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Abstract. We evaluate mirror-based and achromatic optics at different working temperatures and cell-to-primary optical element (POE) distances. The magnitude and the effect of chromatic aberration and non-uniform flux profiles are assessed under controlled testing conditions. Our characterization tool is called METHOD [1]: it is capable of measuring multi-spectral irradiance profiles of concentrator photovoltaic optical systems along with the corresponding current (I)-voltage (V) characteristics produced on a concentrator solar cell receiver. In this study, METHOD is adapted to evaluate a mirror from the APOLLON Project [2], characterized in the framework of the European CPVMatch project.

INTRODUCTION

Commercial multi-junction cells surpass 40% efficiency under standard test conditions. Most commercial modules equipped with multi-junction solar cells present outdoor efficiency values closer to 30%. Different sources of losses cause this decrease of efficiency between the cell and the module. In particular, real conditions differ from standard test conditions, misalignment caused by tracker inaccuracy, the effect of optical elements and cell performance under continuous non-uniform light. When designing and optimizing a CPV setup, attention is turned towards concentration optics and cell electrical performance [2,3]. However, the solar cell is also sensitive to the spectrum and to light distribution which depend on the optics. To study the temperature and the spectrum interaction, CEA has developed a tool called Mechanical, Electrical, Thermal, and Optical characterization on single lens CPV Design (METHOD). The aim is to adapt this setup to the characteristic of the mirror. Mirrors have different parameters and often have off-axis optical systems.

EXPERIMENTAL SETUP

Experimental Setup Description

The experimental setup [1,4], which has been developed to characterize the spectral electrical performances for lenses, needs to be adapted to a new kind of Primary Optical Element (POE), the mirror.

The process implemented to obtain images of the concentrated spot from the achromatic mirror includes an opal diffuser, located at the focal point of the mirror under test (Fig. Figure **1**), that scatters light preventing straight light. The CCD silicon camera is coupled to an automated filter wheel composed of 12 filters covering the spectral range from 375 to 975nm with a Full Width at Half Maximum (FWHM) of 50nm per filter. By imaging the opal diffuser, the camera acquires POE images at relatively limited spectral ranges and with the typical outdoor operation temperatures defined in figure.**FIGURE 2.** Localization of the 5 thermocouples on the edges and at the centre on the

rear face of the mirror under test.FIGURE 2. The camera is triggered by a photoelectric device, and by changing delay we can select which part of the flash we are measuring. The CMOS camera responds to wavelengths between 300 and 1100nm and therefore does not enable to image the bottom subcell. We focus only on top and middle subcells: the dispersion of a typical diffuser is low for higher wavelengths and the bottom subcell has an excess of photocurrent for the multi-junction cells tested,.
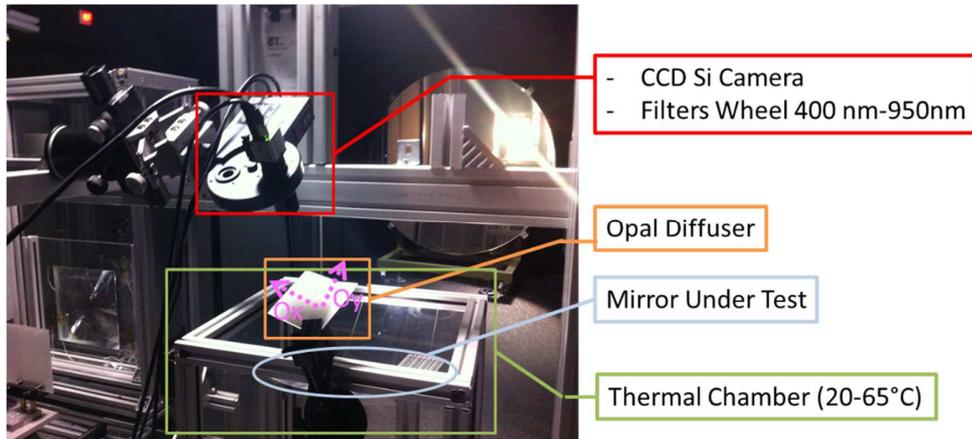

FIGURE 1. Experimental setup of the METHOD optimized for testing mirrors devoted to CPV systems.

