

Implementation of Lenticular Diffusing Panels Using Backward Ray Tracing : Simulating Even-Lighting in PASE

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Introduction

Spatial and temporal light distribution plays a critical role in optimizing photosynthetic efficiency in agrivoltaic systems. Abrupt transitions between light and shade can hinder photosynthesis ([1], [2], [3], reducing crop yields and affecting the overall system's efficiency. The use of diffusers to distribute light uniformly in even-lighting systems has shown promise [4] but requires extensive physical experimentation to evaluate their effects in diverse conditions. This study proposes a simulation-based approach within the Python Agrivoltaic Simulation Environment (PASE).

Lenticular diffusers

Plastic sheets with axial lenses are currently being tested in even-lighting experiments and serve as model for these simulations. The scattering pattern was determined empirically. Light is scattered in a conic pattern (Figure 1). The trace pattern of a scattered light beam on the ground depends on its direction: it is a conic section, either degenerate or not (Figure 2).

γ is the angle between the lens axis and the sun direction vector.

β is the angle between the diffuser plane and the planed defined by the lens vector and sun vector.

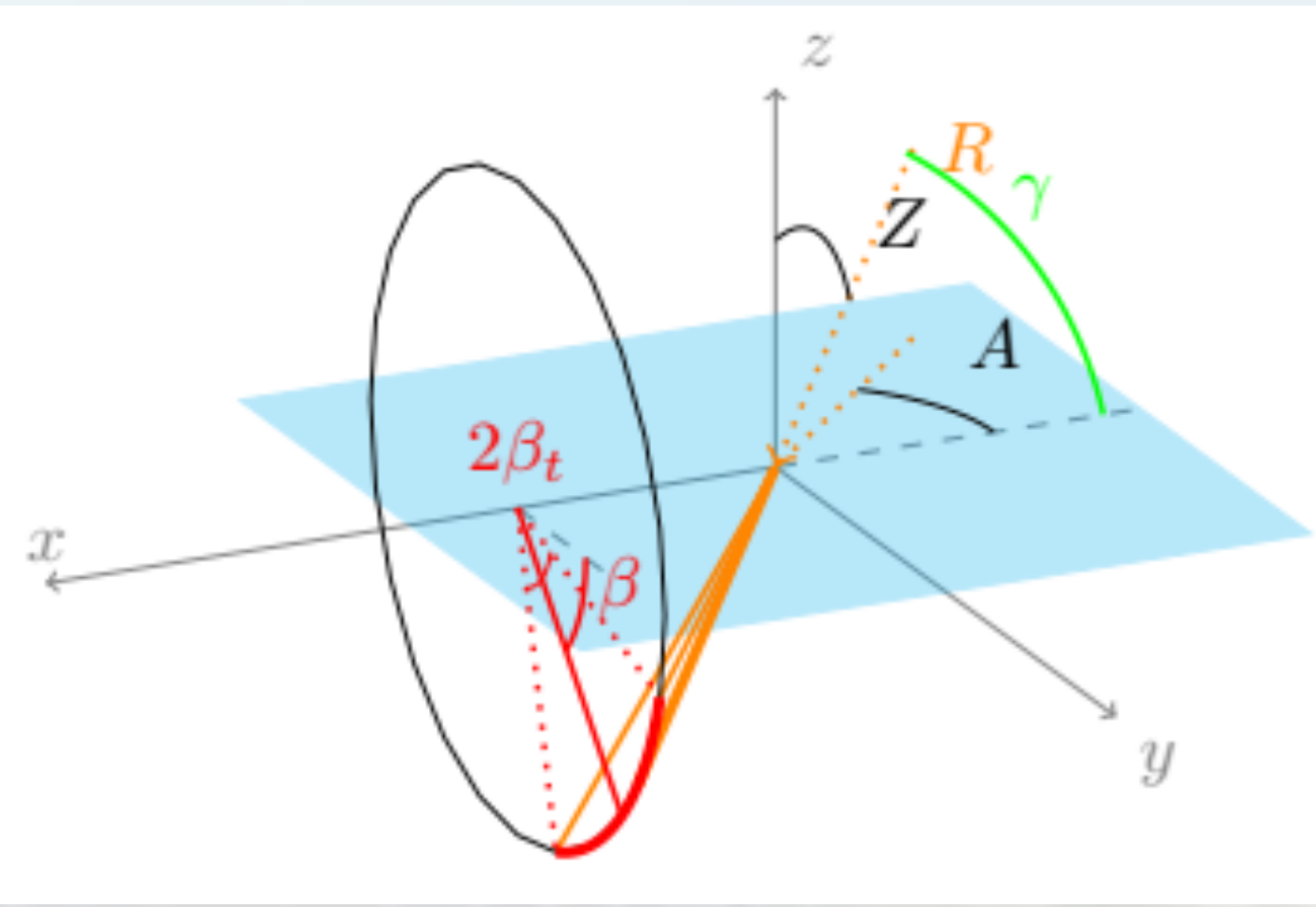


Figure 1 - Definitions of quantities.
R: direction of the Sun ; A: Sun azimuth ;
Z: Sun zenithal angle ; γ : angle of a cone;
 β : orientation of the scattered sector;
 β_t : opening angle of the scattered sector

Transfer function

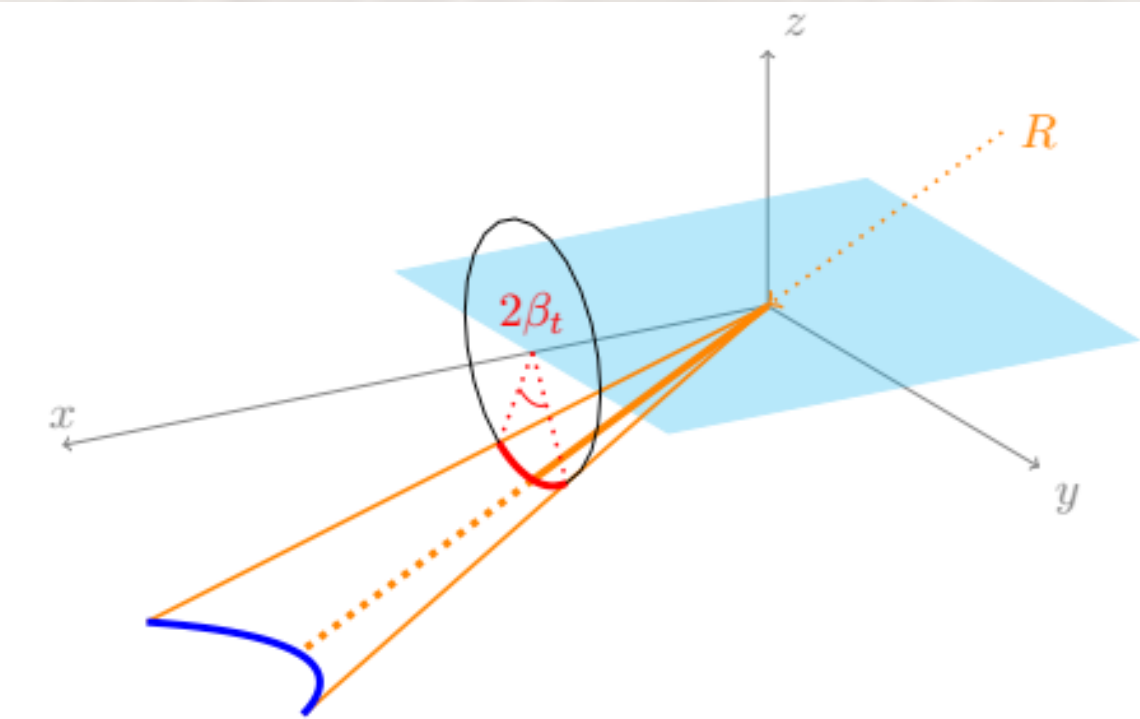
$$\cos \gamma = \frac{\vec{R} \cdot \vec{x}}{|\vec{R}| |\vec{x}|}$$

$$\cos \beta = \frac{(\vec{R} \times \vec{x}) \cdot \vec{z}}{|\vec{R} \times \vec{x}| |\vec{z}|}$$

