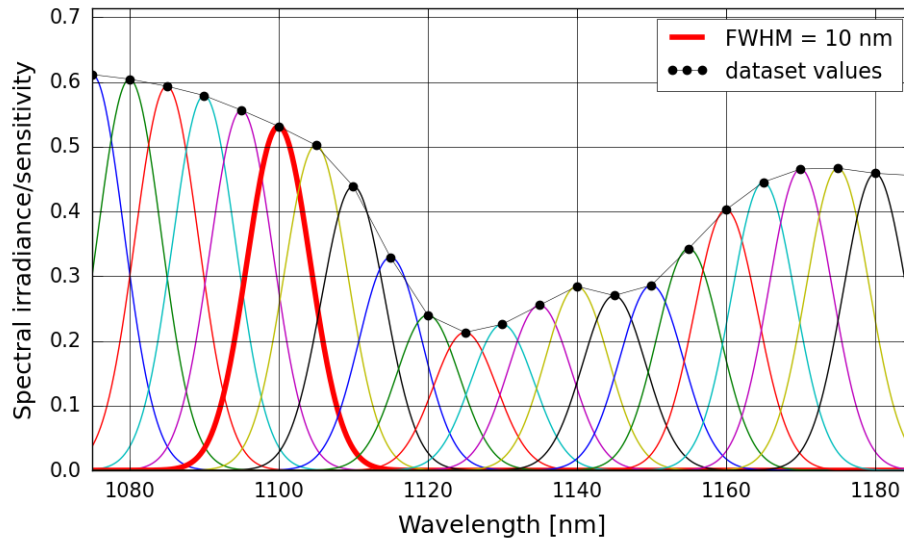


Figure 3 Illustration of the effective resolution relation to the wavelength interval for the dataset

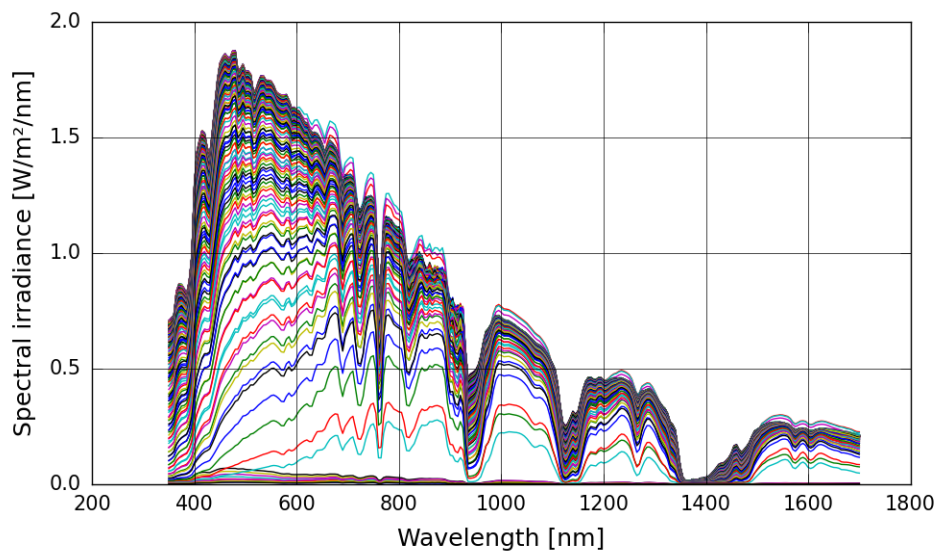


Figure 4 Spectral irradiance over the course of a clear day (June 1)

3.3 Corresponding broadband irradiance

As the spectra are recorded precisely every 5 minutes, it is most useful to provide broadband values taken simultaneously rather than one- or five-minute averages. The broadband irradiance was measured nominally every 3 seconds, but not precisely, so these measurements coincide with the spectral measurements at the five-minute mark only one third of the time. This situation is similar to the one above where we need to interpolate between irregularly-spaced points, and there is a physical property of the instrument that is limiting the signal bandwidth: in this case it is the thermal mass of the detector element acting like a single-pole low-pass filter. [1] But an important difference is that the measurands are under-sampled rather than generously over-

sampled, and the objective is to obtain isolated values at the five-minute marks rather than represent a continuous variable. Thus, a monotonic polynomial interpolation is used to obtain the needed values between samples, provided the gap is less than 15 seconds duration. For gaps of longer duration, the values are considered missing, and these records are excluded from the dataset.

