Optical Design of a 4-Off-Axis-Unit Cassegrain Ultra-High CPV Module with Central Receiver

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Ultra-High Concentrator Photovoltaics, UHCPV, with concentrations higher than 1000 suns, has been pointed by different authors to have a great potential for being a cost-effective PV technology. This Letter presents a UHCPV Cassegrain-based optical design in which the sunrays are concentrated and sent from four different and independent paraboloid-hyperboloid pairs optical units onto a single central receiver. The optical design proposed has as main advantage the achievement of ultra-high concentration ratios, using relative small mirrors, with similar performance values of efficiency, acceptance angle and irradiance uniformity than other designs.

OCIS codes: *(080.2740) Geometric optical design; (350.6050) Solar energy; (220.1770) Concentrators; (220.4298) Nonimaging optics; (040.5350) Photovoltaic.*

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Concentrator Photovoltaic (CPV) technology presents some advantages respect to other renewable energy ones (efficiency, etc.), however, CPV systems have to be improved in order to be a more competitive technology [1, 2]. Different authors have pointed the advantages and potential in terms of cost reduction of Ultra-High CPV (UHCPV) systems with effective concentration ratios equal or higher than 1000 suns [3]. Despite such excellent potential, different technological barriers must to be eliminated at such elevated concentration levels, namely, (1) to develop solar cells with efficiencies peaking at irradiance values higher than 1000 suns [4]; (2) to design the suitable cooling mechanism capable to remove the high heat power density generated by the cells [5, 6]; and (3) to develop optical designs able to reach ultra-high concentration levels with an adequate optical performance [7]. This letter is focused in this last concern.

In relation to the optical systems involved in the UHCPV, the use of Fresnel lenses seems to limit the effective concentration ratio at around 1000 suns due to the chromatic aberration [8]. Moreover, the use of mirrors offers a promising alternative solution to get ultra-high fluxes since they are not limited by the chromatic aberration [9]. However, they have the disadvantage that large mirrors are usually required [10]. Hence, they are affected by the common associated problems involved in the fabrication of large reflective optical devices: they are usually expensive and difficult to manufacture [11].

In this Letter, a UHCPV module based on a new optical design that concentrates sunrays from different and independent optical units onto the same single solar cell is proposed. This approach resembles telescopes based on segmented mirrors and is intended to avoid the use of large reflective optical devices. The aim is to offer an alternative optical solution to those currently being discussed in the literature in order to develop successful UHCPV systems [7]. In this work, Cassegrain-based concentrators are considered as concentrators on account of their achromatism and ultra-compactness [12, 13]. Other concentrators are based also on using pairs of primary-secondary reflective elements, some of them are compact and reach and maximum-performance [14]. Moreover, the design exposed in this Letter utilizes the well-known Köhler technique to produce uniform illumination on a target [15].

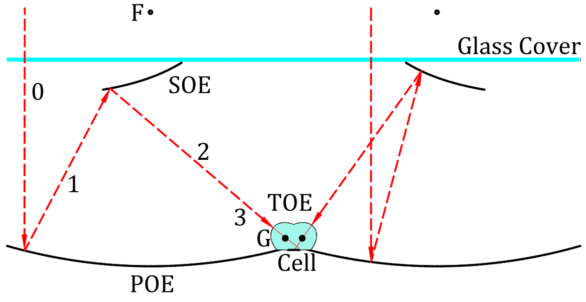


Fig. 1. Two-dimensional sketch of the rays' paths for the transverse section of two optical units through a module's diagonal. (0) incoming sunrays; (1) reflected rays on the primary optics; (2) reflected rays on the secondary optics; (3) rays transmitted through the tertiary optics and impinging the solar cell. The foci of the two-sheeted circular hyperboloid are (F) and (G), where (F) is also the circular paraboloid's focus.

