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ANALYSIS OF SOLAR TWO HELIOSTAT TRACKING ERROR SOURCES

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ABSTRACT

This paper explores the geometrical errors that reduce heliostat tracking accuracy at Solar Two. The basic heliostat control architecture is described. Then, the three dominant error sources are described and their effect on heliostat tracking is visually illustrated. The strategy currently used to minimize, but not truly correct, these error sources is also shown. Finally, a novel approach to minimizing error 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 Co. (MMC) during the early 1980's for the 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 original, corroded 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.

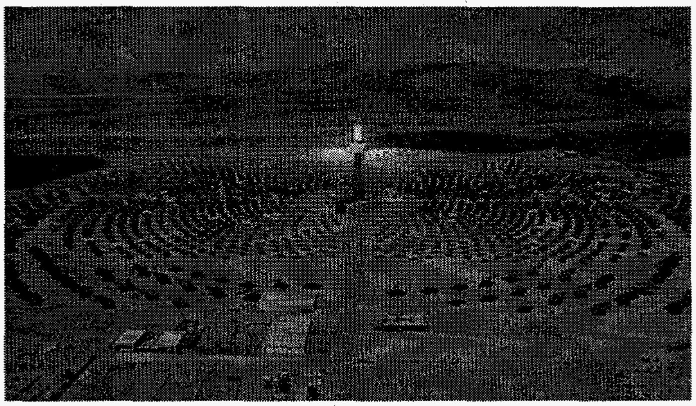

Figure 1. The Solar Two Power Tower Plant

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

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and excessive flux on the oven covers (the white panels located directly 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.

TRACKING CONTROL SYSTEM DESCRIPTION

The heliostat tracking control system that controls the original Solar One field is an open loop distributed system (Stone, 1995) with the purpose of aiming heliostats so that the reflected beam will be continuously incident on the desired receiver aim point as the sun moves. There are three hardware components in the control system. The 1818 Heliostat Controllers (HC) calculate the required azimuth and elevation angles given the sun position and aim point and move the heliostats to those angles. The 64 Heliostat Field Controllers (HFC) handle communications with the maximum of 32 heliostats under their control. The third component is the Heliostat Array Controller (HAC) that interfaces with the operator, calculates the sun position vector and aim points, and communicates with the HFC units. Because of the high cost of replacing the heliostat control system, the basic Solar One control system is being used at Solar Two. The HAC computing hardware was replaced but most of the Solar One HAC software was transferred. The 108 new Lugo heliostats use a slightly different control system that was interfaced with the original system, and are not analyzed in this paper. Since the time Solar One tracking algorithms were developed and implemented, new techniques have been developed that can improve heliostat tracking accuracy. Unfortunately, the distribution of the tracking control logical functions among the different controllers is typically believed to make it difficult and costly to implement these techniques.

TRACKING ERROR SOURCES

The heliostat control system described above is subject to many different types of error sources. Some of the commonly thought of error sources are azimuth rotational axis tilt, incremental encoder granularity, control system granularity, atmospheric refraction, gravity bending, pivot point offset, mirror alignment or "canting" non-orthogonality relative to the heliostat centerline, and azimuth and elevation reference position (referred to as the mark position) error. Other errors which probably contribute a small amount to the tracking error are sun position algorithms, latitude and longitude field variation, leap second, computation time error, transmission time error, algorithm accuracy, etc.

A geometrical error model was developed that predicts the tracking error of a single heliostat over the course of a single day based on information about its various geometrical error sources. Stone (1998) describes the error model geometry and mathematics in more detail. The error model was implemented in a spreadsheet to produce the results and plots shown here. Three geometrical error sources are believed to be dominant at Solar Two and are the focus of this paper: azimuth rotational axis tilt, encoder reference position error, and mirror alignment/canting non-orthogonality errors. In addition, the effect of the procedure currently used at Solar Two to minimize these geometrical errors is shown. A novel, new approach to improving heliostat tracking is also presented. The purpose is to familiarize the reader with the geometrical error sources present at Solar Two and also show that the approaches used at Solar One, at Solar Two, and the new approach proposed to address these errors are merely "Band-Aids" to hopefully minimize the problem, not true fixes that correct the problems.

To objectively evaluate strategies to improve heliostat tracking, one must base decisions on more information than how the strategy affects a single heliostat on a single day, as shown here. Ideally, the strategies would be compared based upon their effect on the tracking of the entire field of heliostats on an annual basis. A companion paper (Jones and Stone, 1999) addresses this question.

