Alignment of an inexpensive paraboloidal concentrator for hybrid solar lighting applications

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ABSTRACT

We describe a practical method for precisely aligning the optical components of a low-cost solar concentrator developed for fiber optic solar lighting applications. A two-stage alignment process, involving both mechanical and optical alignment techniques, is described which allows the tilt, centering, and focal alignment of a large parabolic primary reflector relative to a segmented planar secondary mirror to be accurately determined. The alignment strategy is well suited to optical systems utilizing large reflectors with non-referenced optical axes and non-precision surface characteristics, as is typical of many inexpensive reflectors.

Keywords: Optical alignment, solar lighting, solar concentrator

1. INTRODUCTION

1.1 Overview

Oak Ridge National Laboratory (ORNL) is developing a Hybrid Solar Lighting (HSL) System that collects and couples visible sunlight into large-core plastic optical fibers for use in internal lighting[1,2] (see Figure 1). A major step towards the realization of this energy-saving technology is the development of an efficient solar concentrator constructed from low-cost optical components. Figure 2 illustrates one of the concentrator designs which has recently been constructed, deployed, and is currently being evaluated by ORNL. This design consists of a commercially-available glass parabolic primary mirror (1.2m diameter) that reflects sunlight toward an eight-segmented planar secondary mirror. The secondary mirror is coated with a cold mirror coating that reflects visible light toward eight large-core optical fibers (12mm diameter), which receive and conduct the collected light into the interior of a building. For optimum performance, each of the eight focal spots created by the segmented secondary mirror should be centered on the face of a corresponding optical fiber. When the system is properly aligned, eight focal spots are produced that are each approximately 6mm in diameter, easily fitting within the diameter of an optical fiber.

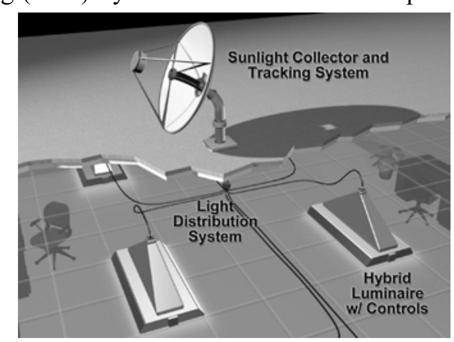
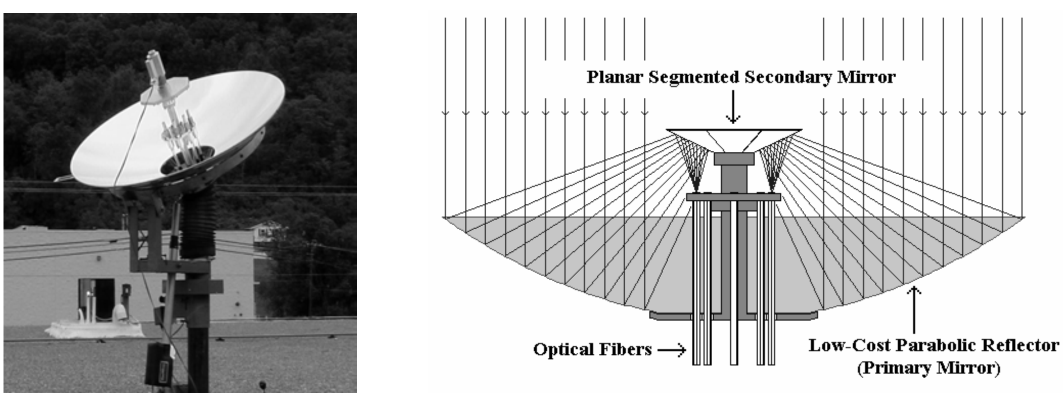


Figure 1. HSL Overview



(a) (b)

Figure 2: a) Photo of Prototype Solar Concentrator b) Ray-Trace Model of Prototype Solar Concentrator

"Under-filling" the optical fiber provides a valuable means of compensating for mechanical errors in the solar tracking hardware (i.e. backlash, pointing errors, etc.). To achieve this condition requires that the solar concentrator's primary mirror, secondary mirror, and optical fibers be aligned as accurately as possible. For a low-cost paraboloidal concentrator design, this can often be difficult to achieve. Large inexpensive parabolic reflectors are often fabricated with no reliable reference to the paraboloid's optical axis, and lower-grade mirror surfaces can hinder traditional optical alignment techniques. In addition, limited adjustments in a large mirror's mounts can be a further obstacle to precision alignment. This paper focuses on the challenges of working with low-cost, large diameter optics/mounts and details a two-stage alignment process that was recently developed by ORNL to precisely align a low-cost parabolic mirror with a segmented planar secondary mirror. Recent data and conclusions drawn from the application of this technique to the alignment of the ORNL prototype solar concentrator are presented and discussed.

