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Novel sky discretization method for optical annual assessment of solar tower plants

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ABSTRACT

Optical assessment of Central Receiver Solar Tower systems should be based on annual simulations due to the high variability of solar radiation throughout the year. The most basic approach is using a discretization of the temporal domain which requires a large number of computationally costly optical simulations. This study proposes an alternative approach based on a discretization of the sky which reduces the required number of simulations and therefore the computational effort significantly. For the subsequent annual performance assessment data three different interpolation methods are presented, compared and their respective advantages and drawbacks are discussed. The methodology is demonstrated by means of three representative heliostat field setups: the PS10 field, the Gemasolar field and a small, generic field. In this context, the dependency of the interpolation accuracy with respect to the resolution of the sky grid is investigated. For this purpose, annual optical efficiency weighted with *direct normal irradiation* is used as an integral figure of merit, while the *Root-mean-square deviation* is calculated as a benchmark value for single time step assessment. Eventually, it is shown that the proposed method decreases the required time for the annual optical assessment by several orders of magnitude while maintaining the original accuracy.

1. Introduction

Solar energy technologies and especially *concentrated solar power* (CSP) systems depend highly on locally available *direct normal irradiation* (DNI). Due to the strong diurnal and seasonal fluctuation of irradiation and optical efficiency, system performance must be studied with annual simulations. For this purpose, time-variant (e.g. hourly) DNI data has to be taken into account. Amongst others, *ray tracing* as an optical simulation technique is commonly applied for the assessment of optical system efficiency. It allows for the accurate representation of very complex optical setups, but implies comparatively heavy demands in terms of computational power. More detailed information about *ray tracing* in general can be found in Pharr and Humphreys (2004) and Glassner (2002). Ho (2008) and Dilip and Venkatraj (2013) treat *ray tracing* in a CSP context.

The most basic approach for optical annual assessment is the temporal discretization of a year (e.g. hourly) and an assessment of the system performance at these time steps. However, this implies a large number of computationally costly simulations. Furthermore, many of these simulations are performed for similar sun positions and therefore yield similar results, for example the same hour on two subsequent days. This illustrates the optimization potential for more suitable discretization solutions.

The sun position dependency of collector efficiency relates to the degrees of freedom of receiver movement (tracking). If tracked ideally, *Parabolic Dish collector* efficiency is independent of the solar vector, for *Parabolic Trough collectors* the longitudinal sun position (along the collector axis) has to be taken into account and *Linear Fresnel* collector efficiency depends on longitudinal and transversal sun position. For the latter, a factorization of the optical efficiency in a longitudinal and transversal component (in the collector coordinate system) is possible and reduces the computational effort significantly (Heimsath et al., 2014). This technique cannot be applied for *Central Receiver Solar Tower systems* (CRS), as in CRS all heliostats are independently tracked in two axes.

In this paper, a method is presented that is based on a spatial discretization of the sky hemisphere. It avoids the time-consuming temporal discretization and can be applied to two-axis tracking systems like CRS. Therefore, it allows for the quick, yet accurate determination of time-variant optical CRS efficiency. This is necessary for the assessment of annual CRS performance.