AZIMUTH AXIS TILT ERRORS

At the time the heliostat field was installed, the azimuth rotational axis tilt was the primary error source considered in the design of the system. This type of error would most likely occur due to a tilt of the heliostat pedestal, so is often referred to as pedestal tilt error. It can also occur due to other mechanical errors that tilt the azimuth rotational axis relative to the vertical coordinate at the plant, such as errors in the gear drive. At Solar One, a very accurate, electronic inclinometer was used to measure the azimuth axis tilt angle and the foundation bolts at the base of the pedestal were adjusted to minimize this error. This was an expensive procedure, and it still did not totally eliminate the error. A survey of 16 randomly selected heliostats at Solar Two indicated the average tilt magnitude was about 0.5 mrad (Jones et al., 1995).

Figure 2 shows the horizontal and vertical tracking errors on summer solstice of a heliostat 305 m (1000 ft) north of the tower with a 1 mrad pedestal tilt in the north direction. The target sits atop the tower at a height of 90.1 m (296 ft), matching the location of the receiver midpoint at Solar Two. Each point on the graph corresponds to the centroid location of the heliostat beam on the target at 1 hour increments of local solar time. Three of the data points have a label indicating the solar hour (6, 12, 18) so that the reader may ascertain the direction of the beam movement from morning to afternoon. Additionally, there is substantial data regarding the graph in the adjacent boxes. The heliostat location and date are listed above the chart. The error profile used in the calculations is listed to the top right. In this case, there is only a north-south pedestal tilt of +1 mrad (north). In addition to the graph that shows the movement of the beam (its "signature"), the box to the lower right contains data on the tracking accuracy of the heliostat. The daily RMS errors are followed by the daily peak tracking errors. Both metrics are tallied for each axis and also for the total of the two axes.

This example is shown first because it is easier to visualize the relation between the error source and the beam movement than with many of the other examples in this paper. At noon, when the tower and the sun are due south of the heliostat, the northward pedestal tilt causes the beam to track high on the target. Conversely, a pedestal tilt to the south would cause the beam to track low at solar noon. In the morning and afternoon, the sun is not due south of the heliostat, causing the tracking error to have both vertical and horizontal components. As can be seen, the 1 mrad pedestal tilt has caused a peak 2 mrad beam position error because of the law of reflections. The daily RMS beam tracking error is a substantial 1.61 mrad. Tracking errors scale linearly with error sources, so a 2 mrad northward tilt would lead to a peak error of 4 mrad and a daily RMS error of 3.22 mrad for this heliostat.

Another example of pedestal tilt is shown in Figure 3. In this case, the pedestal is instead tilted 1 mrad in the east direction. The movement of the beam over the day has changed substantially, and the daily peak and RMS tracking errors have dropped slightly to 1.23 and 1.26 mrad respectively. The location of the heliostat in the field also affects the nature of the tracking errors. If the heliostat shown in Figure 3 were moved to 244 m (800 ft) east of the tower, it would have the tracking signature shown in Figure 4. This heliostat has a peak beam error of 2 mrad and a daily RMS tracking error of 1.96 mrad. Heliostats in the south field tend to have tracking signatures similar to those in the north field for equivalent error profiles. The same is true of east and west field heliostats. Figure 5 shows a heliostat 122 m (400 ft) south and west of the tower with a 1 mrad pedestal tilt in the southeast direction. It is difficult to visualize how the error source causes the beam movement of this heliostat that nonetheless has similar daily peak and RMS tracking errors of 2.00 and 1.81 mrad respectively.

Seasonal effects can also been seen in the tracking errors. One would expect larger changes for heliostats in east, west, and southern region of the field since the tracking angles of these heliostats change more with season than the heliostats in the northern region of the field. Figure 6 shows the same scenario as Figure 5, except on winter solstice instead of summer solstice. The signature has changed (note the starting and ending points), yet the peak and daily RMS tracking accuracy remain similar.

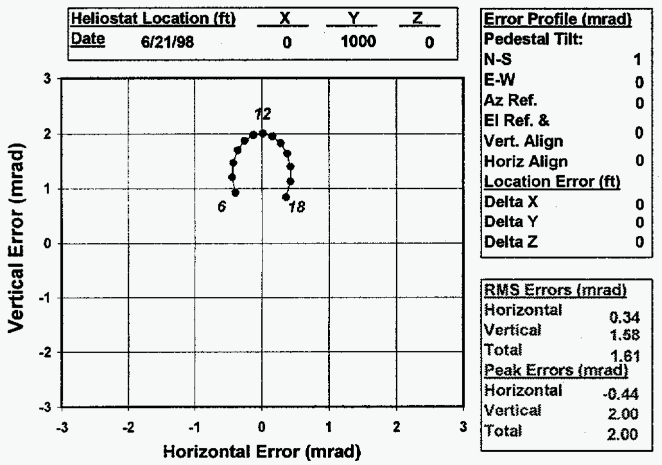

Figure 2. Tracking error signature on summer solstice of a north field heliostat with a 1 mrad pedestal tilt to the north.

