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Incidence angle effects on circular Gaussian flux density distributions for heliostat imaging

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Abstract

Circular Gaussian distribution methods are used in certain applications to determine the flux distribution of central receiver systems. Although the method is computationally inexpensive, some assumptions bring the accuracy of the results into question. This paper addresses the confines in which acceptable accuracies are maintained. Flux distributions of an implemented HFLCAL-type model and a ray tracer are compared, and deviations of up to 20% are found in cases where both high incidence angles and high normal vector errors are present. The deviations result from the circular Gaussian distribution method not accounting for the shortening of the minor axis of the elliptical image. A modification is proposed that incorporates the effect of the incidence angle into the beam quality and tracking error terms. The modification corrects for the deviation, has negligible computational expense and is shown to be robust. In a case study of a commercial central receiver system, accuracy of the flux distribution was improved by up to 16%.

Keywords: Central receiver system; Heliostat; Optics; Flux distribution

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1. Introduction

Flux distribution (FD) models of varying accuracy and efficiency are used in the design, optimisation and operation of central receiver systems (CRS). The accuracy of an FD model improves as more variables are taken into account, but as the model complexities increase the model becomes more computationally expensive. Computationally efficient models make assumptions which simplify the computation of the FD. Although these assumptions attempt to represent realistic scenarios, they introduce uncertainty. Several analytical models, such as UNIZAR (Collado et al., 1986) and HFLCAL (Schwarzbözl et al., 2009), rely on the assumption that the FD from a heliostat is normally distributed and that beam dispersion errors are statistically independent (Guo and Wang, 2011). Full use of these models can be made by pushing the boundaries of their applications, but the confines of acceptable accuracies must be quantitatively known beforehand.

Numerous models that determine the FD are reviewed by Garcia et al. (2008). Convolution methods (also known as cone optics) use the convolutions of Gaussian distributions corresponding to various error sources to calculate an error cone. In reality the FD over a planar image will be closer to an elliptical Gaussian distribution (Guo and Wang, 2011; Rabl, 1985), although the image is commonly modelled as a circular Gaussian distribution (CGD) to further reduce the computational expense (Garcia et al., 2008).

Typical applications for convolution methods are field layout optimisations and plant performance estimations.

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Nomenclature

ϕ	incidence angle (deg)
ϕ_{rec}	receiver incidence angle (deg)
ρ	reflectivity (%)
σ_{ast}	astigmatic aberration (mrad)
σ_{bq}	beam quality (mrad)
σ_{CG}	radial standard deviation of circular Gaussian image (mrad)
σ_{RT}	radial standard deviation of ray traced image (mrad)
σ_{SSE}	radial surface slope errors (mrad)
σ_{sun}	sunshape (mrad)
$\sigma_{\mathrm{t\_pri}}$	tracking error of the primary axis (mrad)
$\sigma_{\mathrm{t\_sec}}$	tracking error of the secondary axis (mrad)
σ_{tot}	total standard deviation (mrad)
σ_{t}	tracking error (mrad)
A_{m}	heliostat reflective area (m^2)
D	heliostat diagonal length or diameter (m)
d	slant range (m)
f	focal length (m)
f_{at}	attenuation factor (%)
F_{r}	focal ratio, d/D (–)
h_{tan}	1-sigma-radius of the tangential astigmatism of the beam; position is at the target and in a direction normal to the axis of the incident radiation (m)
I_{D}	direct normal irradiance (W/m^2)
P_{h}	power from the heliostat (W)
R	multiple of tower height (–)
r	radius (m)
w_{sag}	1-sigma-radius of the sagittal astigmatism of the beam; position is at the target and in a direction normal to the axis of the incident radiation (m)
x	Cartesian coordinate (m)
y	Cartesian coordinate (m)
z	Cartesian coordinate (m)
CGD	circular Gaussian distribution
DNI	direct normal irradiance
FD	flux distribution
SSE	Surface Slope Error
TE	Tracking Error

As Garcia et al. point out, "the greatest errors observed on annual performance of a CRS do not come from the optical model but from the other component models (turbine, storage...)" (Garcia et al., 2008). For this reason the inaccuracy of convolution methods has not been much of a concern in the past. Recent applications, specifically looking at obtaining an instantaneous FD, require more from convolution models. These applications, such as aiming strategy optimisation, require higher accuracies and inexpensive computational times. One such model, a software tool for Heliostat Field Layout CALculations (HFLCAL), has been used in aiming strategy optimisation in various publications (SOLGATE Report, 2005; Besarati et al., 2014; Salomé et al., 2013) and was chosen as the representative convolution method for the purposes of this paper.

Some inaccuracies in the CGD method's prediction of the FD have been documented, but the reason for these inaccuracies apparently are not well understood (SOLGATE Report, 2005; Besarati et al., 2014; Salomé et al., 2013; Collado, 2010). Schwarzbözl et al. (2009) validate the method for collinear cases and suggest that the method is inappropriate for detailed FD analysis. This raises the question, whether its increasing use for the analysis of FD is in fact appropriate. It is essential to know the confines in which acceptable accuracies are maintained to ensure validity of the method's results. This study aimed to investigate the validity of the CGD method.

In this paper, an interpretation of the HFLCAL method was implemented, and the resulting FD was compared to that of a ray tracer with common input parameters. Substantial deviations were observed in cases where both high incidence angles and normal vector errors are present. This paper investigated the reasons for these deviations and found there to be a non-astigmatic aberration of the image, that result from surface normal vectors at increased incidence angles. The deviations were due to the CGD method not accounting for the shortening of the minor axis of the elliptical image with increasing incidence angles. An alteration to the computation of the beam quality term and tracking error term are proposed to correct for the deviations. The correction factor in the proposed modification has been used previously (Collado et al., 1986) but it does not appear in HFLCAL (SOLGATE Report, 2005; Besarati et al., 2014; Salomé et al., 2013; Collado, 2010), and to the authors' knowledge, an understanding of the implications of the term is not in the public domain. The meaning and sensitivities of the proposed alteration are provided in Sections 3 and 4.

2. Evaluation method

The interpretation of the CGD method used in this paper (HFLCAL) is described in detail in Appendix A. Readers unfamiliar with HFLCAL are encouraged to read Appendix A first to ease the understanding of the terms and variables referred to in the remainder of this paper.

The inaccuracies of the CGD method were quantified by comparing it to the SolTrace ray tracer (Wendelin, 2003), which is able to determine the FD on the receiver aperture in detail (Garcia et al., 2008). The modelled system was simplified as much as possible to isolate the elementary