1.2 Alignment tolerances and challenges

The ORNL prototype solar concentrator utilizes a custom-built frame for mounting the primary mirror, secondary mirror, and optical fibers. To reduce system cost and mechanical complexity, the mounting frame was designed with only minimal position/tilt adjustments for the various optical components. The least adjustable optical component is the secondary mirror, which is bolted directly to the mounting frame and has no positional or tilt adjustment. Second is the primary mirror, which is attached to the mounting frame with a silicone epoxy that attaches the mirror to twelve slotted aluminum tabs that, in turn, are bolted to the mounting frame. The slow-curing silicone epoxy requires two to three days to cure, allowing ample time to adjust the aluminum tabs and alter the centering, tilt, and height of the primary mirror relative to the secondary mirror (see Figure 3). However, once the epoxy has set, the position of the primary mirror is fixed and can no longer be adjusted.

In contrast, the optical fibers are mounted to the frame through an adjustable optical fiber mount. Although limited in its range of adjustment, the optical fiber mount does allow the position of the optical fibers to be adjusted in the pitch (+/- 3mm), the yaw (+/- 3mm), and the focus (+/- 15mm) directions (see Figure 3), making the optical fiber mount the sole post-assembly compensator for optical alignment errors in the concentrator.

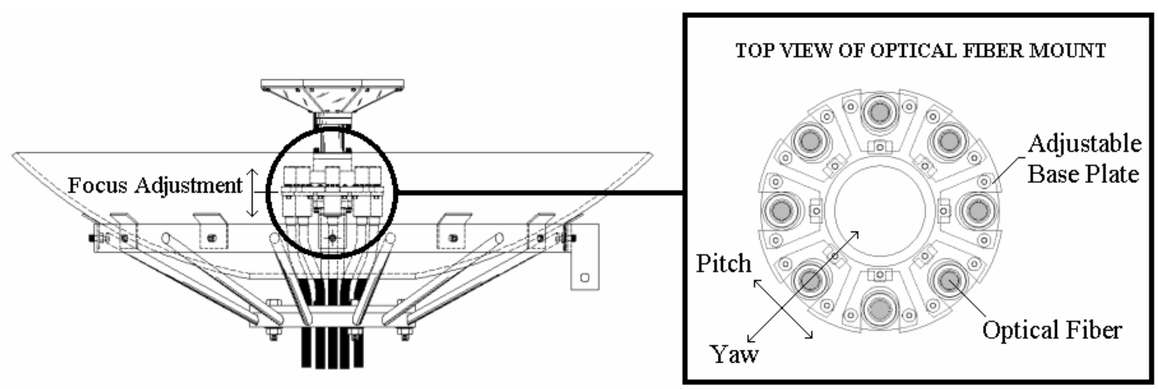


Figure 3. Adjustment Mechanisms

Given these constraints, and the optical requirement that each of the eight focused spots be centered on their corresponding optical fibers, the concentrator design shown in Figure 2 was modeled in ZEMAX to evaluate the required alignment tolerances for the primary and secondary mirrors. Because the position/tilt of the secondary mirror cannot be modified, the resulting alignment tolerances are described in terms of the primary mirror's tilt and de-center (which are still adjustable while the mounting epoxy is setting). The alignment tolerances, illustrated with greatly exaggerated errors, are shown in Figure 4:

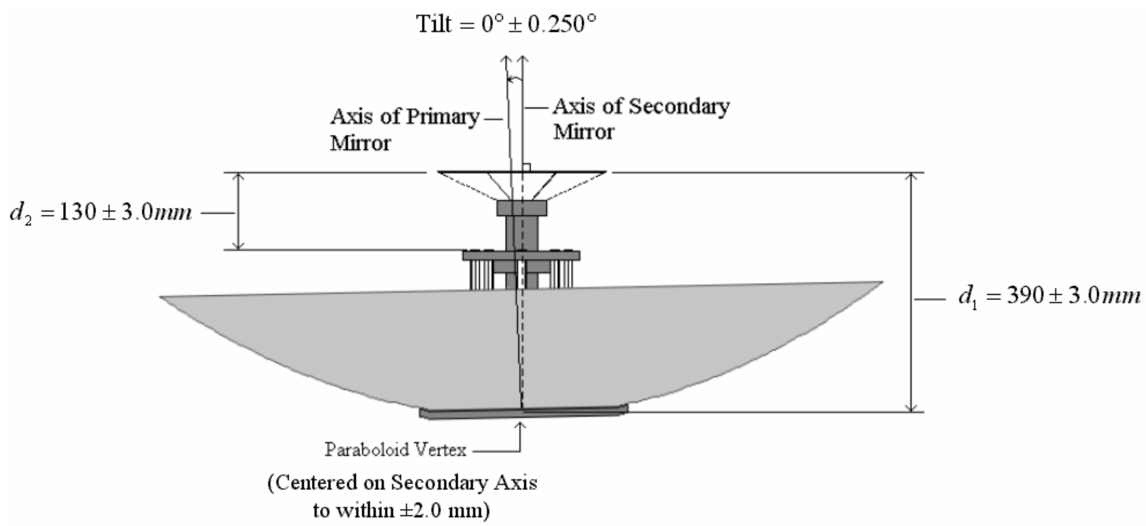


Figure 4. Alignment Tolerances

From Figure 4, it can be seen that the axis of the parabolic primary mirror must be parallel with the known axis of the secondary mirror to within ±0.250°. Similarly, the vertex of the primary must be centered on the optical axis of the secondary mirror to within ±2.0mm. Spacing between the primary and secondary mirrors, as well as the secondary mirror and optical fibers, must be accurate to within ±3.0mm. These tolerances are particularly challenging to meet when dealing with large, heavy reflectors that are not mounted on conventional optical breadboards or with fully adjustable optical mounts. In addition, because the fabricators of low-cost reflectors often do not provide reliable references to a reflector's optical axis, the first task in aligning a low-cost parabolic reflector is often to accurately determine the reflector's optical axis.

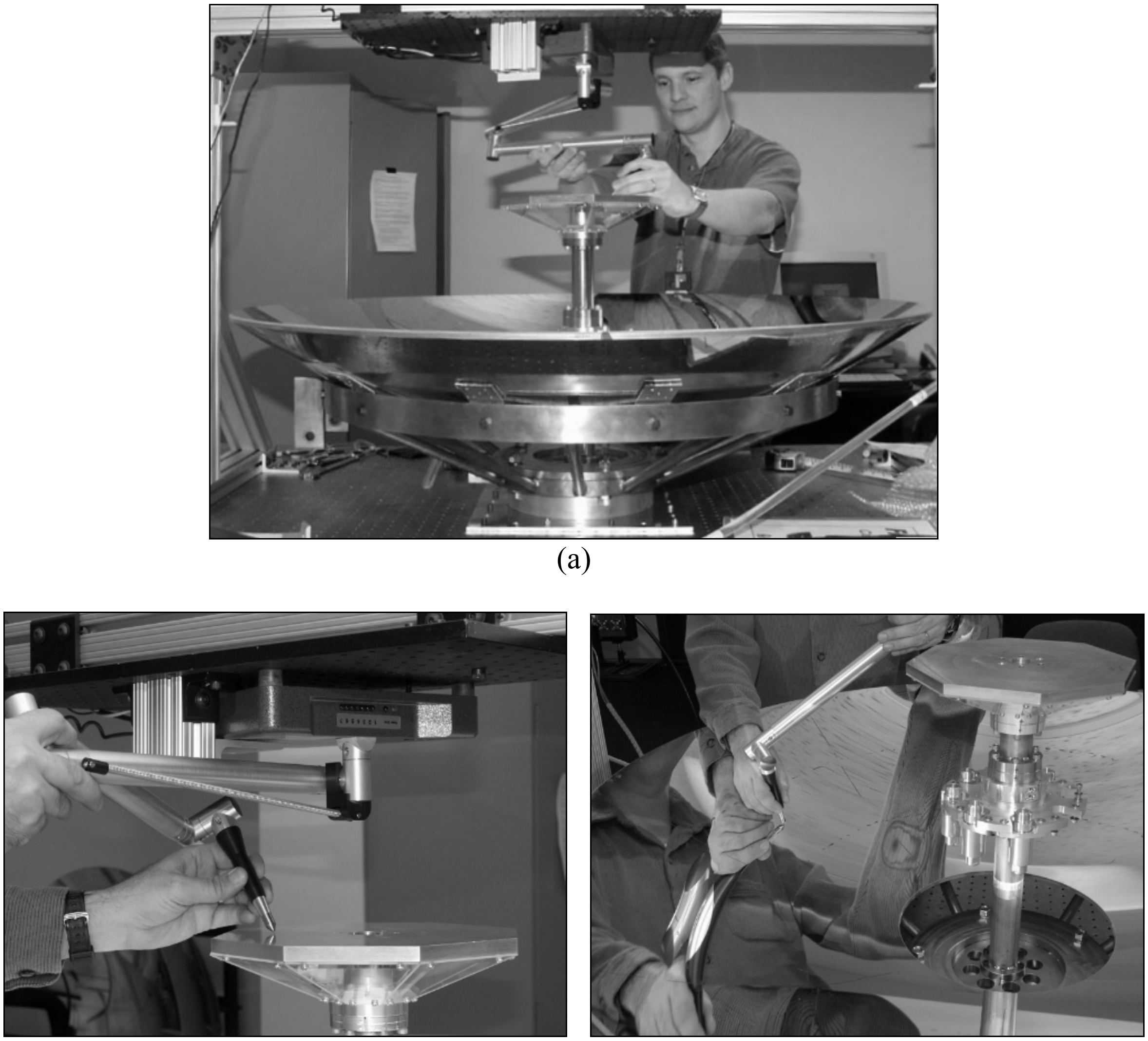
To achieve the accurate assembly of the ORNL prototype solar concentrator, ORNL developed a two-stage alignment process that can accurately align a parabolic mirror, with no known vertex and no optical axis fiducial features, to the known axis of a secondary mirror. The two-stage alignment method utilizes both mechanical and optical measurement techniques. The first stage of the procedure aligns the primary mirror relative to the secondary mirror's axis using a mechanical 3D measurement arm that characterizes the shape/orientation of the primary mirror relative to a reference plane located on the secondary mirror. The second stage involves the use of a geometric optical technique for evaluating the fine positioning of the optical fibers relative to the eight focal spots resulting from the concentrator's segmented secondary mirror. Both alignment stages are described and representative data presented.

