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Testing the 'Segmented Dish' Piecewise-Focusing Solar Collector

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Abstract

The concept of a piecewise-focusing solar collector is proposed and investigated. The scales of vertical and horizontal sun-tracking motion are separated. The concept is realised as a 'segmented dish' with cavity receiver, in which about 100 mirror units mounted on a base-frame track the sun's elevation, and the entire base-frame tracks the sun in azimuth. The mirror units approximate the surface of a paraboloid tilted at a fixed angle. Each mirror unit rotates about a single nearly-horizontal axis attached at a particular angle to the base frame, such that it is perfectly aimed at three sun elevations and only slightly mis-aimed otherwise.

A 3.6 m diameter partial physical model was constructed, equipped with ten mirror units in 'worst-case' positions, focusing on a flat target. A corresponding numerical model allowed greater precision in results and a greater range for analysis; the models agreed within the limits of the physical model's precision. Aiming errors from the centres of the mirror units were generally very small, always less than a few milliradians. Aiming errors from the corners of the finite-size mirror units were examined separately; they were generally larger than for the mirror centres, but only significant at very high or very low sun elevations. Systematic aiming errors are less than 7 milliradians for most of the mirror surface at most sun elevations, which allows a concentration ratio of order 2000+ at the entrance to a cavity receiver.

It is suggested that because of its non-elevating framework the segmented dish could be built economically in sizes an order of magnitude larger than for a paraboloidal dish. The concept may be capable of reducing the overall cost of concentrating solar thermal power stations.

Introduction

For $100MW_e$ of steam-turbine-based concentrating solar power (CSP), including thermal storage for around ten hours of operation after sunset, the cost of collectors and receivers has been estimated at 55-70% of the total cost of the plant (Kolb et al 2007, 2011). Therefore it is essential to reduce the cost of collectors and receivers in any CSP cost reduction program. Complementary approaches include (a) designing for maximum collector efficiency, i.e. the heat collected per unit area, and (b) reducing the cost per unit area, including the costs of connection to the central power block.

The most efficient collector design is the paraboloidal dish, but it is expensive to build in very large sizes; the minimum cost per unit area when used in large arrays occurs for dishes of order 500 m^2 (Burgess et al 2011). More than a thousand dishes would be required for the above CSP plant, and therefore the costs and complexity of connection to the the power block are very significant. The central receiver or 'power tower' design, on the other hand, reduces costs by using reflected sunlight to transfer energy to the vicinity of the power block, and as part of its structure uses the earth itself, as the base for its multiplicity of heliostats. However the heliostat mirrors are often very oblique to the sun, the majority of heliostats are very distant from the central receiver and therefore difficult to aim (they are widely spaced to reduce mutual shading and blocking), and the open-type receiver has much greater losses than the cavity-type used with dishes. Also, heliostats require dual-axis motion, which is not cheap to implement with the required accuracy and ability to resist wind forces.

The piecewise-focusing collector design — the segmented dish — combines some of the advantages of both paraboloidal dishes and myriad heliostats, in order to reduce the cost per unit area while retaining good collector efficiency. All point-focus CSP collectors must track the sun in both elevation and azimuth. Dishes track in both directions at the largest scale, the scale of the entire collector, whereas central receiver plants track in both directions at the smallest possible scale, that of the individual heliostat. Piecewise focusing separates the scales of azimuth and elevation tracking: azimuthal rotation at the largest scale as for the dish, and elevation tracking at small scale (as for heliostats) so that there is no need to raise and lower the whole collector. The general concept is sketched in Figure 1. Note that scale separation is complete: unlike other attempts at 'moving fields' of mirrors and the like (see Discussion), the individual mirror units only rotate about single nearly-horizontal axes fixed to the base-frame. This is a key aspect of the piecewise-focus concept for cost reduction. The aims of the present work are to assess the optical performance of a segmented dish, and its comparative costs.

