AN IMPROVED SOLAR TRACKING SYSTEM WITH LINEAR REGRESSION ERROR CORRECTION

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Abstract

A motor driven two-axis optical mount combined with PC-based solar position and correction software is easily set up and provides highly accurate tracking of the sun. During setup, the tracker needs only to be approximately aligned, then a series of simple, manual corrections can be made which lead to automatic correction for misalignment. With accurate manual corrections, the tracking accuracy can approach 0.1 degrees. Various tracking options allow the user to scan repeatedly across the solar disc, track a position offset from the sun, or reflect the solar image into another instrument.

The system includes a two-axis mount driven by servo motors with optical encoder position indication; servo amplifiers; a personal computer equipped with a two-axis motor controller; software for calculating solar position; and error correction software. The optical encoders have a resolution of 0.1 arcseconds per step, and the solar position software agrees to within 1.25 arcminutes with U.S. Naval Observatory calculations of solar position. The error correction software applies linear regression viasingular value decomposition to a series of manual tracking corrections. The regression creates a best-fit compensation for misalignment of the mount.

Several factors are evaluated for their influence on tracker performance. These factors include the initial misalignment of the tracker, errors in the manual corrections, and the frequency of the manual corrections. Performance is largely insensitive to the magnitude and orientation of the initial misalignment, but sensitive to the accuracy and frequency of manual corrections. Based on this sensitivity, a manual correction scheme is developed which improves the performance of the correction software.

The performance of the tracker, employing the correction scheme, is evaluated using both a computer simulation of the tracker and field testing. Computer tests with simulated random manual correction errors show that the correction algorithm can achieve accuracy within two times the standard deviation of the correction errors. This accuracy is maintained following final manual correction for test periods as long as 54 hours. In the field test, highly accurate manual corrections were made by reflecting the solar image to a wall about 100 feet from the tracker. The observed tracking errors are 0.11 +/- 0.05 degrees for 48 hours following the final manual corrections.

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1.0 Introduction

In field projects involving measurements of direct solar radiation, solar tracking devices are often problematic. Instruments such as the Normal Incidence Pyrheliometer and the small field of view radiometers depend on a fairly high degree of solar tracking accuracy to make measurements of the sun's output.

In our experience with solar tracking mounts, we have found that the performance is highly dependent on setup errors, especially errors in the meridional (north-south) alignment and level of the tracker. In past field operations, these errors were addressed by making iterative manual adjustments to the alignment and level of the tracker's base. Small adjustments were made at various times during the day until an optimum setup was reached. In a field environment accurate manual setup usually requires an experienced operator, cooperative cloud conditions and multiple iterations which may not always converge; even then this method often results in accurate solar tracking only around the time of day of the last adjustment.

To simplify the adjustments for setup errors, a semi-automated correction method was developed. The correction method applied in this solar tracker is similar to coordinate transformations used in computer graphics applications and other mathematical transforms. In three-dimensional computer graphics, objects are rotated and translated using a single 4 x 4 matrix which encompasses any number of rotations, translations and scaling factors. A similar 3 x 3 transformation matrix can be found for any given set of setup errors, allowing true solar coordinates (as calculated from astronomical software) to be transformed into the applied solar coordinates required for the tracker.

This 3 x 3 transformation matrix can be calculated as corrections are made to the tracker's position. A correction is made simply by changing the azimuth and elevation angles of the tracker so that it is pointing directly at the sun. After the tracker is set up, three (or more) manual correction points are made over the course of a day. Once these correction points are in the system, one can solve for the transformation matrix which converts the true solar coordinates into the applied coordinates used by the tracker. While a minimum of three points are required, additional points allow averaging to minimize the effects of random errors in the individual data points used in the correction.

2.0 Design

2.1 Hardware Design

The final design includes a two-axis gimbal optical mount driven with servo motors, servo motor amplifiers, and a personal computer equipped with a two-axis motor controller card. A mount with an eight inch optics mounting ring was chosen, taking into account the maximum solar angles expected and the maximum instrument aperture.

A two-axis mount was used for this project for several reasons. First, the azimuth-elevation nature of the mount translates easily into azimuth-elevation solar data. Second, a two-axis mount allows for two modes of operation: a direct mode with instruments mounted directly on the gimbal, and a mirror mode with a mirror mounted on the gimbal. In the mirror mode, the solar image can be reflected into larger instruments which could not otherwise track the sun.

Servo motors were chosen over stepper motors because of the active position feedback available through the use of encoders, and the absolute position information available through the use of the encoder index signal. The encoders have a resolution of 216,000 steps per revolution (600 steps/degree, or 0.1 arcsec per step) on each axis. The servos operate in current mode for positioning purposes; initially this choice presented a problem with stability. If the control signal from the PC were interrupted, the servo driver inputs would float, causing the servo motors themselves to accelerate wildly, a condition referred to as "run-away." An electronic safety switch was constructed to prevent this problem. This switch was later replaced with mechanical limit switches.

2.2 Software Design

The PC software requires:

- a highly accurate routine to calculate the true solar coordinates as a function of time and location on the earth
- manual correction capabilities
- interfaces to the motor control software libraries
- and all routines needed to calculate and implement the transformation matrix

The algorithm to calculate the true solar coordinates was adopted from *Astronomical Algorithms* by Jean Meeus (1991) and *Astronomical Algorithms "C" Software Toolbox*, by Jeffrey Sax (1991).

The calculation of the transformation matrix proved to be more complicated than first expected. For a 3 x 3 matrix, three data points would provide sufficient information to solve for the matrix elements. But what about a case when more data points were available? The over-determined case could provide better results, but a regression algorithm had to be developed to include all available correction points.

The routine employed is a matrix solution to the regression problem. If $\boldsymbol{c}$ is the vector (x_c, y_c, z_c) containing the true solar coordinates, $\mathbf{A}$ is the 3 x 3 transformation matrix, and $\boldsymbol{p}$ is the vector (x_p, y_p, z_p) containing the observed solar coordinates (in the tracker's coordinate frame), then the transformation equation is:

$$c\,A = p \tag{1}$$

Then if the matrix ***C*** contains the ***c*** vectors from a series of corrections, and the matrix ***P*** contains the corresponding ***p*** vectors,

$$C = \begin{bmatrix} x_{cl} & y_{cl} & z_{cl} \\ x_{c2} & y_{c2} & z_{c2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ x_{cN} & y_{cN} & z_{cN} \end{bmatrix} \tag{2}$$

$$P = \begin{bmatrix} x_{pl} & y_{pl} & z_{pl} \\ x_{p2} & y_{p2} & z_{p2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ x_{pN} & y_{pN} & z_{pN} \end{bmatrix} \tag{3}$$

where the subscript N is the number of corrections, the matrix ***A*** can be calculated by any one of a number of different methods. A typical method is to calculate ***A*** as:

$$A = (C^T C)^{*}\,(C^T)\,P \tag{4}$$

where $\boldsymbol{C^T}$ is the transpose of ***C***, and $\boldsymbol{(C^T C)^*}$ is the inverse of the product of $\boldsymbol{C^T}$ and ***C***. Then $\boldsymbol{(C^T C)^*}$ is evaluated using Gauss-Jordan elimination. Initially, this method was used in the solar tracker software. However, testing of the software revealed that the matrix $\boldsymbol{(C^T C)}$ was ill-conditioned at times. In these cases, Gauss-Jordan elimination failed.

To resolve this problem, a singular value decomposition technique was used. Details of the technique are described in Press *et al.,* 1992. The matrix ***C***, which is of size N x 3, is first decomposed into:

$$C = U \begin{bmatrix} w_1 & & \\ & w_2 & \\ & & w_3 \end{bmatrix} V^T \tag{5}$$

where ***U*** is an N x 3 column-orthogonal matrix, ***W*** is a 3 x 3 diagonal matrix with positive or zero elements, and $\boldsymbol{V^T}$ is the transpose of a 3 x 3 orthogonal matrix. Then the matrix ***A*** can be found from:

$$A = (V)(diag(1/w_j))(U^T)P \qquad (6)$$

The matrix *diag(**1/w**$_j$)* is formed by taking the reciprocals of the elements $\boldsymbol{w_j}$ of the matrix *W*. For any elements $\boldsymbol{w_j}$ which are exceedingly small (indicating column degeneracies in matrix ***C***), the corresponding reciprocals $\boldsymbol{1/w_j}$ are set to zero.

3.0 Theory of Operation

3.1 *Setup Errors*

Assuming we can determine the position of the solar disk with sufficient accuracy, any error in pointing an automated instrument at the sun can be attributed to setup error. This setup error can be broken down into the following components:

+ observer's position on the earth (latitude and longitude)
+ altitude above sea level
+ time synchronization with GMT
+ meridional (north-south) alignment of the instrument
+ level of the instrument
+ atmospheric refraction (not truly a setup error, but included here anyway)

The first two sources of error can be minimized with accurate data on the deployment site; a GPS receiver is an ideal source of this information in the field. Synchronization with GMT to within one second can be readily achieved in the field through use of WWV shortwave radio signals. And atmospheric refraction errors are negligible during most of the day, becoming appreciable only near sunrise and sunset. This leaves two sources of error: meridional alignment and level.

To model these errors, we envision the actual setup of the instrument as differing from the ideal by a simple rotation about some axis. If the error were strictly an error in level, the rotation axis would lie in the horizontal plane. If the error were in meridional alignment only, the axis of rotation would be vertical.

3.2 *Coordinate Systems*

In our application two different coordinate systems must be overlaid: the earth coordinate system, in which the true solar coordinates are calculated using astronomical software, and the tracker coordinate system, which is defined by the initial setup of the tracker. Both coordinate systems are represented as three-dimensional cartesian coordinates for the transformation mathematics. For our purposes, the axes are defined in a left-handed sense so that positive x is to the south, positive y is to the west, and positive z is up (Figure 1).

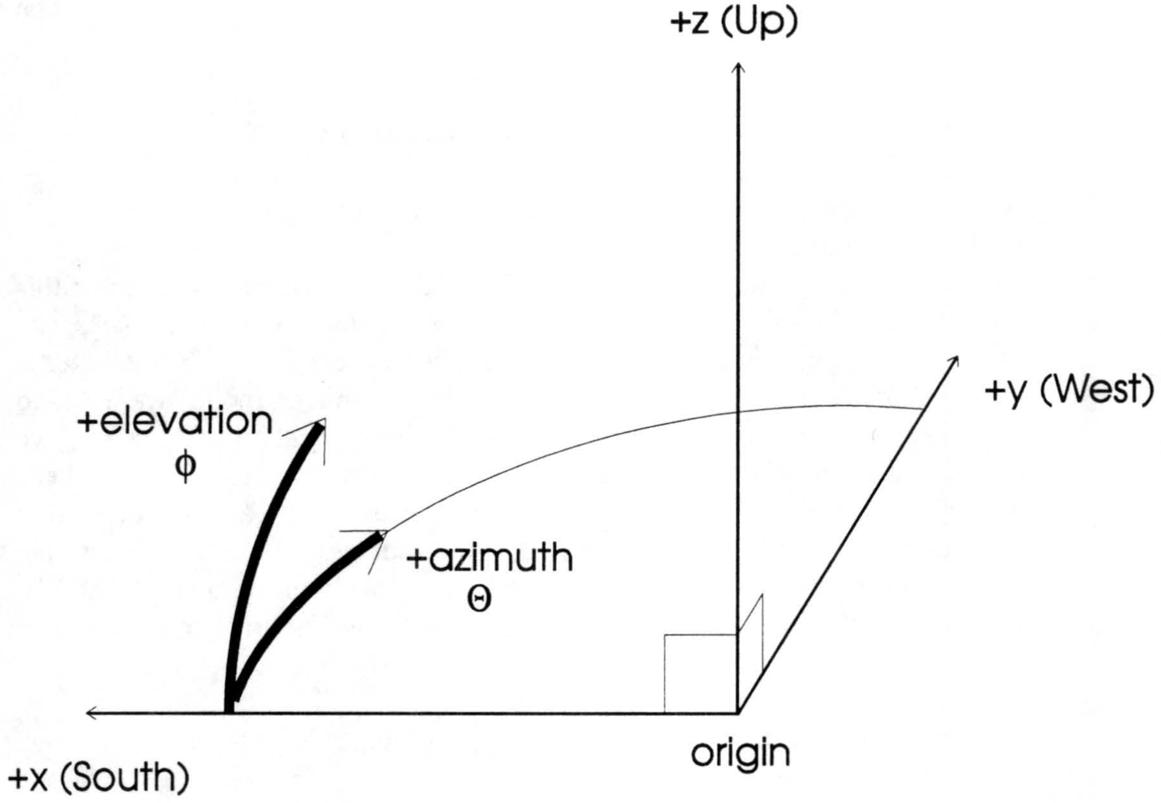


Figure 1: Cartesian and Spherical coordinates, with tracker located at origin.

The tracker is positioned using spherical (azimuth, elevation) rather than cartesian (x,y,z) coordinates. Conversion between cartesian coordinates and spherical coordinates is accomplished with the following equations:

$$x = (\cos\theta)(\cos\phi)$$

$$y = (\sin\theta)(\cos\phi) \tag{7}$$

$$z = (\sin\phi)$$

$$\theta = \pm\cos^{-1}\left[\frac{x}{\sqrt{x^2+y^2}}\right]$$

$$\phi = \sin^{-1}\left[\frac{z}{\sqrt{x^2+y^2+z^2}}\right] \qquad \textbf{(8)}$$

Assuming the coordinate systems share the same origin, an arbitrary set of coordinates can, through the use of a 3 x 3 transformation matrix, be transformed into another arbitrary set of coordinates. In the direct mode of operation of this system, the true solar coordinates are calculated, then the coordinates are transformed into the appropriate coordinates in the tracker's frame. The tracker is then moved to the transformed coordinates. In the mirror mode, we wish to reflect the sun's image to a nearby instrument. When using the mirror mode, we position the instrument at zero azimuth angle, zero elevation angle in the tracker's frame (or (1,0,0) in the defined cartesian coordinates). Again the true solar coordinates are calculated and transformed into coordinates in the tracker's frame. The transformed coordinates are then used, along with the known instrument position, to calculate the required mirror position. Then the tracker is moved to this position.

