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Tailored solar optics for maximal optical tolerance and concentration

Alex Goldstein [a], Jeffrey M. Gordon [a,b,*]

[a] Department of Solar Energy and Environmental Physics, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Israel
[b] The Pearlstone Center for Aeronautical Engineering Studies, Department of Mechanical Engineering, Ben-Gurion University of the Negev, Beersheva, Israel

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A B S T R A C T

Recently identified fundamental classes of dual-mirror double-tailored nonimaging optics have the potential to satisfy the pragmatic exigencies of concentrator photovoltaics. Via a comprehensive survey of their parameter space, including raytrace verification, we identify champion high-concentration high-efficiency designs that offer unprecedented optical tolerance (i.e., sensitivity to off-axis orientation) – a pivotal figure-of-merit with a basic bound that depends on concentration, exit angle, and effective solar angular radius. For comparison, results for the best corresponding dual-mirror aplanatic concentrators are also presented.

1. Introduction

Ostensibly practical constraints in concentrator photovoltaics (CPV) translate into fundamental challenges in optical design. Examples from the wish list of the CPV industry include (a) a sizable gap between the absorber and the optic at negligible loss in collection efficiency or concentration, (b) an upward-facing absorber that permits unproblematic passive cooling of the solar cells, (c) averting the need for an optical bond between the solar cell and refractive elements, (d) negligible dispersion losses, and (e) the ability to realize compact, low-mass configurations – all while attaining high concentration at acceptance angles substantially larger than the angle subtended by the solar source.

These practical requirements prompted the development of dual-mirror aplanatic optics (a purely imaging strategy that completely eliminates spherical aberration and coma) in a variety of incarnations [1–6], some of which have already been adopted for large-scale CPV systems [3,7,8]. The primary limitation of aplanats is worsening of collection efficiency at acceptance half-angles above ~20 mrad, which motivated the recent investigation [11] of dual-mirror double-tailored (a.k.a. simultaneous multiple surface [9,10]) nonimaging optics. Ref. [11] derived the basic solutions, identified the fundamental categories, and provided sample designs as proof-of-concept, e.g., concentrators with an acceptance half-angle as large as 30 mrad, which can generate a flux concentration close to 1000.

The purpose of this paper is to identify champion, practical and high-concentration CPV designs with high collection efficiency, from among the wide range of optical strategies depicted in Ref. [11]. Special emphasis is placed on maximizing optical tolerance (sensitivity to off-axis orientation), which constitutes a distinct and central figure-of-merit in CPV assessment, where more liberal tolerances translate into lower system cost and superior robustness.

2. Optical tolerance

The averaged flux concentration C_{flux} is bounded by [9]

$$C_{flux} \leq \left(\frac{n\sin(\theta_{out})}{\sin(\theta_{in})}\right)^2 \quad \text{with} \quad C_g = \frac{C_{flux}}{\eta_{opt}}, \tag{1}$$

where θ_{out} is the exit half-angle at the absorber, n the refractive index of the concentrator element in optical contact with the absorber ($n=1$ when optical bonds are to be avoided), η_{opt} the optical efficiency, and geometric concentration C_g is the ratio of entry to absorber area.

Achieving optical tolerance requires the acceptance half-angle θ_{in} for which a solar concentrator is designed to exceed the effective solar angular radius θ_{sun}. (θ_{sun} comprises the convolution of the intrinsic solar disc of 4.7 mrad with all optical errors.) It was shown in Ref. [4] that the corresponding bound for optical tolerance half-angle θ_t is

$$\theta_t \leq \frac{n\sin(\theta_{out})}{\sqrt{C_g}} - \theta_{sun}. \tag{2}$$

* Corresponding author at: Department of Solar Energy and Environmental Physics, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Israel.
E-mail address: jeff@bgu.ac.il (J.M. Gordon).

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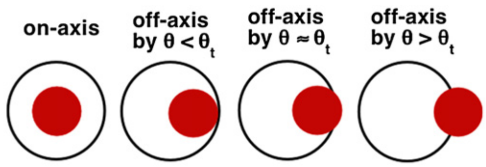

Fig. 1. Schematic of the displacement of a spot of concentrated sunlight (solid circle, based on θ_{sun}) relative to the absorber (larger circle, sized based on θ_{in}) with increasing off-axis angle θ.

The bound of Eq. (2) refers to no light being shed outside the absorber. The current convention for optical tolerance, however, is the maximum off-axis angle up to which 90% of on-axis collection efficiency is retained (see Fig. 1) – a criterion indicated in the performance graphs that follow.

3. Candidates among dual-mirror double-tailored nonimaging optics

The approach in Ref. [11] aspired to attain the fundamental bound of Eq. (1) by simultaneously satisfying (a) the edge-ray principle (the guiding tenet of nonimaging optics [9]) whereby the two families of incident extreme rays from the solar source are also extreme at the absorber (''extreme'' meaning at the boundary of the coordinate-directional cosine phase space) and (b) the minimum absorber size corresponding to Eq. (1). The tailoring algorithms are inherently 2D; and the corresponding 3D axisymmetric concentrators follow by rotating the 2D designs about their optic axis.

The solutions for the mirror contours do not admit analytical formulae, so a point-by-point numerical procedure is required. The complete theory and calculational methods for these optics are depicted extensively in Ref. [11] and hence will not be elaborated here. That notwithstanding, a few observations merit review.

