PVRAD: supplement to the paper "Irradiance and cloud optical properties from solar photovoltaic systems"

James Barry[1,2]

[1] *International Centre for Sustainable Development, Hochschule Bonn-Rhein-Sieg, Sankt Augustin*
[2] *Institute of Environmental Physics, University of Heidelberg, Germany*

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1 Introduction

This is a brief documentation of the software `PVRAD` used in the context of the MetPVNet project (Meilinger et al., 2021) and specifically in the paper by Barry et al. (2023) to extract irradiance and atmospheric optical properties from solar photovoltaic data. Besides the main module there are various submodules used for data processing and validation.

2 `PVRAD` code overview

Figure 1 provides a schematic of the software: data sources are shown in green, software modules in blue and parameters in orange. In what follows the different modules will be explained in more detail.

2.1 Process measured data – `pvdataprocess`

The first step is to import data for processing in Python. The data import script creates a master dictionary called "pvsys" that contains further subdictionaries for each measurement station, and each of these has substations for different types of measurements. The initial raw data are saved in separate dictionaries, but the interpolation script then combines them into dataframes with unified timestamps, depending on the resolution given in the config file. ¸

1. Import station configuration from Excel spreadsheet
2. Import data from CSV: PV power, irradiance, temperature, windspeed, PMAX-DOAS data
3. Save data in binary format for fast import into Python, using `pickle` package

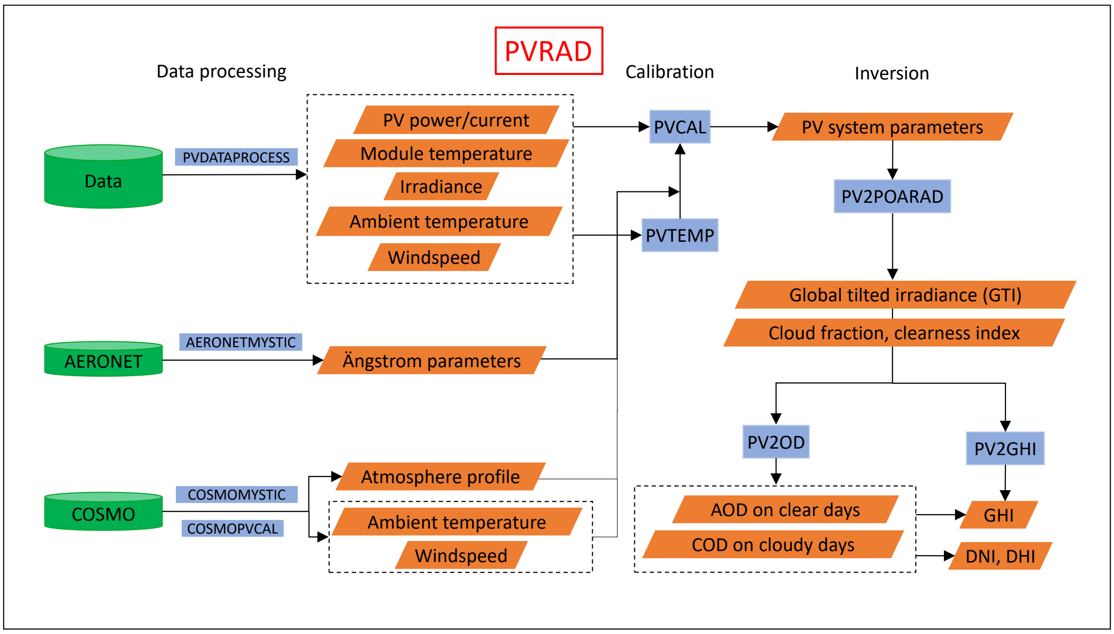

Figure 1: Schematic overview of the `PVRAD` software, with different submodules in blue, data sources in green and parameters in orange.

