High Frequency GBT Corrections

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With thanks to Dave Frayer, Natalie Butterfield, Will Armentrout, and Anika Schmiedeke
GBT Telescope Optics

- 110m x 100m of a 208m parent paraboloid
  - Effective diameter: 100 m (high sensitivity)
  - Off axis - Clear/Unblocked Aperture (low sidelobes, high dynamic range imaging)
The Active Surface -> 2209 actuators
Help achieve a more parabolic surface.

Currently rms ~230µm at night with good corrections. Means deviate from parabola by ~200µm.

Makes the GBT the largest single-dish operating efficiently at 3mm in the world.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Surface RMS/Diameter</th>
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</thead>
<tbody>
<tr>
<td>GBT</td>
<td>2.3e-6</td>
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<tr>
<td>ALMA</td>
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<tr>
<td>VLA</td>
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<tr>
<td>VLBA</td>
<td>1.4e-5</td>
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<tr>
<td>NGVLA</td>
<td>~1.0e-5</td>
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</tbody>
</table>
Improvements to Active Surface in 2009

January 2009  February 2009  March 2009  September 2009

Broken Actuators

$\Delta$Elev (deg) $\Delta$CrossElevation (deg) 11.7 GHz beam pattern dB = $-40$ $-20$ 0

Microns
The GBT Achieves its Theoretical Beam at 110 GHz

GBT memo #296 – demonstrates the success of the pointing-and-control system and the gravity and thermal modeling with active surface corrections – lots of work by many people over the last decade....

GBT/X-band 9.0 GHz  

GBT/Argus 109.4 GHz
A Surface with random large-scale errors

Receiver Response

Surface Errors

(Taper/Apodisation/…)

(Projected to an imaginary surface)
What can cause deviations from perfect parabola and theoretical beam?

Deformations caused by:

Gravity

Differential Heating

Changes with elevation

Why do these deformations matter at high frequency and not at low frequency?

Quite simply, in the mm range this is where these deviations in the dish are larger than the wavelength.
Model Surface Using Zernike Polynomials

Set of orthogonal polynomials that are used to reconstruct geometric features across a circular aperture. Derived by Frits Zernike in 1934 (Nobel Prize in 1953).

0th
- offset
  - $Z_0^0$

1st
- gradient across
  - $Z_1^{-1}$
  - $Z_1^1$

higher
- more complex geometric shapes
  - $Z_2^{-2}$
  - $Z_2^0$
  - $Z_2^2$
  - $Z_3^{-3}$
  - $Z_3^{-1}$
  - $Z_3^1$
  - $Z_3^3$
  - $Z_4^{-4}$
  - $Z_4^{-2}$
  - $Z_4^0$
  - $Z_4^2$
  - $Z_4^4$
  - $Z_5^{-5}$
  - $Z_5^{-3}$
  - $Z_5^{-1}$
  - $Z_5^1$
  - $Z_5^3$
  - $Z_5^5$
GBT Zernike-Gravity Model

Each Zernike parameter fitted as a function of elevation:

\[ Z_n = A_n \sin(\text{el}) + B_n \cos(\text{el}) + C_n \]

The updated 2014 gravity model improved telescope performance (PTCS PN#76)

<table>
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<tr>
<th>Z</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>(\sigma_A)</th>
<th>(\sigma_B)</th>
<th>(\sigma_C)</th>
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<td>382.46</td>
<td>174.01</td>
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</table>
Surface Improvements with Gravity Model + Active Surface

Source: GBT Memo #301
But wait there is STILL more!

Accounted for:
• Tracking model
• Gravity model

Fixed:
• Broken actuators
• Zero-point offset of actuators

There are still errors on surface!!

Differential Heating
Surface Improvements with OOF

Use Out Of Focus (OOF) mapping (holography) observations of bright point sources to derive Zernike parameters and correct for all other deviations in dish away from perfect parabola.

