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Citation: AIP Conference Proceedings **1766**, 120001 (2016); doi: 10.1063/1.4962123
View online: http://dx.doi.org/10.1063/1.4962123
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1766?ver=pdfcov
Published by the AIP Publishing

Measuring Primary Lens Efficiency: A Proposal for Standardization

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Abstract. This article describes the procedure proposed by IES-UPM to measure the optical efficiency and the irradiance of the focused spot of a primary optic for concentrator PV (CPV). The method using a broadband source (solar simulator) with a solar cell as the sensor and analysis of the focused spot recorded by a camera is described in detail here to convey the details of the optical characterization in the emerging IEC 62989 technical specification. Special emphasis is placed in noting the main sources of error and the accuracy of the measurement method. As an example, the main outcomes attained in the characterization of a set of Fresnel lenses are reported.

INTRODUCTION

At the current stage of Concentrator Photovoltaics (CPV) development there is a need to standardize both the definition of optical efficiency and its measuring methods in order to allow fair and accurate comparison among different technologies. Additionally, reliable and repetitive efficiency measurements are needed to assess the degradation of lenses and mirrors. In recent years several experimental techniques have been developed to characterize optics for CPV. This article draws on all those works both those reported by other labs [1–6] and the experience accumulated in the CPV systems group at the Solar Energy Institute of the Technical University of Madrid (IES-UPM) [7–11].

We, together with several other research laboratories and companies, participated in the IEC-TC 82 Working group 7 to draft a Technical Specification for CPV primary optics, IEC 62989. This paper seeks to contribute to the ongoing discussion regarding definitions and methods used to characterize primary optics for CPV. In the second section, a general description of the phenomena reducing the efficiency of a lens can be found. Then, several concepts are reviewed in order to clarify the exact definitions adopted in this text. Based on the previous experience at IES-UPM, we propose the use of complementary characterizations for primary optics [11]. First, an indoor solar cell is used to estimate the optical efficiency. Secondly, the irradiance spot is photographed using a charge-coupled device (CCD) camera and adequate filters to determine the intercept radius. Both methods are described in section 4 where special emphasis is placed to identify the main sources of error. Finally, section 5 includes the result of the characterization of a set of 6 Fresnel lens and the quantification of the experimental uncertainty.

PHENOMENA AFFECTING THE EFFICIENCY OF PRIMARY OPTICS

The phenomena that affect the optical efficiency of a lens can be organized into two groups. On one side, those which lower the throughput of radiant power, including: absorption in the lens material, reflections at any of the lens faces, losses due a large number of grooves and their draft angles and tip rounding, high-angle Lambertian scattering at the interfaces etc. In general, these parameters will have the same effect on the system optical efficiency

12th International Conference on Concentrator Photovoltaic Systems (CPV-12)
AIP Conf. Proc. 1766, 120001-1–120001-6; doi: 10.1063/1.4962123
Published by AIP Publishing. 978-0-7354-1424-2/$30.00

regardless of the size of the receiver (in other words, the operating geometric concentration) and the type of solar cell. On the other side, we find characteristics that affect the spectral and spatial irradiance distribution at the lens focus, including: chromatic aberration, the width of the Fresnel grooves, low-angle scattering due to surface quality, lack of flatness or other manufacturing errors, and temperature effects. These characteristics affect the focusing of the light (that is, how well the lens acts as a concentrator) and therefore their effect on overall system optical efficiency is, to a greater or lesser degree, dependent on the receiver and cell properties. This dependence may follow from the area of the cell (which determines the geometric concentration ratio) or more complex technological parameters such as the distribution of the series resistance throughout the device [12,13] or phenomena like radiative coupling among the different subcells.