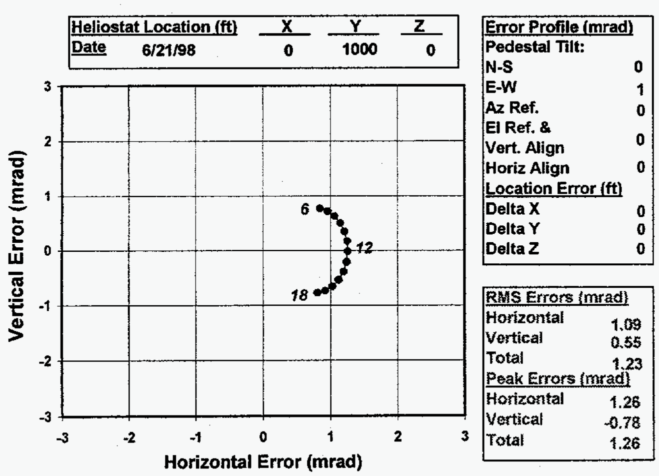

Figure 3. Same as Figure 2, but pedestal tilt is to the east.

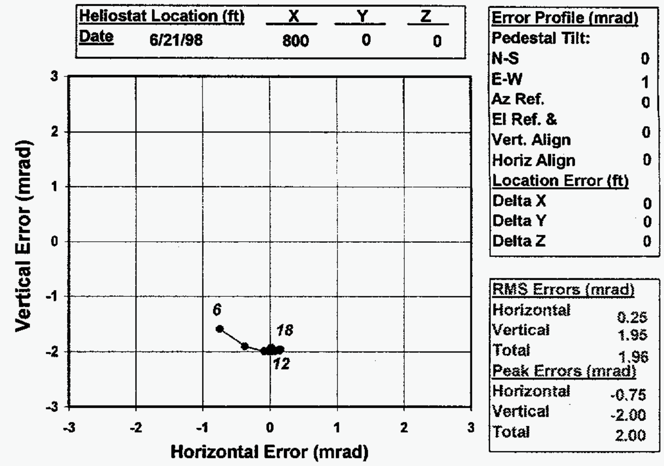

Figure 4. Same as Figure 3, but heliostat east of the tower.

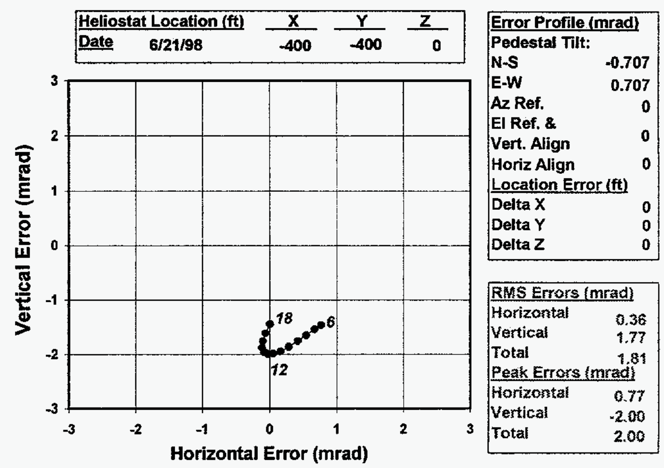

Figure 5. Tracking errors on SS of a southwest heliostat with 1 mrad of pedestal tilt in the southeast direction.

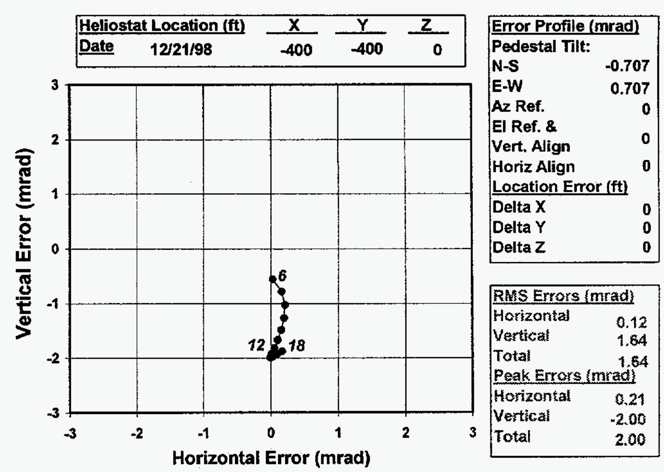

Figure 6. Same as Figure 5, but on winter solstice.