Ref. [11] established 8 basic categories of dual-mirror double-tailored nonimaging concentrators, that derive from: (a) the absorber facing upward or downward (2X) and (b) the reflectors' initial conditions and the directionality of ray mapping (4X). Two of the 8 categories were shown to be unphysical (possessing virtual rather than real absorbers, i.e., all incident rays are shaded or blocked from reaching the focal plane). Half of the remaining 6 categories have a downward-facing absorber, which is incommensurate with modular passively cooled CPV. Of the remaining 3 categories, one was found to incur excessive ray loss. It is from the two remaining categories – illustrated in Figs. 2–6 – that we explore potentially viable optics for CPV, with an emphasis on realizing maximal optical tolerance.

These optics are divided into classes that (a) can satisfy both the edge-ray principle and the étendue limit to concentration, but with the solutions then being restricted to $\theta_{out}=90^{\circ}$ and (b) respect the edge-ray principle but cannot satisfy the étendue limit to concentration, thereby necessitating either rejection of rays at maximum concentration or dilution of absorber power density (oversizing the absorber) at maximum collection efficiency. The latter is preferable in CPV, where collection efficiency is crucial. The designs that nominally achieve the étendue limit are found to consistently incur on-axis losses that are substantially greater than those for the design class that requires oversizing of the absorber, and are hence not pursued further.

In the nomenclature of Ref. [11], the most promising CPV optics (expanded upon below) correspond to class III (specifically, IIIA, $IIIB_1$, and $IIIB_2$). Sections 5–7 report on these nominally optimal concentrator configurations, including quantification of the attainable optical tolerances.

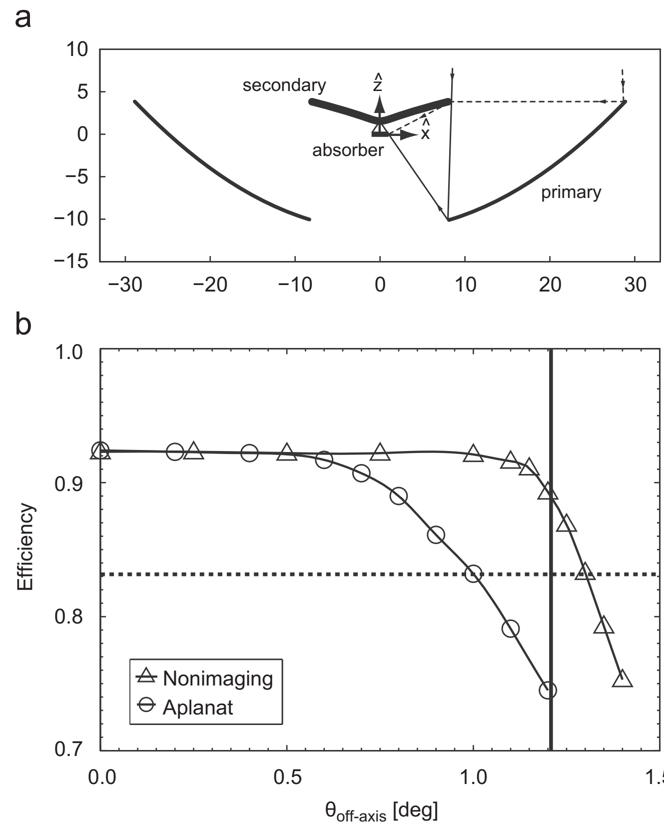

Fig. 2. (a) Nominally optimized nonimaging design that approaches the fundamental limit for compactness. Designed for $\theta_{in}=30$ mrad, it has $C_g=838$. Here and in subsequent concentrator drawings, the right-hand and left-hand extreme rays (at incidence angles $\pm\theta_{in}$ relative to the optic axis) are represented by solid and dashed lines, respectively. Explicit indication of the x–z axes (with an origin at the center of the absorber) is omitted in order to clarify the edge rays at the absorber. In all concentrator illustrations, the thicker line type indicates the secondary mirror, an absorber radius of unity defines the length scale, and the shaded region of the primary is deliberately omitted. (b) Optical tolerance function. The broken horizontal line indicates 90% of on-axis efficiency. The solid vertical line corresponds to the limit of Eq. (2) (which corresponds to the theoretical bound on the angle up to which essentially 100% of on-axis collection efficiency can be maintained, and is different for each concentrator in Figs. 2–6).

4. Performance criteria and concentrator comparisons

An effective $\theta_{sun}=10$ mrad is adopted in the analyses that follow – a value readily achieved in large-scale CPV installations [7,8,12–14]. With current commercial, ultra-efficient, multijunction cells exhibiting efficiencies that peak in the range of 200–500 suns [12–14] (1 sun$=1$ mW/mm^2), we aimed for C_g values of the order of hundreds. Concurrently, with the CPV industry standard for θ_t standing at $\sim 1.0^{\circ}$ [7,8,14], only designs with noticeably larger θ_t values are considered.

Precisely because liberal tolerance is vital, the acceptance half-angle θ_{in} for which the concentrator is designed must be considerably greater than the actual effective θ_{sun} (otherwise one would attain high concentration but negligible tolerance). Accordingly, designs were sought for the largest θ_{in} values consistent with high concentration, e.g., $\theta_{in}=30$–40 mrad.

On-axis losses were required not to exceed a few percent. Aiming for the highest concentration possible, $\sin(\theta_{out})=0.9$ was deemed the largest realistic value when the angular dependence of reflective losses of solar cell surfaces is accounted for [15].

The geometrical optical losses accounted for below include shading, blocking, ray rejection, and in the optics of Section 7, rays that miss the primary and remain uncollected (material-related losses due to absorption in the mirrors, reflections off the entry