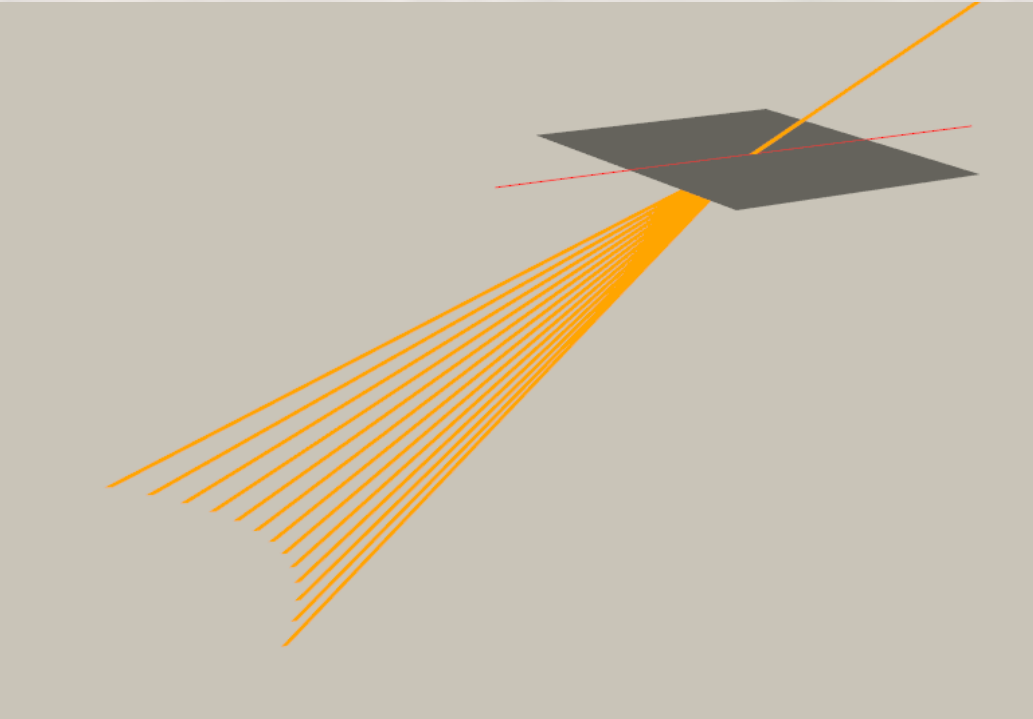
$$\beta_{\text{eff}} = [\beta - \beta_t ; \beta + \beta_t]$$

Directions of scattered rays:

$$\begin{cases} x = \cos \gamma \\ y = \sin \gamma \cos \beta_{\text{eff}} \\ z = \sin \gamma \sin \beta_{\text{eff}} \end{cases}$$



(a)



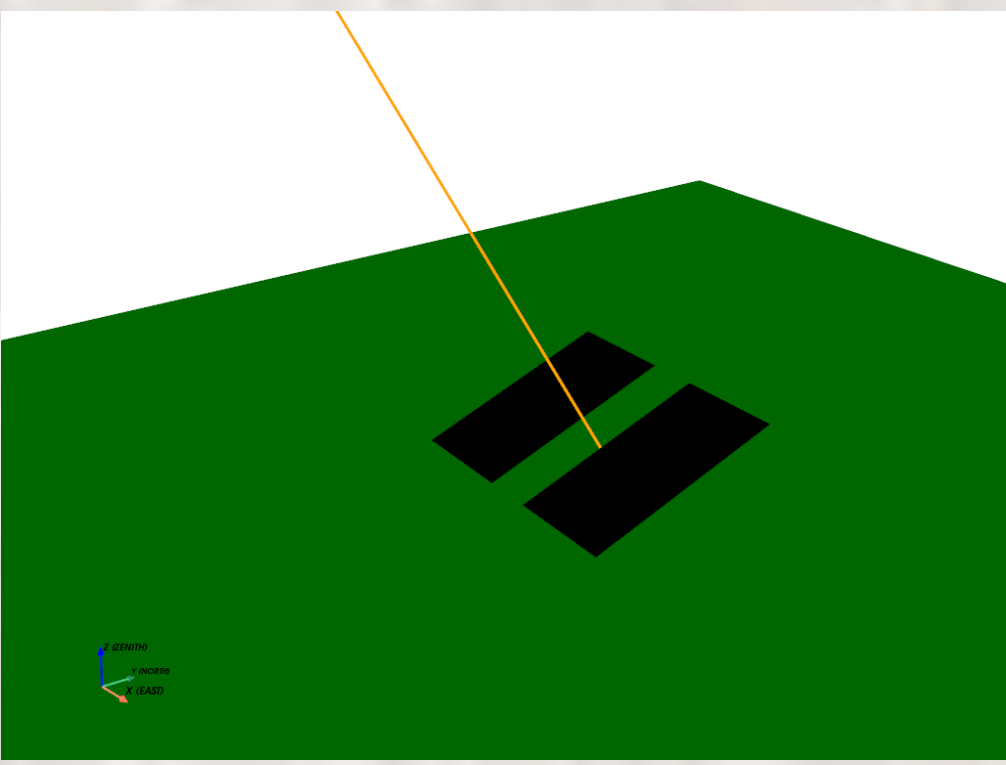
(b)