MIRROR ALIGNMENT/CANTING ERRORS

At Solar One, all the heliostats were aligned, or "canted" for a 365 m (1200 ft) focal length. This caused the beams of heliostats close to the receiver to be quite large. In fact, spots from all 12 facets could be seen rather than one contiguous beam. This was fine for the large Solar One receiver with low flux limits. In order to minimize spillage on the smaller, Solar Two receiver, the heliostats were re-aligned to shorter focal lengths. A study showed that aligning the inner 17 rows of heliostats to their slant range (the line-of-sight distance to the receiver) would provide as much benefit as re-canting the entire field, so this was done (Jones et al., 1995). Unfortunately, a tracking error source may have unintentionally been increased in the process of mirror alignment.

A tracking error occurs when the heliostat mirrors are aligned to a point that does not lie on the normal vector to the heliostat's local elevation plane defined by the gear drive assembly. In this case, the alignment is non-orthogonal to the local elevation plane. This can easily occur in both optical (on-sun and lookback) alignment techniques as well as mechanical approaches (inclinometer and offset measurement). The error source can be divided into two components, vertical and horizontal. The vertical component is indistinguishable from an elevation reference mark error to be discussed next.

Figure 7 shows a heliostat 244 m (800 ft) west of the tower with a 1 mrad horizontal alignment error. This heliostat has a daily peak tracking error of 2 mrad and a daily RMS tracking error of 1.88 mrad. The tracking signature is unique in the large shift that occurs from 17 to 18 hours solar time. This is the result of singularity, when the heliostat azimuth axis must rotate quickly to properly track the sun. This occurs when a heliostat is pointing nearly face up and is in line between the sun and the tower. It is interesting to note that the change in sun trajectory encountered just one month later prevents this singularity from occurring, as shown in Figure 8. Stone and Lopez (1995) have shown how the biasing approach can in some cases double tracking errors when used on heliostats in the south field that undergo singularity.

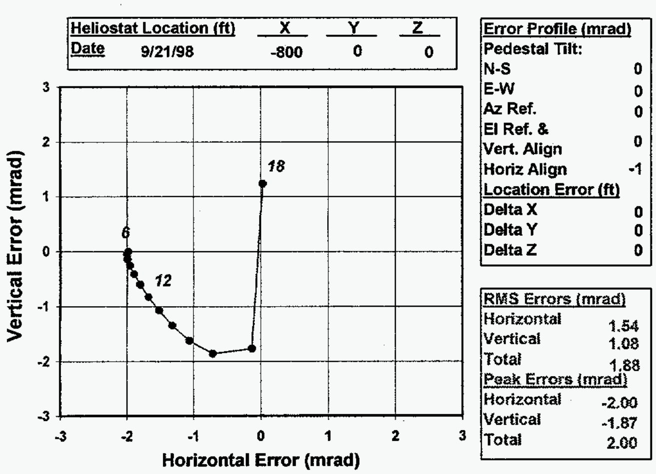

Figure 7. Tracking error signature on the autumnal equinox of a west field heliostat with a horizontal alignment error of 1 mrad. The effect of singularity can been seen at the end of the day.

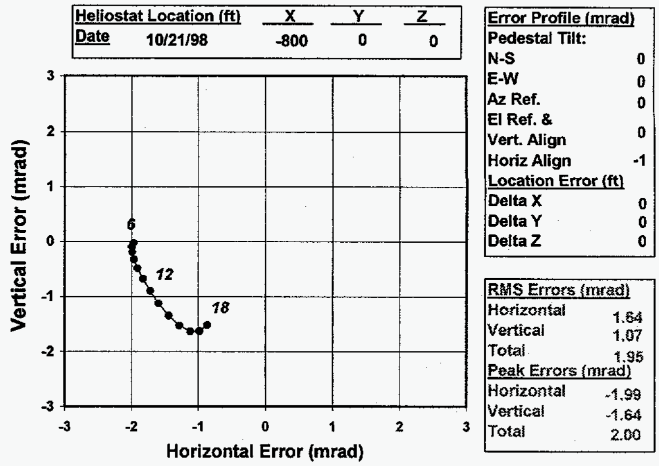

Figure 8. Same as Figure 7, but 1 month later when singularity no longer occurs.

ENCODER REFERENCE ERRORS

The function of the heliostat control system is to rotate the heliostat to azimuth and elevation angles that will result in the reflected beam being incident at a given aim point. An encoder is used to determine when the heliostat is at the required angles. The accuracy of this process depends both upon the accuracy of the encoder, and also upon the accuracy of a reference position that correlates the encoder position to the plant coordinate system. The MMC heliostats at Solar Two use an incremental, optical encoder with a built in "mark" pulse to establish the reference[1]. When the incremental encoders are first installed on the heliostat, the reference mark could probably be positioned within 1 degree of the desired location. However, this position should ideally be known to within a fraction of a milliradian (1-2 orders of magnitude more accurate).

