Design, Optimization and Characterization of Secondary Optics for a Dish-Based 1000x HCPV System

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Abstract: This paper presents a novel design of a solar secondary optics used in a dish-based HCPV system at 1000x. Different optimizations were conducted as well as experiments to determine its optimum configuration.
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1. Introduction

A new system has been developed at the University of Arizona to collect solar radiation and convert it into electricity at low system cost. The new design was invented by Dr. Roger Angel. This design combines experience from astronomy to make large low-cost but efficient mirrors that concentrate the light, and innovative ideas to improve the acceptance angle and tolerance to mispointing errors [1]. Utilizing secondary optics as the heart of the system efficiency and optimizing them was crucial in order to achieve the best performance for the final system. Different designs were initially considered but only one was successfully selected for the final design and prototype. This paper will briefly present the system and then focus on the secondary optical design. Finally, an overview of its optimization process will be discussed and the shape and the reflectance of the optics will be determined through an experimental setup. .

2. Design overview and breakdown

The design has a unique layout that is composed of four different stages with specific roles and the full system concentrates the light at 1000x on triple-junction cells. To achieve this high concentration ratio, a large square paraboloidal back-silvered primary reflector (3.1 m x 3.1 m) concentrates the light inside a fused-silica ball field lens. The lens not only makes uniform the light at an image of the primary reflector, it also corrects small mispointing errors. At the image, whose position is independent of mispointing, are high reflective funnels that concentrate the light even more onto the cells to reach 1000x concentration (Figure 1). The funnel entrance apertures are constructed so that each cell receives an equal amount of light and thus the cells can all be connected in series. The 36 cells produce an output > 2 kW [2].

The converging rays from paraboloidal reflector (left side of each picture) are focused in the ball lens and are refracted into the secondary funnels to be finally concentrated onto the cells (right side).

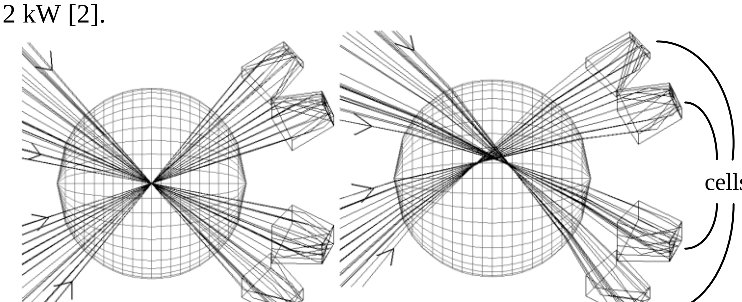

Figure 1. Ball lens principle, 3D view, on-axis (left) and off-axis (right)

3. Optimization of the secondary optics

The optical system images the primary onto the entrance aperture of the secondary. If the principle of reversibility of light is used, the secondary aperture images onto the primary and a given area on the mirror is uniquely related to a photovoltaic cell. The layout of the secondary optics will thus define the filling factor of the primary mirror, in other words the proportion of light hitting the primary mirror that will make it through to the funnels, geometrically. We analyzed two main designs: the ring and the square, as shown in Figure 2. The ring layout is used with reflectors that are all similar size. Since the concentration is increasing as the polar angle grows, each ring of increasing radius yields more current, with all the reflectors in one ring receiving the same irradiance. Each ring can therefore be wired in series to keep the same current along the cells of the ring. However, the optical filling factor is only about 78 %. The square layout is used with varying size reflectors so that the increase in concentration is compensated in order to produce the same current from all the cells. The wiring is also facilitated due to the fact that all the cells are in series. The filling factor is 98 % (only loss due to the central obscuration). The square layout was finally selected to be fabricated for the prototype because of the high-filling factor and the easier wiring process.

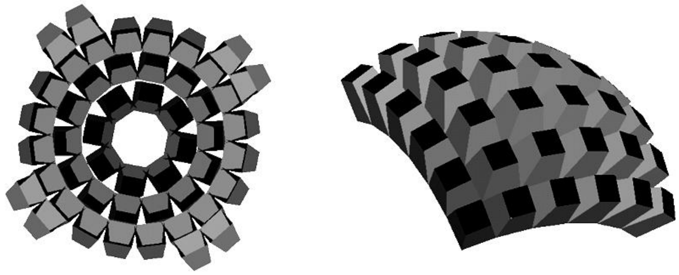

Figure 2. Secondary reflectors ring layout (left) and square layout (right)

The secondary reflectors also have a specific design, independent of the layout explained above. At their entrance aperture where the light is uniform, the concentration ratio is variable with radius, averaging about 400x. To reach a concentration factor of 1000x at the cells, the secondary funnels need to add a 2.5x factor. This factor is the ratio of the entrance area by the cell area (225 mm^2). This 2.5x factor is actually not the best concentration factor, but it is very close to it. Maximizing the power produced by the cells implies two things, includinghaving the highest concentration ratio and the best uniformity on the cells to avoid any heat spots (i.e. minimizing the variance of the rays on the cell). A funnel model was designed to calculate what the best concentration ratio was for square reflectors (Figure 3). The pattern of the rays obtained in Figure 3 clearly shows how the rays are concentrated on the cell, like how many reflections the rays encounter and how much direct light hits the cell. The model uses on-axis collimated rays for the source. As explained in the previous paragraph, the square layout requires the design to have various types of funnel entrance shapes. Only one kind has been modeled here but the difference between the various types is very small.