Qualification of the Thermal Chamber

The mirror is introduced in a thermal chamber where the temperature is controlled in a homogeneous way along the lens/mirror up to approximately 65°C (far above typical POE temperatures under outdoor performance, even under extreme environmental conditions). The temperature homogeneity of the POE inside the thermal chamber has been characterized throughout the whole heating and cooling cycle using thermocouples located at different points along mirror surface (as depicted in FIGURE 2). The temperature rises up to approximately 70°C in less than 5 minutes (Figure 3). Heating is quicker than for the lens thanks to the metallic-substrate of the mirror. During the cooling phase, starting from 55°C, the standard deviation of the temperature, measured at the 5 points of the mirror, is lower than 1°C, which is accurate for appropriate CPV characterization with METHOD.
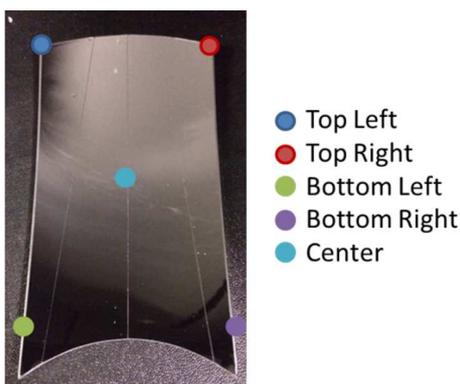

FIGURE 2. Localization of the 5 thermocouples on the edges and at the centre on the rear face of the mirror under test.
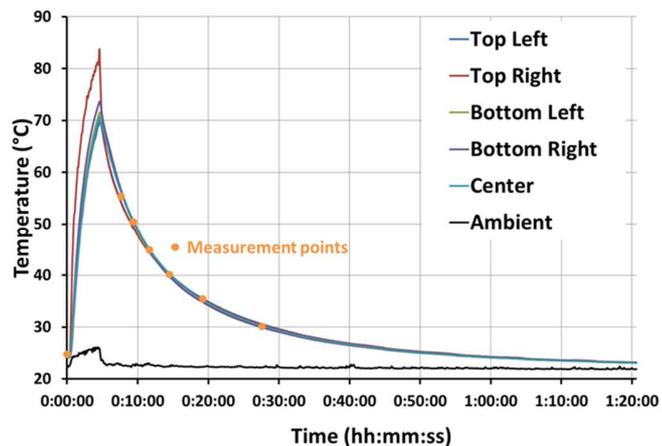

