The Details....
Previous Focus Tracking Curves
Previous Focus Tracking Curves

- Default and new focus models

- Focus (mm)

- Default

- New

- Difference

- Elevation

SPIE – June 25, 2004
Structural Temperatures

Alidade Composite Temperature, 7/30–31/03

Graph showing temperature variations over time with labels for different parts of the structure.
Focus Model

- Gravity

\[ \Delta F = a_1 + a_2 \sin(\phi) + a_3 \cos(\phi). \]

- SR-Primary

\[ T_1^{(F)} = T_{SR} - \frac{T_{B1} + T_{B2} + T_{B3} + T_{B4} + T_{B5}}{5}. \]

- VFA-Primary

\[ T_2^{(F)} = \frac{T_{F1} + T_{F2} + T_{F3} + T_{F4} + T_{F5}}{5} - \frac{T_{B1} + T_{B2} + T_{B3} + T_{B4} + T_{B5}}{5}. \]

- HFA

\[ T_3^{(F)} = \frac{T_{H2} - T_{E1} + T_{H1} - T_{E2}}{2}. \]

- BUS

\[ T_4^{(F)} = \frac{T_{B1} + T_{B2}}{2} - T_{B5}. \]

\[ T_5^{(F)} = \frac{T_{B1} + T_{B2}}{2} - \frac{T_{E1} + T_{E2}}{2}. \]

\[ T_6^{(F)} = \frac{T_{B3} + T_{B4} + T_{B5}}{3} - \frac{T_{E1} + T_{E2}}{2}. \]
Elevation Model

- **Gravity**
  \[ \Delta E = -(IE) - (AW) \sin(\theta) + (AN) \cos(\theta) + (HZCZ) \sin(\phi) + (HZSZ) \cos(\phi) \]

- **BUS**
  \[ T_1^{(e)} = \frac{T_{B3} + T_{B4} + T_{B5}}{3} - \frac{T_{B1} + T_{B2}}{2} \]

- **HFA**
  \[ T_2^{(e)} = \frac{T_{H2} - T_{E1} + T_{H1} - T_{E2}}{2} \]

- **VFA**
  \[ T_3^{(e)} = \frac{T_{F2} + T_{F4}}{2} - \frac{T_{F3} + T_{F5}}{2} \]

- **Alidade**
  \[ T_4^{(e)} = \frac{T_{A4} + T_{A2}}{2} - \frac{T_{A3} + T_{A4}}{2} \]
Azimuth Model

• Gravity

\[ \Delta A = (CA) + (NPAE) \sin(\phi) + (L1) \cos(\phi) + (AW) \cos(\theta) \sin(\phi) + (AN) \sin(\theta) \sin(\phi) \]

• Alidade

\[ T_1^{(a)} = \sin(\phi) \left[ \frac{T_{A1} + T_{A2}}{2} - \frac{T_{E1} + T_{A1}}{2} + T_{E1} \right]. \]

• HFA

\[ T_2^{(a)} = \frac{T_{H2} - T_{E1} - T_{H1} + T_{E2}}{2}. \]

• BUS

\[ T_3^{(a)} = \frac{T_{B1} + T_{B4}}{2} - \frac{T_{E1} - T_{B2} + T_{B3}}{2} + T_{E2}. \]

• VFA

\[ T_4^{(a)} = \frac{T_{F2} + T_{F3}}{2} - \frac{T_{F4} + T_{E5}}{2}. \]
Optimization

- Focus optimization using pseudo-inverse for LSE solution
- Coupled Az and El gravity models (AN, AW constraint)
  - Gradient descent
Unblocked Aperture

- 100 x 110 m section of a parent parabola 208 m in diameter
- Cantilevered feed arm is at focus of the parent parabola
Telescope Structure and Optics
### Development Phases

#### Table 1.1: GBT Telescope Commissioning Phases

<table>
<thead>
<tr>
<th>Phase 1:</th>
<th>Frequencies $\leq 15$ GHz.</th>
<th>Passive surface (surface actuators fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 2:</td>
<td>Frequencies $\leq 50$ GHz.</td>
<td>Active surface in open loop</td>
</tr>
<tr>
<td>Phase 3:</td>
<td>Frequencies $\leq 100+$ GHz.</td>
<td>Active surface in closed loop with laser metrology system</td>
</tr>
</tbody>
</table>
High Frequency Environmental Envelope
# Pointing Accuracy, 5° C Gradient, 5° El