Many believe that an error in the encoder reference position introduces a constant shift in the heliostat beam tracking location. This is false. Figure 9 shows the effect of a 1 mrad elevation reference position error on a north heliostat. The reference error causes a time-variant tracking error similar to that caused by pedestal tilt (see Figure 2). Likewise, Figure 10 shows a time-variant error for an east field heliostat with an azimuth reference position error. In this case, the tracking error signature is different from that for the same heliostat with 1 mrad pedestal tilt shown in Figure 3. However, the daily RMS error is nearly the same (1.22 mrad vs. 1.23 mrad). The day of the year and field location seem to have a larger impact on the daily RMS tracking error than the particular error profile. Of course, the magnitude of the tracking error scales linearly with the magnitude of the error sources. All the errors profiles explored so far have totaled 1 mrad.

Encoder reference errors are unique in that they are easily corrected in software, rather than requiring a hardware fix as would pedestal tilt and alignment errors. Since this error source was also expected to be present after encoder installation, much effort was directed towards correcting it at Solar One and Solar Two. Unfortunately, it is very hard to measure. In fact, since all the heliostats at Solar Two (or any plant) have other error sources present

[1] The Lugo heliostats use incremental, hall-effect encoders, while the limit switches establish the reference positions.

as well, adjusting this error became an attempt to correct all the error sources. This is the subject of the next section.

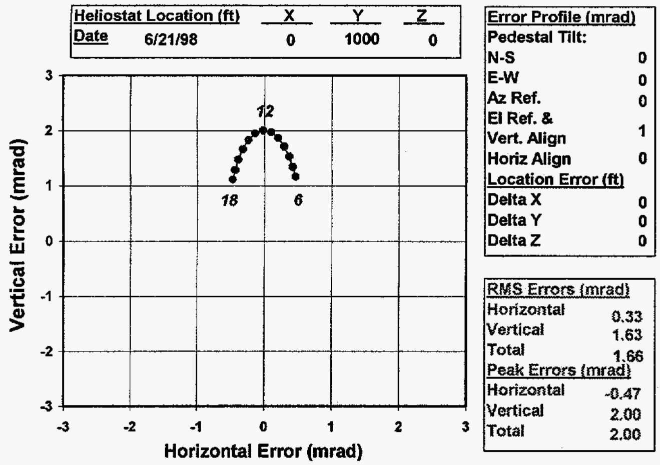

Figure 9. Tracking errors for a north field heliostat on SS due to a 1 mrad elevation reference position error. The effect is similar to the pedestal tilt error shown in Figure 2.

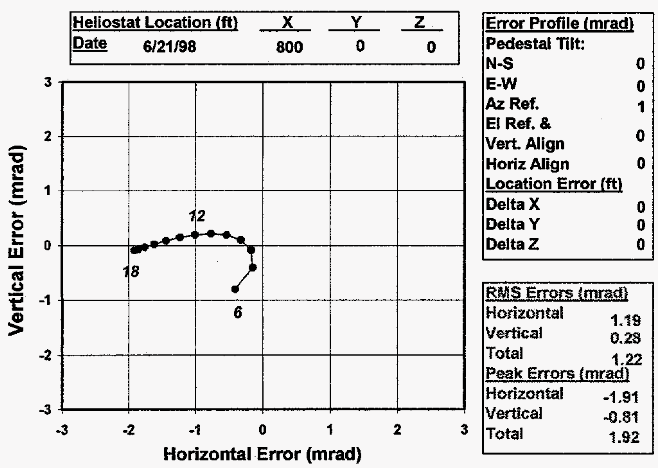

Figure 10. Tracking error signature for an east field heliostat on SS with a 1 mrad azimuth reference position error.

MARK POSITION ADJUSTMENT OR "BIASING"

At Solar One and at Solar Two, heliostat tracking accuracy has been improved by adjusting the encoder reference position errors. This is called heliostat biasing because the location of the encoder reference position (the mark position) of every heliostat is stored as a "bias" value in a database. The Beam Characterization System (BCS) is used to measure heliostat tracking errors needed to perform biasing. Mavis (1988), King (1982), and Strachan (1993) describe the BCS. Basically, a camera records an image of the heliostat beam on one of the 4 targets located beneath the receiver. Normally, the centroid of the recorded image provides the tracking location of the beam.