Determination of mirror-axis mounting angles

Each mirror unit rotates about a single axis fixed to the base frame. For a given mirror unit, vector **a**, the direction of its axis relative to the base frame, and the angle α between the axis and the plane tangent to the centre of the mirror unit, are to be determined. Note that all

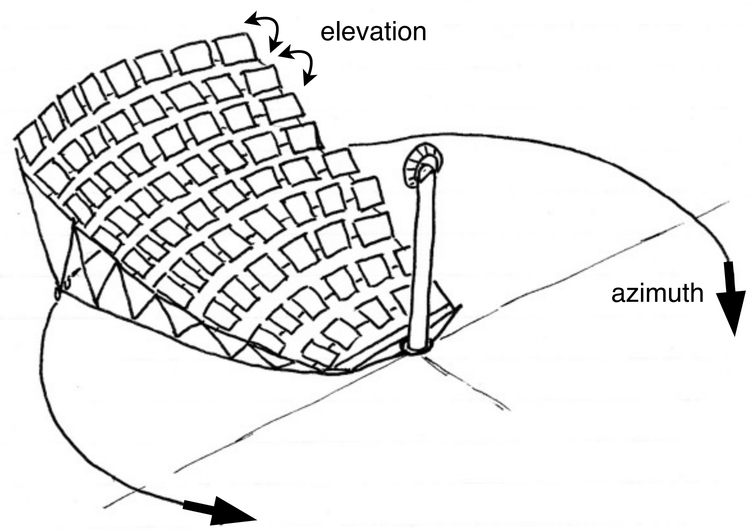

Figure 1. Concept sketch. A large base-frame of truss-like construction rotates azimuthally, and supports multiple mirror units that track the sun in elevation. The point-focus receiver can be supported by either the base-frame or a separate tower.

vectors in the following are of unit length, and therefore only two components of **a** are independent — there are three unknowns including α.

Let **r** and **r″** be respectively the directions from sun to mirror and from mirror to receiver; **r″** is fixed, and **r** depends only on sun elevation. Let **n** be the inwards normal to the mirror; then it is required that

$$\mathbf{n} = (\mathbf{r}-\mathbf{r}'')/|\,\mathbf{r}-\mathbf{r}''\,|$$

Also, since α is fixed for a given mirror unit,

$$\mathbf{n}\cdot\mathbf{a} = \cos(\pi/2-\alpha) = C \text{ (const.)}$$

or,

$$\mathbf{n}\cdot(\mathbf{a}/C) = 1$$

Select three values of sun elevation, giving three numerically different versions of this equation, and solve simultaneously for the three Cartesian components of (**a**/C). Finally,

$$\alpha = \pi/2 - \arccos C$$

The result is a mirror unit with perfect aim from its centre at any three chosen sun elevations, and small aiming errors at other elevations.

Design of the tested device

Physical and numerical models with a circular aperture of area about 10 m^2 were constructed (Figure 2), but fitted with only a few mirror units in mainly 'worst case' (diagonal) positions. Though the shape is arbitrary (as indicated in Figure 1), the collector surface tested, when