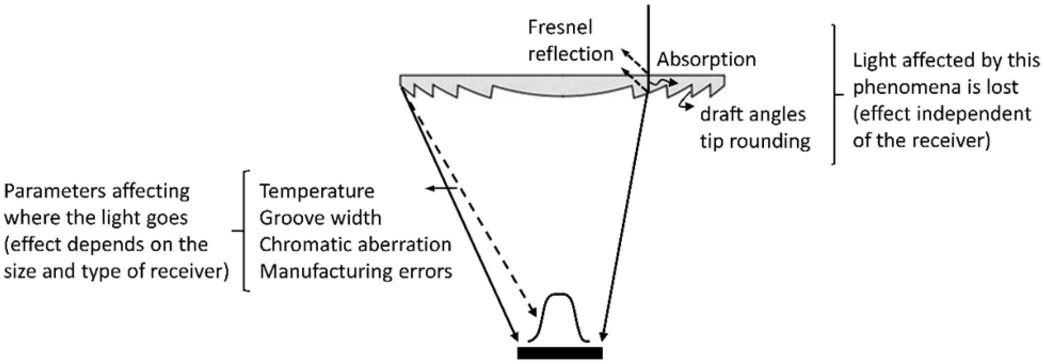


FIGURE 1. Schematic representation of the main phenomena affecting the efficiency of a primary lens. Reproduced from [11].

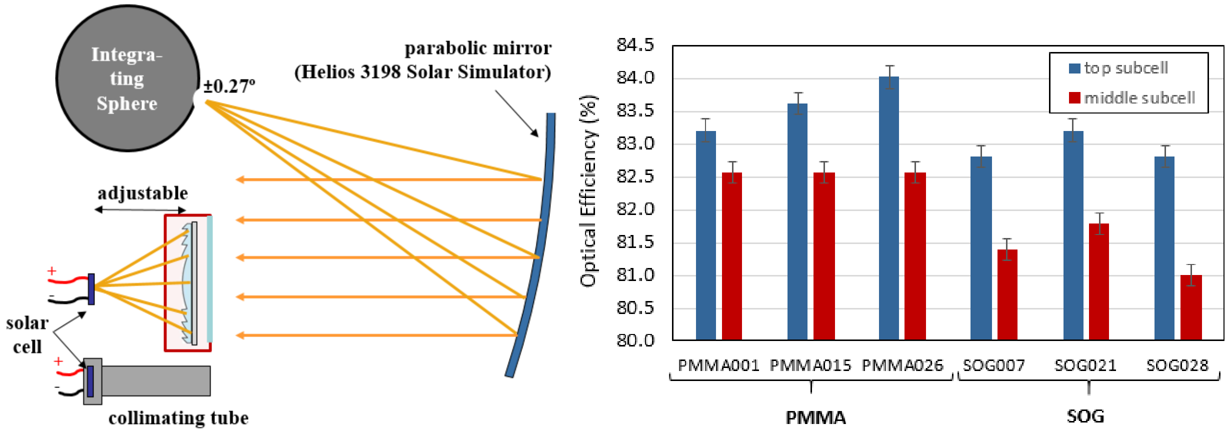
METHODS PROPOSED AT IES-UPM

Based on previous experience at IES-UPM, and taking into account the availability of irradiance sensors we proposed using two methods to perform a complete characterization of a primary lens, *i.e*., using a large area solar cell to determine the lens efficiency (that is, the transmitted light) and the CCD camera to measure the size of the irradiance spot.

