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TRACKING SYSTEMS EVALUATION FOR THE "HYBRID LIGHTING SYSTEM"

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ABSTRACT

As part of the design and development effort for the "Hybrid Lighting System," Oak Ridge National Laboratory (ORNL) scientists have evaluated two potential candidate-tracking systems for the solar collector. The first system, the WattSun Solar Tracker, built by Array Technologies, utilizes a patented, closed loop, optical sun sensor to sense the sun's position and track it. The second tracking system, SolarTrak Controller, built by Enhancement Electronics, Inc., is a micro controller-based tracking system. The SolarTrak micro controller-based Tracker's sun position is determined by computing the celestial bearing of the sun with respect to the earth using the local time, date, latitude, longitude and time zone rather than sensing the relative bearing of the sun with optical receptors. This system connects directly to the mechanical system hardware supplied by Array Technologies. Both the WattSun Solar Tracker and the SolarTrak Controller were mounted on the prototype "Hybrid Lighting" mechanical system (array) hardware. A simple switch allowed independent testing of each system.

Upon completion of the evaluation of the two systems we found the WattSun Solar Tracker controller to be unacceptable for use with our prototype hybrid lighting system. The SolarTrak Controller has performed well to date and provides suitable tracking accuracy for use with our prototype "Hybrid Lighting System". After a six-month evaluation period at ORNL, the first prototype "Hybrid Lighting System" was installed at Ohio University as part of an "Enhanced Practical Photosynthetic CO2 Mitigation." This document will highlight the results of the tracker investigation and outline the remaining issues to be addressed, to provide a suitable tracking system for our "Hybrid Lighting" collector.

INTRODUCTION

As part of the design and development effort for the "Hybrid Lighting System," ORNL scientists have evaluated two potential candidate-tracking systems for the solar collector. The first system, the WattSun Solar Tracker, built by Array Technologies, utilizes a patented, closed loop, optical sun sensor to sense the sun's position and track it. The second tracking system, the SolarTrak Controller, built by Enhancement Electronics, Inc., is a micro controller-based tracking system. The SolarTrak micro controller-based system determines sun position by computing the celestial bearing of the sun with respect to the earth using the local time, date, latitude, longitude and time zone rather than sensing the relative bearing of the sun with optical receptors. This system connects directly to the mechanical system hardware (which will be referred to as the array) supplied by Array Technologies. Both the WattSun Solar Tracker and the SolarTrak Controller were mounted on the array and used a simple switch to allow independent testing of each system.

The collector alignment along with the tracking accuracy is critical to the performance of the "Hybrid Lighting System," In order to better understand the issues of alignment and tracking accuracy, ZEMAX ray-tracing software was used to optically model and analyzed the complete Hybrid Lighting Solar Collector system. The sensitivity of the modeled solar collector to various internal misalignments was analyzed and acceptable alignment tolerances determined. These same tolerances apply to both the alignment of the collector as well as the tracking accuracy. Five alignment parameters were identified as critical

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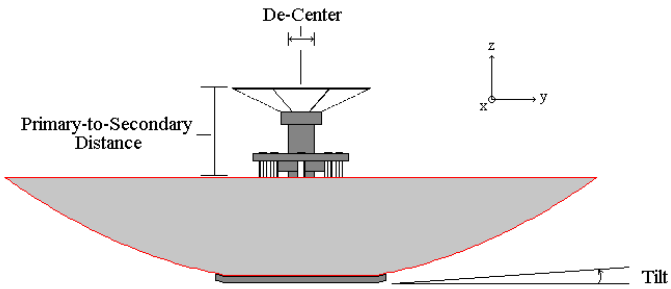
to the proper operation of the solar collector. These alignment parameters are shown in Fig. 1:



- X-Tilt = X-Axis Tilt of Primary Mirror Axis Relative to Secondary Axis
- Y-Tilt = Y-Axis Tilt of Primary Mirror Axis Relative to Secondary Axis
- X-De-Center = Offset in the X-Axis Between Secondary Center and Primary Center
- Y-De-Center = Offset in the Y-Axis Between Secondary Center and Primary Center
- Prim-to-Sec Distance = Distance Between Secondary and Primary Mirror

Fig. 1. Critical Internal Alignment Parameters

If each of the alignment parameters in Fig. 1 is perfectly adjusted (zero alignment errors), and the collector is properly tracking the sun, then the sunlight collected by the solar collector will be precisely focused into the center of each of the eight fiber optic cores (see Fig. 2a). However, if the alignment parameters are not perfectly adjusted, as is typically the case, the focused sunlight will be off-center to the core of the optical fiber (see Fig. 2b) and may even miss the fiber core altogether.

