A COMPARISON OF ON-AXIS AND OFF-AXIS HELIOSTAT ALIGNMENT STRATEGIES

Scott A. Jones
Sun♦Lab
Sandia National Laboratories
PO Box 5800-0703
Albuquerque, NM 87185

ABSTRACT

Heliostat installation and alignment costs will be an important element in future solar power tower projects. The predicted annual performances of on- and-off axis strategies are compared for 95 m^2 flat-glass heliostats and an external, molten-salt receiver. Actual approaches to heliostat alignment that have been used in the past are briefly discussed, and relative strengths and limitations are noted. The optimal approach can vary with the application.

1. INTRODUCTION

All costs must be minimized in the quest to build competitive solar power plants. For power tower plants, the cost of heliostat installation and alignment are significant. This paper provides information about the performance and practical issues associated with different alignment approaches. Although not exhaustive, this work opens a topic that may ultimately be helpful in minimizing the overall system cost of new plants.

The annual performance predictions discussed in this study were originally undertaken to support the Solar Two project. In addition to predicting the annual performance expected of the Lugo heliostats, suggested times for off-axis alignment were presented [1]. One hundred and eight, 95 m^2 Lugo heliostats, shown in Figure 1, were added to the south field of the original Solar One heliostats to even out the flux distribution on the new molten-salt receiver. After installation, the Lugo heliostats were aligned using an off-axis strategy because of the simplicity and low cost of that approach.

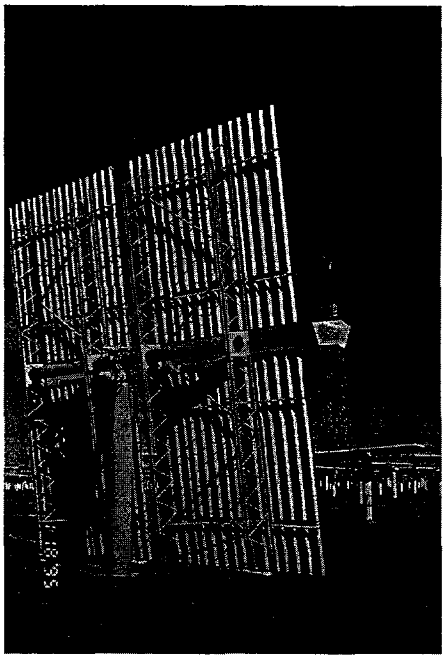

Fig. 1 Lugo heliostat at Solar Two. Original Solar One receiver is visible in the background.

Additionally, experiments showed the nominally flat, but somewhat twisty, Lugo mirror modules prevented the use of an on-axis, lookback camera approach for alignment [2].

The Lugo heliostats and the molten salt receiver at Solar Two are representative, with two exceptions, of the current state-of-the-art design that would be used on near-term hybrid or solar-only plants. Consequently, the previously mentioned study was expanded slightly to provide a more general overview of heliostat alignment strategies.

DISCLAIMER

One exception to being representative is that the Lugo heliostats are larger than optimal for the small Solar Two receiver. They are appropriately sized for a 30 MW_e plant, rather than a 10 MW_e plant. Also, the Lugo heliostats use flat, rather than focused, glass mirror modules. For the Solar Two project, the cost savings from using the large, second-hand, nominally flat mirrored heliostats more than outweighed the reduction in performance. These two factors lead to annual spillage on the order of 20-30%, rather than around 5%.

Next-generation stretched membrane heliostats that may be used on future plants would eliminate the need for the type of alignment discussed herein, although their field installation costs may be higher.

2. ALIGNMENT STRATEGIES

In this paper, the term heliostat alignment refers to the tilting or "canting" of discrete mirror modules on their support structure. This is independent of the focal length of each module.

An *on*-axis alignment occurs when all mirror modules' normal vectors intersects at a point twice the focal distance. This alignment condition is termed on-axis because it is optimized for the geometry where the heliostat center, the target, and the sun all fall along a line. An on-axis alignment is normally implemented by mechanical means that do not involve tracking the sun such as using an inclinometer, a lookback camera, or a laser system. Because these methods rely on calculations of the desired mirror normal pointing vector, it is possible to implement any focal length in the canting process.

