SAND2010-4450P

Presentation to PWR

Canoga Park, CA, June 22, 2010

Automated Correction of Heliostat Tracking Errors Caused by Fabrication and Installation Errors

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Overview

- Introduction
- Tracking Error Sources
- Error Correction Theory
- Automated Error Correction
- Summary and Ongoing Work

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Introduction

- **For large heliostat fields, cost and time constraints increase likelihood of heliostat fabrication and installation errors**


Photo by J. Pacheco, 1999

Introduction

- **<u>Problem:</u> Tracking Errors**
  - Unfeasible to identify and fix so many fabrication and installation errors

- **<u>Solution:</u> Adjust tracking algorithm to compensate for errors**

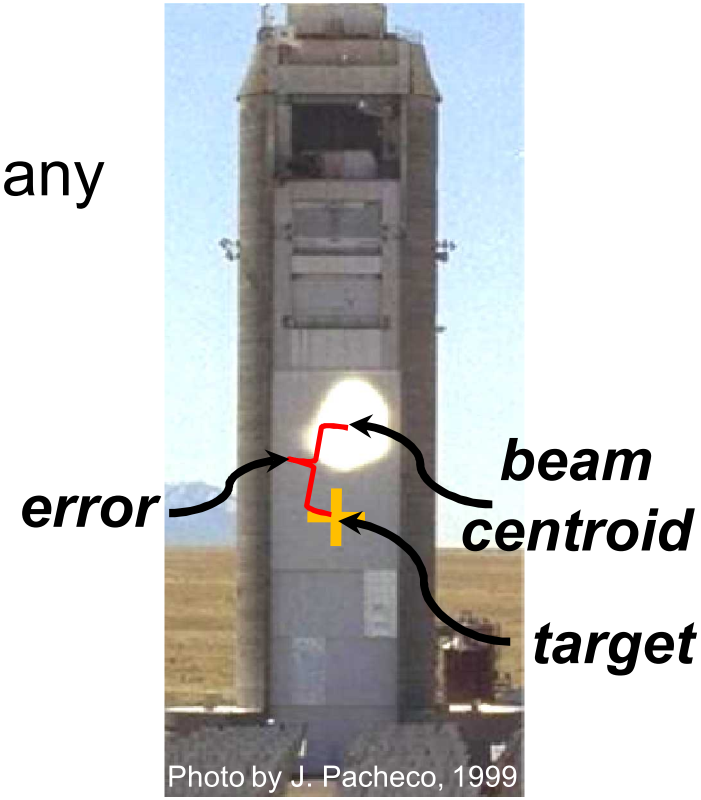

Photo by J. Pacheco, 1999

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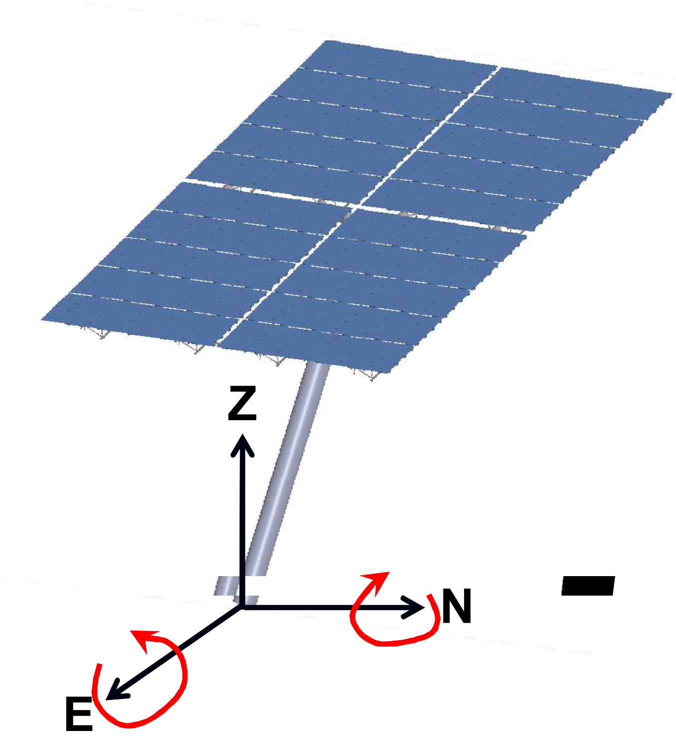
Tracking Error Sources

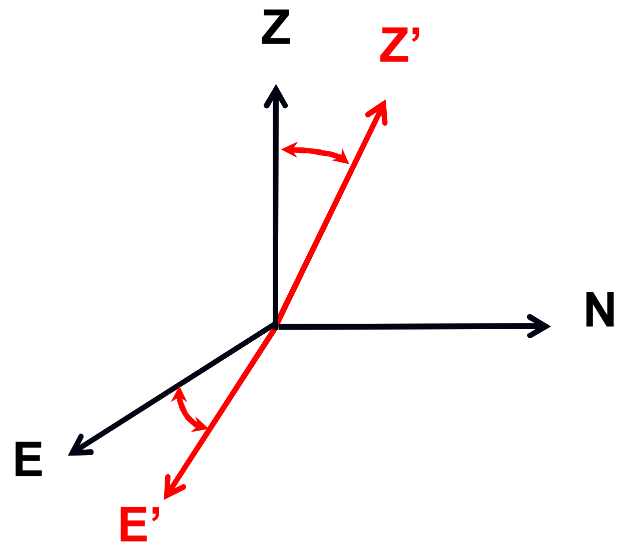
1. Pedestal Tilt



- **Actual mirror coordinate system is rotated away from ideal coordinate system**

