



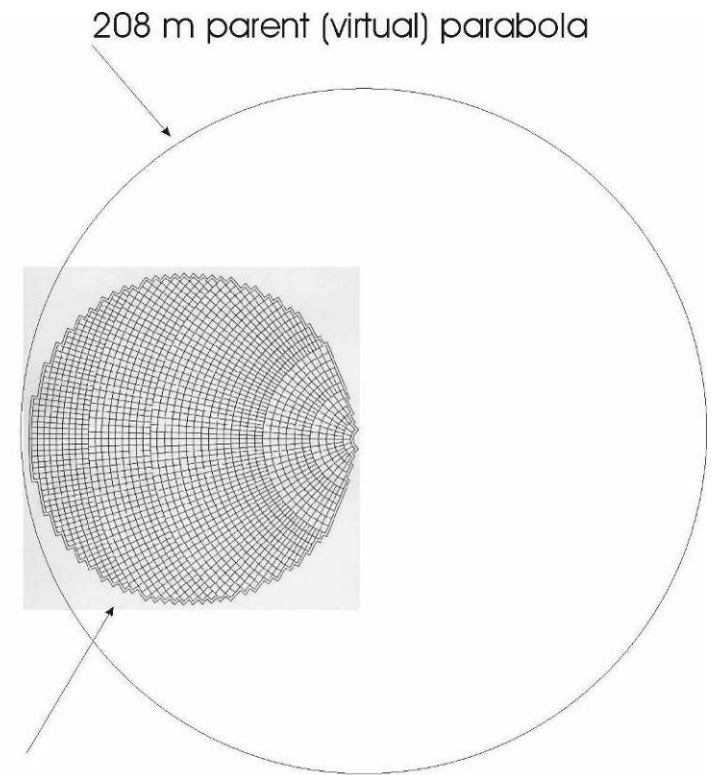
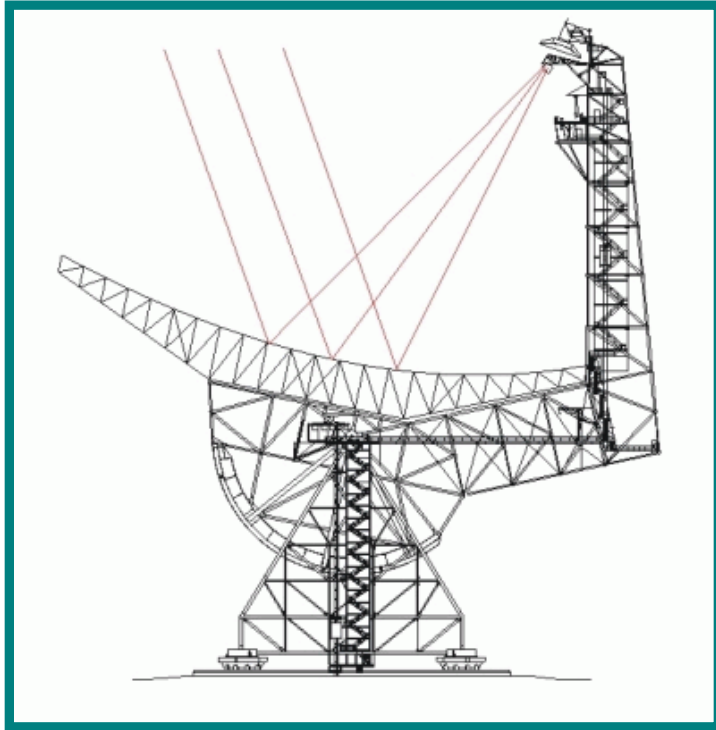
High Frequency GBT Corrections

Natalie Butterfield (GBO Postdoc)



GBT Telescope Optics

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



GBT 100 x 110 m Parabola Section

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	$\sim 1.0\text{e-}5$

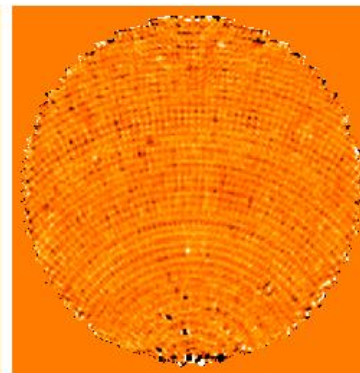
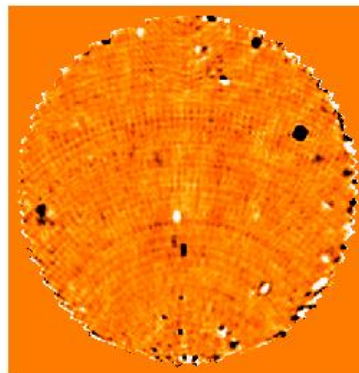
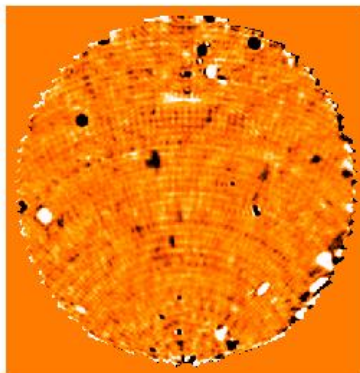
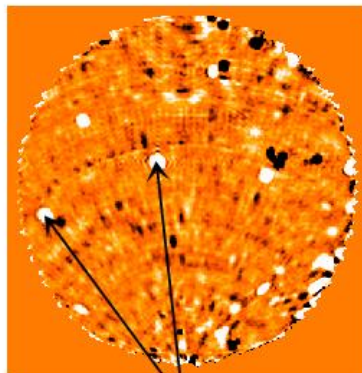
Improvements to Active Surface in 2009

January 2009

February 2009

March 2009

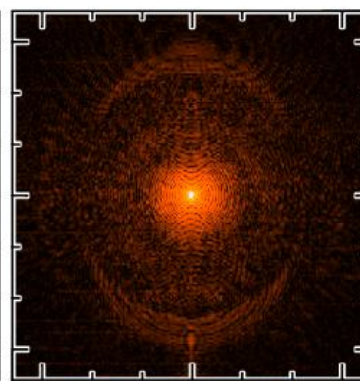
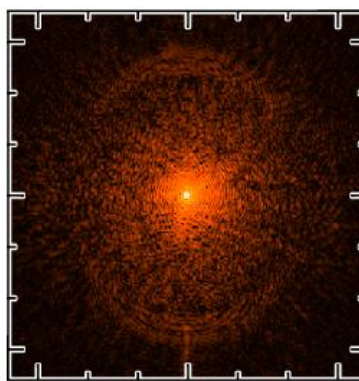
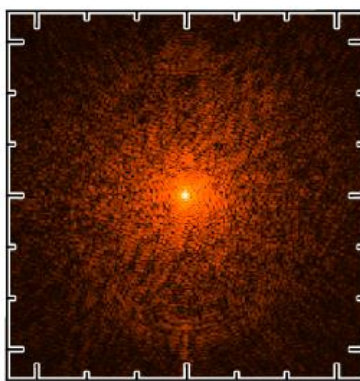
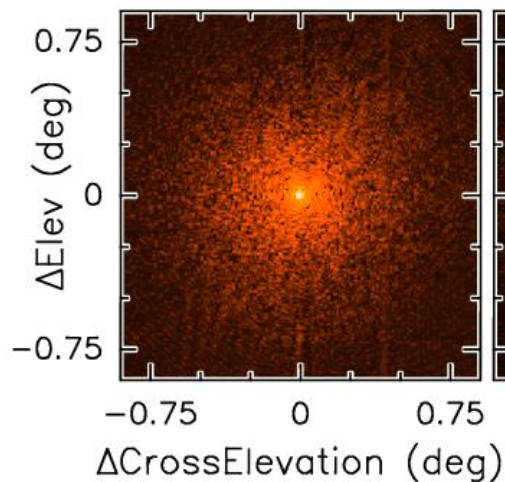
September 2009



