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A DETERMINISTIC METHOD FOR ALIGNING MULTIPLE OPTICAL WAVEGUIDES TO A PARABOLOIDAL COLLECTOR

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ABSTRACT

For solar lighting systems employing fiber optic waveguides[1,2], to conduct the collected light, paraboloidal mirrors are the preferred reflector choice. To achieve optimum performance in systems with relatively small collection apertures, both the quality of the mirror and the quality of optical system alignment must be well controlled.

In systems employing multiple waveguides with a single paraboloid, the focus of the paraboloid must be segmented into several separate focal points directed into individual fibers. Each waveguide entrance aperture must be accurately co-located with its designated focal point so that the image that is formed on the fiber will have the fewest possible aberrations and thus, the smallest possible focused spot size.

Two methods for aligning individual optical waveguides in a multi-aperture paraboloidal collection system are described. The first method employs a commercially available collimation tester to incrementally improve the alignment. The second, a deterministic method, employs a cube corner retro-reflector and an easily constructed imaging system to reliably align the fibers to their respective segments of the parent paraboloid. The image of the focused spot formed by the light that is returned from the retro-reflector reveals alignment information that is easily interpreted to enable pitch, yaw and focus errors to be systematically removed. This ensures that the alignment of the system is optimized to reduce aberrations prior to final adjustment of the system "on-sun".

INTRODUCTION

A paraboloidal mirror is uniquely suited for the collection of sunlight for distribution via optical waveguides. It represents the mathematically perfect solution to the energy concentration challenge. That is to say, it is the only shape that can perfectly reflect parallel rays to form an un-aberrated focused spot. The sun, because of its finite size and great distance, can be considered a source of parallel rays. And the introduction of sunlight into optical waveguides requires the ability to form a well-focused spot at the waveguide entrance aperture. To collect all of the light, the spot must obviously be smaller than the entrance aperture of the waveguide and the collection angle must not exceed that allowed by the numerical aperture of the waveguide[3].

The quality of the mirror and the alignment of the optical system both have a significant influence over the ultimate size of the focused spot. The minimum spot size that can be realized by a given mirror is determined by the degree to which the mirror represents a perfect paraboloid. Irregularities in the paraboloidal shape of the mirror, as well as any roughness or fine structure in the reflective surface, will cause light to stray from the intended point of focus. This results in a larger than optimum spot size and a degradation in optical performance. The physical imperfections in the paraboloid will determine the limit of the best performance that can be achieved with a particular mirror. Actually obtaining that level of performance requires that the mirror be perfectly aligned into the collection system. Any misalignment will create aberrations that further increase the spot size and decrease performance.

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A solar tracker employing fiber optic waveguides is shown in Figure 1. As the light reflected from the paraboloidal mirror converges, it intercepts an assembly of plane mirrors. These mirrors (see Figure 2.) divide and fold the collected light to form eight individual focused spots. A large core (12mm) optical waveguide is positioned at each of the focused spots to receive and conduct the collected light.

Figure 1. Solar tracker and collector system partially populated with four waveguides

Figure 2. Collection optics close up, showing segmented planar secondary mirrors

A solar collection system of this type could be constructed with little regard for the axis of the paraboloid. Conceivably such a system might even function well enough to get light into all of the waveguides. The system as a whole would, however, function with diminished performance. If the optical axis of the paraboloid were pointed a few degrees away from the sun, it would still concentrate the light but the alignment aberrations would produce (relatively) large and asymmetric focused spots.

Paraboloidal collector alignment – practical considerations

In order to appreciate the importance of properly aligning the paraboloidal primary mirror in a waveguide-distributed solar lighting system, the relationship of that alignment to the cost and performance of the system must be understood. Within such a system, the characteristics of the primary mirror, the solar tracking system and the waveguides for distribution of the collected sunlight are mutually interdependent. The collection of light into a fiber optic waveguide requires a mirror capable of producing a focused spot that will fit within the entrance aperture of the selected waveguide. In addition, the accuracy of the tracking system must be such that the focused spot remains within the aperture of the waveguide throughout the tracking process.