To compensate for these misalignments, the eight optical fibers are mounted in movable holders that can move ±4 mm in any direction. Unfortunately, this limited fiber mobility provides only marginal compensation for misalignments, and thus, imposes a relatively high tolerance on the five alignment parameters identified in Fig. 1. Using the ZEMAX model of the solar collector, the alignment tolerances needed to insure the complete capture of focused sunlight into all eight optical fibers was computed. If a misalignment caused any portion of the focused sunlight to exceed the reach of the fiber optic cores, the misalignment was deemed unacceptable. Given these conditions, the acceptable alignment tolerances were calculated from the model and provided in Table 1.

Parameter	Tolerance
X-Tilt	±0.125°
Y-Tilt	±0.125°
X-De-Center	±3.0 mm
Y-De-Center	±3.0 mm
Prim-to-Sec Distance	±2 mm

Table 1. Acceptable Alignment Tolerances

To meet these desired tolerances, the assembly of the solar collector was performed in a laboratory setting and the placement/orientation of the collector's components were precisely measured with a Faro SpaceArm 3D digitizer (See Fig. 3).

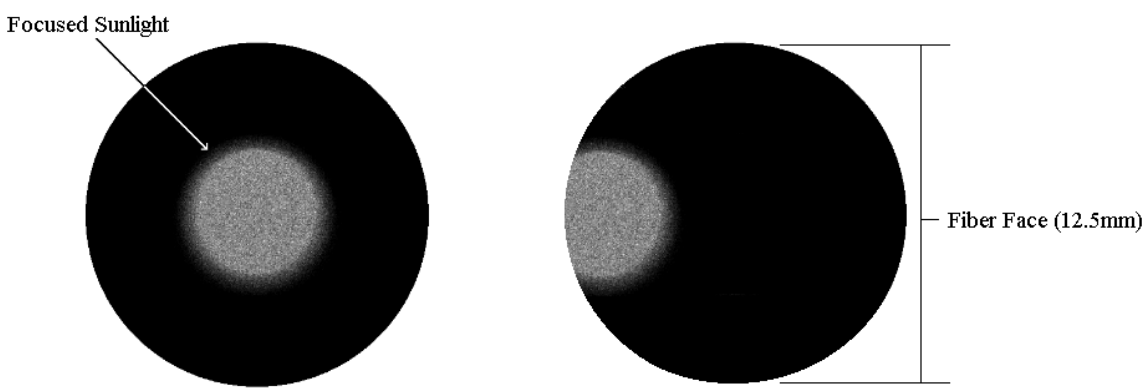


Fig. 2a) Collection of Sunlight Under Ideal Alignment Conditions, b) Collection of Sunlight When Internal Misalignments Present

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Fig. 3. Measurement and Alignment of Collector Optics

After assembly, the errors on the various alignment parameters were measured and summarized in Table 2.

Parameter	Error
X-Tilt	+0.089°
Y-Tilt	-0.209°
X-De-Center	0.1 mm
Y-De-Center	0.5 mm
Prim-to-Sec Distance	-1.55 mm

Table 2. Final Measured Alignment Errors

Due to the crude and limited adjustments available during assembly, one of the five acceptable alignment tolerances was not met. However, it was determined that, because of the relatively small errors experienced in the other alignment parameters, this error would only result in a small (< 5%) decrease in the final efficiency of the solar collector. Therefore, the re-alignment of the solar collector was not attempted. In order for the tracking system to meet these same tolerances, the tracking system must be able to track the sun well enough to meet the X- and Y-tilt tolerances outlined in Table 1.

WattSun Solar Tracker Evaluation

General Description

The WattSun Solar Tracker, built by Array Technologies, utilizes a patented, closed loop, optical sun sensing system to sense the sun's position and track it. The optical sun sensor consists of a square post machined to a cone tip with four individual optical sensors. Figure 4 shows a photo of the optical sun sensor with the individual optical sensors mounted at approximately 45 degrees to the face of the square post. The optical sun sensor is mounted such that its axis is parallel to the center axis of the solar collector. When the cone tip is pointed toward a light source (the sun) the controller circuitry sums the signals from the four individual sensors. The closed loop system feeds information to the controller electronics about the direct component of sunlight available, the diffuse amount of sunlight, the total amount of sunlight as well as the differential amount of sunlight on the opposing sensors. The control electronics then provides a signal to the azimuth-elevation motors to move the optical sun sensor until the individual optical sensors balance.

Test Set-Up

The test set-up consisted of the WattSun Tracker Mechanism with a frame attached to provide a sun pointer mechanism to allow us to monitor the tracking accuracy of the overall system using the WattSun optical sun sensor. The overall WattSun Tracker system mechanism is shown in Fig. 5.

Figure 6 shows a close-up view of just the collector-mounting frame along with the pinhole-mounting frame, the sun pointer grid mounting, and the optical sun sensor arrangement. An aluminum plate is mounted on the pinhole-mounting frame with a 1 mm pinhole in the center. The pinhole projects sunlight onto a 38.1 X 38.1 mm (1.5 X 1.5 inch) grid paper 673.1 mm (26.5 inches) below the pinhole. The optical sun sensor is mounted such that its apparent centerline is parallel to the sunlight projected through the pinhole and onto center of the grid paper. This allows one to monitor the tracking ability of the WattSun tracker and determine the tracking error projected over the 673.1 mm (26.5 inch) light path.

