

The Green Bank Telescope

OOF Processing



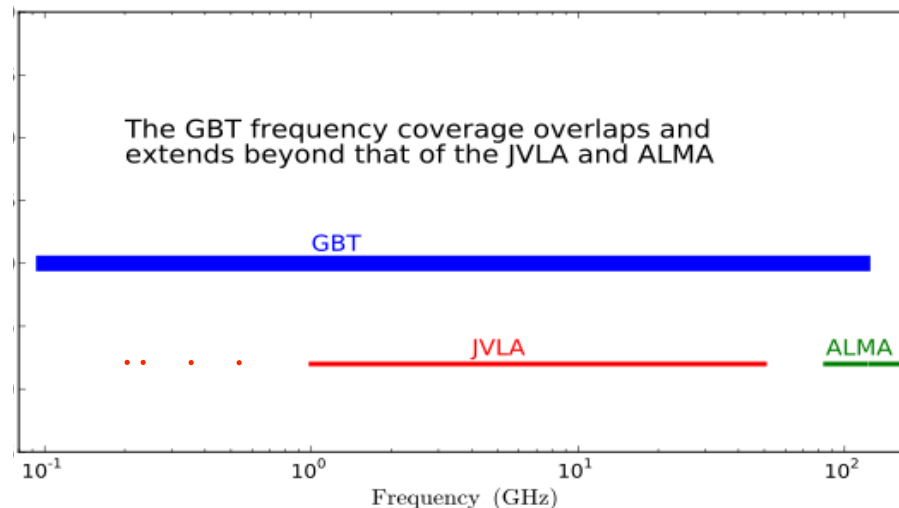
David Frayer (GBO)

- Argus Instrument Scientist
- 4mm Instrument Scientist
- GBT PTCS and Observer Support
- Research in the evolution gas in star-forming galaxies.



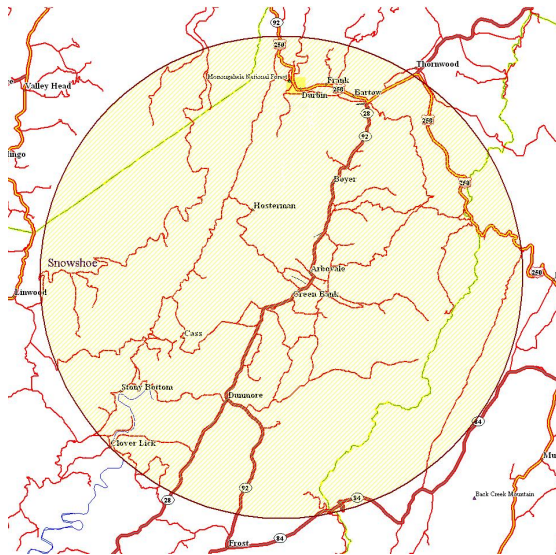
Key Capabilities of the GBT

- 100 meter diameter unblocked
- Receivers cover 0.1 to 116 GHz
- Excellent point-source sensitivity
- Unsurpassed sensitivity for extended objects
- >85% of total sky covered ($\delta \geq -46^\circ$)
- Location in the National Radio Quiet Zone



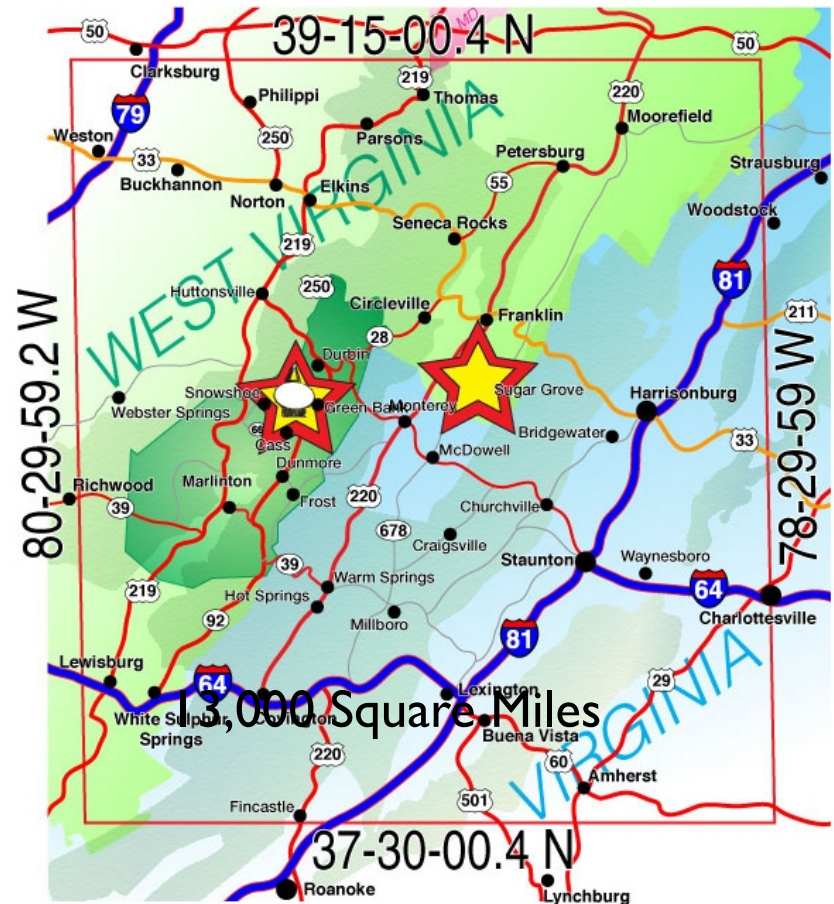
Site protected from Radio Interference

WV Radio Astronomy Zone
Established by the West Virginia
Legislature (1956)



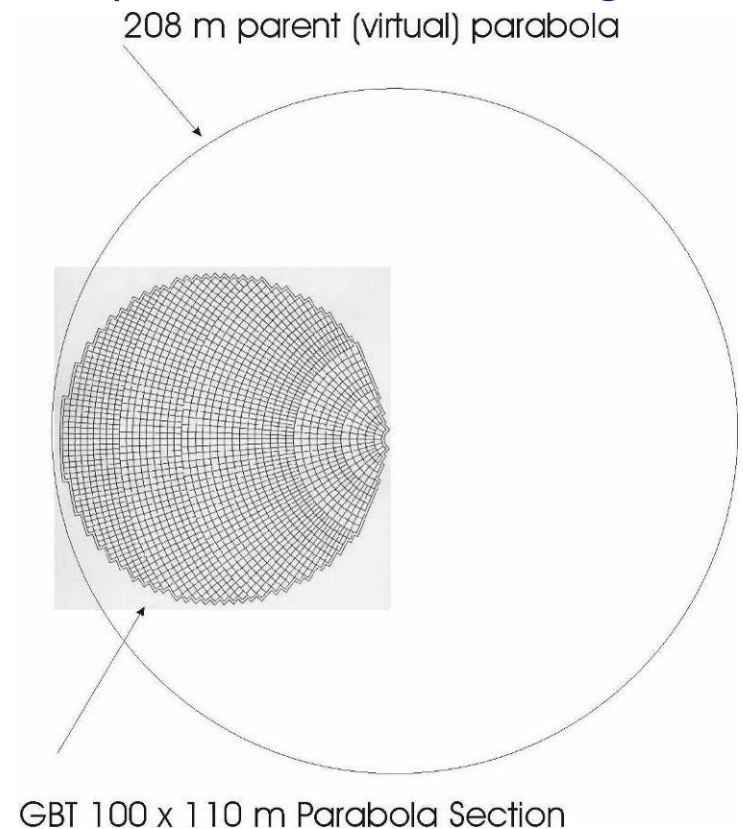
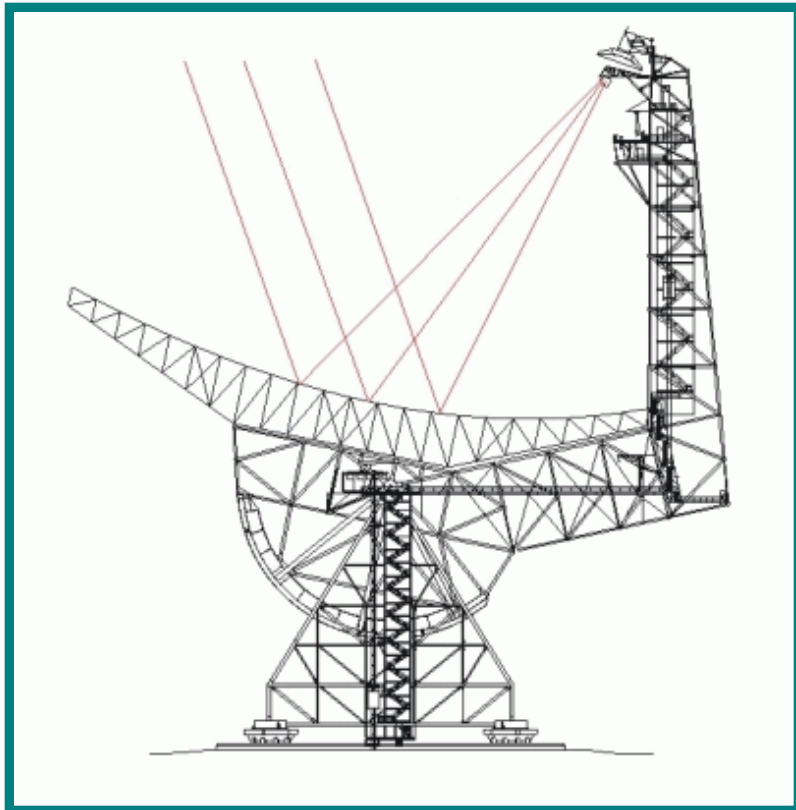
Protection within ten miles
of the Observatory

National Radio Quiet Zone
Established by the FCC and NTIA
(1957)



GBT Telescope Optics

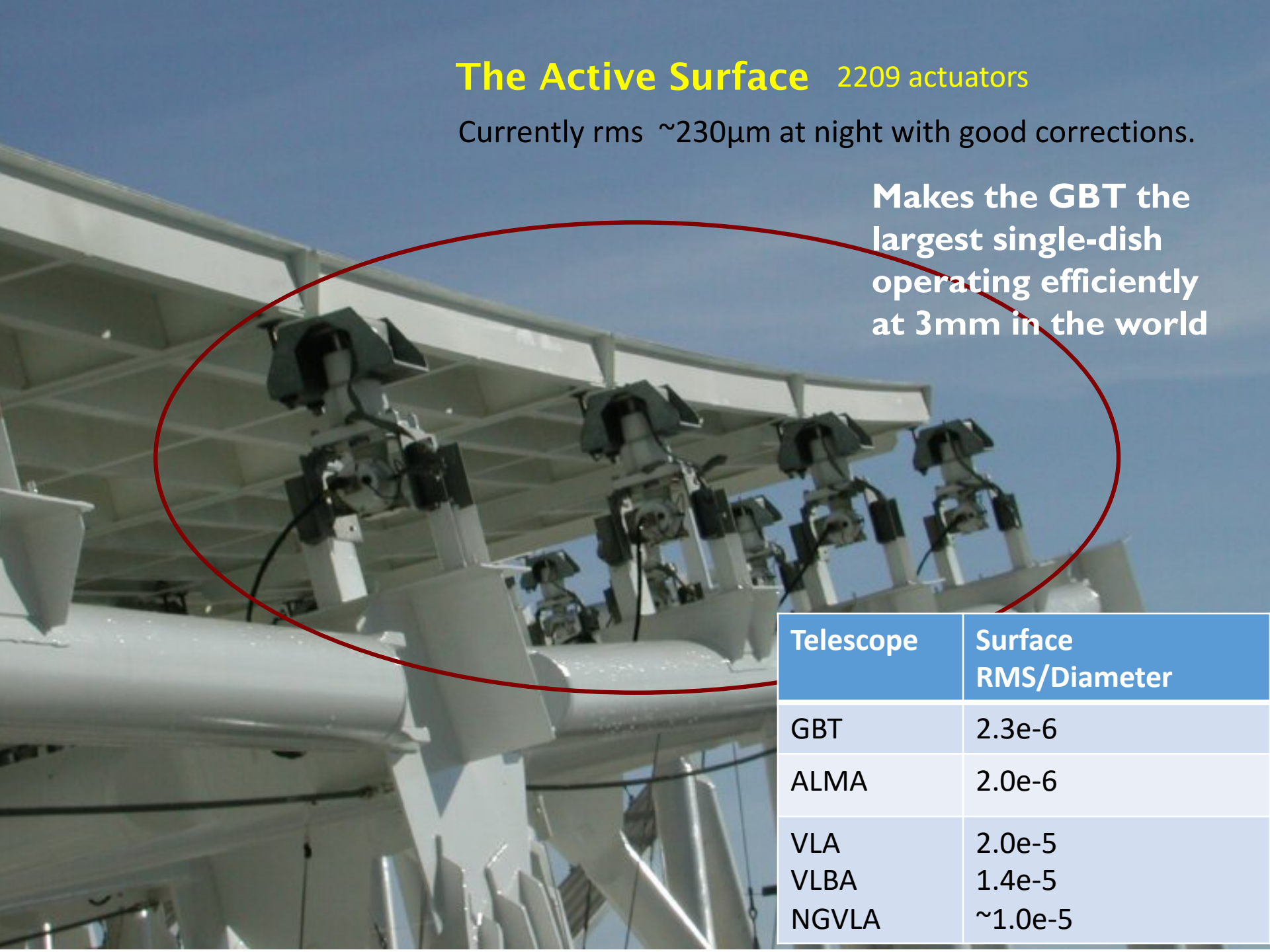
- 110 m x 100 m of a 208 m parent paraboloid
 - Effective diameter: 100 m
 - Off axis - Clear/Unblocked Aperture (low sidelobes, high dynamic range imaging)



The Active Surface 2209 actuators

Currently rms $\sim 230\mu\text{m}$ at night with good corrections.

