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ANALYSIS OF STRATEGIES TO IMPROVE HELIOSTAT TRACKING AT SOLAR TWO

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ABSTRACT

This paper investigates different strategies that can be used to improve the tracking accuracy of heliostats at Solar Two. The different strategies are analyzed using a geometrical error model to determine their performance over the course of a day. By using the performance of heliostats in representative locations of the field and on representative days of the year, an estimate of the annual performance of each strategy is presented.

INTRODUCTION

The 10 MW_e Solar Two Power Tower Plant located near Barstow, CA has a field of 1926 heliostats which reflect the sun's power on a cylindrical, tower-top receiver. Figure 1 shows the Solar Two plant. The heliostat field consists of 1818 heliostats that were developed by Martin Marietta during the early 1980's for the US Department of Energy's Solar One project and 108 Lugo heliostats that were added to the field for the Solar Two project. Kelly and Singh (1995) describe the design of the Solar Two plant and the changes from Solar One. The design specifications for Solar One heliostats required root mean square (RMS) tracking accuracy of less than 1.5 milliradians (mrad) in no wind conditions for each horizontal and vertical axis (2.1 mrad total for both axes). The molten salt receiver at Solar Two has 1/3 the surface area of the water/steam receiver used at Solar One, increasing the potential for spillage—light reflected from heliostats that misses the receiver.

The project goals at Solar Two have been oriented more toward proving operation of the molten salt system than characterizing the heliostat field, since the heliostat field was proven during Solar One. However, some changes to the field were made to better match the new receiver. In order to increase the field area and redistribute the flux profile, salvaged mirror modules were used to replace the corroded original mirror modules and to build the Lugo heliostats. These cost-saving compromises resulted in a reduction in the optical beam quality of the heliostats. Re-alignment of the heliostats for the smaller receiver also introduced errors to the field. Jones et al. (1995) provide more details on the Solar Two heliostat field optics.

The Solar Two plant has recently met thermal to electric conversion and parasitic power use goals. However, the energy collection has been 10-20% lower than expected, suggesting that the heliostat field was not performing up to expectations. The accuracy of heliostat tracking was believed to be a possible cause of the reduced performance. The observation of occasional miss-tracking heliostats and excessive flux on the oven covers (the white panels located above and below the receiver) bolstered this suspicion. A study was initiated to investigate the possible causes of poor heliostat tracking. In addition to hardware failures, it was found that a number of geometrical error sources could interfere with proper heliostat tracking.

A discussion of these error sources is the subject of a companion paper (Stone and Jones, 1999). Briefly, the results of that paper are: 1) that the "tilt" of the heliostat pedestals introduces tracking errors; 2) that heliostat alignment or "canting" can also introduce tracking errors; 3) that heliostat biasing, the processes of establishing the encoder reference "mark", can actually introduce error in the heliostat tracking, with the currently used approach possibly making the situation worse; and 4) that all of these errors sources cause tracking errors that vary over the day (time-variant tracking errors). While the companion paper explains these error sources in detail and illustrates their effect on tracking, this paper is intended to examine possible strategies for improving the tracking accuracy of heliostats at Solar Two. To accomplish this task, an attempt was made to evaluate strategies on the

