Performance of the GBT at 3 mm

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Performance requirements for 3mm (70-115 GHz)

- Surface accuracy
- Pointing accuracy
- Tracking accuracy

Current status and Outlook
90 GHz images from the GBT

Note: These images were acquired with a 10% surface, i.e. prior to the recent doubling of the aperture efficiency via holography.
Surface requirements for 3 mm
Aperture efficiency

Aperture efficiency is a product of several terms:

$$\eta_{\text{aperture}} = \eta_{\text{surface}} \times \eta_{\text{illumination}} \times \eta_{\text{spillover}} \times \eta_{\text{blockage}}$$

For the GBT:
- off-axis design: $$\eta_{\text{blockage}} = 1$$
- 14dB taper implies: $$\eta_{\text{spillover}} = 0.9895; \eta_{\text{illumination}} = 0.707$$
- Ruze formula: $$\eta_{\text{surface}} = \exp(- (4\pi\sigma/\lambda)^2)$$

GBT specification on surface rms: $$\sigma \leq (\lambda / 4\pi)$$ i.e. $$\eta_{\text{surface}} = 1/e = 0.367$$

For 115.27 GHz = 2.60 mm, we need: $$\sigma \leq 210$$ microns rms
(Note: all individual panels are < 75 microns rms)

<table>
<thead>
<tr>
<th>Date</th>
<th>Technique</th>
<th>$\sigma$</th>
<th>90 GHz</th>
<th>115 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000-2008</td>
<td>photogrammetry</td>
<td>400µm</td>
<td>10%</td>
<td>1.5%</td>
</tr>
<tr>
<td>May 2009</td>
<td>12 GHz holography</td>
<td>300µm</td>
<td>22%</td>
<td>9%</td>
</tr>
<tr>
<td>Goal</td>
<td>(still in progress)</td>
<td>210µm</td>
<td>40%</td>
<td>25%</td>
</tr>
</tbody>
</table>
Some of the important spectral lines in the 3mm window

GBT Aperture Efficiency (with 12dB taper)

% Transmission (Elev=45°, PWV=10mm)

Frequency (GHz)

terrestrial oxygen (O₂)

goal=210µm

now=300µm

MUSTANG filter width

GBT
Reduction of small-scale surface errors

January 2009 (v1.3)   February 2009 (v2.35)   March 2009 (v2.64)
Reduction of total surface errors

![Graph showing median absolute deviation over time for outer and inner dishes.](image)
Current status and outlook

The good news:
Inner 56m diameter (31% of the area) is 220 microns rms, suggesting that the spec can be met.

The less good news:
The outer portion is still about 350 microns rms. Progress here is slower probably due to effect of the diffraction rings.
The good news: Inner 56m diameter (31% of the area) is 220 microns rms, suggesting that the spec can be met.

The less good news: The outer portion is still about 350 microns rms. Progress here is slower probably due to effect of the diffraction rings.
Raw holography results

May 03, 2009  (surface v2.81)

Amplitude (quadratic removed)  Phase = surface error (±1 mm)
A warning about beam patterns when you have \(~22\%\) efficiency
Example: tracing interarm gas

IRAM 30m 11” beam

proposed GBT array footprint at CO 1-0:

7 Mpc
At night, large-scale gravitational error is compensated online by elev-dependent FEM model plus a residual Zernike model measured in 2005 by out-of-focus holography.

But during sunny days, large-scale error dominates over small-scale error. Total surface rms can reach 550 μm.
Out-of-focus holography:

New “AutoOOF” tool can measure and correct the time-variable large-scale error. Useful above 40 GHz. Essential above 70 GHz.
Pointing requirements for 3 mm

1) Blind pointing
2) Offset pointing
3) Dynamic pointing
Blind pointing performance

Need to be able to find a calibrator anywhere in the sky

- GBT Pointing model has 21 terms (10 classical, 9 thermal, 2 hysteretic) plus an azimuth track table
- GBT Focus model has 9 terms (3 classical, 6 thermal)
- Blind pointing performance is currently good enough to always see a pointing calibrator after a long slew, even at 3 mm (7” beam)

Standard deviations of Blind pointing and focus:

<table>
<thead>
<tr>
<th>Axis</th>
<th>Night</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>3.7”</td>
<td>6.5”</td>
</tr>
<tr>
<td>Cross Elev.</td>
<td>3.4”</td>
<td>4.3”</td>
</tr>
<tr>
<td>Focus</td>
<td>2.0 mm</td>
<td>6.8 mm</td>
</tr>
</tbody>
</table>
Offset pointing requirements for 3 mm

1) Point on bright quasar
2) Observe source of interest

10 degrees

Requirement for 10% photometric error = 1/5 beam rms = 1.3” rms at 115 GHz
Current performance: 2.8” rms in each axis (successive peaks on same source: 2” rms)

Repeatability may be limited by structural motion during traditional linear peak scans (e.g. 40”/sec at X-band). Alternative scan techniques: circle at half-power or spiral. e.g. Daisy petal scans used by MUSTANG....
Advanced trajectories

Example used by MUSTANG to repeatedly cover a compact target: “Daisy petal”

Offset path (60 seconds):

Resulting image:
Dynamic pointing issues

Relative motion between the feedarm and the dish will cause pointing errors.

Can be driven by servo system and/or winds.

Major natural frequencies of the structure are 0.6 and 0.8 Hz. Largest motion is in the cross-elevation direction.
Quadrant detector system

View from receiver room:

LED Illuminator

Detector

Two-dimensional PSD, 4mm
Quadrant detector system

Quadrant detector accurately picks up the structural resonance.

Digital servo upgrade to main drives will provide the tools to try to avoid exciting the resonances.
Quadrant detector used by MUSTANG

Before correction

After correction
Tracking requirements for 3 mm

Azimuth rotating weight = 16 million pounds
Tracking requirements for 3 mm

\[
g(\rho) = \exp \left[ -4 \ln 2 \left( \frac{\rho}{\theta} \right)^2 \right]
\]

\[
\left( \frac{\theta}{740 \text{ arcsec}} \right) \approx \left( \frac{\text{GHZ}}{v} \right)
\]

\[
\langle \rho^2 \rangle \equiv \sigma^2 = \sigma_{Az}^2 + \sigma_{El}^2
\]

\[
f \equiv \left( \frac{\sigma^2}{\theta} \right) \quad \text{Good} \quad (\sigma_s = 5\%) \rightarrow f \approx 0.14
\]

\[
\text{Usable} \quad (\sigma_s = 10\%) \rightarrow f \approx 0.20
\]

At 115 GHz, beamsize = 6.5", so the tracking requirement for 10% error = 1.3” rms

Present performance: 1.75” + 0.24*[Wind(m/s)]^2

Much of this problem is due to an oscillation, and will be addressed during the digital servo upgrade to the main drives.
Example of Oscillation in the present PI loop: Azimuth
Summary

- **Surface:**
  - **300 microns:** already more effective collecting area than the IRAM 30m at 115 GHz (650 m² vs 500 m²)
  - Holography continuing, may reach spec. of 210 microns rms

- **Pointing:**
  - blind pointing meets spec. (< 4” rms in each axis)
  - offset pointing (4” = 2.8” in each axis) needs work to reach spec. of 1.3” rms. Use quadrant detector and explore alternative scan strategies

- **Tracking:**
  - **1.75” rms:** fails spec. even in zero wind – no margin remains!
  - Digital servo replacement project underway
Science drivers discussion
Study of (pre-)protostellar cores

At the smaller scales of dense, protostellar cores, CO is no longer a good tracer
Study of (pre-)protostellar cores

Once CO, O, N$_2$ have frozen onto grains, the reaction:

\[ \text{HD} + \text{H}_3^+ \rightarrow \text{H}_2\text{D}^+ \]

leads to abnormally high D/H ratio in the remaining gas

extreme case:
ND$_3 \sim 0.001$ NH$_3$

instead of $1e-15$

Fig. 1 Chemical differentiation of starless core as predicted by “complete freeze-out” models. The “classical” molecular tracers, such as CO and CS, are only abundant in the outer layers of pre-stellar cores.
Quadrant detector

May also improve pointing-scan fits...
Present tracking performance

Measured using half-power tracking tests

Limited by servo oscillation at low wind: 1.75” rms