FIGURE 3. Temperature profiles of 5 probes located at the top left, top right, bottom left, bottom right and at centre of the mirror versus time, and standard deviation of these 5 probes. The measurement points are shown in orange.
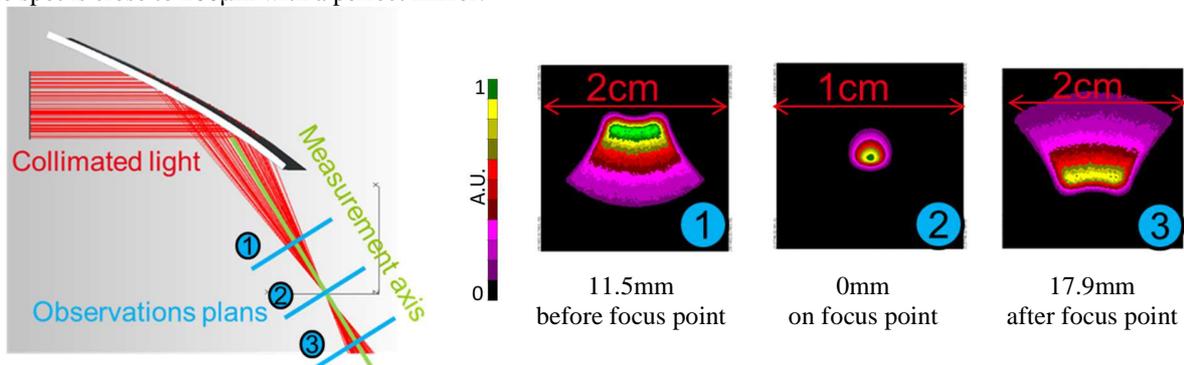
Another important point is to qualify optically the thermal chamber. Actually, unlike the lens configuration where the glasses are perpendicular at the optical axis, the light crosses the glasses with a high incidence angle after the reflection on the mirror. To qualify this point, two configurations with and without glasses are studied. Figure FIGURE **4** presents a schematic view of the configurations of the thermal chamber and the position of the energetic spot center along the measurement axis while moving on the transversal (Ox) and longitudinal (Oy) axes. Each point is the value integrated on ten 50nm band pass filters from 450nm to 900nm. The maximum standard deviation is 65µm for the transversal axis and 130µm for the longitudinal one. The variation of the position of the spot center for the transversal axis is less than 160µm while it is 1200µm for the longitudinal axis for all locations. As the displacement is constant, measurements could be corrected by taking into account this offset.
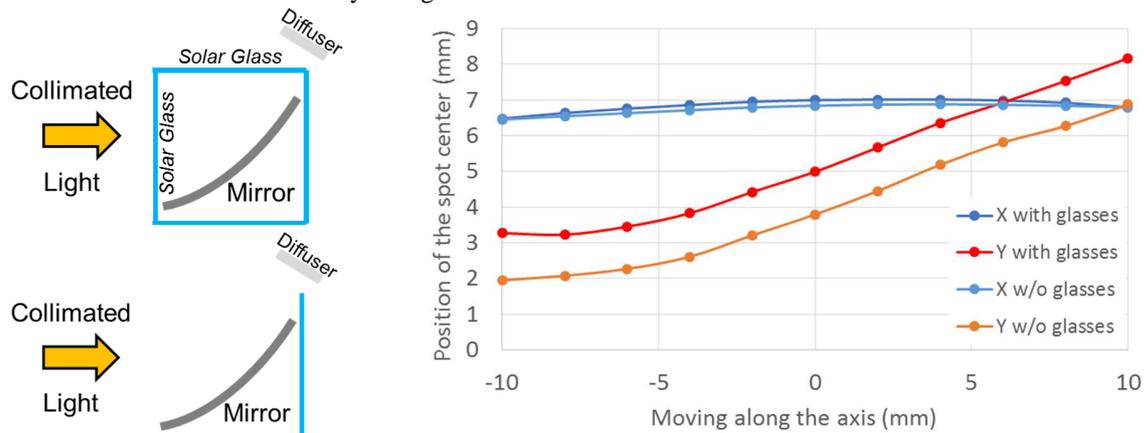
FIGURE 4. Two configurations tested with and without the solar glasses at the entrance and the exit of the thermal chamber.

Sample Description

The device under test is a mirror provided by ASSE srl. The mirror is composed of a metallic thin substrate of 1mm which is coated by a silver metallic reflective layer protected from oxidation by a top dielectric layer [5]. The four-stripes, reflective layer is laminated on the substrate. In the final optical system this mirror is the POE and it is associated to a reflective Secondary Optical Element (SOE) which is fixed on a cell of 5.5x5.5mm². We focused our study only on the POE characterization. The mirror is designed from two parabolic curves and it does not have an optical axis. It is therefore necessary to define a measurement axis to be able to characterize the power of focalization of this mirror. The measurement axis is hereafter defined as the median axis of all rays impacting the mirror (see Figure 5). The position of the focus point is determined via modelling. Figure Figure **6** presents spot diagrams along the measurement axis for three positions. The shape of the spot is almost symmetrical and the minimum diameter of the spot is close to 200µm with a perfect mirror.