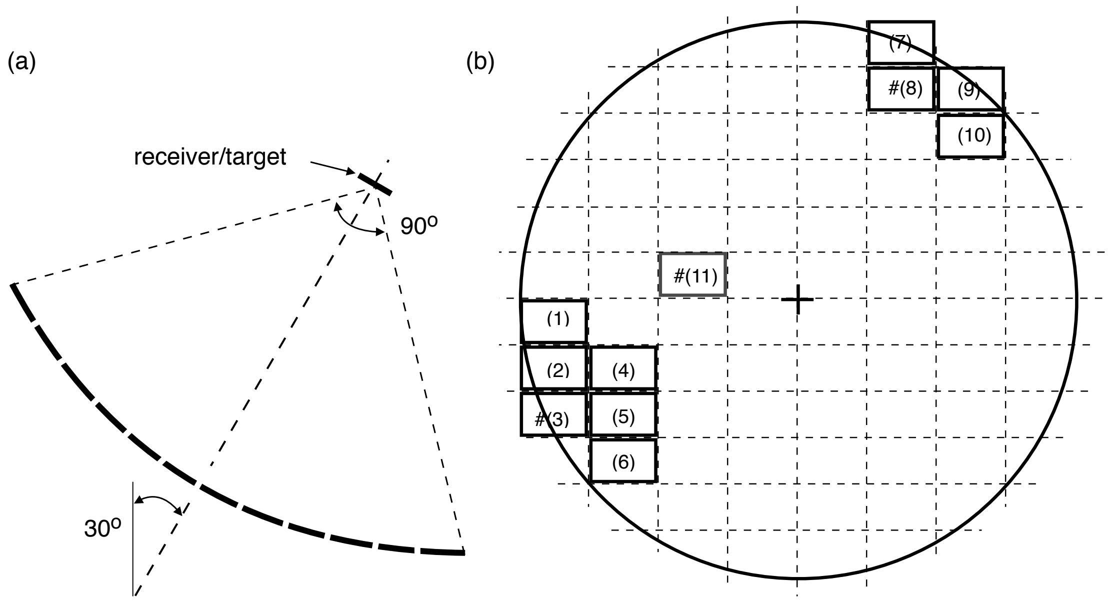

Figure 2. (a) Side view cross-section. (b) Top view of the 3.6 m diameter aperture, showing division into 80 mirror units of nominally 450 x 300 mm. Mirror units (1) through (10) were fitted with 100 x 100 mm central mirror tiles (see Figure 3). Units with a hash symbol (#) were fitted with mirror tiles on their corners also.

fully equipped with mirrors, is approximately a paraboloid tilted towards the sun by 30°. Any tilt angle can be used, but there is a trade-off between greater tilt for better performance in winter and smaller tilt for cheaper construction. The paraboloidal shape minimises shading of mirror units and ensures that there is no mutual blocking, even when the sun elevation is very low. The physical model is shown in Figure 3. Note that mirror units rotate about their axes by only about half the change in sun elevation (Figure 3b). Mounting axes for mirror units at the sides of the collector are at considerable angles to the mirror planes (Figure 3c). The three sun elevations chosen for determining the axis angles were (25°, 50°, 75°) in both physical and numerical models, and further results with the latter were obtained for (10°, 45°, 75°).

Results — numerical model

The numerical model takes as input the same mirror-position and axis-angle data used to construct the physical model. For a given sun elevation, a specified mirror unit is rotated about its axis in very small steps until the aiming error of its reflected ray reaches a minimum, which is reported in milliradians. Then the reflected ray is intersected with the target plane and the 2D error on the target is reported in millimetres. Since mirror unit axes are nearly horizontal, the reflected image on the target moves nearly vertically when a mirror unit is rotated, so vertical aiming errors can be made very small. Therefore the main aiming errors on the target are horizontal (i.e. left-right). Figure 4(top) shows left-right aiming errors as a function of sun elevation for two mirror units in their design state. As expected, the errors are zero at the elevations used for determining axis directions. They are quite small between these elevations, and increasing rapidly (for Unit 3 at least) as the sun approaches the horizon. Note that 3 mm = 1 milliradian approximately (varies somewhat for different mirror units).

Since it is not possible to build physical devices precisely in their design states (indeed the physical model here is surely imprecise), it is useful to investigate the consequences of small construction errors, and hence obtain an idea of whether high (expensive) precision in construction is critical. For Units 3 and 7 it was assumed in the numerical model that the angle between the mirror and its mounting axis was wrong by about one degree, i.e. the distances from the mirror to its mounting screws (Figure 3c) were out by a millimetre or two.

Figure 3. Physical model. (a) Sun elevation 60°, mirror units aligned with paraboloidal surface. (b) Sun elevation 14°, mirror units rotated to suit. (c) Typical axis of rotation for a mirror unit, defined by its mounting screws (circled).