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



Telescope	Surface RMS/Diameter
GBT	2.3e-6
ALMA	2.0e-6
VLA	2.0e-5
VLBA	1.4e-5
NGVLA	$\sim 1.0\text{e-}5$

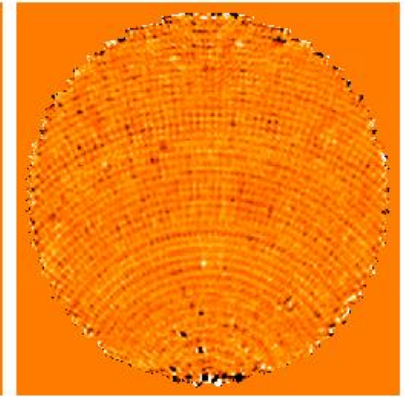
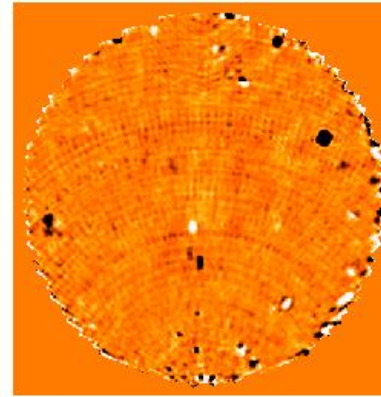
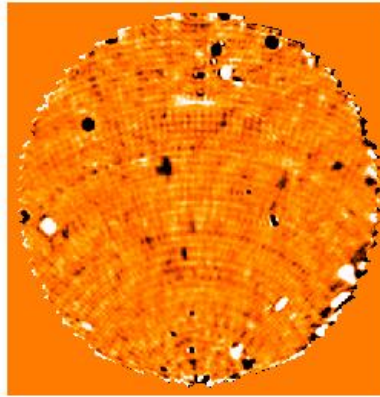
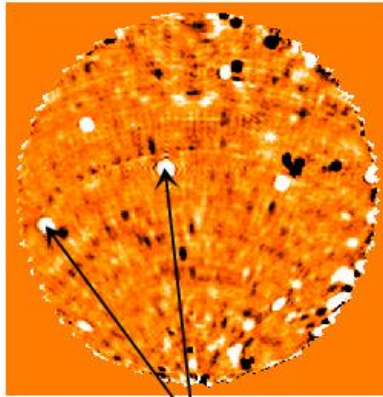
Improvements to Surface in 2009

January 2009

February 2009

March 2009

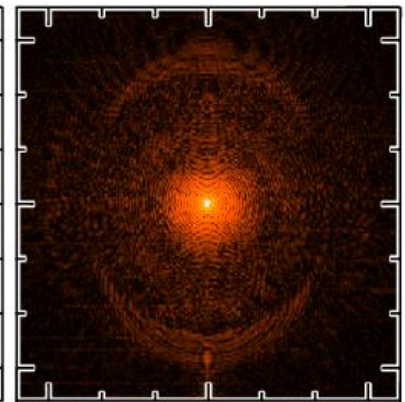
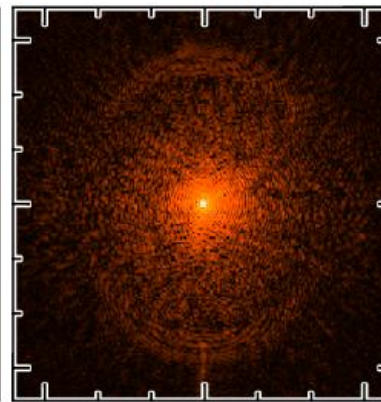
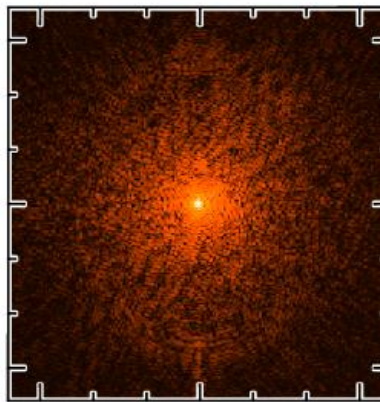
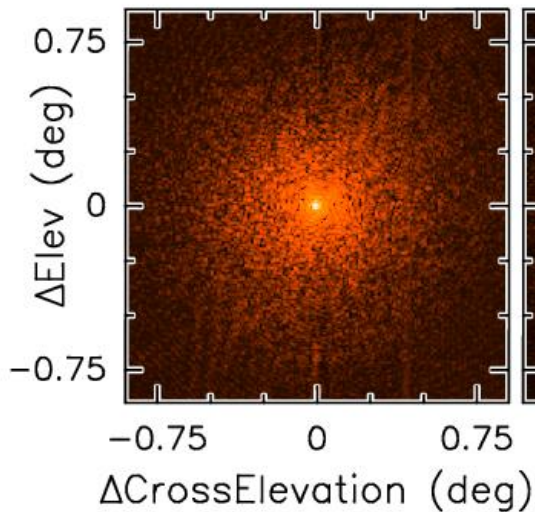
September 2009



Broken Actuators



-500 0 500 Microns

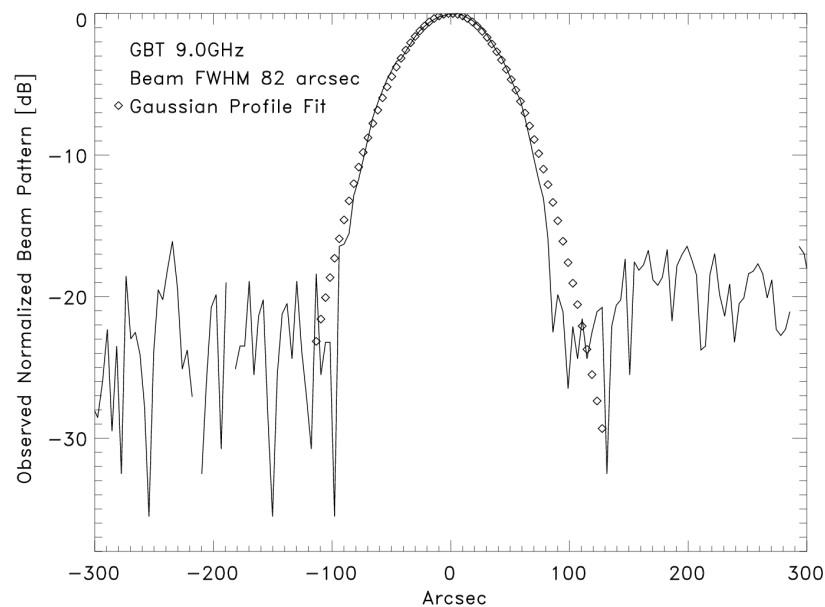


11.7 GHz beam pattern

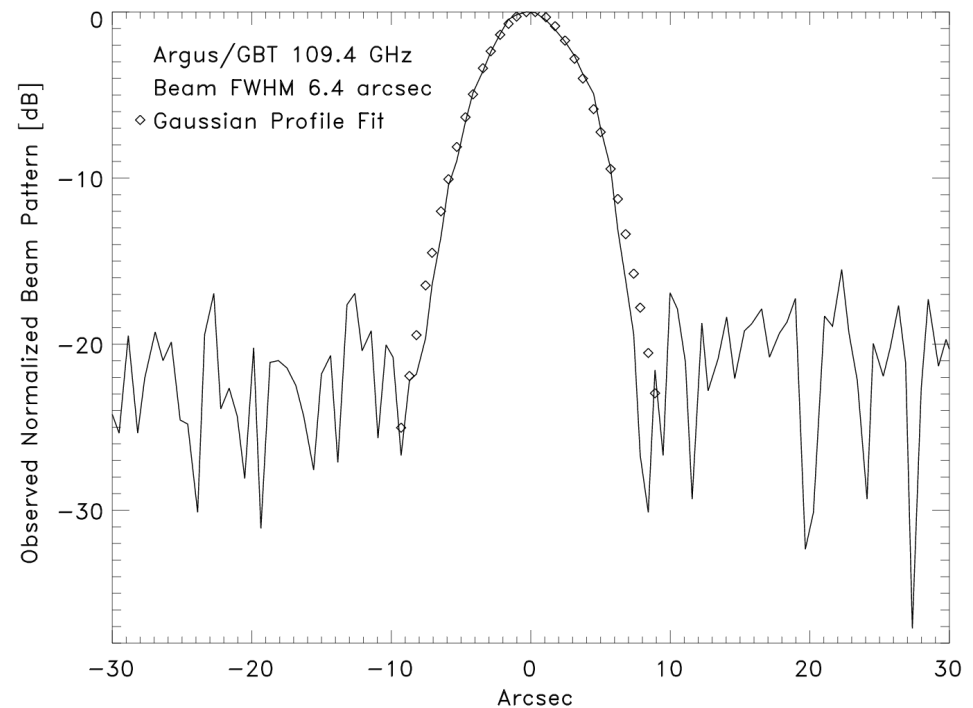
dB = -40 -20 0

The GBT Achieves its Theoretical Beam at 110 GHz

GBT memo #296 – demonstrates the success of the pointing-and-control system, 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