Conversely, an *off*-axis alignment is optimized for a geometry where the heliostat center, the target, and the sun do not fall along a line. There are an infinite number of different off-axis alignments for a given slant range, but only one on-axis alignment. The mirror modules' normal vectors do not all intersect at a single point for an off-axis alignment. This type of alignment is normally implemented by tracking the sun and adjusting the aiming of each mirror module to minimize the size of the reflected beam upon a target. The overall heliostat focal length by default becomes the distance between the heliostat and the alignment target. At Solar Two, the distance between the heliostats and the Beam Characterization System (BCS) alignment target is only slightly less than the distance between the heliostat and the receiver (slant range).

While there are a number of differences between the two alignment strategies, both provide optimum heliostat performance for only one particular geometry (i.e. sun position). Since the sun's position changes significantly with time of day, and its trajectory varies with season, a heliostat's annual performance is strongly influenced by its performance in non-optimal geometry. On-axis alignment is sometimes intuitively cited by those with heliostat experience as providing superior annual performance. However, the results will show this is not always the case because of the value of optimizing alignment at times of high effectiveness (energy transfer to the receiver). The time of peak heliostat effectiveness depends upon the position of the heliostat in the field, and occurs when the product of the insolation and the cosine factor is maximum.

3. ANNUAL PERFORMANCE

The best figure of merit, or metric, to evaluate the performance of a canting approach is the Annual, Incident-Power-Weighted Intercept (AIPWI) because it is directly tied to the plant economics. This is the fraction of the beam power leaving the heliostats over a year that actually lands upon the receiver. A larger number is better.

The DELSOL computer code [3] was used to calculate the AIPWI values for a group of heliostats called a cell. DELSOL computes the daily and annual average intercepts and performs insolation weighting. The details of the study are discussed elsewhere [1]. Please note that the scope of this study has been expanded to include winter solstice, not just equinox and summer solstice. This, plus the addition of a north field cell, make the results more general.

The four cell locations blacked out in Figure 1 were evaluated in this study. Cell location is referenced by its radius in tower heights from the center of the tower, and its azimuth location in clockwise degrees from north. For instance, the center of cell (5.27,90) is located 5.27 tower heights (282 m) from the tower's center, and 90° clockwise from north. These cells were chosen because they provide valuable insights into the effect of cell azimuth and canting time on annual performance. As cell radius decreases, AIPWI will increase because of the beam divergence.

The analysis performed permits symmetric east cell results to be applied to west cells simply by changing the canting time about solar noon. For instance, the AIPWI for cell (3.97,150) canted on equinox at +3 hours from solar noon is equal to the AIPWI for cell (3.97,210) if canted on equinox at solar noon -3 hours.

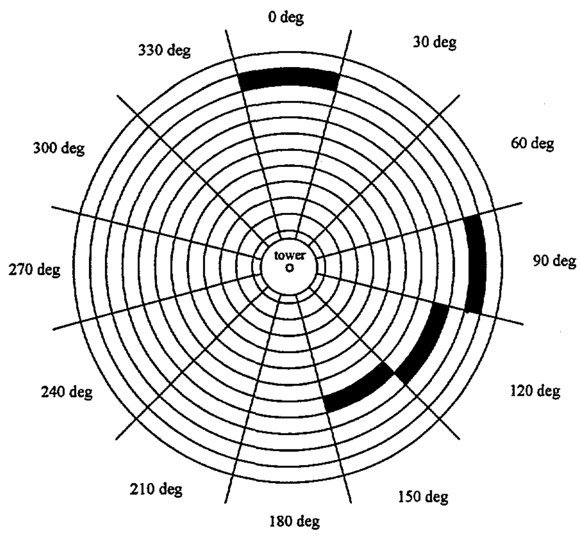

Fig. 2 Matrix of cells used in DELSOL to model the heliostat field.

The results are presented in Figures 3 through 6. Since cell (5.27,0) is located due north of the tower, the data presented in Figure 3 are symmetric about solar noon. In general, the results can be summarized as follows. Off-axis alignment performance varies greatly with the time of day and season it was implemented, and can actually exceed the performance of on-axis alignment in some cases. However, on-axis alignment provides uniformly high performance independent of cant time.