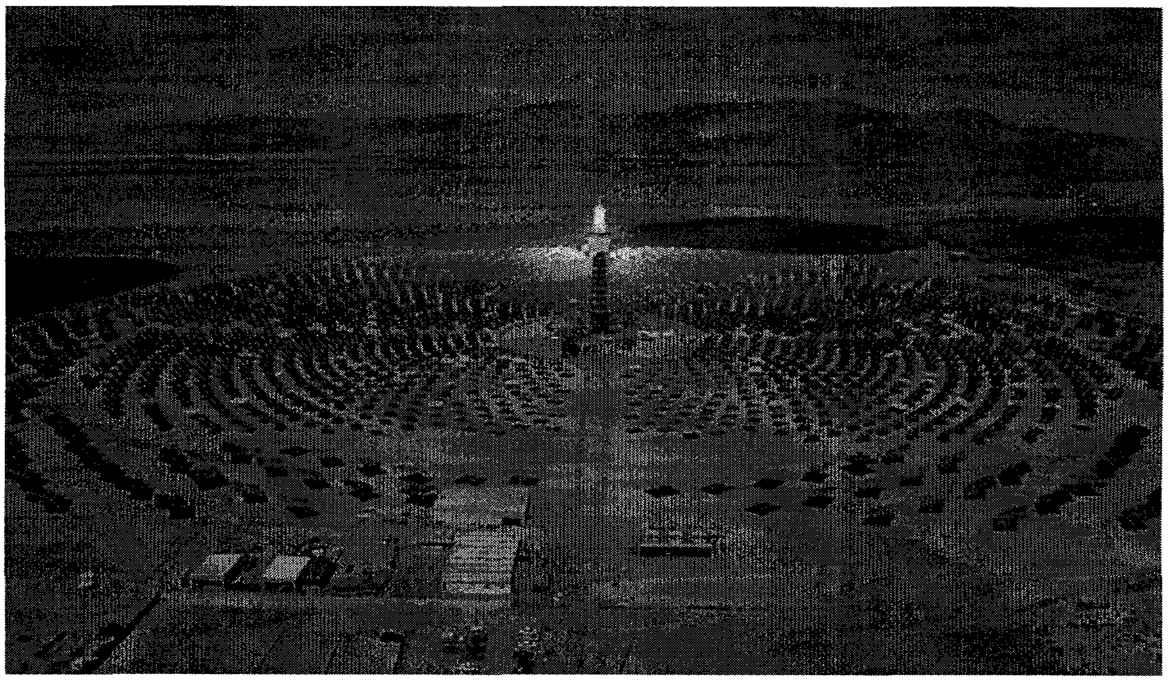

Figure 1. The Solar Two Power Tower Plant

basis of how they would affect the entire field over the course of a year, rather than a single heliostat on a single day. The Lugo heliostats are not included in this study.

STRATEGIES TO IMPROVE TRACKING ACCURACY

Three strategies for improving heliostat tracking are discussed in this paper:

- **Mark Position Adjust or "Bias":** Use tracking accuracy data to calculate a change in the heliostat azimuth and elevation encoder reference or "mark" positions to minimize the time-variant tracking errors. This approach has also been referred to as "biasing" the heliostat, where the bias values are synonymous terms for the position of the encoder reference marks in the plant coordinate system. Slightly differing approaches to this strategy have been used at Solar One and Solar Two.
- **Move:** Use tracking accuracy data to calculate an offset in the database location of the heliostat (without actually moving the heliostat) to minimize the time-variant tracking errors. This strategy is a new proposal and has never before been used.
- **Correction Model:** Implement an error-correcting model in the heliostat control system that eliminates time-variant tracking errors. This requires many tracking accuracy measurements over a day to calculate the magnitude of each error source. But once implemented need only be updated when encoders are replaced. This approach has been used before in prototype heliostats.

The first 2 strategies are easily implemented in the current control system, but are actually "Band-Aids" that only serve to minimize the problem, not solve it. The third strategy solves the problem and can achieve a very high tracking accuracy (0.5 mrad RMS or better). The authors believe this would be the preferred approach to use on the next commercial plant. However, it is difficult to implement in the Solar Two heliostat control system. The current study focused on the performance of the Bias and Move strategies, but further discussion of the correction model strategy is also provided later for comparison. For all strategies, the heliostat tracking accuracy at a point in time would be measured with the Beam Characterization System (BCS) at the Solar Two site. Strachan (1993), King (1982), and Mavis (1988) describe the BCS.