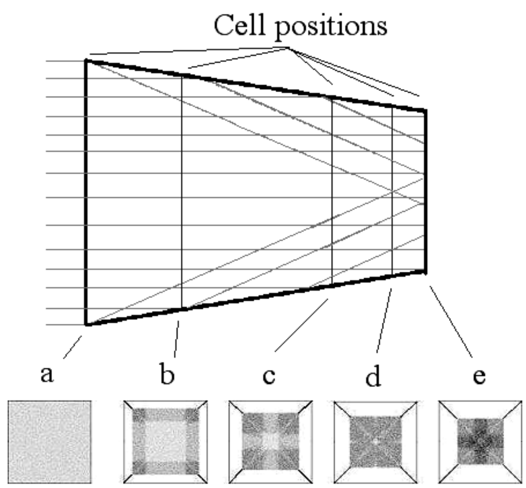

Figure 3. Inside view of a reflector showing ray paths for different cell positions with increasing depth and concentration (top), top view of secondary reflectors showing illumination patterns at the locations indicated above (bottom)

The third funnel (c) in Figure 3 clearly shows a bright cross, meaning that the reflections from the two opposite sides did not yet join in the center. The last funnel shows a dark cross, meaning that those reflections crossed over the middle, proving there is an extremum in between those two cases. To find this extremum, which will define the best concentration ratio, the merit function $\frac{\sigma}{E}$ has to be minimized, E being the collected power and σ the standard deviation of the irradiance. Having the most power and the most uniform pattern is the objective, as depicted in the 4th funnel (d) of Figure 3. The merit function has been plotted as a function of the concentration ratio in Figure 4 and shows the extremum as being 2.57x. The solid line indicates the mathematical model and the dots represent simulation for on- and off-axis rays sent into the funnel. For this particular case, a 2.5x ratio is very close to the optimal ratio of 2.57x, therefore the funnels should achieve good behavior in uniformity. The power is also well controlled off-axis due to the system tolerance to mispointing and the high acceptance angle [2].

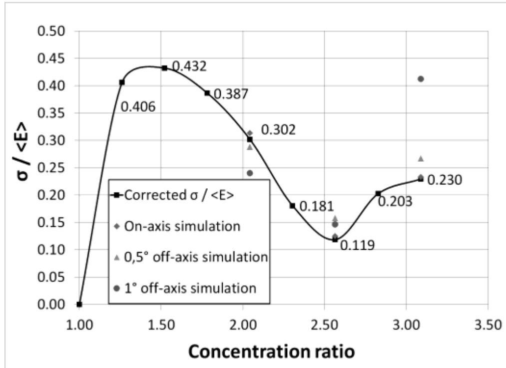

Figure 4. Funnel merit function as a function of concentration ratio

4. Characterizing the funnels reflectivity and concentration ratio

Coating the funnels with silver for high reflectivity is a challenge [3]. We plan to do an experiment to measure the concentration ratio and the reflectivity of the funnels to verify that they conform to the optimal ratio and theoretical reflectance. The experiment is supposed to simulate the real system in order to have a true concentration ratio and reflectance measurement (Figure 5). We will also measure the two parameters for different wavelengths using a setup with LEDs.

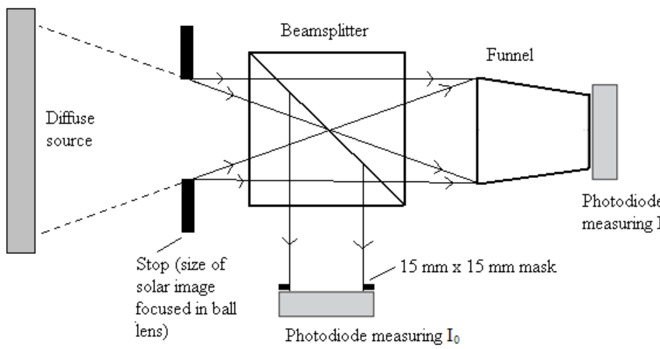

Figure 5. Experimental setup for the funnel characterization

The reflectivity is derived from a formula that takes into account the design of the 9 kinds of funnels. If I_0 is called the power collected without the funnel on the 15 mm x 15 mm cell and I the power collected with the funnel, the reflectivity can be deduced from it. If a is called the geometric portion of light going directly on the cell, b the portion reflected once, and c the portion reflected twice before hitting it, the reflectance simply follows a quadratic equation: $R^2 + \frac{b}{c}R + \frac{a}{c}(1 - \frac{I}{I_0}) = 0$. The three geometric parameters can be determined from the model of the funnel and typical values are approximately $\{a, b, c\} = \{0.3, 0.5, 0.2\}$. For those parameters, $I / I_0 = 3.2$ is equivalent to $R = 95.5\%$. The experiment to measure R from the ratio I / I_0 will be performed soon in our lab.

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6. References

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