4. Save interpolated data as CSV
5. Generate plots if required

2.2 Ångström parameters from AERONET data – `aeronetmystic`

2.2.1 Download AERONET data

In order to obtain accurate information about atmospheric aerosols, the `aeronetmystic` tool imports data from the AErosol RObotic NETwork (AERONET), a ground-based remote sensing aerosol network that provides public domain data on aerosols stretching back more than 25 years. These data need to be downloaded manually from the AERONET website:

1. For a quick look at the data from different stations use the data display tool and zoom in to the station of choice
2. Select the AERONET station that is closest to the PV system (for example "Kempten_UAS", shown in Fig. 2)
3. Choose "Level 2.0" wherever possible, since these data have been properly filtered for clouds
4. Click on "More AERONET Downloadable Products..." in order to select exact dates and data products
5. On the "Direct Sun Algorithm" page (see Fig. 3), select required dates and select Level 2.0 for "Aerosol Optical Depth (AOD) with Precipitable Water and Angstrom Parameter"
6. Download both all points and daily averages

7. Back at the station page, choose "Version 3 Inversion", and again click on "More AERONET Downloadable Products..." in order to select exact dates and data products

8. On the "Version 3 Direct Sun and Inversion Algorithm" page (see Fig. 4), select required dates and under "Derived Inversion Products" select "Single Scattering Albedo"

9. Download both all points and daily averages

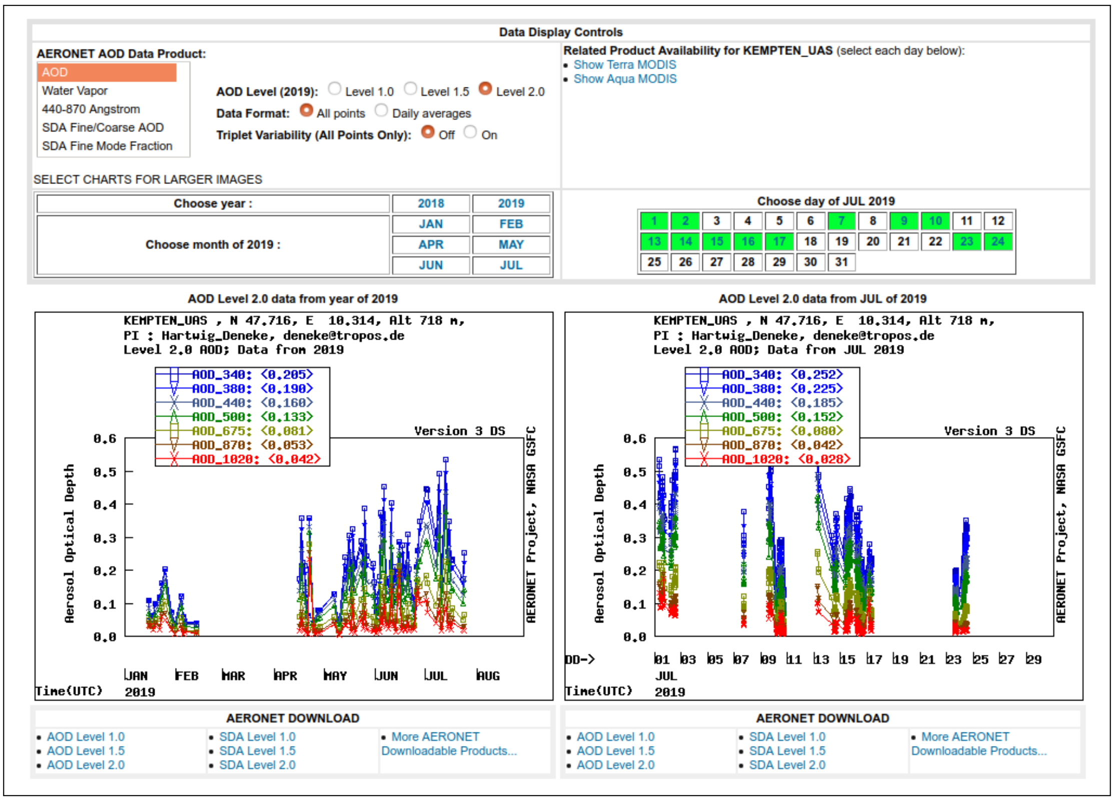

Figure 2: AERONET landing page for Kempten_UAS, with available Level 2.0 AOD data plotted

2.2.2 Run `aeronetmystic`

The current version of `PVRAD` uses the Ångström parameters as inputs for the calibration routine `PVCAL`, as well as for comparison with the AOD retrievals. The SSA is currently not used.