VARIATIONS ON BIAS AND MOVE STRATEGIES

For each of these strategies, different variations were considered in terms of the number of BCS measurements taken over the day and the number of times the strategy was repeated each year. The variations are listed in Table 1. Note that the numbers at the end of each strategy name contain the information found in the following columns, so reference to a "1/D-4/Y" strategy later is this paper means a strategy that requires one BCS measurement per day repeated 4 times per year. At Solar One, a mark position adjustment strategy using 3 measurements over the day was used (Mavis, 1989 and Stone and Lopez, 1995). At Solar One, the BCS was automated to help take large numbers of measurements. The automation of this system was complicated and it experienced conflicts with the master control system that limited its use. For these reasons, a simple, PC-based system was installed at Solar Two. The Bias-1/D-4/Y strategy represents the approach currently used at Solar Two and was selected to reduce the labor requirements and to encourage high quality over high quantity in the BCS measurements performed each day. It was also believed that if the one BCS measurement needed in this approach was performed (and hence the tracking accuracy optimized) at a time of day when that heliostat was likely to deliver the most power to the receiver, the integrated daily energy delivered to the receiver would also be maximized. For this reason, time guidelines were set for biasing each quadrant of the field based upon when the combined solar insolation and cosine performance were maximal.

Table 1. Strategies Evaluated

Strategy	BCS Measurements per Day	Repeats per year
Bias-1/D-4/Y	1	4
Move-1/D-4/Y	1	4
Bias-1/D-1/Y	1	1
Move-1/D-1/Y	1	1
Bias-3/D-1/Y	3	1
Move-3/D-1/Y	3	1
Bias-3/D-4/Y	3	4

PERFORMANCE METRICS

For each strategy and variation, a number of annual-average metrics was computed to evaluate its performance and the change in performance from the strategy currently used at Solar Two. The annual-average metrics calculated include:

- RMS tracking error - total of horizontal plus vertical axes
- RMS vertical tracking error
- Peak tracking error - total of horizontal plus vertical axes

Multiple metrics were used to better characterize the performance of a heliostat field with time-variant tracking errors. The annual-average RMS track error indicates the average tracking performance over the year. The RMS vertical error is of interest because it reflects the tendency to spill light on to the oven covers located above and below the receiver. This can damage the oven covers and cause a plant outage, whereas horizontal tracking errors tend to cause spillage that misses the receiver and oven covers altogether. The peak error metric is valuable in evaluating the annual-average of the worst daily tracking errors.

MODELING APPROACH

A geometrical error model was developed that predicts the tracking error of a single heliostat over the course of a single day based on inputs such as the location, pedestal tilt, canting error, and encoder reference error. Stone (1998) describes the error model in more detail. To evaluate strategies for improving heliostat tracking, one must base decisions on more information than how the strategy affects a lone heliostat on a single day. Ideally, the strategies would be compared based upon their effect on the tracking of the entire field of heliostats on an annual basis. Unfortunately, no computational tools exist to perform the desired annual analysis. Instead, an estimate of annual performance was made by a weighted averaging of results from many runs of the single heliostat, single day model. To limit the analysis to a reasonable degree, only a single heliostat error profile was considered, but multiple heliostat locations, days of the year, and BCS measurement times were averaged. Table 2 lists the values of the control variables and their respective weighting factors that were used in this analysis.

The heliostat location weighting factors represent the actual percentages of heliostats in each quadrant of the field. It is assumed that the performance of the East heliostat is representative of a West heliostat because of the geometrical symmetry, so the 0.51 weighting factor is representative of the number of heliostats located in both the East and West quadrants at Solar Two. The three days evaluated in the study are typically used for solar energy analysis because they represent the outer bounds (SS and WS) and the midpoint (EQ) of the sun's movement. Equinox received double the weighting of the other days because it occurs twice each year. For all cases, the day was assumed to be 12 hours long for the computation of daily RMS tracking error. The time of the BCS measurements is similar in that it represents the outer bounds and the midpoint of a 4-hour time window appropriate for each quadrant. These time windows reflect the constraints currently in use at Solar Two.