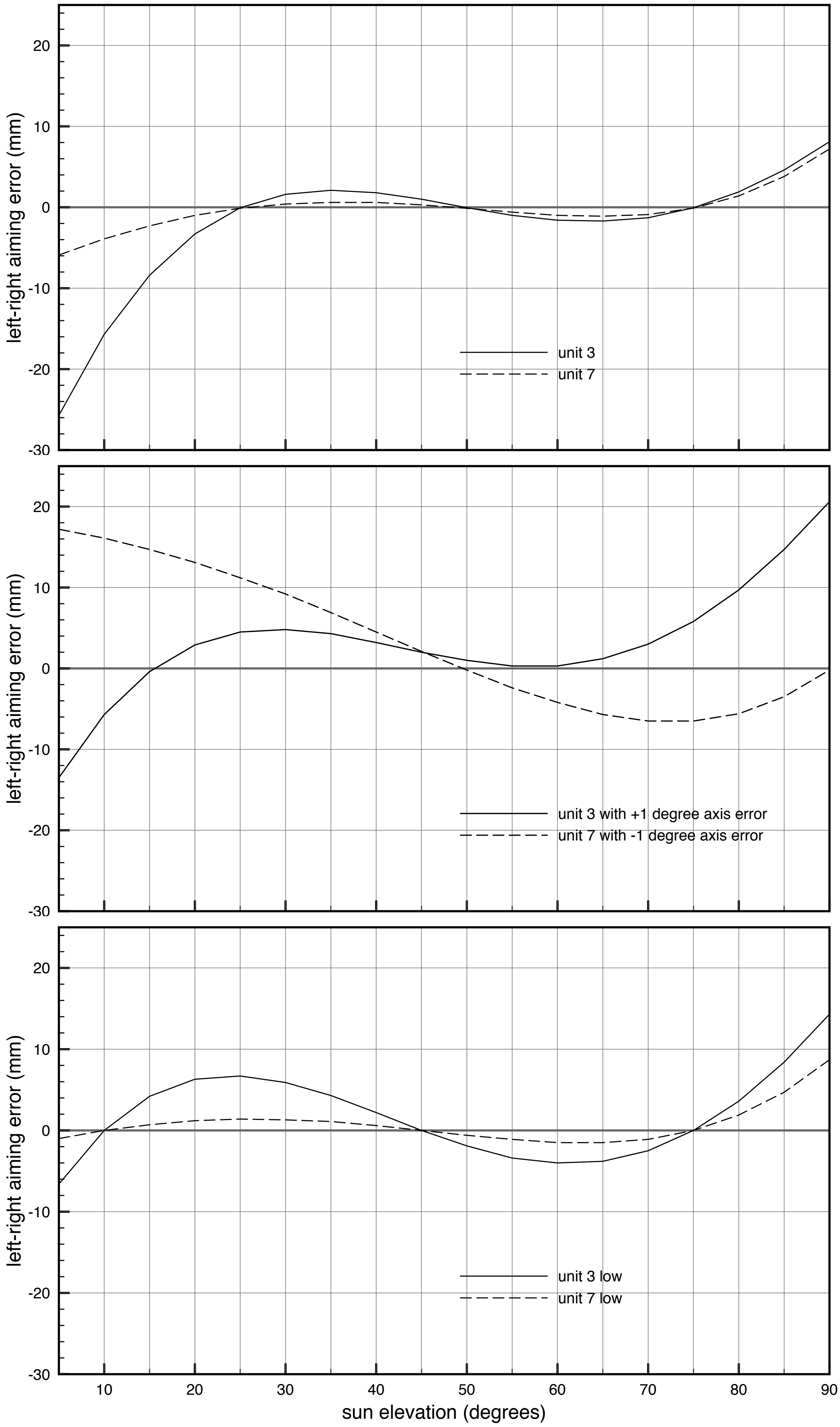

Figure 4. Left-right aiming errors from two mirror units. (top) Design state. (middle) With 1-degree errors in mirror mounting, compensated (see text). (bottom) Using (10°, 45°, 75°) as the set of sun elevations for setting mirror unit axis directions.

Then the axis mounting angle (relative to the base frame) was adjusted by trial-and-error in the numerical model until the left-right aiming error was very small at a sun elevation around 50°. Results are shown in Figure 4(middle). The aim from Unit 7, previously better than from Unit 3, was degraded significantly, while Unit 3 was actually improved at low sun elevations (though a bit worse at high elevations). In any case, it can be concluded that the design is not overly sensitive to small construction errors, and real-world errors are likely to be smaller than 1° as assumed here. The actual deviations of the present physical model from the design state are unknown, and therefore could cause difficulties for making quantitative comparisons between the physical and numerical models.

Since mirror unit aim in the design state is worst at low sun elevations, i.e. below the range of the set of elevations used to determine axis directions, the effect of choosing a broader set of elevations was examined. Figure 4(bottom) shows aiming errors where (10°, 45°, 75°) was used for setting axis directions instead of (25°, 50°, 75°). Errors for Unit 3 in particular are much reduced at low sun elevations, and not much increased elsewhere. The corresponding total aiming errors are less than 2 milliradians for sun elevations below 85°.