2. METHODOLOGY

2.1 Alignment of the primary mirror relative to the secondary mirror

To align the parabolic primary mirror relative to the planar secondary mirror first requires that the vertex and optical axis of the parabolic mirror be determined. Upon first consideration, this task 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[3]. However, for various reasons, most notably difficulties in mounting and adjusting the large primary mirror and difficulties in creating a large-aperture collimated light source, the star test was deemed non-feasible for alignment of the ORNL solar concentrator. Instead, an alternative approach emerged utilizing an inexpensive 3D portable measurement arm (the Faro SpaceArm®) that allowed points in 3D space to be measured with millimeter accuracy (±2.0mm). The SpaceArm® is a hinged arm, equipped with rotational encoders, that measures the (x,y,z) coordinates of a hand-guided probe. The probe can be fashioned with a variety of probe points and, because of the delicate nature of mirror coatings, a spherical ball probe was chosen for all mirror measurements.

The SpaceArm® is used to digitize the top plane of the secondary mirror mount and software associated with the SpaceArm® is used to define this plane as the x-y reference plane for all subsequent coordinate measurements (see Figure 5a,b). With the top plane of the secondary mirror as a reference, the probe can be used to map the entire front surface of the primary mirror (see Figure 5c). At least two hundred measurements should be taken evenly across the surface of the primary mirror. To assist in this effort, dry erase marker may be used to delineate four measurement quadrants of the mirror. The quadrants can be arbitrarily labeled as north(N), south(S), east(E), and west(W) and the labels digitized with the probe to assist in later interpretation of the acquired surface data.



(a)

(b) (c)

Figure 5: a) Faro SpaceArm® Measurement Setup b) Measurement of the Secondary Mirror Reference Plane
c) Measurement of the Primary Mirror Surface

To determine the optical axis of the primary mirror and its orientation relative to the secondary mirror, the equation for a true paraboloid is fit to the measurement data obtained from the primary mirror. A least-squares algorithm solves for the best-fit parameters of a true paraboloid that may be rotationally and translationally transformed relative to the secondary mirror. The best-fit solution, which describes these rotational and translational transformations, provides the tilt and de-center error present in the primary mirror (in its current measured position). Based on this information, the necessary adjustments required to properly align the primary mirror with the secondary mirror can be estimated and made. Using the SpaceArm® as a measurement guide, the primary mirror can be "nudged" into correct alignment and re-measured.

Once a suitable alignment has been achieved and verified, the primary mirror is epoxied in place and re-measured to verify its alignment. If the alignment has unintentionally shifted, the necessary corrections can be made before the epoxy sets (usually several hours).

With the primary mirror and secondary mirror aligned, the distance from the secondary mirror to the optical fibers can be measured with the SpaceArm® and the optical fibers adjusted to the desired position. However, unavoidable errors in the alignment of the primary and secondary mirror will most likely alter the exact positioning of the eight focal spots resulting from the secondary/primary mirrors. Therefore, positioning of the optical fibers with the SpaceArm® is just a crude attempt at actual alignment of the optical fibers relative to the secondary mirror. A second, more precise, optical alignment method is used, once the primary mirror's epoxy has cured, for final positioning of the eight optical fibers.