Figure 2 - Conic pattern of light scattering. (a) As theorized based on empirical observations, the trace on the ground (blue) is a conic section arc. (b) Simulation of the scattering pattern in PASE.

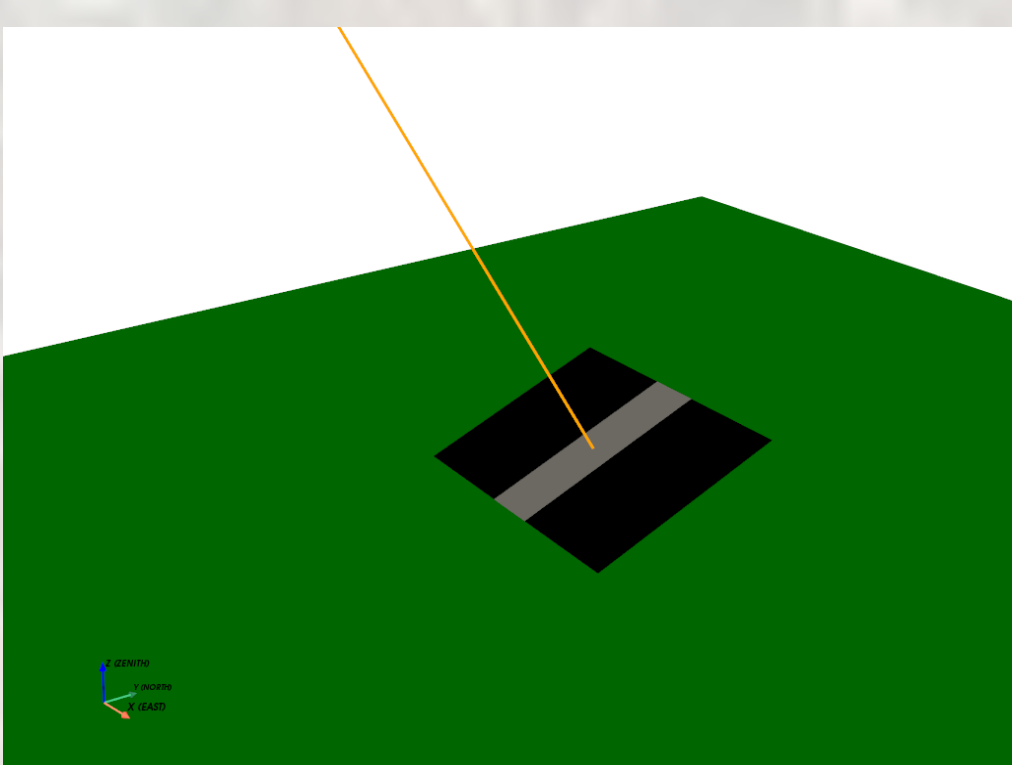
Simulation setup

The simulation setup was designed with 2 solar modules separated by a 0.6 m gap. In the standard agrivoltaics (APV) configuration, the gap is empty and in the even-lighting (EL) configuration the gap is replaced by a lenticular diffusing sheet. The system is south facing with an elevation angle of 20°, and the center of the modules is at a 1.2 m height.

The lenticular diffusing sheet is parametrized with a half opening angle of 60° and the numerical angular resolution of the diffusion is 0.25°.



(a)



(b)

Figure 3 - Domain geometry. The orange line shows the direction of the Sun. (a) Standard agrivoltaics (APV) with a 0.6 m gap between solar modules. (b) Even-lighting configuration with a lenticular diffusing sheet between two solar modules.