The geometrical error profile used for every heliostat was a 0.5 mrad pedestal tilt in the NE direction. This tilt magnitude was the average value from 16 measured at random in the field. The results scale linearly, so the effects of a different magnitude tilt can be calculated by simply multiplying the results shown here by the ratio of the new to old tilt magnitude. For this study, the tilt was chosen to be in the NE direction so that tilt components in both the North-South and East-West directions were present for every heliostat location evaluated. Different tilt directions will change the character of the tracking error (Stone and Jones, 1999), but it is assumed that the

Table 2. Control Variables for Annual Performance Metrics

Heliostat Location		Day Evaluated		BCS Measurement Time (Solar Time)			
Values	Weighting Factor	Values	Weighting Factor	North & South Heliostats	Weighting Factor	East Heliostats	Weighting Factor
1000 ft North (N)	0.38	Summer Solstice (SS)	0.25	10:00	0.33	12:00	0.33
800 ft East (E)	0.51	Equinox (EQ)	0.5	12:00	0.33	14:00	0.33
400 ft South (S)	0.11	Winter Solstice (WS)	0.25	14:00	0.33	16:00	0.33
Total	1.0	Total	1.0	Total	1.0	Total	1.0

$$
\begin{aligned}
RMS_{Ann\,Avg} = {} & 0.38\left[\begin{array}{l} 0.25\left(\dfrac{RMS_{N,SS,10}+RMS_{N,SS,12}+RMS_{N,SS,14}}{3}\right)+0.5\left(\dfrac{RMS_{N,EQ,10}+RMS_{N,EQ,12}+RMS_{N,EQ,14}}{3}\right)+ \\ 0.25\left(\dfrac{RMS_{N,WS,10}+RMS_{N,WS,12}+RMS_{N,WS,14}}{3}\right) \end{array}\right] \\
& +0.51\left[\begin{array}{l} 0.25\left(\dfrac{RMS_{E,SS,12}+RMS_{E,SS,14}+RMS_{E,SS,16}}{3}\right)+0.5\left(\dfrac{RMS_{E,EQ,12}+RMS_{E,EQ,14}+RMS_{E,EQ,16}}{3}\right) \\ +0.25\left(\dfrac{RMS_{E,WS,12}+RMS_{E,WS,14}+RMS_{E,WS,16}}{3}\right) \end{array}\right] \\
& +0.11\left[\begin{array}{l} 0.25\left(\dfrac{RMS_{S,SS,10}+RMS_{S,SS,12}+RMS_{S,SS,14}}{3}\right)+0.5\left(\dfrac{RMS_{S,EQ,10}+RMS_{S,EQ,12}+RMS_{S,EQ,14}}{3}\right) \\ +0.25\left(\dfrac{RMS_{S,WS,10}+RMS_{S,WS,12}+RMS_{S,WS,14}}{3}\right) \end{array}\right]
\end{aligned}
\qquad (1)
$$

distribution of tilt directions expected for the Solar Two field will be accounted for by the extensive averaging done in this study. Additionally, the use of daily RMS values in the calculations of 2 metrics minimizes the need to simulate every possible error profile since many error profiles have similar RMS tracking error values (Stone and Jones, 1999). Since we have no good estimate of a representative magnitude for canting tilt error or encoder reference error, none were assumed. For the reasons just mentioned, the impact of these other error sources can be approximated by simply increasing the magnitude of the tracking error results based solely on pedestal tilt.

As mentioned previously, annual-average performance is estimated by a weighted average of the daily performance for different field locations, days of the year, and times of the day for BCS measurement. For example, the annual-average RMS track error calculation for the Bias-1/D-4/Y strategy is shown in Equation 1, where RMS stands for the daily root mean square tracking error, and the subscripts represent the heliostat's field location, the day of year, and the time of day that the single BCS measurement was taken (see Table 2 for abbeviations). The calculations of metrics for other strategies differ, but equations are not shown here for purposes of brevity. The inherent assumption is that the random distribution of dates and times of the BCS measurements to be expected in practice is sufficiently represented by this type of averaging.

Before calculating the tracking error for each daily case, one or more BCS measurements were first used to either adjust the mark position or calculate location offset value. These adjustments were calculated using an iterative, numerical approach. More specifically, a forward-difference, quasi-Newton approach was used with a convergence criteria of 0.001 mrad required for 5 consecutive steps. Basically, the mark position or X,Y,Z location offsets, depending upon the strategy, were changed in small increments until the desired output was minimized. In the case of the 1/D strategies, the tracking errors were minimized for a single time of the day. For the 3/D strategies, the RMS tracking error as calculated from 3 times of the day was minimized. The 3 times selected were the same as those listed in Table 2. For the north and south field, the 3 measurements are taken at 10:00, 12:00, and 14:00 solar time.