The DELSOL predicted AIPWI values assume perfectly executed on- and off-axis canting of the heliostats. In reality, physical limitations prevent perfect alignments, causing the achieved annual performance to be slightly less than is shown in the graphs.

As mentioned previously, the Lugo heliostats are oversized and have nominally flat glass. This causes the predicted AIPWI values for both alignment strategies to be lower than would occur for an optimized plant.

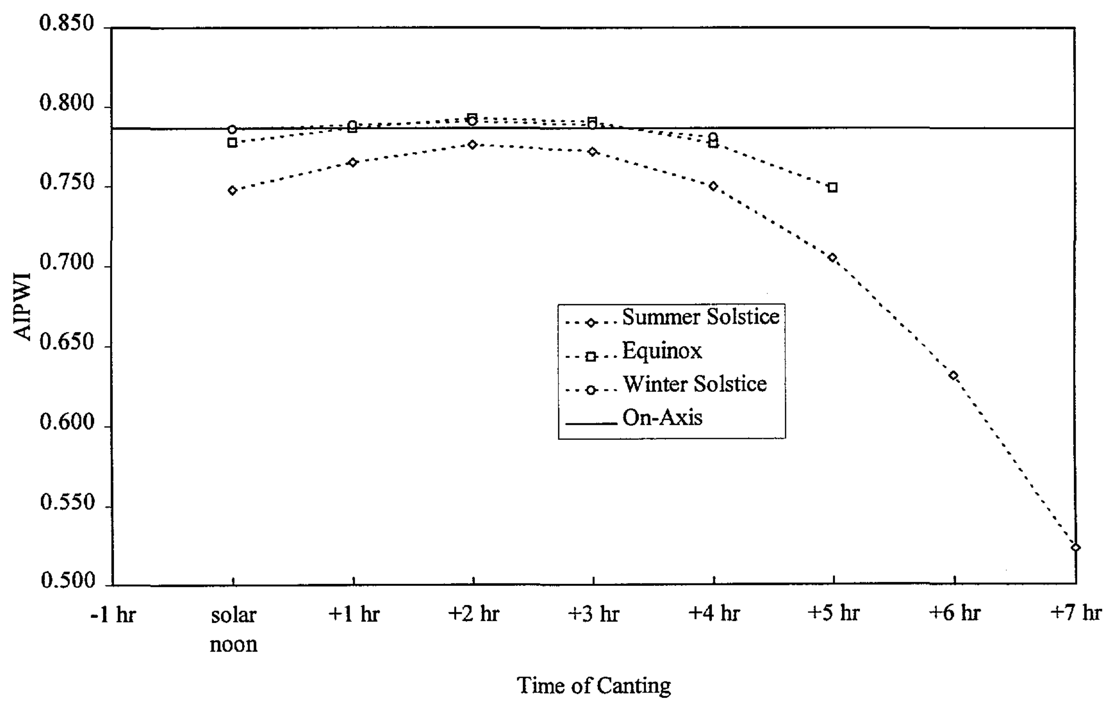

Fig. 3 Lugo heliostat annual performance for cell (5.27,0).