PASE Gitlab repository : <https://gitlab.uliege.be/deal-public/pase>

Spatial spread

From a spatial perspective, the interest of diffusing light under an agrivoltaics system is to spread light, preferably in the direction of shaded areas i.e. under the solar modules. This is illustrated in Figure 4.
The graph shows irradiance profiles in two different scenarios shown in Figure 3. Those irradiance profiles differ in nature as the diffused irradiance replaces the direct irradiance in the area directly beneath the solar modules.

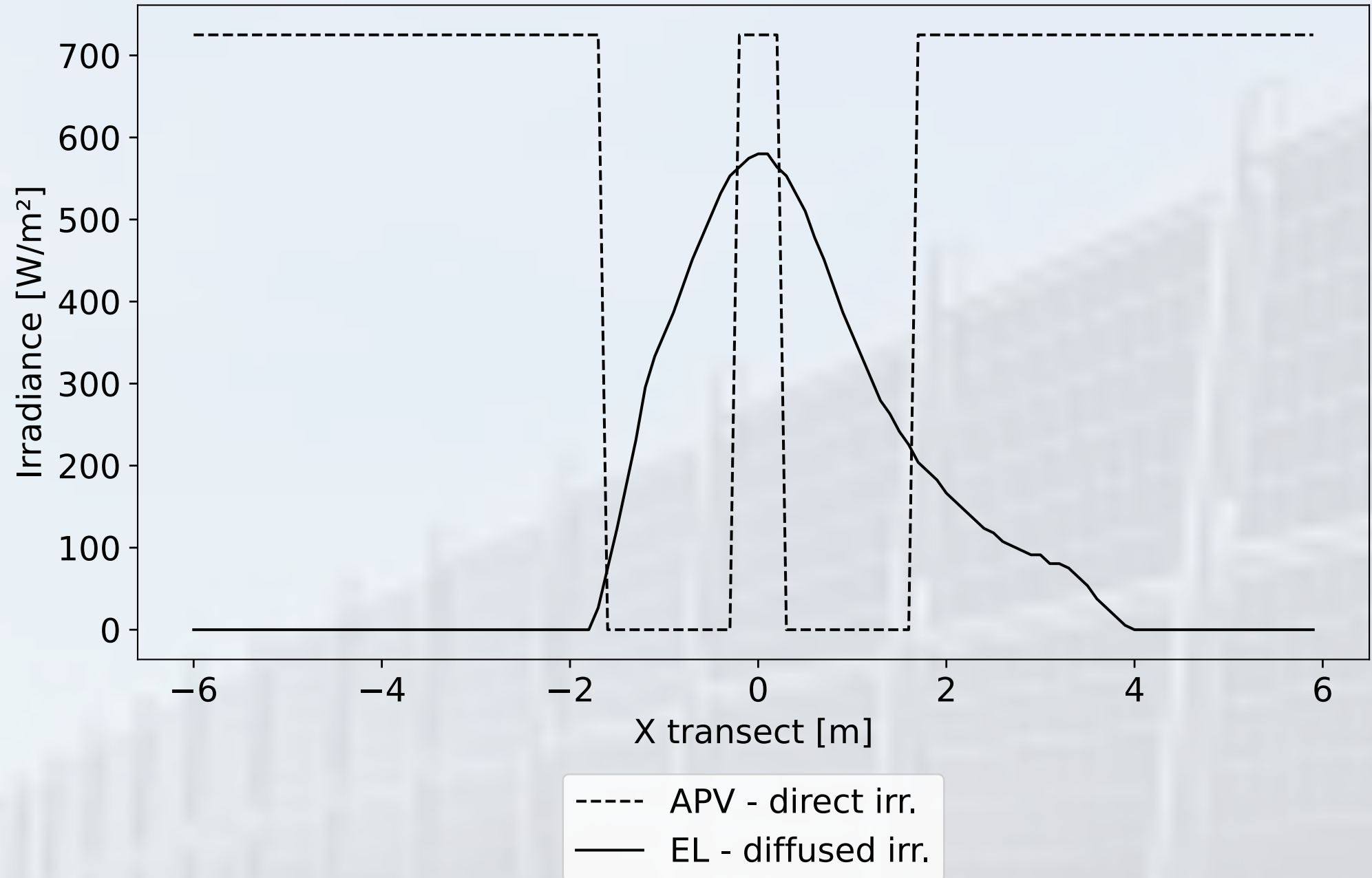


Figure 4 - East-west transect of the simulation domain at ground level with Sun full south.

