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The Green Bank Telescope Panel Setting Tool Instrumentation

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1 Introduction

The GBT panel setting tool will be used to set the relative positions of each of the four panel corners mounted over an actuator as described in memos AS005 and AS080 [1,2], and shown on drawings D35420M148 sheets 1–4 and D35420M152. In order to correct for small panel manufacturing errors, each panel will be measured on a coordinate measurement machine and a best fit will be done with respect to a cardinal point near each corner as described in CRSI document 122452A and drawing 120520.

The panel setting tool will be equipped with four digital indicators which will measure the distances to the panel with respect to a reference plane on the instrument, where the reference plane is calculated from the telescope model. To correct for small angle misalignments, the instrument will include a dual axis inclinometer and software to correct the actual measurements to the measurements with respect to the design tangent. An alignment telescope on the instrument will be used to align an axis toward the vertex. A handheld computer and barcode reader will be interfaced to make all measurements, calculations, and panel identifications. Measurements will be made remotely, with the mechanics standing on adjacent panels to avoid distortions.

2 GBT Geometry

Using the notation on C35102M081B, and substituting (u, v, w) for the reflector coordinate system, the equation of the reflector is

$$w = \frac{u^2 + v^2}{4c} \quad (1)$$

where $c = 60$ meters. To locate the panel corners by hoop (radius) and rib (angle) as shown on drawing 121010 sheet 7, it is also convenient to write the equation in cylindrical coordinates

$$w = \frac{r^2}{4c} \quad (2)$$

where

$$u = r \sin \theta \quad (3)$$

$$v = r \cos \theta \quad (4)$$

$$w = w \quad (5)$$

$$r = (u^2 + v^2)^{1/2} \quad (6)$$

$$\theta = \frac{\text{rib\#} \ 2\pi}{10 \ 360} \quad (7)$$

$$= \arctan \frac{u}{v} \quad (8)$$

and the radius r of each rib is shown in Table 1 on drawing 120520 sheet 2. Note that θ is measured clockwise from the axis of symmetry (v axis).

The reflector panels will be set at the "birdbath" elevation (65.77° 065-46-12), which makes it necessary to convert from the reflector (u, v, w) coordinates to the fixed ground (x, y, z) coordinates in order to use gravity referenced survey instruments. This transformation can be expressed as

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos \alpha_a & \sin \alpha_a & 0 \\ -\sin \alpha_a & \cos \alpha_a & 0 \\ 0 & 0 & 1 \end{pmatrix} \left\{ \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & \sin \alpha_e & \cos \alpha_e \\ 0 & -\cos \alpha_e & \sin \alpha_e \end{pmatrix} \begin{pmatrix} u & 0 \text{ mm} \\ v & -54 \ 839.108 \text{ mm} \\ w & 4 \ 999.990 \text{ mm} \end{pmatrix} \right] + \begin{pmatrix} 0 \text{ mm} \\ 0 \text{ mm} \\ 48 \ 260.000 \text{ mm} \end{pmatrix} \right\}. \quad (9)$$

Thus, one can go from the hoop and rib to the (u, v, w) coordinates and then to the (x, y, z) coordinates as a function of azimuth, α_a , and elevation, α_e .

It is immediately recognized that at the birdbath elevation, all symmetry is lost in the (x, y, z) coordinate system and the coordinates and tangent plane must be calculated for each actuator position.

3 Surface Tilts

In order to establish the panel setting tool reference plane, dual axis inclinometers are located on the instrument. One axis measures tilt (with respect to gravity) of the surface tangent plane along the radial direction i.e., in the reflector coordinate

system $w - r$ plane. Another inclinometer axis measures tilt in the orthogonal θ direction.

The problem of establishing the desired inclinometer angles reduces to calculating the angles in the (u, v, w) coordinate system and then rotating them into the (x, y, z) (gravity referenced) coordinate system.

Fortunately, Fred Schwab has already derived the direction vectors in GBT Memo 64 [3]. With a change in notation to match the coordinate system defined on C35102M081B, the three direction vectors are

$$\vec{r} = (2c \sin \theta, 2c \cos \theta, r) / \sqrt{r^2 + 4c^2} \quad (10)$$

$$\vec{\theta} = (\cos \theta, -\sin \theta, 0) \quad (11)$$

$$\vec{n} = (-r \sin \theta, -r \cos \theta, 2c) / \sqrt{r^2 + 4c^2} \quad (12)$$

where \vec{r} is the surface tangent vector along one inclinometer axis, $\vec{\theta}$ is the surface tangent vector along the other inclinometer axis, \vec{n} is the surface normal vector, and

$$\vec{\theta} \times \vec{r} = \vec{n}. \quad (13)$$

The problem now is to calculate the \vec{r} and $\vec{\theta}$ vectors in the reflector coordinate system and then rotate them into the ground based coordinate system. The transformation matrix for vectors is a modification of the coordinate transformation without the translations. The vector transformation can be written as

$$\begin{pmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{pmatrix} = \begin{pmatrix} \cos \alpha_a & \sin \alpha_a & 0 \\ -\sin \alpha_a & \cos \alpha_a & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sin \alpha_e & \cos \alpha_e \\ 0 & -\cos \alpha_e & \sin \alpha_e \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} \quad (14)$$

$$= \begin{pmatrix} \cos \alpha_a & \sin \alpha_a \sin \alpha_e & \sin \alpha_a \cos \alpha_e \\ -\sin \alpha_a & \cos \alpha_a \sin \alpha_e & \cos \alpha_a \cos \alpha_e \\ 0 & -\cos \alpha_e & \sin \alpha_e \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} \quad (15)$$

where

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} \quad (16)$$

is replaced by the components of \vec{r} , $\vec{\theta}$, or \vec{n} .

Note that the components $(\tilde{x}, \tilde{y}, \tilde{z})$ are the cosine of the angle between the rotated surface vector and the ground based basis vectors (x, y, z) . Also note that the \tilde{z} component of \vec{r} is the component sensed by the radial inclinometer and the \tilde{z} component of $\vec{\theta}$ is the component sensed by the θ inclinometer. Therefore, the slope of the radial inclinometer is $\arcsin \tilde{z}$ for \vec{r} and the slope of the θ inclinometer is $\arcsin \tilde{z}$ for $\vec{\theta}$, or

$$\angle \vec{r} = \arcsin \left(-\frac{\cos \alpha_e \cos \theta}{\sqrt{1 + r^2/(4c^2)}} + \frac{r \sin \alpha_e}{2c\sqrt{1 + r^2/(4c^2)}} \right) \quad (17)$$

$$\angle \vec{\theta} = \arcsin(\cos \alpha_e \sin \theta). \quad (18)$$

4 Inclinator Corrections

In the ideal situation, the instrument will be placed on an interface adapter that is a fixed reference distance from the top of the actuator and tilted normal to the surface tangent along \vec{n} , i.e., the two inclinometers will measure $\angle \vec{r}$ and $\angle \vec{\theta}$ as calculated for that hoop and rib on the surface. This table of angles will be calculated for the surface setting elevation as a function of hoop and rib and downloaded into the handheld CMT instrument computer. This will be an extension of the spreadsheet described in GBT Memo 114 [4,5]. A sample is included in Appendix A.

Each panel will be measured at the factory on a coordinate measuring machine (CMM) and a best fit analysis will generate an offset from the nominal height of each panel corner at the panel setting instrument measurement points as defined on drawings D35420M148 sheets 1-4. Each panel corner will be identified with a unique optical barcode that identifies the panel serial number and corner orientation as shown on drawing 120520C sheet 1. A table of offsets, indexed to the barcode, for each panel corner will also be downloaded into the CMT computer.

In the actual situation, the panel setting instrument will not be tilted to the calculated angles. These small angle deviations must be compensated for and the corrections applied to the CMM offsets in the table. One way to model the tilt angle deviations is to assign a coordinate system on the instrument and then rotate the instrument about the $\vec{\theta}$ and \vec{r} axes by the small angle deviations.