2.2 Alignment of the optical fibers

For optimum performance, each of the eight optical fibers must be positioned and centered on one of the focal spots of the primary/secondary mirrors. Errors in the alignment of the primary and secondary mirror are unavoidable and, consequently, the focal spots of the primary/secondary mirror often deviate from their designed positions. To compensate for these errors, the position of each optical fiber can be adjusted slightly in the pitch, yaw, and focus directions (see Figure 3). To center each fiber on a focal point, a geometric optical alignment technique was developed that allows the best focus of each segment of the primary/secondary mirror to be determined. This technique utilizes a point source of light placed near the estimated focus of the primary/secondary segment. The location of the point source can then be finely adjusted until the reflected rays from the planar secondary mirror and primary paraboloidal mirror form an un-aberrated parallel beam. Although local variations in the mirror segments might cause the individual best-fit paraboloids to have different optical axes, the aggregate should coincide with the axis of the parent mirror. Two methods were developed for locating the focus of the primary/secondary mirror segments by using a point source located near the estimated 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[4,5] to enable the aberrations to be very systematically interpreted to deterministically correct the alignment.

For both methods, the alignment of each large-core optical fiber is achieved by placing a small-core fiber optic "point source" in an adapter designed to fit into the mounting for the large-core optical fibers. The location of the "point source", mounted in the optical fiber holder, can then be adjusted until the aberrations in the collimated beam reflected from the secondary and primary mirror are removed. The adjustments can be locked down and the height of the point source location recorded. After removing the point source, the large-core optical fiber can be replaced in the holder and its input aperture positioned at the recorded height. For all data presented in this paper, a single mode optical fiber was used as the alignment point source. The end of this small-core optical fiber is mounted in the center of an aluminum rod of the same diameter as the large-core optical fibers. This enabled the point source to be easily secured into the mounting structures for the optical fibers. A low-power helium neon laser is focused onto the opposite end of the single mode fiber using a microscope objective in a three-axis translation mount. The light from the end of the fiber forms a diverging beam that illuminates the central portions of the secondary and primary mirror segments being aligned.

The position of the point source is adjustable using the translation slots provided in the optical fiber 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 ±3mm 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 6.

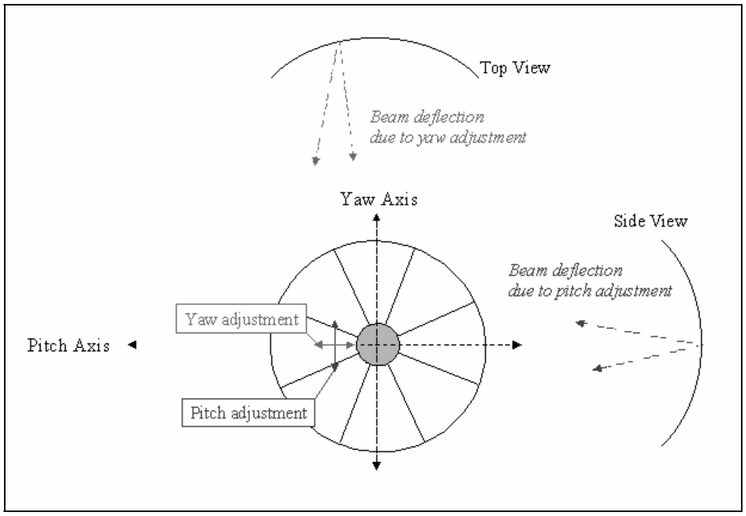


Figure 6. Schematic representation of parabolic concentrator illustrating axis definitions, pitch and yaw adjustment axes and associated beam deflections

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.

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[6]. It uses a thick glass plate to shear the incoming beam with respect to itself, producing an overlap region as shown in Figure 7.

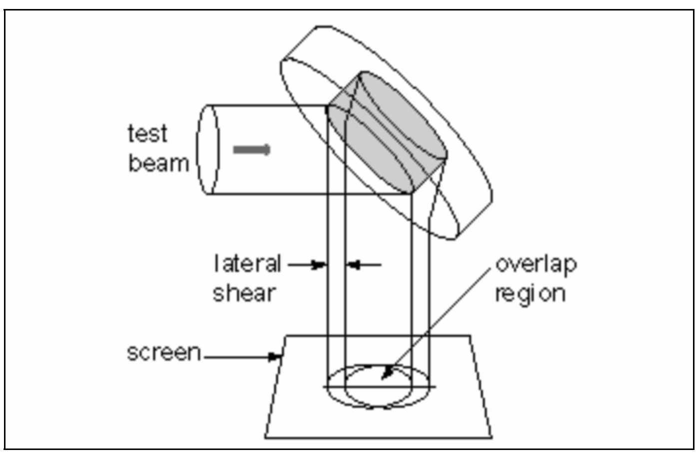


Figure 7. Schematic representation of shear plate

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 8). 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.

