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OPTICAL MODELS OF LIGHT COLLECTION IN SOLAR CONCENTRATORS

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ABSTRACT
A review of models of light collection in solar concentrators is here reported [1-5], together with new advancements of the theoretical analysis, leading to new optical concepts and new optical quantities. For some of them a similarity with electrical quantities is suggested. In this work we present a general theoretical approach to the study of solar concentrators, looked at as generic optical components whose reflectance, absorbance and transmittance properties are expressed with respect to a variety of irradiation conditions. In particular, they are studied under collimated or diffuse light, under local or integral irradiation, including that in which light direction is reversed, that is directed from the exit towards the entrance aperture. The classical view of the concentrator fully irradiated on the front side by a collimated beam has been in this way upset, and a new way of looking to it has been introduced through the concept of "inverse" irradiation. By inverting the direction of irradiation on the concentrator and by using a lambertian distribution of light at output, new and surprising results appear, which allow us to disclose, besides other things, the full direct optical transmission properties of a solar concentrator. All the results have been obtained by applying and extending two optical concepts: the reversibility principle and the efficiency of transmission through the solar concentrator of an elemental beam. This theoretical investigation of solar concentrators improves the knowledge of their optical properties, potentially expands the field of their applications and opens new perspectives to the methods of their characterization.

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[2] A. Parretta, A. Antonini, M. Butturi, E. Milan, P. Di Benedetto, D. Uderzo, P. Zurru, *"Optical Methods for Indoor Characterization of Small-Size Solar Concentrators Prototypes"*, Advances in Science and Technology, Vol. 74 (2010) pp. 196-204. Trans Tech Publications, Switzerland.
[3] A. Parretta, D. Roncati, *"Theory of the "inverse method" for characterization of solar concentrators"*, Optics for Solar Energy (SOLAR)", Tucson, AZ, USA, June 7-10, 2010.
[4] A. Parretta, G. Martinelli, A. Antonini, D. Vincenzi, *"Direct and inverse methods of characterization of solar concentrators"*, Optics for Solar Energy (SOLAR)", Tucson, AZ, USA, June 7-10, 2010.
[5] A. Parretta, L. Zampierolo, *"Theoretical Aspects of Light Collection in Solar Concentrators"*, Optics for Solar Energy (SOLAR)", Tucson, AZ, USA, June 7-10, 2010.
[6] A. Antonini, M.A. Butturi, P. Di Benedetto, D. Uderzo, P. Zurru, E. Milan, M. Stefancich, M. Armani, A. Parretta, N. Baggio, *"Rondine® PV Concentrators: Field Results and Developments"*, Progress in Photovoltaics **17**, 451 (2009).
[7] A. Parretta, A. Antonini, E. Milan, M. Stefancich, G. Martinelli, M. Armani, *"Optical efficiency of solar concentrators by a reverse optical path method"*, Optics Letters **33**, 2044 (2008).

EXTENDED ABSTRACT

Solar concentrators (SC) are usually characterized in order to know their optical transmission properties when they are irradiated by a uniform, collimated light beam simulating the direct component of the solar radiation. The result is the optical transmission efficiency curve drawn as function of the incidence angle of the collimated beam (see Figure 1). The transmission curve is characterized by an acceptance angle θ_{acc}^{50} , corresponding to the 50% of the efficiency measured at 0°. This is valid for generic applications, whereas, for photovoltaic applications, an acceptance angle, θ_{acc}^{90} , corresponding to the 90% of the efficiency measured at 0°, is usually adopted. The optical transmission curve establishes how much precise must be the solar tracker bringing the SC, when pointing towards the sun disk, in order to keep always the efficiency on the top of the curve. The other important property which is largely investigated in a solar concentrator is the spatial or angular distribution of the flux on the receiver, of minor importance in thermodynamic solar concentrators, but of crucial importance in photovoltaic ones. These are the basic information which are generally pursued, both theoretically or experimentally, by the people working on solar concentrators.

In this paper we try to go beyond this view by proposing a new scenario in which a solar concentrator, regardless if 2-D or 3-D, refractive or reflective, imaging or nonimaging, is studied as a generic optical component for which reflection, absorption or transmission properties can be defined respect to specific models of irradiation. We distinguish, for example, between "direct" and "inverse" irradiation depending on the direction of the incoming light, or between "local" and "integral" irradiation depending if the irradiation is limited to a portion area of the aperture, or if it is extended to the entire aperture area; we finally distinguish between a collimated irradiation, in contrast to a "diffuse" irradiation by a lambertian source. In the last case we speak of a "lambertian" irradiation, where radiance is constant from all directions within a maximum value θ_m of the polar angle.