Tracking Error Sources

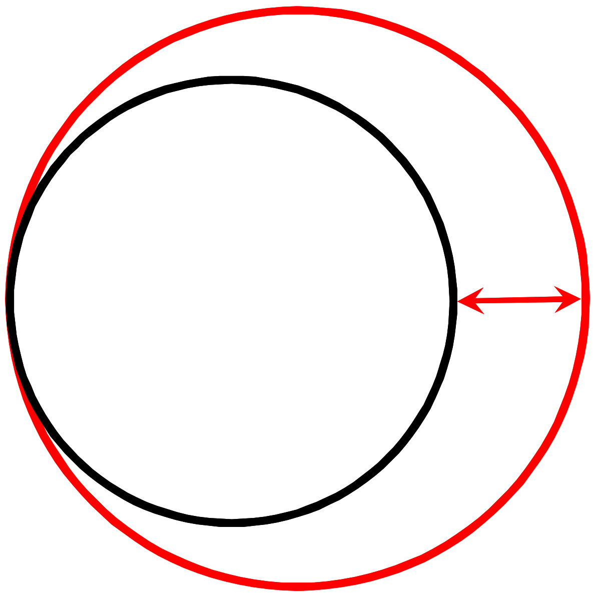
2. Reference Bias



- True Zenith and/or true East are offset from assumed Zenith and East references

Tracking Error Sources

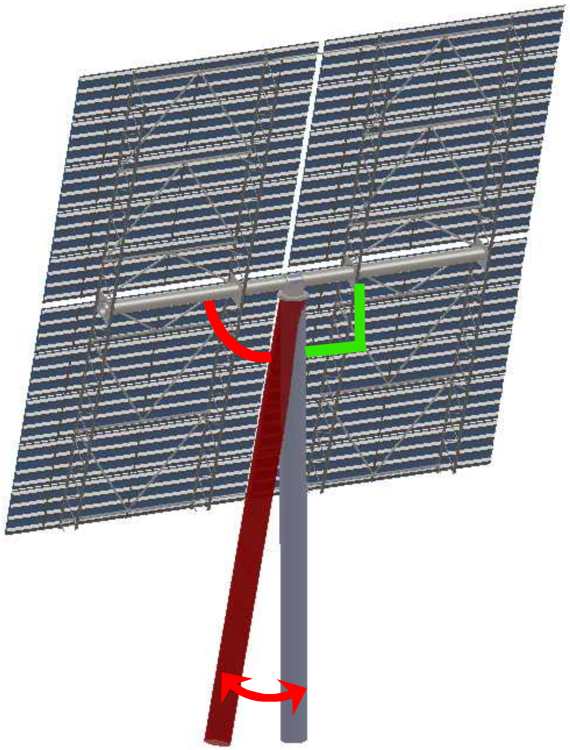
3. Drive Wheel Diameter Error



- Inaccuracy in conversion factor from angle to number of drive axis turns

Tracking Error Sources

4. Drive Axis Non-Orthogonality



- Non-square attachment between azimuthal and elevation drive axes
- An elevation-axis rotation causes an azimuthal error

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Error Correction Theory

Open-Loop Error Correction

1. Develop physical model for errors
2. Measure errors
3. Calculate error parameters
4. Adjust tracking algorithm

Error Correction Theory

Open-Loop Error Correction

1.Develop physical model for errors

$$\begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \end{pmatrix} \begin{matrix} \leftarrow \text{Pedestal tilt about azimuth} = 90° \text{ axis} \\ \leftarrow \text{Azimuth reference bias} \\ \leftarrow \text{Pedestal tilt about azimuth} = 0 \text{ axis} \\ \leftarrow \text{Fractional error in azimuth wheel radius} \\ \leftarrow \text{Fractional error in elevation wheel radius} \\ \leftarrow \text{Elevation reference bias} \\ \leftarrow \text{Axis non-orthogonality error} \end{matrix}$$

$$\begin{pmatrix} \text{Azimuthal Error, } \Delta\theta \\ \text{Elevation Error, } \Delta\alpha \end{pmatrix} \approx \begin{pmatrix} \dfrac{\sin\theta}{\tan\alpha} & -1 & \dfrac{\cos\theta}{\tan\alpha} & \theta & 0 & 0 & \dfrac{1}{\tan\alpha} \\ -\cos\theta & 0 & \sin\theta & 0 & \alpha & -1 & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \end{pmatrix}$$

Notes:

- a_1 to a_7 are assumed to be small
- θ is azimuthal angle, α is elevation angle (α=0 at zenith)
- Method for a_1 to a_6 originally described by R. Baheti and P. Scott (1980); a_7 by C. Andraka (2000)