The proposed design is based on an adaptation of the Cassegrain concept and consists of a kind of an off-axis Cassegrain design. The sunrays concentration is performed after three optical steps in each optical unit (see a two-dimensional sketch in Figure 1): (1) Incoming parallel sunrays reach the primary optics and are reflected on the concave paraboloid of revolution mirror surface (primary optical element, POE). Since these rays are parallel to the paraboloid's optical axis, then they are focused toward its focus, "F"; (2) The convex hyperboloid of revolution mirror surface (secondary optical element, SOE) reflects and focuses the sunrays toward its far focus, "G", (that it is located inside the homogenizer), since the sunrays of step 1 converge to its near focus, "F". POE and SOE are optically coupled, since both the paraboloid's focus and the near hyperboloid's focus coincide at the same three-coordinate point; (3) Sunrays of step 2 are refracted by the homogenizer (tertiary optical element, TOE) and spread on the cell's surface. The homogenizer's optical active surface is a Cartesian oval of revolution optically coupled to the hyperboloid mirror.

The module presented in this Letter is composed of four symmetrical and independent optical units (see Figure 2), being the axis of symmetry the normal at the solar cell's plane through its center. Each optical unit is based on the adaptation of the Cassegrain design described above (see Figure 1) and consists of a set of three optical elements: one square paraboloid mirror (POE); one trimmed (resulting four edges) hyperboloid mirror (SOE); and one Cartesian oval of revolution (TOE). The homogenizer is the assembly of the four Cartesian ovals of revolution (one for each optical unit) and functions as a Köhler integrator, thus it contributes to spread out the sunrays onto the solar cell [16] (as it is shown in Fig. 2 (b)). Each Cartesian oval of revolution couples the more external vertex of each secondary mirror with each vertex of the opposite side of the solar cell [17]. More in detail, each POE mirror is based on a circular paraboloid described as:

$$\frac{x^2}{24.5^2}+\frac{y^2}{24.5^2}-z=0. \tag{1}$$

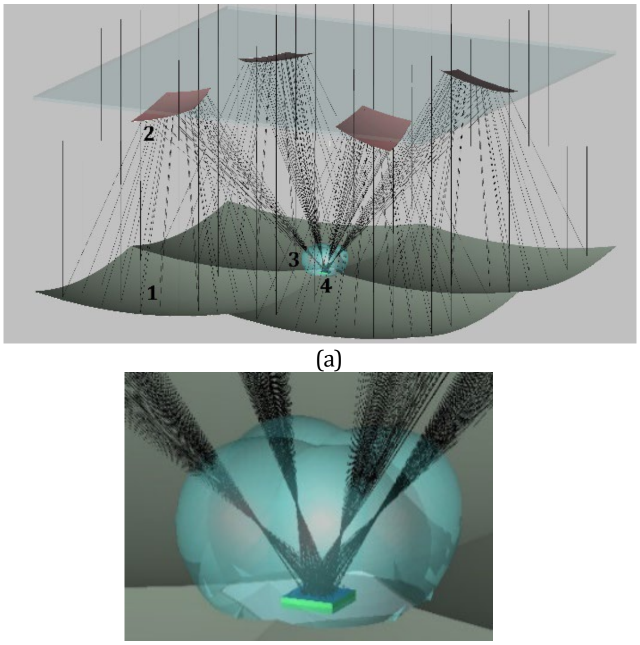
Whereas each secondary mirror is based on the sheet open upwards of a two-sheeted circular hyperboloid, which can be described as:

$$\frac{x^2}{64.5^2}+\frac{y^2}{64.5^2}-\frac{z^2}{42.5^2}=-1, \tag{2}$$

where x, y and z are in mm. In the case of the design proposed, the SOE's shape has been trimmed by the contour of the light beam that impinges its reflecting surface. The shape of each Cartesian oval of revolution has as generatrix curve the locus resulting after solving the differential equation of conservation of optical path length of any ray trajectory between a vertex of the solar cell and the opposite vertex of the correspondent secondary mirror. The generatrix curve is then revolved around the axis defined between the two vertexes. The height of each individual solid Cartesian oval of revolution along its longitudinal axis is chosen to be 20 mm from its basis–the basis matches the correspondent solar cell vertex. The location of the far focus of the SOE mirror has as relative positive Cartesian coordinates respect to the solar cell surface's center (which is 10 mm over the plane defined by the vertexes of the POE mirrors) the next values: $(x, y, z) = (3.54, 6, 3.54)$ mm. The module has symmetry around the normal at the solar cell's center in steps of 90°, i.e. each of the 4 optical units corresponds to an identical quadrant portion of the module. For the simulations, a glass frontal exterior covering, needed to protect the module against soiling, water, etc., is also included. The SOE mirrors can be fixed to the interior side of the glass covering by adding a small support like a cylinder.