Only OOF for W, Q, ARGUS, and M2
Surface Improvements with OOF

Out Of Focus (OOF) - AutoOOF - active surface (RMS + map), pointing (Az,El), focus corrections (mm)

In Focus  - de-focus  + de-focus
AutoOOF Solutions

• OOF image - displays the measured Δ’s from the current surface to the computed optimal surface. The algorithm takes raw data, fits Zernikes to that data, and produces the Δ map (the combination of these Zernikes builds the surface corrections).

• \( Z_{\text{tot}} = Z_{\text{grav}} + Z_{\text{thermal}} \)
  
  • OOF measures the \( Z_{\text{tot}} \) at the elevation of your OOF target, refers to models for \( Z_{\text{grav}} \) and then derives \( Z_{\text{thermal}} \)

  • \( Z_{\text{thermal}} \) is the difference between measured \( Z_{\text{tot}} \) and the models (\( Z_{\text{grav}} \)).

  • Thus the solutions are often called “Zernike Thermal Solutions” or “Thermal Coefficients” for short
AutoOOF Example Solutions

**Good solution**
Broad features; low rms

**Bad solution**
Sharp features; rms > ~350µm

Surface rms = 197 µm

Surface rms = 626 µm
Quiz
Time

A. Surface rms = 638 µm
B. Surface rms = 207 µm
C. Surface rms = 226 µm
D. Surface rms = 879 µm
E. Surface rms = 438 µm
How do you find a bright calibrator source?

ALMA Calibrator Source Catalogue

https://almascience.nrao.edu/sc  https://almascience.eso.edu/sc  https://almascience.nao.ac.jp/sc
Example of Argus AutoOOF Observations:

Early Scans - setup
Example of Argus AutoOOF Observations:

(scan 3) Argus OOF map-1 data - default focus

First map at default focus and should see source at good S/N.
Example of Argus AutoOOF Observations:

(scan 4) Argus OOF map-2 data at +12mm

Counts lower since map made out of focus (+12mm)
Example of Argus AutoOOF Observations:

(scan 5) Argus OOF map-3 data at -12mm

3rd OOF map with focus at -12mm peaks higher than +12mm map so focus LFC will be negative
AutoOOF Solutions

Be weary of “rms” >400 microns (which happens in windy conditions)
AutoOOF Solutions

Zernike, LPCs (arcmin), LFC (mm)

Typically pick between z4, z5, z6 based on residual rms and beam fits (z5 default). LFC a few mm.
AutoOOF Solutions

Send solutions

Click yellow button after OOF processing to send corrections to GBT and turn on the thermal zernike’s.

Send Selected Solution with Point and Focus Corrections (new, recommended method)

Reanalyze OOF (Online Only)

Send Selected Solution with no Point or Focus Correction (original method)

Zero and Turn Off Thermal Zernike Solution
AutoOOF Beam Fits

VEGAS balance values on sky: ~-20(+/3)

Cleo Status Window

Az,El LPCs

Focus YFC

Active Surface ON with Thermal corrections from OOF

VEGAS balance values on sky: ~-20(+/3)
AutoOOF ‘Raw Data’

Observation Management - 1  DataDisplay - 1  GbtStatus - 1

Observation State: NotConnected
GBT State: NotConnected
Queue Control: Halt Queue
Observation Control: Pause  Stop  Abort  Interactive

Pointing  Focus  Continuum  OOF

Zernike Solutions  LPCs (a22, e1)  LFCy
- z2
- z3 (+0.06, +0.35) -3.75 mm
- z4 (+0.06, +0.35) -2.55 mm
- z5 (+0.06, +0.35) -2.60 mm
- z6

raw data

fitted beam map

Show Fixed-Scale Image  Show Solutions with Focus Removed
AutoOOF Processing Status: Complete

Project Name: AGBT17B_044_02
Scan Number: 3

Send Selected Solution with Point and Focus Corrections (new, recommended method)
Reanalyze OOF (Online Only)
Send Selected Solution with no Point or Focus Correction (original method)
Zero and Turn Off Thermal Zernike Solution