Optical Efficiency Measurement

FIGURE 2 (a) shows a scheme of the lab set-up for the method proposed to estimate the optical efficiency value. Details of the instrument, including the make and model of the components are described in Ref. [11]. The Helios 3198 solar simulator is employed to illuminate the entrance aperture of the primary optic with collimated light whose spectral distribution designed to simulate AM1.5D. An integrating sphere is used to attain an angular collimation of ±0.27º. A transparent thermal chamber is used to control the samples temperature. The radiant power at the entrance of the optics and at the focal plane is measured from the short-circuit current of a solar cell. Either a silicon or a multijunction (MJ) solar cell can be used. For the latter, the subcell limitation diagrams can be used to determine the optical efficiency corresponding to the wavelengths range converted into electricity by the top and middle subcells. The subcell limitation diagram represents the evolution of the ratio of short-circuit currents of the MJ solar cell to the isotype cell vs. the variation of the spectral distribution through the flash decay. It allows the determination of the short-circuit current of every subcell within the MJ solar cell. A detailed description of this diagram can be found in Ref. [14]. The distance between the primary optics and the solar cell can be varied to find the optimum focus. In addition, the lens can be placed into a regulated enclosure to perform the measurement at different temperatures. A detailed description of this method together with other proposed strategies can be found elsewhere [11].

The concerns that should be considered to reduce experimental errors include: the size of the solar cell must be large enough; the cell's response should be linear for the concentrated irradiance cast by the lens; and errors due to non-uniformity effects, front-grid shading, and distinct angular distribution over the cell must be avoided. The uniformity across the area illuminated by the CPV solar simulator probably introduces additional and significant uncertainty. To reduce the uncertainty a single lens of similar size and material must be kept as reference and remeasured prior to every measurement session. **FIGURE 2** (b) reproduces the efficiency of the set of Fresnel lenses measured at the IES-UPM (see section 4). For the instrument described, while the reproducibility has been estimated to be ±0.5% the accuracy of the measurement is quantified to be ±2%.



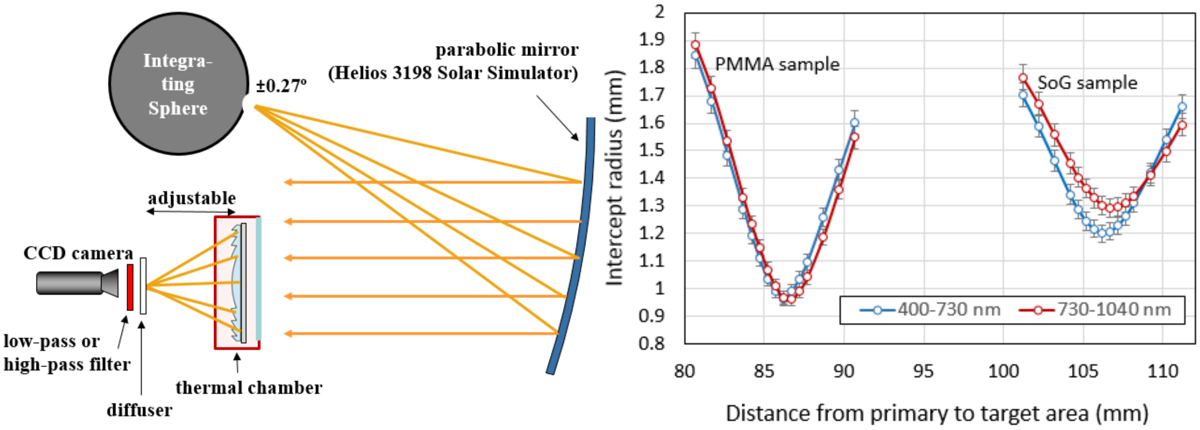
(a) (b)

FIGURE 2. (a) Schematic diagram of the measuring set-up employed to estimate the optical efficiency. (b) Optical efficiency values for the six Fresnel lenses measured at the IES-UPM.

Irradiance Spot Measurement

The set-up in **FIGURE 2** (a) was modified to measure the distribution of irradiance at the focal plane, shown in FIGURE 3 (a). The solar cell was replaced by a thin translucent Lambertian diffusor where the light spot is projected. A CCD camera photographs the diffusor, and bandpass filters are added to select the wavelengths range converted into electricity either by the top or the middle subcell (FIGURE 3). Then, the image is processed for the determination of the centroid of the focused spot. Using the centroid as the origin, the encircled energy graph can be calculated and the intercept radius (as defined in section 4) assessed, as in Ref. [11]. The previous steps are repeated as the primary to diffuser separation distance is varied, to find the position where the intercept radius is minimized. The temperature of the lens can be modified to study the thermal sensitivity of the optics. Reference [11] includes a more detailed description of this measurement and compares it with other existing alternatives to quantify the intercept radius as a function of temperature.