Wattsun Tracker Array with Optical Sun Sensor Test Results

The tracker system was evaluated under various sun conditions; bright sunny days with clear conditions, slightly hazy days with few clouds, partial overcast days and overcast days. We found that the WattSun Tracker with the optical sun sensor performed reasonably well only on days with bright sun and clear conditions. On days with hazy or cloudy conditions, when the system's metal frame did not project a strong shadow, or there was not enough light to project a sun spot via the sun pointer, the system would not consistently or accurately track the sun. In fact, the system would often search during cloudy or hazy times and then if the sun came out from behind a cloud, the sun spot projected by the sun pointer would be off considerably from were it should be.

Furthermore, because the system seeks to balance the signal from the individual sensors opposite one another on the optical sun sensor, partial sky shadowing effects from building's in the near vicinity of the tracker or dark clouds in a portion of the sky would cause the system not to track properly. These problems cause the WattSun optical sun sensor to be unacceptable for use on our hybrid lighting system which requires that the axis of the primary and secondary mirrors be precisely aligned with the sun at all times in order for the system to operate efficiently.

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Fig. 4. Optical Sun Sensor device used to provide feedback to the electronics control system

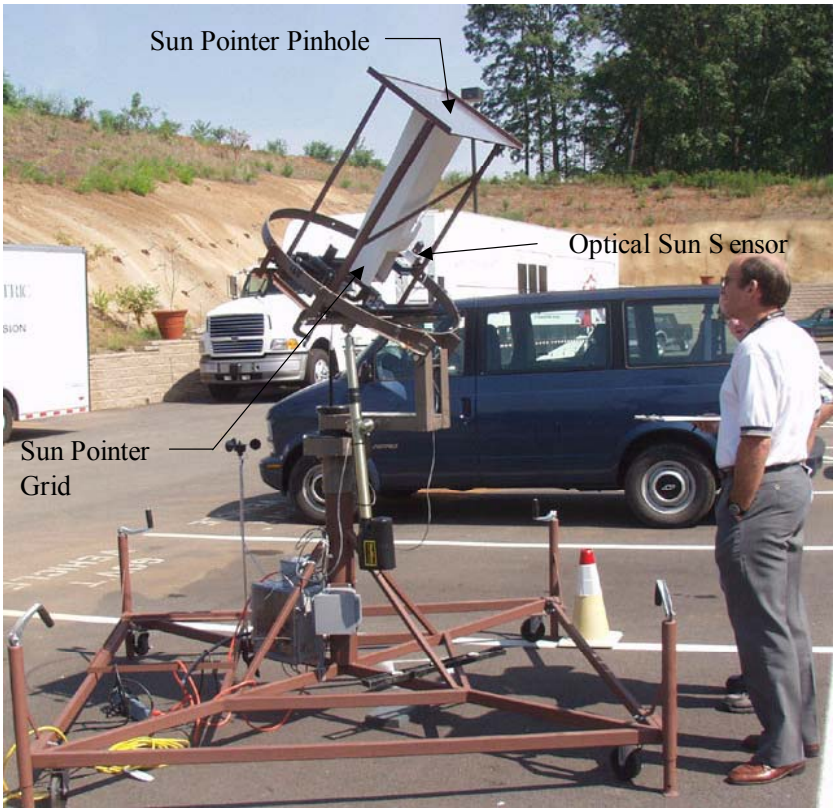

Fig. 5. Overview of the WattSun Tracker with a frame added to provide a sun pointer for monitoring overall system tracking accuracy