Biasing is a "Band-Aid" approach to hopefully minimize the daily tracking errors, but not truly correct the problem. Another problem with biasing heliostats is that changing the bias values does not introduce a constant shift in the beam. Rather, a time-variant tracking error is introduced, as was shown earlier. It uses one time-variant tracking error source to try to compensate for others. Sometimes, this is very effective. Other times it is not.

Two of the key parameters in heliostat biasing are the number of BCS measurements per day used to adjust the bias, and the number of updates performed per year. The companion paper explores the relative merits of the many potential combinations of these parameters by running hundreds of case studies (Jones and Stone, 1999). Only two scenarios will be shown here to illustrate the impact of biasing.

To start, a heliostat with a simple error profile, consisting of a single error source, will be investigated. Figure 11 shows the same scenario as Figure 2, except the elevation bias has been adjusted (note the elevation reference error of –1 mrad) so as to minimize the heliostat tracking error at noon. The peak tracking error has been reduced from 2.0 to 0.89 mrad and the daily RMS error has been reduced from 1.61 to 0.67 mrad. This is a significant improvement, although time-variant tracking errors still exist. However, noon was the best time to bias this heliostat. Had biasing instead been performed at 10 or 14 hours, the RMS tracking error would increase to 0.86 mrad, while the peak error would rise to 1.43 mrad. If three tracking error measurements at 10, 12, and 14 hours had been used to bias the heliostat, an improvement very similar to the noon bias would occur.

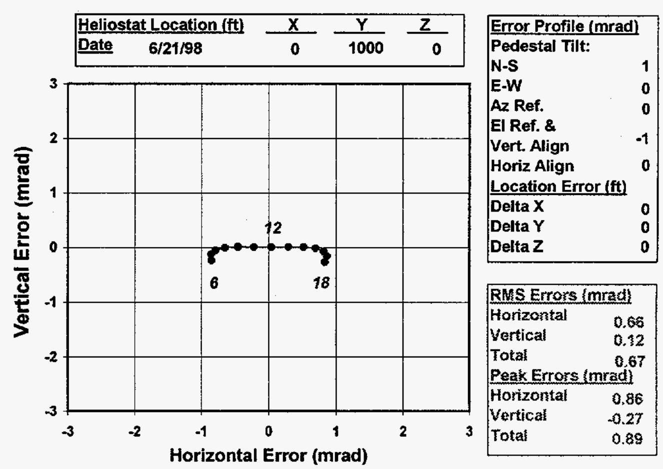

Figure 11. Heliostat from Figure 2 biased at noon with a –1 mrad elevation reference position error.

The second scenario involves a more likely error profile for a heliostat in the southeast region of the field. This heliostat has 1 mrad of pedestal tilt in the northwest direction and 1 mrad of alignment error equally distributed between horizontal and vertical axes. Finally, this heliostat also has an azimuth bias error of 1 mrad. Figure 12 shows the tracking signature of this hypothetical heliostat. Figure 13 shows the tracking signature for this heliostat after biasing using a tracking error measurement at solar noon. The signature has been changed because of the influence of the encoder reference error that was introduced in biasing. The impact of biasing the heliostat at different times and using multiple tracking error measurements is listed in Table 1. As with the previous scenario, Table 1 indicates that one measurement is capable of delivering results almost as good as achieved with multiple measurements if the timing is optimal (slightly before or after solar noon).

Table 1. Results of Variations in Biasing for the Hypothetical Heliostat Shown in Figure 12

Tracking Error Measurement Times (solar hour)	Daily RMS Tracking Error (mrad)	Daily Peak Tracking Error (mrad)
12	1.06	1.56
14	1.30	2.04
10,12,14	0.96	1.38
12,14,16	1.10	1.73

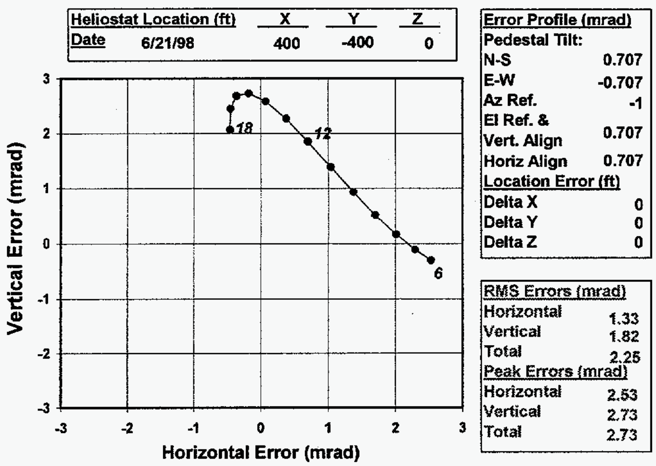

Figure 12. Tracking error signature of a southeast field heliostat on SS with a 1 mrad pedestal tilt to the northwest and 1 mrad of total horizontal and vertical alignment error.