Using a left-handed coordinate system, a rotation of angle θ about the x axis may be represented by the matrix equation:

$$\begin{bmatrix} x & y & z \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} = \begin{bmatrix} x_r & y_r & z_r \end{bmatrix} \qquad \textbf{(9)}$$

A rotation of angle θ about the y axis would be performed with:

$$\begin{bmatrix} x & y & z \end{bmatrix} * \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} = \begin{bmatrix} x_r & y_r & z_r \end{bmatrix} \qquad \textbf{(10)}$$

Similarly, a rotation of angle θ about an arbitrary vector (x,y,z) (Figure 2) would be represented by the matrix:

$$\begin{bmatrix} [x^2+(1-x^2)\cos\theta] & [xy(1-\cos\theta)+z\sin\theta] & [xz(1-\cos\theta)-y\sin\theta] \\ [xy(1-\cos\theta)-z\sin\theta] & [y^2+(1-y^2)\cos\theta] & [yz(1-\cos\theta)+x\sin\theta] \\ [xz(1-\cos\theta)+y\sin\theta] & [yz(1-\cos\theta)-x\sin\theta] & [z^2+(1-z^2)\cos\theta] \end{bmatrix} \tag{11}$$

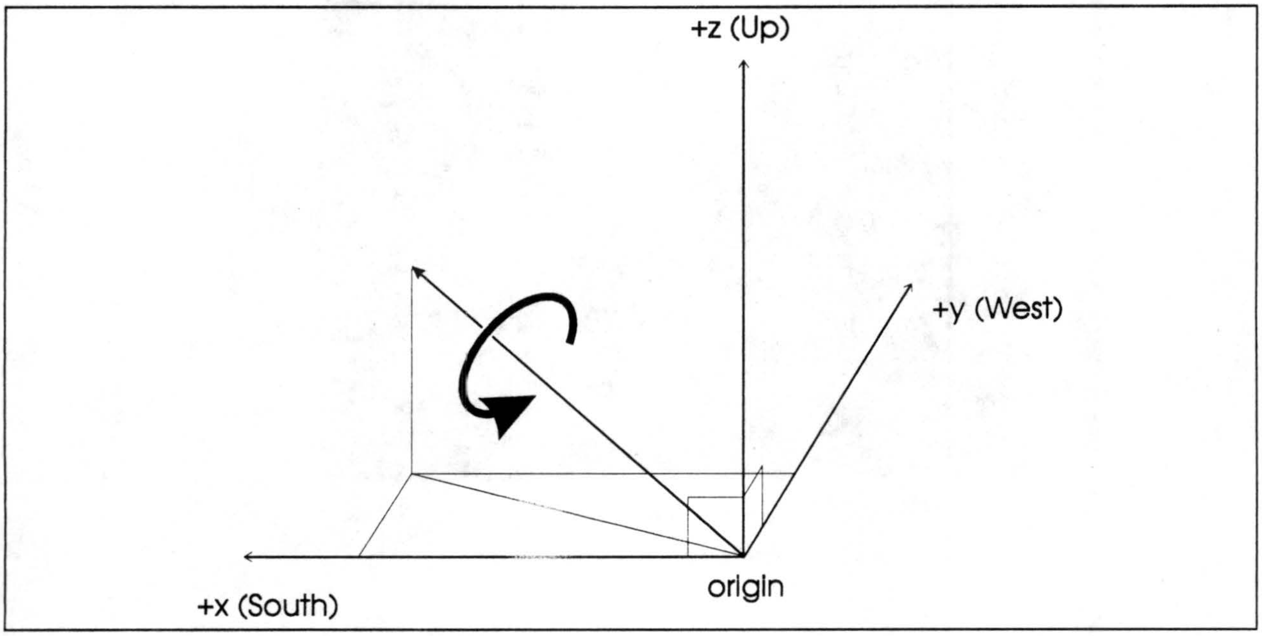


Figure 2: Rotation about an arbitrary axis

4.0 The Instrument

4.1 Construction

The mount is a standard two-axis motorized gimbal optical mount with azimuth and elevation adjustment (Figure 3). The azimuth motor turns the base platform, upon which sits the gimbal yoke with the elevation motor. The instrument or mirror attaches to a circular mounting ring in the yoke. The mount is designed to be installed on a level platform.

4.2 Additions

The azimuth limit switches are mounted on the table surrounding the azimuth servo motor. There is a stop block mounted under the rotating platform to trip the limit switch should the platform rotate too far. The switches are connected to the FAULT input of the servo amplifiers. When closed, this input disables the output stage of the amplifier, effectively removing power to the motor.

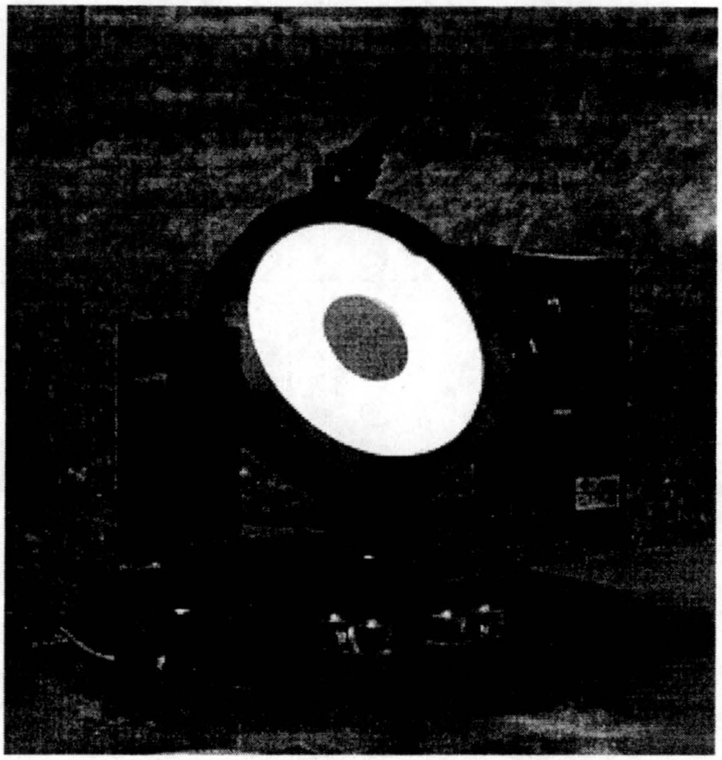


Figure 3: Solar Tracker

A similar circuit is used for the elevation stage, with the limit switches mounted on an extension to the base. If the mounting ring rotates too far up or down, one of these switches will trigger the FAULT input of the elevation servo amplifier. These switches were added to prevent damage to the cables or surrounding equipment in the event of a "run-away" condition.

A rifle scope can be installed on top of the mounting ring. This allows for a consistent zero position from day to day. The user may make a note of the position of the crosshairs of the scope when the mount is at the zero position. Later, by aligning the mount to that same position, the alignment can be reproduced.

5.0 Performance

The defining element in assessing the performance of the tracker is its accuracy. In order for the tracker to locate the sun, three systems come in to play:

- the astronomical algorithms which calculate theoretical solar position
- the correction algorithms which adjust for tracker misalignment

- the electromechanical system which moves the gimbal

The accuracy of these three systems defines the accuracy of the tracker as a whole.

5.1 Astronomical Algorithm

Tests of the astronomical algorithm used to calculate the true solar position, as implemented on a personal computer with an Intel 80386 processor, showed accuracy better that 1.2 minutes of arc (0.02 degrees). The astronomical algorithm was used to calculate the true solar position (azimuth and elevation) at ten minute intervals on five distinct days and locations through the year 1992. The results were compared with azimuths and elevations calculated from U.S. Naval Observatory data which are accurate to 0.1 minute of arc (0.00167 degrees) (Nautical Almanac Office, U.S. Naval Observatory, 1991). The comparison showed that the solar positions obtained from the solar tracker algorithms deviated by no more than 1.15 minutes of arc (0.0192 degrees) from those obtained from the U.S. Naval Observatory data.

Results from three of the tests are shown in Figure 4. This figure shows the deviation between the solar position as calculated by the astronomical algorithm and the solar position calculated from the Air Almanac. The deviation in degrees is plotted versus local standard time in hours. Of the five tests performed, these three showed the largest deviations. The remaining two tests showed deviations smaller than 0.42 minutes of arc (0.00700 degrees). The simulation dates and site locations for the five tests are shown in the table below:

Test	Date	Latitude	Longitude
1 A	1 Jan 92	40 N	105 W
1 B	1 Jul 92	40 N	105 W
1 C	1 Jul 92	80 N	105 W
1 D	1 Jan 92	80 N	105 W
1 E	1 Jul 92	0 N	105 W

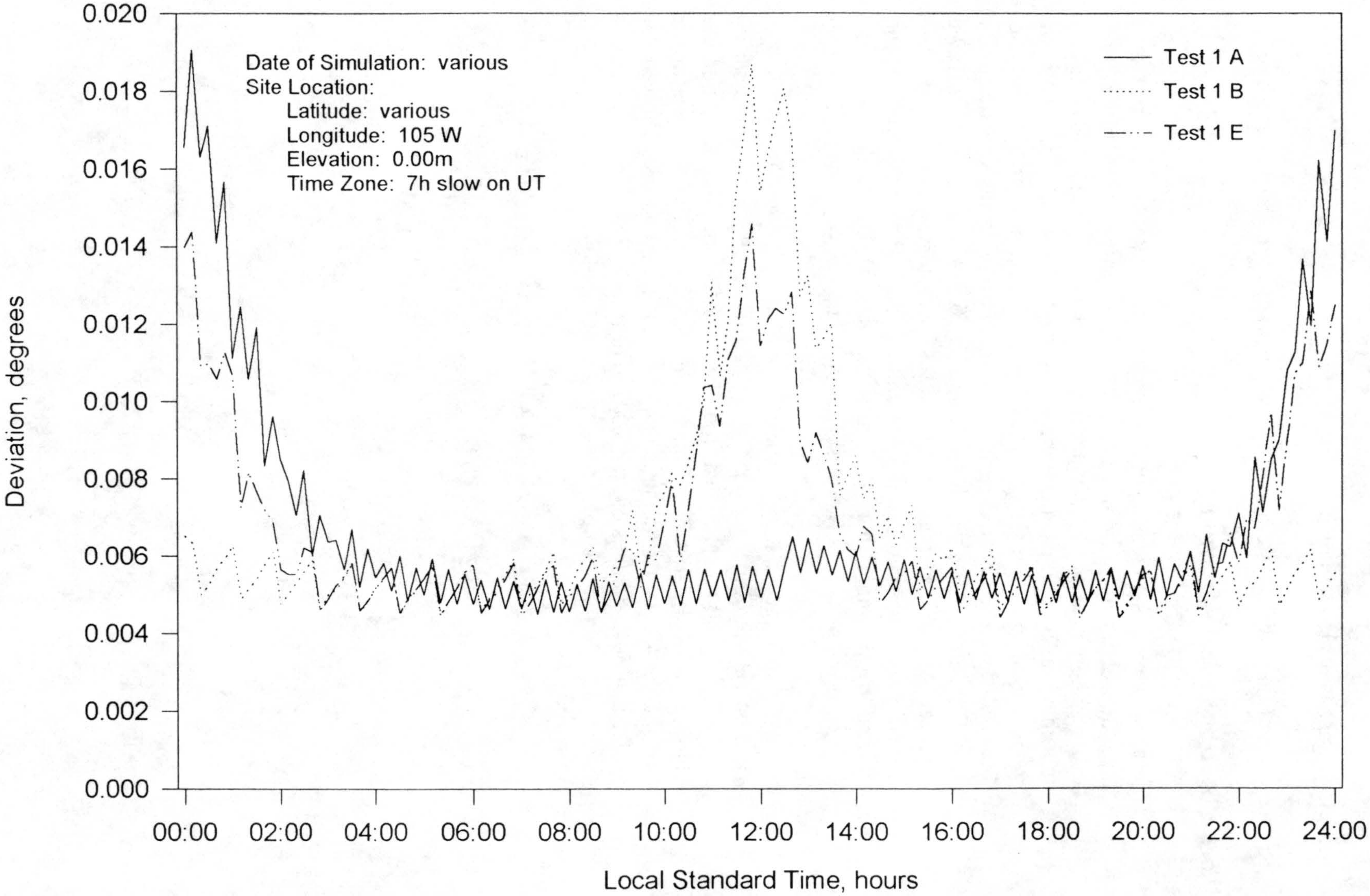


Figure 4: Deviation of solar position (Astronomical Algorithms) from solar position (USNO data)

5.2 *Correction Algorithm*

Based on tests of a computer simulation of the tracker, the performance of the correction algorithm is improved by making several corrections spaced evenly during the day, and by using a more precise sighting device when making manual corrections. Under these conditions, the simulation was capable of controlling the tracker position to within 2σ, σ being the standard deviation associated with the errors in the manual corrections. The more precise the sighting device and the more accurate the manual corrections, the smaller will be σ.

A number of factors were expected to influence tracker performance. These included the initial misalignment of the tracker, errors in the manual corrections, and the frequency of the manual corrections. The testing of the simulation led to several conclusions about the influence of these factors:

- **The performance of the tracker was largely insensitive to the orientation of the initial misalignment.**

  Over a series of four tests, each with a different misalignment orientation, the average tracking errors agreed within +/- 0.1 degrees.

- **The performance of the tracker was largely insensitive to the magnitude of the initial misalignment.**

  Over a series of three tests, with misalignment magnitudes ranging from 0.5 to 15 degrees, the average tracking errors agreed within +/- 0.1 degrees.

- **The more accurate were the manual corrections, the more accurate was the corrected position of the tracker.**

  Over a series of three tests the accuracy of the manual corrections was varied from a standard deviation of 0.01 degrees to a standard deviation of 1.00 degrees. The maximum average tracking error ranged from 0.018 degrees for the first case to 1.77 degrees for the last case.

- **More accurate tracker positioning was achieved when:**

  + **correction times were spread at intervals through the morning, midday and evening hours, rather than being clustered into a short part of the day,**

  + **several repeated corrections were made at each correction time, to reduce random correction error, and**

  + **more than two correction times were used during the day.**

  Using a correction scheme as described above, with a modelled standard deviation of 0.153 degrees for the manual corrections, average tracking errors of less than 0.2 degrees were achieved over a sixty hour time period.

The following discussion describes the operation of the simulation and covers each of these conclusions in more detail.

5.2.1 The Simulation

The operation of the simulation is analogous to the tracker. In this simulation, the axes of the tracker can be misaligned by a known amount. As the simulation runs, the display shows both the tracker position and the solar position at ten minute intervals. Manual corrections, including simulated random errors, can be made to the tracker position. After three or more corrections, the correction algorithm can be called to calculate the correction matrix and apply it to the tracker position. The performance of the correction algorithm is judged by comparing the solar position with the corrected tracker position. This comparison is made by calculating the tracking error at each ten minute interval:

$$\varepsilon = [\,(A_t - A_s)^2 + (h_t - h_s)^2]^{1/2} \qquad \textbf{(12)}$$

where:

ε = tracking error, degrees
A_t = azimuth of tracker, degrees
A_s = azimuth of sun, degrees
h_t = elevation of tracker, degrees
h_s = elevation of sun, degrees

The initial misalignment of the tracker is accomplished by defining a rotation of the tracker coordinate system about an arbitrary axis (as described above in section 3.2). Thus, to define the rotation, both an axis of rotation and an angular magnitude of rotation need to be specified. The misalignment is varied by changing the orientation of the rotation axis and the magnitude of the rotation.

5.2.2 Sensitivity to Orientation of Misalignment

Figure 5 shows the results of testing the simulation with four different orientations of misalignment. Average tracking errors in degrees are plotted versus local standard time. The four curves exhibit roughly the same shape and the same magnitude of error.

Each test was performed by running the simulation for forty-eight hours with a given misalignment orientation. During the first simulation day, corrections were made at half-hour intervals between 0630 and 1800 local standard time (LST). Then the correction matrix was applied during the second simulation day. Each test was repeated three times and the average tracking error was calculated at each ten-minute time interval. The tracking errors displayed in Figure 5 are the averages over each set of three tests.

The misalignments which were used represent various errors ranging from poor leveling to north-south misalignment. In all four cases the magnitude of the misalignment was 5°, where rotation is positive in a left-handed sense.

Test 7 A
This case represents a pure leveling error. The orientation of the rotation axis is 0° azimuth, 0° elevation.

Test 7 B
This case represents a combined leveling and north-south misalignment. The orientation of the rotation axis is -90° azimuth, 30° elevation.

Test 7 C
This case represents a combined leveling and north-south misalignment. The orientation of the rotation axis is -180° azimuth, 45° elevation.

Test 7 D
This case represents a pure north-south misalignment. The orientation of the rotation axis is 90° elevation.

5.2.3 Sensitivity to Magnitude of Misalignment

Figure 6 shows the results of testing the simulation with three different magnitudes of misalignment. Average tracking errors in degrees are plotted versus LST. The three curves exhibit roughly the same shape and the same magnitude of error.