Broken Actuators



-500 0 500 Microns

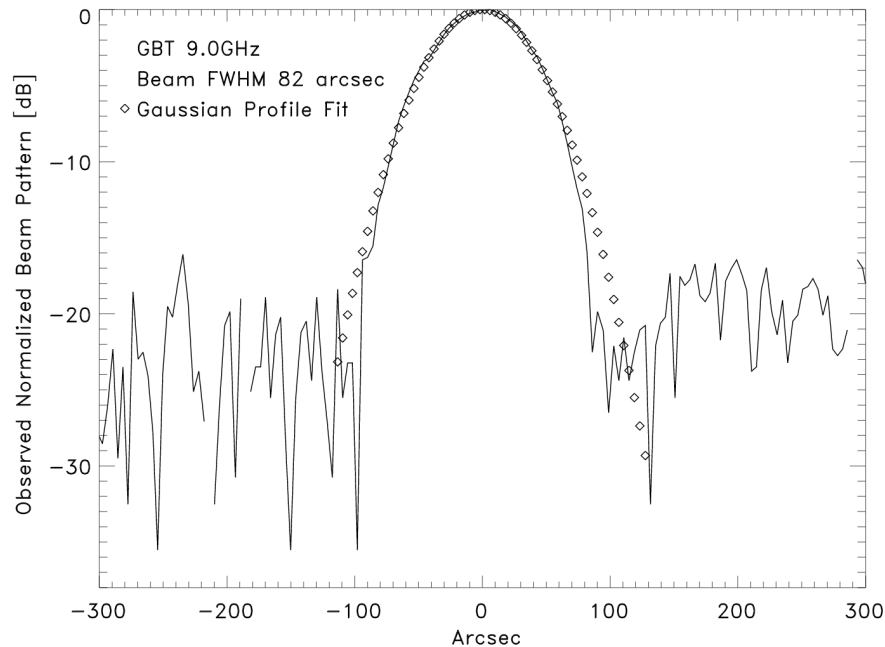


11.7 GHz beam pattern

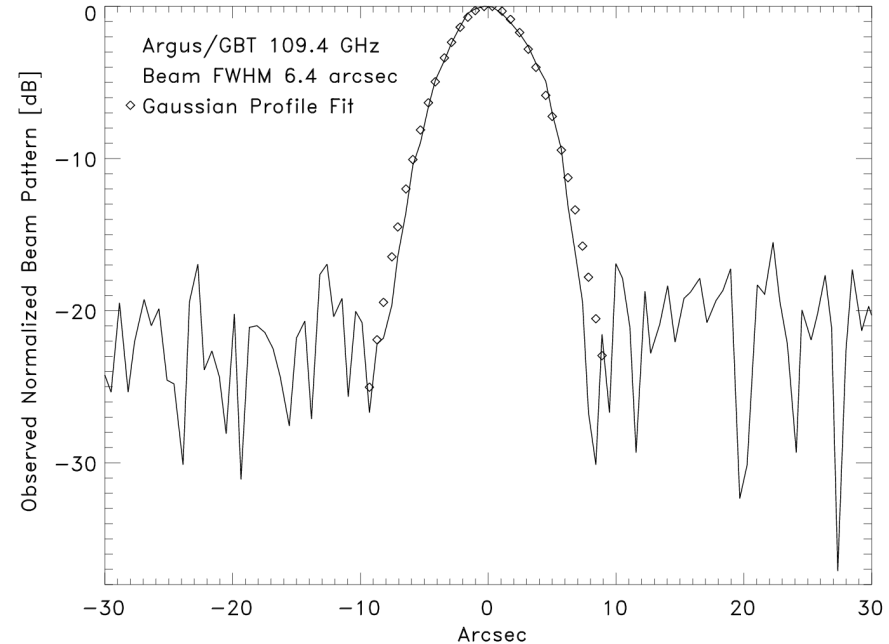
dB = -40 -20 0

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

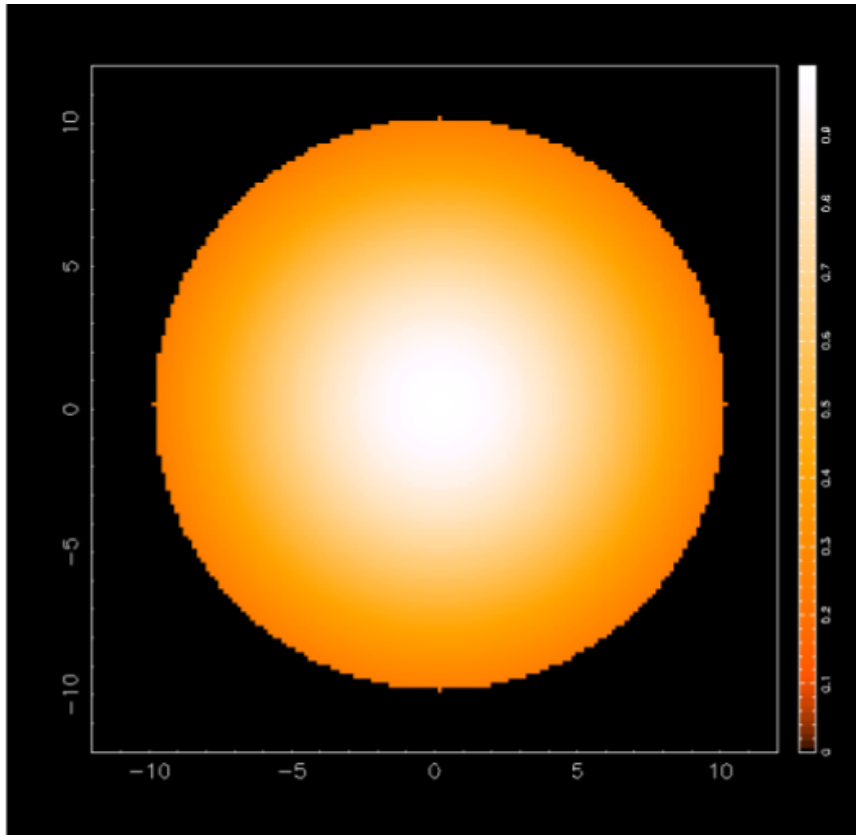


GBT/Argus 109.4 GHz

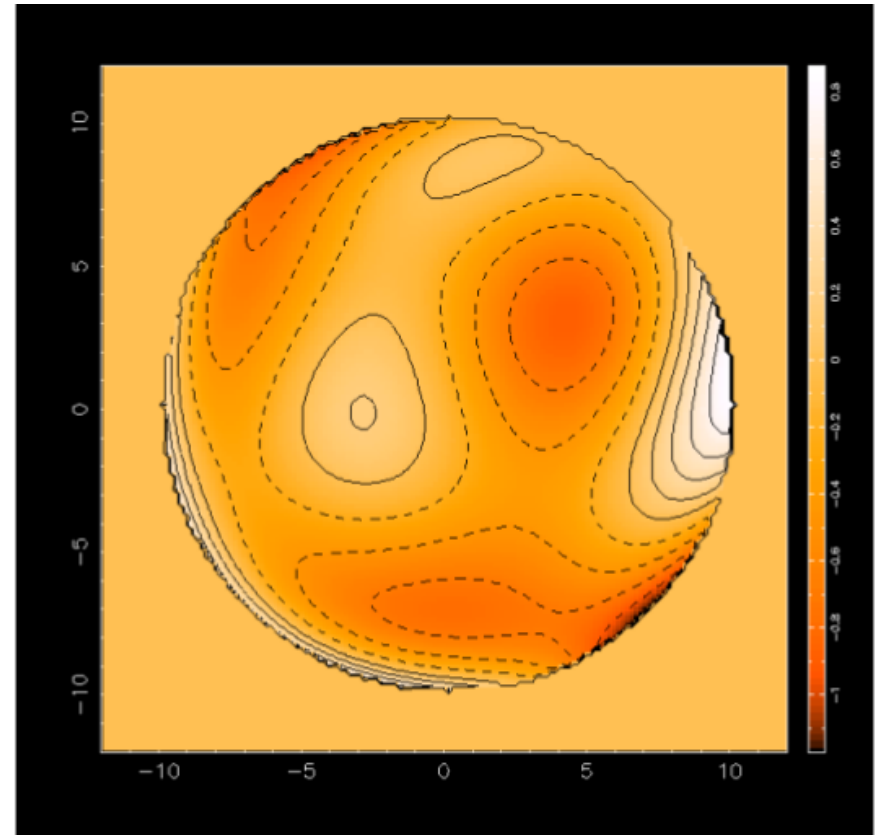
Unblock GBT aperture → first side-lobe predicted at -27dB

A Surface with random large-scale errors

Receiver Response
(Taper/Apodisation/...)