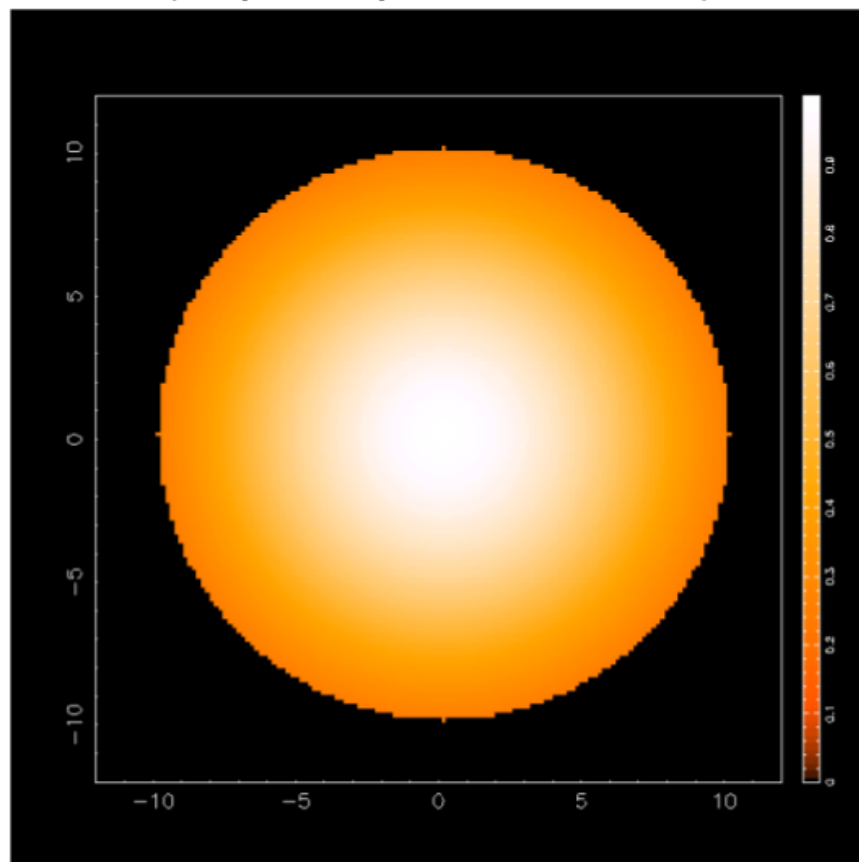


GBT/Argus 109.4 GHz

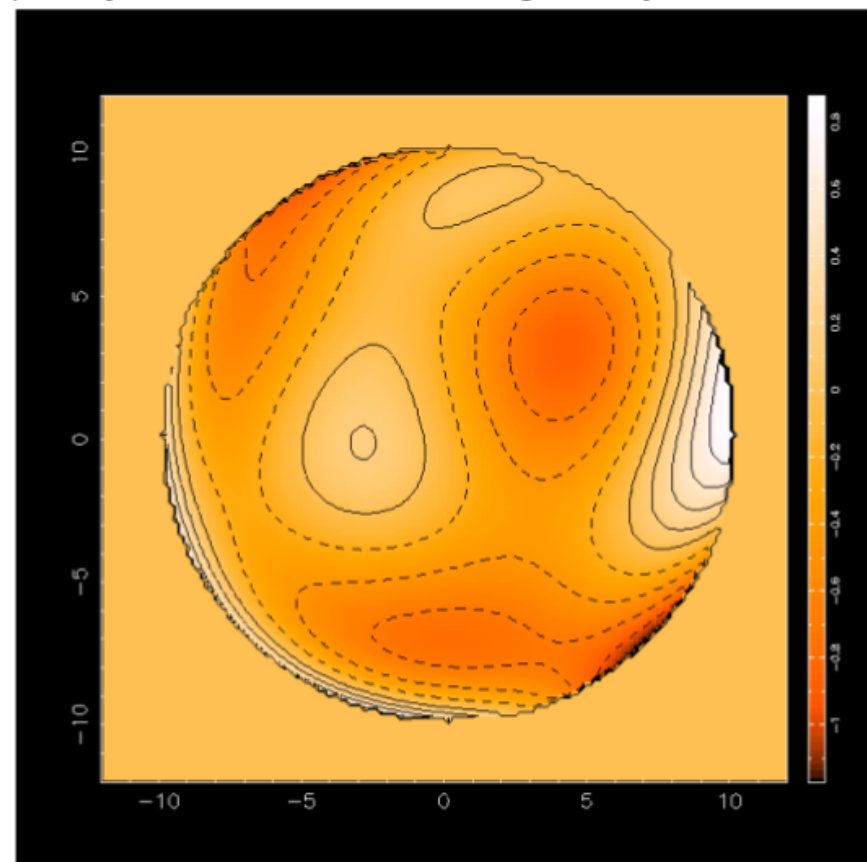
Unblock GBT aperture → first side-lobe predicted at -27dB

A surface with random large-scale errors

Receiver Response
(Taper/Apodisation/...)



Surface Errors
(Projected to an imaginary surface)



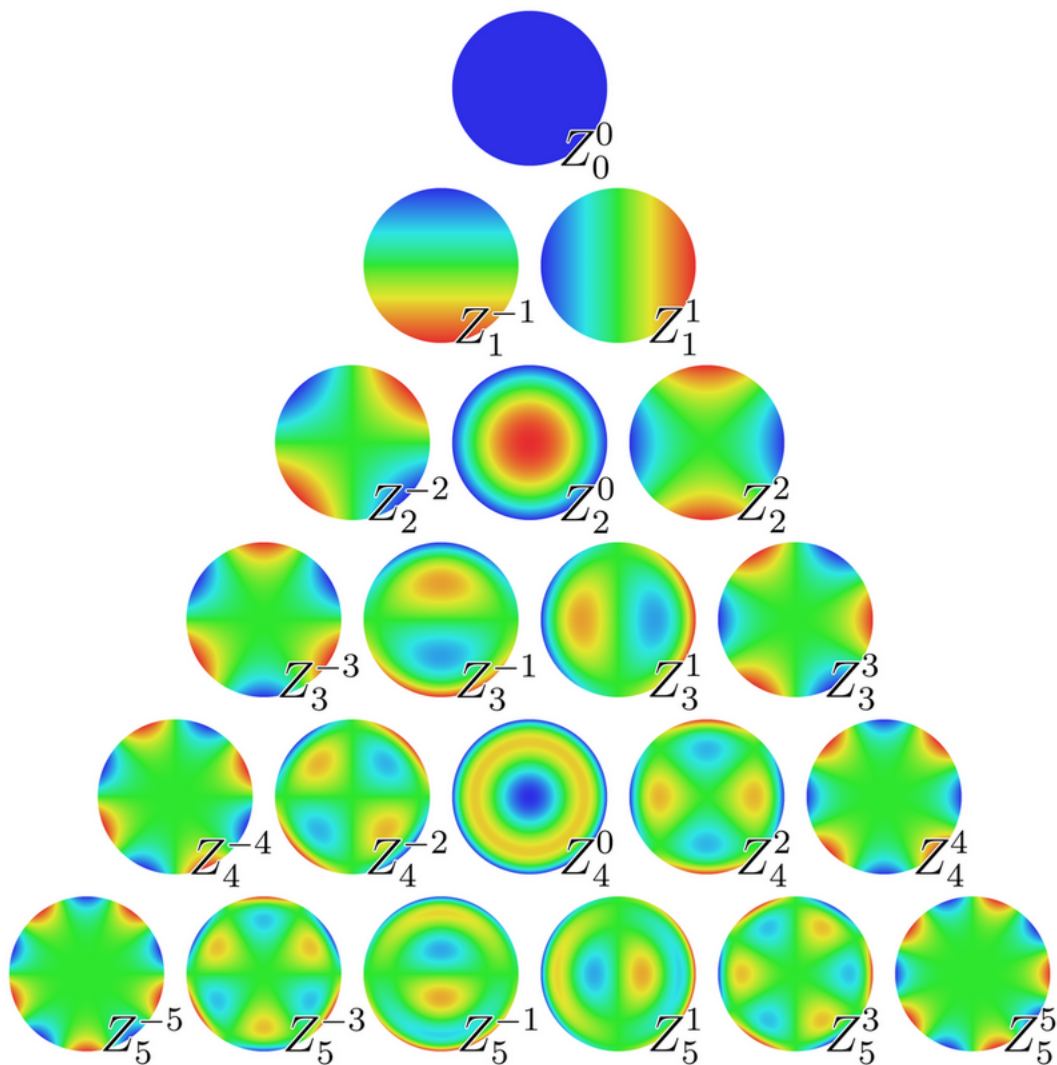
Model Surface Using Zernike Polynomials

Zernike polynomials [\[edit \]](#)

The first few Zernike modes, with [OSA/ANSI](#) and [Noll](#) single-indices, are shown below

$$\int_0^{2\pi} \int_0^1 Z_j^2 \rho d\rho d\theta = \pi.$$

	OSA/ANSI index (j)	Noll index (j)	Radial degree (n)	Azimuthal degree (m)	Z_j
Z_0^0	0	1	0	0	1
Z_1^{-1}	1	3	1	-1	$2\rho \sin \theta$
Z_1^1	2	2	1	+1	$2\rho \cos \theta$
Z_2^{-2}	3	5	2	-2	$\sqrt{6}\rho^2 \sin 2\theta$
Z_2^0	4	4	2	0	$\sqrt{3}(2\rho^2 - 1)$
Z_2^2	5	6	2	+2	$\sqrt{6}\rho^2 \cos 2\theta$
Z_3^{-3}	6	9	3	-3	$\sqrt{8}\rho^3 \sin 3\theta$
Z_3^{-1}	7	7	3	-1	$\sqrt{8}(3\rho^3 - 2\rho) \sin \theta$
Z_3^1	8	8	3	+1	$\sqrt{8}(3\rho^3 - 2\rho) \cos \theta$
Z_3^3	9	10	3	+3	$\sqrt{8}\rho^3 \cos 3\theta$
Z_4^{-4}	10	15	4	-4	$\sqrt{10}\rho^4 \sin 4\theta$
Z_4^{-2}	11	13	4	-2	$\sqrt{10}(4\rho^4 - 3\rho^2) \sin 2\theta$
Z_4^0	12	11	4	0	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$
Z_4^2	13	12	4	+2	$\sqrt{10}(4\rho^4 - 3\rho^2) \cos 2\theta$
Z_4^4	14	14	4	+4	$\sqrt{10}\rho^4 \cos 4\theta$



GBT Zernike-Gravity Model

Each Zernike parameter fitted as a function of elevation:

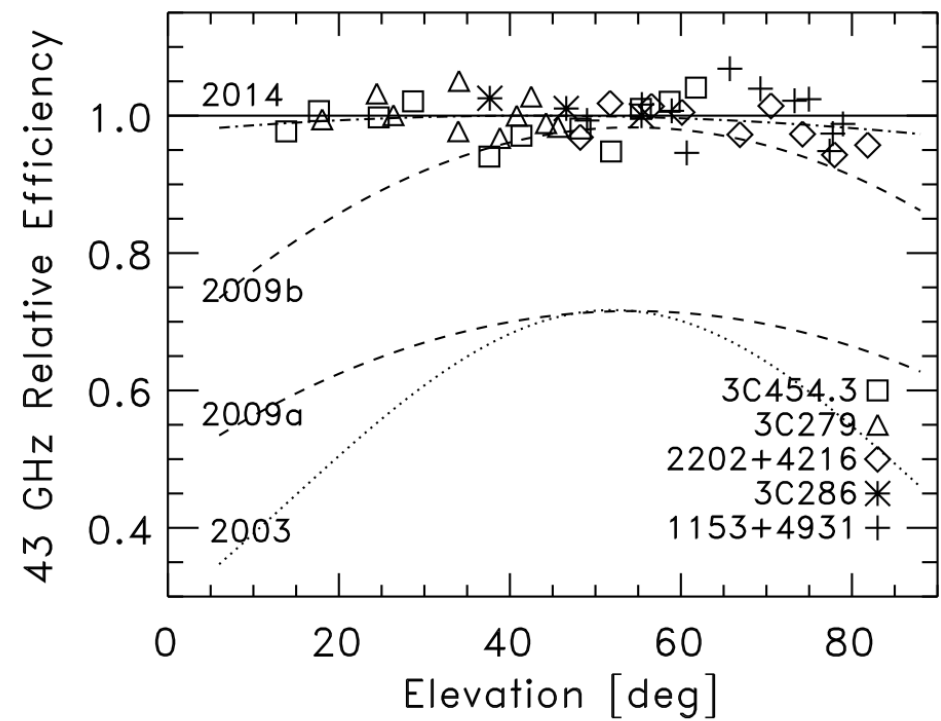
$$Z_n = A_n \sin(el) + B_n \sin(el) + C_n$$

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

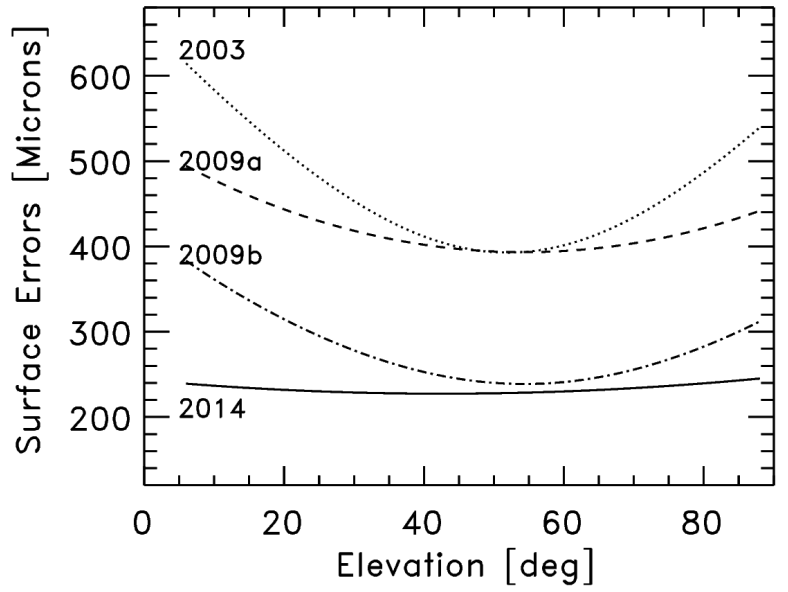
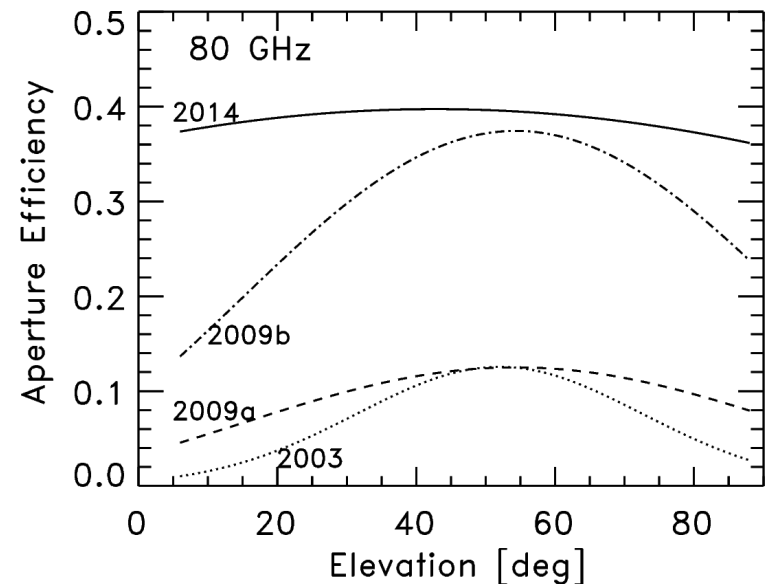
TABLE 1:

Z	A	B	C	σ_A	σ_B	σ_C	rms
4	-697.71	697.91	550.68	905.87	775.82	1137.56	517.55
5	-148.22	-482.95	136.07	540.74	463.11	679.05	308.94
6	319.46	154.68	-535.72	319.70	273.80	401.46	182.65
7	-554.68	-327.02	632.92	378.25	323.95	475.00	216.11
8	-65.60	53.89	108.34	268.56	230.01	337.25	153.44
9	588.39	1305.77	-1063.37	341.03	292.07	428.25	194.84
10	932.92	542.64	-1119.48	481.14	412.07	604.20	274.89
11	136.83	923.46	-288.13	329.68	282.35	414.01	188.36
12	-532.04	-177.33	440.51	238.51	204.27	299.52	136.27
13	360.71	62.38	-94.13	160.01	137.04	200.94	91.42
14	-38.56	15.16	-160.13	188.20	161.18	236.34	107.52
15	-622.70	-414.96	744.87	288.93	247.45	362.83	165.07
16	121.80	-38.60	16.58	293.75	251.58	368.89	167.83
17	-210.31	-198.02	203.98	161.70	138.48	203.05	92.38
18	71.68	3.62	-266.29	142.96	122.44	179.53	81.68
19	579.23	-51.98	-392.41	178.29	152.70	223.89	101.86
20	243.95	-121.70	-6.45	194.88	166.91	244.73	111.34
21	593.36	1065.48	-1287.78	304.57	260.84	382.46	174.01

Surface Improvements with Zernike-Gravity Model

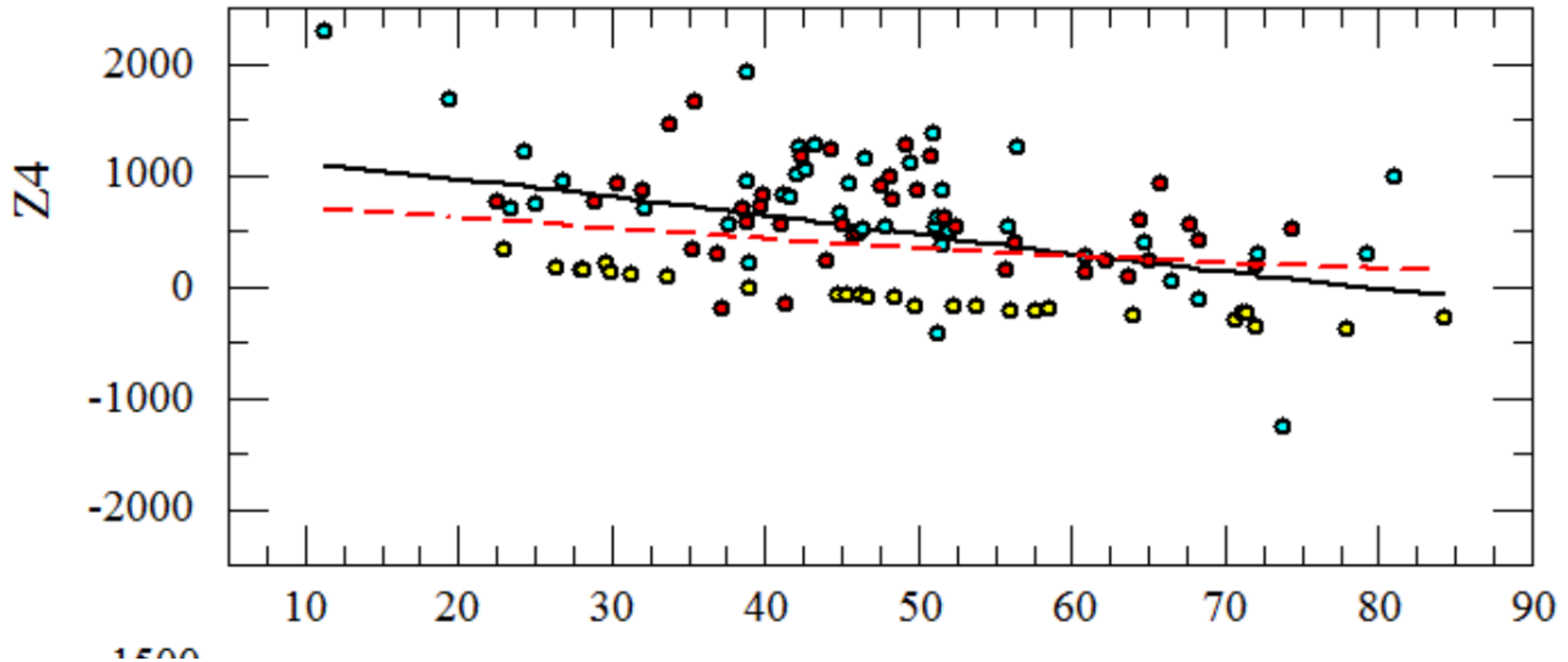


Improvements to the Zernike-Gravity model in 2014 yields a flat gain curve with elevation and has significantly improved the GBT performance at high-frequency (GBT Memo#301)



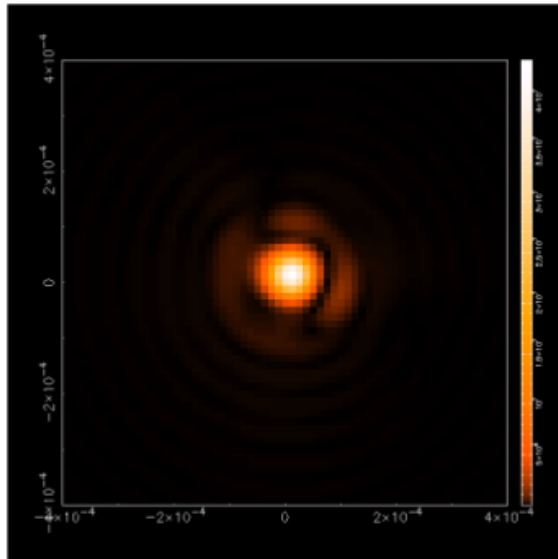
Some Zernike parameters depend strongly on the current "Thermal" conditions of the antenna (large scatter) and require real-time corrections to the gravity model.

$$Z_n(\text{total}) = Z_n(\text{gravity}) + Z_n(\text{thermal})$$

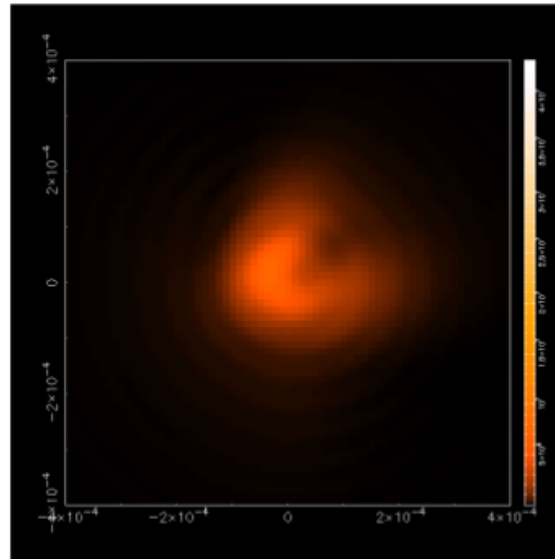


Use Out Of Focus (OOF) mapping observations of bright point sources to derive Zernike parameters