The interdependent nature of the system components has significant practical (and financial) implications. For example, assume it is possible to obtain a "perfect" solar tracking system for use with a convenient diameter of commercially available optical waveguide. The paraboloidal primary mirror for use in such a system could contain imperfections as long as it was of sufficient quality to collect the light into a spot the size of the entrance aperture of the waveguide. Since the cost of the mirror increases with the degree of accuracy of the paraboloidal surface, this would set an economic baseline.

However, real solar trackers are not perfect. They are constructed with mechanical drive mechanisms that may have slack or backlash in them, and they are controlled by feedback systems with gain and dead-band control limitations or by pre-programmed algorithms with finite inaccuracies. Thus, in a real tracking system the focused spot will move around relative to the aperture of the waveguide during the tracking process. To ensure that the focused light remains within the aperture of the waveguide, a better (more expensive) paraboloidal mirror may be necessary. Alternately, a lager (more expensive) waveguide might be chosen to accommodate the tracking system deviations. To keep the costs of the mirror and waveguide within manageable bounds, a more accurate (more expensive) tracker might have to be developed.

Whatever balance in performance is finally distributed among the three interdependent components, it is clear that any degradation in performance of one element will affect the requirements of the other two, as well as the overall system cost. It is for that reason that the alignment of the paraboloidal primary mirror is of such importance. Ultimately, the performance of the paraboloidal mirror is only as good as the quality of its alignment within the complete solar collection system.

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The challenge of aligning the paraboloid is that neither the optical axis nor the focal point can be directly measured by any mechanical means. Their locations can only be inferred through tedious physical measurements of the paraboloid's surface. With some manufacturing processes, such as single point diamond turning, it is easy to incorporate fiducial reference features for accurately locating the axis and focal point. Due to cost constraints, however, mirrors produced through (relatively) inexpensive replication processes are more likely candidates for use with solar lighting systems. With such mirrors, it is usually necessary to optically locate the focus and axis of the paraboloid.

Methods for optically locating the paraboloidal focus

Upon first consideration, the process of locating the focal point of a paraboloid may seem trivial. In principal, given a source of parallel rays, one need only adjust the paraboloid relative to the parallel rays, until an un-aberrated image is obtained. This general method is actually known as a "star test" and is widely used in amateur astronomy and optical testing[4]. The location of the best focus of that image is the focal point of the paraboloid, and the axis is the line that passes through that focus and is parallel to the rays from the source.

There are several challenges associated with using the star test method. Choosing a good source of parallel rays, for alignment of a large paraboloidal mirror, is not trivial. The source should be large enough to illuminate a representative portion of the aperture of the paraboloid and must not have any detectable divergence or convergence. Precisely adjusting the angular position of the mirror relative to the source of parallel rays can be an engineering challenge in itself, further complicating the overall alignment challenge. Evaluating the quality of the focused spot is non-trivial, requiring high resolution to reveal subtle alignment cues in the image. Even after an un-aberrated focus is obtained, however, identifying its position in a way that is useful for the alignment of the subsequent components may be difficult.

There is an alternate approach to locating the focus of a paraboloid that essentially reverses the approach used in the star test. Instead of beginning with a distant source of parallel rays, a point source is placed near the focus of the paraboloid. The location of the point source is then adjusted until the reflected rays from the paraboloid form an un- aberrated parallel beam. There are advantages to this method that make it very attractive. One advantage to this approach is that it is relatively simple to move the point source relative to the paraboloid. The need to precisely tip and tilt the mirror relative to a parallel source is eliminated. Another advantage to this method is that the apparatus that is used to position the point source provides an un-ambiguous reference, clearly marking the location of the focal point of the paraboloid.

The challenge with this method is that it is more difficult to observe aberrations in a parallel beam than it is to detect them in a focused spot. Two methods are described for locating the focus of a paraboloidal mirror by using a point source located near the focus. These methods require relatively simple hardware for detecting the aberrations in a parallel beam of light. The first method employs a commercially available collimation tester to incrementally improve the alignment. The second of the two methods uses a beamsplitter to sample the light returned from a retroreflector. The latter method builds upon a novel approach developed previously[5,6], to enable the aberrations to be very systematically interpreted to deterministically correct the alignment.