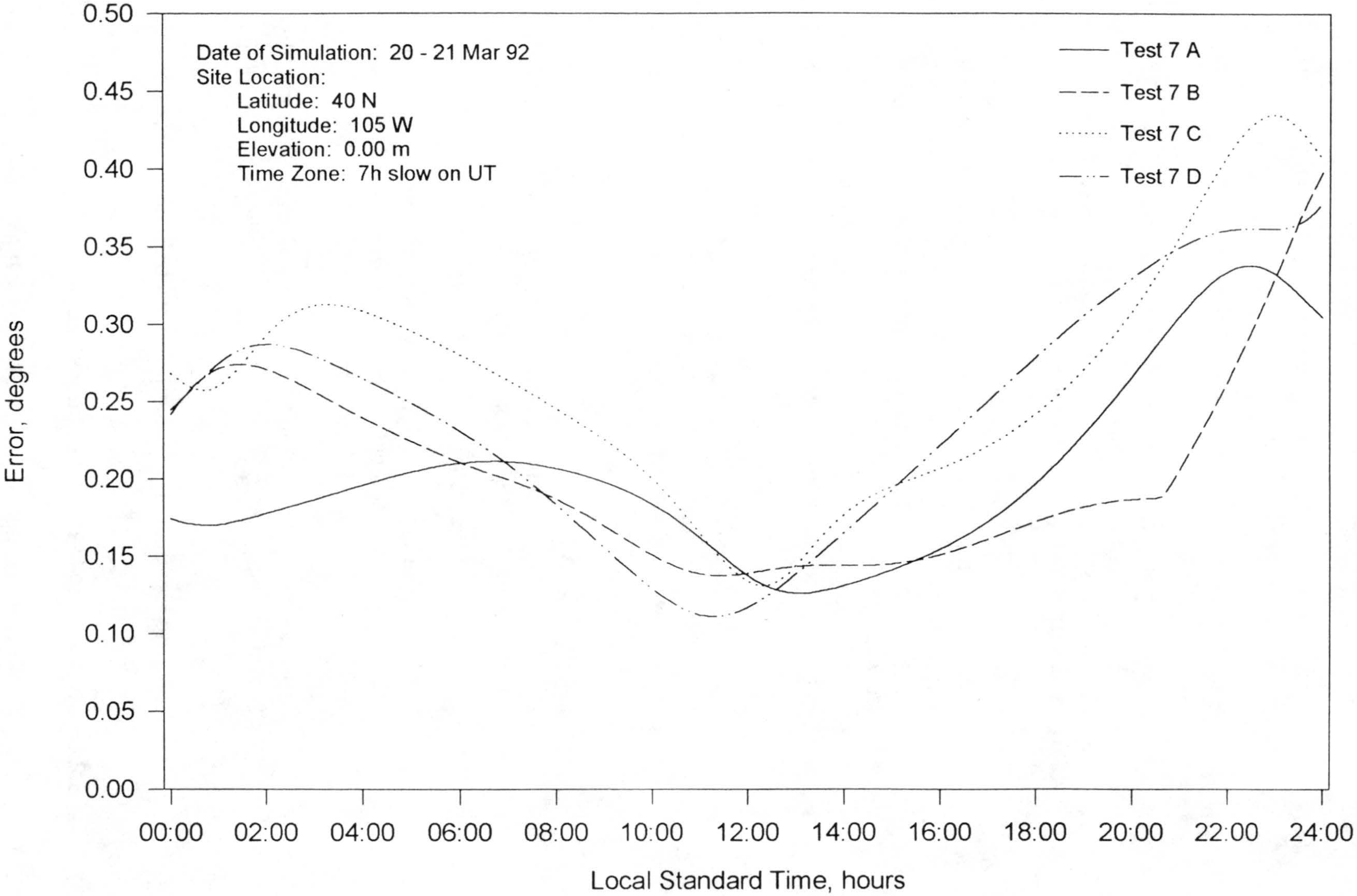


Figure 5: Tracking Error for Various Orientations of Misalignment

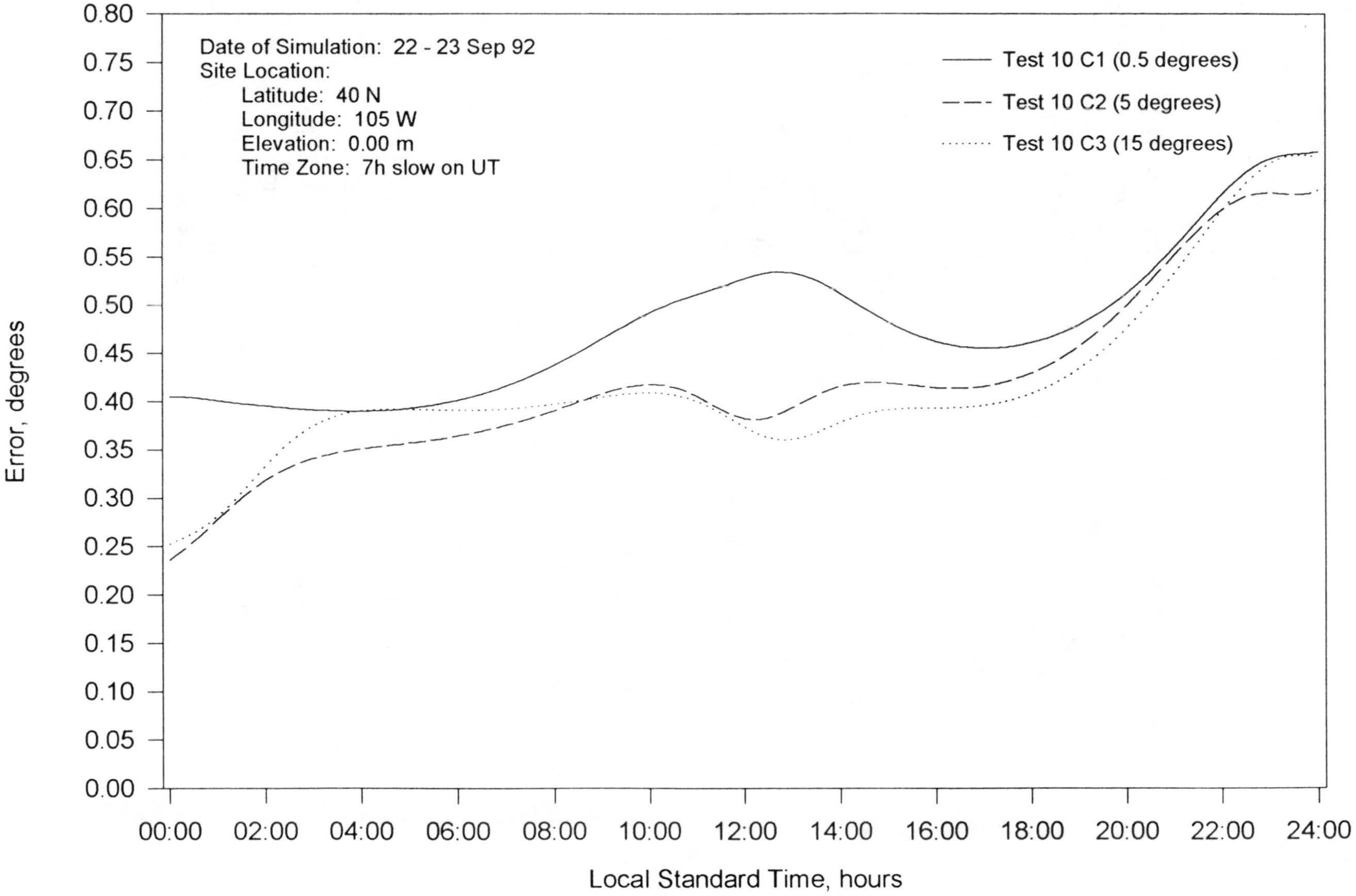


Figure 6: Tracking Error for Various Magnitudes of Misalignment

As above, each test was performed by running the simulation for forty-eight hours. The rotation axis (axis C: -180° azimuth, 45° elevation) was kept constant for all three tests while the magnitude of the misalignment rotation was varied from 0.5° to 15°. During the first simulation day, corrections were made at half-hour intervals between 0630 and 1800 LST. Then the correction matrix was applied during the second simulation day. Each test was repeated three times and the average tracking error was calculated at each ten-minute time interval. The tracking errors displayed in Figure 6 are the averages over each set of three tests.

5.2.4 Sensitivity to Errors in Manual Corrections

To evaluate the sensitivity to errors in the manual corrections, three tests were run with varying degrees of manual correction error. Figure 7 shows the results of these tests, with tracking error in degrees plotted versus LST. As can be seen in the figure, tracking errors increase as the parameter sigma increases. Sigma is a scaling factor for the manual correction error. As sigma increases, the magnitude of manual correction errors increases. Minimum and maximum values of tracking error for each case are shown below:

Sigma	Min. Tracking Error degrees	Max Tracking Error degrees
0.01	0.00557	0.01817
0.10	0.08613	0.23667
1.00	0.52960	1.76883

For each case, the resulting tracking error runs from approximately 0.5*sigma to 1.5*sigma.

Manual correction errors were simulated as normally-distributed random deviates and sigma can be related to the standard deviation of the distribution. A simple central limit theorem approach was used to model the correction errors. A series of twelve numbers from a pseudo-random number generator was summed and modified as shown below:

$$n = [\textstyle\sum_{i=1}^{12} U_i - 6]\sigma + \mu \tag{13}$$

where:

n = the desired manual correction error

U_i = the ith uniformly distributed random deviate

σ = the desired standard deviation for the modelled normal distribution

μ = the desired mean for the modelled normal distribution

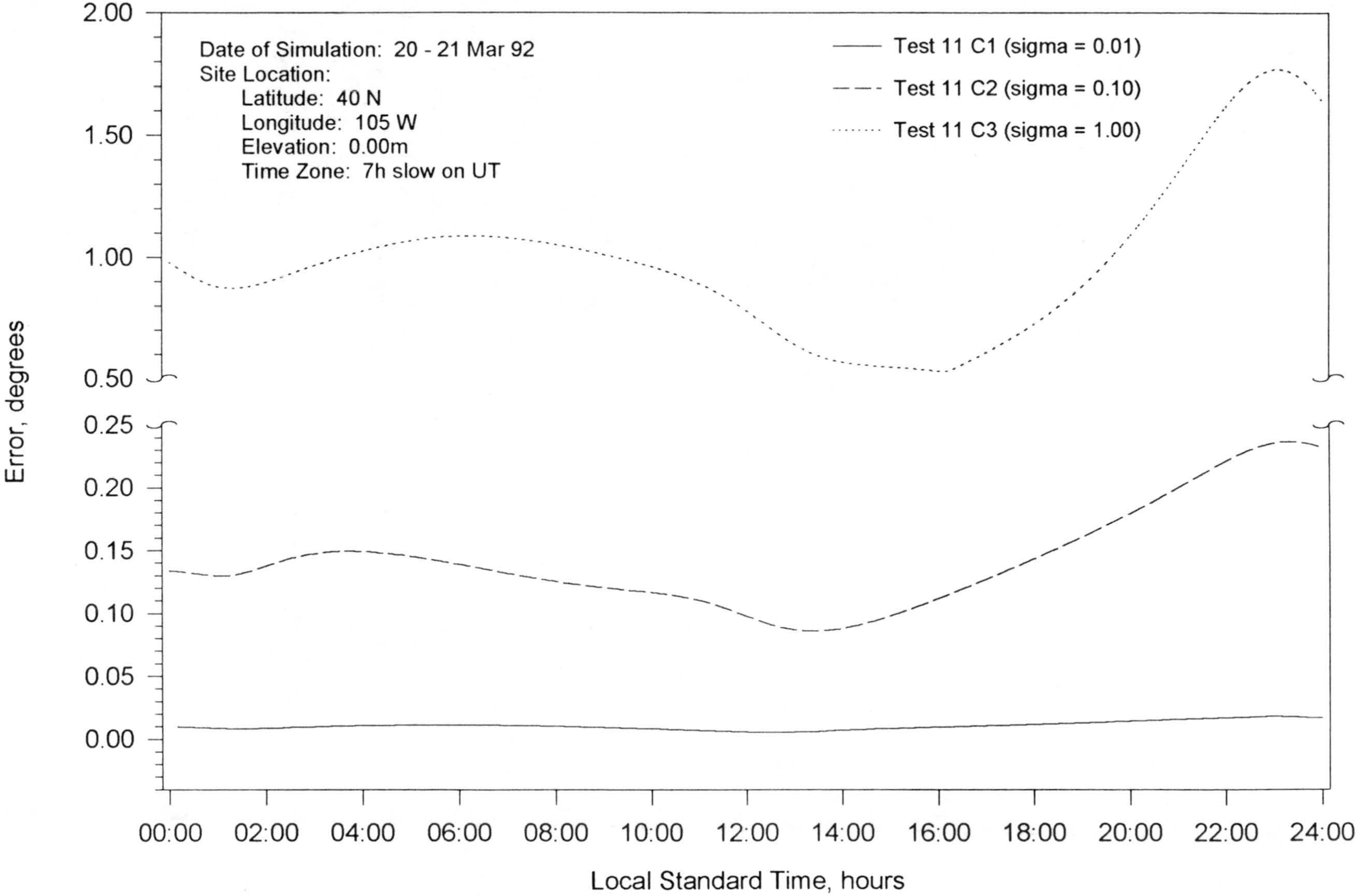


Figure 7: Tracking Error for Various Manual Correction Errors

For simulating manual correction errors, the model mean is chosen to be zero. The standard deviation depends on the accuracy of the device used to make the manual corrections. The desired standard deviation can be determined by assuming that the manual correction errors should fall within a specified range with a specified probability. For example, if we desire a 95% or greater probability that the manual correction errors fall between -0.3 degrees and +0.3 degrees, the desired standard deviation can be found to be 0.153 degrees. Similar calculations for the sigma values used in the tests give:

Sigma	Magnitude of errors (95% probability)
0.01	+/- ~0.02 degrees
0.10	+/- ~0.20 degrees
1.00	+/- ~2.00 degrees

So for the most accurate case, with an expected range of manual correction errors of +/- 0.02 degrees, the test showed a tracking error ranging from about 0.005 degrees to about 0.018 degrees. For the least accurate case, with an expected range of manual correction errors of +/- 2.00 degrees, the test showed a tracking error ranging from about 0.5 degrees to about 1.8 degrees.

As in the tests described in sections 5.2.2 and 5.2.3, each test was performed by running the simulation for forty-eight hours. The rotation axis (axis C: -180° azimuth, 45° elevation) was kept constant for all three tests, as was the magnitude of the misalignment rotation (5 degrees). Corrections were made at half-hour intervals during the first simulation day, then the correction matrix was applied during the second simulation day. Each test was repeated three times and the average tracking error was calculated at each ten-minute time interval. The tracking errors displayed in Figure 7 are the averages over each set of three tests.

5.2.5 Sensitivity to Timing of Corrections

Simulation test results suggest that good tracking performance is achieved when multiple corrections are made in several groups distributed throughout the day. Multiple corrections made at nearly the same time appear to reduce the potential random variation in tracking error, much as replicate measurements reduce the random error in a measurement. However, by itself, a single group of closely-spaced corrections will not typically give a good solution to the regression matrix and the tracking error will increase rapidly with time. By spacing corrections over several hours, a good regression matrix is obtained and tracking error is more stable with time, but the influence of random errors in the manual corrections is stronger.

These observations are illustrated in Figures 8(a), 8(b), 8(c) and 8(d). Each plot shows the results of making six corrections at various time intervals. For each plot, three simulations were run, then the average and standard deviation of the tracking error were calculated and plotted versus time. The dotted lines on the plots show the average tracking error plus and minus one standard deviation.

In Figure 8(a), corrections were made at thirty-minute intervals beginning at 0630 LST. The standard deviation of the tracking error remains small over time, but the average tracking error shows a strong increase with time.

In Figure 8(b), corrections were made at approximately two-hour intervals beginning at 0630 LST. The average tracking error shows about half the rate of increase with time compared to Figure 5(a), but the standard deviation is much larger and increases with time.

In Figure 8(c), corrections were made at approximately six-hour intervals beginning at 0630 LST (note that no corrections were made during nighttime hours). The average tracking error varies somewhat regularly with time but shows almost no increasing tendency. The standard deviation shows a similar regular variation with time and also shows an increasing tendency.

In Figure 8(d), corrections were made at approximately twelve-hour intervals beginning at 0630 LST (and again with no nighttime corrections). Although the average tracking error exhibits no strong tendency over multiple days, strong variation does occur over each twelve-hour time period. This would be expected in a cyclic process in which only two corrections were made in any cycle and suggests that this correction scheme should be avoided.