DISCLAIMER

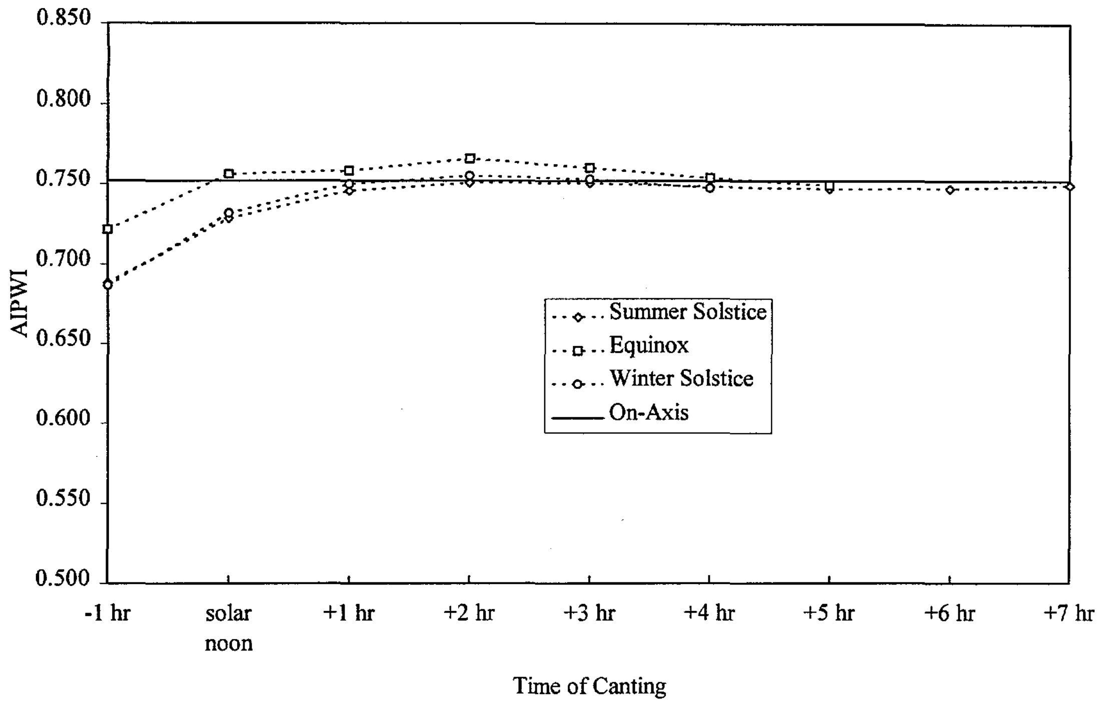

Fig. 4 Lugo heliostat annual performance for cell (5.27,90).

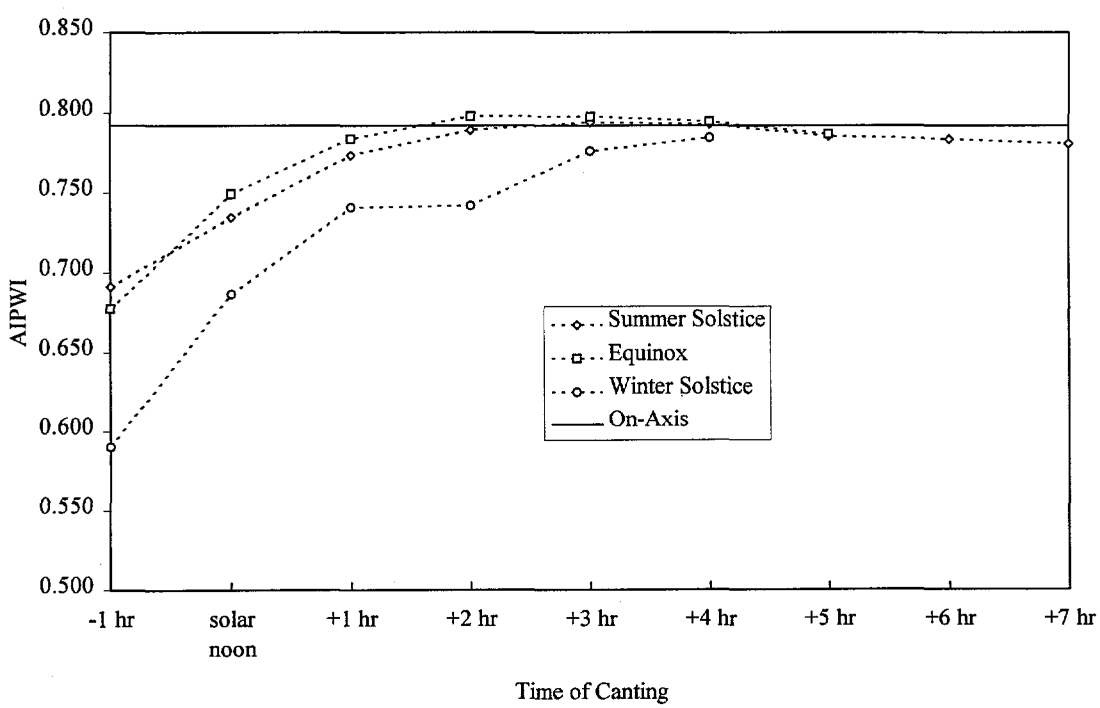

Fig. 5 Lugo heliostat annual performance for cell (4.40,120).