Error Correction Theory

Open-Loop Error Correction

2.Measure errors

θ Intended Azimuth (deg)	α Intended Elevation (deg)	θ' Measured Azimuth (deg)	α' Measured Elevation (deg)
71.01	66.32	72.69	68.17
70.84	66.12	72.51	67.96
70.66	65.93	72.33	67.76

⋮

$$\begin{pmatrix} \text{Azimuthal Error, } \Delta\theta_i \\ \text{Elevation Error, } \Delta\alpha_i \end{pmatrix} \equiv \begin{pmatrix} \theta_i' - \theta_i \\ \alpha_i' - \alpha_i \end{pmatrix}$$

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Error Correction Theory

Open-Loop Error Correction

3.Calculate error parameters

Least-Squares Algorithm:

$$\mathbf{a} = \left[\sum_i \mathbf{H}_i^{\mathrm{T}} \mathbf{H}_i\right]^{-1} \left[\sum_i \mathbf{H}_i^{\mathrm{T}} \mathbf{q}_i\right]$$

Error Parameter Vector

Definitions:

$$\mathbf{a} \equiv \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \end{pmatrix} \qquad \mathbf{H}_i \equiv \begin{pmatrix} \dfrac{\sin\theta_i}{\tan\alpha_i} & -1 & \dfrac{\cos\theta_i}{\tan\alpha_i} & \theta_i & 0 & 0 & \dfrac{1}{\tan\alpha_i} \\ -\cos\theta_i & 0 & \sin\theta_i & 0 & \alpha_i & -1 & 0 \end{pmatrix} \qquad \mathbf{q}_i \equiv \begin{pmatrix} \text{Azimuthal Error, } \Delta\theta \\ \text{Elevation Error, } \Delta\alpha \end{pmatrix}$$

Error Correction Theory

Open-Loop Error Correction

4. Adjust tracking algorithm

Intended Pointing Angles: $$\mathbf{p}_i \equiv \begin{pmatrix} \theta_i \\ \alpha_i \end{pmatrix}$$

Adjusted Pointing Angles Supplied to Heliostat: $$\mathbf{p}'_i = \mathbf{p}_i + \mathbf{H}_i \mathbf{a}$$

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Automated Error Correction

1. Order heliostat to point at target
2. Take photo and calculate beam centroid
3. Calculate azimuthal and elevation errors, and append to error vector
4. Calculate error parameters and adjust tracking algorithm
5. Point heliostat at receiver
6. Repeat steps 1 to 5 for next heliostat
7. After procedure is completed for all heliostats, repeat entire procedure

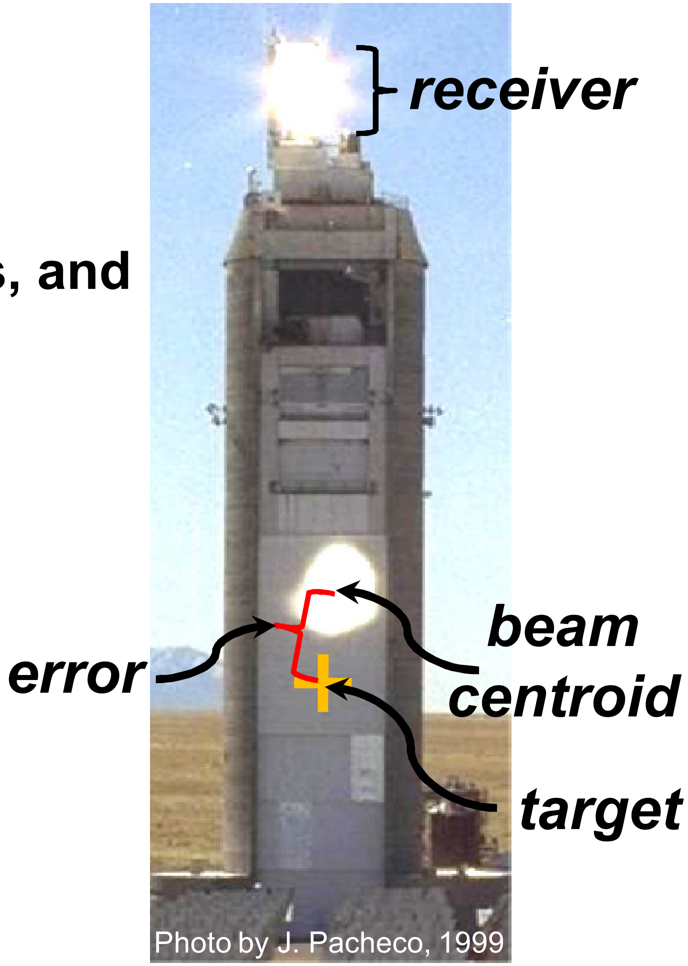

Photo by J. Pacheco, 1999

➢ **Error vectors keep growing and error parameter estimates improve**

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Summary and Ongoing Work

- **Heliostat fabrication and installation errors are very likely for large fields**
- **Can compensate for errors using automated tracking algorithm adjustments**
- **Ongoing Work:**
  - Plot tracking errors for a heliostat before and after automated error correction