Surface Errors
(Projected to an imaginary surface)



Model Surface Using Zernike Polynomials

Derived by Frits Zernike in 1934 (a won him the Nobel Prize in 1953)

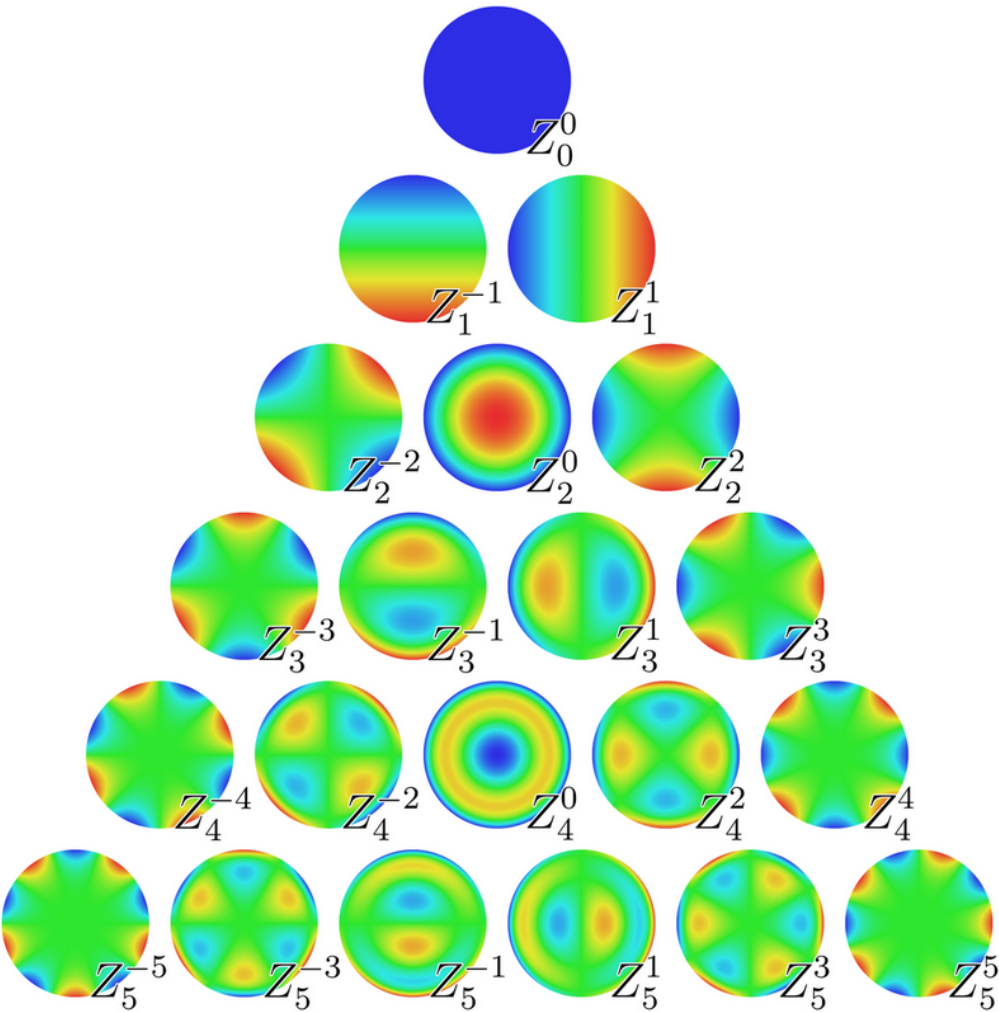
Essential in determining beam optics

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	0	0	1		
	Z_1^{-1}	1	3	1	1	-1	-1	$2\rho \sin \theta$		
	Z_1^1	2	2	1	1	+1	+1	$2\rho \cos \theta$		
	Z_2^{-2}	3	5	2	2	-2	-2	$\sqrt{6}\rho^2 \sin 2\theta$		
	Z_2^0	4	4	2	2	0	0	$\sqrt{3}(2\rho^2 - 1)$		
	Z_2^2	5	6	2	2	+2	+2	$\sqrt{6}\rho^2 \cos 2\theta$		
	Z_3^{-3}	6	9	3	3	-3	-3	$\sqrt{8}\rho^3 \sin 3\theta$		
	Z_3^{-1}	7	7	3	3	-1	-1	$\sqrt{8}(3\rho^3 - 2\rho) \sin \theta$		
	Z_3^1	8	8	3	3	+1	+1	$\sqrt{8}(3\rho^3 - 2\rho) \cos \theta$		
	Z_3^3	9	10	3	3	+3	+3	$\sqrt{8}\rho^3 \cos 3\theta$		
	Z_4^{-4}	10	15	4	4	-4	-4	$\sqrt{10}\rho^4 \sin 4\theta$		
	Z_4^{-2}	11	13	4	4	-2	-2	$\sqrt{10}(4\rho^4 - 3\rho^2) \sin 2\theta$		
	Z_4^0	12	11	4	4	0	0	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$		
	Z_4^2	13	12	4	4	+2	+2	$\sqrt{10}(4\rho^4 - 3\rho^2) \cos 2\theta$		
	Z_4^4	14	14	4	4	+4	+4	$\sqrt{10}\rho^4 \cos 4\theta$		



GBT Zernike-Gravity Model

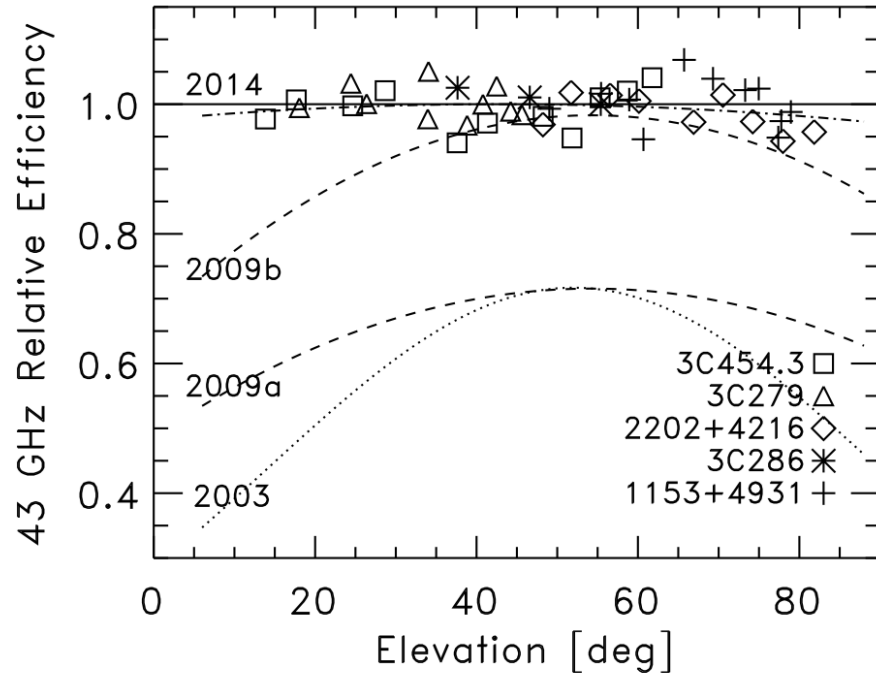
Each Zernike parameter fitted as a function of elevation:

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

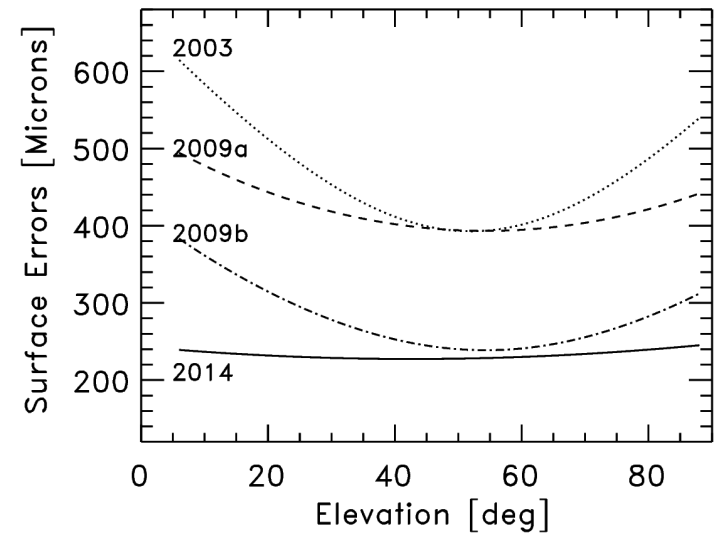
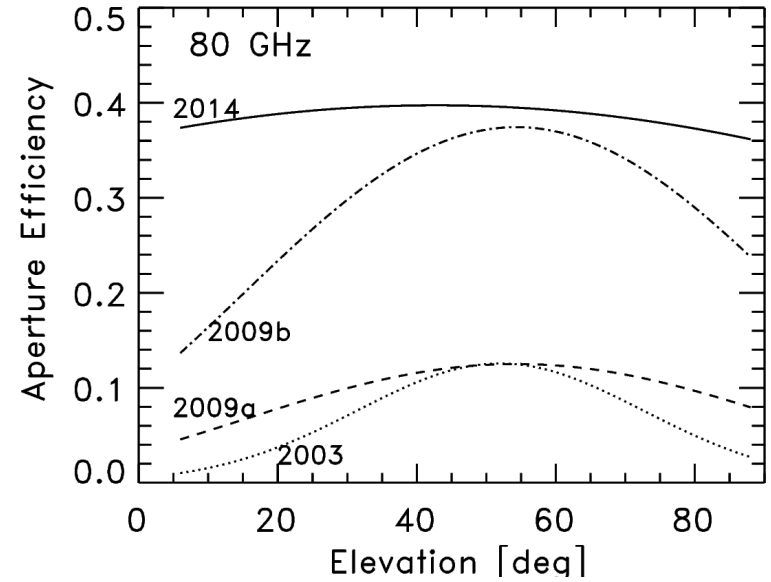
The updated 2014 gravity model improved telescope performance (PTCS PN#76)