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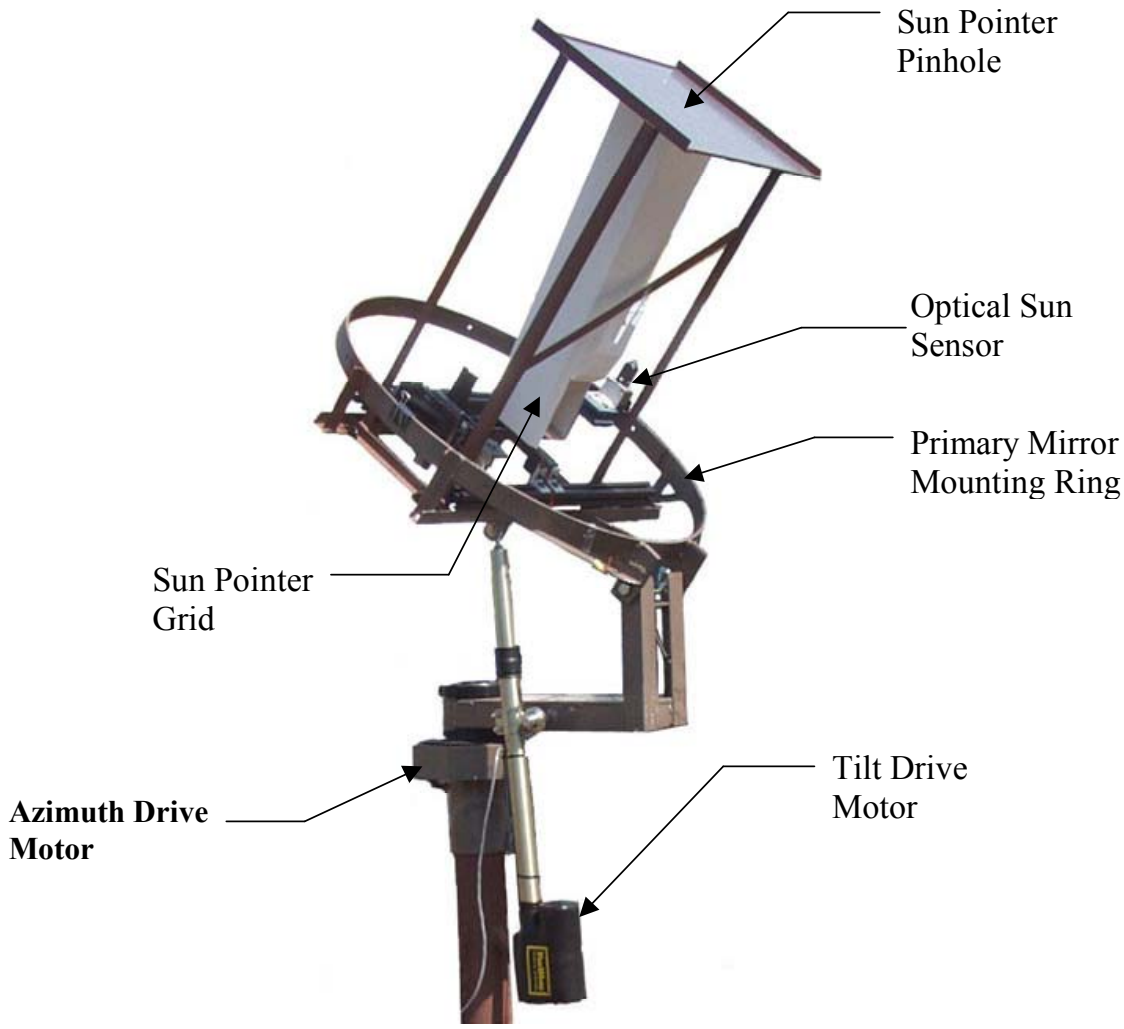

Fig. 6. Close-up view of the collector mounting ring along with the pinhole mounting frame, the grid paper mounting, and the optical sun sensor arrangement

In order to fully evaluate the WattSun optical sun sensor and attempt to quantify its accuracy, we performed two types of tests under bright, sunny, clear conditions. The tests were performed to determine the accuracy of the WattSun optical sun sensor under ideal conditions. The WattSun tracker system has two modes of operation: 1) manual, which allows one to manually move the tracker via a joystick type arrangement, and 2) automatic, which uses the optical sun sensor to sense the position of the sun and serve as a feedback to automatically track the sun. The first series of tests performed consisted of:

1) placing the WattSun Tracker in the automatic mode and noting the position of the projected sunspot;
2) switching the system to manual and moving the tracker until the sunspot was misaligned approximately 1 inch in a given direction;
3) switching it back to automatic and allowing it the reposition the sun spot and noting the degree of misalignment of the new position; and finally,
4) this process was repeated five times for each direction, (east, west, north, south, southeast, southwest, northeast, and northwest) and the amount of misalignment or error were noted.

The spot size of the projected sunspot was approximately 6.35 mm (0.25 inches) and the maximum error recorded for the center movement was +/- 10.16 mm (0.40 inches) in the X direction and +/- 8.89 mm (0.35 inches) the Y direction. This corresponds to an angular error of +/- 0.75 degrees in the X

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direction and +/-0.86 degrees in the Y direction. Referring to the Acceptable Alignment Tolerances outline in Table 1 of the introduction, the misalignment due to tracking with the optical sun sensor is unacceptable.

The second series of tests consisted of allowing the system (again under ideal, bright, sunny conditions) to track the sun during a period from 11 a.m. (once there was no building shadowing effect) until 5:15 p.m. During this period, the position of the sunspot was noted at regular time interval. Under these ideal conditions, the system was able to maintain the center point of the projected sunspot to within +/- 6.35 (0.25 inches) in the X direction and +/- 6.35 mm (0.25 inches) in the Y direction. This corresponds to an angular error of +/- 13.72 mm (0.54 inches) the X direction and +/- 13.72 mm (0.54 inches) the Y direction. Again referring to the Acceptable Alignment Tolerances outline in Table 1 of the introduction, the misalignment due to tracking with the optical sun sensor is unacceptable.