2.3 Generate libRadtran atmosphere files from COSMO model data – `cosmomystic`

In order to properly take into account the state of the atmosphere, in particular the water vapour content, the `cosmomystic` tool can be used to generate atmosphere input files for libRadtran , using data from the COSMO model.

The COSMO netCDF files contain 4D information about the state of the atmosphere, specifically the parameters in Table 1 on a latitude, longitude and altitude grid, for specific timestamps.

The `cosmomystic` software then performs the following functions:

1. Load data from COSMO NetCDF files

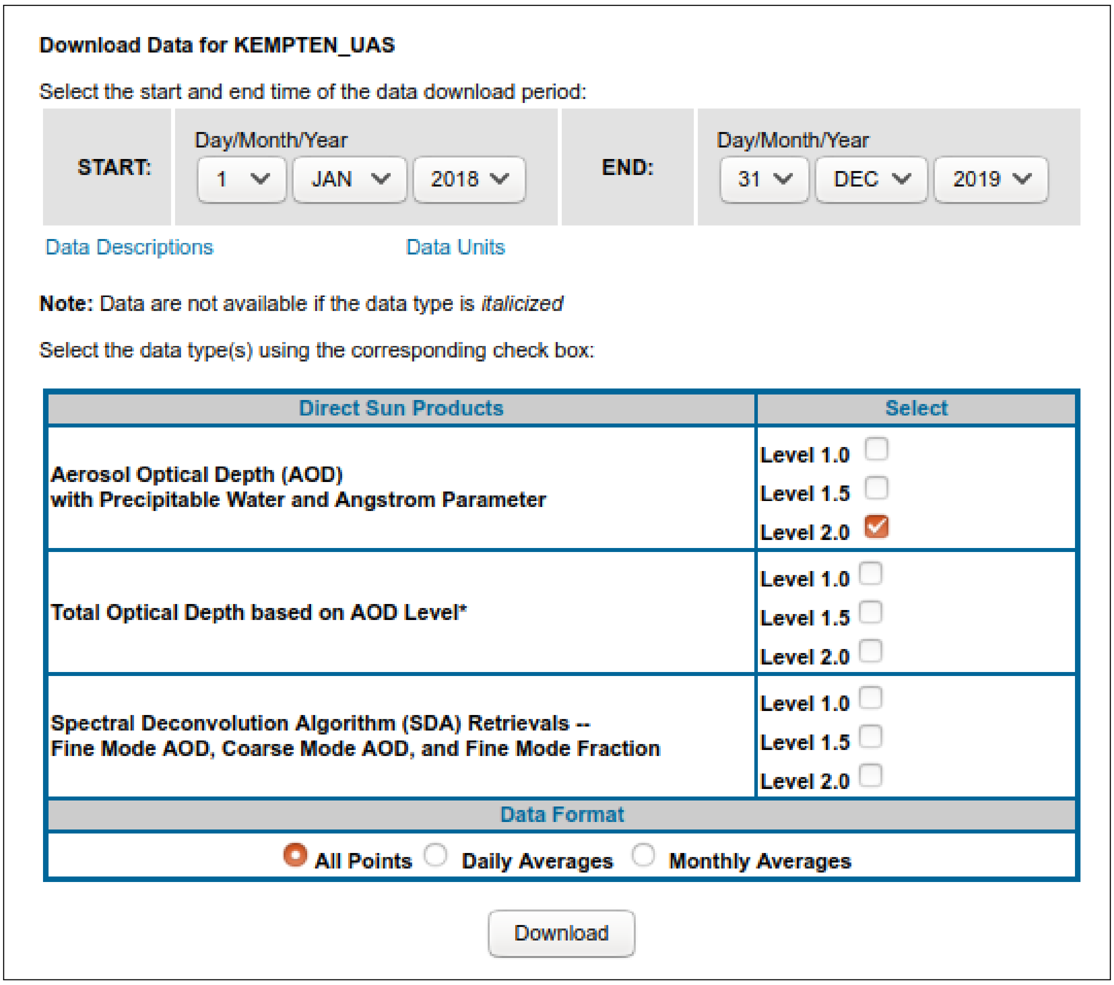

Figure 3: Download page for the AERONET direct sun algorithm, i.e. AOD and Angstrom Parameter