Alignment strategy

In the system shown in Figures 1 and 2, the mechanical mounting assembly that holds the waveguides in place allows for about 5mm of adjustment laterally in two dimensions (see Figure 3.) The vertical position of the waveguide can be adjusted to place its aperture at the height of the folded focal point from the paraboloid. It was determined that, using these available adjustments, each waveguide could be individually aligned to the best-fit parabolic surface of its respective octant of the mirror. Although local variations in the mirror might cause the individual best-fit paraboloids to have different optical axes, the aggregate should coincide with the axis of the parent mirror.

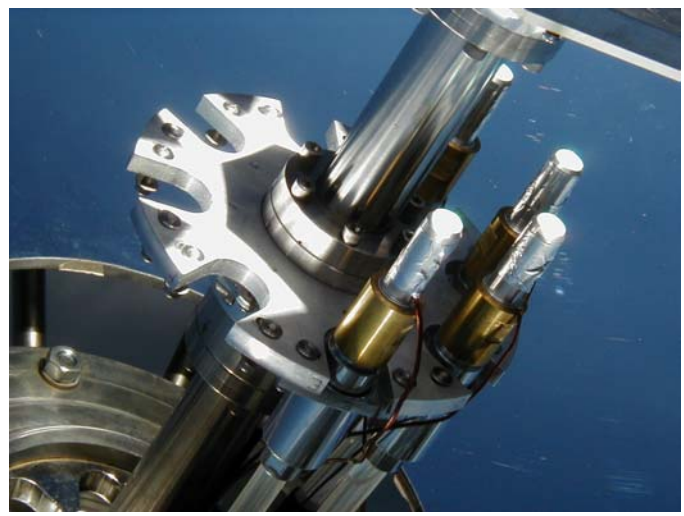

Figure 3. Close up of waveguide mounting structure showing slotted positioning mechanism (pitch adjustment slots visible at edges of round clamping nuts)

The alignment of each waveguide holder would be achieved by placing a fiber optic "point source" in an adapter designed to fit the mounting hardware for the waveguides. The location of the point source, mounted in the waveguide holder, would be adjusted until the aberrations in the collimated beam reflected from the paraboloid were removed. The adjustments would then be locked down and the height of the point source location recorded. After removing the point source, the waveguide would then be placed into the holder and is input aperture adjusted to the measured height.

After aligning the individual waveguides, the mirror would be pointed toward the sun. The azimuth and elevation would

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be adjusted to achieve a "best fit" of the multiple focused spots to the entrance apertures of the waveguides. This would, in effect, arrive at the average agreement in the location of the optical axis, accounting for any variations among the individual segments. Minor adjustments of selected waveguide positions would then ensure the foci were centered within the apertures of all of the waveguides.

Alignment procedure

To implement the alignment strategy, a single mode optical fiber was used for a point source. The end of this optical fiber was mounted in the center of an aluminum rod of the same diameter as the large core optical fiber waveguides. This enabled the point source to easily be secured into the mounting structures for the waveguides. A low-power helium neon laser was focused onto the opposite end of the single mode fiber using a microscope objective in a three-axis translation mount. The light from the fiber formed a diverging beam that illuminated the central portion of the collection area of the paraboloid octant being aligned.

The position of the point source was adjusted using the translation slots provided in the waveguide mounts. These are two orthogonal pairs of slots, one pair on the mount itself and one pair in the plate to which it is attached. Together they enable about 5mm of travel in the two axes. Movement of the mount radially in and out is referred to as "yaw" adjustment and the transverse adjustment is referred to as "pitch" adjustment. These refer to the influence that the two adjustments have on the beam direction. In both cases, pitch and yaw, the adjustment produces a deflection similar to that which would result from rotating the mirror about its associated (pitch or yaw) axis as illustrated in Figure 4. It is important to note that the adjustment for each segment has the same pitch and yaw nomenclature and that the frame of reference is tied to the individual mirror segment, without regard for where it is (e.g. 9 o'clock position versus 12 o'clock position) within the collector assembly.