In this paper we discuss theoretical models of irradiation, which are simplifications of the real irradiation conditions found outdoors. For each model we derive a specific method of characterization of the SC, that can be applied by optical simulations at a computer or by experimental measurements. A generic solar concentrator is schematised as a device confined between an entrance aperture (ia) with area A_{in} and an exit aperture (oa) with area A_{out}, where $A_{in} > A_{out}$, as the definition of solar concentrator requires. A solar concentrator operates in practice under "direct" irradiation, that is under irradiation on the entrance aperture and with a receiver, the energy conversion device, at the exit aperture.

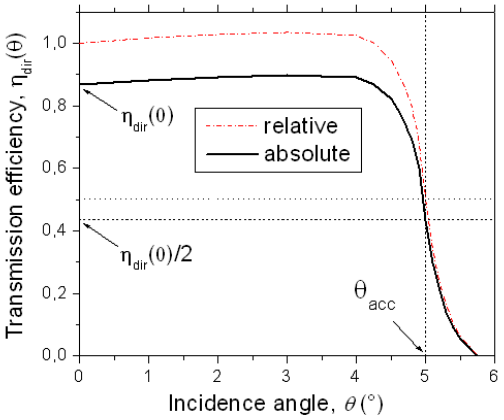


Figure 1. Typical optical transmission curve of a nonimaging solar concentrator.

In our models, however, we imagine to replace the receiver by any detector suitable to measure the total output flux, or its spatial and angular distribution; we imagine also to use the entrance and exit apertures to put any source of light for direct or inverse irradiation, respectively. What is there between the two apertures is specific of a particular fabrication technology and will not be considered here because not relevant, in principle, for a general discussion of the overall optical properties of the SC.

As the main question relative to the operation of a solar concentrator is its ability to transfer light to the output, the simplest question to ask is: how an elementary beam, incident on (ia) at the point $P(x, y)$ from (θ, φ) direction, is transmitted by the concentrator? This question introduces the first and simplest method of characterization of the solar concentrator: the *"Direct Local Collimated Method"* (DLCM). To apply this method in the most general form we should consider also the polarization of the beam and its spectrum. In this paper, however, we simplify our discussion by considering always unpolarized and monochromatic light at input. The role played by unpolarized light, in fact, has a significant importance in this work. On the one hand a solar concentrator works mainly with direct sunlight, which is strictly unpolarized, on the other one, in the following, all the presented methods of SC characterization include the use of unpolarized light. With the DLCM irradiation the elemental collimated beam is transmitted to output with an efficiency expressed by the quantity $\eta_{dir}(P,\theta,\varphi)$, the local optical transmission efficiency.

If the collimated irradiation is extended to the entire area of input aperture of SC, we talk about the *"Direct Collimated Method"* (DCM) (see Figure 2).

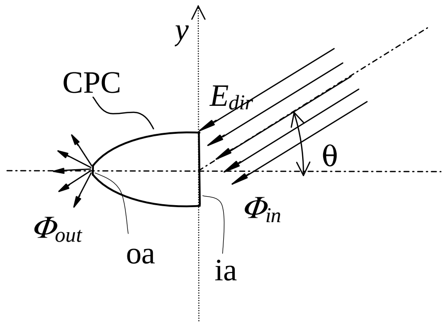


Figure 2. Basic scheme of the Direct Collimated Method (DCM).

Before describing the DCM, as well as the other methods discussed in this work, it is necessary to go to an "ab initio" investigation of the SC under the irradiation of an elementary beam. Figure 3 shows examples of the optical paths that an elementary beam can follow inside a SC, of refractive or reflective type, from (ia) to (oa) and vice versa. The beam can be totally reflected backwards (Figures 3e,f), or totally absorbed inside the concentrator (Figures 3g,h): these are extreme cases in which we cannot draw a path for light from the entrance to the exit aperture or vice versa. In all the other cases we can follow the beam from one aperture to the opposite one. We distinguish therefore between "connecting" and "not connecting" paths, when the paths connect or not the two apertures, respectively. Thus, we have connecting paths with direct irradiation in Figures 3a,d, and connecting paths with inverse irradiation in Figures 3b,c.