These results suggest that an appropriate correction scheme would consist of several groups of closely spaced corrections made at several-hour intervals through the day. A scheme consisting of six groups at approximately six-hour intervals (again with no corrections during nighttime hours), with three corrections per group, was tested and the results are shown in Figure 9. The average and standard deviation of the tracking error were improved over any previous test. The average tracking error for this test was less than 0.2 degrees after the final correction and remained so for the rest of the test period. The standard deviation was less than 0.1 degrees after the final correction and showed only a slight increasing tendency during the remainder of the test.

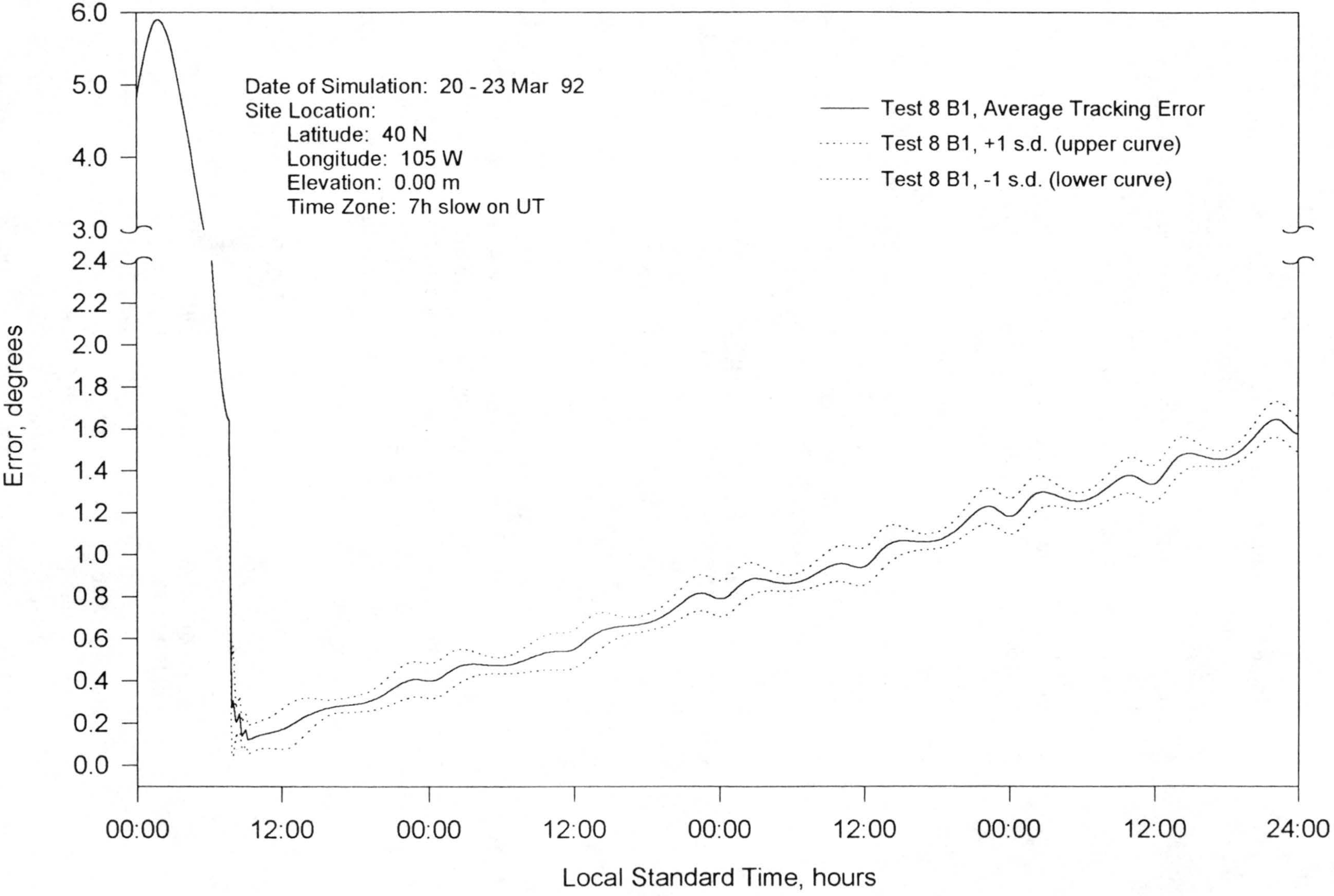


Figure 8(a): Tracking Error, Manual Corrections at 30-minute Intervals

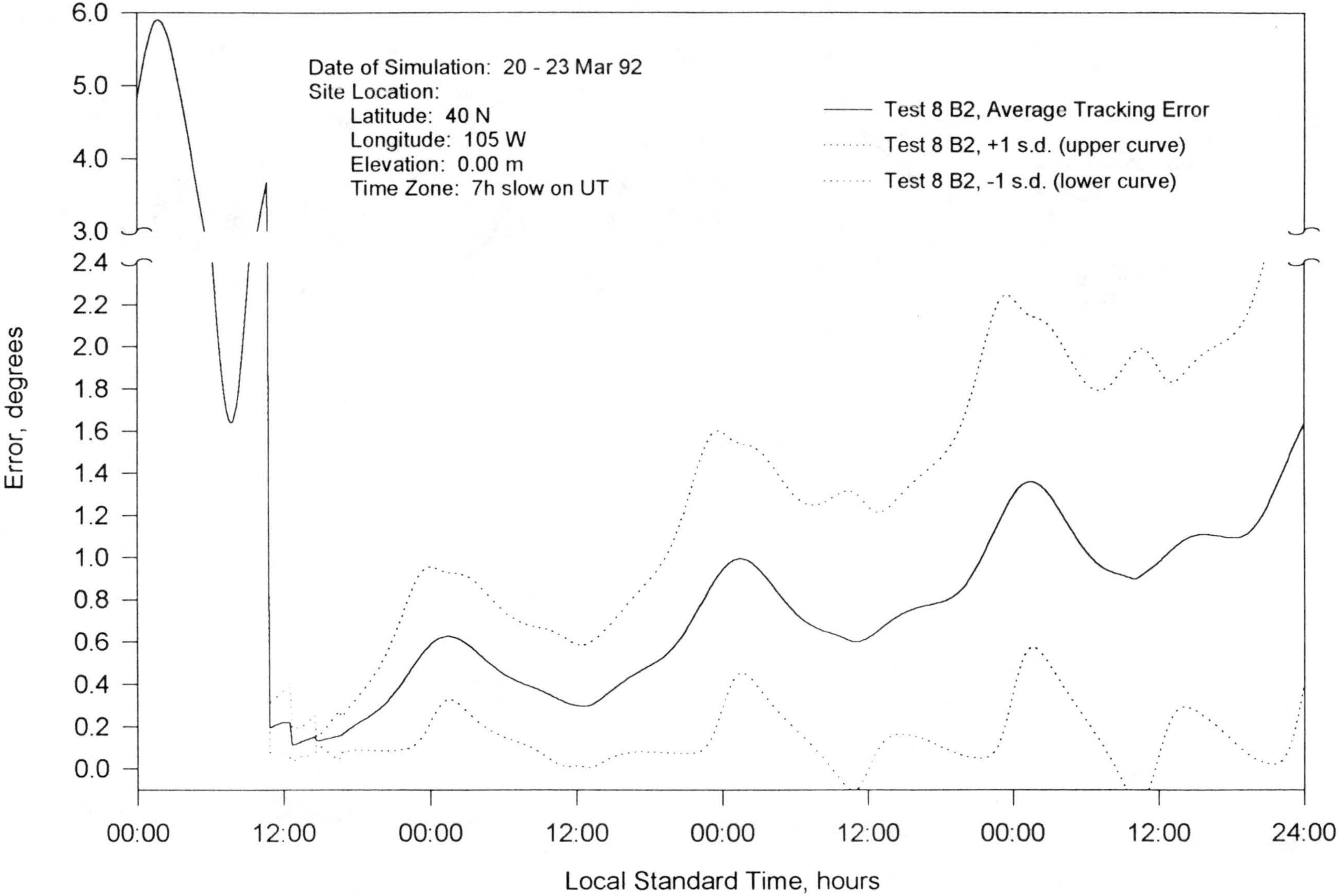


Figure 8(b): Tracking Error, Manual Corrections at 2-hour Intervals

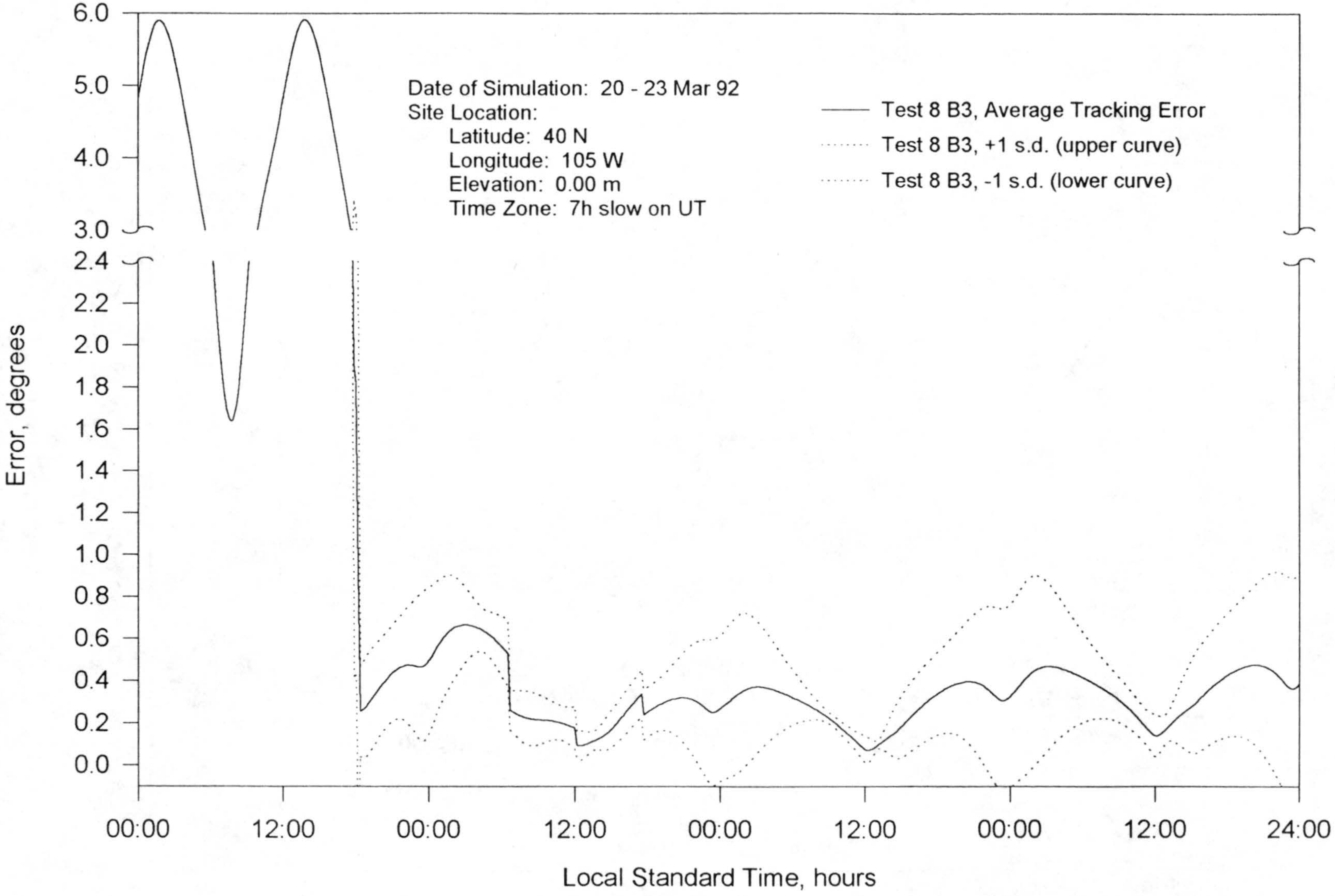


Figure 8(c): Tracking Error, Manual Corrections at 6-hour Intervals

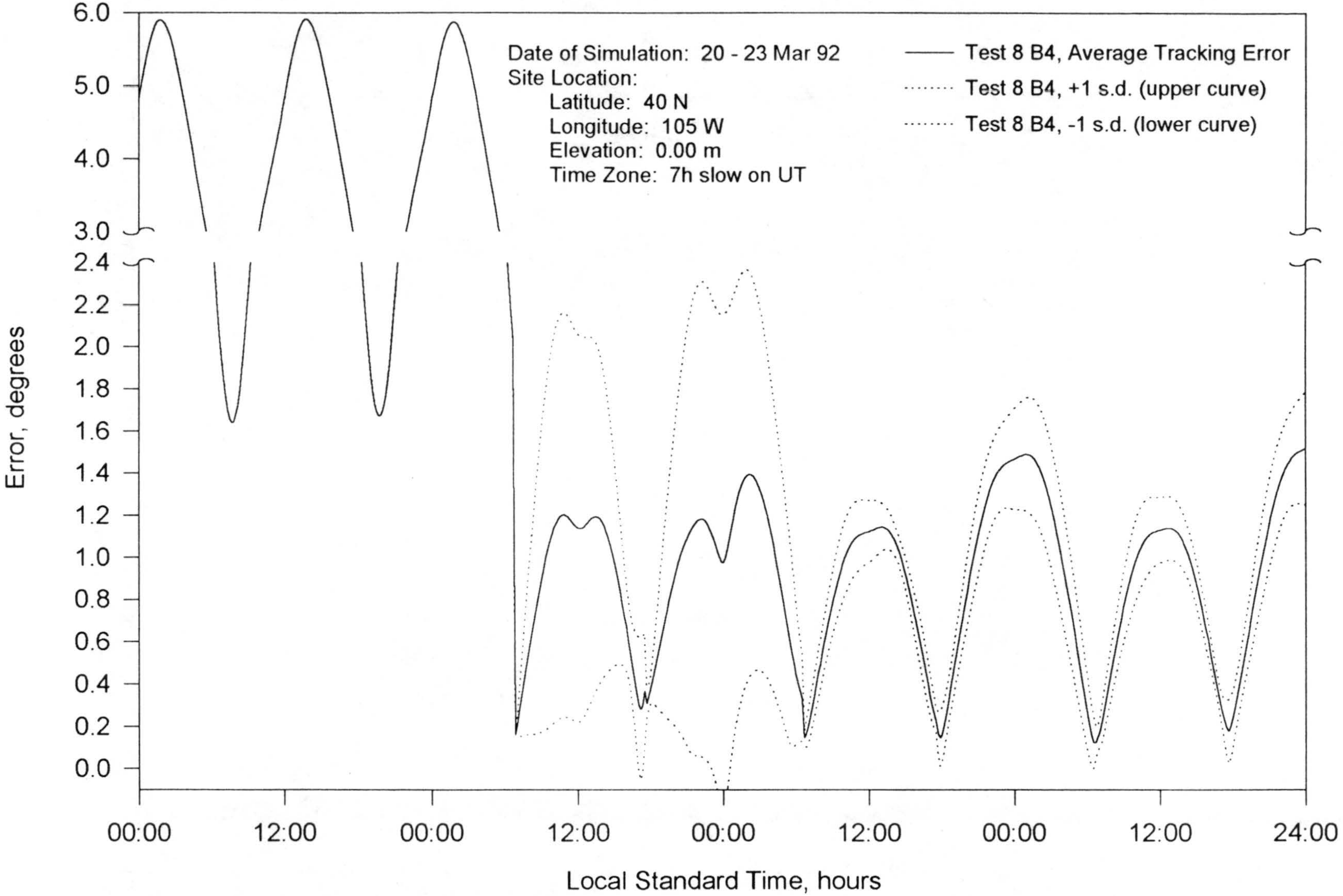


Figure 8(d): Tracking Error, Manual Corrections at 12-hour intervals

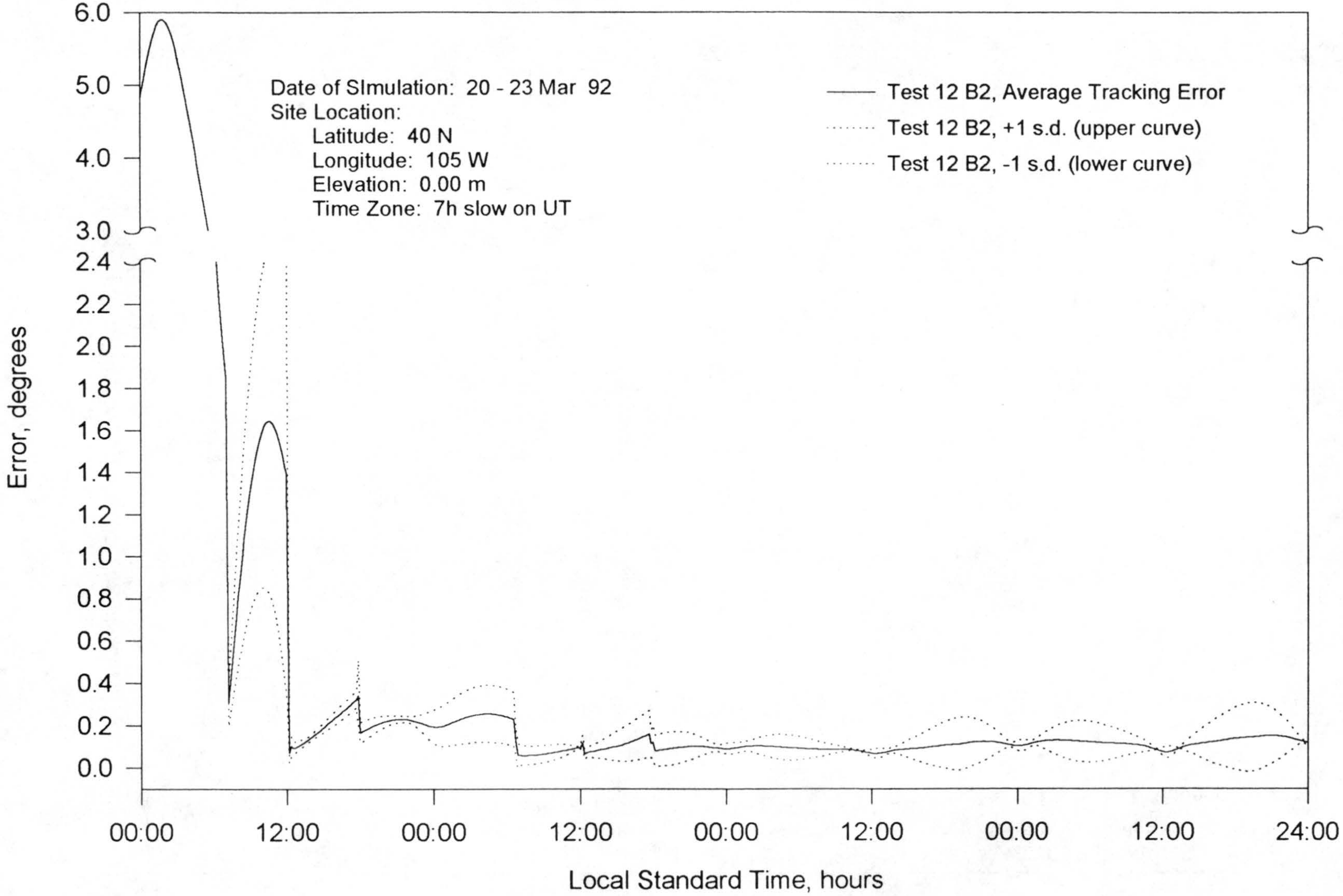


Figure 9: Tracking Error, Improved Manual Correction Scheme

5.3 Electromechanical System

Two sources of error occur in the electromechanical system (i.e., the servo motor amplifiers, the servo motors, and the gimbal optical mount). The first, the servo error, arises when the servo motor position deviates from the position commanded by the control software. The servo error is expected to be mainly a function of the motor control variables, such as gain, pole and zero, and the load on the gimbal. The second, the mechanical error, occurs when, because of looseness or friction in the drive train, the position of the gimbal does not match that of the servo motors. The mechanical error is expected to be mainly a function of the fit of the drivetrain and the load on the gimbal.

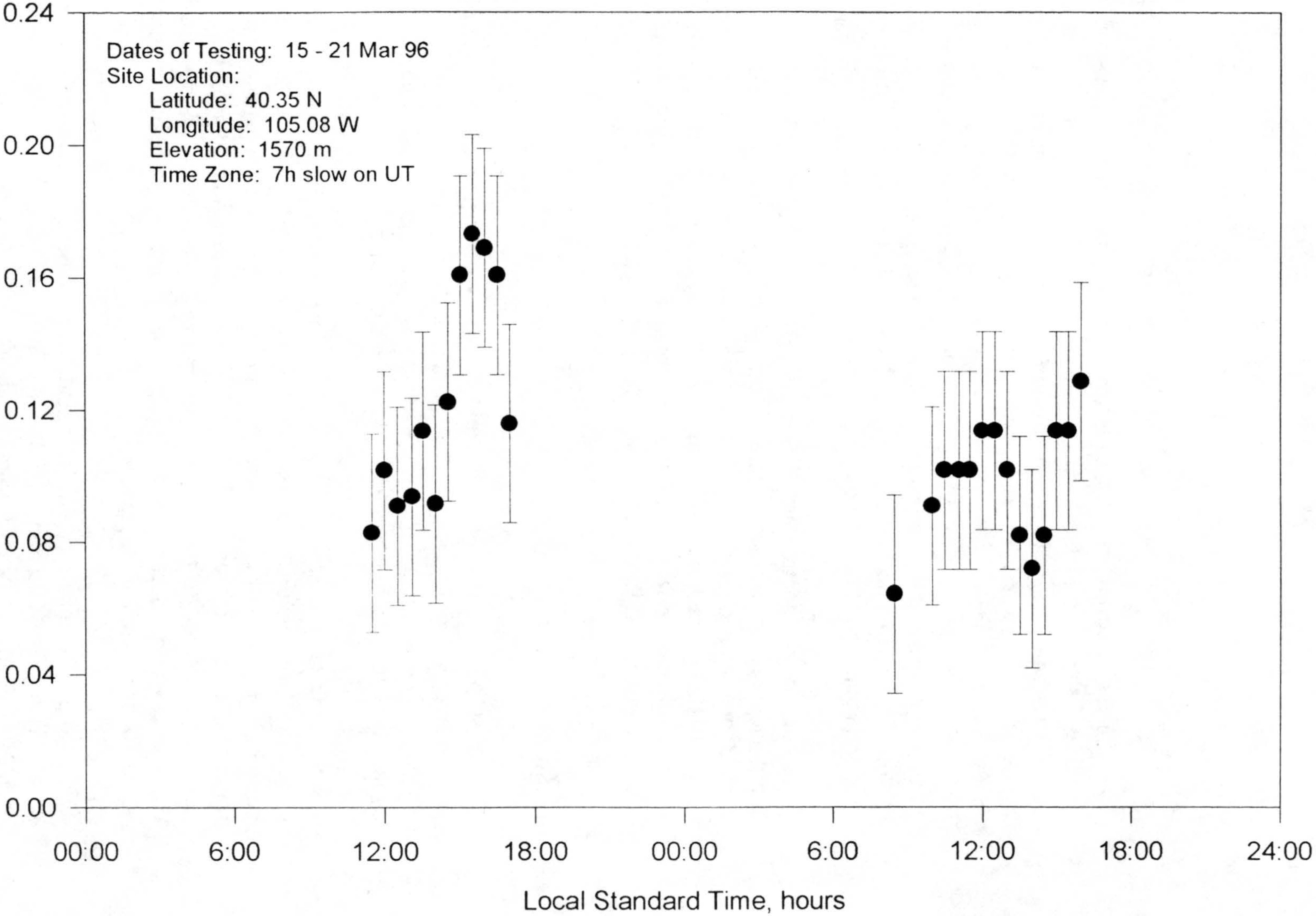
The solar tracker control program measures the servo error by comparing the command position with the position indicated by the motor encoders. During normal operation of the tracker, the servo error is typically about 15 encoder counts (0.025 degrees) for each axis with a light load in the gimbal. An estimate of the mechanical error is available from manufacturer's literature for the optical mount (Aerotech, 1991). The accuracy for both axes is specified as 0.05 degrees.

5.4 System Testing

Testing of the solar tracker in the field showed an average tracking error of 0.11 degrees over a two day period. The results of the test are shown in Figure 10. The tracking error ranged from 0.06 degrees to 0.17 degrees and appeared to vary cyclically with time, much as occurred in the simulations.

For the test, the tracker was set up with an intentional misalignment, a series of corrections were made, then the tracking error was measured over a two-day period. The tracker was mounted on a sturdy aluminum table and the table was rotated to an azimuth angle of about 1.5 degrees, then tilted approximately 1.2 degrees (downward to the west). To improve the resolution of the subsequent corrections and measurements, the tracker was zeroed to a point marked on a wall about 100 feet south of the tracker.

Corrections were made on the first and fourth days of the test, following the scheme described in section 5.2.5 above. Three groups of corrections were made each day, the groups were separated by about three hours (four hours on the fourth day), and individual corrections were separated by about five minutes. The tracker was operated in mirror mode, so the solar image was projected to the zero point on the wall south of the tracker. Corrections were made by adjusting the tracker so that the solar image was centered on the zero point.



Dates of Testing: 15 - 21 Mar 96
Site Location:
Latitude: 40.35 N
Longitude: 105.08 W
Elevation: 1570 m
Time Zone: 7h slow on UT

Figure 10: Tracking Error Test Results

On the fifth and sixth day of the test, no corrections were made, and the tracking error was measured at approximately half-hour intervals. The distance from the center of the solar image to the zero point was measured and converted to an angular error.

6.0 Conclusions

Two main advantages are provided by the solar tracker described here. First, this tracker simplifies the setup process. Rather than making iterative adjustments to the meridional alignment and level of the tracker, the user needs only to establish approximate meridional alignment and level. Then further corrections are made simply by correcting the aim of the tracker so that it points toward the sun. A series of three or more corrections allows automatic adjustment for misalignment of the tracker. Second, this particular combination of hardware and software provides highly accurate tracking. The true solar position is calculated to an accuracy near 0.02 degrees, and the accuracy of the electromechanical system is near 0.075 degrees. Simulation of the correction algorithm showed that it was capable of correcting for tracker misalignment to within two times the standard deviation of the manual corrections. With highly accurate corrections, the accuracy of the tracker could approach 0.1 degrees.

7.0 Acknowledgements

We wish to express our thanks to John Davis and Dave Wood. They provided assistance with the field operation of the solar tracker as well as valuable advice regarding its testing. Thanks also to Melissa Tucker for assisting with the preparation of this manuscript. This research has been supported by the National Aeronautics and Space Administration under contract number NAG 1-1704 and the Office of Naval Research under contract number N000014-91-J-1422, P00007.

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Appendix 1: Operation of the Solar Tracker

A1.0 Operation

A1.1 Overview