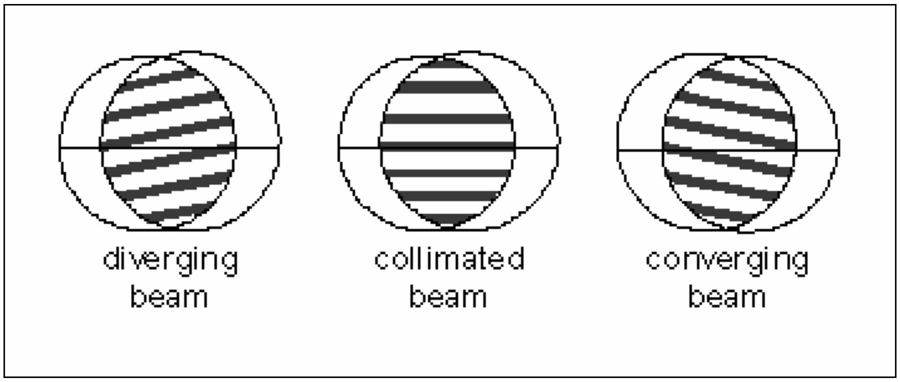


Figure 8. Shear plate interferograms showing divergent, collimated, and convergent beams

In the first alignment method, the shear plate is placed in the semi-collimated beam reflected from the parabolic primary mirror. The shear axis of the plate should be aligned with the radial axis of the segment being tested (i.e. the pitch axis). The height of the point source is first adjusted to eliminate the tilt in the interference fringes, so that they are parallel to the reference line. The shear plate is then rotated 90° so that its shear axis is perpendicular to the previous orientation. Any tilt observed in the fringes will indicate that the beam is astigmatic.

To reduce the astigmatism, the "pitch" translation axis of the optical fiber mount should be 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 is stabilized and (with the shear axis again aligned to the pitch axis of the segment) the focus error again minimized with the height adjustment. This process is then repeated using the "yaw" translation axis to attempt to remove the astigmatism by equalizing (for all shear plate orientations) any focus error that is observed. The highly iterative process consists 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 continues until the defocus and astigmatism are minimized.

The second method for identifying and removing aberrations in the beam reflected from the primary/secondary mirrors employs 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 is placed in the semi-collimated beam reflected from the parabolic primary mirror, it returns the light back to the same portion of the paraboloid from whence it came. That light is then re-focused onto the end of the single mode fiber. A beamsplitter and a CCD camera (just the CCD array with no lens) are used to sample part of the returned light to evaluate the quality of the focused spot. A microscope cover slip can be 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 are mounted on a single mounting structure that is attached to the aluminum rod containing the point source. This assembly, shown in Figure 9, places the beamsplitter at 45° to the returned beam and positions the plane of the CCD array so that it and the point source are both equidistant from the beamsplitter.

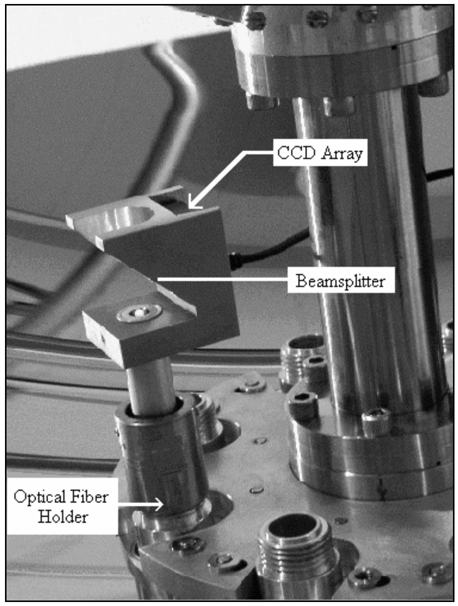


Figure 9. Beamsplitter/camera mount attached to single mode fiber adapter in waveguide mounting structure

The output of the CCD array can be observed on a television monitor. As the height of the point source is adjusted, the focused spot on the camera can immediately be interpreted to see if the returned light is focused or not. The position of the point source can 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, primary/secondary mirrors, and a corner cube functioning together to produce the source of the parallel light rays.