The attenuation that a light ray or an elementary beam experiments inside the SC is the result of all the interactions with the surfaces and the interfaces met during its travel. In the hypothesis that the beam undergoes only reversible processes, in particular reflections and/or refractions at planar surfaces, excluding surface diffusion or diffraction phenomena, the total attenuation of the beam can be derived by applying repeatedly the Fresnel equations. By indicating with φ the incidence angle and with φ' the transmission angle (by reflection or refraction), it can be found, by Eqs. (1) and (1'), that the transmission factors T_{refl} for reflection and T_{refr} for refraction do not change at exchanging φ and φ' angles, that is inverting the direction of travel of the light path, as established by the "reversibility principle": "the attenuation undergone by an unpolarized beam on the same path, but at opposite direction, is the same".

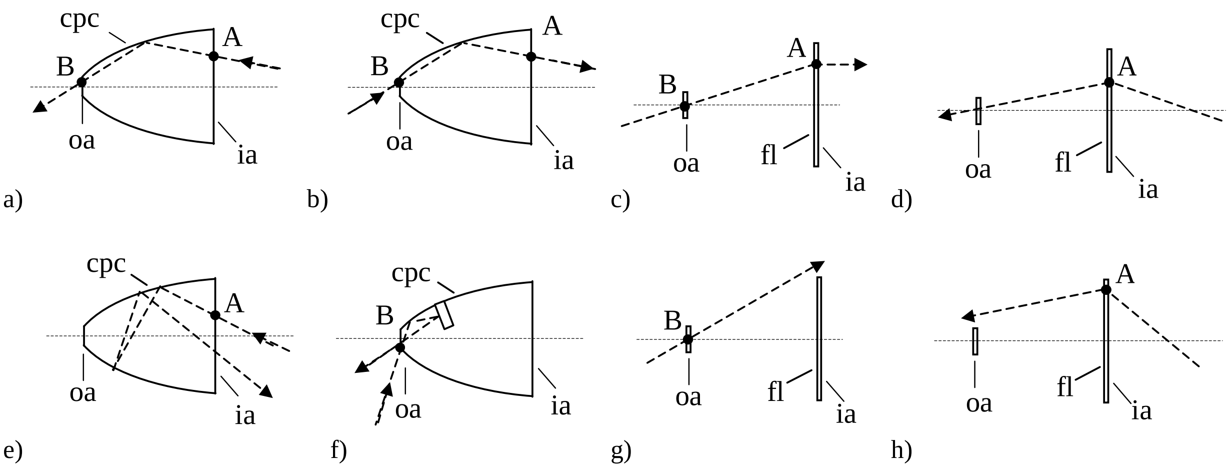
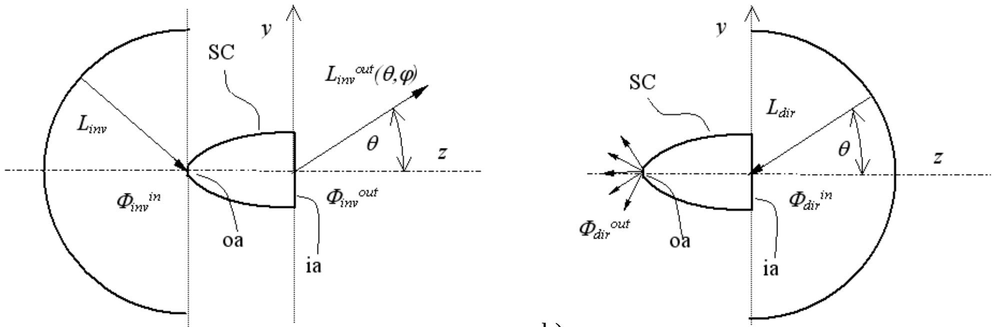


Figure 3. Examples of "connecting" (a-d) and "not connecting" (e-h) light paths; (cpc): nonimaging concentrator, (fl): imaging Fresnel lens; beams: (a, d) direct transmitted; (b, c) inverse transmitted; (e) direct reflected; (f) inverse reflected; (g) inverse absorbed (h) direct absorbed.