The solar tracker control program contains routines to calculate the true solar coordinates, to allow the user to manually correct the tracker position, to calculate from those corrections a transformation matrix which transforms the true solar coordinates to the applied solar coordinates in the tracker's coordinate system, and to allow the user control over the program and the mount.

A1.2 Preliminary Set Up

The two-axis mount is attached to a table and connected to the computer and amplifiers as shown in Figure 3. The table should be near level and the mount should be positioned pointing south. Looking through the scope, the user can manually adjust the gimbal position to sight on a permanent landmark.

A1.3 Starting the program

The user then starts the program, TRACK1.EXE. The tracking program displays an information screen describing the program and asks whether or not to continue. Next the program enters the manual correction mode. The user manually adjusts the gimbal position to point directly south (zero point) or to the sun. Then the user initializes the tracker's position by either setting the zero point (directly south) or, if the mount is pointed at the sun, by having the computer calculate the zero point from the solar position along with the known site location and local time. This causes the computer to store the servo motor encoder values that correspond to the tracker's zero position.

Once initialized, the program switches to run mode and begins tracking along the expected solar path. This path will not match the actual solar path unless the tracker is perfectly aligned meridionally and is on a perfectly level plane.

A1.4 Program Modes

A1.4.1 Run Mode

This mode is the normal operating mode for the solar tracker software. In Run mode, the program retrieves the current time from the PC clock, and calculates the true solar coordinates. If the transformation matrix is activated (see section A1.5.2.5 Select Matrix below), these coordinates are transformed through the matrix. Then the new position information is sent to the motor controller, and the numerical displays on the screen are updated. These displays include site parameters (latitude, longitude, altitude, and time zone), time and date, calculated solar position, calculated mount position, and the mount positioning error.

A1.4.2 Manual Correct Mode

Once the device is in Run mode, corrections can be made using the Manual Correct mode.

Once a manual correction is completed and the tracker is aligned with the current solar position, the user presses the **S** key. This enters the correction data into memory and updates the correction matrix. The program then returns to Run mode.

After three or more corrections are entered, the program is capable of calculating a transformation matrix for the current setup. Once the transformation matrix is activated, the program processes its true solar coordinates through this matrix before outputing them to the motor control software.

A1.4.3 Graphics Display Mode

The Graphics Display mode is similar to Run mode, except without the numerical displays. Instead, the screen displays the day's calculated solar path, and the position of the mount relative to the path. The horizontal axis of the graph is azimuth, the vertical axis is elevation, and both axes are labelled in degrees.

This mode is useful when a solar offset is being used. The user can watch a sinusoidal offset represented graphically on the screen as the tracker sweeps out the path.

A1.5 Program Options

A1.5.1 File Menu

The file menu allows users to perform various functions of saving and retrieving data from disk. The filenames for save and load operations are hardcoded into the program. For example, when the "Save Site and Correction Data" option is selected, the computer writes file RESTART.DAT. This is the same filename written upon exit. If the user wishes to retain the previous file, the DOS Command option can be used to copy one file to another.

A1.5.2 Parameter Menus

Various parameters may be changed while the program is running. These include the site parameters, the current local time and date, the motor control parameters, the solar offset variables, and the correction matrix selection. Each of these options is included in the Main Menu while in Run mode. Examples of these menus appear in the appendix.

A1.5.2.1 Edit Site

The site editing menu is used for setting the correct values of the site parameters longitude, latitude, altitude and timezone offset from GMT.

A1.5.2.2 Edit Time and Date

This menu is used to enter corrections to the current local time and date. When entered, these corrections update the PC's clock and calendar.

A1.5.2.3 Edit Motor

The user can change the values of motor control variables like gain, pole and zero using this menu. The values can be changed for each axis of motion. This should only be attempted by a knowledgeable user, as it can cause problems with the motors. If a gain value is too large, the motor could vibrate. A gain too small could cause a large positioning error, or a complete lack of movement.

A1.5.2.4 Solar Offset

The tracker is capable of tracking a known angle off the sun. There are two methods of doing this: a time offset, and a sinusoidal offset in azimuth and/or elevation. If a time offset is used, the tracker will move to the position on the solar path corresponding to the present time plus the offset. The offset may be negative, to allow tracking behind the sun. The angular value of an offset of five minutes will vary depending on time of day and day of year.

To implement a sinusoidal offset, the user must enter an amplitude in degrees and a frequency in sec^{-1}. The angular offset is then added to the appropriate axis (azimuth or elevation). A frequency of 0.1 sec^{-1} will yield a period of 20π seconds (approximately one minute and three seconds).

The equation used to calculate the offset is:

$$F = M^{*}\cos\,(\omega t) \qquad \textbf{(A1)}$$

where F is the number of degrees to add to the azimuth or elevation, M is the maximum amplitude of the offset, ω is the frequency as described above, and t is the number of seconds since 0:00 local time.