Temporal spread

From a temporal perspective, crops' photosynthetic efficiency suffers from abrupt shade to sun and sun to shade transitions. When facing these transitions, the photosynthesis dynamic must adapt to changing conditions, which means that some of the energy harvested by crops is wasted [1, 2, 3].

The purpose of scattering light under an agrivoltaics system is to provide crops with a smoother irradiance profile and thus improve their photosynthetic efficiency. This is illustrated in Figure 6.

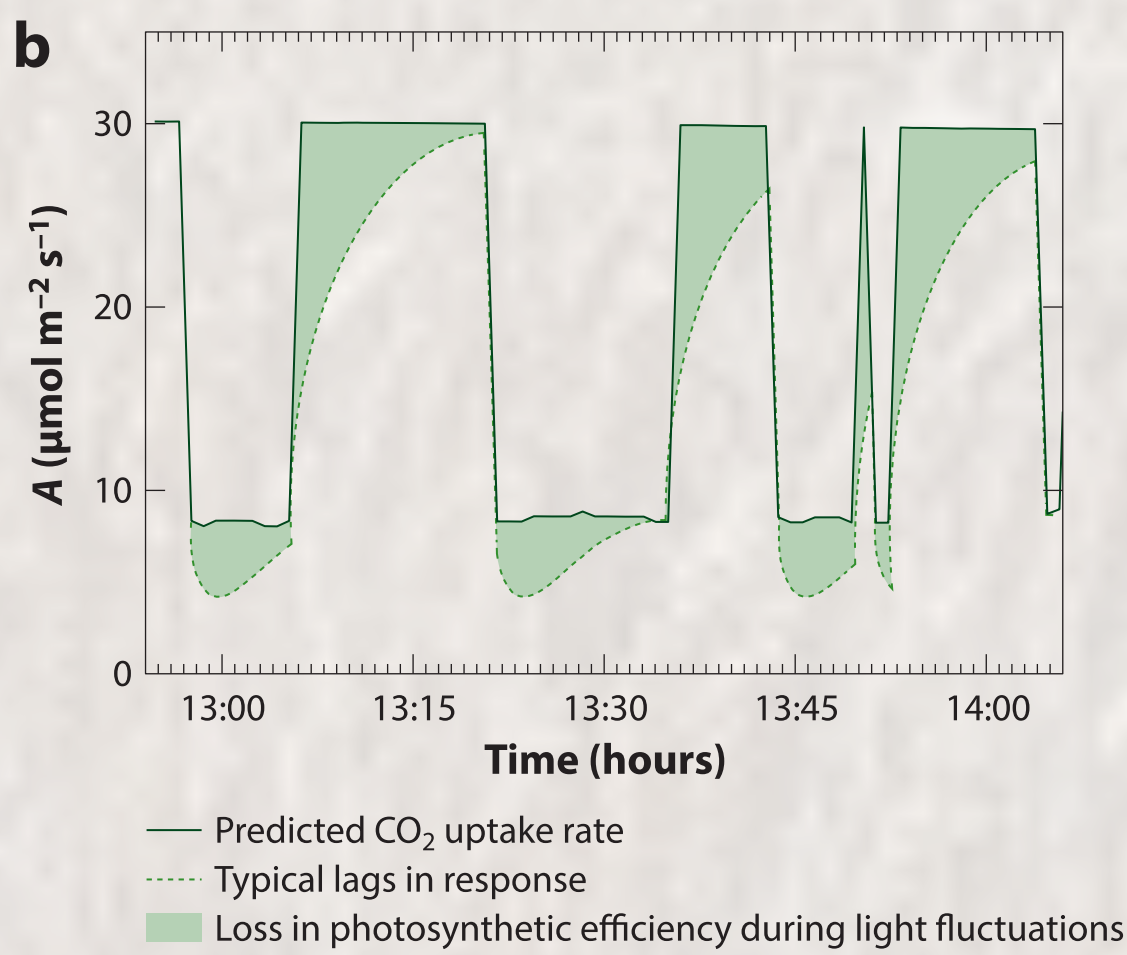


Figure 5 - Loss of photosynthetic efficiency due to light fluctuations [5].