3. DATA

3.1 Alignment Data

To evaluate the effectiveness of the two-staged alignment procedure, the described alignment methods were used to align the ORNL prototype solar concentrator. Following the in-lab alignment, the solar concentrator was mounted onto a solar tracking mechanism that allowed the concentrator to be accurately pointed toward the sun. If the alignment had been performed successfully, all eight focal spots created by the primary/secondary mirrors would be centered on the large-core optical fibers. If the alignment errors exceeded the tolerances specified in Figure 4, it would not be possible to illuminate all eight optical fibers. This on-sun test provided the most direct measurement of the alignment techniques effectiveness.

In determining the optical axis of the primary mirror, the 3D measurement arm (the Faro SpaceArm®) was used to acquire the data shown in Figure 10.

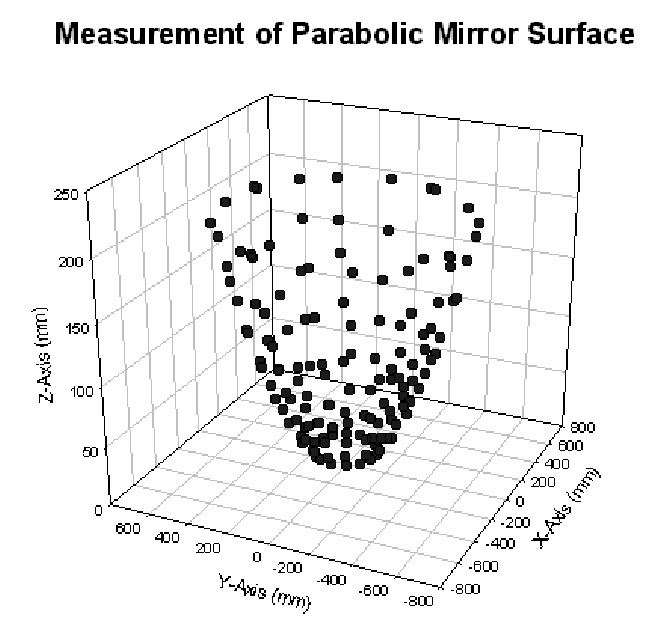


Figure 10. Measurement data on parabolic primary mirror

This data was fit to the equation of a generalized paraboloid (which incorporated translational and rotational transformations). An evaluation of the least-squares error showed that the fit (which was performed over approximately 200 points) determined the vertex of the paraboloid to ±0.4mm and identified the tilt in the paraboloid's optical axis to ±0.03°. The results of an initial fit showed that the primary mirror was significantly tilted relative to the secondary mirror. Therefore, the tilt of the primary mirror was corrected and 3D measurements repeated. Typically, three to four re-position/re-measurement iterations were required before a suitable alignment was verified. Once obtained, the primary mirror was epoxied in place and its final position/orientation re-measured.

With the primary and secondary mirrors aligned, the fine positioning of the optical fibers remained. The two optical alignment methods previously described were used to accurately adjust the position of the optical fibers relative to the focus of the primary/secondary mirror. The first method, which utilized a sheer plate, was helpful in eliminating de-focus errors and in identifying local distortions in the primary mirror which might influence the validity of the optical measurements (see Figure 11).

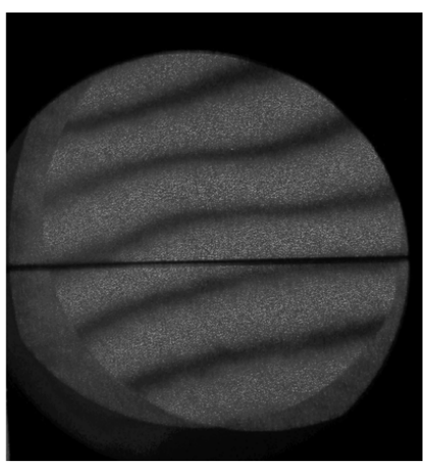
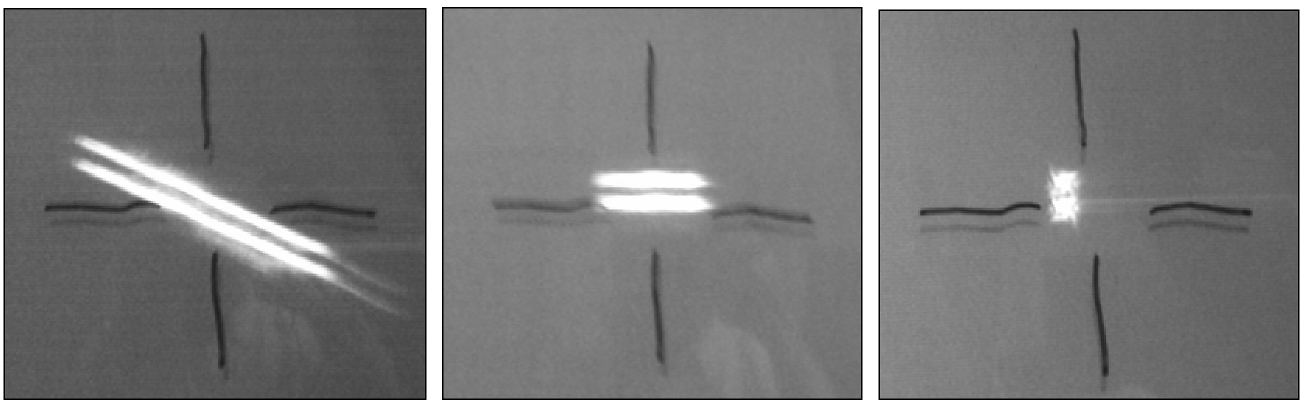