A1.5.2.5 Select Matrix

This menu selection allows the user to choose which matrix is used for transforming the calculated solar coordinates. The choices are: none, regression matrix, and manual matrix. After selecting the manual matrix, the user has the option of manually inputing the matrix. Alternately, the user could load the manual matrix from the file MATRIX.DAT using the File Menu "Load Matrix" command.

Appendix 2: Examples of Program Status Screens

```
                        Solar Tracker Control Program
Direct                     Status:  Running....                 Matrix OFF N 13
+-----------------------------------------------------------------------------+
|                 Site Parameters                    |  Local Time and Date    |
|  Lat:   40.5833           Lng:   105.1250          |  Time:   08:05:03.92    |
|  Alt:    1568.00 m        Timezone: +6.00 to UT    |  Date:   07 Apr 1994    |
|-----------------------------------------------------------------------------|
|  Solar Position      |  Gimbal Position      Counter    |       Error       |
|  AZ:   -85 03'30"    |  AZ: -85 03'30"       -51034     |       +0          |
|  EL:   +16 18'04"    |  EL: +16 18'04"       +9780      |       +0          |
|-----------------------------------------------------------------------------|
|                                                                             |
|                                                                             |
|                                                                             |
|                                                                             |
|                                                                             |
|                                                                             |
|-----------------------------------------------------------------------------|
|                               Main Menu                                     |
|  P - Pause/Resume         E - Edit Motor               D - Mirror/Direct     |
|  Q - Quit                 C - Manual Correct           I - Reinitialize      |
|  S - Edit Site            V - View Matrices            M - Select Matrix     |
|  T - Edit Time/Date       O - Solar Offset             F - File Menu         |
|  G - Graphics Disp        N - Redraw Screen                                  |
+-----------------------------------------------------------------------------+
```

Screen 1 is an example of a typical screen during Run Mode. The upper left corner indicates Mirror or Direct operation. Under the program name is the operational mode (Initializing, Running or Paused). The upper right corner contains the matrix correction information. The matrix status (ON or OFF) is followed by a letter indicating which matrix is in use (N = none, R = Regression, M = Manually input matrix). The number following shows how many correction points are currently in memory.

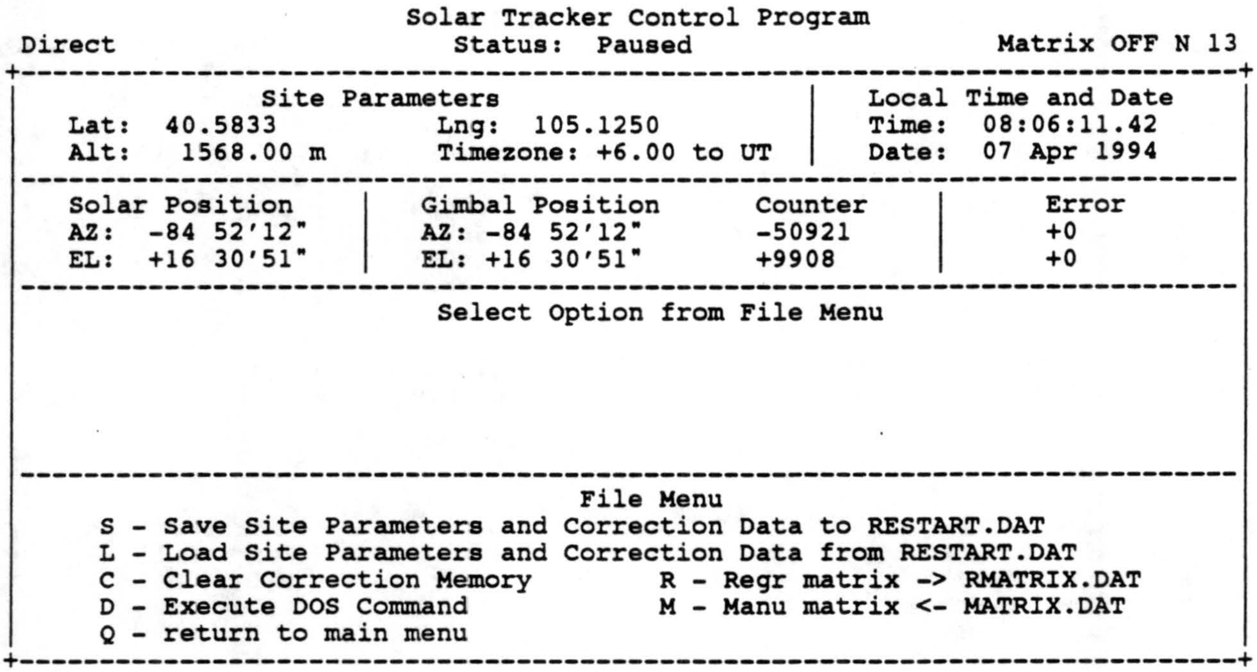
The upper left box contains the site data being used in the solar calculations. These values may be changed by hitting the S key, for the Edit Site option. Latitude and longitude are given in degrees, positive to the North and West. Altitude is in meters. Time zone is represented in the number of hours added to local time to equal GMT.

The upper right box displays the current local time and date, which may be changed by hitting the T key.

The second row of boxes contains position information. The leftmost box shows the calculated solar position. The next box displays the current command position for the two-axis mount. (This will be different from the solar position when a correction matrix is being used, or when a correction offset is in place.) This box also displays the command position in encoder counts. (600 counts = 1°.) The rightmost window then displays the motor position error (command position - actual position) in encoder counts.

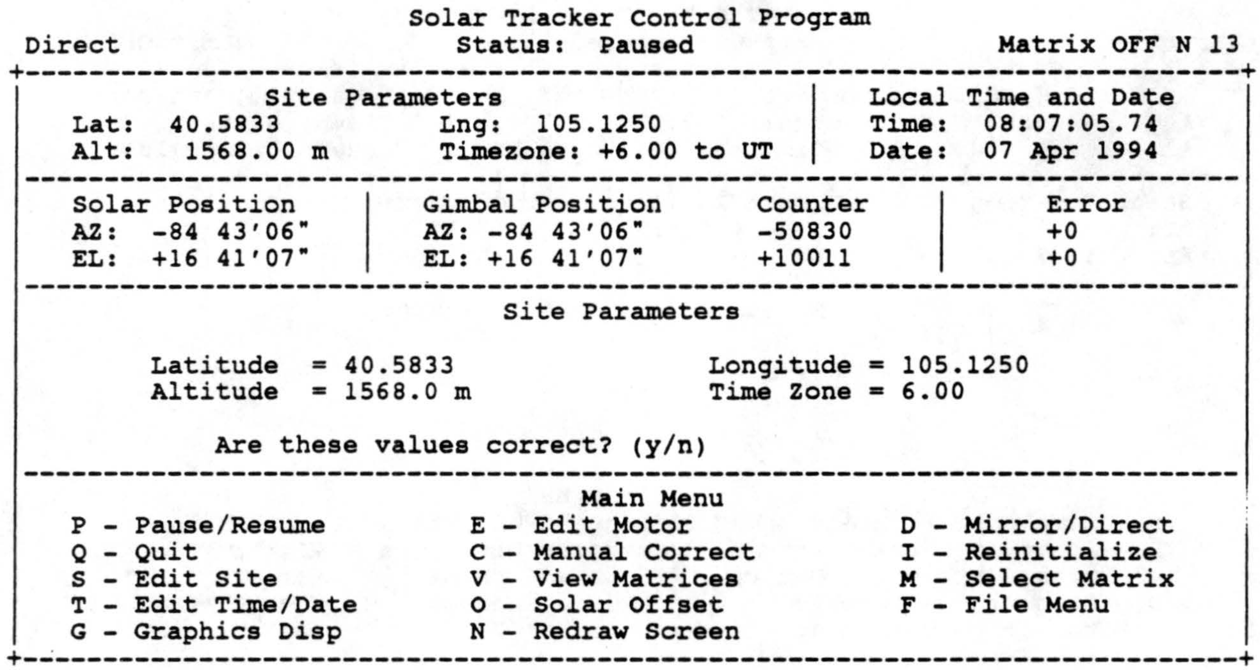
The middle window is for user interaction with the various menu commands. During normal operation, it remains blank unless a user command is being performed.

The lower window shows the keys used to activate various user commands. Some of these commands work instantly (**Q**uit, **P**ause, **G**raphics display, Redraw Scree**N**, **D**irect/Mirror toggle) while others access a separate routine for displaying or inputing new data (Edit **S**ite, Edit **T**ime/Date, **E**dit Motor, **V**iew Matrices, Solar **O**ffset, Select **M**atrix). Still other commands access other menus (Manual **C**orrect, Re**I**nitialize, **F**ile Menu).



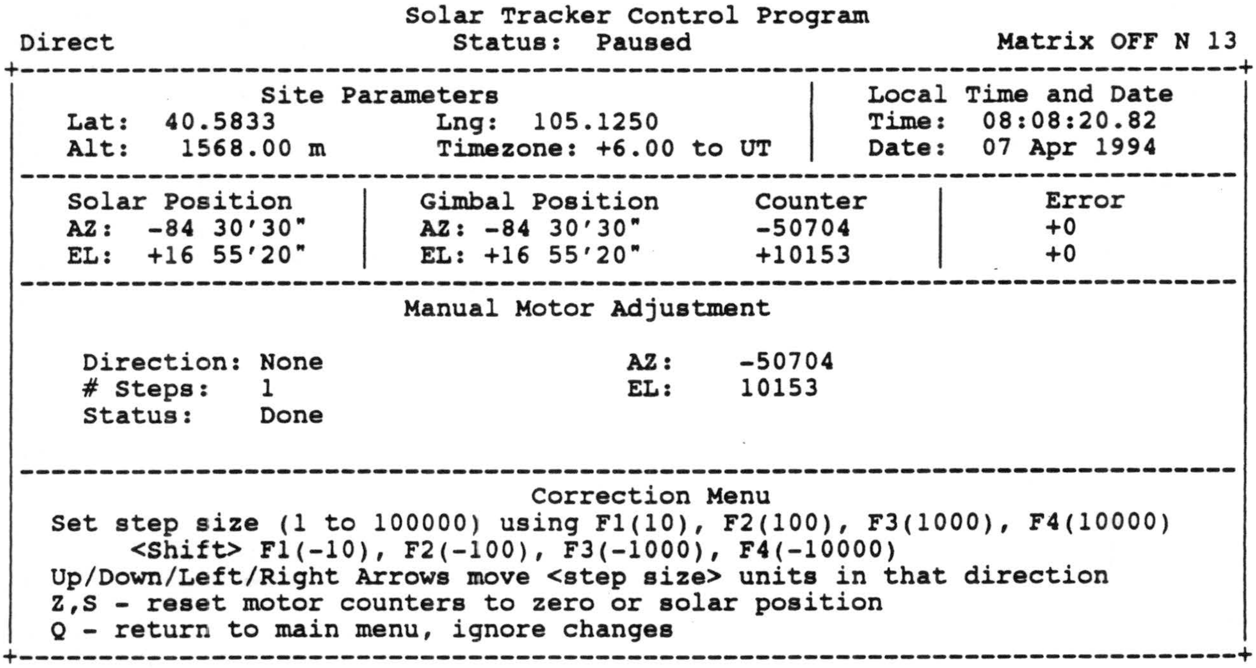
```
                          Solar Tracker Control Program
 Direct                        Status:  Paused                      Matrix OFF N 13
+-----------------------------------------------------------------------------+
|                 Site Parameters                     |   Local Time and Date  |
|    Lat:   40.5833           Lng:   105.1250         |   Time:   08:06:11.42  |
|    Alt:     1568.00 m       Timezone: +6.00 to UT   |   Date:   07 Apr 1994  |
|-----------------------------------------------------------------------------|
|    Solar Position     |   Gimbal Position     Counter     |        Error     |
|    AZ:   -84 52'12"   |   AZ: -84 52'12"      -50921      |        +0        |
|    EL:  +16 30'51"    |   EL: +16 30'51"      +9908       |        +0        |
|-----------------------------------------------------------------------------|
|                         Select Option from File Menu                        |
|                                                                             |
|                                                                             |
|                                                                             |
|                                                                             |
|-----------------------------------------------------------------------------|
|                                  File Menu                                  |
|      S - Save Site Parameters and Correction Data to RESTART.DAT           |
|      L - Load Site Parameters and Correction Data from RESTART.DAT         |
|      C - Clear Correction Memory           R - Regr matrix -> RMATRIX.DAT   |
|      D - Execute DOS Command               M - Manu matrix <- MATRIX.DAT    |
|      Q - return to main menu                                                |
+-----------------------------------------------------------------------------+
```

Screen 2 shows the program screen as it appears after the **F** key has been pressed to activate the File Menu. The lower window now displays the File Menu options, including **S**ave startup data (site parameters and previously entered correction data) to file RESTART.DAT, **L**oad startup data from RESTART.DAT, **C**lear all previously entered corrections from memory, execute a **DOS** command, save a calculated **R**egression matrix to file RMATRIX.DAT, load a **M**atrix from file MATRIX.DAT to the manually entered matrix, and **Q**uit the File Menu.



```
                          Solar Tracker Control Program
Direct                       Status:  Paused                    Matrix OFF N 13
+------------------------------------------------------------------------------+
|              Site Parameters                      |  Local Time and Date     |
|   Lat:  40.5833            Lng:  105.1250          |  Time:  08:07:05.74      |
|   Alt:    1568.00 m        Timezone: +6.00 to UT   |  Date:  07 Apr 1994      |
|------------------------------------------------------------------------------|
|   Solar Position       |  Gimbal Position      Counter      |      Error     |
|   AZ:   -84 43'06"     |  AZ: -84 43'06"       -50830       |       +0       |
|   EL:  +16 41'07"      |  EL: +16 41'07"       +10011       |       +0       |
|------------------------------------------------------------------------------|
|                                  Site Parameters                             |
|                                                                              |
|        Latitude   = 40.5833                  Longitude = 105.1250            |
|        Altitude   = 1568.0 m                 Time Zone = 6.00                |
|                                                                              |
|            Are these values correct? (y/n)                                   |
|------------------------------------------------------------------------------|
|                                      Main Menu                               |
|   P - Pause/Resume           E - Edit Motor             D - Mirror/Direct    |
|   Q - Quit                   C - Manual Correct         I - Reinitialize     |
|   S - Edit Site              V - View Matrices          M - Select Matrix    |
|   T - Edit Time/Date         O - Solar Offset           F - File Menu        |
|   G - Graphics Disp          N - Redraw Screen                               |
+------------------------------------------------------------------------------+
```

Screen 3 is an example of pressing the **S** key while in Run Mode. If the user answers No, the program will display each parameter in turn, prompting the user to accept the present value or enter a new value. Then the program will again display all four parameters, prompting the user with this screen until the user accepts the parameters.



```
                         Solar Tracker Control Program
 Direct                     Status:  Paused                    Matrix OFF N 13
+-----------------------------------------------------------------------------+
|               Site Parameters                    | Local Time and Date      |
|   Lat:   40.5833          Lng:   105.1250         | Time:   08:08:20.82      |
|   Alt:    1568.00 m       Timezone: +6.00 to UT   | Date:   07 Apr 1994      |
|----------------------------------------------------------------------------|
|   Solar Position     |  Gimbal Position     Counter    |      Error          |
|   AZ:  -84 30'30"    |  AZ: -84 30'30"      -50704     |      +0             |
|   EL:  +16 55'20"    |  EL: +16 55'20"      +10153     |      +0             |
|----------------------------------------------------------------------------|
|                        Manual Motor Adjustment                              |
|                                                                             |
|    Direction: None                       AZ:     -50704                     |
|    # Steps:   1                          EL:     10153                      |
|    Status:    Done                                                          |
|                                                                             |
|----------------------------------------------------------------------------|
|                                Correction Menu                              |
|  Set step size (1 to 100000) using F1(10), F2(100), F3(1000), F4(10000)     |
|       <Shift> F1(-10), F2(-100), F3(-1000), F4(-10000)                      |
|  Up/Down/Left/Right Arrows move <step size> units in that direction         |
|  Z,S - reset motor counters to zero or solar position                       |
|  Q - return to main menu, ignore changes                                    |
+-----------------------------------------------------------------------------+
```