First assume an instrument centered coordinate system (i, j, k) where \vec{i} points along the $\vec{\theta}$ direction, \vec{j} points along the \vec{r} direction, and \vec{k} points along the \vec{n} direction for the ideal design paraboloid, and the origin is centered on the actuator and 5.3100 inches above the top of the actuator stud. If the panel corners are identified as a,b,c,d with a in the upper (outer hoop) left corner and b,c,d measured clockwise, as shown in Figure 4, the ideal coordinates (in inches) will be

$$(2.500, 2.500, z_{d0}) \quad (19)$$

$$(2.500, -2.500, z_{a0}) \quad (20)$$

$$(-2.500, -2.500, z_{b0}) \quad (21)$$

$$(-2.500, 2.500, z_{c0}) \quad (22)$$

where it is understood that $z_{a0}, z_{b0}, z_{c0}, z_{d0}$ are the CMM calibration numbers for the four corners of different panels joined at an actuator bracket. Note that by reading the four barcodes at an actuator, the combination of panel serial number and corner of the panel yields a unique identification of each panel constant without any requirement on the mechanic to read the barcodes in any special order. Note that

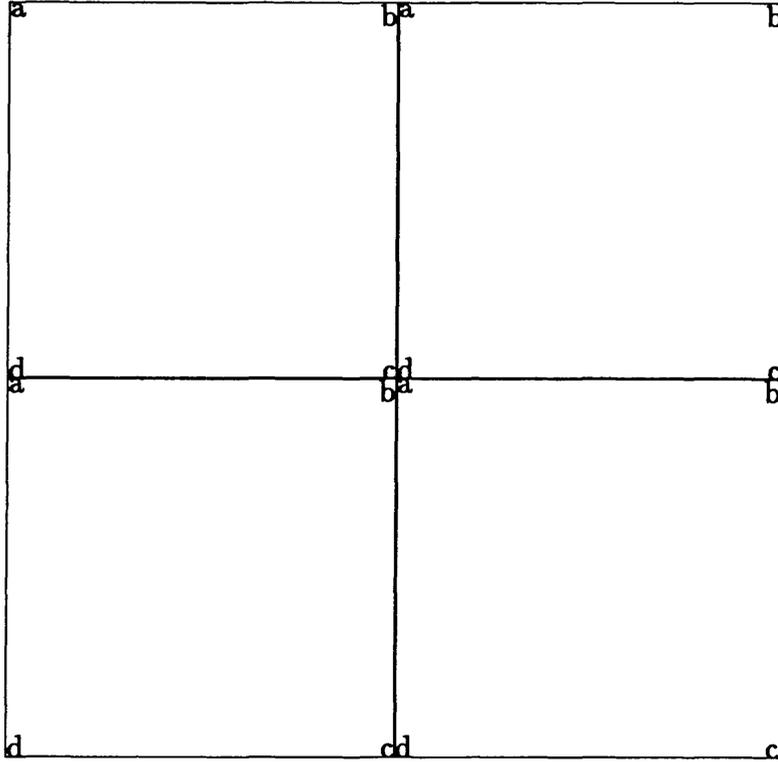


Figure 1: Panel corner identification.

the instrument will have the information required to determine the hoop (radius) location from the corner barcodes, but the rib (angle) location must be obtained from a schedule of actual installed panel locations which must also be downloaded into the CMT (one other option is to include a digital compass on the instrument). This combination of coordinates will be required to calculate the surface tangent.

Now if the instrument is rotated about the $\vec{\theta}$ axis (tipped toward the vertex) by γ_i and then rotated about the \vec{r} axis by γ_j , where γ_i and γ_j are the small deviations from the design paraboloid (actual-ideal), the new coordinates as seen by the instrument will be

$$\begin{pmatrix} \tilde{i} \\ \tilde{j} \\ \tilde{k} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma_i & \sin \gamma_i \\ 0 & -\sin \gamma_i & \cos \gamma_i \end{pmatrix} \begin{pmatrix} \cos \gamma_j & 0 & -\sin \gamma_j \\ 0 & 1 & 0 \\ \sin \gamma_j & 0 & \cos \gamma_j \end{pmatrix} \begin{pmatrix} i \\ j \\ k \end{pmatrix} \quad (23)$$

$$= \begin{pmatrix} \cos \gamma_j & 0 & -\sin \gamma_j \\ \sin \gamma_i \sin \gamma_j & \cos \gamma_i & \sin \gamma_i \cos \gamma_j \\ \cos \gamma_i \sin \gamma_j & -\sin \gamma_i & \cos \gamma_i \cos \gamma_j \end{pmatrix} \begin{pmatrix} i \\ j \\ k \end{pmatrix}. \quad (24)$$

For small angles, we can ignore the \tilde{i} and \tilde{j} movement of the digital indicator point over the surface, i.e., assume a flat surface. \tilde{k} will be the component actually

measured by the digital indicators where \tilde{k} decreases for an extension of the indicator stem. These actual indicator measurement components can be written as

$$\begin{pmatrix} \tilde{z}_a \\ \tilde{z}_b \\ \tilde{z}_c \\ \tilde{z}_d \end{pmatrix} = \begin{pmatrix} 2.500 \cos \gamma_i \sin \gamma_j + 2.500 \sin \gamma_i + z_a \cos \gamma_i \cos \gamma_j \\ -2.500 \cos \gamma_i \sin \gamma_j + 2.500 \sin \gamma_i + z_b \cos \gamma_i \cos \gamma_j \\ -2.500 \cos \gamma_i \sin \gamma_j - 2.500 \sin \gamma_i + z_c \cos \gamma_i \cos \gamma_j \\ 2.500 \cos \gamma_i \sin \gamma_j - 2.500 \sin \gamma_i + z_d \cos \gamma_i \cos \gamma_j \end{pmatrix}. \quad (25)$$

The objective is to read the actual measured indicator components ($\tilde{z}_a, \tilde{z}_b, \tilde{z}_c, \tilde{z}_d$) at an arbitrary orientation and correct them to the indicator components (z_a, z_b, z_c, z_d) that would be measured at the ideal orientation (on the CMM) and give the mechanic an indication of the panel setting error. This is easily generated by inverting the matrix in equation 24

$$\begin{pmatrix} i \\ j \\ k \end{pmatrix} = \begin{pmatrix} \cos \gamma_j & 0 & -\sin \gamma_j \\ \sin \gamma_i \sin \gamma_j & \cos \gamma_i & \sin \gamma_i \cos \gamma_j \\ \cos \gamma_i \sin \gamma_j & -\sin \gamma_i & \cos \gamma_i \cos \gamma_j \end{pmatrix}^{-1} \begin{pmatrix} \tilde{i} \\ \tilde{j} \\ \tilde{k} \end{pmatrix} \quad (26)$$

$$= \begin{pmatrix} \cos \gamma_j & \sin \gamma_i \sin \gamma_j & \cos \gamma_i \sin \gamma_j \\ 0 & \cos \gamma_i & -\sin \gamma_i \\ -\sin \gamma_j & \sin \gamma_i \cos \gamma_j & \cos \gamma_i \cos \gamma_j \end{pmatrix} \begin{pmatrix} \tilde{i} \\ \tilde{j} \\ \tilde{k} \end{pmatrix}. \quad (27)$$

Finally, the CMT computer will read each indicator and inclinometer and correct the indicator readings back to the ideal case CMM equivalent readings, i.e.,

$$\begin{pmatrix} z_a \\ z_b \\ z_c \\ z_d \end{pmatrix} = \begin{pmatrix} -2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_a \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_b \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_c \cos \gamma_i \cos \gamma_j \\ -2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_d \cos \gamma_i \cos \gamma_j \end{pmatrix} \quad (28)$$

and the setting errors are

$$\begin{pmatrix} \Delta z_a \\ \Delta z_b \\ \Delta z_c \\ \Delta z_d \end{pmatrix} = \begin{pmatrix} -2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_a \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_b \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_c \cos \gamma_i \cos \gamma_j \\ -2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + \tilde{z}_d \cos \gamma_i \cos \gamma_j \end{pmatrix} - \begin{pmatrix} z_{a0} \\ z_{b0} \\ z_{c0} \\ z_{d0} \end{pmatrix}. \quad (29)$$

5 Calibration

The dual axis inclinometers will require calibration in the lab. There is a slight interaction between the two axes and the transducers may have some nonlinearity and offset, so a series of sine bar angle measurements are made for rotations about

each axis, i.e., a four quadrant calibration. In order to insure exactly 90° between quadrants, the inclinometer is mounted on a reference block and rotations are made with respect to the same edge. A two dimensional regression is then performed to yield a set of coefficients

$$\begin{pmatrix} V_r \\ V_\theta \end{pmatrix} = \begin{pmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{pmatrix} \begin{pmatrix} \sin \angle \vec{r} \\ \sin \angle \vec{\theta} \end{pmatrix} + \begin{pmatrix} V_{r0} \\ V_{\theta0} \end{pmatrix} \quad (30)$$

or solving for the angles

$$\begin{pmatrix} \sin \angle \vec{r} \\ \sin \angle \vec{\theta} \end{pmatrix} = \begin{pmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{pmatrix}^{-1} \begin{pmatrix} V_r - V_{r0} \\ V_\theta - V_{\theta0} \end{pmatrix} \quad (31)$$

where V_r and V_θ are the two transducer voltages and V_{r0} and $V_{\theta0}$ are the offset voltages. Note that the transducer output is proportional to the sine of the angle.

Solving for the angles

$$\angle \vec{r} = \arcsin \left(\frac{\lambda_{22}(V_r - V_{r0}) - \lambda_{21}(V_\theta - V_{\theta0})}{\lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21}} \right) \quad (32)$$

$$\angle \vec{\theta} = \arcsin \left(\frac{-\lambda_{12}(V_r - V_{r0}) + \lambda_{11}(V_\theta - V_{\theta0})}{\lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21}} \right) \quad (33)$$

$$\gamma_i = \arcsin \left(\frac{\lambda_{22}(V_r - V_{r0}) - \lambda_{21}(V_\theta - V_{\theta0})}{\lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21}} \right) - \angle \vec{r}(\text{hoop, rib}) \quad (34)$$

$$\gamma_j = \arcsin \left(\frac{-\lambda_{12}(V_r - V_{r0}) + \lambda_{11}(V_\theta - V_{\theta0})}{\lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21}} \right) - \angle \vec{\theta}(\text{hoop, rib}) \quad (35)$$

where $\angle \vec{r}(\text{hoop, rib})$ and $\angle \vec{\theta}(\text{hoop, rib})$ are from equations 17 and 18. An example calibration of a $\pm 12.5^\circ$ inclinometer is included in Appendix B [6].