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Nomenclature

$\Delta\eta_{\text{an}}$	difference between reference and interpolated annual efficiency
η	optical efficiency of the heliostat field
$\eta_{\text{an,interp}}$	interpolated annual efficiency
$\eta_{\text{an,ref}}$	reference annual efficiency
$\eta_{\text{lin}}(\mathbf{p})$	optical efficiency at $\mathbf{p}$ obtained with linear interpolation
$\eta_{\text{RBFN}}(\mathbf{p})$	optical efficiency at $\mathbf{p}$ obtained with RBFN interpolation
η_i	optical efficiency at sky node i
η_t	optical efficiency at time step t
$\eta_{\text{nn}}(\mathbf{p})$	optical efficiency at $\mathbf{p}$ obtained with nearest neighbor interpolation
$\eta_{t,\text{interp}}$	interpolated optical efficiency at time step t
$\eta_{t,\text{ref}}$	reference optical efficiency at time step t
γ_s	solar azimuth angle
ρ_{ray}	ray density = number of rays per unit area perpendicular to the solar vector
σ	Gaussian spread of the radial basis function
DNI_t	DNI at time step t
$\text{DNI}_{i,\text{cum}}$	cumulated DNI at sky node i
row_i	i-th row of sky discretization
row_n	last row of sky discretization
θ_z	solar zenith angle
$\underline{G}$	RBFN coefficient matrix
$\mathbf{c}$	Gaussian kernel center vector
$\mathbf{p}$	point on hemisphere surface
A	spherical triangle area
A_1	area of spherical sub-triangle $\mathbf{p}\mathbf{p}_2\mathbf{p}_3$
A_p	sky patch area
A_s	area of full spherical triangle $\mathbf{p}_1\mathbf{p}_2\mathbf{p}_3$
A_t	accumulated area of all patches
A_{HSF}	heliostat field gross mirror area
a_{ij}	great-circle distance between points $\mathbf{p}_i$ and $\mathbf{p}_j$
C_i	circumference of row $i$of sky discretization
$h(\mathbf{p},\mathbf{c})$	Gaussian kernel function
I_i	intensity of ray i absorbed on the receiver surface
l_p	side length of sky patch
N	number of rays incident on the receiver surface
n	number of daylight hours where zenith angle $\theta_z < 90°$, number of hourly simulations
n_{rows}	number of rows in sky discretization
$O(x)$	complexity of order x
s	spherical triangle semi-perimeter
$w_{i,\text{lin}}$	spherical barycentric coordinate for linear interpolation
$w_{i,\text{RBF}}$	RBF weight
Z	selected node count of sky discretization
Z_{full}	total node count of sky discretization
Z_i	node count in row i of sky discretization
$Z_{\text{last row}}$	node count in the last row of sky discretization
AF	acceleration factor for annual assessment
CRS	Central Receiver Solar Tower system
CSP	concentrated solar power
DNI	direct normal irradiation
RBF	radial basis function
RBFN	radial basis function network
RMSD	root-mean-square deviation of hourly efficiency

1.1. Related work

Another approach to tackle the high computational cost of a pure temporal discretization is presented by Noone et al. (2012). Instead of simulating at discrete and equidistant time steps, the presented approach iterates in the "solar state space" (Noone et al., 2012, p. 793). By using a constant step size in terms of the solar angles, many sun positions are taken into account in zones where the solar azimuth angle rapidly changes. The authors claim that using this method decreases the number of required iterations roughly by a factor of two compared to a temporal discretization, while maintaining the accuracy. Whereas the latter is equally a claim of the method presented in the current study, the number of required simulations will be reduced by a much higher factor.

A related method for the discretization of the annual DNI is presented by Binotti et al. (2014). Solar elevation and azimuth angles are discretized using an equidistant grid. Consequently, annual DNI is accumulated in the respective grid cells. Even if the described discretization has a different objective than the one investigated here, the aim of Binotti et al. (2014) and the current study complement one another to a certain degree. Thus, in Section 2.6 a potential combination of both is proposed.

In the domain of daylight simulations the *Tregenza sky discretization* is a common means to subdivide the sky hemisphere for luminance measurements (Tregenza and Waters, 1983; Tregenza, 1987). The purpose of this method is different, but it likewise addresses the challenge of obtaining a grid with roughly homogeneous cells (see Section 2.2). This method however implies two characteristics which are detrimental for the objectives of this study: the cell centers don't fully cover the hemisphere and the node density of the grid cannot be arbitrarily fine-tuned. The approach of the hereinafter proposed model to overcome the drawbacks of the *Tregenza sky discretization* will be presented in Section 2.2.

1.2. Structure of this study

The structure of the study is as follows: In Section 2, the scheme of the novel sky discretization is described (Section 2.2). Furthermore, it is explained how a selection of relevant nodes can be created (Section 2.3). In addition, it is clarified how optical simulations on those sky nodes can be performed (Section 2.4) and how results for intermediate sun positions can be derived by application of different interpolation methods (Section 2.5). In Section 3 a comparison between the sky discretization method and hourly simulations is presented. For this purpose, figures of merit are defined (Section 3.1), their confidence interval from the underlying ray tracing simulations is determined (Section 3.3) and three comparison setups are specified (Section 3.2). Eventually, the influence of the sky grid density for different interpolation techniques and both comparison setups is investigated and the required density is derived (Section 3.4). In Section 4, methodology and results are summarized and finally an outlook for further improvements is given.

2. Methodology

To overcome the drawbacks of the aforementioned approaches for optical annual simulations, a spatial discretization of the *sky hemisphere* based on sky nodes is proposed. *Sky hemisphere* in this context means one half of a unit sphere located on top of a plane tangent to the earth surface. The sun angles θ_z and γ_s can be described with a spherical coordinate system in this hemisphere. As the annual path of the sun only partially covers the hemisphere