This approach takes care of providing synchronized measurements but does not alleviate the problem that the response times of the broadband thermopile instruments are slower than that of the spectroradiometer. Thus, under rapidly changing conditions, the integrated spectral irradiance will deviate further from the broadband measurements. Such conditions can be identified with a stability indicator.

3.4 Stability indicator

Under windy and partly cloudy conditions irradiance levels can change so rapidly that a single recorded spectrum no longer represents a stable condition and broadband instrument values are inconsistent with each other because their response times differ. To rate the stability of the measurement conditions, therefore, an additional irradiance value is calculated, *dni_range*. This records the difference between the maximum and minimum DNI in a 15 s window surrounding each spectral measurement. A threshold of 10 W/m² is a good starting point for separating the stable times from the unstable. Note that even in overall stormy weather a brief, well-timed break in the clouds will be identified as stable: it is an indicator for the measurement stability, not the overall weather stability.

4. COMPLEMENTARY DATA

The calculation of spectral mismatch requires not only measured spectral irradiance, but also a reference spectrum and of course the spectral response of the PV cell or module. Both are included in this dataset for convenience and their use is demonstrated in the accompanying example program.

4.1. Compatible reference spectrum

The AM15G spectrum is defined in ASTM G173-12 [2] and also in IEC 60904-3 [3], where it is scaled down slightly. The wavelength resolution in the standard is variable from 0.5 nm to 5 nm so that many features of the atmosphere are clearly visible. As explained above, however, it is not necessary or useful to keep these high-resolution features for spectral mismatch calculations. This dataset therefore provides alternate versions of the reference spectra (both global tilted and direct normal) that have been smoothed to simulate a 10 nm optical resolution and resampled to 5 nm intervals to match the reduced spectral irradiance data.

4.2. Example spectral response

For the purpose of the sample mismatch calculation, the example program includes a spectral response curve which is representative for crystalline silicon. It has data points at only 13 wavelengths, which were chosen so that a smooth continuous curve can be generated between them using cubic spline interpolation. From this continuous curve, points can be calculated to match the wavelengths of the spectra, in this case at 5 nm intervals. The spectral response is shown in **Figure 5** and the calculated mismatch in **Figure 6**.