Although it appears that the WattSun tracking controller would work well for applications for which it was designed such as positioning a large panel of photovoltaic solar cells, the solar panel application does not require the precision alignment of our hybrid lighting system. Even under ideal conditions the error manifest in the WattSun optical sun sensor are unacceptable for maintaining the focused spot within the target 12 mm (approximately 0.50 inches) fiber diameter for the required 8 fibers.

Solartrak Controller Evaluation

General Description

Where the WattSun controller uses a remote sensor module for closed-loop feedback sensing and control described earlier, the SolarTrak is an open-loop system. The SolarTrak Controller, built by Enhancement Electronics, Inc., is a micro controller-based tracking system. This micro controller-based SolarTrak Controller's sun position is determined by computing the celestial bearing of the sun with respect to the earth using the local time, date, latitude, longitude, and time zone rather than sensing the relative bearing of the sun with optical receptors. It uses an embedded microprocessor to derive the computed position of the sun (Request Position) and drive the motor to control the physical orientation (the Array Position) of the mechanical system. The computerized controller calculates the Request Position based on the precise position on the earth (latitude and longitude), the date, and the time of day. It then drives the azimuth and elevation actuators to cause the Array Position to coincide with the calculated Request Position. The embedded processor is a Motorola 68HC11, and the software is written in assembly language, adapted from code originally developed at Sandia National Laboratories, Albuquerque.

The SolarTrak controller can be programmed and calibrated at the unit by means of manual controls and a small display mounted directly on the controller card. In addition, it can be controlled remotely through separate software running on an IBM-compatible computer connected with an RS-232 cable.

The computer maintains an internal clock that must be synchronized to an external time source. A software procedure provides for correcting drift in the internal clock. The latitude, longitude, and certain physical parameters are input into the controller at time of installation. These parameters describe the physical dimensions of the elevation actuator geometry and the gear ratios of the drive mechanisms. A calibration procedure is provided to correct the computed tracking position for errors introduced by any vertical misalignment of the mounting post. A Reference Offset value is also determined during calibration to allow the computer to orientate the coordinate system of the Array with the coordinate system of the Earth.

The controller monitors the actual Array Position by counting pulses (turncounts) from magnetic reed switches mounted in the drive gearboxes of both the azimuth and elevation actuators. Once each morning, the system does a Reference Check. It returns both axes of the array to fixed reference points provided by limit switches mounted on the Array, calculates the current position of the Sun in the sky, corrects the calculation with the calibration factors, determines the desired machine coordinates, and drives the axis motors to position the Array. As the Array is moved, it accumulates turncounts from the reed switches to monitor the actual position of the physical Array hardware. The controller monitors the Array Position continuously and makes small adjustments throughout the day.

Test Set-Up

The test set-up for the evaluation of the SolarTrak Controller was somewhat different from that of the WattSun Solar Tracker tests with the optical sun sensor. As outlined earlier, the two systems were mounted on the prototype "Hybrid Lighting" array with simple switches to allow independent testing of each system. Enhancement Electronics, Inc. furnished the SolarTrak controller and software. Enhancement Electronics provided electrical diagrams for wiring of the system to the existing Array Technology array. By the time the SolarTrak controller evaluation began, the primary and secondary mirrors had been assembled and a new sun pointer system was required to be built into the "Hybrid Lighting" assembly. Figure 7 shows a picture of the assembled Hybrid Lighting System" illustrating the components of the reflective sun pointer. Figure 8 is a schematic illustrating the principle of the sunspot pointing device. The light enters through the pinhole orifice and travels through the secondary support tube to a mirror mounted at the bottom of the support tube mounting plate, and then returns to a grid mounted on the back side of the orifice pinhole where it is viewed via a camera. As the system tracks throughout the day, the sunspot position was monitored and recorded. Below the quantification of error for this sunspot pointing device is illustrated in Fig. 9.