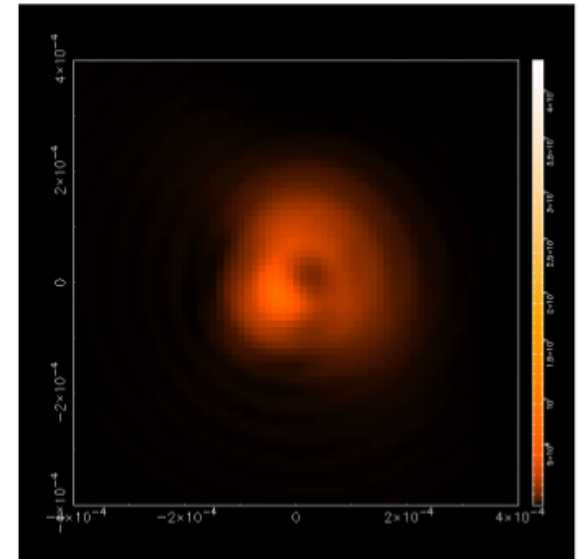
In-Focus



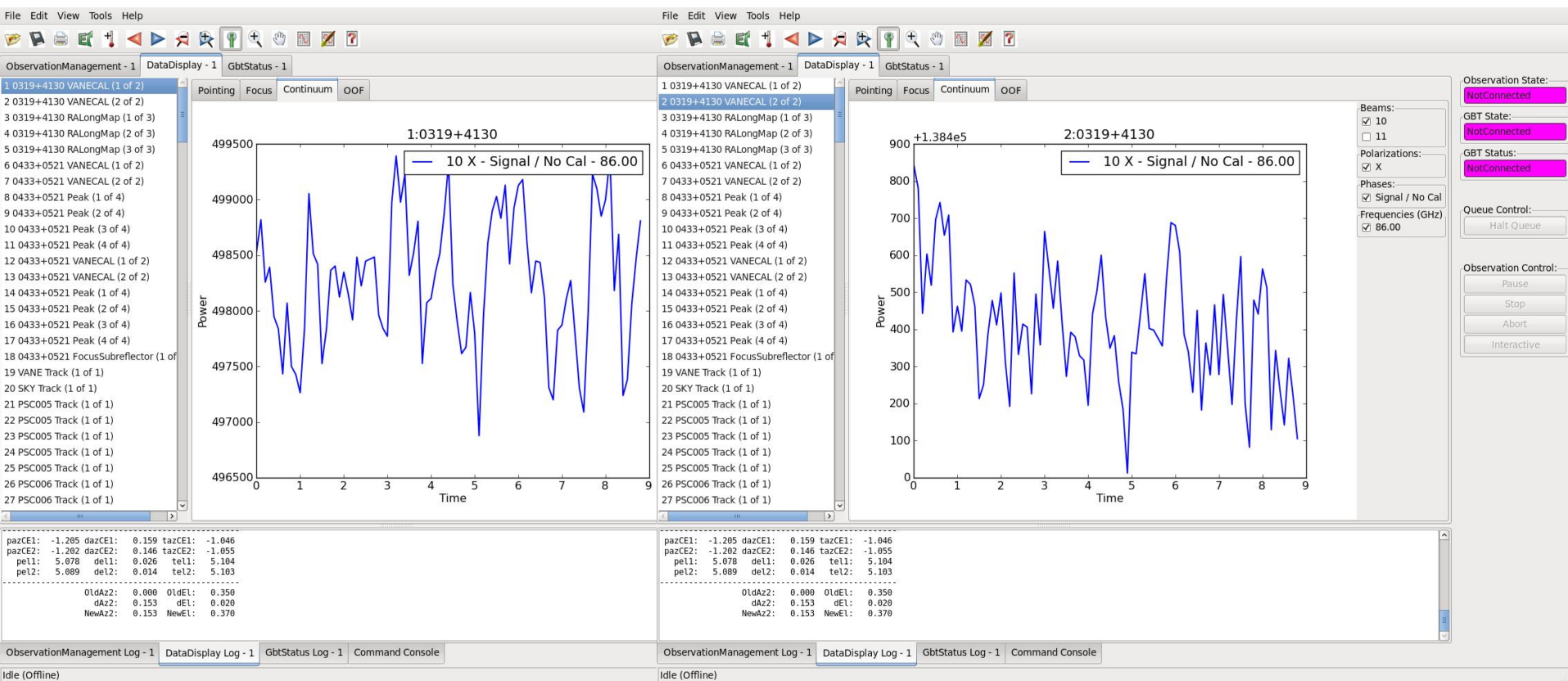
-ve De-Focus



+ve De-Focus

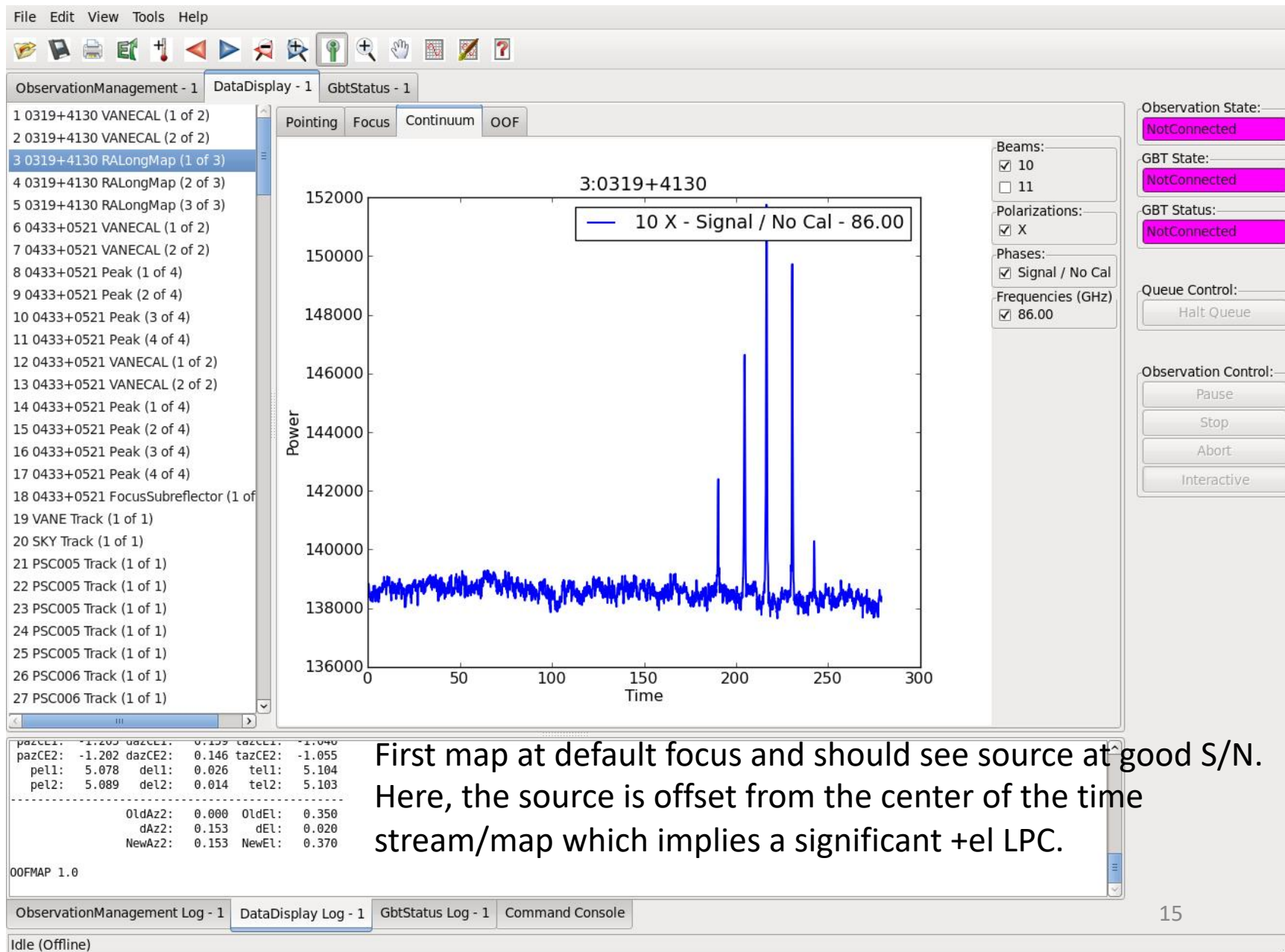


Example Argus AutoOOF Observations: (scans 1+2) Vanecal-scans with the DCR

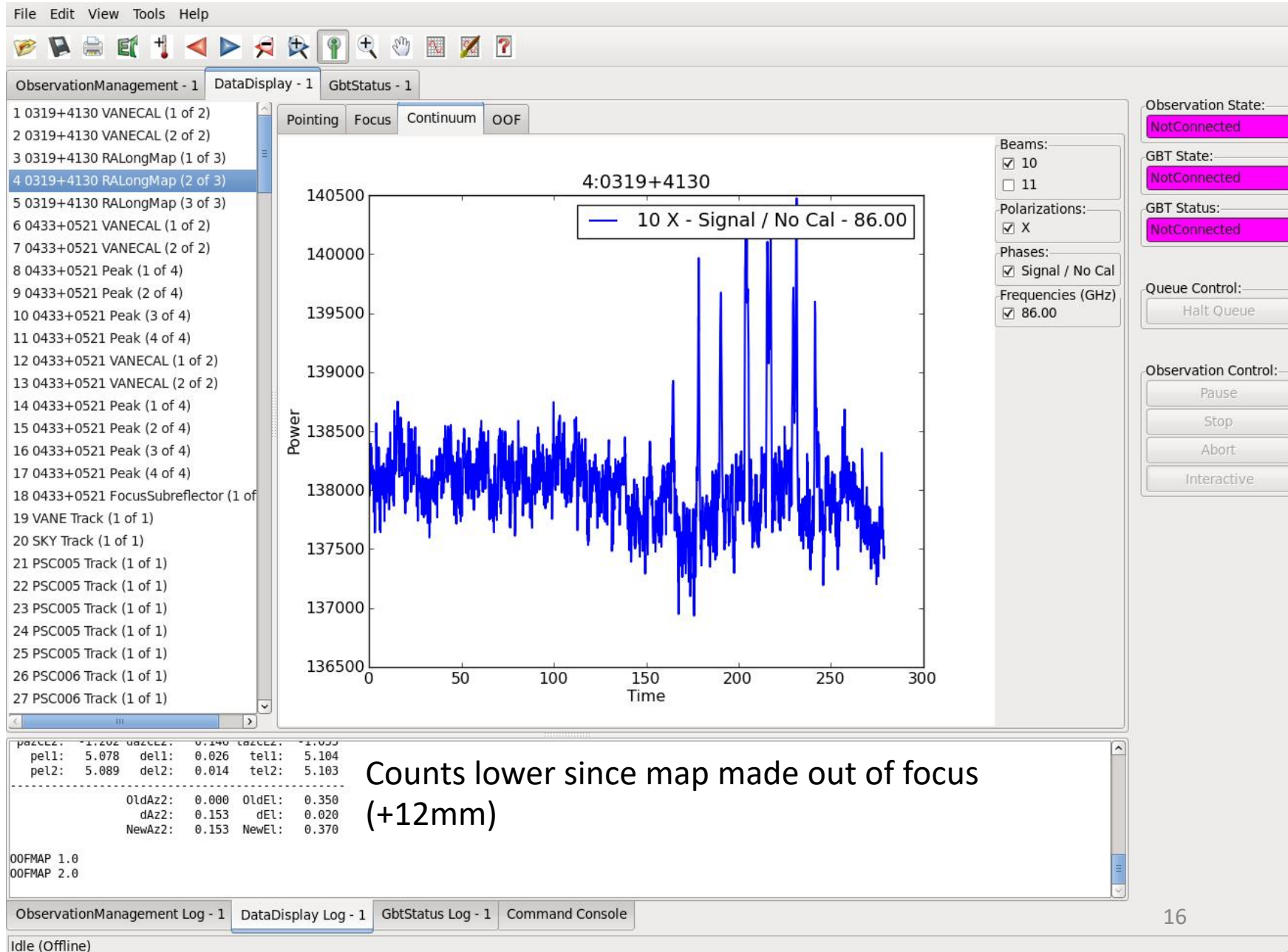


Vanecal scans with the DCR – first scan is with VANE (4.985e5 counts) and second scan is on SKY (1.354e5+500 counts). $T_{\text{sys}} \sim T_{\text{warm}}(\text{SKY}/(\text{VANE}-\text{SKY})) = 104 \text{ K}$ for $T_{\text{warm}} \sim 270$. **Should have VANE/SKY > ~3 in good conditions.**