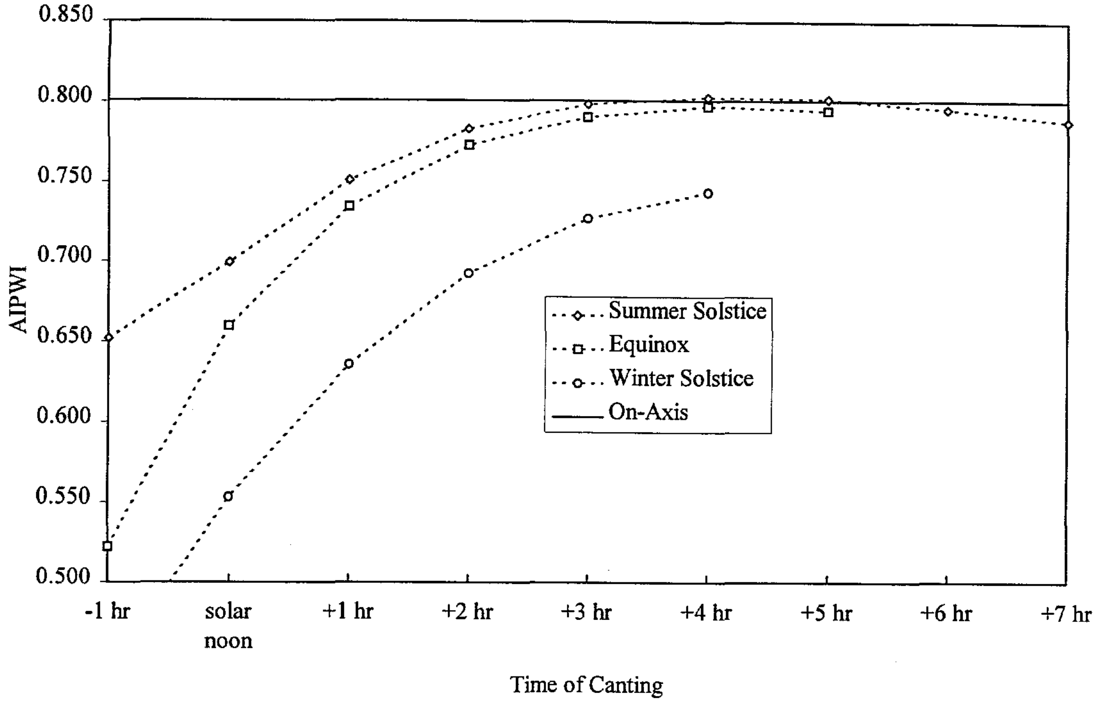

Fig. 6 Lugo heliostat annual performance for cell (3.97,150).

4. ALIGNMENT APPROACHES

The approaches or methods to align heliostats may be categorized in many ways. Here, I will discuss three categories: sun-tracking , optical, and mechanical approaches.

A sun-tracking approach normally provides an off-axis alignment. However, it can provide a nearly on-axis alignment for limited areas of the field at those specific times when the heliostat, target, and sun all fall nearly in line[1]. This approach can only be used after heliostats have been installed on their pedestal, and at times of clear sunshine. A sun-tracking alignment is fast and easy (inexpensive) to perform, but its annual performance is highly dependent on time of canting. Alignment errors are introduced in this method when beams from the multiple mirror modules land upon the target at once. This makes it more difficult to properly align each mirror module, particularly when less precise mirror modules such as the Lugo's are used. The use of mirror covers can alleviate this problem but the slight improvement in performance is unlikely to offset the additional cost for most applications. A camera located at the focal point can also help identify the correct alignment of each module. Finally, if the target is not the same distance from the heliostat as the receiver, the alignment distance can differ from the slant range and reduce performance.

In the past, the optical and mechanical approaches have been used solely to implement on-axis alignments, but they could also be used to implement optimum off-axis alignments. While the results presented here indicate this may yield slightly higher performance, it is not clear if the additional calculations required would be worth the slight gains over an on-axis cant to slant range. For these categories, the uncertainties in the hardware and measurement techniques add error to the alignment that may reduce performance.