The GageTalker A/D unit must also be calibrated to convert from counts to voltage. Due to the high output impedance of the inclinometer (16 k Ω) the GageTalker A/D had to be modified to remove a 10 k Ω shunt resistor across the input.

5.1 Field Calibration

These coefficients should remain constant, unless the instrument is dropped or the transducers are disturbed. The digital indicators will need a zero point calibration in the field however and it is a simple matter to check the inclinometers, so the following procedure is recommended.

A calibration test stand will be provided which includes a small surface plate, a fixture which holds the instrument 5.3100 inches above the surface plate, and a fixture which allows the instrument to rotate about a radius of 5.3100 above the surface plate. A precision level will also be required to level the surface plate.

Starting with a level surface plate, the instrument is placed on the fixture. With the CMT program in the calibration mode, it reads the four digital indicators (which read zero in the position they happen to be powered up) and two inclinometers. In this condition, the indicator readings need to be corrected to zero when the instrument is exactly level. This would be very difficult to achieve in the field. An alternative method is the following. From equation 29, set the errors and offsets to zero and the tilt angle to zero. The only modification required is to include a constant in each indicator reading. Equation 29 reduces to

$$\begin{pmatrix} -2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_a - k_a) \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_b - k_b) \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_c - k_c) \cos \gamma_i \cos \gamma_j \\ -2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_d - k_d) \cos \gamma_i \cos \gamma_j \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (36)$$

Solving for the constants,

$$\begin{pmatrix} k_a \\ k_b \\ k_c \\ k_d \end{pmatrix} = \begin{pmatrix} (-2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j) / \cos \gamma_i \cos \gamma_j \\ (2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j) / \cos \gamma_i \cos \gamma_j \\ (2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j) / \cos \gamma_i \cos \gamma_j \\ (-2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j) / \cos \gamma_i \cos \gamma_j \end{pmatrix} + \begin{pmatrix} \tilde{z}_a \\ \tilde{z}_b \\ \tilde{z}_c \\ \tilde{z}_d \end{pmatrix}_{\text{cal}}. \quad (37)$$

Equation 29 can now be written as

$$\begin{pmatrix} \Delta z_a \\ \Delta z_b \\ \Delta z_c \\ \Delta z_d \end{pmatrix} = \begin{pmatrix} -2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_a - k_a) \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j - 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_b - k_b) \cos \gamma_i \cos \gamma_j \\ 2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_c - k_c) \cos \gamma_i \cos \gamma_j \\ -2.500 \sin \gamma_j + 2.500 \sin \gamma_i \cos \gamma_j + (\tilde{z}_d - k_d) \cos \gamma_i \cos \gamma_j \end{pmatrix} - \begin{pmatrix} z_{a0} \\ z_{b0} \\ z_{c0} \\ z_{d0} \end{pmatrix}. \quad (38)$$

The CMT is then put into the measure mode and the instrument is then placed on the rotation fixture. The corrected readings should all be 0.0000 ± 0.0002 for small angle rotations about the radius. An additional check that will expose a defective indicator, an indicator that is counting in the wrong direction, a bent probe, an indicator cosine theta error, or an indicator that is not located on the 2.500 inch grid, is to sum the 4 raw indicator readings. This number should remain a constant for small rotations on the surface plate. This process should be repeated at the start of each day and a check of the zero point numbers should be done several times during the day and at the end of the day to insure closure.

6 Error Analysis

From the spreadsheet, the maximum nominal angles the inclinometers will see are: $-22^\circ 19' 15''$ at location 01+000, and $+16^\circ 41' 07''$ at location 45+000 for the radial

angle; and $\pm 22^{\circ}21'57''$ along the ± 680 rib line for the θ angle. This is well within the range of the Schaevitz LSRP $\pm 30^{\circ}$ dual axis Clinometer. The target adjustment of the panels is ± 0.001 inches, or about 83 arcseconds for a 2.500 inch arm. GageTalker will soon offer a 14 bit A/D interface module, which would correspond to a resolution of about 13 arcseconds (for the assumption, $\sin \theta = \theta$) even if the span is kept at the full $\pm 30^{\circ}$. This is not a match for the Mitutoyo Digimatic indicator with a resolution of 0.0001 inches, but the overall accuracy should be about 0.0002 inches—or 5 times better than the surface setting accuracy.

A Spreadsheet

Panel Setting Tool Data 1-25-96 J.S.
 Derived from actuator W.P. table

File: PSTDATA.WQ2
 Equations 17,18 surface.tex 1-18-96 DHP

alpha e (RAD) = 1.1479
 c (IN) = 2362.2

HOOP NUMBER	ANGLE	X	Y	Z	RADIUS (R1)		Theta (RAD)	Angle/10 (RAD)	r (DEG)	theta (DEG)
					INNER (IN)	r (RAD)				
1	-480	-117.030	105.375	2.625	157.48	-0.2466	-0.3099	-0.8378	-14.1274	-17.7574
1	-320	-83.452	133.551	2.625	157.48	-0.3231	-0.2192	-0.5585	-18.5098	-12.5610
1	-160	-43.407	151.379	2.625	157.48	-0.3725	-0.1134	-0.2793	-21.3401	-6.4953
1	0	0.000	157.480	2.625	157.48	-0.3896	0.0000	0.0000	-22.3209	0.0000
1	160	43.407	151.379	2.625	157.48	-0.3725	0.1134	0.2793	-21.3401	6.4953
1	320	83.452	133.551	2.625	157.48	-0.3231	0.2192	0.5585	-18.5098	12.5610
1	480	117.030	105.375	2.625	157.48	-0.2466	0.3099	0.8378	-14.1274	17.7574
2	-560	-213.447	143.971	7.015	257.463	-0.1805	-0.3472	-0.9774	-10.3425	-19.8913
2	-480	-191.332	172.276	7.015	257.463	-0.2265	-0.3099	-0.8378	-12.9783	-17.7574
2	-400	-165.494	197.228	7.015	257.463	-0.2675	-0.2670	-0.6981	-15.3252	-15.2957
2	-320	-136.435	218.341	7.015	257.463	-0.3025	-0.2192	-0.5585	-17.3316	-12.5610
2	-240	-104.720	235.204	7.015	257.463	-0.3307	-0.1677	-0.4189	-18.9500	-9.6091
2	-160	-70.966	247.489	7.015	257.463	-0.3515	-0.1134	-0.2793	-20.1388	-6.4953
2	-80	-35.832	254.957	7.015	257.463	-0.3642	-0.0571	-0.1396	-20.8659	-3.2743
2	0	0.000	257.463	7.015	257.463	-0.3685	0.0000	0.0000	-21.1107	0.0000
2	80	35.832	254.957	7.015	257.463	-0.3642	0.0571	0.1396	-20.8659	3.2743
2	160	70.966	247.489	7.015	257.463	-0.3515	0.1134	0.2793	-20.1388	6.4953
2	240	104.720	235.204	7.015	257.463	-0.3307	0.1677	0.4189	-18.9500	9.6091
2	320	136.435	218.341	7.015	257.463	-0.3025	0.2192	0.5585	-17.3316	12.5610
2	400	165.494	197.228	7.015	257.463	-0.2675	0.2670	0.6981	-15.3252	15.2957
2	480	191.332	172.276	7.015	257.463	-0.2265	0.3099	0.8378	-12.9783	17.7574
2	560	213.447	143.971	7.015	257.463	-0.1805	0.3472	0.9774	-10.3425	19.8913
3	-640	-321.166	156.643	13.513	357.33	-0.1108	-0.3778	-1.1170	-6.3511	-21.6457
3	-560	-296.240	199.816	13.513	357.33	-0.1608	-0.3472	-0.9774	-9.2106	-19.8913
3	-480	-265.548	239.100	13.513	357.33	-0.2065	-0.3099	-0.8378	-11.8327	-17.7574
3	-400	-229.687	273.731	13.513	357.33	-0.2472	-0.2670	-0.6981	-14.1649	-15.2957
3	-320	-189.356	303.033	13.513	357.33	-0.2820	-0.2192	-0.5585	-16.1571	-12.5610
3	-240	-145.339	326.437	13.513	357.33	-0.3100	-0.1677	-0.4189	-17.7628	-9.6091
3	-160	-98.493	343.488	13.513	357.33	-0.3306	-0.1134	-0.2793	-18.9415	-6.4953
3	-80	-49.731	353.852	13.513	357.33	-0.3432	-0.0571	-0.1396	-19.6622	-3.2743
3	0	0.000	357.330	13.513	357.33	-0.3474	0.0000	0.0000	-19.9047	0.0000
3	80	49.731	353.852	13.513	357.33	-0.3432	0.0571	0.1396	-19.6622	3.2743
3	160	98.493	343.488	13.513	357.33	-0.3306	0.1134	0.2793	-18.9415	6.4953
3	240	145.339	326.437	13.513	357.33	-0.3100	0.1677	0.4189	-17.7628	9.6091
3	320	189.356	303.033	13.513	357.33	-0.2820	0.2192	0.5585	-16.1571	12.5610
3	400	229.687	273.731	13.513	357.33	-0.2472	0.2670	0.6981	-14.1649	15.2957
3	480	265.548	239.100	13.513	357.33	-0.2065	0.3099	0.8378	-11.8327	17.7574
3	560	296.240	199.816	13.513	357.33	-0.1608	0.3472	0.9774	-9.2106	19.8913
3	640	321.166	156.643	13.513	357.33	-0.1108	0.3778	1.1170	-6.3511	21.6457
4	-640	-410.784	200.353	22.107	457.039	-0.0914	-0.3778	-1.1170	-5.2363	-21.6457
4	-560	-378.903	255.573	22.107	457.039	-0.1411	-0.3472	-0.9774	-8.0837	-19.8913
4	-480	-339.646	305.819	22.107	457.039	-0.1866	-0.3099	-0.8378	-10.6919	-17.7574
4	-400	-293.779	350.112	22.107	457.039	-0.2271	-0.2670	-0.6981	-13.0097	-15.2957
4	-320	-242.194	387.591	22.107	457.039	-0.2616	-0.2192	-0.5585	-14.9879	-12.5610
4	-240	-185.895	417.526	22.107	457.039	-0.2894	-0.1677	-0.4189	-16.5809	-9.6091
4	-160	-125.977	439.334	22.107	457.039	-0.3098	-0.1134	-0.2793	-17.7498	-6.4953
4	-80	-63.608	452.591	22.107	457.039	-0.3223	-0.0571	-0.1396	-18.4641	-3.2743
4	0	0.000	457.039	22.107	457.039	-0.3265	0.0000	0.0000	-18.7044	0.0000
4	80	63.608	452.591	22.107	457.039	-0.3223	0.0571	0.1396	-18.4641	3.2743
4	160	125.977	439.334	22.107	457.039	-0.3098	0.1134	0.2793	-17.7498	6.4953
4	240	185.895	417.526	22.107	457.039	-0.2894	0.1677	0.4189	-16.5809	9.6091
4	320	242.194	387.591	22.107	457.039	-0.2616	0.2192	0.5585	-14.9879	12.5610
4	400	293.779	350.112	22.107	457.039	-0.2271	0.2670	0.6981	-13.0097	15.2957
4	480	339.646	305.819	22.107	457.039	-0.1866	0.3099	0.8378	-10.6919	17.7574
4	560	378.903	255.573	22.107	457.039	-0.1411	0.3472	0.9774	-8.0837	19.8913
4	640	410.784	200.353	22.107	457.039	-0.0914	0.3778	1.1170	-5.2363	21.6457
5	-640	-500.221	243.974	32.781	556.547	-0.0720	-0.3778	-1.1170	-4.1280	-21.6457
5	-560	-461.398	311.217	32.781	556.547	-0.1215	-0.3472	-0.9774	-6.9631	-19.8913
5	-480	-413.595	372.403	32.781	556.547	-0.1668	-0.3099	-0.8378	-9.5576	-17.7574
5	-400	-357.742	426.340	32.781	556.547	-0.2070	-0.2670	-0.6981	-11.8611	-15.2957
5	-320	-294.925	471.979	32.781	556.547	-0.2413	-0.2192	-0.5585	-13.8253	-12.5610
5	-240	-226.368	508.431	32.781	556.547	-0.2689	-0.1677	-0.4189	-15.4060	-9.6091
5	-160	-153.405	534.987	32.781	556.547	-0.2891	-0.1134	-0.2793	-16.5652	-6.4953
5	-80	-77.456	551.131	32.781	556.547	-0.3015	-0.0571	-0.1396	-17.2732	-3.2743
5	0	0.000	556.547	32.781	556.547	-0.3056	0.0000	0.0000	-17.5114	0.0000