Figure 4 also shows how the aim from the centre of any mirror deviates alternately right and left from the exact target as sun elevation increases through the three values used for axis setting. The errors from mirror units in the upper-left and lower-right quadrants, not shown here, are opposite in sign from those in the lower-left and upper right quadrants used for testing (Figure 2(b)), which means that the effective spread of errors over the whole collector is double that shown in Figure 4. However the resulting 4 milliradian spread is rather less than the size of the sun's disc (9 milliradians) and is therefore inconsequential.

The edges of the finite-size mirrors employed are at quite a distance from the centres where aim is determined initially, and this can be expected to degrade the focus of each mirror unit overall, even if it is curved for perfect focus at a particular sun elevation. To investigate this issue, the numerical model used earlier was extended to include an offset point on a given mirror unit at a specified position relative to the unit's centre. Such points are generally not coincident with the mirror unit axis of rotation, so translation of the point is accounted for as the mirror unit rotates, as well as angular change. The aim from the offset point is set precisely with the sun at a specified elevation, after finding the best aim from the centre point. The relationship between the mirror-normals for offset and centre points is kept constant for all other sun elevations. The reflected rays from both points are intersected with the target plane, and 2D errors reported in mm. For results given here, the corner points were placed corresponding to the centres of 100 x 100 mm mirror tiles mounted on the corners of the mirror units, i.e. 50 mm inwards both ways from the unit corners, at ±175 mm horizontally and ±100 mm vertically. The original mirror-unit axis directions were used (same as for the physical model), and 45° sun elevation was used to set the initial aims for the offset points.

Results from the corners of three mirror units are given in Figure 5, along with results from unit centres. Unit 3 (right at the edge of the collector aperture) has the largest aiming errors, and Unit 11 (closer to the centre of the aperture) has the smallest errors, but all of the corner errors at low and high sun elevations are far larger than the errors from the unit centres. Unit 3 aiming errors are worst at low sun elevations, but are also significant at high elevations. Unit 8 is worst at high sun elevations, and Unit 11 errors are more evenly distributed, as well as smaller overall. Since 20 mm on the target plane corresponds to about 7 milliradians of angular error, it can be said that the systematic aiming errors across most of the aperture are