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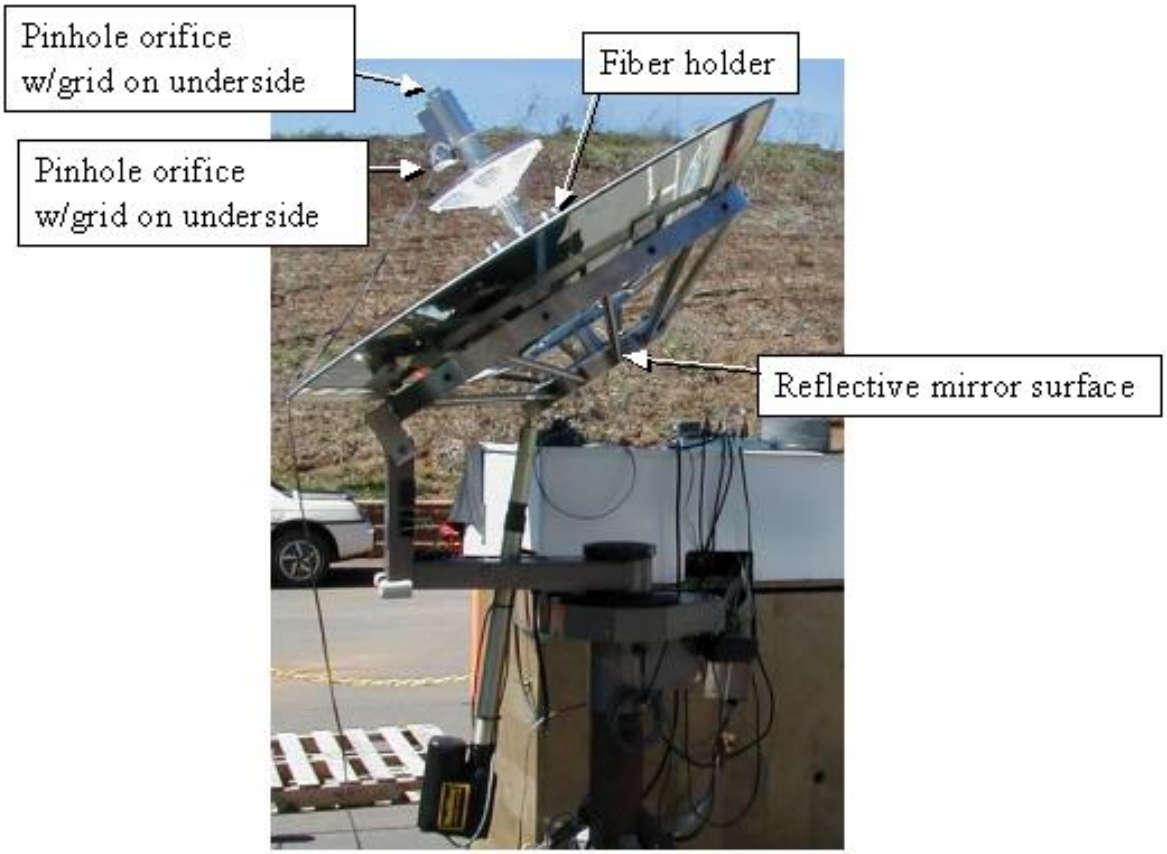

Fig. 7. Assembled "Hybrid Lighting System"