BIAS AND MOVE STRATEGY RESULTS

Tables 3-5 list the results of the study, a compilation of 243 individual daily runs. A reduction in tracking error is beneficial, so a negative change from the current strategy is desirable. Because of the assumptions and averaging used in this study, there is some uncertainty in the results. It would therefore be inappropriate to differentiate between strategies with small differences in performance. The annual-average RMS tracking error results have the least uncertainty of the three because of the previously mentioned fact—many error profiles have similar RMS tracking error magnitudes. This makes the selections of the control variables and the error profile less significant. Conversely, the annual-average vertical error results have more uncertainty because they are more influenced by the choice of error profile.

For most metrics, the overall magnitude of the tracking errors is ~0.5 mrad on an annual basis, a comparable value to the tilt magnitude used in the error profile. However, the annual-average peak error was much higher, averaging ~0.9 mrad, with the worst daily result from the 243 runs (not shown due to space constraints) of 1.8 mrad. However, these tracking errors are lower that typically measured at Solar Two. A recent survey of historical BCS measurements indicated that the field RMS tracking error, when using one BCS measurement from each heliostat, was about 7 mrad rather than the 0.5 mrad obtained from this error profile based upon the pedestal tilt measurements of 16 heliostats. Likely, the other 2 error sources, alignment plane and encoder reference error, are significant contributors. It is also possible the sample of 16 randomly selected heliostats did not provide an accurate measure of the average pedestal tilt magnitude. In either case, the results should scale linearly so the relative differences between strategies should still be applicable to Solar Two.

One interesting result is that the 1/D-4/Y strategies perform better for every metric than the equivalent 1/D-1/Y strategies since they are updated seasonally. The effect of seasonal updates are less effective for strategies with 3 BCS measurements per day (compare Bias-3/D-1/Y to Bias-3/D-4/Y), most likely because some of the benefits inherent in averaging multiple measurements are already provided.

Table 3. Annual-Average RMS Tracking Error

Strategy	Heliostat Location			Field Average	Change from Current Strategy
	North	East/ West	South		
Bias-1/D-4/Y	0.42	0.50	0.50	0.47	0.0%
Move-1/D-4/Y	0.39	0.45	0.51	0.44	-8.2%
Bias-1/D-1/Y	0.45	0.52	0.51	0.49	4.5%
Move-1/D-1/Y	0.41	0.51	0.53	0.48	1.3%
Bias-3/D-1/Y	0.40	0.48	0.48	0.45	-5.1%
Move-3/D-1/Y	0.37	0.46	0.48	0.43	-10.7%
Move-3/D-1/Yb	0.47	0.48	0.43	0.47	-0.4%
Bias-3/D-4/Y	0.37	0.44	0.44	0.41	-13.7%

Table 4. Annual-Average RMS Vertical Tracking Error

Strategy	Heliostat Location			Field Average	Change from Current Strategy
	North	East/ West	South		
Bias-1/D-4/Y	0.36	0.31	0.41	0.34	0.0%
Move-1/D-4/Y	0.34	0.23	0.43	0.29	-17.7%
Bias-1/D-1/Y	0.36	0.35	0.40	0.36	4.5%
Move-1/D-1/Y	0.34	0.32	0.43	0.34	-2.0%
Bias-3/D-1/Y	0.31	0.31	0.35	0.31	-9.5%
Move-3/D-1/Y	0.28	0.31	0.35	0.30	-14.4%
Move-3/D-1/Yb	0.36	0.32	0.30	0.33	-3.0%
Bias-3/D-4/Y	0.32	0.28	0.37	0.30	-13.7%