<table>
<thead>
<tr>
<th>Error Sources</th>
<th>El Errors (arcsec)</th>
<th>X-El Errors (arcsec)</th>
</tr>
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<tbody>
<tr>
<td></td>
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<tr>
<td><strong>Mechanical Alignments</strong></td>
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<td></td>
</tr>
<tr>
<td>RF/El Axes Orthogonality</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>El/Az Axes Orthogonality</td>
<td>0.0</td>
<td>5.2</td>
</tr>
<tr>
<td>Az Axis Verticality</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Structural Deformations</strong></td>
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<td>0.3</td>
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<tr>
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<td></td>
<td>11.5</td>
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<tr>
<td><strong>Servo and Drive</strong></td>
<td>0.9</td>
<td>0.3</td>
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<tr>
<td><strong>Miscellaneous</strong></td>
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<tr>
<td>El Bearing Wobble</td>
<td>1.0</td>
<td>0.4</td>
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<td>Encoder Accuracy</td>
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<td>1.2</td>
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<tr>
<td>Encoder Coupling</td>
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<td>1.8</td>
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<tr>
<td>Encoder Referencing</td>
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<tr>
<td><strong>RSS Subtotals</strong></td>
<td>11.3</td>
<td>12.1</td>
</tr>
</tbody>
</table>
Pointing
Data Quality

Gaussian Fits (Az, El, Focus)

Polarization (LCP – RCP)

Direction (Forward – Backward)

Jack Scan
Data Quality: Pointing (LCP – RCP)
Structural Temperature Sensors

- 19 locations, 0.2°C interchangeable accuracy, 0.01°C resolution, 1Hz, range –35 to 40°C. (actual accuracy is ~0.1°C, temp control of conversion elex)
- Design documentation:
  - PTCS Wiki (AntennaInstrumentation)
  - PTCS Project Note PTCS/PN12
- Accuracy tested in lab:
  - Solar/convective loading
  - Selected unit-to-unit accuracy, repeatability
  - Electronics temperature range
- RFI mitigated, ESD protected
- Two thermistor failures, forensics with YSI
- Integrated into M&C
- First cut pointing, focus predictive algorithms tested
Focus Model Tests

- Wind < 2.5 m/s
- $15^\circ < \text{elevation} < 85^\circ$
- 9/5 is NCP
- 11/20 is all-sky
- Excludes 1000-1800
- Graphs show thermal contributions only
Elevation Model Test

Dataset Test12: 9/5/03 Elevation

- El Offset (Arcsec)
- Azimuth
- Elevation
- Meas-Pred

Linear trend 0.0/hour
Residual 2.4"
Elevation Model Test

Dataset Test 15: 11/20/03 Elevation

- El. Offset (Arcsec)
- Azimuth
- Elevation
- Mea.-Pred

Linear trend: -0.8"/hour
Residual: 2.8"
Azimuth Model

\[
\Delta A(\phi, \theta, T_i^{(a)}) = M^{(e)} \times \begin{bmatrix}
T_1^{(a)} \\
\vdots \\
T_4^{(a)} \\
\frac{1}{\sin(\phi)} \\
\frac{\cos(\phi)}{\sin(\phi)} \\
\frac{\cos(\theta)}{\sin(\phi)} \sin(\phi) \\
\end{bmatrix} = M^{(o)} \times T^{(a)}.
\]

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient</th>
<th>Min-Max</th>
<th>Significance</th>
<th>Parameter</th>
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<tbody>
<tr>
<td>M₁</td>
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Azimuth Model Estimation

Dataset Train12: 9/11, 10/2, 11/10 Azimuth

$\sigma = 3.9$
Azimuth Model Test
Azimuth Model Test
Holography Results
Finite Element Model Predictions
Efficiency and Beam Shape

![Graphs showing efficiency and beam shape](image)
Fig. 7.— The rms pointing errors $\sigma_2$ needed for accurate tracking ($f = 0.14$), adequate tracking ($f = 0.20$), and blind pointing ($f = 0.43$) with the GBT are shown as functions of frequency. Abscissa: Frequency (GHz) Ordinate: RMS pointing error $\sigma_2$ (arcsec)
Fig. 6.— Tracking errors reduce the average on-source gain $\langle g \rangle$ of the GBT. The solid curves show $\langle g \rangle$ as a function of frequency for several values of the rms tracking error $\sigma_2$. For comparison, the dashed curves show the surface efficiency $\eta$ as a function of frequency for several values of the rms surface error—1.25 mm, 0.42 mm and 0.22 mm correspond to the Phase I, II, and III expected errors (Hall et al. 1993). It appears that surface errors will have a much larger effect than pointing errors on the average on-source gain of the GBT. Abscissa: Frequency (GHz) Ordinates: Relative gain (dimensionless)
## Pointing Accuracy, 6 m/s wind

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Architecture of current GBT Observing System

Figure 1: The GBT observing system
Architecture of HFOS

Figure 3: Upgraded Observing System
Architecture of PCS
Telescope Structure and Optics

- Optics: 110 m x 100 m of a 208 m parent paraboloid
  - Effective diameter: 100 m
  - Offaxis feedarm
- Elevation Limit: 5 degrees
- Slew Rates: Azimuth – 40deg/min; Elevation – 20deg/min
- Main Reflector: 2209 actuated panels with 68 µm rms.
  - Total surface: rms 400 µm
- FWHM Beamwidth: 740"/f(Ghz)
- Prime Focus: Retractable boom
- Gregorian Focus:
  - 8-m subreflector with 6-degrees of freedom
  - Rotating Turret with 8 receiver bays