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



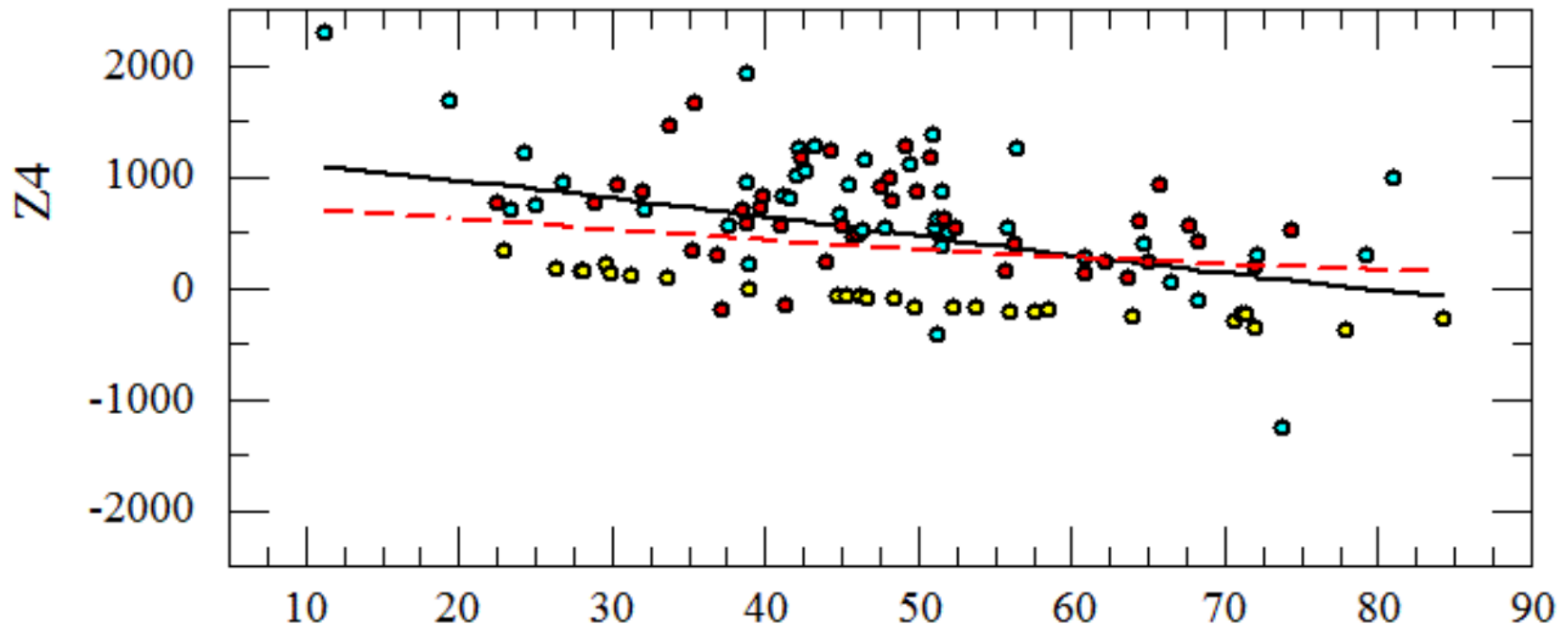
Improvements to the Zernike-Gravity model in 2014 yields a flat gain curve with elevation and has significantly improved the GBT performance at high-frequency (GBT Memo#301)



Surface Improvements with Zernike-Gravity Model

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

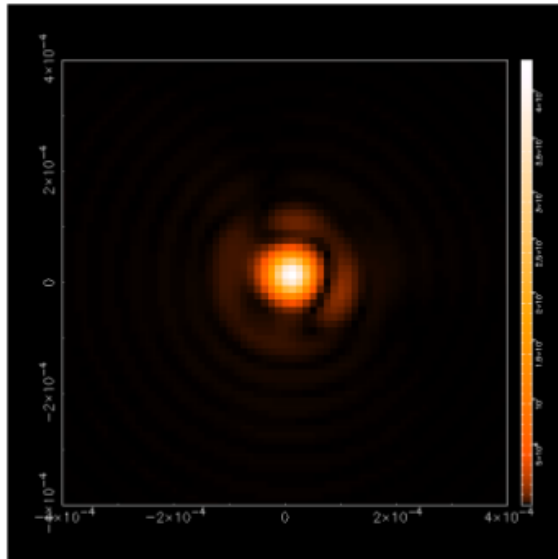
$$Z_n(\text{total}) = Z_n(\text{gravity}) + Z_n(\text{thermal})$$



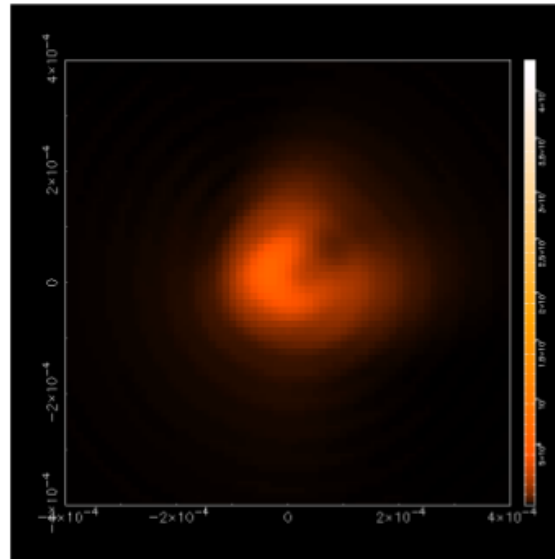
Surface Improvements with Zernike-Gravity Model

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

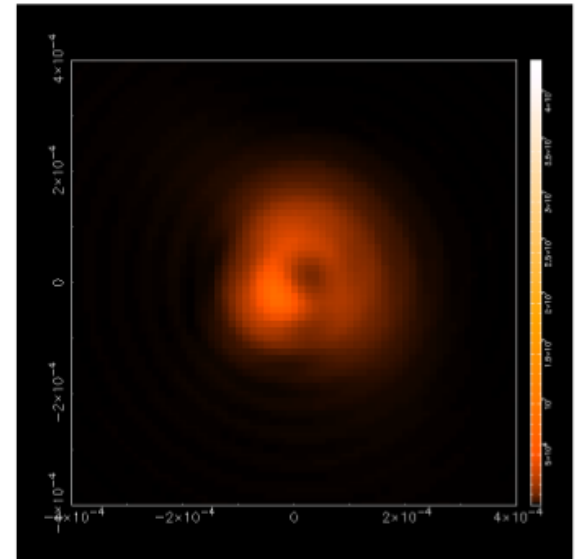
In-Focus



-ve De-Focus

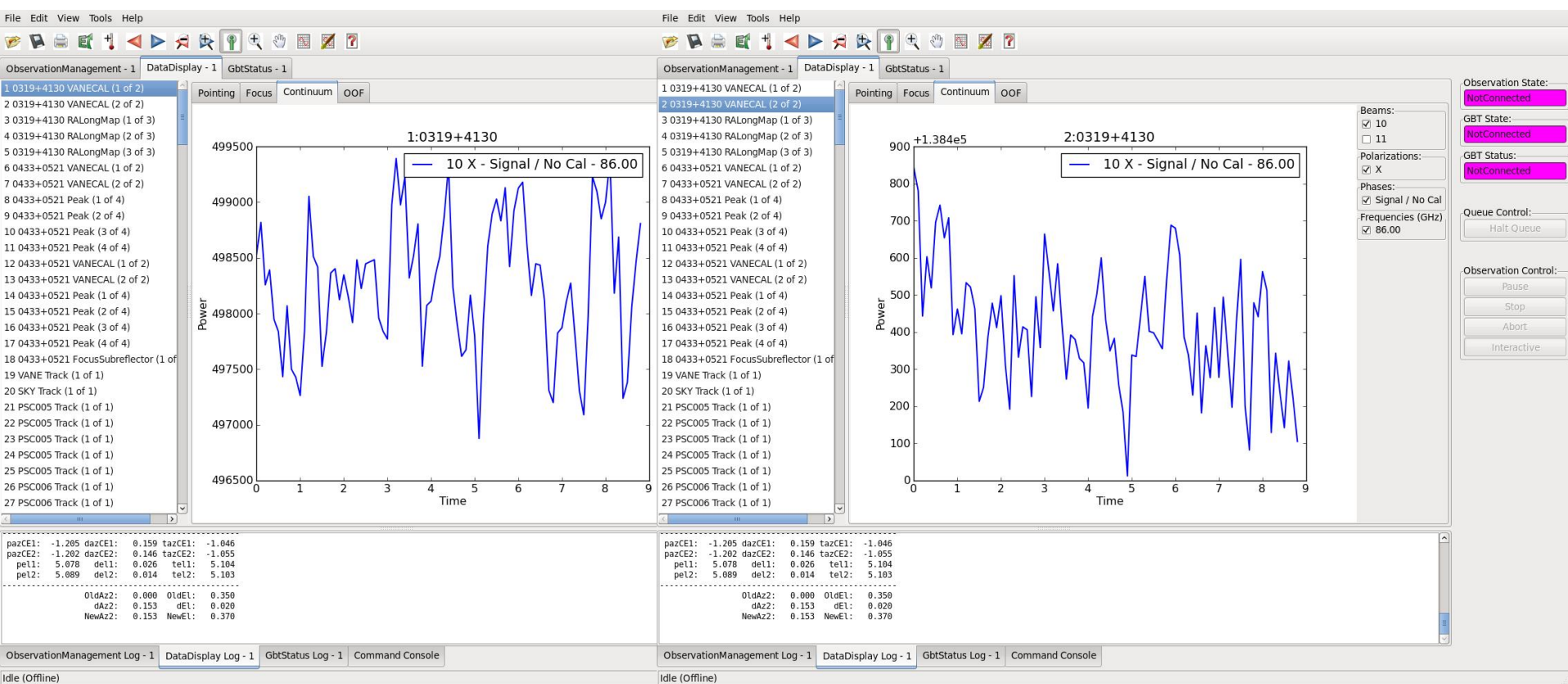


+ve De-Focus



Example of Argus AutoOOF Observations:

(scans 1+2) Vanecal-scans with the DCR



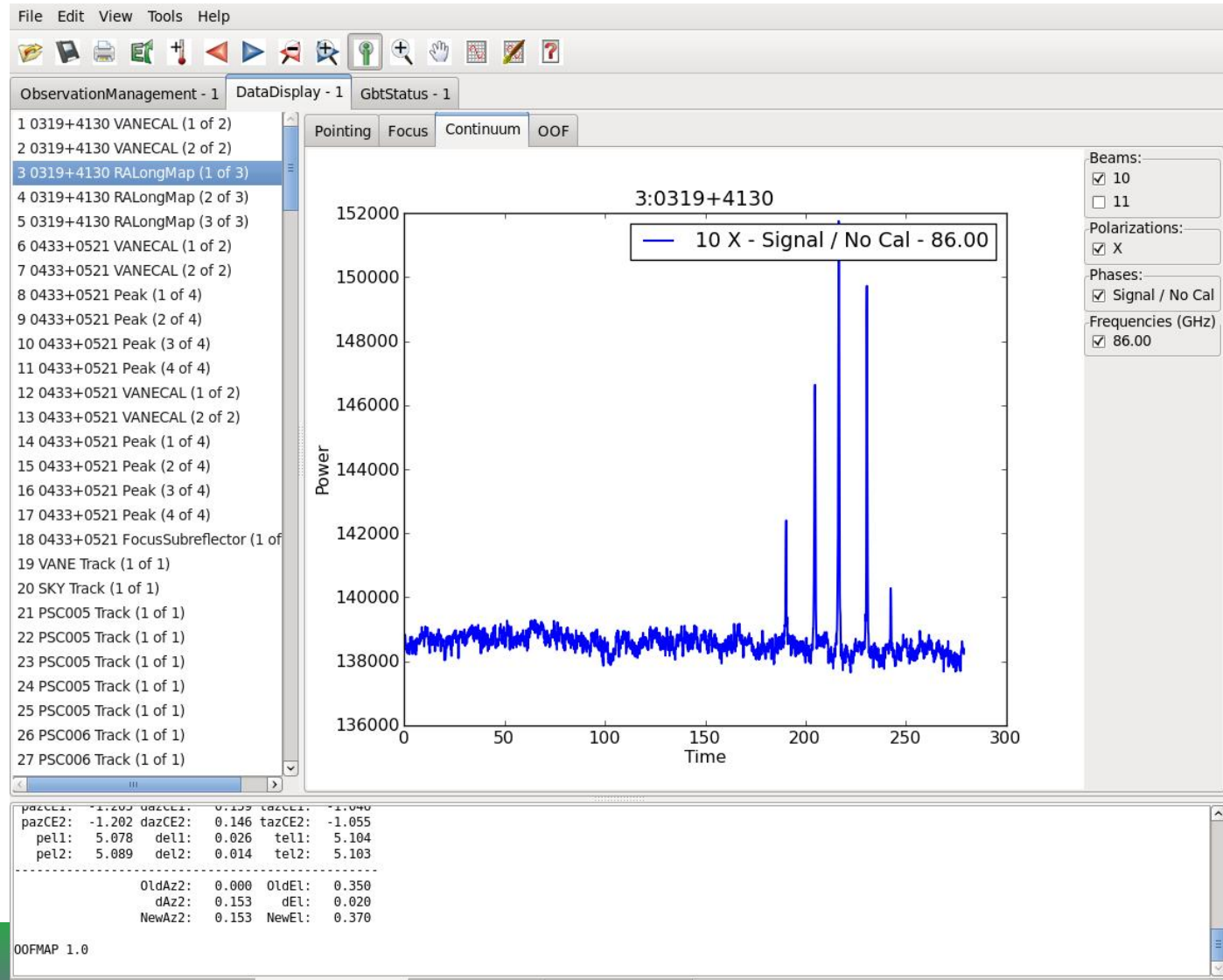
Vanecal scans with the DCR – first scan is with VANE (4.985e5 counts) and second scan is on SKY (1.354e5+500 counts). $T_{\text{sys}} \sim T_{\text{warm}}(\text{SKY}/(\text{VANE}-\text{SKY})) = 104 \text{ K}$ for $T_{\text{warm}} \sim 270$. **Should have VANE/SKY > ~3 in good conditions.**



Example of Argus AutoOOF Observations:

(scan 3) Argus OOF map-1 data

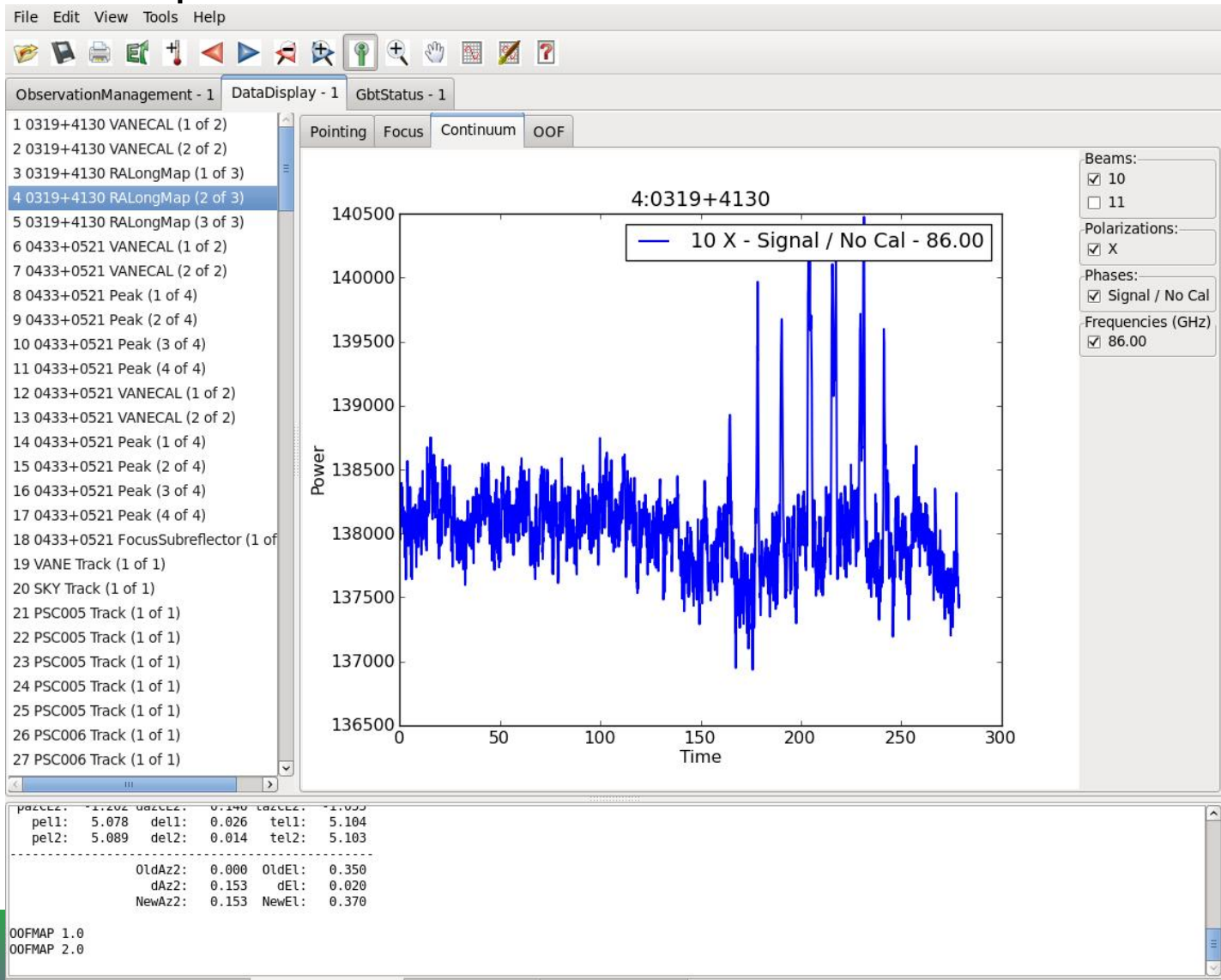
First map at default focus and should see source at good S/N. Here, the source is offset from the center of the time stream/map which implies a significant +el LPC.