Optical approaches are used after heliostats are installed. The heliostat is rotated and the mirror modules are adjusted to make a reflection land in the correct place as set forth by calculations. A laser-based approach was used years ago at the NSTTF in Albuquerque, NM [4]. The equipment was complicated and expensive. The alignments were mainly

[1] An exactly on-axis alignment is not possible with a sun-tracking approach because of the shadow cast by the target.

limited to nighttime hours and were later redone because of dissatisfaction with the results.

An approach based on a video camera has been used successfully at the Weismann Institute research facility in Israel[2]. A similar system with RF communications was originally used at Solar Two for re-canting inner row Solar One heliostats. Problems with the field and limited resources forced a switch to faster, off-axis sun canting. There were also problems with the video image washing out in bright sunlight. This system could be used at night with some auxiliary lighting.

The mechanical approaches use instruments to measure tilt or displacement from a reference plane before final installation, and can usually be performed day or night. The desired tilt of the mirror module's normal vector or displacement of its mounting points is determined by calculations. It is critical with these methods to correct for gravity sagging of the structure when aligning. Typically, this is done by mounting an assembled mirror/drive unit horizontally and face-up on a short pedestal; aligning it; then craning the whole unit to its intended pedestal. Error is introduced because the gravity sagging corrections occur when pointing 90° above the horizon, whereas most of the power to the receiver is provided by heliostats pointing at 25-45° above the horizon. This approach also limits the options for installation methods. These approaches seem to be more sensitive to wind, but this could be overcome by installing wind shielding fences around the alignment area.

An elaborate example of this approach using linear displacement transducers was implemented at Solar One [5]. A simpler approach[3] uses a transit to provide the reference plane for displacement measurements made with a plumb bob or bubble-leveled rod. An inclinometer could also be used at the mirror modules center to implement the correct tilt, but would have the disadvantage of being subject to localized mirror shape errors.

5. CONCLUSIONS

The predicted annual performance of on- and off-axis heliostat alignment strategies was investigated for representative, state-of-the-art components. On-axis alignments were found to have uniformly high performance. Off-axis alignment performance could theoretically exceed that of on-axis, but was very dependent on time-of-day and seasonal effects. Various methods for implementing both of these alignment strategies with their strengths and limitations were discussed. The optimal approach may vary with application. For the three year operation of a refurbished Solar Two plant, the inexpensive, off-axis, sun-canting alignment approach was the best match for the limited budget and nominally flat Lugo heliostats. For a new plant with a 30-year lifetime, a different approach may be better. A more detailed performance and work flow analysis would be required to determine the optimal approach for a new plant.

6. ACKNOWLEDGMENTS

I would like to thank Greg Kolb of Sandia National Laboratories for his assistance in this study. This work was supported by the U.S. Department of Energy under Contract DE-AC04-94AL85000.

7. REFERENCES

(1) Jones, S.A., Annual Performance Prediction for Off-Axis Aligned Lugo Heliostats at Solar Two, Proceedings of the American Society of Mechanical Engineers Solar Energy Division Meeting, March 31-April 3, 1996, San Antonio, Texas.

(2) Jones, S.A., R.M. Edgar, R.M. Houser, Recent Results on the Optical Performance of Solar Two Heliostats, Proceedings of the American Society of Mechanical Engineers Solar Energy Division Meeting, March 19-24, 1995, Maui, Hawaii.

(3) Kistler, B. L., A Users Manual for DELSOL3: A Computer Code for Calculating the Optical Performance and Optimal System Design for Solar Thermal Central Receiver Plants, Sandia National Laboratories, Albuquerque, New Mexico, SAND86-8018, 1986.

(4) Holmes, J.T., Heliostat Operation at the Central Receiver Test Facility (1978-1980), Sandia National Laboratories, Albuquerque, New Mexico, SAND81-0275, 1981.

(5) Schultz, H.W., Assembly Canting Fixture Operations-Phase II, Report number 40 M 500 2M, DOE/SF/10539-24 (STMPO-574), Martin Marietta, 1981.

[2] The system was conceived by Harald Ries of the Paul Scherrer Institute and is used by Doron Leiberman of the Weismann Institute.

[3] Developed by David Gorman of Advanced Thermal Systems in Colorado.