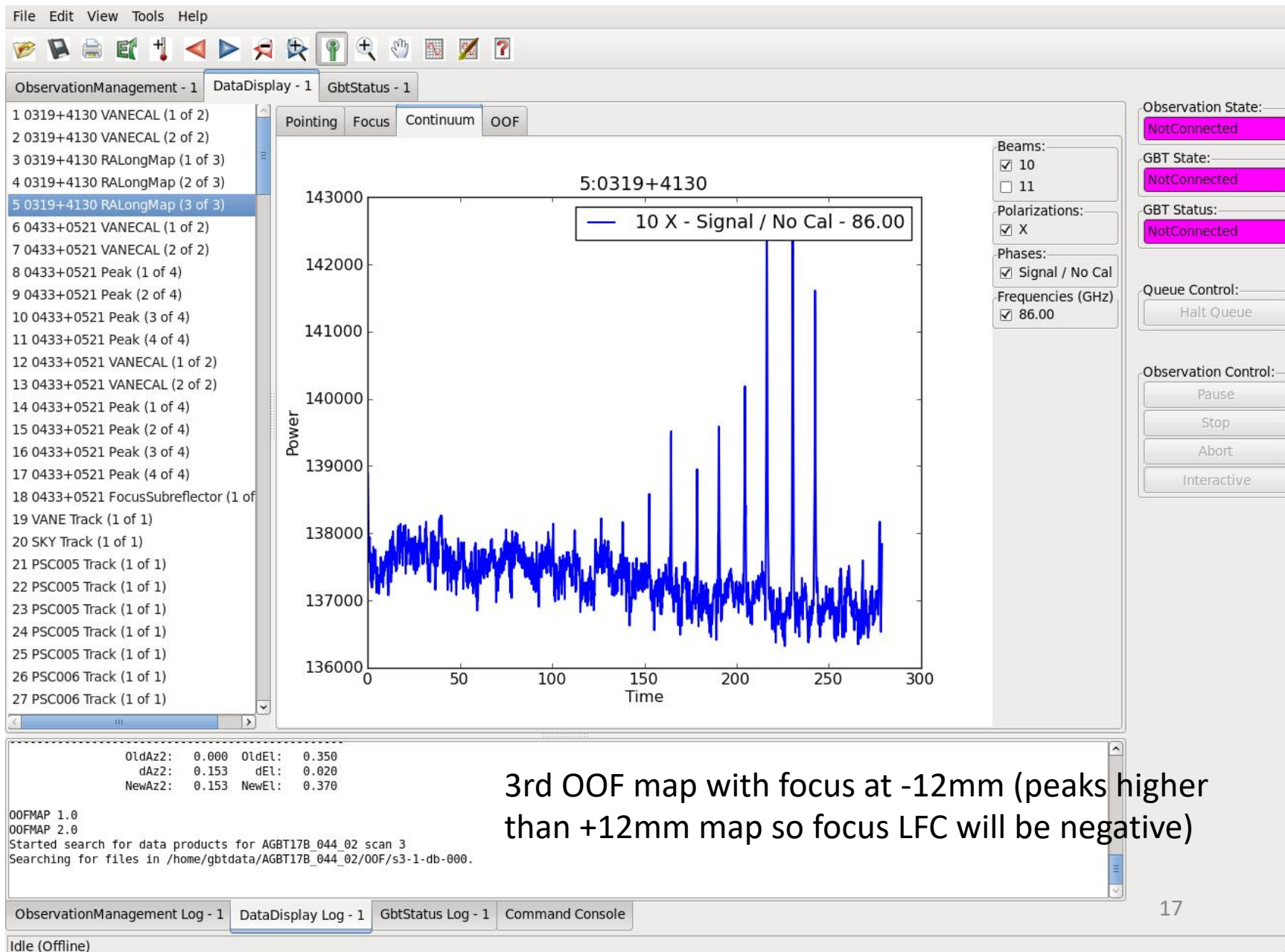
(scan 3) Argus OOF map-1 data



(scan 4) Argus OOF map-2 data



(scan 5) Argus OOF map-2 data

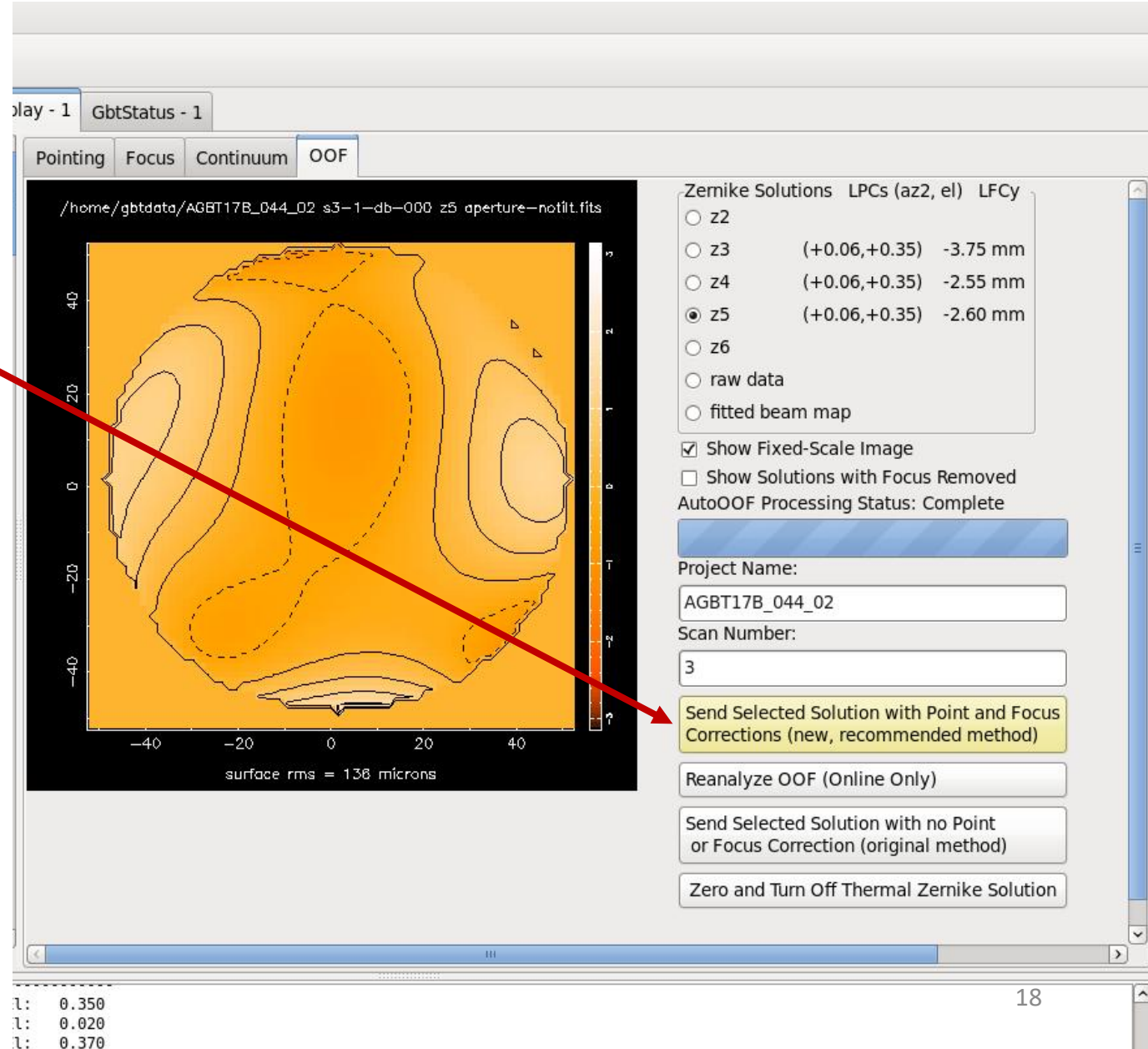


AutoOOF Solutions

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

Typically pick between z4,z5,z6 based on residual rms and beam fits (z5 default).

Be weary of "rms" >350 microns (which happens in windy conditions)



The screenshot shows the AutoOOF software interface. The main window displays a contour plot of a surface, with the title bar indicating the file path: `/home/gbtdata/AGBT17B_044_02 s3-1-db-000 z5 aperture-notilt.fits`. The plot shows a complex, irregular shape with a color scale on the right ranging from -2 to 3. Below the plot, the text "surface rms = 138 microns" is displayed. The interface includes several tabs: "Pointing", "Focus", "Continuum", and "OOF". The "OOF" tab is currently selected. On the right side, there is a panel titled "Zernike Solutions LPCs (az2, el) LFCy" with a list of options:

- ☐ 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

Below this list, there are checkboxes for "Show Fixed-Scale Image" (checked) and "Show Solutions with Focus Removed" (unchecked). The "AutoOOF Processing Status" is shown as "Complete". A blue progress bar is visible. Below the progress bar, there are input fields for "Project Name:" (AGBT17B_044_02) and "Scan Number:" (3). At the bottom of the panel, there are several buttons: "Send Selected Solution with Point and Focus Corrections (new, recommended method)" (highlighted in yellow), "Reanalyze OOF (Online Only)", "Send Selected Solution with no Point or Focus Correction (original method)", and "Zero and Turn Off Thermal Zernike Solution". A red arrow points from the text "Click yellow button after OOF processing to send corrections to GBT and turn on the thermal zernike's." to the yellow button.

1: 0.350
1: 0.020
1: 0.370

AutoOOF "Raw data"

File Edit View Tools Help

ObservationManagement - 1 DataDisplay - 1 GbtStatus - 1

1 0319+4130 VANECA1 (1 of 2)
2 0319+4130 VANECA1 (2 of 2)
3 0319+4130 RALongMap (1 of 3)
4 0319+4130 RALongMap (2 of 3)
5 0319+4130 RALongMap (3 of 3)
6 0433+0521 VANECA1 (1 of 2)
7 0433+0521 VANECA1 (2 of 2)
8 0433+0521 Peak (1 of 4)
9 0433+0521 Peak (2 of 4)
10 0433+0521 Peak (3 of 4)
11 0433+0521 Peak (4 of 4)
12 0433+0521 VANECA1 (1 of 2)
13 0433+0521 VANECA1 (2 of 2)
14 0433+0521 Peak (1 of 4)
15 0433+0521 Peak (2 of 4)
16 0433+0521 Peak (3 of 4)
17 0433+0521 Peak (4 of 4)
18 0433+0521 FocusSubreflector (1 of 1)
19 VANE Track (1 of 1)
20 SKY Track (1 of 1)
21 PSC005 Track (1 of 1)
22 PSC005 Track (1 of 1)
23 PSC005 Track (1 of 1)
24 PSC005 Track (1 of 1)
25 PSC005 Track (1 of 1)
26 PSC006 Track (1 of 1)
27 PSC006 Track (1 of 1)

Pointing Focus Continuum OOF

Raw data
Time (minutes)
After baseline removal
Time (minutes)
Elev Offset (arcsec)
Cross-Elev Offset (arcsec)

$\Delta\text{focus} = +0.00 \text{ mm}$ $\Delta\text{focus} = +12.00 \text{ mm}$ $\Delta\text{focus} = -12.00 \text{ mm}$

Observed beams

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

☒ 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

Observation State:
NotConnected

GBT State:
NotConnected

GBT Status:
NotConnected

Queue Control:
Halt Queue

Observation Control:
Pause
Stop
Abort
Interactive

OldAz2: 0.000 OldEl: 0.350
dAz2: 0.153 dEl: 0.020
NewAz2: 0.153 NewEl: 0.370

OOFMAP 1.0
OOFMAP 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-000.

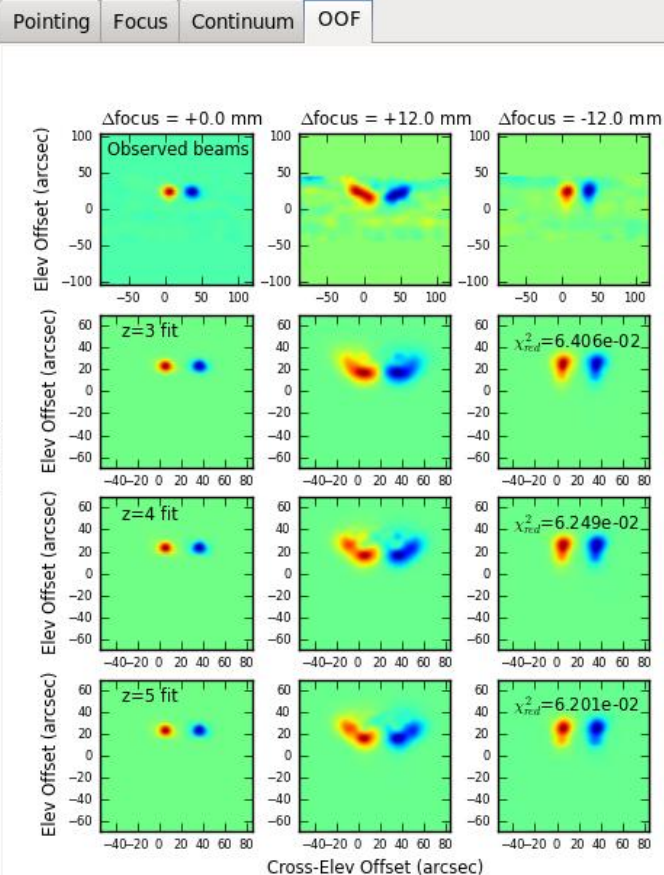
AutoOOF Beam Fits

File Edit View Tools Help



ObservationManagement - 1 DataDisplay - 1 GbtStatus - 1

1 0319+4130 VANECA (1 of 2)
2 0319+4130 VANECA (2 of 2)
3 0319+4130 RALongMap (1 of 3)
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11 0433+0521 Peak (4 of 4)
12 0433+0521 VANECA (1 of 2)
13 0433+0521 VANECA (2 of 2)
14 0433+0521 Peak (1 of 4)
15 0433+0521 Peak (2 of 4)
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27 PSC006 Track (1 of 1)



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

☒ 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

Observation State:

NotConnected

GBT State:

NotConnected

GBT Status:

NotConnected

Queue Control:

Halt Queue

Observation Control:

Pause

Stop

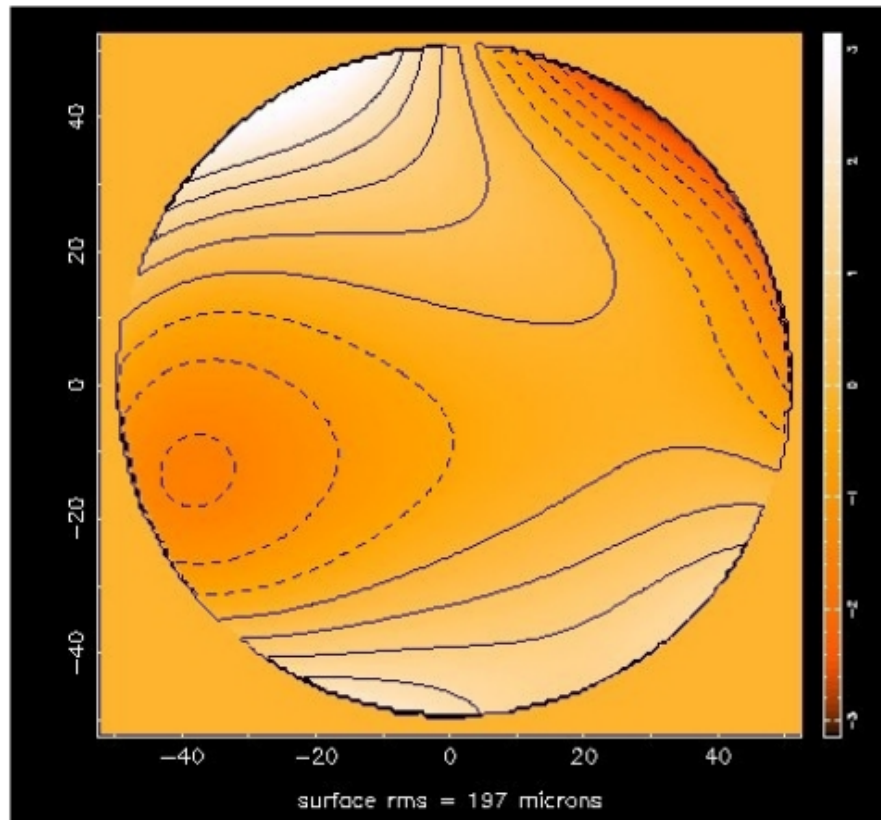
Abort

Interactive

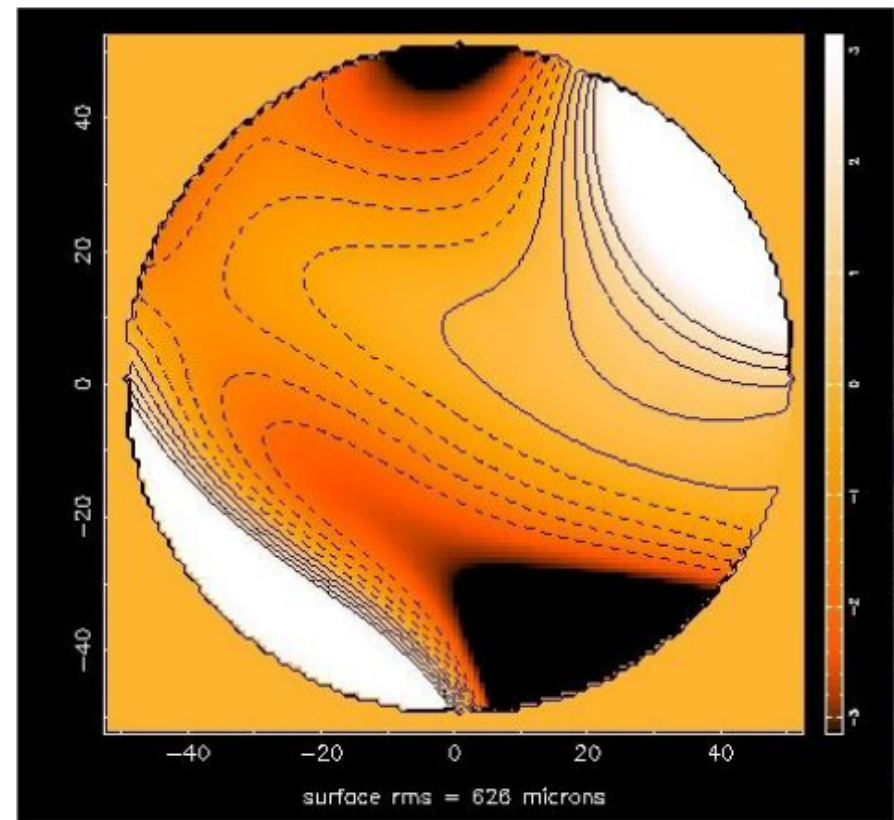
OldAz2: 0.000 OldEL: 0.350
dAz2: 0.153 dEL: 0.020
NewAz2: 0.153 NewEL: 0.370

OOFMAP 1.0
OOFMAP 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-000.