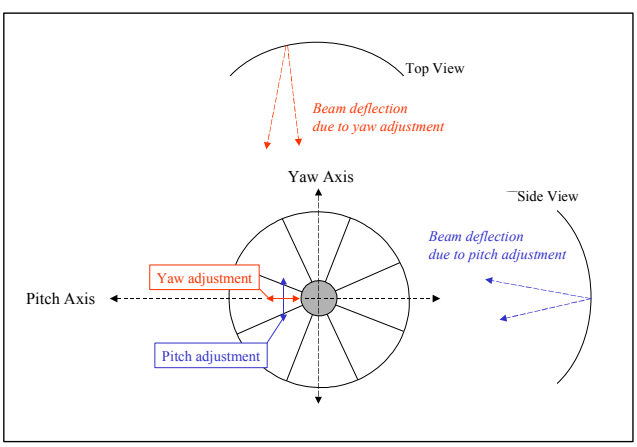

Figure 4. Schematic representation of parabolic collector illustrating axis definitions, pitch and yaw adjustment axes and associated beam deflections

The first method for identifying and eliminating aberrations in the collimated beam used a shear plate collimation tester (or shear plate interferometer). A shear plate interferometer is a simple device for evaluating the collimation of a laser beam[7]. It uses a thick glass plate to shear the incoming beam with respect to itself, producing an overlap region as shown in Figure 5. It incorporates an imaging screen upon which interference fringes are formed and a reference line is incorporated into the imaging screen so that the collimation can be evaluated (see Figure 6). When the fringes are parallel to the reference line, the light is collimated. If the light is either converging or diverging, the interference fringes will cross at an angle to the reference line. The sign of the slope indicates whether the beam is converging or diverging. The collimation of a beam is only evaluated along one axis (the shear axis along the reference line) at a time. When a beam contains astigmatic aberrations, the shear plate may show it to be perfectly collimated in one axis but will reveal defocus when the shear plate is rotated to analyze another axis.

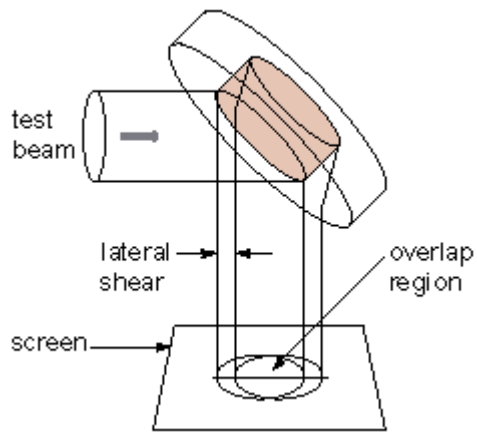

Figure 5. Schematic representation of shear plate *Source*: "Theory and uses of shear plates," http://photon.bu.edu/PRIDE/SC570/labs /lab1/theory.htm

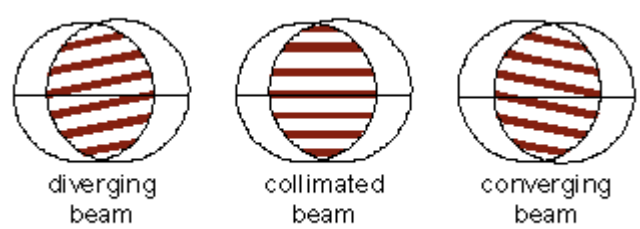

Figure 6. Shear plate interferograms showing divergent, collimated, and convergent beams *Source*: "Theory and uses of shear plates," http://photon.bu.edu/PRIDE/SC570 /labs/lab1/theory.htm

In the alignment process, the shear plate was placed in the semi-collimated beam reflected from the paraboloid. The shear axis of the plate was aligned with the radial axis of the segment