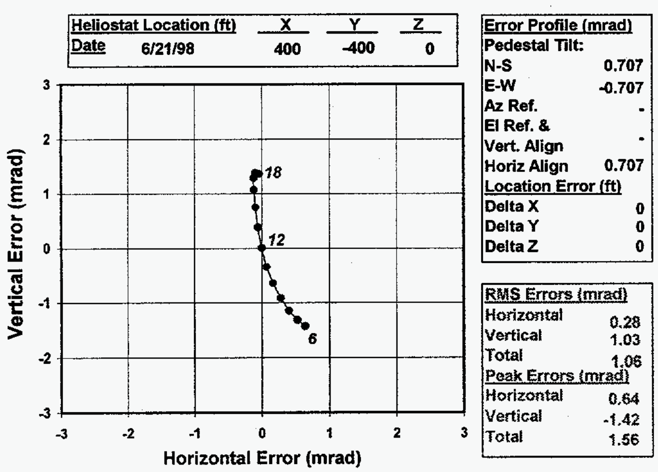

Figure 13. Heliostat from Figure 12 after biasing at noon.

At Solar One, a bias adjustment strategy using three tracking error measurements over the day was used (Mavis, 1989). Additionally, 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 initially limited its use. For these reasons, a simple, PC-based system was installed at Solar Two and a biasing approach using only one BCS measurement per day was selected to encourage high quality over high quantity in the BCS measurements performed. 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. The guidelines call for the west field to be biased just before solar noon, the east field just after solar noon, and the north and south fields about solar noon.

A NOVEL APPROACH—THE MOVE STRATEGY

If there is an error in the known location of a heliostat, a tracking error will result. Figure 14 shows a heliostat 305 m (1000 ft) north of the tower with a 0.3 m (1 ft) shift east and up from its true location, but no other error sources. The heliostat beam will likewise shift 0.3 m (1 ft) east and up on the target. Figure 14 shows the angular values of the shift rather than the linear values. The slant range of the heliostat—in this case, 318 m (1040 ft)—relates these two measures. The locations of the heliostats at Solar Two were surveyed very accurately[2] and are stored in a database, so tracking errors of this type are likely negligible.

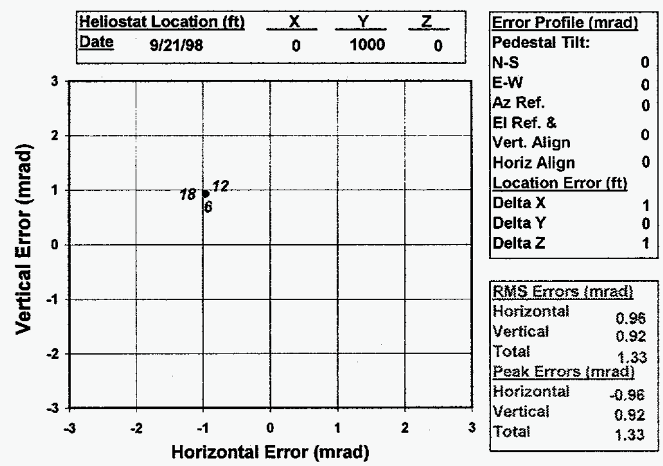

Figure 14. Tracking error signature of a heliostat with location errors of 0.3 m (1 ft) up and east.

However, this error source offers another possible method for improving the daily heliostat tracking accuracy that has never before been proposed. The fact that the beam is simply shifted provides a potentially desirable advantage over biasing. This approach to improving heliostat tracking will be termed the "move" strategy. Its effect will be shown for the same scenarios explored for the bias strategy.

[2] to a few centimeters (~1 inch) accuracy, most likely.

Figure 15 shows the impact of the move strategy on the simple error profile of the heliostat shown in Figure 2. Unlike the bias approach, the move strategy is more effective at 10 and 14 hours than at noon. In this "best" case, the RMS error is comparable to the bias strategy, although the peak error is 0.3 mrad larger. Comparing the worst cases (not shown), the move strategy has a small advantage of 0.2 mrad only in the peak error. Using three measurements at 10,12, and 14 hours, the move strategy peak tracking error is again 0.3 mrad larger than the bias strategy. Like the bias strategy, a single measurement approach is nearly as good as a three measurement approach.