Table 1: Parameters from COSMO model required for radiative transfer simulation, temperature modelling and validation.

Parameter	Description
`pres_generalVerticalLayer`	Pressure at each atmospheric layer
`t_generalVerticalLayer`	Temperature at each atmospheric layer
`q`	Specific humidty at each atmospheric layer
`sp`	Surface pressure
`2t`	Temperature at 2m above the surface
`2r`	Relative humidity at 2m above the surface
`HHL`	Geometric height
`10u`	Zonal (eastward) windspeed at 10m above the surface
`10v`	Meridional (northward) windspeed at 10m above the surface
`SWDIR_S`	Direct component of shortwave downwelling irradiance
`SWDIFD_S`	Diffuse component of shortwave downwelling irradiance
`clwmr`	Cloud mixing ratio

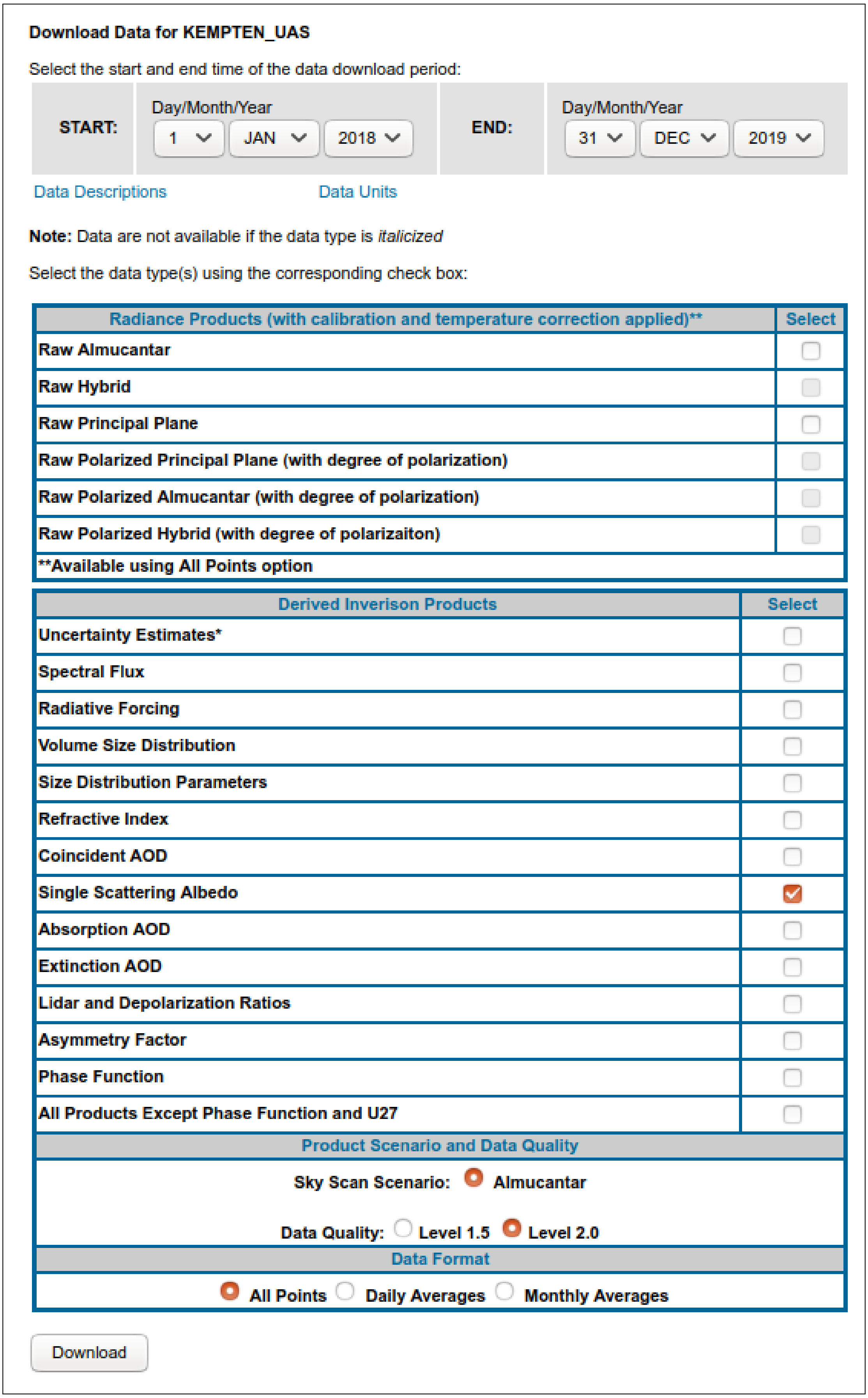

Figure 4: Download page for the AERONET inversion algorithm, i.e. SSA

2. Combine layer and surface properties (temperature, pressure, humidity) into a 4D grid
3. Find grid point nearest to the PV stations' coordinates
4. Load libRadtran standard atmosphere file
5. Convert COSMO layers to the correct format for libRadtran: interpolate in space and time
6. Save atmosphere files for each station and time to file

2.4 Import temperature and wind data from COSMO – `cosmopvcal`

In cases where there is no PV module temperature measurement, both ambient temperature and windspeed data are needed in order to model the module temperature. The `cosmopvcal` software module import these data (2m temperature and 10m windspeed) and converts them into appropriate file to use for temperature modelling. In addition the irradiance data are extracted and saved for validation later on.

1. Load surface and irradiance data from COSMO NetCDF files
2. Find grid point nearest to the PV stations' coordinates
3. Interpolate profiles in time and calculate windspeed from components
4. Save surface files with temperature and windspeed
5. Save irradiance files with direct and diffuse components

2.5 PV model calibration with `PVCAL`

The program `pvcal` performs the intial angle calibration in order to determine the orientation and inclination angles of the PV plant. The program is divided into various subroutines:

1. `pvcal_radsim_disort_parallel`
   a) Read in config file
      i. `data_configfile` - configuration for data import and plotting if required
      ii. `rt_configfile` - configuration for libRadtran simulation
      iii. `pvcal_configfile` - configuration for PV model and inversion
   b) Import data, either from binary files or from CSV
   c) Resample data to 15 minutes for libRadtran simulation
   d) Select clear sky days from the data
   e) Calculate sun position with `PyEphem`
   f) Run `cosmomystic` to generate atmosphere files
   g) Run `aeronetmystic` to import aerosol data and perform log-linear fit

   h) Set constant albedo (in future include MODIS)

   i) Run libRadtran simulation, save downward direct irradiances $G_{\rm dir}^{\downarrow}$ and diffuse radiance fields $L_{\rm diff}^{\Omega}$ to file (both using pickle as a binary stream and as a CSV file using pandas)

2. `pvcal_forward_model` contains all functions necessary to calculate the PV power and perform calibration, including:

   a) Simple power model with temperature models

   b) Plane-of-array irradiance calculation using DISORT simulation

   c) Numerical differentiation of irradiance with respect to different parameters

   d) Optical model and derivatives with respect to refractive index n

3. `pvcal_inversion`

   a) Load results of radiative transfer simulation, including resampled data

   b) Load surface data from `cosmopvcal`

   c) Load water vapour content from COSMO files

   d) Load original dataframes, choose clear sky periods

   e) Choose time resolution for inversion, if necessary interpolate libRadtran results

   f) Calculate diffuse component in the plane-of-array by explicit integration of $L_{\rm diff}^{\Omega}$

   g) Calculate modelled power and derivatives of forward model (defined in `pvcal_forward_model`)

   h) Perform calibration in order to extract θ and ϕ with uncertainties (functions defined in `inversion_functions`

   i) Generate plots showing results of the calibration inversion routine

The config files contains the following information:

1. PV stations with coordinates

2. File path for PV power data

3. Dates of clear sky days

4. Source of aerosol information

5. Source of atmosphere files

6. Angular resolution for diffuse radiance simulation

7. Albedo

3 Inversion onto irradiance and atmospheric optical properties

Once the PV systems have been calibrated the model can be inverted in order to extract irradiance and optical properties. The first step is to use PV power measurements under all-sky conditions to extract plane-of-array irradiance, the so-called "global tilted irradiance" (GTI). This is then used to estimate the cloud fraction, which is used in the next step to find the global horizontal irradiance (GHI) via a MYSTIC-based lookup table.

3.1 Plane-of-array irradiance with `pv2poarad`

In this software module the broadband GTI is extracted from the PV power measurements with the following steps:

1. Load radiative transfer simulation data for both PV wavelengths (300-1200nm) and pyranometers (broadband)
2. Create linear fit for spectral mismatch as a function of COSMO water vapour
3. Load calibration results with optimal fit parameters, perform error propagation
4. Load power, temperature and wind data and interpolate / downsample to the correct resolution
5. Invert PV power model including spectral mismatch factor to find the GTI for all available data points
6. Calculate clearness index and cloud fraction using clear sky simulation

3.2 Optical depth lookup tables using libRadtran with DISORT

In order to find both the aerosol optical depth (AOD) and cloud optical depth (COD), libRadtran with the DISORT solver is used to create lookup tables for each PV station. In the scripts `pv2cod_radsim_disort` and `pv2aod_radsim_disort`, the AOD and COD are varied in order to create lookup tables between optical depth and irradiance, taking into account the local atmospheric conditions from the COSMO atmosphere files.

The modules `pv2cod_radsim_disort` and `pv2aod_radsim_disort` have the following structure:

1. Load station metadata as well as GTI inversion time series
2. Load configuration for cloud or aerosol from config files
3. Perform DISORT simulation by running libRadtran in parallel
4. Save simulation (direct irradiance and diffuse radiance distribution) to binary stream files using pickle

The scripts `pvpyr2cod2rad_interpolate_fit` and `pvpyr2aod2rad_interpolate_fit` then perform the interpolation:

Table 2: Limits on the input parameters for the MYSTIC LUT.

Input parameter	Limits
SZA (θ_0)	[20°, 60°]
Tilt angle (θ)	[0°, 50°]
Relative azimuth ($\|\phi - \phi_0\|$)	[0°, 90°]
Cloud fraction	[0.13, 0.82]

1. Load optical depth lookup table results along with GTI inversion time series (or pyranometer data)
2. Calculate tilted irradiance-optical depth LUT using direct and diffuse components from simulation
3. Interpolate the LUT in time to match the inverted GTI time series
4. Use the LUT to extract either COD or AOD from GTI (in the case of COD, only for points with cloud fraction equal to one, under a cloud)
5. Save results to file

3.3 MYSTIC lookup table for the GHI

As described in the paper, the MYSTIC lookup table receives system geometry and sun position, along with cloud fraction, and can then translate the tilted irradiance to horizontal irradiance, subjec to the limits shown in 2.

The script `gti2ghi_lookup` uses the LUT saved in the NetCDF file "gti2ghi_lut_v1.nc" in order to extract GHI from inverted GTI or GTI from pyranometer measurements.

The script `pvpyr2ghi_lut` performs the following functions:

1. Load both inverted GTI as well as tilted and horizontal pyranometer measurements
2. Call the script `gti2ghi_lookup`, which uses the LUT saved in the NetCDF file "gti2ghi_lut_v1.nc" in order to extract GHI from inverted GTI or GTI from pyranometer measurements
3. Save results to file and create scatter plots

4 Analysis and statistics

References

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