$$T_{refl} = \frac{1}{2} \cdot \sin^2(\varphi - \varphi') \cdot \left[\frac{\cos^2(\varphi + \varphi') + \cos^2(\varphi - \varphi')}{\sin^2(\varphi + \varphi') \cdot \cos^2(\varphi - \varphi')} \right] \quad (1a) \qquad T_{refr} = 2 \cdot \sin\varphi \cdot \sin\varphi' \cdot \cos\varphi \cdot \cos\varphi' \left[\frac{1 + \cos^2(\varphi - \varphi')}{\sin^2(\varphi + \varphi') \cdot \cos^2(\varphi - \varphi')} \right] \quad (1b)$$

The rays back reflected or totally absorbed, that is the rays completely lost, have a transmission factor equal to zero and no "connecting" paths between the two apertures can be defined for them. The identical connecting paths, as A→B of Figure 3a and B→A of Figure 3b, have the same transmission factor: $T_{AB} = T_{BA}$, when the starting beams are unpolarized. The condition $T_{AB} = T_{BA}$ is the basis of the so called *"Inverse Lambertian Method"* (ILM), which has been conceived for deriving the absolute transmission efficiency of DCM by analysing, instead of the flux collected at the output aperture with direct irradiation, the flux collected at input aperture with the inverse irradiation. In order to apply this concept, it is necessary that the rays analysed with the "direct" irradiation overlap those analysed with the "inverse" irradiation, that is, that the respective optical paths be identical.

Now, in the direct irradiation by DCM, the input beam should be varied in the 0°-90° range of polar angle. In order to deduce, therefore, the attenuation undergone by the direct rays inclined at any polar angle respect to the optical axis, it is necessary to analyse all the inverse rays emitted by the concentrator in any direction from the input aperture. The source of the inverse rays must be placed in correspondence of the receiver (the output aperture) and must be able to emit rays, from each point and in any direction inside the SC, at constant radiance, in order to not discriminate any direction. Only in this way it will be possible to produce, in the inverse mode, all the connecting paths which will overlap with those that are produced in direct mode by a collimated beam inclined at different polar angles between 0° and 90°. In order to apply the "inverse" method ILM in a correct way, therefore, we need to put a spatially uniform lambertian source at the output aperture, as shown in Figure 4a, where L_{inv} is the constant radiance of the inverse lambertian source.



a) b)

Figure 4. a) Scheme of the "Inverse Lambertian Method" (ILM). b) Scheme of the "Direct Lambertian Method" (DLM). In both cases we consider a limit polar angle θ_m = 90°.

If we want to analyse the SC, activating simultaneously all the connecting paths in direct mode, we should consider an infinity of beams impinging on the input aperture at different polar angles. This is achieved as well by using a spatially uniform lambertian source placed at the input aperture, as schematised in Figure 4b, where L_{dir} is the constant radiance of the direct lambertian source.

If the concentrator is irradiated simultaneously in "direct" and "inverse" modes by lambertian sources, all the connecting paths will overlap and, putting $L_{dir} = L_{inv}$, also the elementary flux flowing through any connecting path will be the same along the two directions. Then, with $L_{dir} = L_{inv}$, also the total flux flowing through the concentrator from one aperture to the other will be the same in the two directions, that is the net flux will be zero. If $L_{dir} \neq L_{inv}$ then we can express the net flux through SC in the direct direction as function of the radiance difference $\Delta L = L_{dir} - L_{inv}$:

$$\Delta\Phi = (\pi \cdot A_{in} \cdot \tau_{dir}^{lamb}) \cdot \Delta L \qquad (2)$$

where τ_{dir}^{lamb} is the *"direct lambertian transmittance"* of the SC: $\tau_{dir}^{lamb} = \Phi_{dir,lamb}^{out} / \Phi_{dir,lamb}^{in}$. Eq. (2) is similar to the Ohm's law: $I = G \cdot \Delta V$ where $\Delta\Phi$ (W) has the role of current, ΔL (W/sr·m^2) the role of potential difference and $(\pi \cdot A_{in} \cdot \tau_{dir}^{lamb})$ (sr·m^2) the role of conductance. We are therefore compelled to define $(\pi \cdot A_{in} \cdot \tau_{dir}^{lamb})$ as the "direct conductance under lambertian irradiation" or *"direct lambertian optical conductance"* of the SC:

$$G_{dir}^{lamb} = (\pi \cdot A_{in} \cdot \tau_{dir}^{lamb}) \qquad (3)$$