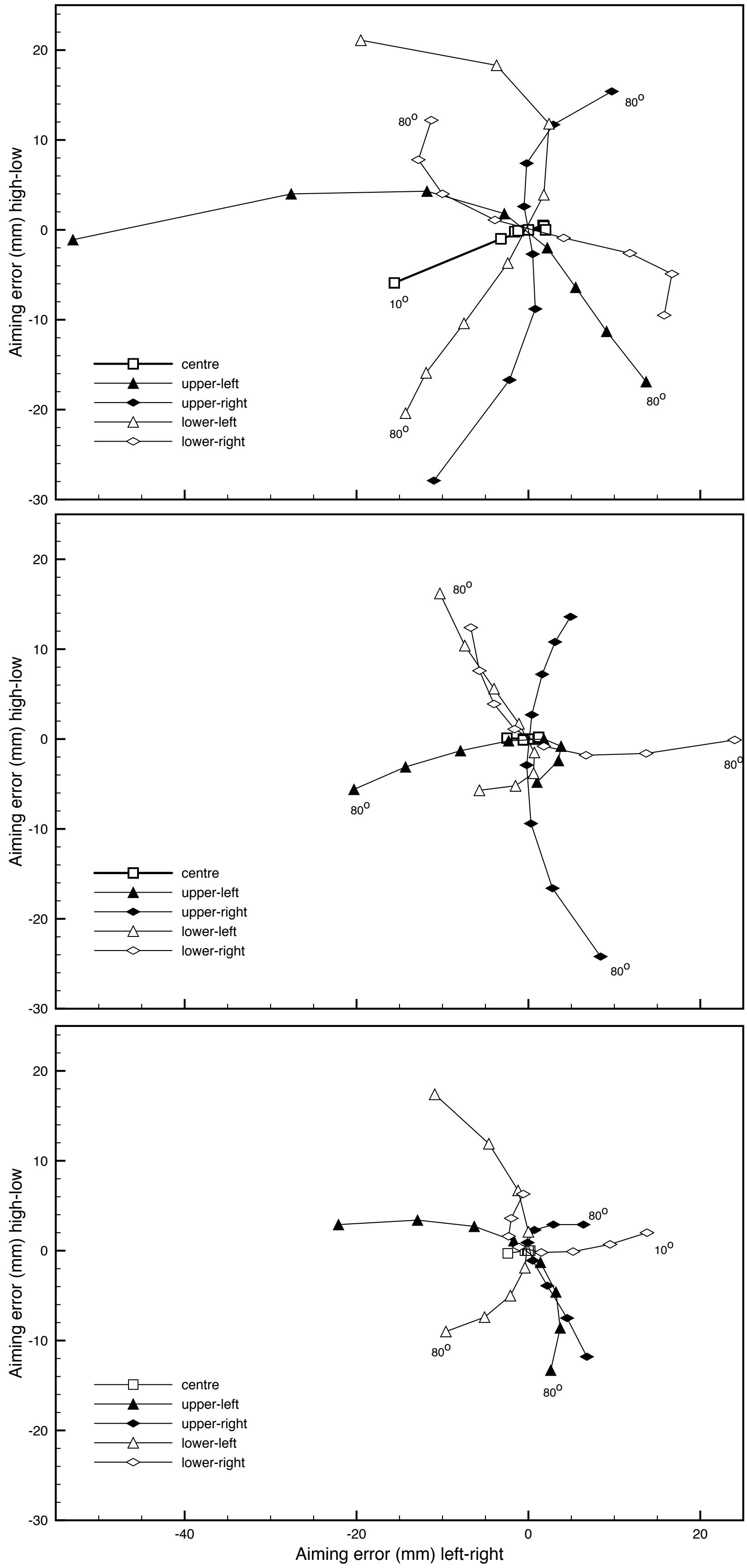

Figure 5. Aiming errors from the corners of mirror units at sun elevations from 10° to 80° in 10° steps. (top) Unit 3. (middle) Unit 8. (bottom) Unit 11.

Figure 6. Images on the 300 x 300 mm target from 100 x 100 mm mirror tiles at the centres of 10 mirror units. Sun elevations (a) 78°, (b) 49°, (c) 9°.

less than 7 milliradians for most sun elevations. Including 9 milliradians for the solar disc, the focused image would generally be less than 23 milliradians across (not counting random errors in construction), or about 70 mm in diameter. This corresponds to an (ideal) average concentration ratio of about 2700.

Results — physical model

The physical model was used as both a practical investigation of issues involved in designing and constructing a segmented dish, and a confirmation (within the limits of model construction accuracy) of results from the numerical model. Only a few indicative results are presented here. Figure 6 shows the composite image formed on the target by mirror tiles at the centres of the ten mirror units pictured in Figure 3(a), for three sun elevations. The best that can be expected from flat mirror tiles is that all light falls within the 150 x 150 mm ruled square on the target. In reality there is some spread horizontally caused (presumably) by construction errors and the timber-and-plywood model's lack of stiffness. The third image, at an elevation well below the three elevations used for determining axis directions, shows some additional spread as expected from the numerical model results.

Additional mirror tiles were fitted to the four corners of Units 3 and 8 (the latter can be seen in Figure 3(a), upper-right). As shown in Figure 7(b), the corner mirrors were adjusted for best aim at sun elevation 56°. Only a small amount of spreading occurred at higher elevations, but at low elevations the image spread considerably, both horizontally and vertically, as expected from the numerical results in Figure 5(top). These and other results (not shown) generally support conclusions drawn from the numerical results.

Figure 7. Images from the corner mirror tiles (plus centre) of Unit 3 at sun elevations (a) 78°, (b) 56°, (c) 16°. The additional patches of light come from other mirror units aimed slightly above the target.

Discussion

The impact of systematic errors resulting from using relatively large mirror units can be reduced: (i) The initial focus for each mirror unit could be set at a lower sun elevation than used here, given that the sun only reaches its highest elevations for short periods around the summer solstice. (ii) Different elevations could be used for focusing different mirror units to obtain a more even spread of errors. (iii) Mirror units can be made different sizes, i.e. made smaller where angular errors from their corners are greater. (iv) The number of units can be increased overall, making each mirror unit relatively smaller. (v) The mirror unit aspect ratio should be investigated — a squarer shape than the 3:2 rectangle used here may be better.

