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The geometric-optics relation between surface slope error and reflected ray error in solar concentrators

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Abstract

In typical reflection-based solar concentrators, surface slope error mainly causes the reflected ray to deviate from the specular reflection direction and eventually from a target. Hence a fundamental understanding of the relation between surface slope error and reflected ray error is important for evaluating optical performance of solar concentrators. It has been widely accepted that when surface slope error follows the Rayleigh distribution, reflected ray error also follows. However, including this conventional relation, the relevant studies to date relied on purely geometric calculations and overlooked features of light scattering. In this study, the bidirectional reflectivity from geometric optics in light scattering theory is employed to derive a more rigorous distribution of reflected ray error. For the reflector surface without refraction, the geometric-optics relation demonstrates that the conventional relation holds only at normal incidence and becomes more and more incorrect as the incidence angle increases because of diminishing scattering effects. As a result, the conventional relation underestimates the peak flux produced by solar concentrators and their optical performance. The treatment that is able to account for scattering features and thereby overcome the limitations of the conventional relation is suggested in the use of the Monte Carlo ray-tracing method.

Keywords: Solar concentrator; Surface slope error; Reflected ray error; Bidirectional reflectivity; Geometric optics; Ray tracing

1. Introduction

Solar concentration with reflectors is based on specular reflection to re-direct the beam component of sunlight to a target. Various errors in a solar concentrator lead to angular deviation of reflected sun rays from the specular reflection direction and thereby degrade concentration performance. Sources of reflected ray errors can be roughly classified into four groups: specularity error, slope error, shape error, and tracking error (Cooper and Steinfeld, 2011; Rabl, 1985). Material defects and imperfections, whose characteristic length scale is smaller than or comparable to the solar spectrum, scatter sunlight. The error due to such sub-wavelength scatterers is called the specularity error. The slope error refers to errors in the surface normal vector that are caused by topographical deviations in a larger scale than the solar spectrum. The shape error and the slope error are similar and hard to differentiate. However, the shape error stands for the total surface rather than the local surface, which usually implies errors during construction, erection, and alignment of concentrators. The tracking error covers tracking-related, time-varying errors, such as inaccurate pointing of the sun position and imperfect driving mechanisms.

Because the reflective surface area of typical solar concentrators is very large, it is often assumed that reflected ray errors statistically follow Gaussian distribution (or equivalently Rayleigh distribution) (Bendt et al., 1979; Cooper and Steinfeld, 2011; Huang and Han, 2012;

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Nomenclature

A	autocorrelation function
C	angular term in the bidirectional reflectivity model
f	bidirectional reflectivity
I	radiative intensity
n	surface normal vector
P	probability density function
R	uniform random number between 0 and 1
s	ray direction vector

Greek symbols

α	SD of surface height error
β	SD of surface slope error
λ	wavelength
ζ	surface slope error
θ	zenith angle
ξ	surface height error
ρ	reflectivity
σ	SD of reflected ray error
ϕ	azimuth angle
χ	autocorrelation length of surface height
ψ	rim angle of parabolic dish
ω	solid angle

Subscripts

0	ideal surface
e	reflected ray error
h	surface height error
i	incidence
n	normal
r	reflection
s	surface slope error
x, y, z	x, y, or z component, respectively

Abbreviations

MCRT	Monte Carlo ray tracing
PDF	probability density function
SD	standard deviation

Johnston, 1995; Pettit, 1977; Rabl, 1985; Wendelin, 2003). The sum of the variances of individual reflected ray errors results in a total variance, σ^2, and the standard deviation (SD), σ, is regarded as a representative parameter of optical performance of solar concentrators.

$$\sigma^2 = \sigma^2_{specularity} + \sigma^2_{slope} + \sigma^2_{shape} + \sigma^2_{tracking} \approx \sigma^2_{slope.effective} \qquad (1)$$

Various error sources and complicated interplays between them make it difficult to identify errors individually and to quantify their own impacts. Nevertheless, it has been demonstrated that in typical solar concentrators the SD of the surface slope error, β ranges from 2 to 4 mrad (Johnston, 1995; März et al., 2011; Pottler et al., 2005; Shortis and Johnston, 1997). The optical modeling based on surface slope measurement is able to predict the measured solar flux distribution accurately, which suggests that investigation of the slope error should be crucial for evaluating optical performance of solar concentrators (Andraka et al., 2011; Belhomme et al., 2009; Shortis and Johnston, 1997; Ulmer et al., 2011). If the shape error and the tracking error randomly occur at a large scale, the slope error can further include them in a broad sense because their impacts to the reflected ray error are apparently similar despite different underlying mechanisms. In the viewpoint of light scattering, this broad interpretation implies that the shape error and the tracking error behave like surface scatterers. Therefore, the slope error can play a role of the total effective error that accounts for the combination of all error sources on the surface, and thereby the effective slope error can solely represent surface scattering. This study also adopts this interpretation while assuming that the specularity error is negligible. In summary, the effective slope error can be approximated as a main source of reflected ray error as depicted in Fig. 1. Hereafter simply the slope error stands for the effective slope error while σ signifies $\sigma_{slope.effective}$ in Eq. (1). However, it should be noted that as time goes on the specularity error tends to increase due to soiling and degradation of the reflector surface and the assumption of the dominant surface scattering becomes invalid.

An important question is how to relate surface slope error to reflected ray error. Traditionally, a simple relation based on the reflection law and geometric calculations has been widely used (Bendt et al., 1979; Cooper and Steinfeld, 2011; Rabl, 1985; Wendelin, 2003). When a surface slope error follows the Rayleigh distribution function, a reflected ray error also follows with σ two times greater than β ($\sigma = 2\beta$). This traditionally established relation will be referred to as “the Rayleigh relation” hereafter. The Rayleigh relation relies on purely geometric calculations

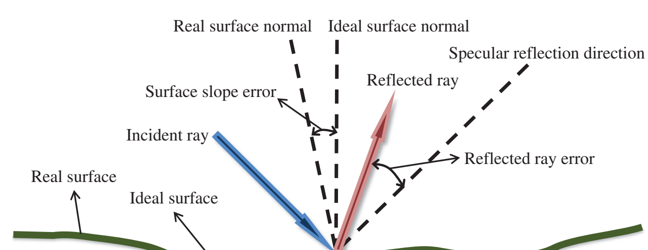

Fig. 1. Schematic sketch of a reflected ray error; an incident ray is deviated from the specular reflection direction mainly due to the surface slope error. The deviations over the entire reflector surface cause the distribution of reflected ray error.