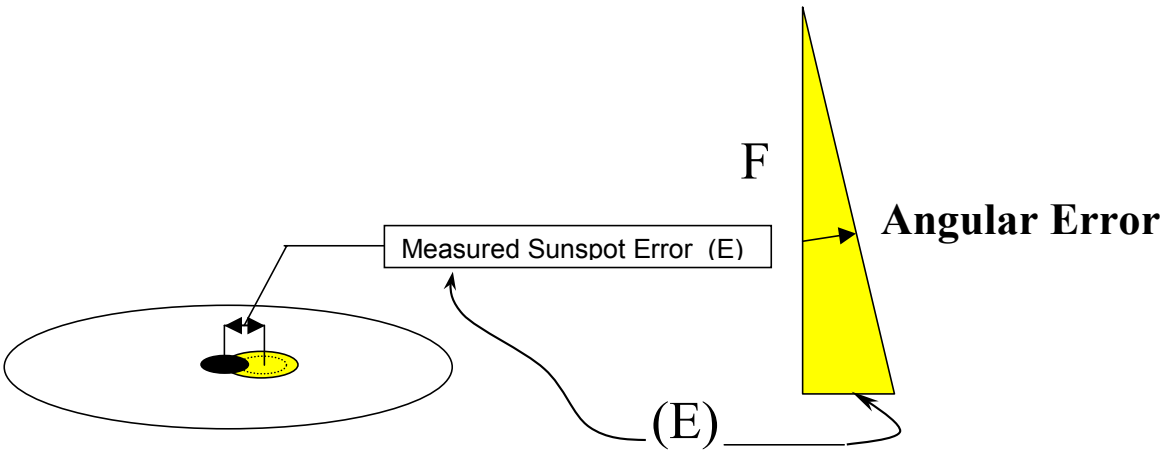

Fig. 9. Quantification of Error for Sunspot Pointing Device

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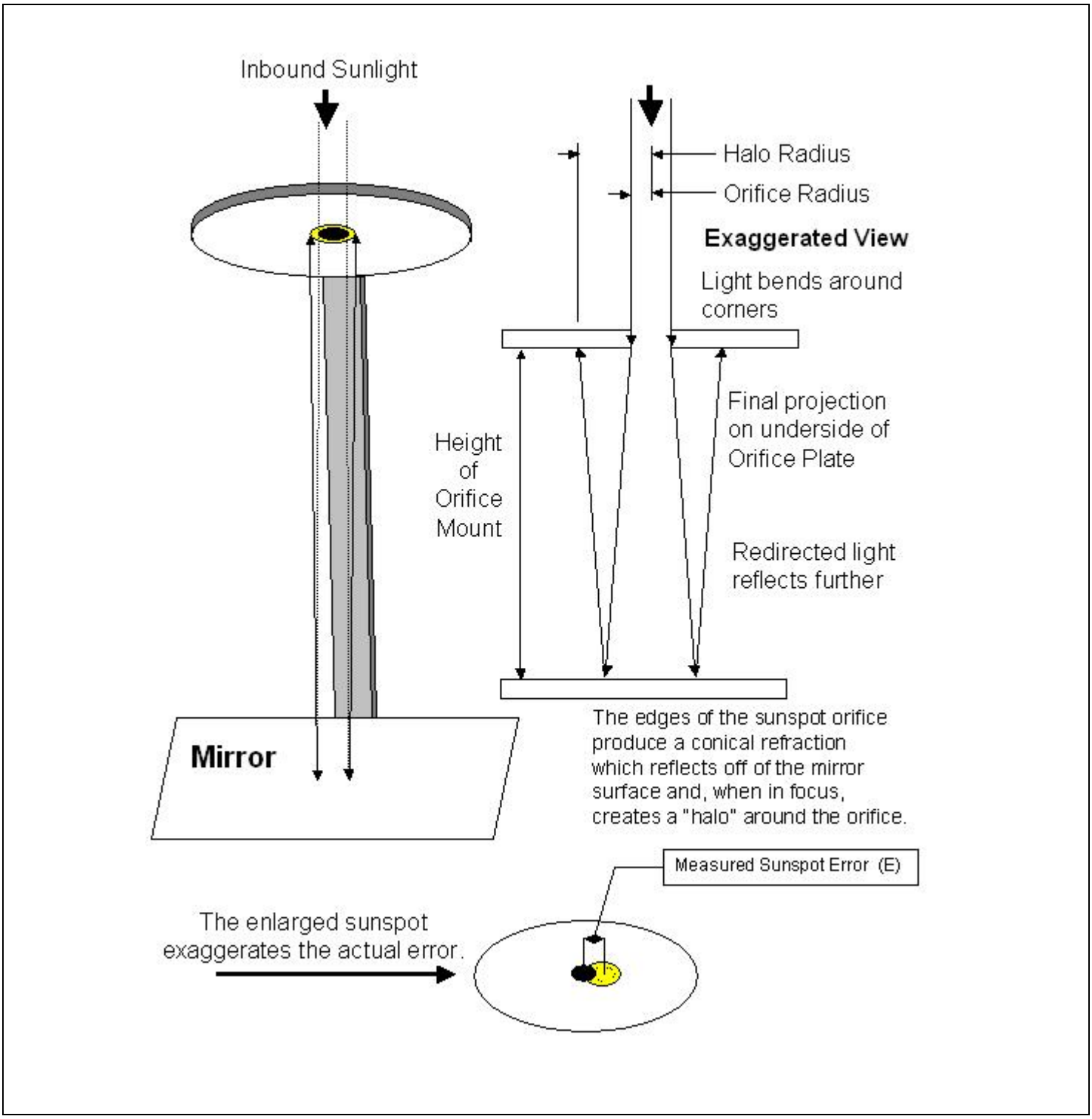

Fig. 8. Reflected Sunspot Pointing Device

Requirements:
Measure 'Height of Orifice Mount' (**H**), Focal length = **F = 2 * H**

2. Measure Error (**E**), from center of the sunspot to the center of the pinhole

*** Any Consistent Units will do ***

Angular Error = Arc TAN (E / F)

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WattSun TRACKER ARRAY WITH SolarTrak CONTROLLER TEST RESULTS

The tracker system was evaluated under various sun conditions; bright sunny days with clear conditions, slightly hazy days with few clouds, partial overcast days and overcast days. As expected, the SolarTrak controller was unaffected by sun conditions. We tested the programming and control of the SolarTrack Controller using the remote computer interface. The remote computer interface provided easier access to parameters and calibration data than the onboard controller display. Physical Array parameters were entered into the controller along with the latitude and longitude (as determined from GPS readings) and the Coordinated Universal Time (CUT) obtained from a U.S. government time source. The steel frame of the tracker was positioned in an asphalt area with a clear view of the sky and indexing marks allowed it to be returned to the same orientation after it is moved into position for the day. The tracker frame was adjusted with the corner screw jacks until the vertical alignment of the azimuth axis was as close as could be determined with a bubble level, and the turn count of each jack recorded to provide for consistent realignment.

Using the sun pointer described above, we tested the calibration procedure and made observations of the tracking performance. The maximum error recorded for the center movement was +/- 2.77 mm (0.109 inches) in the X direction, and +/- 2.39 mm (0.094 inches) in the Y direction. This corresponds to an angular error of +/- 0.120 degrees in the X direction and +/-0.103 degrees in the Y direction. Referring to the Acceptable Alignment Tolerances outline in Table 1 of the introduction, the misalignment due to tracking with the SolarTrak controller is within the acceptable limits.