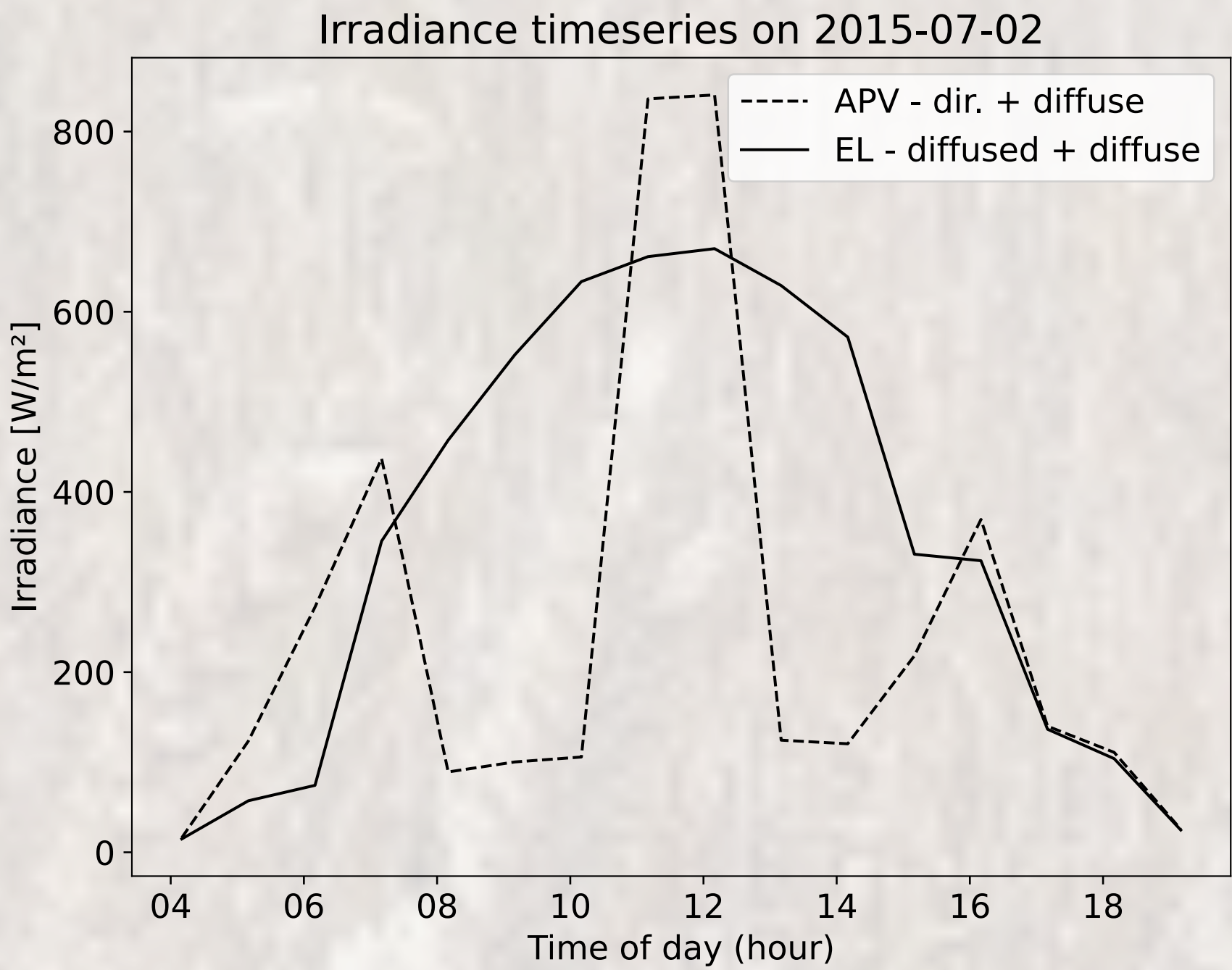


Figure 6 - Hourly time series of irradiance profiles under APV and EL systems (see Figure 3), beneath the diffuser at ground level. The APV irradiance profile presents abrupt transitions from shade to sun and sun to shade, and higher irradiance when receiving sunlight. Conversely, the EL profile is overall smoother, with no abrupt transitions.

Perspectives

Repeating the alternating pattern of PV and diffusing panels would provide a spatially and temporally smoother irradiance profile, compared to PV modules with a gap between them. Although some numerical inconsistencies seem to affect computations, the simulations provide first plausible results of a physically based simulation of diffusing panels in agrivoltaics. We expect to improve the implementation of the scattering transfer function in a future release of PASE.

References

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