Table 5. Annual-Average Peak Tracking Error

Strategy	Heliostat Location			Field Average	Change from Current Strategy
	North	East/ West	South		
Bias-1/D-4/Y	1.11	0.85	0.77	0.94	0.0%
Move-1/D-4/Y	0.64	0.67	0.84	0.68	-38.9%
Bias-1/D-1/Y	1.13	0.91	0.81	0.98	3.8%
Move-1/D-1/Y	0.66	0.73	0.87	0.72	-31.6%
Bias-3/D-1/Y	0.57	0.88	0.69	0.74	-27.2%
Move-3/D-1/Y	0.54	0.60	0.69	0.59	-60.7%
Move-3/D-1/Yb	0.65	0.79	0.63	0.72	-31.5%
Bias-3/D-4/Y	0.55	0.88	0.65	0.73	-29.3%

Additionally, the Bias-3/D-1/Y strategy performance beat the Bias-1/D-4/Y performance in every metric, especially the annual-average peak error. This is an interesting result since these two strategies require approximately the same labor time to implement. The Bias-3/D-4/Y strategy was slightly better yet, but it requires much more labor to implement. However, there are a number of intangible factors to consider in the competition between these two strategies. For instance, one advantage of the Bias-1/D-4/Y strategy over the Bias-3/D-1/Y is that the heliostat is revisited often over the year. This is valuable because it increases the chance a BCS operation will locate a heliostat with an undiagnosed hardware problem, thereby indirectly increasing the field's tracking accuracy and performance. Another intangible benefit of the Bias-1/D-4/Y approach over the Bias-3/D-1/Y approach is that it minimizes tracking errors during the times of the day when the most power is transferred by the field. For example, an East field heliostat transfers more power to the receiver from 12:00 to 16:00 than from 8:00 to 12:00 solar time because the incident angle of the sun is smaller, leading to lower cosine losses and a smaller beam size. However, this effect is not accounted for in any of the metrics because the analysis required to do so was beyond the scope of this study.

Another interesting result is found by comparing the Bias and Move strategies. Upon first inspection, it appears that the Move strategy is clearly superior to the Bias strategy, independent of the frequency of execution. To verify this conclusion, strategy Move-3/D-1/Yb was investigated. It differs from Move-3/D-1/Y only in that a different pre-existing bias value (mark position) was used in the daily performance runs. The conclusion drawn is that the performance of the move strategies is highly dependent upon the pre-existing heliostat bias value. One may further infer that the Move-1/D-4/Y strategy had superior performance to the Bias-1/D-4/Y strategy only because of the pre-existing mark position that was assumed in that case. The Bias strategies appear to be less dependent on the pre-existing mark position than the Move strategies, an advantage since every heliostat at Solar Two has a pre-existing bias value.

CORRECTION MODEL STRATEGY

Tracking control technology has improved since Solar One was developed. Current state-of-the-art technology permits heliostat tracking accuracy of 0.5 mrad RMS or better over the day without adding costly design requirements on the heliostat mechanical and structural systems (Stone, 1998). This approach of using an error-correcting model involves the following steps: 1) develop a heliostat error model in the plant coordinates; 2) obtain tracking accuracy data for every heliostat by taking ~20 BCS measurements over a day; 3) estimate error parameters from the track data; and 4) use the error parameters to modify the tracking commands such that the reflected beam will be incident upon the desired aim point. An example of the achievable tracking accuracy is shown in Figure 2. Sandia took this data in 1982 during the 2nd Generation Heliostat Program (King, 1982). The elevation track error is reduced by more than a factor of 10 and the azimuth error is reduced by over a factor of 2. This approach has also been sucessfully used on solar dish concentrators to improve the tracking accuracy by a factor of 20 (Stone and Lopez, 1995). Another advantage of the correction model over the Bias and Move strategies is that it properly handles south field heliostats that undergo singularity. Stone and Lopez (1995) explain how the bias strategy can be severely flawed for heliostats that undergo singularity.