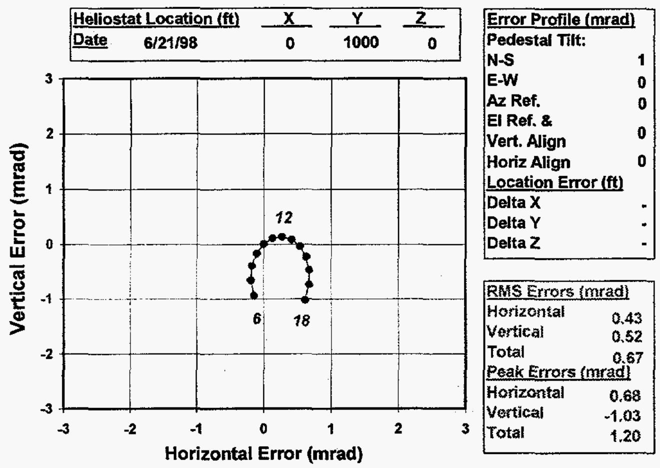

Figure 15. Heliostat from Figure 2 corrected with the move strategy at 10 hours solar time.

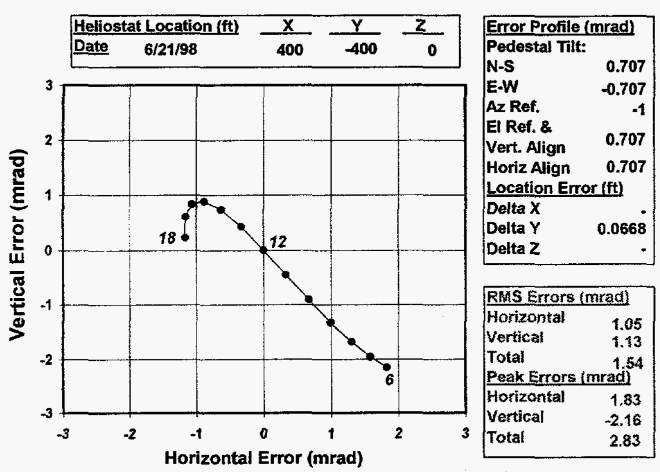

Figure 16. Heliostat from Figure 12 corrected with the move strategy at solar noon.

Figure 12 shows the uncorrected tracking signature for the second scenario studied. Figure 16 shows the impact of the move strategy performed with a single tracking error measurement from solar noon. As expected, the beam path has simply been shifted. Table 2 shows the impact of measurement time and multiple measurements on the move strategy results. For this particular heliostat, the bias strategy provided better results than the move strategy. This was because the encoder reference position errors introduced in biasing actually helped minimize the amount of beam drift over the day caused by the other error sources. It is probably just as likely that the opposite could occur for another heliostat, with biasing increasing the beam drift and providing worse RMS tracking accuracy than the move strategy. So it is unclear which strategy is superior.

Table 2. Results of Variations in the Move Strategy for the Hypothetical Heliostat Shown in Figure 12

Tracking Error Measurement Times (solar hour)	Daily RMS Tracking Error (mrad)	Daily Peak Tracking Error (mrad)
12	1.54	2.83
14	2.00	3.79
10,12,14	1.53	2.77
12,14,16	1.87	3.59

SUMMARY

Three significant error sources that adversely affect heliostat tracking accuracy at Solar Two were described. Pedestal tilt error is introduced when the heliostat is installed. Alignment or "canting" non-orthogonality error was probably inadvertently made much worse at Solar Two when the inner 17 rows were re-canted. Encoder reference position or bias error occurs during initial installation or subsequent replacement. It is currently also used to try to minimize the other error sources in a process called biasing. An error in the heliostat location can also cause tracking errors. Although this is not a likely error source at Solar Two, it is another potential "Band-Aid" solution like biasing to minimize other errors and has the advantage of introducing a constant shift in the beam position. It is unclear whether biasing or moving is a better strategy. Likewise, it is unknown how many tracking error measurements used in either process will deliver the best cost-to-results ratio. These questions are addressed in the companion paper that investigates the effect of different strategies to improve tracking by estimating their effect on annual performance of the entire field (Jones and Stone, 1999)

It was shown that the tracking error signature (the path of the heliostat beam) can vary significantly depending upon the error source profile, the location of the heliostat, and the day of the year. However, the variation in the uncorrected daily RMS tracking error was comparatively less (1.22-1.96 mrad) for the scenarios with a 1 mrad total error profile. In fact, there are many possible combinations of error profiles that could yield the same daily RMS beam tracking error. This fact is used in the companion paper.

An error-correcting model can also be used to greatly improve tracking. Stone (1998) has shown this can provide tracking accuracy of 0.5 mrad RMS or better. This appears to be the clear choice for the approach to use at future plants. In the past, it was thought that implementing such an error-correcting approach at Solar Two was difficult and would require replacing expensive hardware. However, it is likely that a novel approach using only software modifications could be developed and implemented in 6 months time. This would solve the time-variant tracking errors that currently plague the project.

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