Acceptable OOF results typically have an RMS of less than 400-microns in comparison to the gravity model



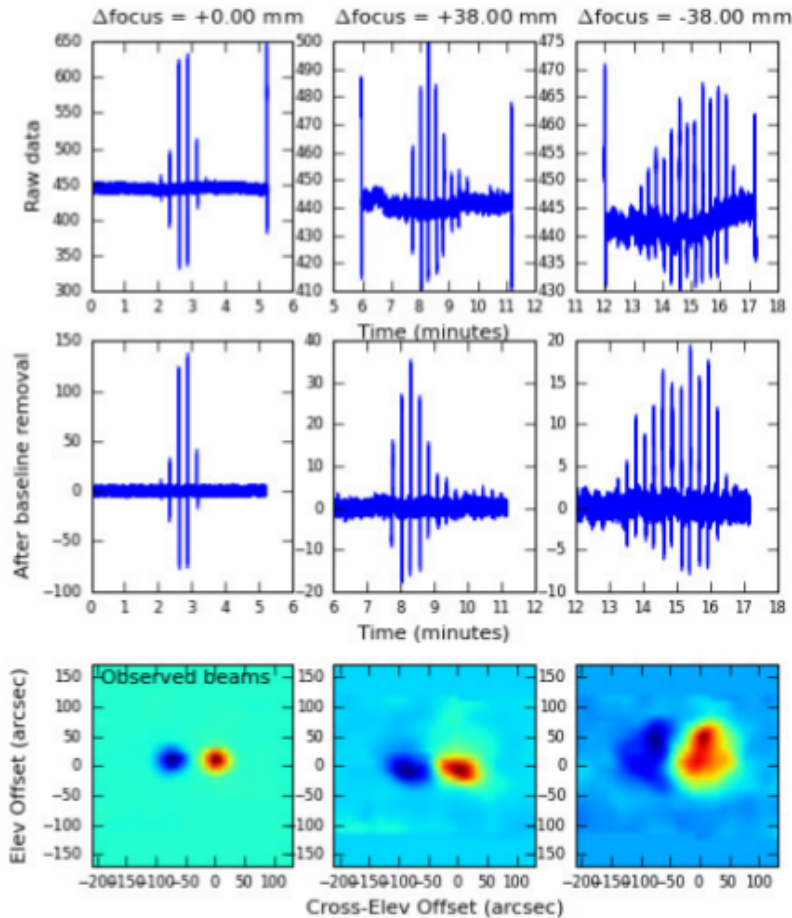
(a) Acceptable OOF solution.



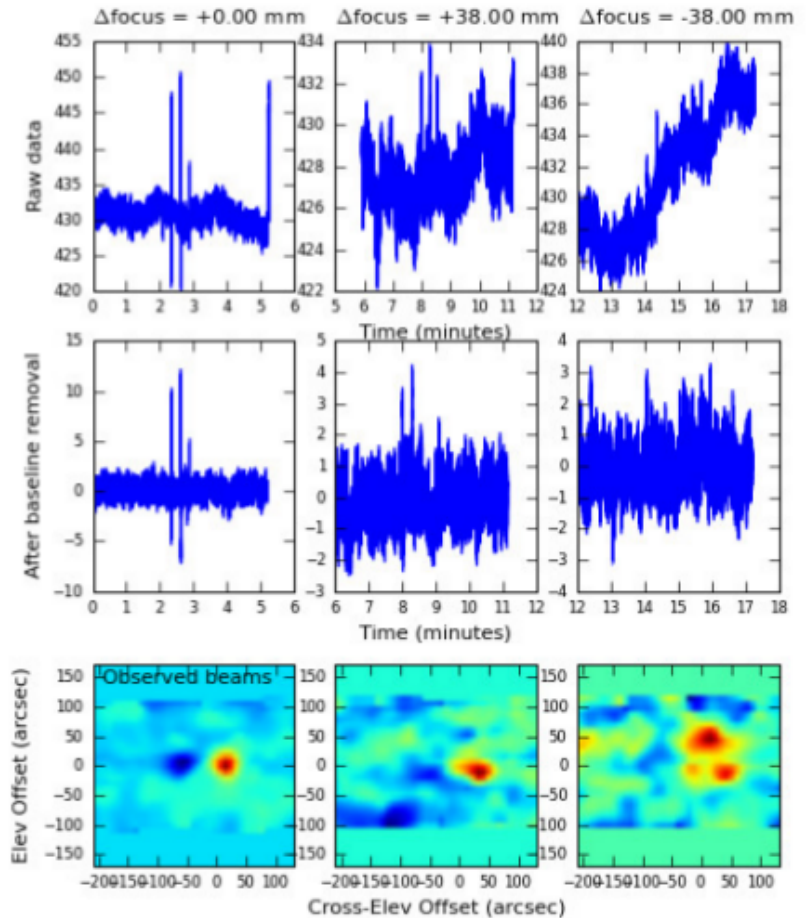
(b) Unacceptable OOF solution.

Figure 5.8: Figure 5.8a shows broad features (± 1.5 radians of phase) with a surface rms of $197 \mu\text{m}$. Figure 5.8b shows steep contour lines (± 15 radians of phase) and a surface rms of $626 \mu\text{m}$. This is likely the result of poor quality raw data and should not be used.

OOF “Raw” Data Streams



(a) A plot of the raw OOF data on a fairly clean Ka-band/CCB dataset.



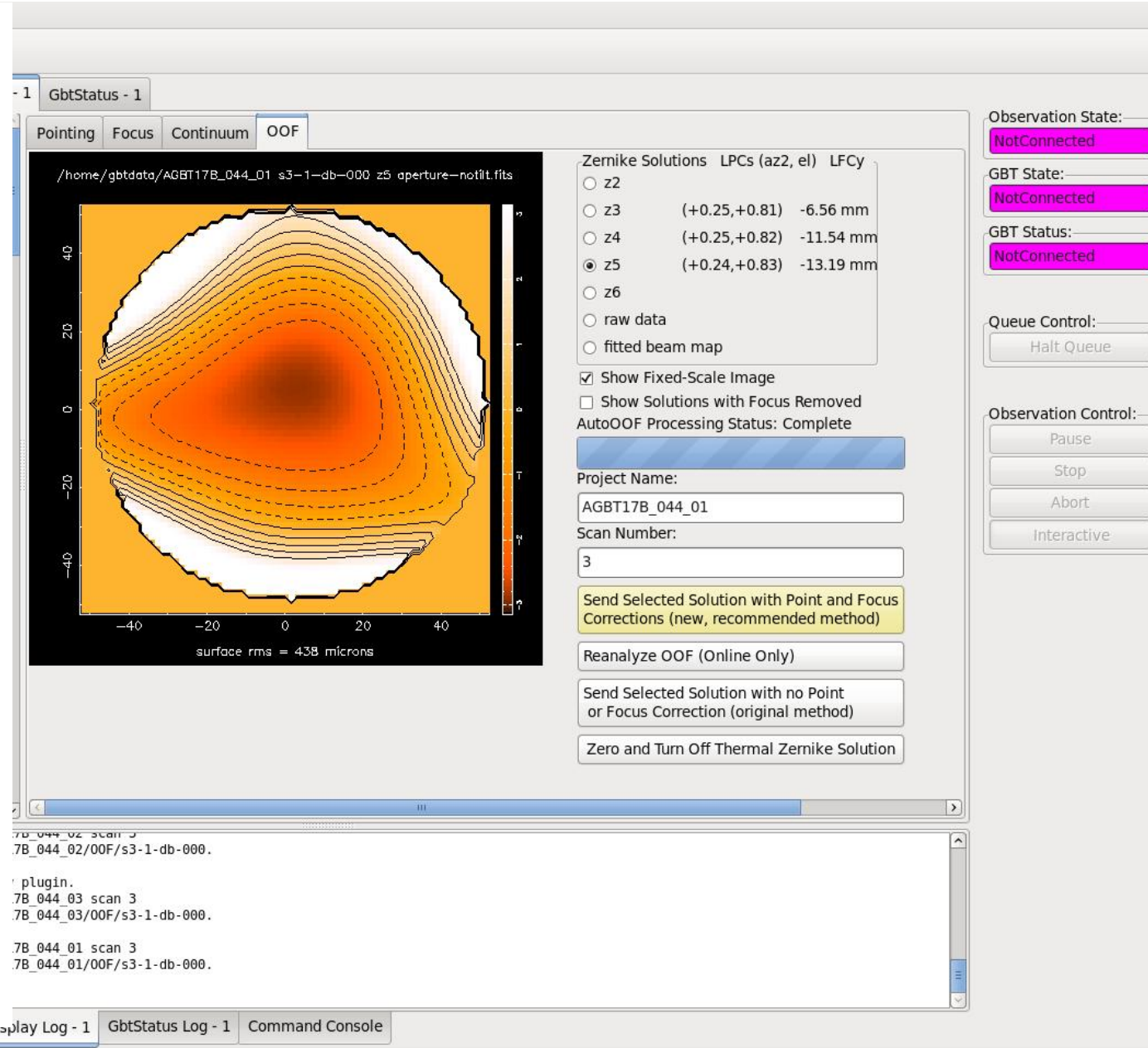
(b) A plot of raw OOF data on a source which is too faint.

Example of a Bad OOF

In this case observations were done in the keyhole at $>85^\circ$ and OOF “rms” 438 μ m with a large implied focus and EL pointing offset.

Solution with large rms $>400\mu$ m should not be used.

Check the raw data and fitted beam maps.