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being tested (i.e. the pitch axis). The height of the point source was first adjusted to eliminate the tilt in the interference fringes, so that they were parallel to the reference line. The shear plate was then rotated 90° so that its shear axis was perpendicular to the previous orientation. Any tilt observed in the fringes (see Figure 7) would indicate that the beam was astigmatic. To reduce the astigmatism, the "pitch" translation axis of the waveguide mount was adjusted to attempt to achieve an equal amount (magnitude and sign) of tilt in the interference fringes for both orientations of the shear plate. Once equalized, that axis was stabilized and (with the shear axis again aligned to the pitch axis of the segment) the focus error again minimized with the height adjustment. The process was then repeated using the "yaw" translation axis to attempt to remove the astigmatism by equalizing (for all shear plate orientations) any focus error that was observed. The highly iterative process consisted of first establishing a near focus condition, then identifying any astigmatism and removing it by making the amount of defocus equal in the two orthogonal shear plate orientations (and in between), then removing the residual focus. The process continued until the defocus and astigmatism were minimized.

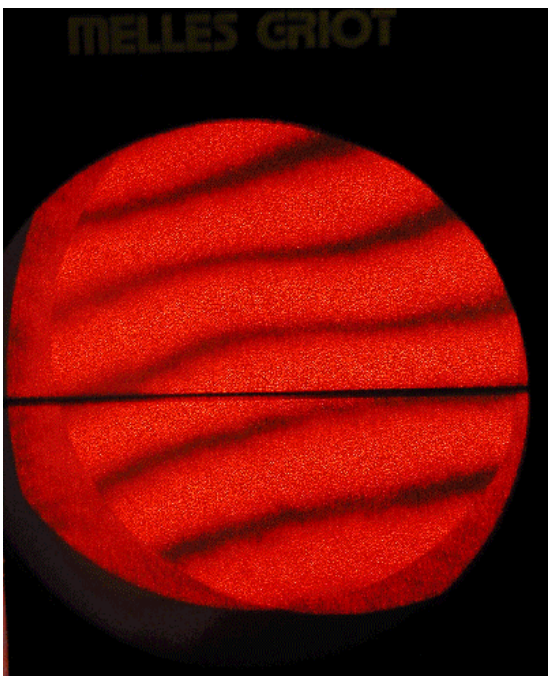

Figure 7. Shear plate interferogram revealing moderate focus error along with wavefront distortion

The second method for identifying and removing aberrations in the beam reflected from the paraboloid employed a large aperture (75mm) corner cube retroreflector. A corner cube retroreflector has the useful property that it returns light rays along a path exactly parallel to the path from which it received them. Thus, when it was placed in the semi-collimated beam reflected from the paraboloid it returned the light back to the same portion of the paraboloid from whence it came. That light was then re-focused onto the end of the single mode fiber. A beamsplitter and a CCD camera (just the CCD array with no lens) were used to sample part of the returned light to evaluate the quality of the focused spot. A microscope cover slip was used for the beamsplitter, making its cost negligible but creating a double image of the focused spot (due to the reflection from both surfaces of the cover slip). The camera and beamsplitter were mounted on a single mounting structure that was attached to the aluminum rod containing the point source. This assembly, shown in Figure 8, placed the beamsplitter at 45° to the returned beam and positioned the plane of the CCD array so that it and the point source were both equidistant from the beamsplitter. The output of the CCD array was observed on a black and white television monitor. As the height of the point source was adjusted, the focused spot on the camera could immediately be interpreted to see if the returned light was focused or not. The position of the point source could then be swiftly and intuitively moved to achieve the best focus of the returned light. It should be noted that this is tantamount to performing a star test, with the point source, paraboloid and corner cube functioning together to produce the source of the parallel light rays.

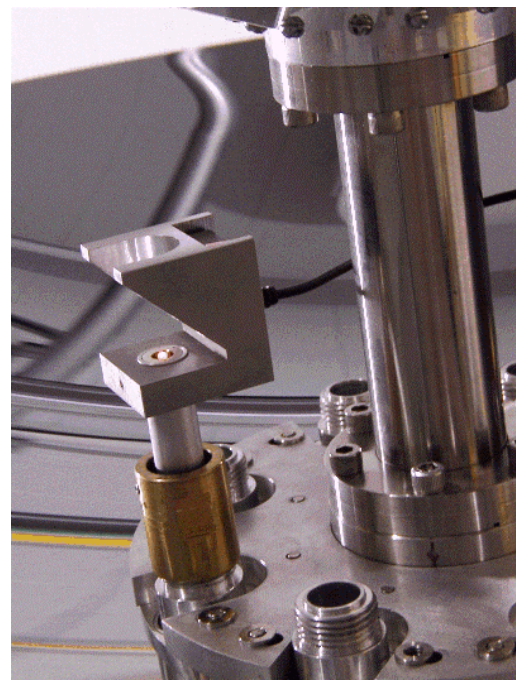

Figure 8. Beamsplitter/camera mount attached to single mode fiber adapter in waveguide mounting structure