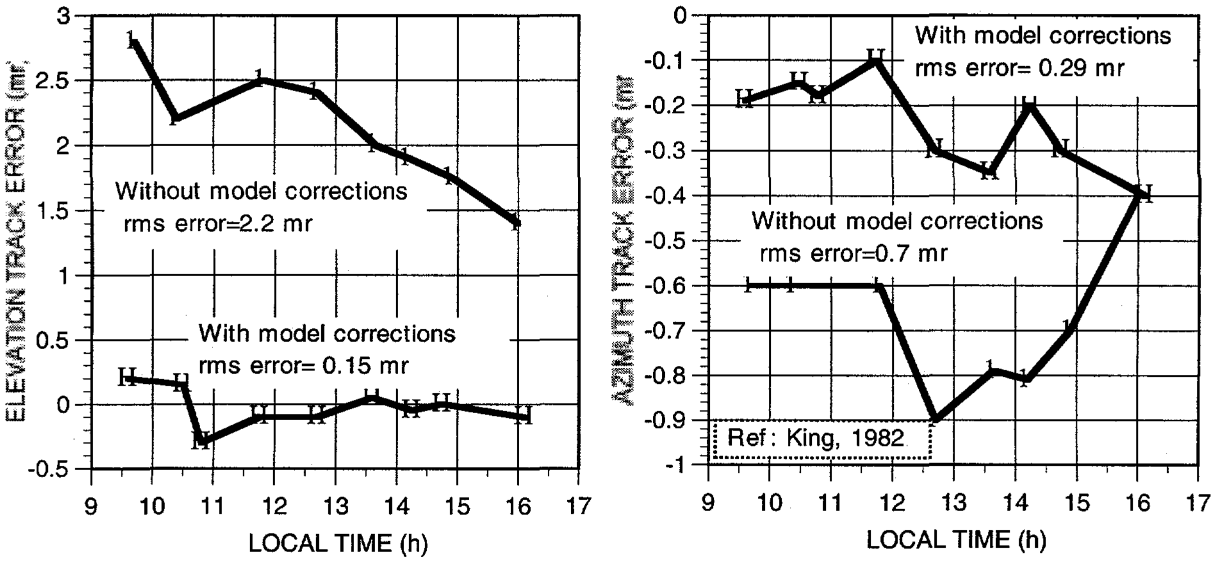

Figure 2. Tracking errors of a prototype heliostat were reduced by a factor of 10 using the correcting model strategy.

The advantage of the correction model is that once implemented, it adjusts the heliostat tracking to correct for the geometrical error sources and prevent time-variant tracking errors. It is effective at all times of the day and all seasons. Although it takes many BCS measurements to implement, the model requires updating only when the azimuth or elevation reference positions change—for example when an encoder or limit switch is adjusted or replaced. This update to the error model can be made with fewer tracking accuracy data points (possibly as few as 3 BCS measurements over a day). Previously, it was thought that expensive hardware changes would be required at Solar Two to implement such a system. However, an innovative approach could probably be developed to implement such an approch without any changes to the control system hardware, only the software. Additionally, about 20 BCS measurements per heliostat would be required to fit the error model parameters. The BCS measurements and software changes would probably take 6 months to implement if proper resources were allocated.

SUMMARY

The main objectives of Solar Two were originally focused on the proof of concept of the molten salt portion of the plant. Recent performance data shows that Solar Two has met the thermal to electric conversion and parasitic energy use goals. However, the energy collection performance is falling 10-20% short of the goals and endangering the future of the technology. The 7 mrad RMS field tracking error is likely a large contributor to this shortfall, so improving heliostat tracking accuracy has become crucial.

The study of the "Band-Aid" approaches has shown that for approximately equal labor use, the Bias-3/D-1/Y strategy appears to provide slighly better performance than the Bias-1/D-4/Y strategy currently used at Solar Two. However, the complexity of the calculations prevented the use of an annual-average RMS tracking accuracy metric that includes incident-power weighting, a factor that could help the performance of the Bias-1/D-4/Y strategy compared with the Bias-3/D-1/Y strategy. Further experimentation and analysis would be beneficial in understanding the competition between these two strategies.

The newly proposed Move strategy appeared superior to the bias strategy in some cases, but inferior in other cases because of a strong dependence on the pre-existing mark position of the heliostat. For this reason, it is not recommended for implementation.

Comparing these strategies may seem like like splitting hairs in light of the tracking accuracy improvement available with the error-correcting model strategy. The future of power towers may depend upon meeting the Solar Two energy collection goals, and that may require the implentation of an error correcting strategy into the control system.

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