Journal of Optics
https://doi.org/10.1007/s12596-026-03088-0

RESEARCH ARTICLE

Application of Monte Carlo method for uncertainty evaluation in photometric measurements using type C goniophotometers

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Received: 14 October 2025 / Accepted: 18 February 2026

Abstract
The Monte Carlo Method is a powerful statistical technique for propagating uncertainty in photometric measurements, particularly when models are nonlinear or input variables deviate from Gaussian distributions. This study explores the application of MCM to luminous flux measurements using Type C goniophotometers, with comparisons to the conventional Root Sum of Squares Method. Three distinct Monte Carlo models were implemented. The first classified uncertainties as Type A or Type B, assigning corresponding probability distributions. The second employed Shannon information theory to derive distributions based on available knowledge, while the third exploratory model randomized distribution selection among normal, uniform, and triangular forms. Sensitivity analysis, guided by the Pareto principle, identified the key variables contributing to 80% of overall variability. Results showed that Root Sum of Squares Method yielded an expanded uncertainty of 3.4%, whereas the first, second, and third Monte Carlo models achieved 3.0%, 2.5%, and 2.3%, respectively. Importantly, the Pareto-based reduction strategy preserved accuracy while lowering computational complexity. These findings demonstrate that Monte Carlo Method provides a more effective framework for uncertainty evaluation in photometry than traditional approaches, with the information theory-based model offering the best balance between accuracy and efficiency. The proposed methodology enhances the reliability of luminaire characterization and supports practical adoption in industrial measurement contexts.

Keywords Monte Carlo method · Uncertainty propagation · Photometry · Luminous flux · Sensitivity analysis

Introduction

The Monte Carlo method was originally developed in the 1940s by John von Neumann and Stanislaw Ulam, becoming widely known within the mathematical community throughout the second half of the 20^{th} century. However, its application in the calibration and metrology industry remained limited for decades, as professionals in this field continued to employ traditional analytical approaches based on complex differential equations and matrix formulations for uncertainty propagation due to limited computational resources at the time.

In the 1990s, what became known as the traditional GUM-based method (Guide to the Expression of Uncertainty in Measurement) was published and standardised, establishing the standard methodology for uncertainty analysis [1]. This approach is founded on the law of uncertainty propagation and quadratic combination of uncertainties through the Root Sum of Squares Method [2]. Despite its widespread adoption, this method presented several limitations that could compromise the reliability of results: the inherent complexity of the equations, the mandatory requirement for input variable distributions to be normal, and the difficulty in handling complex correlations.

Nearly seven decades after its invention, it was only in 2008, that the JCGM (Joint Committee for Guides in Metrology) formalised and standardised the Monte Carlo approach for modelling such systems through the publication of JCGM 101:2008 [3]. This alternative promised to significantly simplify the previous approach, offering a

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Published online: 26 March 2026