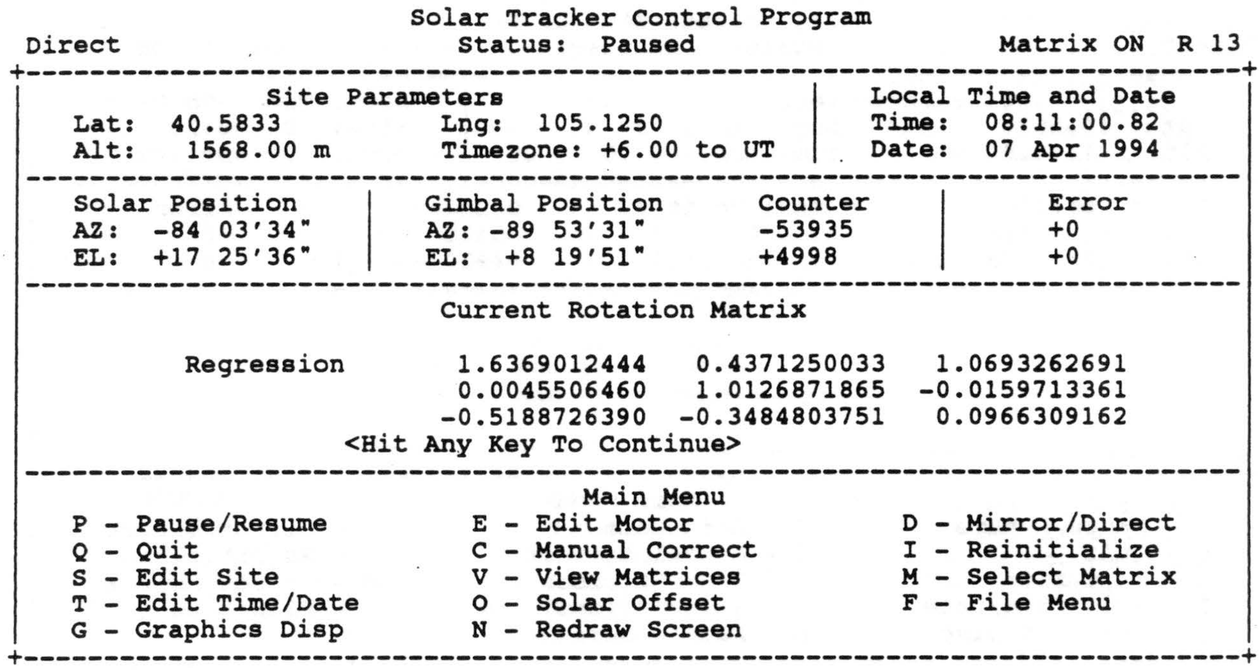
Screen 4 shows the Manual Correction Mode, accessed from Run Mode by pressing the **C** key. In this mode, the user can use the function keys (**F1** through **F4**) and the arrow keys to move the two-axis mount to a desired location (the corrected solar position, or the zero position on startup or reinitialization). Each move requires two steps: setting the step size for the move, and entering the direction for the move. Using the function keys, the user can specify a step size from 10 to 100,000 steps. (There are 216,000 steps per revolution for each stage of the mount.) Pressing function keys in sequence will add the corresponding step size to the total step size, displayed in the middle window. To add negative step sizes, hold down the Shift key while pressing one of the function keys.

Once the desired step size is displayed, the user simply presses one of the arrow keys to enter the direction for the move. The mount will then move to the appropriate position. The up arrow corresponds to an increase in elevation angle. The right arrow will turn the mount clockwise (as viewed from the top).

Example: To move the unit 22010 steps toward the west (clockwise), the user would press the following sequence of keys: F4 F4 F3 F3 F1 <right arrow>

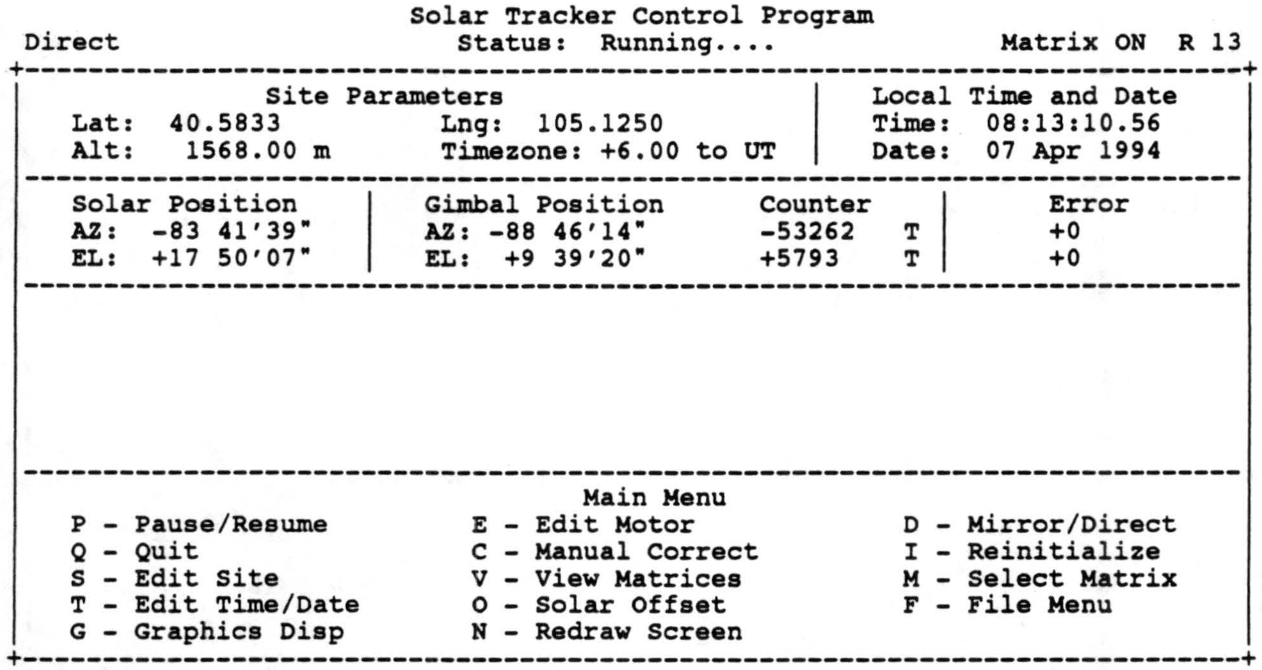
Once the desired position is attained, the user enters either **S** or **Z**, depending on whether they have aligned the tracker with the sun or with the zero azimuth/zero elevation point. The program will then enter Run Mode.

To quit without saving any correction data, the user enters **Q**. The program will return to Run Mode.



```
                         Solar Tracker Control Program
Direct                          Status:  Paused                  Matrix ON  R 13
+------------------------------------------------------------------------------+
|            Site Parameters                       |  Local Time and Date      |
|  Lat:  40.5833          Lng:  105.1250           |  Time:   08:11:00.82      |
|  Alt:   1568.00 m       Timezone: +6.00 to UT    |  Date:   07 Apr 1994      |
|-----------------------------------------------------------------------------|
|  Solar Position     |  Gimbal Position    Counter     |       Error         |
|  AZ:  -84 03'34"    |  AZ: -89 53'31"     -53935      |        +0           |
|  EL:  +17 25'36"    |  EL:   +8 19'51"    +4998       |        +0           |
|-----------------------------------------------------------------------------|
|                           Current Rotation Matrix                           |
|                                                                             |
|         Regression        1.6369012444   0.4371250033   1.0693262691       |
|                           0.0045506460   1.0126871865  -0.0159713361       |
|                          -0.5188726390  -0.3484803751   0.0966309162       |
|                     <Hit Any Key To Continue>                               |
|-----------------------------------------------------------------------------|
|                               Main Menu                                     |
|  P - Pause/Resume          E - Edit Motor              D - Mirror/Direct    |
|  Q - Quit                  C - Manual Correct          I - Reinitialize     |
|  S - Edit Site             V - View Matrices           M - Select Matrix    |
|  T - Edit Time/Date        O - Solar Offset            F - File Menu        |
|  G - Graphics Disp         N - Redraw Screen                                |
+------------------------------------------------------------------------------+
```

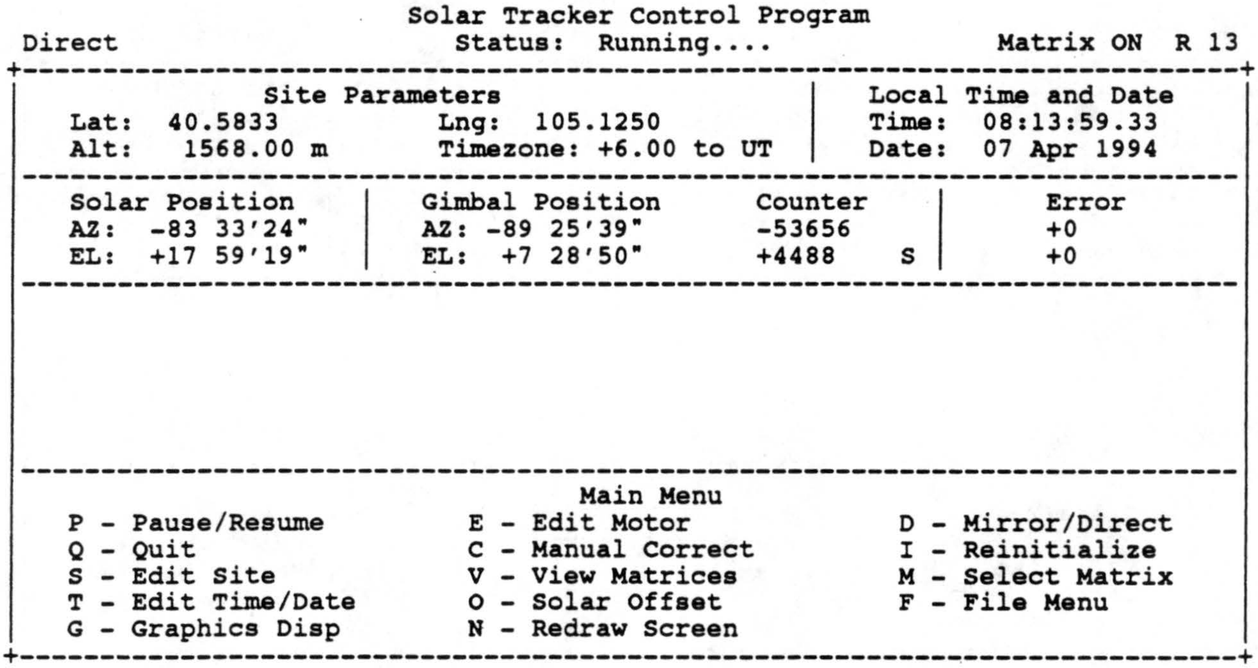
Screen 7 is the display after hitting the **V** key to View the matrices. The displayed matrix is an example of a regression matrix calculated from thirteen correction points.



```
                         Solar Tracker Control Program
Direct                      Status:  Running....                 Matrix ON  R 13
+-----------------------------------------------------------------------------+
|                Site Parameters                       |  Local Time and Date  |
|  Lat:  40.5833             Lng:  105.1250            |  Time:  08:13:10.56   |
|  Alt:    1568.00 m         Timezone: +6.00 to UT     |  Date:  07 Apr 1994   |
|-----------------------------------------------------------------------------|
|  Solar Position        |  Gimbal Position        Counter      |     Error     |
|  AZ:   -83 41'39"      |  AZ: -88 46'14"         -53262    T  |      +0       |
|  EL:  +17 50'07"       |  EL:   +9 39'20"        +5793     T  |      +0       |
|-----------------------------------------------------------------------------|
|                                                                             |
|                                                                             |
|                                                                             |
|                                                                             |
|                                                                             |
|-----------------------------------------------------------------------------|
|                                 Main Menu                                   |
|  P - Pause/Resume          E - Edit Motor              D - Mirror/Direct     |
|  Q - Quit                  C - Manual Correct          I - Reinitialize      |
|  S - Edit Site             V - View Matrices           M - Select Matrix     |
|  T - Edit Time/Date        O - Solar Offset            F - File Menu         |
|  G - Graphics Disp         N - Redraw Screen                                 |
+-----------------------------------------------------------------------------+
```

Screen 8 shows the program running with the regression matrix on, and a time offset in use. The letter T appearing after the counter positions indicates that azimuth and elevation are being affected by the Time Offset.

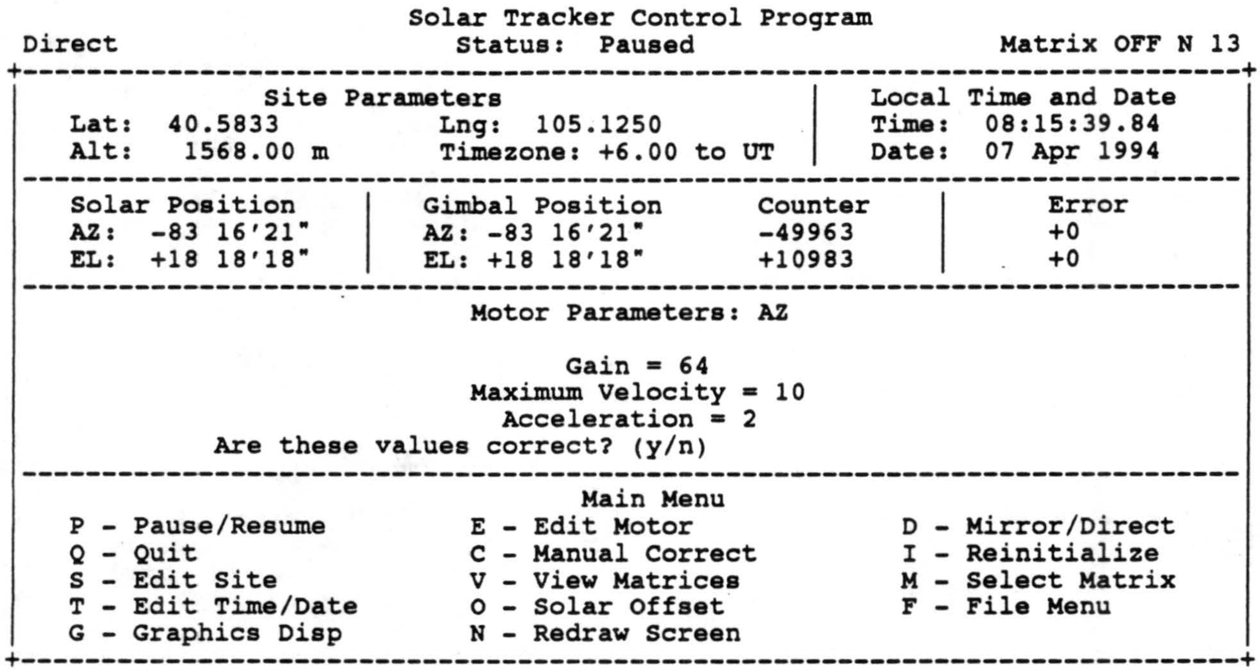
(A time offset can be used to move the solar tracker forward or backward along the solar path. This is useful for taking readings close to, but not directly on, the sun.)



```
                             Solar Tracker Control Program
 Direct                         Status:  Running....                    Matrix ON  R 13
+-----------------------------------------------------------------------------------+
|                     Site Parameters                          |  Local Time and Date  |
|   Lat:  40.5833             Lng:  105.1250                   |  Time:  08:13:59.33   |
|   Alt:    1568.00 m         Timezone: +6.00 to UT            |  Date:  07 Apr 1994   |
|-----------------------------------------------------------------------------------|
|   Solar Position       |  Gimbal Position          Counter      |       Error        |
|   AZ:  -83 33'24"      |  AZ: -89 25'39"           -53656       |        +0          |
|   EL:  +17 59'19"      |  EL:   +7 28'50"          +4488     S  |        +0          |
|-----------------------------------------------------------------------------------|
|                                                                                   |
|                                                                                   |
|                                                                                   |
|                                                                                   |
|                                                                                   |
|                                                                                   |
|-----------------------------------------------------------------------------------|
|                                       Main Menu                                   |
|   P - Pause/Resume          E - Edit Motor                D - Mirror/Direct       |
|   Q - Quit                  C - Manual Correct            I - Reinitialize        |
|   S - Edit Site             V - View Matrices             M - Select Matrix       |
|   T - Edit Time/Date        O - Solar Offset              F - File Menu           |
|   G - Graphics Disp         N - Redraw Screen                                     |
+-----------------------------------------------------------------------------------+
```