B Inclinometer Calibration Example

To: David Parker, Laser Ranging Research Group

From: David Bradley, Drexel Co-op at NRAO

Re: Calibration data for the inclinometer to be used on the GBT panel setting tool prototype.

Date: 02/16/96

The following pages are the reference drawings, data, and a brief error analysis for the inclinometer tested on 02/05/96.

Inclinometer parameters:

Make,	Lucas Schaevitz
Model#,	LSRP-14.5°
Serial #, bottom inclinometer, angle r,	38342
Serial#, top inclinometer, angle theta,	38343

Apparatus used in testing:

Sine bar,	hypotenuse length = 2.9989 inches
Scanning Digital Multimeter,	Make: Keithley
	Model: 199
	Serial#: 47387
	Channel#1: Angle r
	Channel#2: Angle theta

Data archiving and software used:

Test data: Quatro Pro™
System used: IBM compatible
Disk #: B112
Disk names: D02166.wq2

Drawings: Mini-Cad™
System used: Macintosh
Disk #: B113
Disk name: D02166.mac

Data Trends: Excell™
System used: Macintosh
Disk #: B113
Disk name: D02166.mac

Error Analysis: Claris Works™, saved as text file
System used: Macintosh
Disk #: B113
Disk name: D02166.mac

Cover and description: Claris Works™, saved as text file
System used: Macintosh
Disk #: B113
Disk name: D02166.mac

Description of Experiment

Purpose: To determine the rate of change of the output voltage of the inclinometer versus the sine of the angle of inclination.

For each data set, data was taken in 13 steps from a gage block thickness of 0.754 inches to zero inches at increments of 0.058 inches. The sine of the angle of inclination was found by dividing the gage block thickness by the hypoteneuse length of the sine bar.

Data sets were taken at two orientations as shown in figures 2.1 and 2.2.

Figure 1

GBT Panel Installation Tool Inclinator
Orientation and Angular Sign Conventions

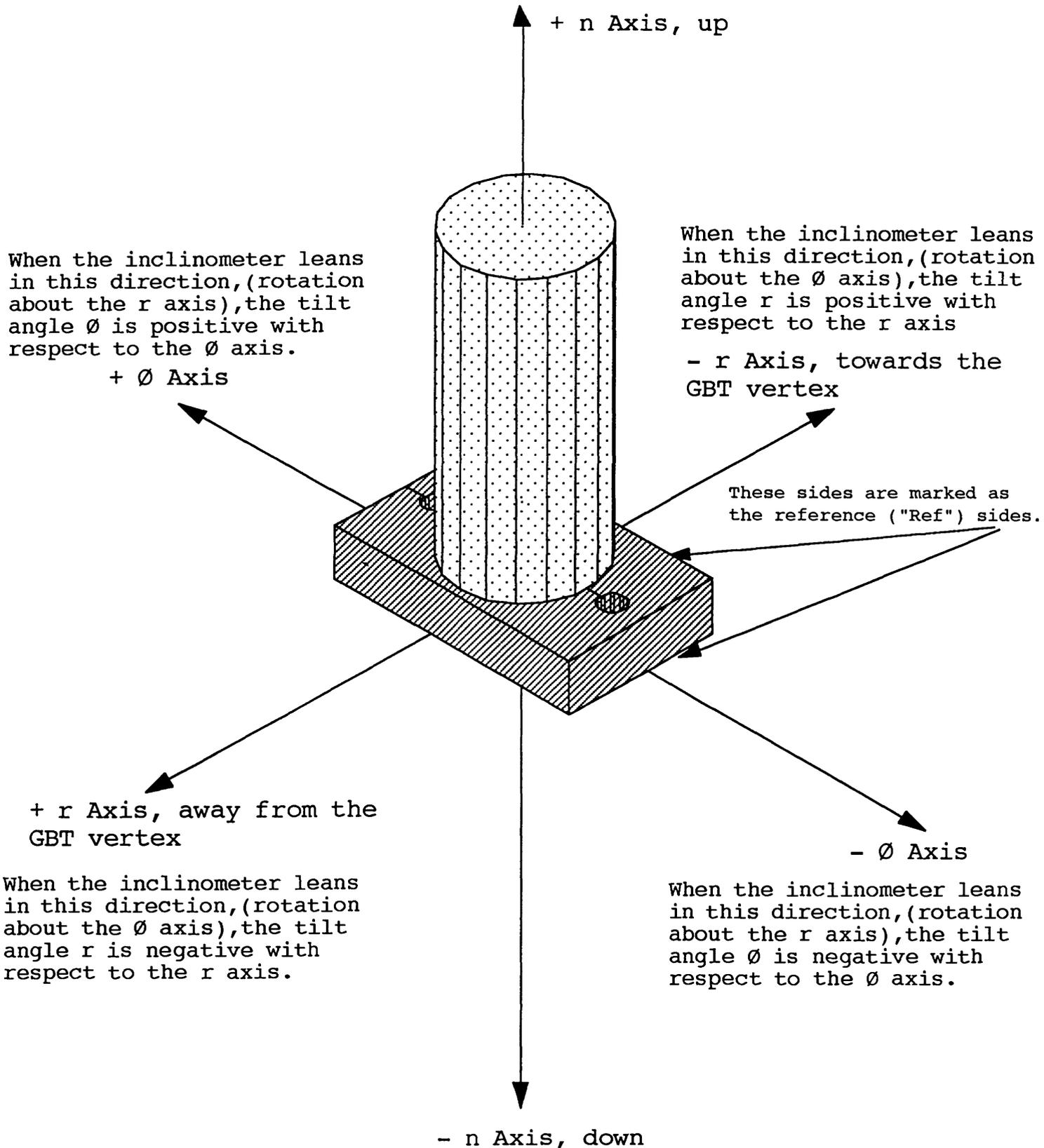
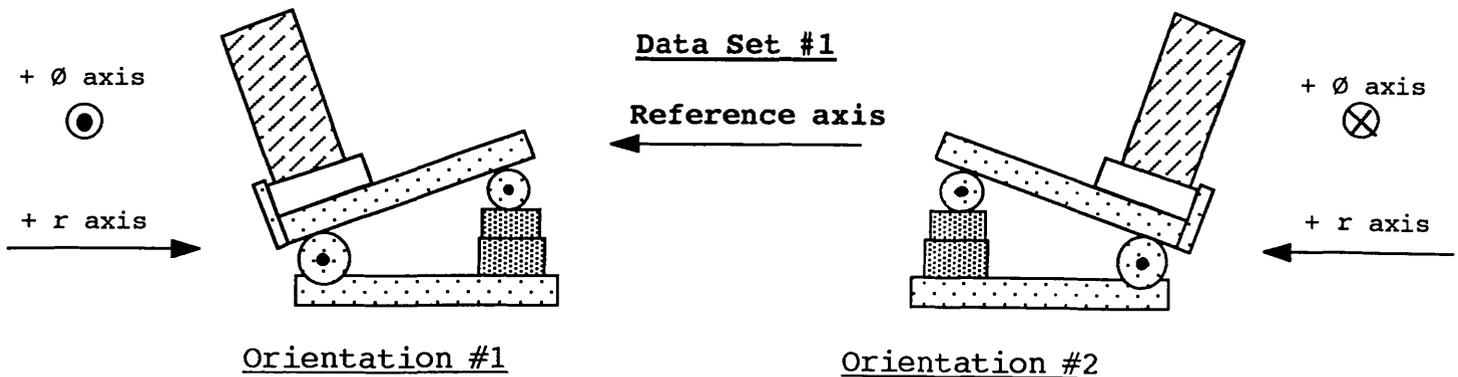
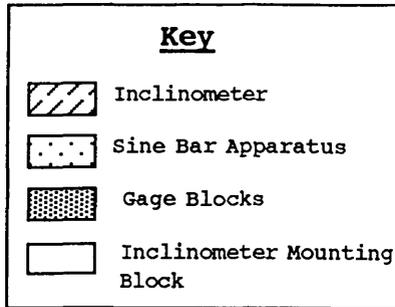