Example of Argus AutoOOF Observations:

(scan 4) Argus OOF map-2 data

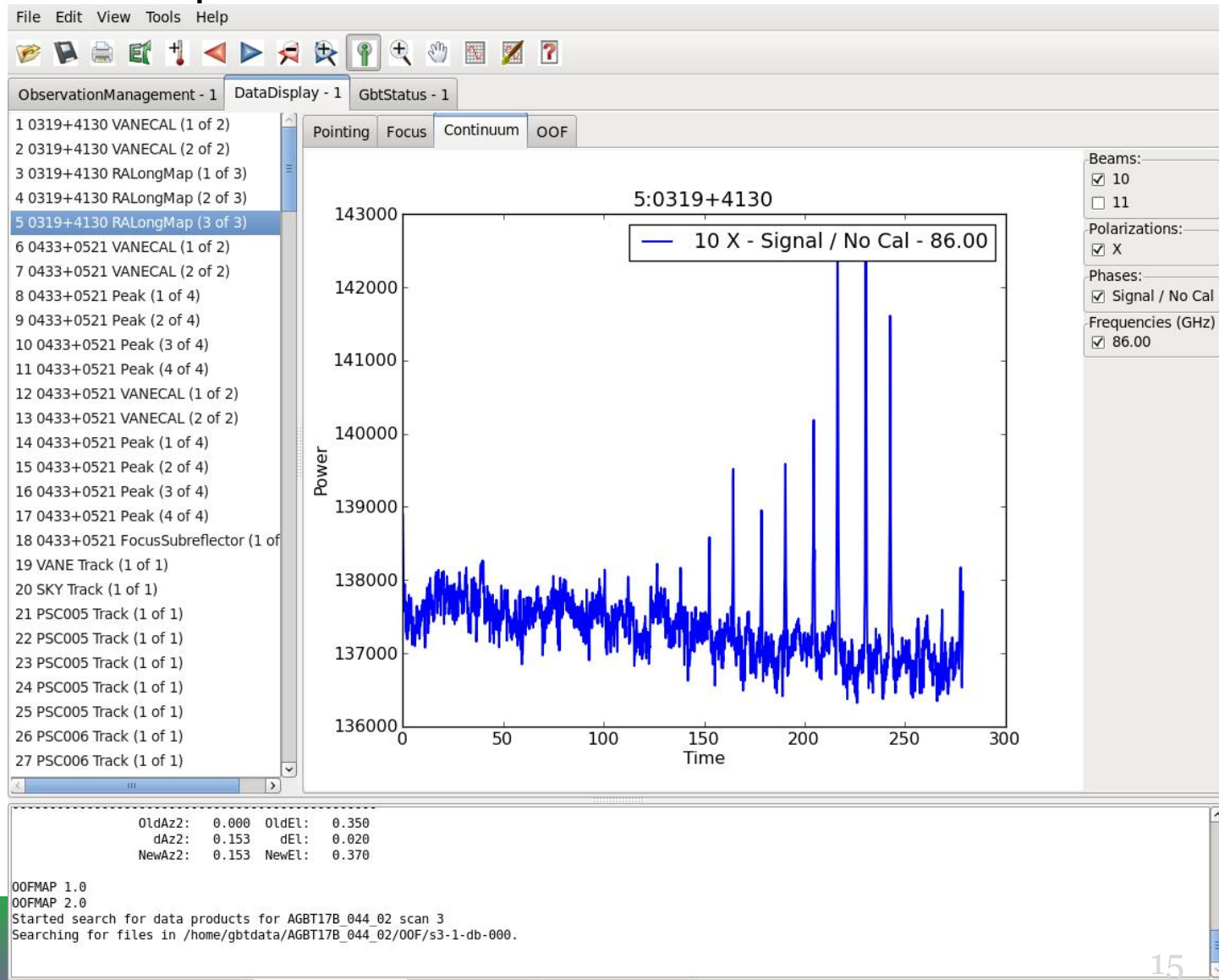
Counts lower
since map
made out of
focus (+12mm)



Example of Argus AutoOOF Observations:

(scan 5) Argus OOF map-3 data

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

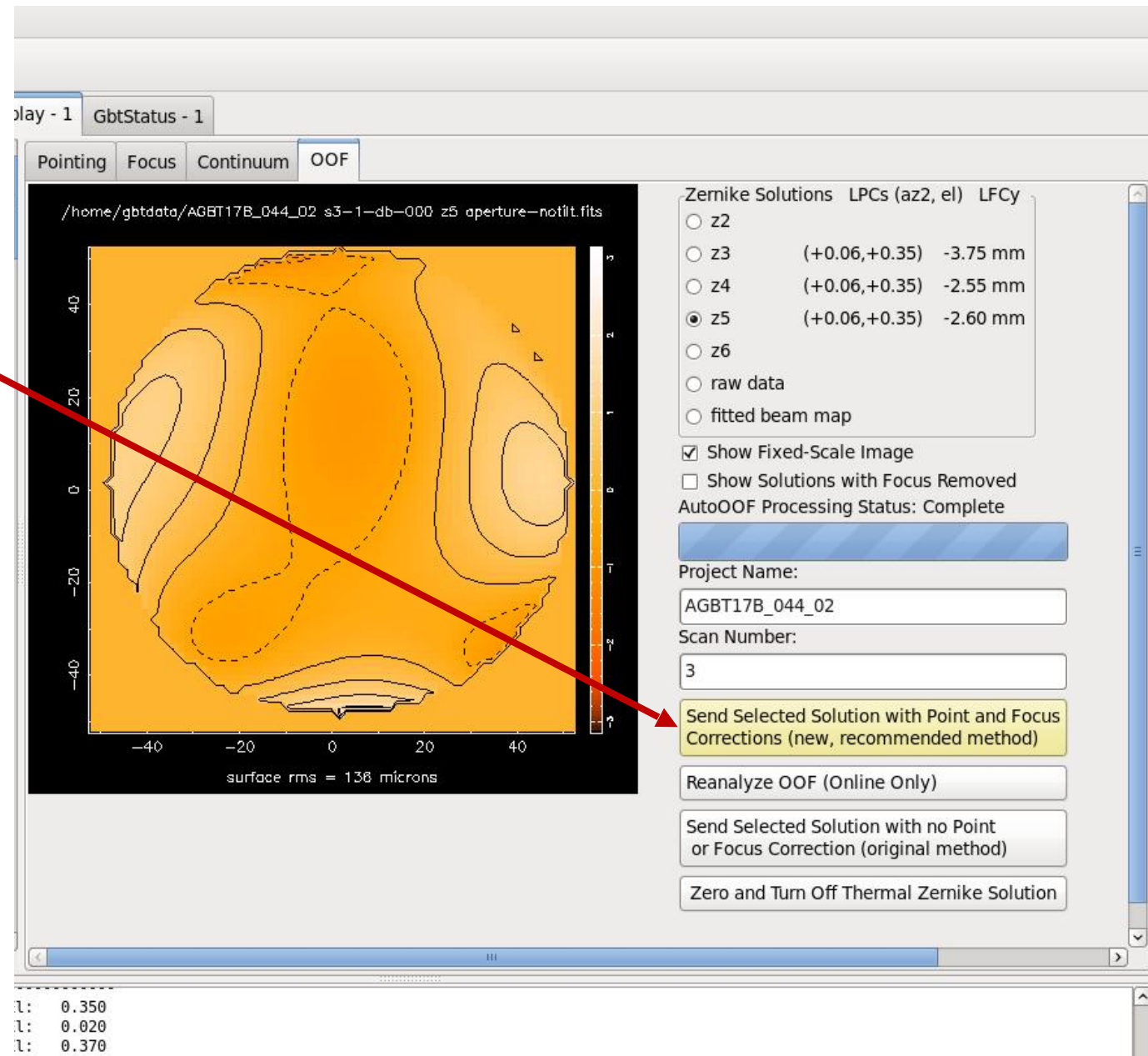


AutoOOF Solutions

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)



AutoOOF 'Raw Data'