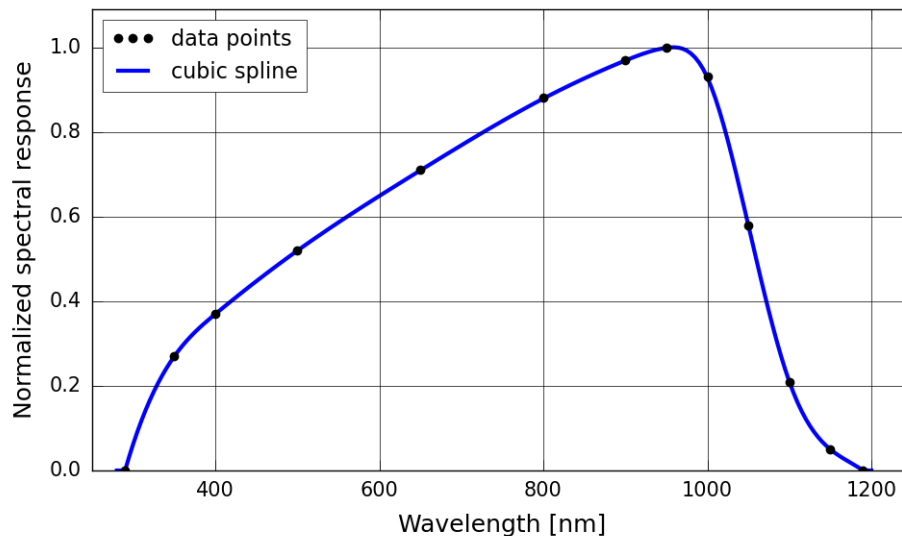


Figure 5 Representative spectral response data for crystalline silicon

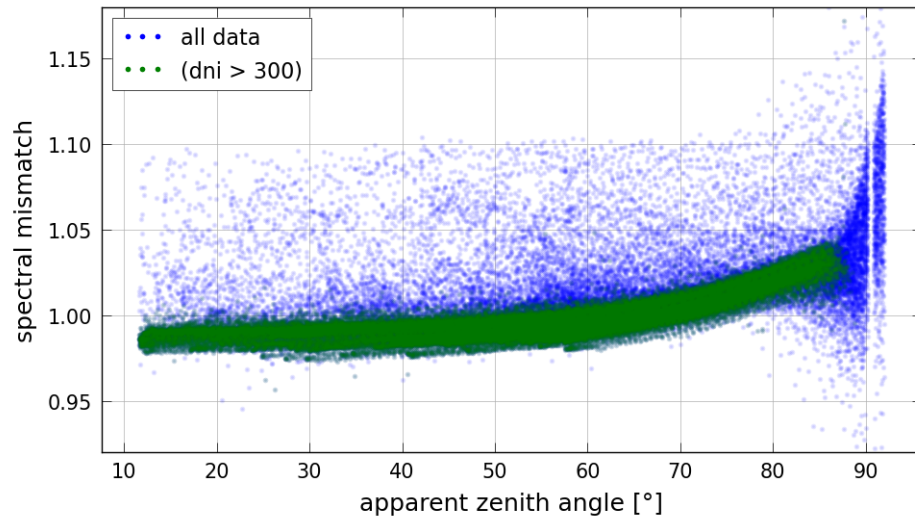


Figure 6 Spectral mismatch for crystalline silicon over the year showing a systematic correlation with zenith angle

5. PRACTICAL DETAILS

5.1. File structure

The measurements are organized in three two-dimensional data tables:

- **weather**: a time-series of broadband irradiance and other weather parameters
- **spectra**: a time-series of spectral irradiance
- **am15**: the two processed reference spectra

Each table is contained in a separate file, which also contains a description of the data table structure and other useful information. Thus the files have three sections:

- **meta**: general information about the data, such as location, contact information
- **cdef**: definitions of the columns of the data table, such as data types, units
- **data**: the data table itself, consisting of rows and columns

Like the data table, the column definitions (**cdef**) are also a two-dimensional table, which has a row corresponding to each column in the **data**. The general **meta** information on the other hand is a text block in YAML format.[4] This type of structured text is easily readable by humans but can also be parsed easily by software. (See **Figure 7.**)

The overall dataset thus consists of three separate files containing three distinct sections each. To maximize universal accessibility, the three files are offered initially in the HDF5 file format [5], which can be read with just a few commands from many programming languages, such as python, MATLAB, R, and others. A plain-text version of the files will be made available if needed.

5.2. Programming notes

Although the HDF5 format can be read using many different programming languages, it does not offer completely transparent cross-language data exchange. The three main points that require attention are:

- Text columns and column names may contain Unicode characters, which we encoded using UTF-8. In some programming languages a UTF-8 decoding may happen automatically when the data is read, in others it must be done in a separate step.
- Timestamps are stored as ISO format text, which must be parsed to produce a date-time value in the reader's language.
- Two-dimensional structures are stored in the convention of the language of the writer, which in this case is Python. Languages with different conventions, such as Matlab and Fortran, may read the two-dimensional data with rows and columns transposed. Thus a transposition step may be necessary after reading.

The data files are accompanied by a sample program in Python, which demonstrates how to read and process all elements of the data and meta data. Sample programs in other languages will be made available if needed.

```

---
title: Measured broadband irradiance and other weather parameters

description: Direct, diffuse, global horizontal and global normal irradiance
            as well as temperature, humidity, windspeed and pressure.
            See citation for more information.

project: 'Global normal spectral irradiance in Albuquerque:
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urls:
  - https://pvpmc.sandia.gov/
  - https://datahub.duramat.org/project/about/spectral-irradiance-data-and-resources

citation: 'A. Driesse and J.S. Stein, "Global normal spectral irradiance in Albuquerque:
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location:
  latitude: 35.0545
  longitude: -106.5401
  elevation: 1660
  city: Albuquerque
  state: New Mexico
  country: USA
  timezone: MST
  climatezone: BSk (Tropical and Subtropical Steppe Climate)

```

Figure 7 Meta data for the weather file in YAML format

5.3. Download locations

There are two primary download locations. The first is on the website of the PV Performance Modelling Collaborative at <https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/irradiance-and-insolation-2/irradiance-data-sources-for-performance-modeling/spectral-irradiance-data-from-albuquerque/> [6]. The second is on the Duramat Datahub at <https://datahub.duramat.org/project/about/spectral-irradiance-data-and-resources> [7].

6. AUTHOR CONTRIBUTIONS

Anton Driesse: Conceptualization, methodology, data curation, software, visualization, writing – original draft. Joshua Stein: Conceptualization, funding acquisition, resources, project administration, supervision, writing – review and editing.

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