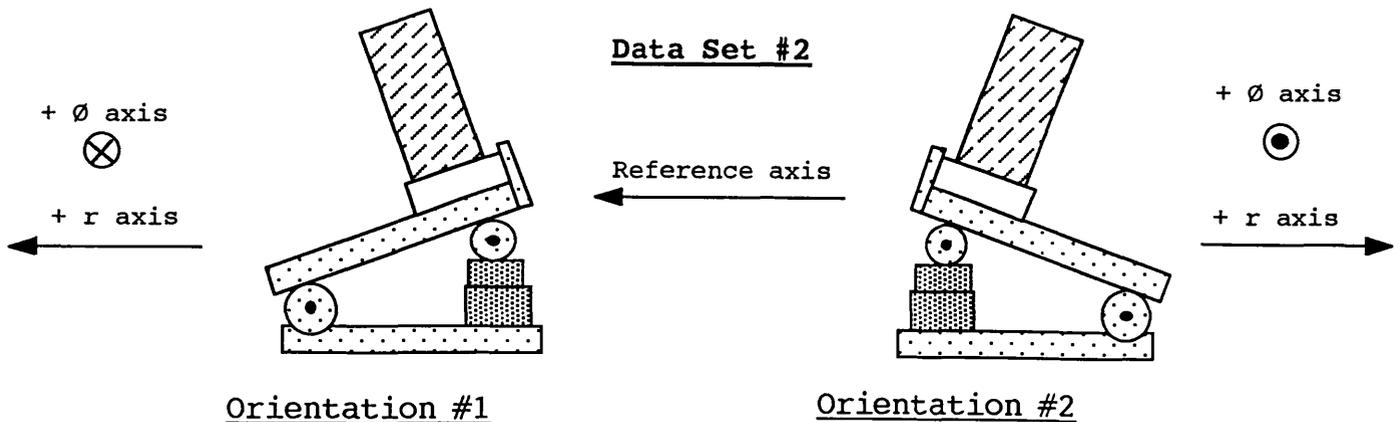
Figure 2.1

Orientation of the Inclinometer for Data Sets 1 and 2



Looking towards the $-\emptyset$ axis reference sides of the inclinometer mounting block are on the left (2.5") and opposite (1.5") sides. Rotation is about the \emptyset axis. The tilt angle r is positive and the $-r$ axis is rotated 0 radians with respect to the reference axis shown above.

Looking towards the $+\emptyset$ axis reference sides of the inclinometer mounting block are on the right (2.5") and facing (1.5") sides. Rotation is about the \emptyset axis. The tilt angle r is positive and the $-r$ axis is rotated π radians with respect to the reference axis shown above.

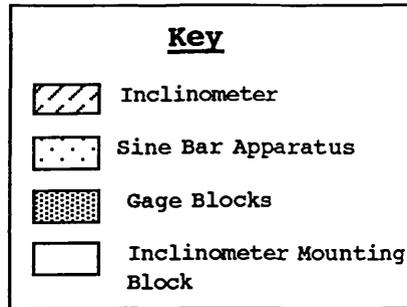


Looking towards the $+\emptyset$ axis reference sides of the inclinometer mounting block are on the right (2.5") and facing (1.5") sides. Rotation is about the \emptyset axis. The tilt angle r is negative and the $-r$ axis is rotated π radians with respect to the reference axis shown above.

Looking towards the $-\emptyset$ axis reference sides of the inclinometer mounting block are on the left (2.5") and opposite (1.5") sides. Rotation is about the \emptyset axis. The tilt angle r is negative and the $-r$ axis is rotated 0 radians with respect to the reference axis shown above.