The image processing should be carefully performed: saturated pixels must by avoiding by reducing the irradiance level, *e.g.*, adding neutral density filters, and background noise must be subtracted from the photographed image to obtain a proper encircled energy graph. FIGURE 3 (b) depicts the intercept radius as a function of the Fresnel lens to target area distance for two samples of different material. Since the refractive index is greatest at short wavelengths, the focal distance that minimizes the spot radius is shorter for the wavelengths corresponding to top subcell. The accuracy of the spot radius measurement is ±2.6%.



(a) (b)

FIGURE 3. (a) Schematic diagram of the measuring set-up employed to estimate the intercept radius. (b) Intercept radius values for two of the lenses measured at the IES-UPM. Experimental uncertainty has been estimated to be ±2.6%. Intercept radius is measured for the light converted by the top (blue) and middle (red) subcells in a classic MJ solar cell. The spot is photographed using a CCD camera and adequate low-pass and high-pass filters.

EXPERIMENTAL RESULTS

Within the framework of the discussion for drafting the IEC62989 Technical Specification for Primary Optics for Concentrator Photovoltaic Systems a round robin is taking place. We report here the results attained at IES-UPM placing special emphasis in the quantification of the uncertainty of the measurements. A set comprising six Fresnel lenses was measured, three of them were made of poly(methyl methacrylate) (PMMA) and three of Silicone on Glass (SoG). The samples were provided by Fresnel Optics GmbH-Orafol and have an optical aperture of 40 x 40 mm. The lens pattern was designed for Polymer on Glass (PoG) and the same design was patterned in PMMA and SoG. The results should not be used to compare performance of PMMA and SoG architectures but only to analyze the similarity of the results attained by lens of the same material.

TABLE 1 summarizes the optical efficiency, the intercept radius and the focal distance determined for every specimen. The mean value and standard deviation for every material are also indicated. The values reproduced in TABLE 1 were calculated according the definitions currently agreed within the IEC 62989 group, including

- The **intercept radius** is defined as the radius of a circle that encompasses 95% of the radiant flux of the focused spot incident on the entire target area.
- The **optical efficiency** is the ratio of radiant flux on the target area within the intercept radius to the radiant flux on the entrance aperture of the primary optics, expressed as percentage value.
  The text in IEC 62989 presently advises that the target area shall have a radius at least 2 times the intercept radius. This requirement is imposed to ensure that the target area is large enough to capture every ray and no error is committed in estimating the optical efficiency due to light straying out of the target area. In addition, it is required to provide the tabulated efficiency vs. radius results, shown schematically in FIGURE 4.
- The **focal distance** is the distance between the entrance aperture (incident surface of the primary optics) and the target area that minimizes the intercept radius.

TABLE 1. Result attained for the six lenses comprising the set, for the three specimens of the same materials the mean and standard deviation σ was calculated. Measurements were carried out at temperatures within the range 25-27.5ºC. The intercept radius, focal distance and lens efficiency were measurement for the bandwidth corresponding to top and middle subcell.

