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Solshade: Terrain-aware Solar Illumination Modelling using Digital Elevation Models and Orbital Geometry

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Software

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Introduction

Solshade is a Python library for modeling solar illumination over complex terrain using *Digital Elevation Models (DEMs)* and precise *orbital geometry*. It bridges geospatial analysis and astronomical modeling, enabling researchers to precisely quantify how sunlight interacts with landscapes over time. Applications include studying permafrost thaw, plant life cycles, snowmelt dynamics, and other solar-driven processes in diverse environments.

Solshade provides both a *command-line interface (CLI)* and a *Python API*. Outputs are written as *GeoTIFFs* for geospatial compatibility, and built-in visualisation tools allow rapid inspection of terrain attributes and solar flux maps.

Statement of Need

Understanding the spatial and temporal variability of solar illumination over terrain is essential for environmental science, ecology, hydrology, and energy modeling. Widely used GIS tools such as *GRASS GIS* and *SAGA GIS* provide terrain analysis and solar radiation estimates, but their focus remains primarily on geospatial processing. These packages often assume simplified astronomical inputs or fixed time intervals, offering limited control over orbital precision or temporal resolution.

Similarly, solar energy modeling tools like *pvlib* or *Solar Analyst* (ArcGIS) provide detailed solar irradiance calculations but lack functionality for high-resolution terrain shading analysis or integration with custom topographic datasets.

Solshade bridges these critical gap by combining:

1. *High-precision solar orbit modeling* using NASA ephemerides via *Skyfield*,
2. *Terrain-aware ray-traced shading* over arbitrary DEMs,
3. *Flexible Python API and CLI workflows* for reproducible analysis.

This integration enables studies requiring both astronomical accuracy and geospatial flexibility, supporting applications from permafrost melt modeling to ecological microhabitat analysis.

Software Design and Theory

Solshade computes solar flux using four main components: terrain modeling, horizon mapping, orbital modeling, and flux computation.

Terrain Modelling

DEMs encode elevation values on a geographic grid. From this data, Solshade computes terrain slope, aspect, and surface normals using Numpy (Harris et al., 2020). These normals form the basis for Lambertian solar flux calculations.

Horizon Mapping

Shadows depend on local topography. For each pixel, Solshade samples discrete azimuthal rays, tracing elevations outward from the pixel center. The peak elevations along each ray define the local horizon profile, enabling shadow masking at arbitrary solar positions.

Solar Orbital Modelling

Using high-precision ephemerides from NASA's Jet Propulsion Laboratory (Park et al., 2021) via Skyfield (Rhodes, 2019), Solshade computes solar position vectors at user-defined times and locations on Earth. This provides accurate solar geometry for any observing period.

Solar Flux Time Series

For each time step, Solshade computes the dot product between terrain normals and solar position vectors, masking periods when the Sun is below the horizon. The result is a per-pixel time series of incident solar radiation, accounting for both terrain slope and topographic shading.

Demonstration

To illustrate *Solshade*'s capabilities, we analyse a Digital Elevation Model (DEM) of an Arctic landscape and compute solar illumination metrics over an entire year. Figure 1 shows three geospatial layers produced by Solshade: (i) the input DEM, (ii) the total accumulated solar energy, and (iii) the day of peak solar energy for each pixel.

The bottom panels show solar irradiance time series for eight selected locations, chosen to span the full range of total energy values. These light-curve panels highlight how topography strongly modulates solar exposure: valley pixels receive sunlight for only brief intervals, while ridgeline pixels remain illuminated nearly all day. The analysis demonstrates how *Solshade* integrates terrain geometry and solar orbital modeling to produce both spatial and temporal diagnostics of solar radiation.

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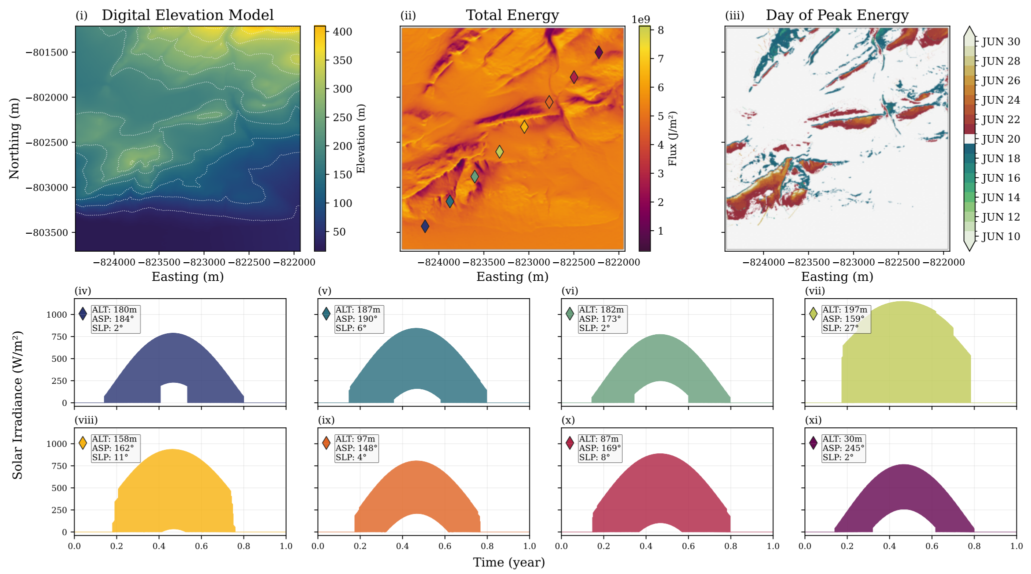

Figure 1: Top row: (i) Digital Elevation Model, (ii) Total solar energy over the study period, and (iii) Day of peak solar energy. Bottom panels: Solar irradiance time series for eight selected locations, illustrating differences in diurnal illumination across terrain features, with legends describing the altitude (ALT), aspect (ASP) and slope (SLP) of the sampled pixel.

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