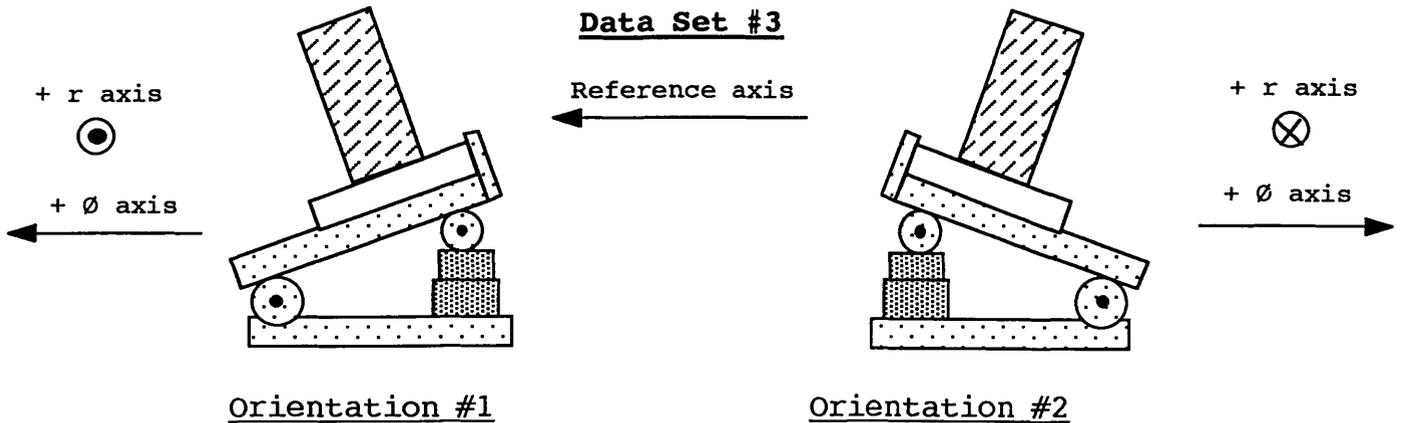
Figure 2.2

Orientation of the Inclinometer for Data Sets 3 and 4



Data Set #3

Reference axis
←

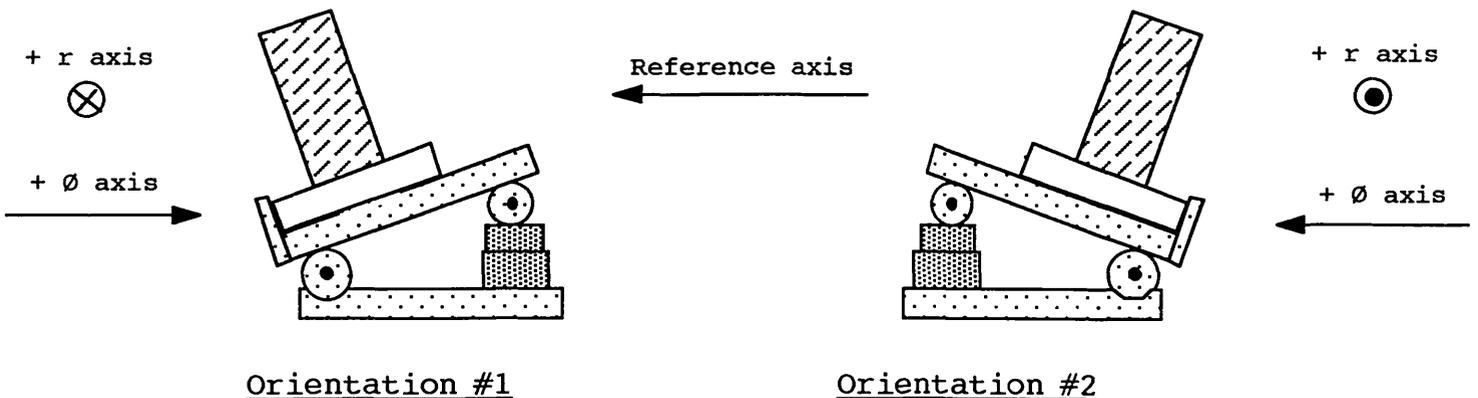


Looking towards the -r axis reference sides of the inclinometer mounting block are on the right (1.5") and opposite (2.5") sides. Rotation is about the r axis. The tilt angle \emptyset is positive and the -r axis is rotated $3\pi/2$ radians with respect to the reference axis shown above.

Looking towards the +r axis reference sides of the inclinometer mounting block are on the left (1.5") and facing (2.5") sides. Rotation is about the r axis. The tilt angle \emptyset is positive and the -r axis is rotated $\pi/2$ radians with respect to the reference axis shown above.

Data Set #4

Reference axis
←



Looking towards the +r axis reference sides of the inclinometer mounting block are on the left (1.5") and facing (2.5") sides. rotation is about the r axis. The tilt angle \emptyset is negative and the -r axis is rotated $\pi/2$ radians with respect to the reference axis shown above.

Looking towards the -r axis reference sides of the inclinometer mounting block are on the right (1.5") and opposite (2.5") sides. Rotation is about the r axis. The tilt angle \emptyset is negative and the -r axis is rotated $3\pi/2$ radians with respect to the reference axis shown above.

GBT Panel Setting Tool Inclinator Calibration Data

Data Set#	Rotate on theta axis [angle r] Gage Bloc thickness	Rotate on the r axis angle theta Gage Bloc thickness	Sine of Angle r	Sine of Angle theta	Sin Phi	Cos Phi	Voltage Angle r Ch#1 bttm	Voltage Angle theta Ch#2 top	Best Fit Angle r	Residual Angle r	Best Fit Angle theta	Residual Angle theta
Data Set1 Orient #1	0.754	0	0.25142552	0	0	1	-5.0231	-0.0174	-5.023859	0.000759	-0.017429	2.91E-05
	0.696	0	0.2320851	0	0	1	-4.6366	-0.0156	-4.636876	0.000276	-0.015859	0.000259
	0.638	0	0.21274467	0	0	1	-4.249	-0.0139	-4.249892	0.000892	-0.014289	0.000389
	0.58	0	0.19340425	0	0	1	-3.8616	-0.0123	-3.862909	0.001309	-0.012719	0.000419
	0.522	0	0.17406382	0	0	1	-3.4742	-0.0105	-3.475925	0.001725	-0.011148	0.000648
	0.464	0	0.1547234	0	0	1	-3.0866	-0.0088	-3.088942	0.002342	-0.009578	0.000778
	0.406	0	0.13538297	0	0	1	-2.6998	-0.0071	-2.701959	0.002159	-0.008008	0.000908
	0.348	0	0.11604255	0	0	1	-2.313	-0.0056	-2.314975	0.001975	-0.006438	0.000838
	0.29	0	0.09670212	0	0	1	-1.9258	-0.0039	-1.927992	0.002192	-0.004868	0.000968
	0.232	0	0.0773617	0	0	1	-1.538	-0.0022	-1.541009	0.003009	-0.003298	0.001098
	0.174	0	0.05802127	0	0	1	-1.1519	-0.0008	-1.154025	0.002125	-0.001727	0.000927
	0.116	0	0.03868085	0	0	1	-0.764	0.0008	-0.767042	0.003042	-0.000157	0.000957
	0.05	0	0.01667278	0	0	1	-0.3234	0.0026	-0.326681	0.003281	0.0016294	0.000971
0	0	0	0	0	1	0.0103	0.0039	0.006925	0.003375	0.002983	0.000917	
Data Set1 Orient #2	0.754	0	0.25142552	0	0	-1	-5.0185	-0.0206	-5.019723	0.001223	-0.020822	0.000222
	0.696	0	0.2320851	0	0	-1	-4.6323	-0.0189	-4.63274	0.00044	-0.019252	0.000352
	0.638	0	0.21274467	0	0	-1	-4.2444	-0.0173	-4.245757	0.001357	-0.017682	0.000382
	0.58	0	0.19340425	0	0	-1	-3.8568	-0.0156	-3.858773	0.001973	-0.016111	0.000511
	0.522	0	0.17406382	0	0	-1	-3.4697	-0.0139	-3.47179	0.00209	-0.014541	0.000641
	0.464	0	0.1547234	0	0	-1	-3.0821	-0.0122	-3.084806	0.002706	-0.012971	0.000771
	0.406	0	0.13538297	0	0	-1	-2.6952	-0.0105	-2.697823	0.002623	-0.011401	0.000901
	0.348	0	0.11604255	0	0	-1	-2.3099	-0.0089	-2.31084	0.00094	-0.009831	0.000931
	0.29	0	0.09670212	0	0	-1	-1.9213	-0.0073	-1.923856	0.002556	-0.008261	0.000961
	0.232	0	0.0773617	0	0	-1	-1.5335	-0.0057	-1.536873	0.003373	-0.00669	0.00099
	0.174	0	0.05802127	0	0	-1	-1.1474	-0.0042	-1.149889	0.002489	-0.00512	0.00092
	0.116	0	0.03868085	0	0	-1	-0.7594	-0.0025	-0.762906	0.003506	-0.00355	0.00105
	0.05	0	0.01667278	0	0	-1	-0.3189	-0.0008	-0.322546	0.003646	-0.001763	0.000963
0	0	0	0	0	-1	0.0149	0.0005	0.011061	0.003839	-0.00041	0.00091	

Data Set#	Rotate on theta axis [angle r] Gage Bloc thickness	Rotate on the r axis angle theta Gage Bloc thickness	Sine of Angle r	Sine of Angle theta	Sin Phi	Cos Phi	Voltage Angle r Ch#1 bttm	Voltage Angle theta Ch#2 top	Best Fit Angle r	Residual Angle r	Best Fit Angle theta	Residual Angle theta
Data Set2 Orient #1	0	0	0	0	0	-1	0.008	-0.0035	0.011061	-0.003061	-0.00041	-0.00309
	-0.05	0	-0.0166728	0	0	-1	0.3463	0.0015	0.344667	0.001633	0.0009438	0.000556
	-0.116	0	-0.0386808	0	0	-1	0.7866	0.0034	0.785027	0.001573	0.0027305	0.000669
	-0.174	0	-0.0580213	0	0	-1	1.1739	0.0049	1.172011	0.001889	0.0043007	0.000599
	-0.232	0	-0.0773617	0	0	-1	1.5606	0.0066	1.558994	0.001606	0.0058708	0.000729
	-0.29	0	-0.0967021	0	0	-1	1.9479	0.0081	1.945978	0.001922	0.007441	0.000659
	-0.348	0	-0.1160425	0	0	-1	2.3373	0.0097	2.332961	0.004339	0.0090112	0.000689
	-0.406	0	-0.135383	0	0	-1	2.7216	0.0112	2.719944	0.001656	0.0105813	0.000619
	-0.464	0	-0.1547234	0	0	-1	3.1089	0.0128	3.106928	0.001972	0.0121515	0.000648
	-0.522	0	-0.1740638	0	0	-1	3.4955	0.0143	3.493911	0.001589	0.0137217	0.000578
	-0.58	0	-0.1934042	0	0	-1	3.8826	0.0159	3.880895	0.001705	0.0152918	0.000608
	-0.638	0	-0.2127447	0	0	-1	4.2695	0.0173	4.267878	0.001622	0.016862	0.000438
-0.696	0	-0.2320851	0	0	-1	4.6562	0.0189	4.654861	0.001339	0.0184322	0.000468	
-0.754	0	-0.2514255	0	0	-1	5.0433	0.0205	5.041845	0.001455	0.0200023	0.000498	
Data Set2 Orient #2	0	0	0	0	0	1	0.0123	0.0001	0.006925	0.005375	0.002983	-0.002883
	-0.05	0	-0.0166728	0	0	1	0.3417	0.005	0.340531	0.001169	0.0043366	0.000663
	-0.116	0	-0.0386808	0	0	1	0.7821	0.0068	0.780892	0.001208	0.0061234	0.000677
	-0.174	0	-0.0580213	0	0	1	1.1694	0.0083	1.167875	0.001525	0.0076935	0.000606
	-0.232	0	-0.0773617	0	0	1	1.5561	0.01	1.554859	0.001241	0.0092637	0.000736
	-0.29	0	-0.0967021	0	0	1	1.9435	0.0115	1.941842	0.001658	0.0108339	0.000666
	-0.348	0	-0.1160425	0	0	1	2.333	0.013	2.328825	0.004175	0.012404	0.000596
	-0.406	0	-0.135383	0	0	1	2.7171	0.0147	2.715809	0.001291	0.0139742	0.000726
	-0.464	0	-0.1547234	0	0	1	3.1044	0.016	3.102792	0.001608	0.0155444	0.000456
	-0.522	0	-0.1740638	0	0	1	3.4912	0.0177	3.489775	0.001425	0.0171145	0.000585
	-0.58	0	-0.1934042	0	0	1	3.8783	0.0193	3.876759	0.001541	0.0186847	0.000615
	-0.638	0	-0.2127447	0	0	1	4.2651	0.0208	4.263742	0.001358	0.0202549	0.000545
-0.696	0	-0.2320851	0	0	1	4.6517	0.0224	4.650726	0.000974	0.021825	0.000575	
-0.754	0	-0.2514255	0	0	1	5.0387	0.0239	5.037709	0.000991	0.0233952	0.000505	