A second test involve setting up the tracker with a single fiber to collect light from one-eight of the collector and focus it into a large core fiber mounted in the fiber holder (See Fig. 7). The intensity of the light entering the fiber was reduced by a factor of approximately 60 to assure that no damage to the fiber would occur that could bias the test results. The output of this large core fiber was monitored over the course of the day using a Labsphere, Inc., Integrating Sphere. Figure 10, top plot, shows the fiber output in lumens as a function of time with the system being monitored from approximately 11:00 a.m. until 4:15 p.m. The bottom plot shows how the intensity of the sun varied over the same time period as measured using an Eppley Laboratory, Inc., Eppley Radiometer (sometimes referred to as a NIP sensor). As can be seen, the SolarTrak Controller performed well tracking the sun throughout the day, providing an output that varied only with the intensity of the sun and did not vary due to misalignment of the system.

Advantages

The SolarTrack computerized controller has many advantages when compared to the WattSun photovoltaic-based controller, including:

- Consistent operation under varied environmental conditions. Note that the WattSun controller exhibited inconsistent tracking under some circumstances, such as with hazy skies and sky views with contrasting elements from certain types of clouds or adjacent objects.
- Greater tracking precision.
- Adaptability. A computerized controller is inherently adaptable by modifying the software routines to incorporate enhanced tracking algorithms, add features, and accommodate specific issues discovered during development.
- Easily interfaced with external control hardware, for example, switches and weather sensors.
- Networkable. A simple RS-232 network allows a central remote location to monitor and control multiple units.

Possible Enhancements

We have identified several areas where the SolarTrack controller may or should be enhanced to meet specific "Hybrid Lighting" needs:

- Evaluate electrical loads of the axis actuator motors and optimize drive electronics.
- Incorporate a GPS chip to synchronize to an atomic clock and provide latitude/longitude coordinates.
- Provide for automatic self-calibration using feedback from an optical sensor.
- Provide user-interface improvements and operation under MS NT and Windows 2000
- Simplify electronics to reduce eventual deployment costs.
- Enhance precision by adding an additional magnetic sensor to double the turncount resolution.
- Evaluate and enhance the calibration software if needed.

CONCLUSIONS

The Hybrid Lighting System requires precise, accurate tracking under all sun conditions. The collector tracking accuracy is critical to the performance of the "Hybrid Lighting System." The SolarTrak computerized controller is far superior to the WattSun controller in applications such as the "Hybrid Lighting System." The SolarTrak Controller performed well tracking the sun throughout the day, providing an output that varied only with the intensity of the sun and did not vary due to misalignment of the system. The misalignment due to tracker error was well within the Acceptable Alignment Tolerances outlined in Table 1 of the introduction.

The WattSun tracking controller with the optical sun sensor performs reasonably well under bright sunny conditions although even under these ideal conditions it did not meet the stringent requirements of our "Hybrid Lighting System." Although the WattSun tracking controller would work reasonably well for applications for which it was designed, it

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was unsatisfactory for tracking control for our "Hybrid Lighting System." In solar panel applications, for which the WattSun tracking controller was designed, the alignment precision is less stringent.

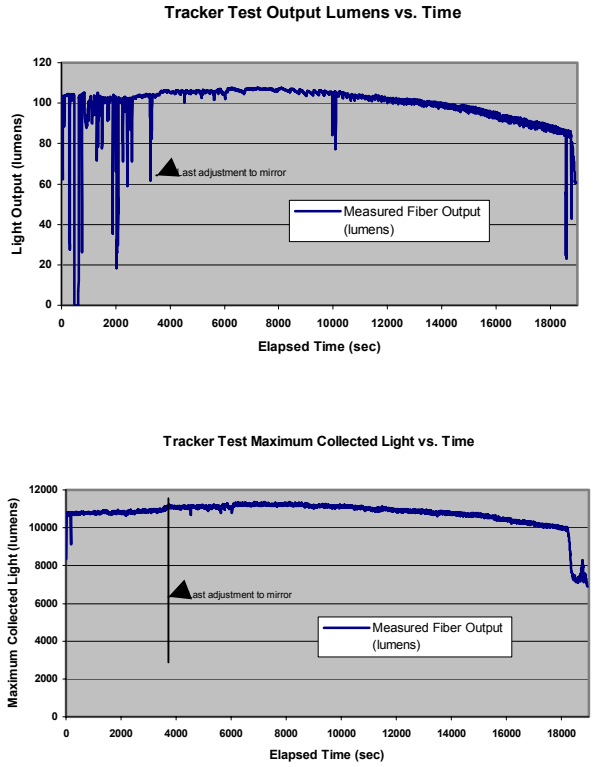

Fig. 10. Maximum Collected Light compared to the Fiber Output

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