The geometrical concentration ratio is $C_g = 2304$X, since the cell is of 5×5 mm^2 and each paraboloid mirror is of 120×120 mm^2. Each paraboloid is of 150 mm focal distance. For each hyperboloid, the far focus is at 120 mm in front of the mirror ("front focal distance") and the near focus is at 35 mm back from the mirror ("back focal distance"). The module has a depth of 123 mm.

The optical simulation was performed by simulating the solar rays source taking into account the solar angular profile (4.65 mrad) and also the solar spectral distribution of energy (for simplicity, extra-terrestrial spectrum ASTM E-490-00). For both, optical design and simulations, the software TracePro was used. Figure 2 shows the ray tracing and the sunrays concentration from the four different optical units to the same target. The planar frontal glass covering is simulated as fused silica. All the mirrors have been simulated as "standard mirror" in TracePro. It corresponds to a surface with the next flux coefficients: absorptance = 0.05; specular reflectivity = 0.949; and, integrated BRDF = 0.001324 (Bidirectional Reflectance Distribution Function), using the ABg scatter model. The homogenizer is simulated as made of B270 glass and the solar cell as perfect absorber.



(a)

(b)

Fig 2. (a) Model and ray tracing of the Cassegrain 4-optical-unit module with central receiver. The elements are marked: (1) paraboloid mirrors (POE), (2) hyperboloid mirrors (SOE), (3) homogenizer (TOE) and (4) solar cell. (b) Detail of ray tracing at the central receiver.

From the optical simulation, the optical efficiency of this design, defined as the ratio between the power reaching the solar cell over the module's incoming power, results η = 73%, resulting an effective concentration ratio of 1682 suns. If the glass covering is not considered, the calculation of the efficiency increases up to 79%. The 3D irradiance map on the cell is not completely uniform and has a relative small "hole" (less irradiance in the cell's center than in its surroundings, see Figure 3). The irradiance distribution on the solar cell reaches a maximum of 5480 suns and has an average value of 1682 suns when simulating an incoming power of 1000 W/m^2 –the maximum value is around 3.3 times higher than the average one. Each of the four rays' beams imping the solar cell with an average angle of approximately 30° respect to the normal at the solar cell's surface.

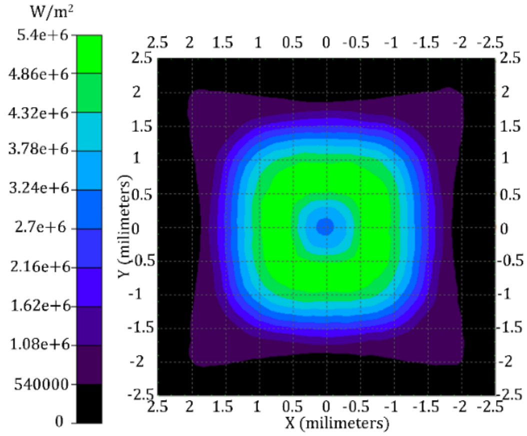


Fig. 3. Two-dimensional irradiance map of the incident rays on the solar cell. The irradiance distribution has a maximum value of around 5480 suns and an average value of 1682 suns when simulating an incoming irradiance of 1000 W/m².

In Figure 4, the effective acceptance angle characteristic (considering the finite angular aperture of the sun) of the whole optical system is presented. The relative transmission efficiency of 0.9 (relative to the maximum optical efficiency value) corresponds to a misalignment angle of 0.61°. From this value, the effective concentration-acceptance angle product, *CAP**, can be calculated, resulting 0.51.