Data Set#	Rotate on theta axis [angle r] Gage Bloc thickness	Rotate on the r axis angle theta Gage Bloc thickness	Sine of Angle r	Sine of Angle theta	Sin Phi	Cos Phi	Voltage Angle r Ch#1 bttm	Voltage Angle theta Ch#2 top	Best Fit Angle r	Residual Angle r	Best Fit Angle theta	Residual Angle theta
Data Set3 Orient #1	0	0.754	0	0.251425523	-1	0	0.0386	-5.0293	0.041636	-0.003036	-5.027976	-0.001324
	0	0.696	0	0.232085098	-1	0	0.0362	-4.6423	0.038995	-0.002795	-4.641271	-0.001029
	0	0.638	0	0.212744673	-1	0	0.0338	-4.2557	0.036354	-0.002554	-4.254566	-0.001134
	0	0.58	0	0.193404248	-1	0	0.0312	-3.8686	0.033713	-0.002513	-3.86786	-0.00074
	0	0.522	0	0.174063823	-1	0	0.0289	-3.4819	0.031072	-0.002172	-3.481155	-0.000745
	0	0.464	0	0.154723399	-1	0	0.0265	-3.095	0.028431	-0.001931	-3.09445	-0.00055
	0	0.406	0	0.135382974	-1	0	0.024	-2.7081	0.02579	-0.00179	-2.707745	-0.000355
	0	0.348	0	0.116042549	-1	0	0.0214	-2.323	0.023149	-0.001749	-2.321039	-0.001961
	0	0.29	0	0.096702124	-1	0	0.019	-1.9352	0.020508	-0.001508	-1.934334	-0.000866
	0	0.232	0	0.077361699	-1	0	0.0164	-1.5476	0.017867	-0.001467	-1.547629	2.9E-05
	0	0.174	0	0.058021274	-1	0	0.0139	-1.161	0.015226	-0.001326	-1.160924	-7.6E-05
	0	0.116	0	0.03868085	-1	0	0.0113	-0.7739	0.012585	-0.001285	-0.774219	0.000319
	0	0.05	0	0.01667278	-1	0	0.0081	-0.3339	0.00958	-0.00148	-0.334175	0.000275
0	0	0	0	-1	0	0.0062	-0.0004	0.007304	-0.001104	-0.000808	0.000408	
Data Set3 Orient #2	0	0.754	0	0.251425523	1	0	0.0421	-5.025	0.045014	-0.002914	-5.023787	-0.001213
	0	0.696	0	0.232085098	1	0	0.0397	-4.6381	0.042373	-0.002673	-4.637082	-0.001018
	0	0.638	0	0.212744673	1	0	0.0372	-4.2514	0.039732	-0.002532	-4.250376	-0.001024
	0	0.58	0	0.193404248	1	0	0.0344	-3.8644	0.037091	-0.002691	-3.863671	-0.000729
	0	0.522	0	0.174063823	1	0	0.032	-3.4775	0.034451	-0.002451	-3.476966	-0.000534
	0	0.464	0	0.154723399	1	0	0.0297	-3.0907	0.03181	-0.00211	-3.090261	-0.000439
	0	0.406	0	0.135382974	1	0	0.0272	-2.7038	0.029169	-0.001969	-2.703555	-0.000245
	0	0.348	0	0.116042549	1	0	0.0247	-2.3189	0.026528	-0.001828	-2.31685	-0.00205
	0	0.29	0	0.096702124	1	0	0.0223	-1.9307	0.023887	-0.001587	-1.930145	-0.000555
	0	0.232	0	0.077361699	1	0	0.0197	-1.5433	0.021246	-0.001546	-1.54344	0.00014
	0	0.174	0	0.058021274	1	0	0.0171	-1.1566	0.018605	-0.001505	-1.156734	0.000134
	0	0.116	0	0.03868085	1	0	0.0146	-0.7696	0.015964	-0.001364	-0.770029	0.000429
	0	0.05	0	0.01667278	1	0	0.0116	-0.3297	0.012959	-0.001359	-0.329985	0.000285
0	0	0	0	1	0	0.0092	0.0039	0.010682	-0.001482	0.0033812	0.000519	

Data Set#	Rotate on theta axis [angle r] Gage Bloc thickness	Rotate on the r axis angle theta Gage Bloc thickness	Sine of Angle r	Sine of Angle theta	Sin Phi	Cos Phi	Voltage Angle r Ch#1 bttm	Voltage Angle theta Ch#2 top	Best Fit Angle r	Residual Angle r	Best Fit Angle theta	Residual Angle theta
Data Set4 Orient #1	0	0	0	0	1	0	0.0098	0.0025	0.010682	-0.000882	0.0033812	-0.000881
	0	-0.05	0	-0.01667278	1	0	0.0071	0.3362	0.008405	-0.001305	0.3367478	-0.000548
	0	-0.116	0	-0.03868085	1	0	0.004	0.7764	0.0054	-0.0014	0.7767917	-0.000392
	0	-0.174	0	-0.058021274	1	0	0.0014	1.1632	0.002759	-0.001359	1.163497	-0.000297
	0	-0.232	0	-0.077361699	1	0	-0.0011	1.5497	0.000118	-0.001218	1.5502022	-0.000502
	0	-0.29	0	-0.096702124	1	0	-0.0039	1.9368	-0.002523	-0.001377	1.9369075	-0.000107
	0	-0.348	0	-0.116042549	1	0	-0.0068	2.325	-0.005163	-0.001637	2.3236127	0.001387
	0	-0.406	0	-0.135382974	1	0	-0.0095	2.7099	-0.007804	-0.001696	2.7103179	-0.000418
	0	-0.464	0	-0.154723399	1	0	-0.0123	3.0964	-0.010445	-0.001855	3.0970232	-0.000623
	0	-0.522	0	-0.174063823	1	0	-0.0152	3.483	-0.013086	-0.002114	3.4837284	-0.000728
	0	-0.58	0	-0.193404248	1	0	-0.0182	3.8694	-0.015727	-0.002473	3.8704337	-0.001034
	0	-0.638	0	-0.212744673	1	0	-0.0211	4.2562	-0.018368	-0.002732	4.2571389	-0.000939
	0	-0.696	0	-0.232085098	1	0	-0.0241	4.6418	-0.021009	-0.003091	4.6438441	-0.002044
	0	-0.754	0	-0.251425523	1	0	-0.0265	5.0288	-0.02365	-0.00285	5.0305494	-0.001749
Data Set4 Orient #2	0	0	0	0	-1	0	0.0059	-0.0015	0.007304	-0.001404	-0.000808	-0.000692
	0	-0.05	0	-0.01667278	-1	0	0.0037	0.3321	0.005027	-0.001327	0.3325586	-0.000459
	0	-0.116	0	-0.03868085	-1	0	0.0006	0.7723	0.002022	-0.001422	0.7726024	-0.000302
	0	-0.174	0	-0.058021274	-1	0	-0.0017	1.159	-0.000619	-0.001081	1.1593077	-0.000308
	0	-0.232	0	-0.077361699	-1	0	-0.0046	1.5455	-0.00326	-0.00134	1.5460129	-0.000513
	0	-0.29	0	-0.096702124	-1	0	-0.0073	1.9328	-0.005901	-0.001399	1.9327182	8.18E-05
	0	-0.348	0	-0.116042549	-1	0	-0.0103	2.321	-0.008542	-0.001758	2.3194234	0.001577
	0	-0.406	0	-0.135382974	-1	0	-0.013	2.7058	-0.011183	-0.001817	2.7061287	-0.000329
	0	-0.464	0	-0.154723399	-1	0	-0.0159	3.0923	-0.013824	-0.002076	3.0928339	-0.000534
	0	-0.522	0	-0.174063823	-1	0	-0.0188	3.4789	-0.016465	-0.002335	3.4795391	-0.000639
	0	-0.58	0	-0.193404248	-1	0	-0.0215	3.8653	-0.019106	-0.002394	3.8662444	-0.000944
	0	-0.638	0	-0.212744673	-1	0	-0.0245	4.2521	-0.021747	-0.002753	4.2529496	-0.00085
	0	-0.696	0	-0.232085098	-1	0	-0.0273	4.6379	-0.024388	-0.002912	4.6396549	-0.001755
	0	-0.754	0	-0.251425523	-1	0	-0.0303	5.0246	-0.027029	-0.003271	5.0263601	-0.00176

X Coefficient(s)	-0.0811857	-19.99466118	0.00209464	0.0016964
Std Err of Coef.	0.00083479	0.000834792	0.00012347	0.0001235

Regression Output:angle r, [2 indep.var.]