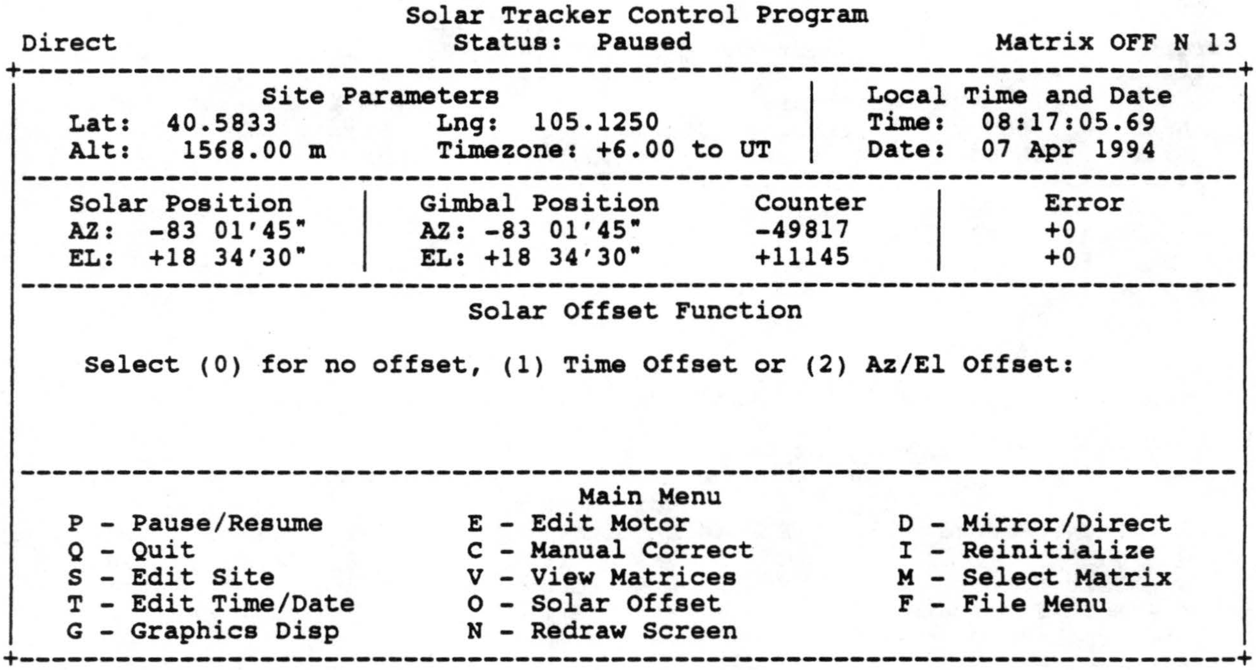
Screen 9 shows the program running with the regression matrix on, and a sinusoidal offset in use. The letter S appearing after the elevation counter position indicates that the elevation is being affected by the Sine Wave Offset.

(A sine wave offset can be used to move the solar tracker in a sinusoidal path centered on the sun. Separate magnitudes and periods can be set for the offsets along the azimuth and elevation directions.)



```
                          Solar Tracker Control Program
 Direct                       Status:  Paused                      Matrix OFF N 13
+---------------------------------------------------------------------------------+
|                    Site Parameters                     |    Local Time and Date |
|   Lat:  40.5833            Lng:  105.1250              |    Time:   08:15:39.84 |
|   Alt:    1568.00 m        Timezone: +6.00 to UT       |    Date:   07 Apr 1994 |
|---------------------------------------------------------------------------------|
|   Solar Position      |    Gimbal Position      Counter       |        Error    |
|   AZ:   -83 16'21"    |    AZ: -83 16'21"       -49963        |        +0       |
|   EL:  +18 18'18"     |    EL: +18 18'18"       +10983        |        +0       |
|---------------------------------------------------------------------------------|
|                              Motor Parameters: AZ                               |
|                                                                                 |
|                                   Gain = 64                                     |
|                              Maximum Velocity = 10                              |
|                                Acceleration = 2                                 |
|            Are these values correct? (y/n)                                      |
|---------------------------------------------------------------------------------|
|                                    Main Menu                                    |
|   P - Pause/Resume          E - Edit Motor              D - Mirror/Direct       |
|   Q - Quit                  C - Manual Correct          I - Reinitialize        |
|   S - Edit Site             V - View Matrices           M - Select Matrix       |
|   T - Edit Time/Date        O - Solar Offset            F - File Menu           |
|   G - Graphics Disp         N - Redraw Screen                                   |
+---------------------------------------------------------------------------------+
```

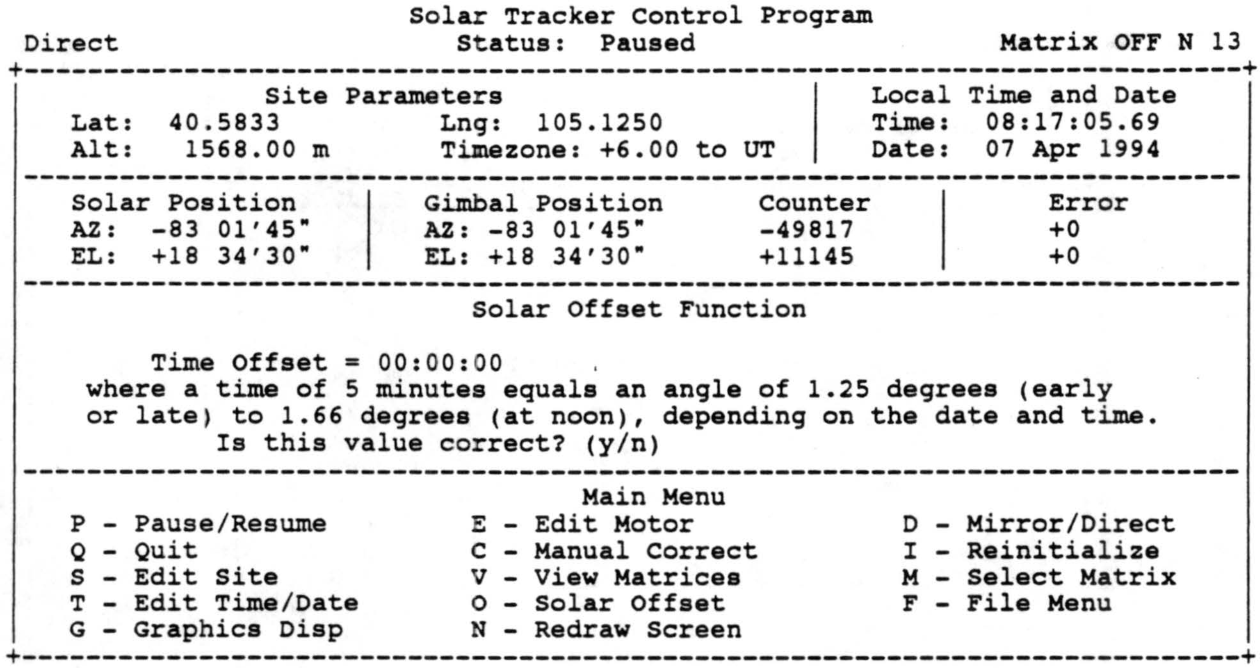
Screen 10 is an example of the Motor Parameter Editing screen, accessed from Run Mode by pressing the **E** key. The routine is similar to that for editing the site parameters.



```
                         Solar Tracker Control Program
 Direct                        Status:  Paused                       Matrix OFF N 13
+------------------------------------------------------------------------------+
|              Site Parameters                          |   Local Time and Date  |
|  Lat:  40.5833            Lng:  105.1250              |   Time:  08:17:05.69   |
|  Alt:   1568.00 m         Timezone: +6.00 to UT       |   Date:  07 Apr 1994   |
|-------------------------------------------------------------------------------|
|  Solar Position       |  Gimbal Position       Counter      |       Error      |
|  AZ:  -83 01'45"      |  AZ: -83 01'45"        -49817       |        +0        |
|  EL:  +18 34'30"      |  EL: +18 34'30"        +11145       |        +0        |
|-------------------------------------------------------------------------------|
|                          Solar Offset Function                                |
|                                                                               |
|   Select (0) for no offset, (1) Time Offset or (2) Az/El Offset:              |
|                                                                               |
|                                                                               |
|                                                                               |
|-------------------------------------------------------------------------------|
|                                Main Menu                                      |
|  P - Pause/Resume          E - Edit Motor               D - Mirror/Direct     |
|  Q - Quit                  C - Manual Correct           I - Reinitialize      |
|  S - Edit Site             V - View Matrices            M - Select Matrix     |
|  T - Edit Time/Date        O - Solar Offset             F - File Menu         |
|  G - Graphics Disp         N - Redraw Screen                                  |
+------------------------------------------------------------------------------+
```

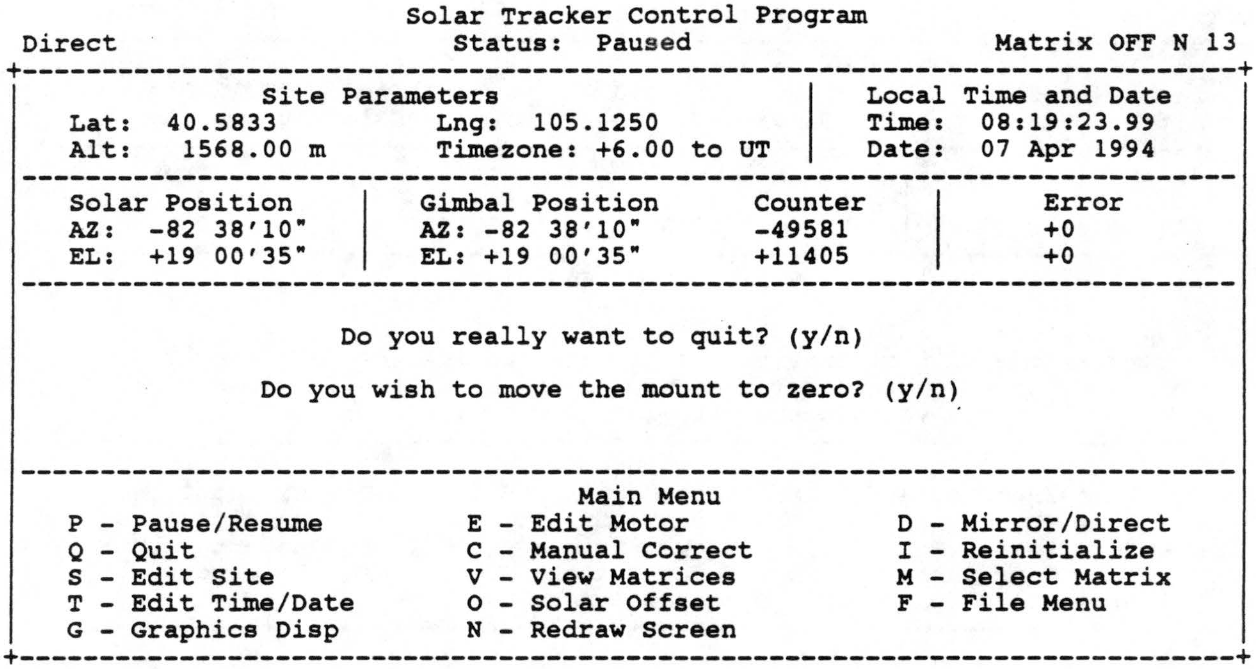
Screen 11 shows the Offset Selection screen. Pressing the **O** key from Run Mode will activate this screen. The user can choose a method of tracking off of the sun by selecting the appropriate number 0, 1 or 2.

A Time Offset will cause the tracker to move to a point ahead of (or behind) the current solar position on the solar path. The user specifies the time offset in hours, minutes and seconds. The angular displacement of a particular time differential will vary depending on date and time of day.



```
                        Solar Tracker Control Program
Direct                     Status:  Paused                       Matrix OFF N 13
+-----------------------------------------------------------------------------+
|              Site Parameters                     |   Local Time and Date     |
|   Lat:  40.5833           Lng:  105.1250         |   Time:  08:17:05.69      |
|   Alt:    1568.00 m       Timezone: +6.00 to UT  |   Date:  07 Apr 1994      |
|-----------------------------------------------------------------------------|
|   Solar Position     |  Gimbal Position     Counter      |        Error     |
|   AZ:   -83 01'45"   |  AZ: -83 01'45"      -49817       |        +0        |
|   EL:   +18 34'30"   |  EL: +18 34'30"      +11145       |        +0        |
|-----------------------------------------------------------------------------|
|                         Solar Offset Function                               |
|                                                                             |
|        Time Offset = 00:00:00                                               |
|    where a time of 5 minutes equals an angle of 1.25 degrees (early         |
|    or late) to 1.66 degrees (at noon), depending on the date and time.      |
|            Is this value correct? (y/n)                                     |
|-----------------------------------------------------------------------------|
|                                Main Menu                                    |
|   P - Pause/Resume          E - Edit Motor              D - Mirror/Direct   |
|   Q - Quit                  C - Manual Correct          I - Reinitialize    |
|   S - Edit Site             V - View Matrices           M - Select Matrix   |
|   T - Edit Time/Date        O - Solar Offset            F - File Menu       |
|   G - Graphics Disp         N - Redraw Screen                               |
+-----------------------------------------------------------------------------+
```

Screen 12 shows the Time Offset Parameter screen, where the user enters a value for the time differential, and a direction (positive or negative) for the offset.



```
                         Solar Tracker Control Program
Direct                      Status:  Paused                       Matrix OFF N 13
+------------------------------------------------------------------------------+
|                Site Parameters                         |   Local Time and Date |
|  Lat:  40.5833           Lng:  105.1250                |   Time:  08:19:23.99  |
|  Alt:    1568.00 m       Timezone: +6.00 to UT         |   Date:  07 Apr 1994  |
|------------------------------------------------------------------------------|
|  Solar Position        | Gimbal Position       Counter       |      Error    |
|  AZ:   -82 38'10"      | AZ: -82 38'10"        -49581        |       +0      |
|  EL:   +19 00'35"      | EL: +19 00'35"        +11405        |       +0      |
|------------------------------------------------------------------------------|
|                                                                              |
|                       Do you really want to quit? (y/n)                      |
|                                                                              |
|                   Do you wish to move the mount to zero? (y/n)               |
|                                                                              |
|                                                                              |
|------------------------------------------------------------------------------|
|                                   Main Menu                                  |
|  P - Pause/Resume          E - Edit Motor              D - Mirror/Direct     |
|  Q - Quit                  C - Manual Correct          I - Reinitialize      |
|  S - Edit Site             V - View Matrices           M - Select Matrix     |
|  T - Edit Time/Date        O - Solar Offset            F - File Menu         |
|  G - Graphics Disp         N - Redraw Screen                                 |
+------------------------------------------------------------------------------+
```

Screen 13 is the screen as it appears just before exiting the program. When the user selects **Q** from the Main Menu during Run Mode, the program prompts the user to confirm the desire to quit. If this is answered affirmatively, the program prompts whether or not to return the mount to the zero position. This is usually desirable, placing the mount in the correct position to start the program again later.