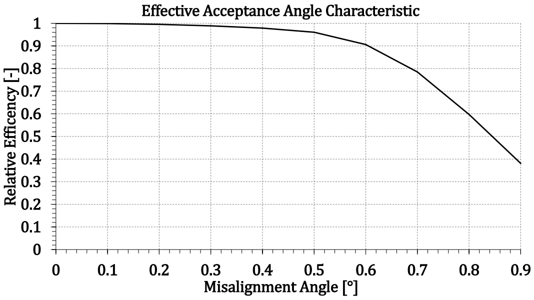


Fig. 4. Effective acceptance angle characteristic of the design.

The summary of simulation results of this 4-optical-unit design module, including its geometrical parameters, is presented in Table 1:

Table 1. Summary of geometrical parameters and simulation results of the 4-optical-unit Cassegrain design module.

Magnitude	Value
Geometrical Concentration Ratio [-]	2304
Optical Efficiency [-]	0.73
Effective Concentration [suns]	1682
Effective Acceptance Angle [°]	0.61
Effective Concentration-Angle Product [-]	0.51
Optical Efficiency without Glass Covering [-]	0.79
Cell's Irradiance Maximum [suns]	5480
Cell's Irradiance Maximum over Average [-]	3.3

The values shown in Table 1 are similar compared to the optical performance results of other Cassegrain designs [18, 19, 20, 21, 22] for which the optical efficiency ranges from 0.62 [18] to 0.85 [21], *CAP** values vary from 0.36 [18] to 0.47 [21], and the geometrical concentration ratio is between 500X [21] and 1057X [19] –much lower than in the design proposed. In relation to the irradiance distribution over the solar cell, the two best designs, among the above cited ones, are: a two-mirror Köhler-based design with a cell's irradiance maximum over average value near to 2.6 [22] and a Cassegrain-based design with a kaleidoscope homogenizer with a value near to 1.4 [21].

Concerning the optical efficiency of the design, the global optical efficiency losses are explained in terms of the next factors: transmission through the planar frontal glass covering (1), shadow of SOE (2) and TOE (3), metallic reflection on POE (4) and SOE (5), and transmission through TOE (6). For each loss factor, an optical efficiency, η_i, and the associated optical losses, $Losses_i = 1 - \eta_i$, can be defined. The global optical efficiency, η_{global}, can be expressed as:

$$\eta_{global} = \prod_{i=1}^{i=6} \eta_i = 0.73, \qquad (3)$$

where $i = 1$ to 6 corresponds to each loss factor item in Table 2. The global losses can be calculated as $Losses_{global} = 1 - \eta_{global} = 0.27$. The correspondent optical efficiencies for each loss factor, and the associated optical losses, are listed in Table 2:

Table 2. Detailed list of optical losses. The global optical efficiency is the product of all the factor efficiencies as given in equation (3).

	Optical Efficiency [-]	Optical Losses [%]
1. Glass Cover Transmission	0.931	6.9
2. SOE Shadowing	0.925	7.5
3. TOE Shadowing	0.991	0.9
4. POE Reflectance	0.949	5.1
5. SOE Reflectance	0.949	5.1
6.TOE Transmission	0.955	4.5
Global	0.73	27

Both SOE and TOE shadowing are shrinkable. Reducing the near focal distance of each SOE, the useful mirror area will decrease. Nevertheless, due to the conservation of the étendue, the sunrays' focalization at the SOE's far focus will be worse, and this has to be consider as a trade-off between both characteristics. Concerning the TOE shadowing, the size of each Cartesian oval of revolution can be reduced in trade-off with the acceptance angle characteristic of the module.

It is important to remark that, although the proposed design may be relative complex due to the relative high number of optical elements needed, it offers some important opportunities. This design is a way of reaching ultra-high concentration ratios while avoiding the use of large concentrating mirrors, which are apparently more expensive and difficult to fabricate than small ones, as previously signaled [10, 11]. Moreover, the height of the POE is reduced 75% (36 mm) when comparing with the case of having one single parabolic mirror of the same focal distance. Furthermore, since POE and SOE are quadric surfaces, they may be easier to be manufactured, in general, than freeform surfaces if these last do not have a symmetry axis [23]. Another opportunity of this design is derived from the use of a Köhler-based homogenizer, which provides more degrees of freedom in the optical design.