RESULTS

Influence of the Shaping Process

First step is visually inspect the mirror and to evaluate the influence of the shaping process on the spot image of the mirror. Figure 7 presents real spots on three locations along the measurement axis. Comparison with theoretical images reveals that the central spot is two times larger, enhancing the influence of the shaping process, and it has a symmetry along the longitudinal axis. With Figure 8 a correlation is made with the real mirror. Before focus, the green areas are darker because of the space between the reflective stripes. Three bright spots come from the upper edge of the mirror. The diffused light around the spot on focus and the light on the red and orange areas come from the two sharp extremities. After focus, the spot has the global theoretical shape but it has bright areas surely due to the shaping process of the substrate and the laminating process of the reflective layer. When the spot is defocused, mechanical constraints could be studied and optimized.
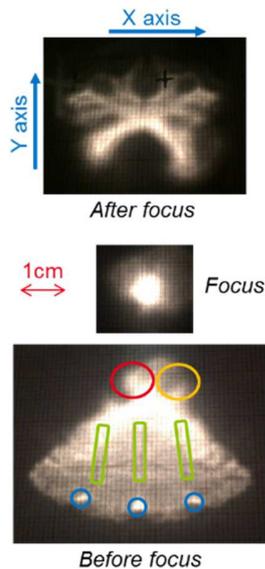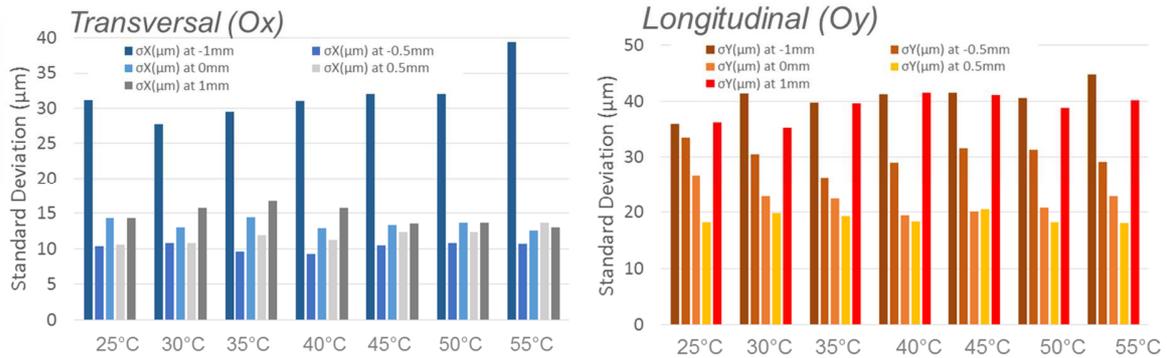

FIGURE 7. Picture of the spot along the measurement axis on three positions.
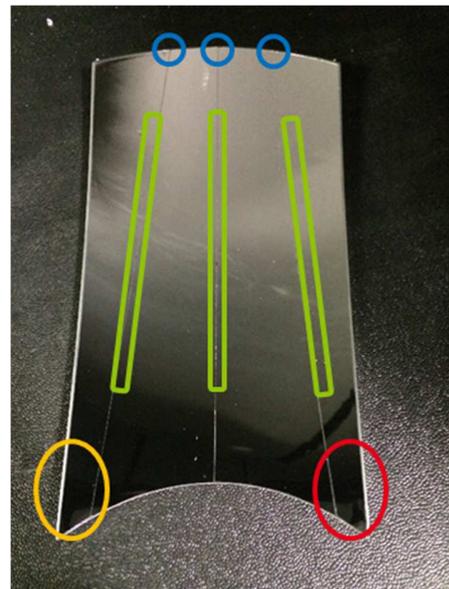
FIGURE 8. Picture of the mirror under test and locations of different singular points observed.