While the calculated concentration ratio is 2700, it must be borne in mind that random errors in construction will reduce it. In comparison, the ANU SG4 'Big Dish' of 489 m^2 aperture has a lower concentration ratio of 2240 at the entrance to its high-efficiency cavity-type receiver (Burgess et al 2011). However this value is constant, whereas the value for the segmented dish varies with sun elevation, and therefore detailed focus design would be required. On the other hand, the receiver of the segmented dish can be optimized for its fixed angle of tilt. Variable tilt is the problem for the paraboloidal dish: the entire device must be lifted bodily in order to track the sun in elevation, which requires separate frames for the dish itself and for the rotating base, and results in large, variable force concentrations at pivot joints. When the sun elevation is low, the dish acts like a giant sail or parachute in the wind, which further increases forces on its mountings and within its structure. The receiver mounting adds another group of eccentric forces that vary with dish elevation. All these variable concentrated forces require strong (and expensive) construction, and limit the size at which a dish can be built.

With a simpler, less expensive frame, and with no need to raise the whole structure bodily, the maximum economically feasible size of a segmented dish could be an order of magnitude (or more) larger than that of a paraboloidal dish. The sizes of heliostats in use or under development range from about 2 to 140 m^2 (Coventry and Pye 2014) . If the mirror units are sized within that range, with 100 units per collector, then 50 m^2 units result in a 5000 m^2 collector, 100 m^2 units give 10,000 m^2, and so on. Each mirror unit requires only a simple off-the-shelf linear actuator for elevation tracking. These collectors are 10 and 20 times larger than the SG4 'Big Dish'. Circular aperture diameters would be about 80 and 113 metres respectively, and the highest point on the collector mirrors (using 30^o tilt) would be 40 or 57 metres from the ground. (Such heights are considerable, but much lower than typical lattice-frame structures such as electricity pylons and TV transmission towers, and half the hub-heights of modern wind turbines.) Larger (hence fewer) collectors greatly reduce the cost and complexity of connecting the collectors to the power block and/or thermal storage. On the other hand, the cosine factor (geometrical collection efficiency) for a dish is 100%, but the annual average cosine factor for the segmented dish would be around 90% (varies with tilt and geographical location), so a 10,000 m^2 segmented dish replaces only 18 SG4 dishes.

For the 'power tower' CSP approach, only one central receiver is used to supply the power-block and thermal storage, and it is completely surrounded by heliostats. Most of the heliostats are at rather oblique angles to the sun most of the time, which reduces the amount of sunlight captured per unit area of heliostat. They are placed with large gaps between them to reduce shadowing and blocking, which means that many of them are at great distances from the receiver and must be focused and aimed very accurately, requiring expensive construction. The central receiver is open on all sides and subject to considerable heat loss by radiation and convection. The big advantage of this approach, however, is that all energy is transferred to the vicinity of the power-block in the form of the reflected sunlight itself, and therefore molten salt (for thermal storage) can be heated directly in the receiver. A 110 MW_e system with storage for 10 hours is now running in Nevada (SolarReserve, 2016).

If the molten salt can be heated indirectly by (for example) compressed gas or molten sodium, a modular tower-heliostat approach can be used, such as in the pilot project near Forbes NSW (Vast Solar, 2016). In each module, heliostats are placed in a fairly narrow 'polar field' aligned opposite the midday sun. They are less oblique to the sun than in surround fields, so geometrical efficiency is higher, and the field could be designed to use a cavity receiver. Each module can be viewed as equivalent to a segmented dish. For similar mirror area, the latter will perform a little better throughout the course of the day because of its large-scale azimuthal tracking, but quantifying the advantage requires detailed analysis of the polar field design. Based on the work of Ruiz et al (2014), a gain of perhaps 8-10% can be expected. Apart from this, cost comparison comes down to the cost of heliostat pedestals and two-axis tracking mechanisms against off-the-shelf linear actuators and a rotating base-frame. Based on data from Kolb et al (2007, 2011) the heliostats may be around 20% more expensive, but this is an area of active development and the current cost disadvantage may be less.

Finally, it may be noted that large-scale 'moving field' azimuthal rotation of itself is not new — for example D Jones mounted mirrors on a moving platform (Kolb et al, 2007), and Ruiz et al (2014) are mounting heliostats on trolleys on circular tracks — but the segmented dish is compact, geometrically superior, and requires only single-axis rotation for the mirror units (unlike previous designs). The present work has shown that its optical qualities are satisfactory, and that it is cheaper to build (at large scale) than paraboloidal dishes, but its cost advantage over single or modular central receiver and heliostat designs is unknown.

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