Analyzing the compactness of this design, there are practical limitations that are related to geometrical issues when sending the sunrays to a central receiver, and also related to the incident angle of the rays' bundles over the cell and Fresnel losses. The more compact this design is, the higher this incident angle of rays is, and therefore, Fresnel losses on the cell are higher. However, the relative low rays' incident angle on the solar cell's plane is a guarantee of not having significant Fresnel reflecting losses at the solar cell's surface [24]. Another limitation is related to the conservation of the étendue, since it contributes to spread out the concentrated sunrays. This is more evident if the design is tuned to reduce the size of the SOE mirrors in order to decrease the shadowing losses.

Comparing this design with Fresnel-based ones, it utilizes hyperboloids to send the light to the desired target (receiver). This idea would also be applicable if the primary optics were Fresnel lenses. In that case, it would be an advantage, in principle, compared with using paraboloids as primary optics, since Fresnel lenses may also function as a frontal covering of the module. Nevertheless, paraboloids are able to focalize better the sunrays since they do not produce chromatic aberrations. This fact is important in this design, since hyperboloids will ideally only reflect rays to their far focus, when those rays were previously converging to their near focus. Therefore, the no perfect sunrays focalization produced by the Fresnel lenses will result amplified at the far hyperboloid's focus. Furthermore, chromatic aberrations may not be significant in the proposed design, since the only lens is the homogenizer, and it is situated at the final optical stage: the rays will go over relatively very short path length from the homogenizer-air interface until reaching the solar cell's surface.

Considering the maximum concentration value over the solar cell (see Figure 3), it does not represent a problem for up-to-date HCPV solar cells in terms of their reliability, since some authors demonstrated by measuring triple-junction cells at very high concentration ratios, even up to around 10^4 suns [25]. The maximum irradiance value of the proposed design results less than four times as high as the average irradiance one on the solar cell, value that is slightly higher than for other designs, as it was mentioned above. This value should be improved in future designs since it may have an impact on the Fill Factor of the solar cell's I-V curve, and therefore, to reduce the efficiency of the whole concentrator module [26]. As can be seen in Figure 3, the irradiance pattern on the cell's surface has a 90°-step symmetry, since the 4 irradiance patterns of the 4 optical units are summed on the solar cell's surface. The impact of the shadow of each SOE on the total irradiance distribution leads to a central region with lower values than its surroundings [16]. The total irradiance distribution over the cell is very sensitive to the far focal point chosen for the SOE, which is one of the degrees of freedom of this design. This degree of freedom can be used to improve the design while taking into account the compromise between irradiance uniformity and acceptance angle. The size of each Cartesian oval of revolution composing the TOE is another degree of freedom and this can be used to improve the acceptance angle since it is limited by the contour of the homogenizer [17].

In order to improve the optical performance of this design, different variations of primary and secondary mirrors' focal distances can be explored. Also the calculation of the homogenizer can be varied, due to the degrees of freedom existing in the design, searching for an improvement of both irradiance uniformity and acceptance angle. Some trade-offs have to be taken into account in order to improve the design's performance in future works, since the conservation of étendue, Fresnel losses on the solar cell, etc. are factors that may limit it.

In conclusion, a new Ultra-High Concentrator Photovoltaic (UHCPV, i.e. effective concentration higher than 1000 suns), module design based on the Cassegrain design (pair paraboloid-hyperboloid) with 4 optical units around a central receiver has been designed. Each one of these optical units is an adaptation of the conventional Cassegrain design in order to send the sunrays out of the axis defined by the paraboloid mirrors (primary optics). The effective concentration-acceptance product (*CAP**) of the design is relative good, 0.51, with an effective acceptance angle, 0.61°. The optical efficiency is 73%, the geometrical concentration ratio is 2304X and the effective concentration value is 1682 suns. Without considering the covering glass, the optical efficiency is 79%. These simulation results assure the optical feasibility of the design concept implemented in this Letter. The ultra-high concentration PV module's optical design proposed represents a good trade-off between acceptance angle and irradiance uniformity, having similar optical performance values than other designs, while avoiding the use of relative large concentrating mirrors.

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