Q0A2Z: 0.000  Q0E1: 0.350
dA2z: 0.153  dE1: 0.026
NewA2z: 0.153  NewE1: 0.376

00FMAP 1.0
00FMAP 2.0
Started search for data products for AGBT17B_044_02 scan 3
Searching for files in /home/gbtdata/AGBT17B_044_02/OOF/s3-1-db-800.
AutoOOF Beam Fits

Zernike Solutions
- LPCs (az2, el)
- LFCy
  - z2
  - z3 (+0.06, +0.35) -3.75 mm
  - z4 (+0.06, +0.35) -2.55 mm
  - z5 (+0.06, +0.35) -2.60 mm
  - z6
  - raw data

Fitted beam map

Options:
- Show Fixed-Scale Image
- Show Solutions with Focus Removed
- AutoOOF Processing Status: Complete

Project Name:
AGBT175_044_02

Scan Number:
3

Send Selected Solution with Point and Focus Corrections (new, recommended method)
Reanalyze OOF (Online Only)
Send Selected Solution with no Point or Focus Correction (original method)
Zero and Turn Off Thermal Zernike Solution

Observation State:
NotConnected

GBT State:
NotConnected

GBT Status:
NotConnected

Queue Control:
Halt Queue

Observation Control:
Pause
Stop
Abort
Interactive
AutoOOF ‘Raw’ Data Streams

(a) A plot of the raw OOF data on a fairly clean Ka-band/CCB dataset.  
(b) A plot of raw OOF data on a source which is too faint.
Example of a Bad AutoOOF Solution

In this case observations were done in the keyhole at >85° and OOF “rms” 438 μm with a large implied focus and EL pointing offset.

Solution with large rms >400 μm should not be used.

Check the raw data and fitted beam maps.
Beam Maps of Example Bad OOF

The “observed” beams should not be streaks or very elongated. This can happen in windy conditions.
Beam Maps of Example Bad OOF

The “observed” beams should not be streaks or very elongated. This can happen in windy conditions.

In this case data were taken in the keyhole causing the apparent focus correction to be very large and a large EL LPC.

Do not apply OOF corrections if you cannot trust the results. Redo.
Another Bad OOF (avoid Z3 Solution)

Take the solution that has better fitted beam maps and reasonable values. In this case z5.

Figure 5.10: The AutoOOF fitted beam maps (left). The observed beams are plotted on the top row with the z3, z4 and z5 fits to the observed beams plotted below. The z3 solution (2\textsuperscript{nd} row down) shows an obvious artifact and should not be used. Also note the significant jump in LPCs and the LFC between the z3 and z4 solutions (above).
Bad OOF with ARGUS? What do you do?

• ARGUS Example
  • Redo
  • Don’t apply corrections
  • Recommended to OOF with Ka-band if on telescope

Notes on Telescope Corrections When Using ARGUS

• OOF surface corrections should be done with Ka+CCB system if available for highest S/N, but can also be done with Argus if Ka+CCB is not available
• Pointing and focus corrections can be done with Argus or at lower frequency (e.g., X-band)
• Users can struggle and waste a lot of time trying to point/focus with Argus (e.g., faint sources/marginal conditions). You should point+focus in X-band if problems arise or if in doubt.
Bad OOF with MUSTANG-2? What do you do?

Zero solutions AND LFCy (ask operator) and Re-OOF (submit OOF script again)
Observing Strategies: Antenna Optimization

Pointing & Focus
- ~ 5 – 10 min
- ideally after 21:00 or 22:00
- solutions good for 2 – 6 h

AutoOOF
- ~ 20 – 25 min
- ideally after 21:00 or 22:00
- surface changes on time scales < 1h

AutoOOF
- every 30 – 50 min
- *M2 every 30
Ways to continue to improve surface
The Green Bank Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.