	Intercept radius (mm)		**Focal distance (mm)**		**Lens efficiency (%)**	
Material	**top**	**mid**	**top**	**mid**	**top**	**mid**
SoG	1.20	1.30	106.2	106.7	82.8	81.4
SoG	1.17	1.24	105.7	106.7	83.2	81.8
SoG	1.18	1.28	105.7	106.2	82.8	81.0
mean	1.18	1.27	105.9	106.5	82.9	81.4
σ	0.02	0.03	0.3	0.3	0.2	0.4
PMMA	0.97	1.01	85.8	86.1	83.2	82.6
PMMA	0.96	0.97	86.4	86.7	83.6	82.6
PMMA	0.97	0.96	86.2	86.6	84.0	82.6
mean	0.96	0.98	86.1	86.4	83.6	82.6
σ	0.00	0.03	0.3	0.3	0.4	0.0

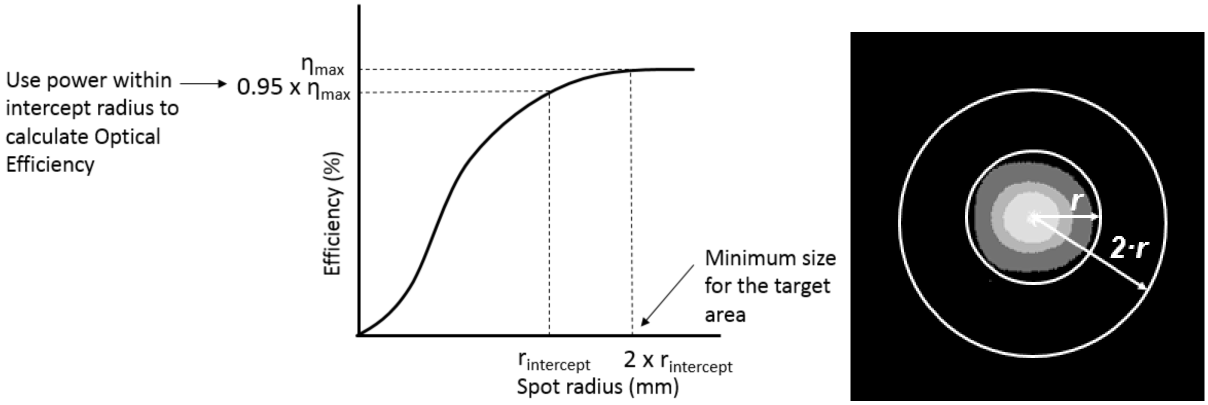


FIGURE 4. Efficiency as a function of the spot radius. The intercept radius r_{int} , is defined as the radius of a circular area that results in 95% of the radiant flux incident on the entire target area. (b) Schematic of a focused spot at the target area where r_{int} and $2 \cdot r_{int}$ are indicated.

CONCLUSIONS

The methods proposed by the IES-UPM to measure the optical efficiency and the radius of the irradiance spot have been presented relative to the emerging IEC 62989 technical specification. As an example the results attained for a set of six 40x40mm Fresnel lenses are reported. The optical efficiency values for the wavelengths ranges corresponding to the top and middle subcells were measured indoors using a MJ solar cell as irradiance sensor. The repeatability has been determined to be ±0.5% and the accuracy of the measurement ±2%. The intercept radius was obtained by photographing the irradiance spot with a CCD camera and adequate filters. The accuracy of the intercept radius measurement is in this case ±2.6%.

The results obtained for several Fresnel lenses will be compared to the values measured by other labs in the round robin that is being carried out within the framework of the IEC62989 draft - Technical Specification for Primary Optics for Concentrator Photovoltaic Systems.

ACKNOWLEDGEMENTS

The authors want to thank the work of all the members of IEC TC82 Workgroup 7, in particular those involved in the IEC 62989 round robin experiment: Ralf Leutz, Steve Scott, Jaione Bengoechea, Peter Nitz and Philippe Voarino. We want to acknowledge David Miller's suggestions that significantly improved this text. This work has received the financial support provided by the Comunidad de Madrid through the program MADRID-PV-CM (S2013/MAE2780), the Spanish Ministerio de Economía y Competitividad (MINECO) under the program I+D – Excelencia 2013 ENE2013-45299-P and the European Union's Horizon 2020 research and innovation programme within the project CPVMatch under grant agreement No 640873.

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