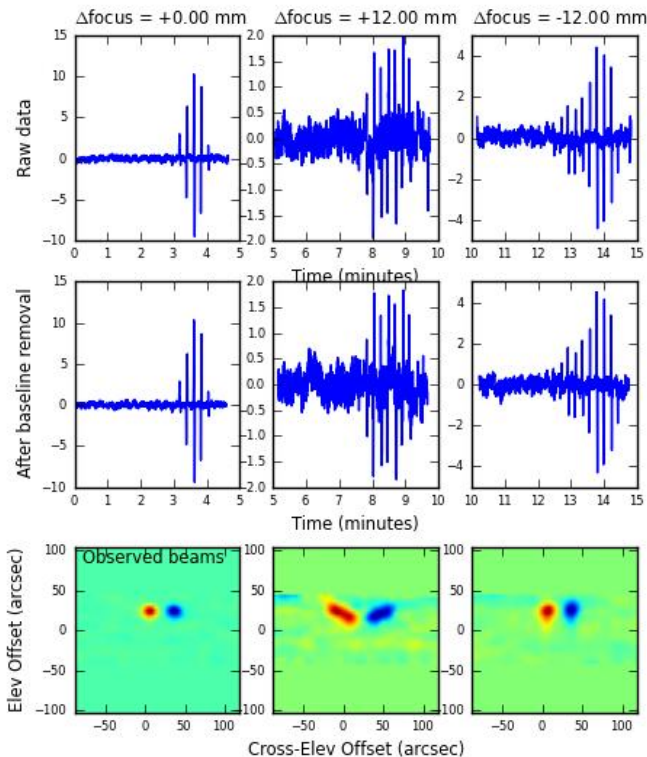
File Edit View Tools Help



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)
- 4 0319+4130 RALongMap (2 of 3)
- 5 0319+4130 RALongMap (3 of 3)**
- 6 0433+0521 VANECA (1 of 2)
- 7 0433+0521 VANECA (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 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)
- 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



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

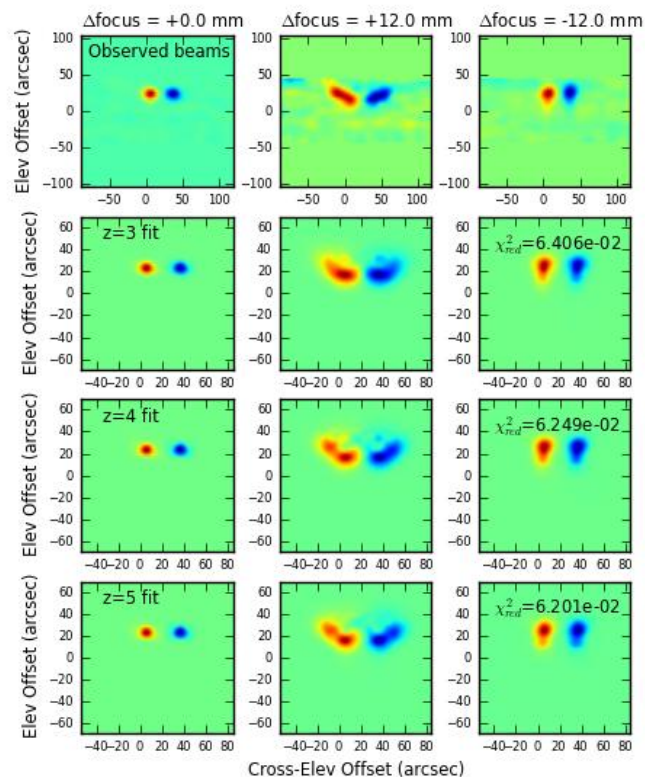
File Edit View Tools Help



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)
- 4 0319+4130 RALongMap (2 of 3)
- 5 0319+4130 RALongMap (3 of 3)
- 6 0433+0521 VANECA (1 of 2)
- 7 0433+0521 VANECA (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 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)
- 16 0433+0521 Peak (3 of 4)
- 17 0433+0521 Peak (4 of 4)
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- 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



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

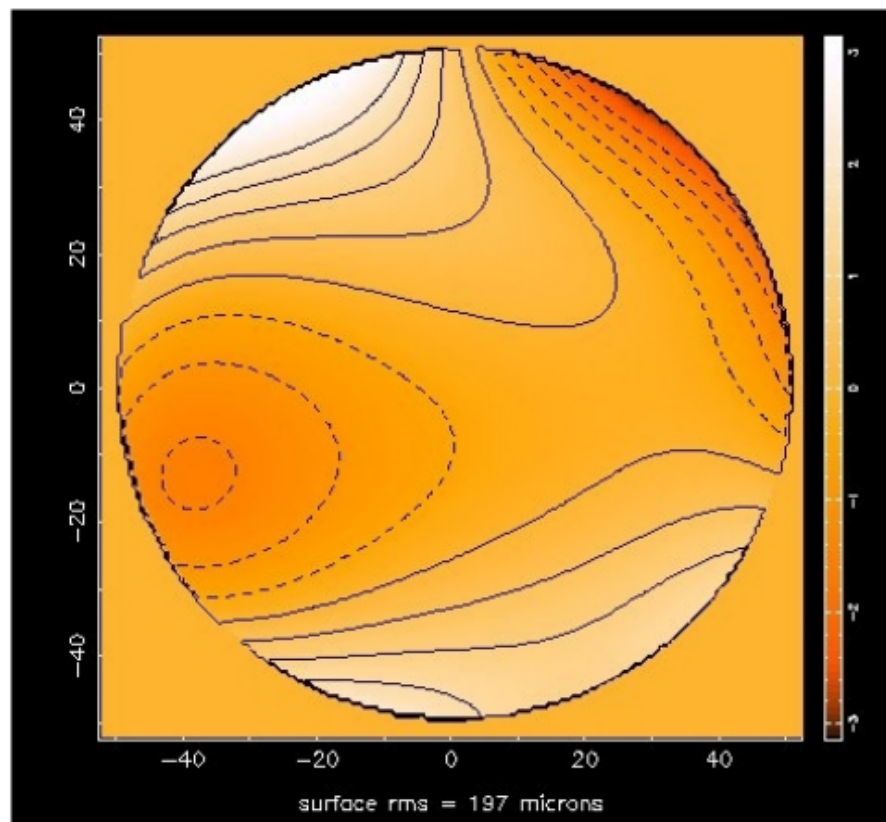
OldAz2: 0.000 OldEL: 0.350
dAz2: 0.153 dEL: 0.020
NewAz2: 0.153 NewEL: 0.370

OOFMAP 1.0
OOFMAP 2.0

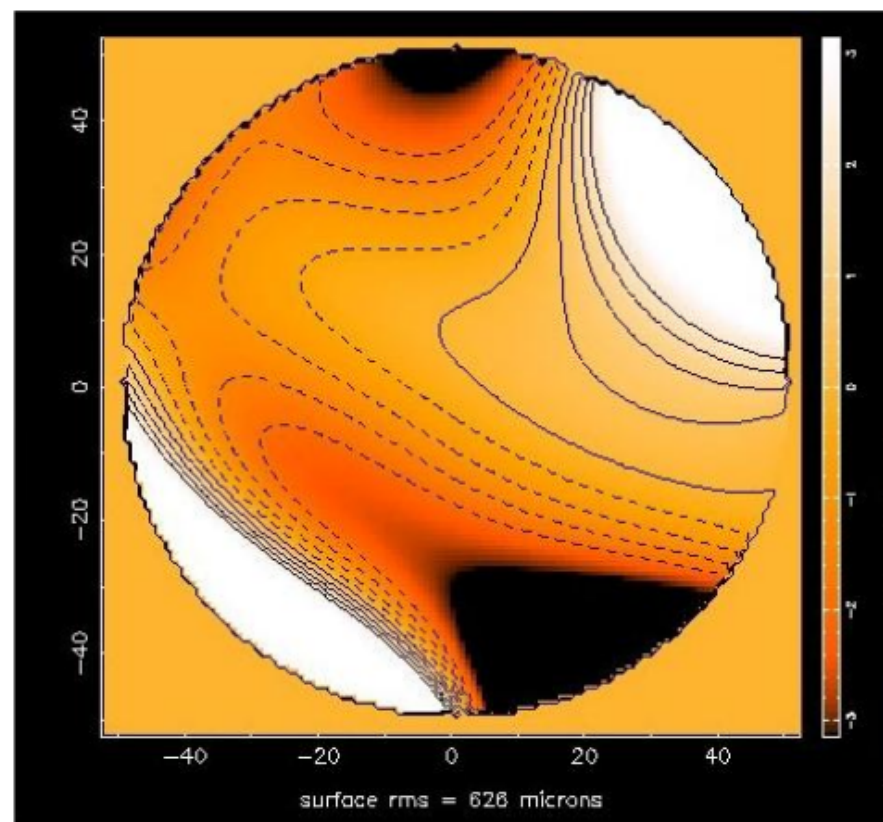
Started search for data products for AGBT17B_044_02 scan 3
Searching for files in /home/gbtdata/AGBT17B_044_02/OOF/s3-1-db-000.

AutoOOF Example Solutions

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



(a) Acceptable OOF solution.