Constant	0.008992857
Std Err of Y Est	0.002905379
R Squared	0.999998124
No. of Observations	112
Degrees of Freedom	109

X Coefficient(s)	-20.009043	0.136549723
Std Err of Coef.	0.00262502	0.002625022

Regression Output:angle theta [2 indep.var.]

Constant	0.001286607
Std Err of Y Est	0.00213792
R Squared	0.999998983
No. of Observations	112
Degrees of Freedom	109

X Coefficient(s)	-0.0811857	-19.99466118
Std Err of Coef.	0.00193162	0.001931619

Regression Output: Angle r

Constant	0.008993
Std Err of Y Est	0.002206
R Squared	0.999999
No. of Observations	112
Degrees of Freedom	107

X Coefficient(s)	-20.00904	0.13655	0.0016893
Std Err of Coef.	0.001993	0.001993	0.0002948

Regression Output: Angle theta

Constant	0.001287
Std Err of Y Est	0.000924
R Squared	1
No. of Observations	112
Degrees of Freedom	107

X Coefficient(s)	-0.081186	-19.99466	0.0020946
Std Err of Coef.	0.000835	0.000835	0.0001235

Factors affecting the inclinometer test data:

1. Tilt in the test bench.

Before testing the inclinometer, the test bench (granite block table) was checked with the Microptic™ Clinometer. This was accomplished by placing the calibrated clinometer against a metal block which was clamped to the test bench.

The block had one side flush to the table edge and one side perpendicular to the same table edge. The clinometer was placed with one side flush against the edge of the metal block which was perpendicular to the table edge.

A reading was then taken and then the clinometer was rotated 180 degrees and another reading was taken. These two readings were in agreement. The clinometer was then rotated 90 degrees to read the orthogonal tilt to the first two readings. The clinometer was then rotated 180 degrees and another reading was taken. These last two readings were in agreement.

After the GBT Panel Setting Tool Inclinometer was tested, the test bench was checked again with the Microptic™ Clinometer using the same technique as described above. These last four readings were in agreement with the first four readings taken approximately twelve hours before.

The indications were that the test bench was tilted at an angle 19 seconds below the reference axis shown in Figures 2.1 and 2.2. The orthogonal tilt in the test bench was 15 seconds below an axis which would be perpendicular to the reference axis and into the page of Figures 2.1 and 2.2.

The 19 second tilt affected the “angles of concern” during testing and the 15 second tilt affected the angles orthogonal to the “angles of concern”.

The results of the 19 second tilt is seen in each data set between orientations one and two. When comparing the readings between orientations one and two for the same data set we see approximately a 4.4 millivolt difference in data sets one and two, an approximate 4.3 millivolt difference in data set three, and an approximate 4.1 millivolt difference in data set four. See the spreadsheet on data trends.

It would seem to be a logical procedure to divide the above voltages by two and subtract the results from orientations one while adding the results to orientations two. However, other factors, less well defined, affected the data thereby making this correction method rather inaccurate.

2. Flatness and squareness of the sine bar testing platform.

The sine bar testing platform was not checked for squareness of the top or bottom edges, nor was it checked for flatness of the mounting surface.

If the top edges, where the inclinometer was mounted, were not coaxial then the zero angle of tilt readings would not agree between, data set one orientation one and data set two orientation two, data set one orientation two and data set two orientation one, data set three orientation one and data set four orientation two, and data set three orientation two and data set four orientation one. An identical situation occurs if the bottom edges, where the sine bar was butted against a metal block, were not coaxial. And finally an identical situation occurs if the inclinometer mounting surface is not flat enough.

While it is shown on the second page of the data trends spreadsheet that the above orientations did not agree, it is probable that these factors were secondary in their effect on the zero angle of tilt data readings.

3. Inclinometer mounting techniques.

If the inclinometer is mounted to the sine bar in such a way as to produce a net torque on the inclinometer mounting block, then this will affect the zero angle of tilt readings as described above.

We see in the comparison of zero angle of tilt readings on the second page of the data trends spreadsheet that they did not agree.

For data sets three and four the clamps on the inclinometer mounting block were on opposite ends and opposite sides. It is probable that this **did not** produce a pronounced torque since we see that the disagreement between readings is close to the noise level.

For data sets one and two the clamps on the inclinometer mounting block were on opposite ends and on the same side. It is probable that this **did** produce a pronounced torque since we see that the disagreement between readings is well above the noise level.

It is probable that this was the reason that the regression analysis for angle r did not produce an acceptable residual voltage between the actual voltage readings and the best fit voltage computation.

<u>Data Set Trends</u>						
<u>set1</u>	<u>set1</u>			<u>set3</u>	<u>set3</u>	
<u>orient 1</u>	<u>orient2</u>		<u>abs.orient((1-2))</u>	<u>Orient#1</u>	<u>Orient#2</u>	<u>abs.(orient(1-2))</u>
-5.0231	-5.0185		0.0046	-5.0293	-5.025	0.0043
-4.6366	-4.6323		0.0043	-4.6423	-4.6381	0.0042
-4.249	-4.2444		0.0046	-4.2557	-4.2514	0.0043
-3.8616	-3.8568		0.0048	-3.8686	-3.8644	0.0042
-3.4742	-3.4697		0.0045	-3.4819	-3.4775	0.0044
-3.0866	-3.0821		0.0045	-3.095	-3.0907	0.0043
-2.6998	-2.6952		0.0046	-2.7081	-2.7038	0.0043
-2.313	-2.3099		0.0031	-2.323	-2.3189	0.0041
-1.9258	-1.9213		0.0045	-1.9352	-1.9307	0.0045
-1.538	-1.5335		0.0045	-1.5476	-1.5433	0.0043
-1.1519	-1.1474		0.0045	-1.161	-1.1566	0.0044
-0.764	-0.7594		0.0046	-0.7739	-0.7696	0.0043
-0.3234	-0.3189		0.0045	-0.3339	-0.3297	0.0042
0.0103	0.0149		0.0046	-0.0004	0.0039	0.0043
<u>set2</u>	<u>set2</u>		<u>set2</u>	<u>set4</u>	<u>set4</u>	<u>set4</u>
<u>Orient#1</u>	<u>Orient#2</u>		<u>abs.(orient(1-2))</u>	<u>Orient#1</u>	<u>Orient#2</u>	<u>abs.(orient(1-2))</u>
0.008	0.0123		0.0043	0.0025	-0.0015	0.004
0.3463	0.3417		0.0046	0.3362	0.3321	0.0041
0.7866	0.7821		0.0045	0.7764	0.7723	0.0041
1.1739	1.1694		0.0045	1.1632	1.159	0.0042
1.5606	1.5561		0.0045	1.5497	1.5455	0.0042
1.9479	1.9435		0.0044	1.9368	1.9328	0.004
2.3373	2.333		0.0043	2.325	2.321	0.004
2.7216	2.7171		0.0045	2.7099	2.7058	0.0041
3.1089	3.1044		0.0045	3.0964	3.0923	0.0041
3.4955	3.4912		0.0043	3.483	3.4789	0.0041
3.8826	3.8783		0.0043	3.8694	3.8653	0.0041
4.2695	4.2651		0.0044	4.2562	4.2521	0.0041
4.6562	4.6517		0.0045	4.6418	4.6379	0.0039
5.0433	5.0387		0.0046	5.0288	5.0246	0.0042

<u>analysis of sine bar mounting position effects</u>				
set1	set1		set2	set2
<u>orient 1</u>	<u>orient2</u>		<u>Orient#1</u>	<u>Orient#2</u>
0.0103	0.0149		0.008	0.0123
<u>(Set1, orient 1)-(set2, orient2)</u>				
-0.002				
<u>(Set1, orient 2)-(set2, orient1)</u>				
0.0069				
set3	set3		set4	set4
<u>Orient#1</u>	<u>Orient#2</u>		<u>Orient#1</u>	<u>Orient#2</u>
-0.0004	0.0039		0.0025	-0.0015
<u>(set3,orient1)-(set4, orient2)</u>				
0.0011				
<u>(set3, orient2)-(set4,orient1)</u>				
0.0014				

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