## Influence of the Chromatic Light on the Energetic Spot's Center

To study the influence of the chromatic light, measurements are performed at five positions along the measurements axis (-1mm, -0.5mm, 0mm, 0.5mm, 1mm). For each position, the thermal chamber is heated to more than 65°C thanks to two fans. Measurements are recorded in the range 55°C to 25°C. Ten images on ten band pass filters mounted on a filter wheel are acquired for each temperature, then, for each image the energetic spot center (centroid) is determined. Figure 9 presents the standard deviation of the movement of the coordinates (Ox and Oy) of the centroid versus the different spectral bands, for each of this configuration. For the transversal axis, the standard deviation is higher for the -1mm position than the others. This is due to the lower signal on the camera, hence higher noise. However, both graphs underline that the standard deviation is lower than 45µm. For each position and each temperature, the coordinates of the centroid do not change with respect to the wavelength.

FIGURE 9. Standard deviation of the movement of the coordinates (Ox and Oy) of the centroid versus the different spectral bands, for 5 locations along the measurement axis and 7 temperatures.

Influence of the Temperature on the Energetic Spot's Center

In order to know the variation of the centroid of the image versus the temperature Figure 10 shows the variation of the image's centroid for the transversal and the longitudinal axes. Coordinates of the centroid are compared with the coordinates determined at 25°C. For the Ox axis, centroid just moves up to 35µm. This means that the effect of the temperature on the transversal axis for all configurations can be neglected. It can be explained thanks to the symmetry of the mirror along the longitudinal axis. For the Oy axis, the centroid can move up than 400µm for a temperature higher than 45°C. If the setup is defocused (±1mm), the centroid can move more than 600µm. The determination of this value is important to position the focus point with other elements, like multi-junction solar cells or SOE. The mirror's temperature under real conditions has to be determined before constructing the final holder structure.
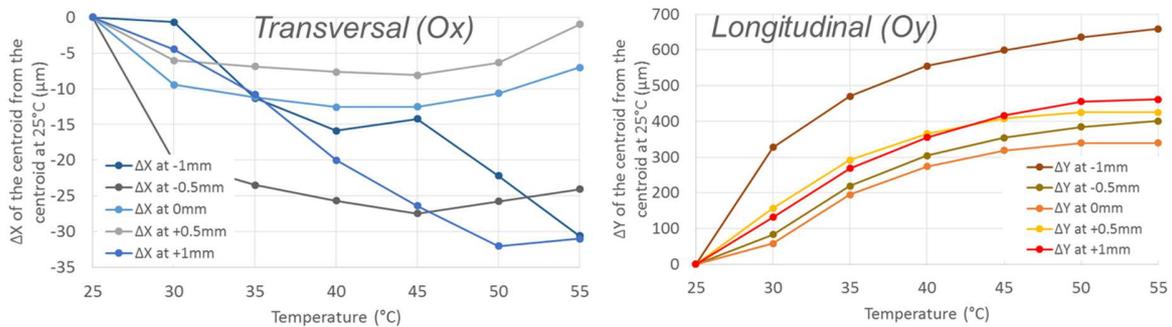
FIGURE 10. Variation of the coordinates of the centroid versus the temperature for five locations along the measurement axis compared to the centroid's coordinates at 25°C.

CONCLUSION

METHOD has been adapted for Mirror Characterization and it is able to reproduce real operating conditions of optics indoors in order to measure their electrical and optical performances. The thermal chamber has been thermally and optically qualified. Moreover, METHOD has been adapted to the POE Mirror with no axis revolution; so that it was necessary to define its own measurements axis. By evaluating the variations of the energetic center of the image versus the temperature and the wavelength, METHOD can determine and optimize the mounting tolerances. Measuring electrical performances with SOE and solar cell (Apollon Configuration), it should be a useful device for an optimization of the module configuration for CSTC/CSOC (optimization in Power or in Energy).

ACKNOWLEDGMENTS

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