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Monte Carlo advances and concentrated solar applications

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Abstract

The Monte Carlo method is partially reviewed with the objective of illustrating how some of the most recent methodological advances can benefit to concentrated solar research. This review puts forward the practical consequences of writing down and handling the integral formulation associated to each Monte Carlo algorithm. Starting with simple examples and up to the most complex multiple reflection, multiple scattering configurations, we try to argue that these formulations are very much accessible to the non specialist and that they allow a straightforward entry to sensitivity computations (for assistance in design optimization processes) and to convergence enhancement techniques involving subtle concepts such as control variate and zero variance. All illustration examples makePROMES - UPR CNRS 8521 - 7, rue du Four Solaire, 66120 Font Romeu Odeillo, France use of the public domain development environment EDStar (including advanced parallelized computer graphics libraries) and are meant to serve as start basis either for the upgrading of existing Monte Carlo codes, or for fast implementation of ad hoc codes when specific needs cannot be answered with standard concentrated solar codes (in particular as far as the new generation of solar receivers is concerned).

Keywords: Monte Carlo algorithm; Concentrated solar energy; Solar energy flux density distribution; Solar concentrators design optimization; Sensitivity computation

1. Introduction

Concentrated solar processes such as solar thermal power plants essentially convert solar energy into high density heat fluxes to be collected by working fluids. As far as radiation is concerned, such processes involve both a concentrating system (an heliostat or an heliostat field) and a receiver. Concentrating systems and first generation receivers were initially designed using geometrical optics, but higher accuracy requirements or advanced receiver technologies imply a deeper entry into physical optics and radiative transfer. This is commonly translated into the development of Monte Carlo codes. They are preferred to other numerical

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simulation techniques because of their flexibility (in terms of inclusion of new physical phenomena) and their ability to deal with geometrically complex realistic systems. But this trend introduces new methodological questions:

– Can we fill the gap between the statement of flexibility and the practical implementation, for instance, of a Monte Carlo code simulating such a complex system as a full heliostat field and a hyperbolic mirror focused on a fluidized bed receiver including multiple reflections at metallic boundaries and multiple scattering by silicate particles?
– Can the computation requirements of Monte Carlo codes be reduced to become compatible with design optimization procedures that engineers have set up thinking of fast geometrical optics convolution methods?
– More positively, can we benefit of the specific features of Monte Carlo methods as far as physical interpretation of simulation results is concerned, that is to say of sensitivity evaluation, adjoint computation, zero-variance formulation, integral reformulation, etc., as ways to understand the impacts of adjustable design parameters?

These three questions (practical implementation, convergence enhancement and identification of leading physical mechanisms) extend way beyond concentrated solar applications and are at the origin of intensive research efforts of Monte Carlo specialists dealing with all kinds of particle transport physics. The objective of the present text is precisely to review those among the corresponding methodological advances that we evaluate as mature enough to directly contribute to today's concentrated solar research.

Among them, a particular attention is devoted to the zero-variance concept and the sensitivity evaluation techniques. Both represent recent significant advances and we try to argue that they are very much accessible to the non-specialist. For didactic reasons, only parts of these two advances are fully exposed: we only consider the part of the zero-variance concept that can be exposed without the use of adjoint formulations and the most subtle part of sensitivity evaluation techniques, corresponding to domain deformation sensitivities, is introduced but is not illustrated. The missing parts would require deeper developments and we hope that the present text will serve as an introduction for the reader wishing to enter the corresponding specialized literature. Another point is also strongly highlighted: toady's easy access to the main concepts and computation tools issued of the computer graphics research community during the last twenty years (in particular under the solicitation of the film and game industries). This constitutes a very significant help for radiation physicists in the process of geometrically defining (modeling) complex scenes and accelerating photon tracking in such scenes. The details of these techniques are avoided here as they strictly belong to the field of computer sciences and are exposed in excellent textbooks, but we try to be as accurate as possible concerning the way they can be translated for practical use in the concentrated solar context. This objective is addressed using the public domain development environment EDStar, a simple implementation strategy example that may be helpful to code designers. EDStar also allows us to provide, on an associated website, the documented codes corresponding to each of the following concentrated solar illustrative examples. The presentation is organized so that these successive examples are representative of the wide diversity of concentrated solar systems and are of increasing complexity, up to quite realistic configurations meant to serve as start basis for researchers facing the need for rapid implementation or upgrade of dedicated Monte Carlo codes, when their questions extend beyond the scope of available simulation tools.

A strong presentation choice was made that consists in putting forward, in a systematic manner, the integral formulation associated to each Monte Carlo algorithm. This led us to a set of coherent conventions and notations that may require an adaptation effort, but the expected reader's benefit is that all methodological questions are then addressed on a common basis, from the most theoretical integral reformulation exercises, to the most practical aspects of code implementation.

The article is organized the following way: the methodological review itself is exposed in Section 2 and the more practical consideration related to implementation are the object of a short separate section (Section 3); four concentrated solar examples are then detailed in Section 4 and the last section (Section 5) is devoted to a brief classification of what we perceive as the main remaining open questions.

2. Integral formulation for variance reduction and sensitivity analysis

Since Metropolis original work in 1949 (Metropolis and Ulam, 1949), numerous monographs and review articles have been devoted to the Monte Carlo method. In the present context, we are essentially concerned by the simulation of a linear transport phenomenon (photons do not interact, neither directly, nor indirectly in most of the above listed radiative transfer problems). But even concentrating on this subclass of Monte Carlo algorithms, numerous excellent specialized monographs and reviews are available. We choose, very arbitrarily, to point out here Hammersley and Handscomb's monograph (Hammersley and Handscomb, 1964) because of the everlasting influence of this short synthesis in the community and Howell's review (Howell, 1998) because of its proximity with our more specific engineering application concerns. These texts provide a sufficient theoretical framework for most of the algorithms commonly encountered in concentrated solar research and may serve as a meaningful ground basis for any further bibliographic research. We also invite the reader wishing to enter more deeply in the field of linear transport Monte Carlo to explore the particle transport literature (Anderson, 1986; Allison, 2006; Agostinelli, 2003), with an emphasis on the neutron transport and plasma physics literature