Figure 11. Shear plate interferogram revealing moderate focus error along with wavefront distortion

However, although helpful in aligning the optical fibers relative to the secondary mirror, the sheer plate method was, in general, difficult to use due to its ability to only measure one adjustment axis at a time. In addition, the response of the sheer plate to pitch and yaw adjustments did not reveal an intuitive path to optimal positioning of the optical fibers.

Fortunately, the second optical method, which utilized a corner cube reflector, did result in a more intuitive alignment technique. In particular, the interpretation of the alignment information contained in the focused spot made this technique particularly useful in separating the various alignment errors encountered. With the beamsplitter/camera mount oriented so that the camera was pointing outward along the radial (pitch) axis of the segment being adjusted, the nature of the interaction between the paraboloid and the retroreflector enabled the elongation of the focused spot to be systematically evaluated to align the system. In that configuration, the following alignment procedure was followed:

Observing the focused spot, it was noted whether the elongated spot was either perfectly vertical or horizontal. If it was tilted with respect to either axis, then that indicated the presence of pitch error as shown in Figure 12a. The pitch translation of the optical fiber mount was adjusted to force the spot elongation into alignment with either the vertical or horizontal axis as shown in Figure 12b. The remaining elongation indicated yaw error and was removed by adjusting the yaw translation axis to produce a round focused spot. The height of the point source was then adjusted to produce the best (smallest) focused spot. If the spot was round (as in Figure 12c) and showed no further elongation, the alignment was declared optimized. Otherwise, the methods of interpretation and adjustment were repeated to eliminate any residual elongation in the focused spot.



(a) (b) (c)

Figure 12. 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

All eight optical fibers were aligned using the optical technique illustrated in Figure 12. Once the optical fibers had been positioned, the ORNL prototype solar concentrator was moved to an outside facility that allowed the concentrator to be accurately pointed toward the sun. The azimuth and elevation were adjusted to achieve a “best fit” of the multiple focused spots to the entrance apertures of each optical fiber. This, in effect, arrived at the average agreement in the location of the optical axis, accounting for any variations among the individual segments. Only minor adjustments of selected optical fiber positions were needed to ensure that the eight foci were centered within the apertures of all of the eight optical fibers. This alignment technique was repeated for two additional solar concentrators and their alignments also successfully verified by “on-sun” tests.

4. CONCLUSIONS

The alignment methods described in this paper have been successfully used to accurately align a large-diameter parabolic reflector with a segmented planar secondary mirror, for use in solar concentration. Based on these successes, this technique may be of value to other technical areas where low-cost parabolic reflectors, with limited or no fiducial reference features, are required. Although not well suited to system alignment on a mass production scale, these alignment methods are valuable for prototype development and alignment evaluation situations.

REFERENCES

1. J. D. Muhs, "Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings", CADDET Energy Efficiency Newsletter December 2000, p. 6.
2. J. D. Muhs, "Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems", *Solar 2000, July 16-21, 2000,* American Solar Energy Society.
3. "Star Tests," Optical Shop Testing, Chapter 11, Edited by Daniel Malacara, John Wiley and Sons Inc., 1978
4. L. C. Maxey, "Novel Technique for Aligning Paraboloids," Proc. SPIE 1531, 147-155, 1991
5. L. C. Maxey, et al., "Automated Alignment System for Aspheric Mirrors," Proc. SPIE 1776, 130-139, 1992
6. "Theory and uses of shear plates," http://photon.bu.edu/PRIDE/SC570/labs/lab1/theory.htm