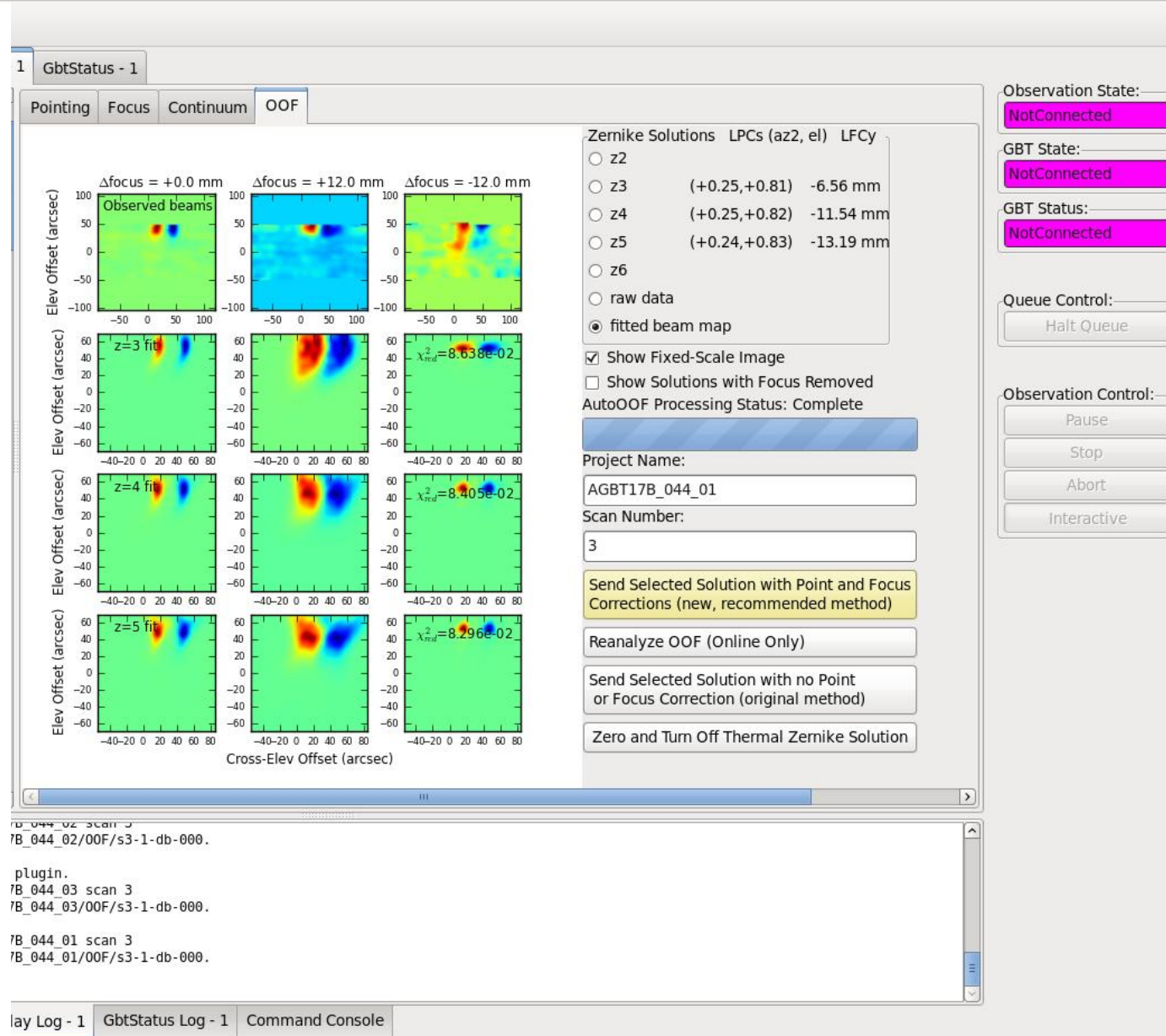


Beam Maps of Example Bad OOF

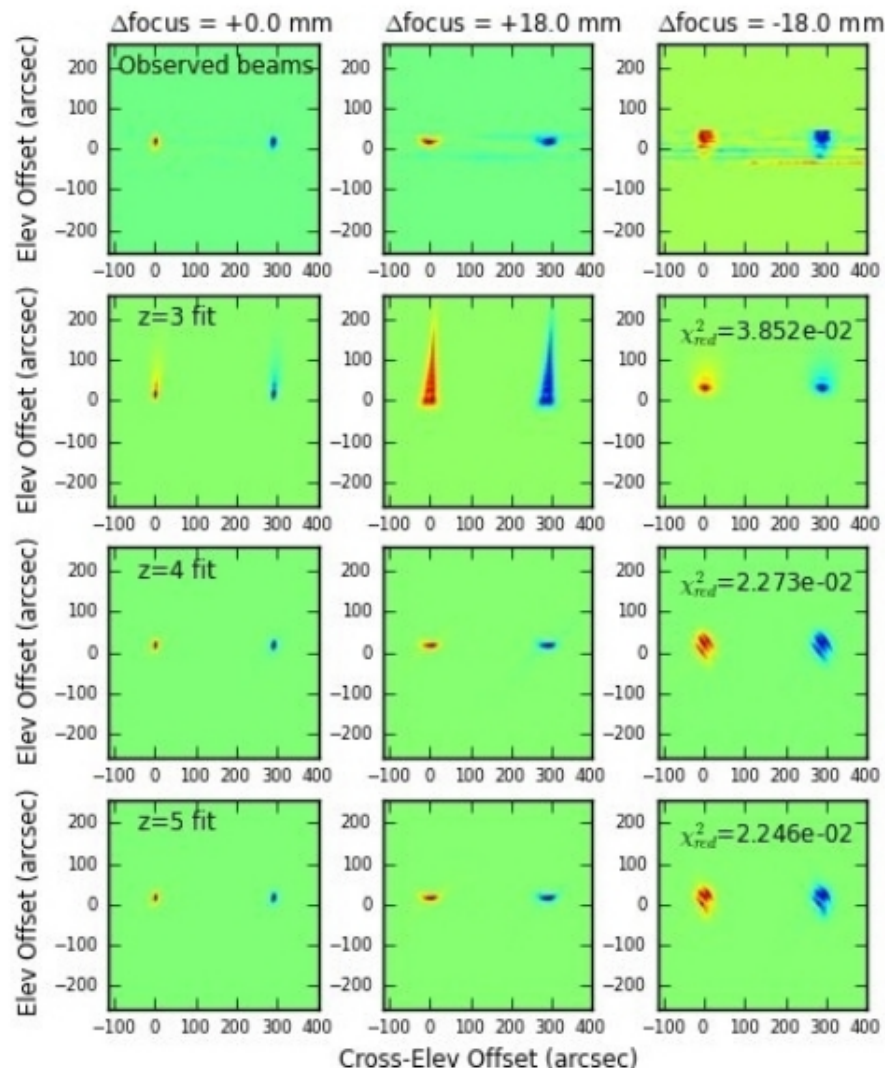
The “observed” beams should not be streaks or very elongated. This can happen in windy conditions.

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.



Another bad OOF (avoid Z3 solution)



Zernike Solutions	LPCs (az2, el)	LFCy
<input type="radio"/> z2		
<input type="radio"/> z3	(+0.04,+1.00)	-22.63 mm
<input type="radio"/> z4	(-0.05,+0.17)	-8.41 mm
<input type="radio"/> z5	(-0.09,+0.12)	-6.11 mm
<input type="radio"/> z6	(Unk,Unk)	Unk mm
<input type="radio"/> z7	(Unk,Unk)	Unk mm
<input type="radio"/> raw data		
<input checked="" type="radio"/> fitted beam map		

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 (2nd 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).

File Launch Help

Status **Error** State **Running** **M** LST **07:09:19** UTC **07:18:45**

Device	Status	State
Antenna	Info	Running
LO1	clear	Running
IFRack	clear	Running
ConverterRack	clear	Running
SwitchingSignalSelector	clear	Running
Measurements	clear	Running
ActiveSurface	clear	Running
QuadrantDetector	Error	Running
VEGAS	clear	Running
RcvrArray75_115	clear	Running
IFManager	clear	Running

Source **CORE06** Scan # **65**

Project **AGBT16B_119_02** SS Master **VEGAS**

Start **07:17:02** Length **120.0**

Countdown **---:--** Remaining **00:00:18**

Observer **Youngmin Seo**

Obs. Type **LINE** Switching **FSW12NOCAL**

Proc Name **Track** Sequence **1 / 1**

Rest Freq **89188.5247** Velocity **7**

Frame **KinematicLSR** Vel Def **Radio**

Time to Set **04:19:29** Encoder **---**

Indicated Azimuth **266.84786** Elevation **53.43131**

Commanded Azimuth **266.84780** Elevation **53.43125**

Rate (°/min) **10.9** **-11.4**

Difference **-0.00006** **-0.00006**

Servo Err (") **-0.3** **-0.1**

On Source **Axis Fault/E-Stop**

Az LPC **-0.0801** El LPC **0.0047**

X FC **0.0** Y FC **0.6** Z FC **0.0** Xt FC **0.00** Yt FC **0.00** Zt FC **0.00** **LFC** **FOC**

Config Model **Guiding**

Model 5r - Latest Coord Mode **J2000**

0 5 10 15 20 25 30 Temp **-5.9**

Dynamic Corrections

DC Pointing **DC Focus** Az1 **0.00** Az2 **0.05** El **0.07** Focus **-13.91**

Wind:2 Temp:2a V(m/s) T(C)

Devices **IF Manager** **Messages**

ActiveSurface

Num Disabled **37** **OOF Zernike Mode** **Sim Mode**

Cmd RMS **33.693** **Zero Offsets** **real**

Peak Resid **34625** **FEM Model** **Ctrl Mode**

Cmd IQ RMS **37.065** **Zernike Coeff** **Enabled**

Cmd Resid **160** **Z Thermal Coeff**

Random Offsets

VEGAS

J1	-19.33	J5	-18.76	J9	-19.81	J13	-19.48
J2	-19.73	J6	-19.63	J10	-19.97	J14	-19.95
J3	-19.84	J7	-19.12	J11	-19.58	J15	-19.53
J4	-20.29	J8	-19.63	J12	-19.76	J16	-19.46

Auto Scroll **Off** **10**

Phase Table... **Other Devices** **Retrace IF**

Cleo Status Window

Az, El LPCs
Focus YFC

Active Surface
ON with
Thermal
corrections
from OOF

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

Backup Slides



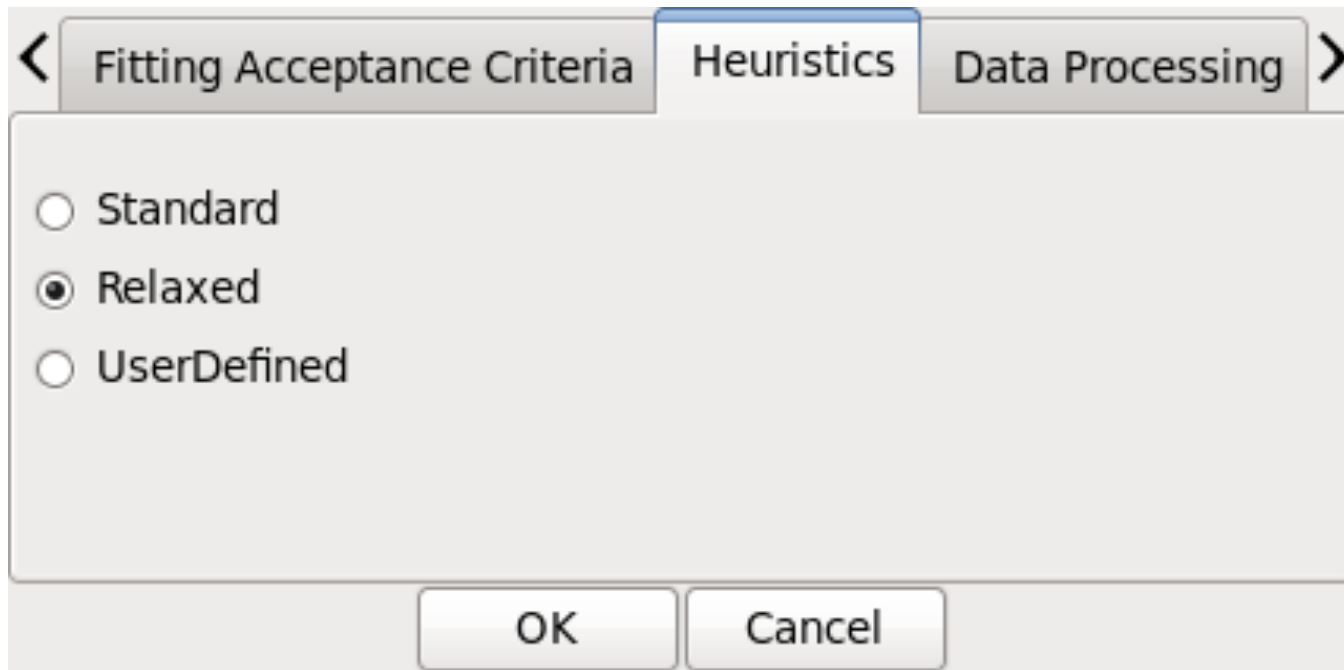
Observing: Antenna Optimization

- Should point+focus (AutoPeakFocus) every 30min-50min depending on conditions (point+focus takes ~5min)
- AutoOOF (which takes ~20min) is used to correct the surface for thermal effects at night.
- Daytime surface changes <1hr time scales and the AutoOOF solutions can cause more harm than good during rapidly changing conditions from the AutoOOF (so it is typically not useful to use the “thermal” corrections during the day).

Astrid/GFM

Important for GBT High-Frequency Pointing/Focus Observations (>20 GHz)

➤ Select Heuristics = “Relaxed”



Brightest OOF Sources 2016/2017

Source	S _{nu} (91.5 GHz) [Jy]
0319+4130	24.3
0854+2006	6.7
1058+0133	6.6
1229+0203	9.9
1256-0547	10.6
2253+1608	15.7

Telescope Optics

Prime Focus: Retractable boom

Gregorian Focus: 8-m subreflector - 6-degrees of freedom



Telescope Optics

Rotating Turret with 8 receiver bays



Telescope Structure

- Fully Steerable
 - Elevation Limit: 5°
 - Can observe 85% of the entire Celestial Sphere
- Slew Rates: Azimuth - $40^\circ/\text{min}$; Elevation - $20^\circ/\text{min}$