It is the interpretation of the alignment information contained in the focused spot that makes this technique particularly useful. Initially the best focus will probably be observed to be somewhat elongated, indicating astigmatism. The nature of the interaction between the paraboloid and the retroreflector enables the elongation of the focused spot to be systematically evaluated to align the system. The beamsplitter/camera mount must first be oriented so that the camera is pointing outward along the radial (pitch) axis of the segment being adjusted. In that orientation, the following procedure can be followed.

Observing the focused spot, note whether the elongated spot is either perfectly vertical or horizontal. If it is tilted with respect to either axis, it indicates the presence of pitch error as shown in Figure 9a. Adjust the pitch translation of the

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waveguide mount to force the elongation into alignment with either the vertical or horizontal axis as shown in Figure 9b. The remaining elongation indicates yaw error and may be removed by adjusting the yaw translation axis to produce a round focused spot. The height of the point source is then adjusted once again to produce the best (smallest) focused spot. If the spot is round (as in Figure 9c) and shows no further elongation, the alignment is optimized. Otherwise, the same methods of interpretation and adjustment should be applied to eliminate any residual elongation in the focused spot.

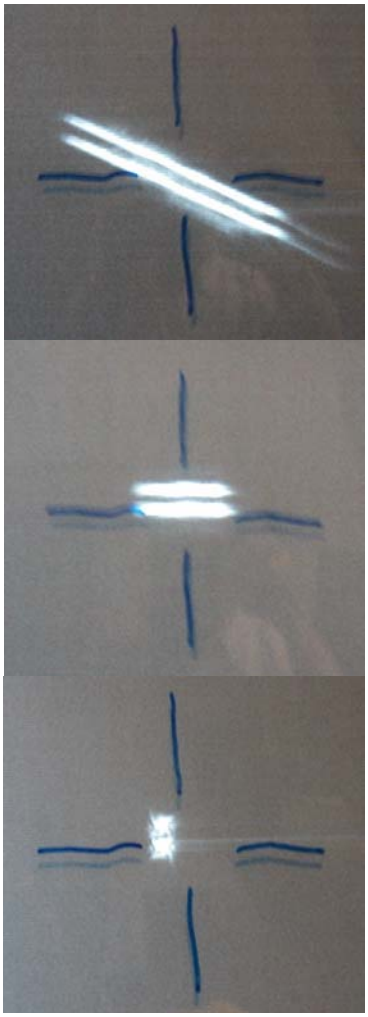

Figure 9. Alignment sequence showing:
a. prior to adjustment, dominant pitch error;
b. pitch error removed, revealing only yaw error;
c. yaw error removed revealing final well focused un-aberrated spots

DISCUSSION AND RESULTS

Both the shear plate method and the corner cube method of alignment proved to be effective, however, the corner cube method was faster, easier, and more reliable. The shear plate revealed some information about local surface irregularities in the mirror that were less obvious in the focused spots obtained with the corner cube method.

Some segments of the mirror showed greater irregularities than others. The focused spots for some segments were almost perfectly circular, while others had residual astigmatism that could not be eliminated through further alignment. Particularly in those cases, determining when the alignment was optimized would have been much more difficult with the shear plate method. During the alignment process, the segments that seemed to have significant distortion in the mirror were noted. During the "on-sun" final alignment, the majority of the spots could be centered in the waveguide apertures by adjusting the azimuth and elevation of the solar tracker. Minor additional adjustments using the translation adjustments on the waveguide mounts were necessary to optimize the alignment into the remaining waveguides.

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