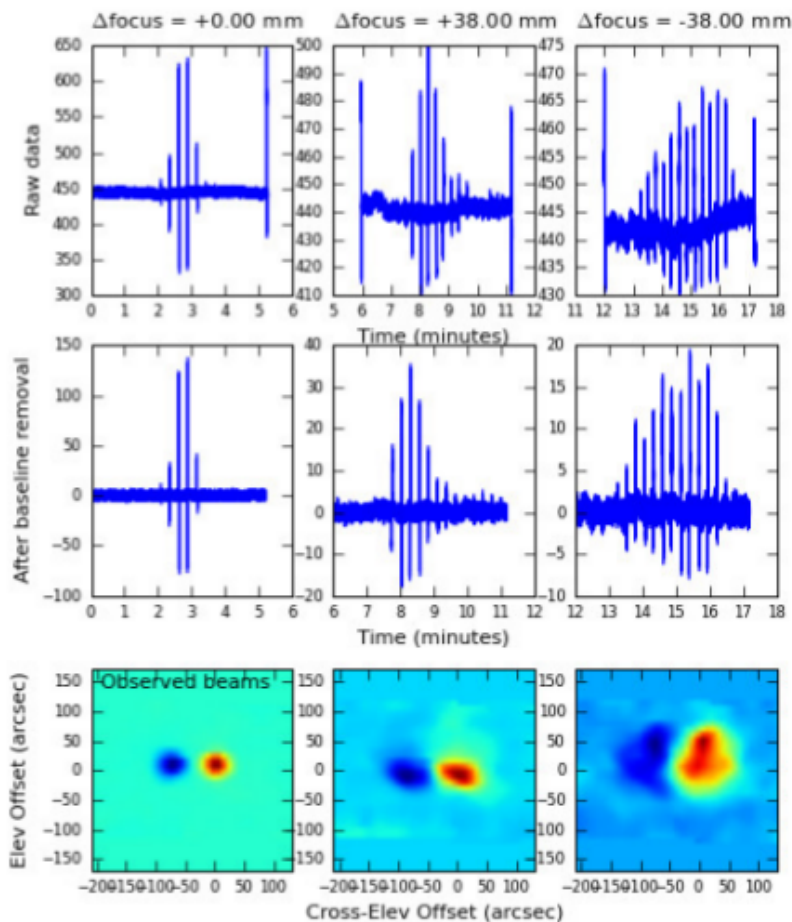


(b) Unacceptable OOF solution.

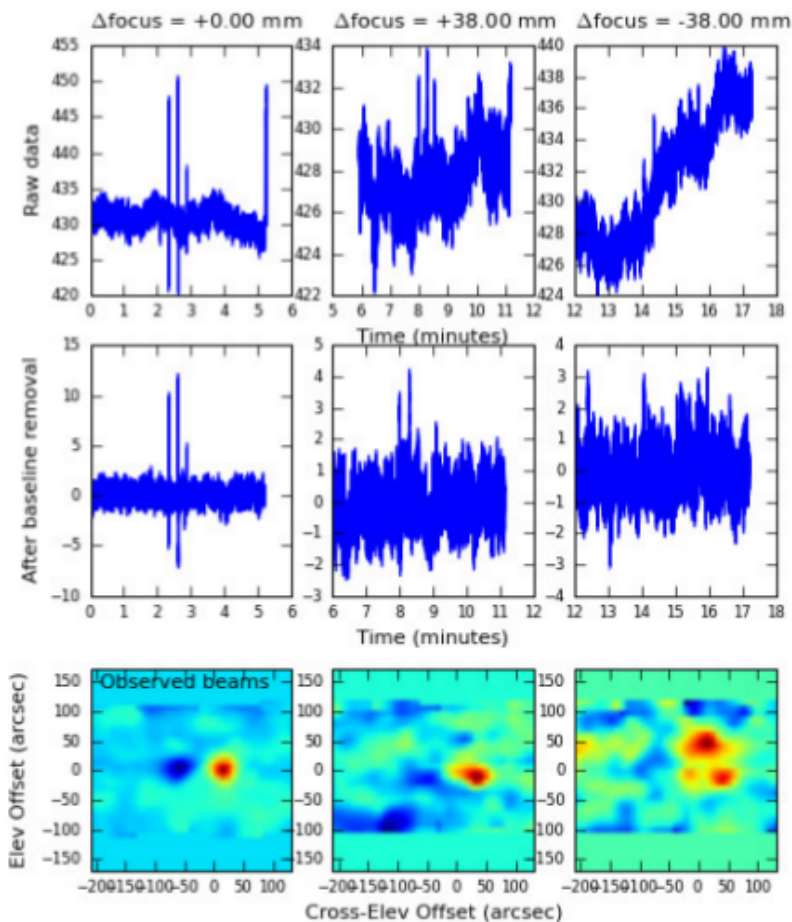
Figure 5.8: Figure 5.8a shows broad features (± 1.5 radians of phase) with a surface rms of $197 \mu\text{m}$. Figure 5.8b shows steep contour lines (± 15 radians of phase) and a surface rms of $626 \mu\text{m}$. This is likely the result of poor quality raw data and should not be used.



AutoOOF 'Raw' Data Streams



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



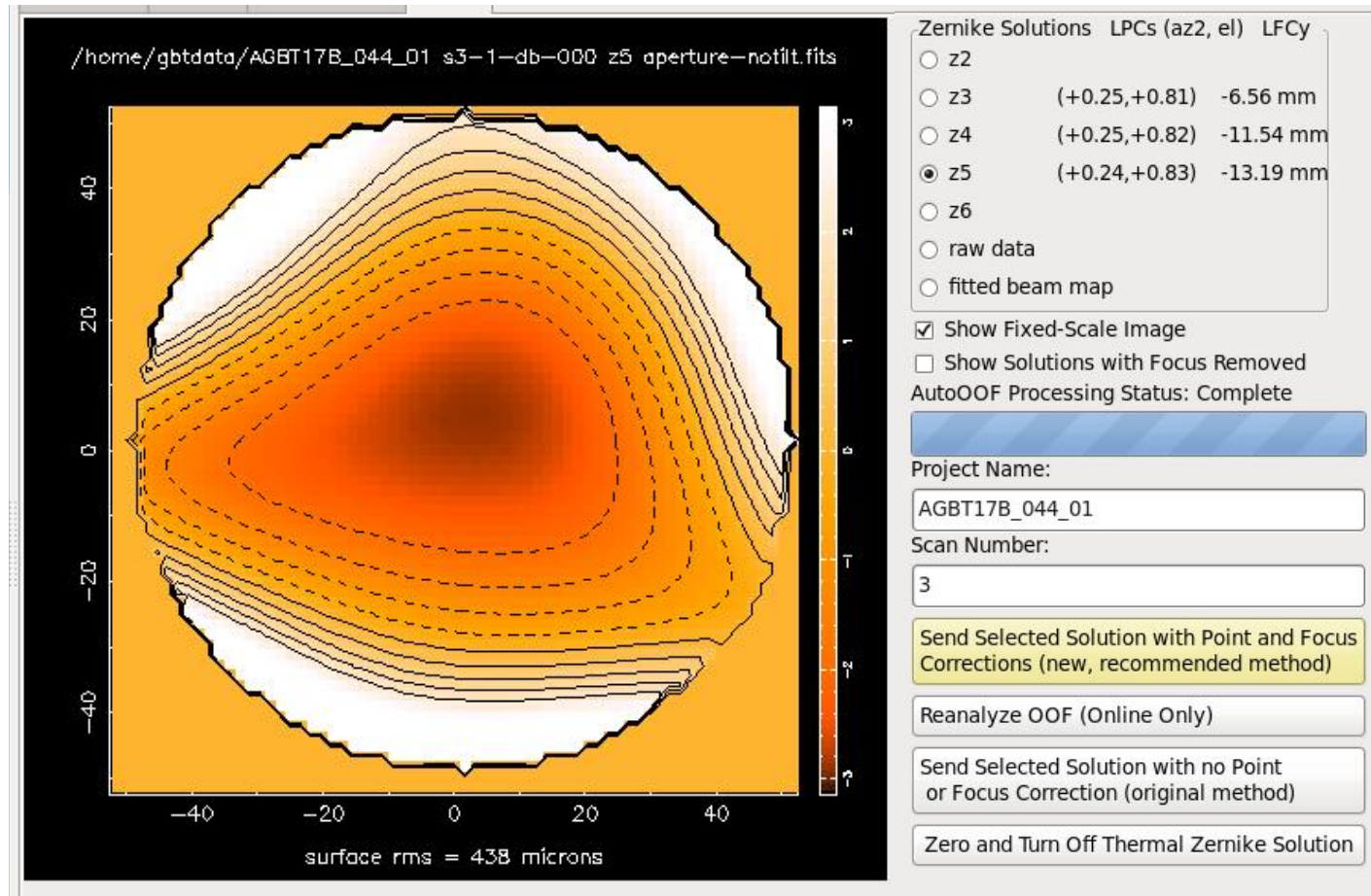
(b) A plot of raw OOF data on a source which is too faint.

Example of a Bad AutoOOF Solution

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

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

Check the raw data and fitted beam maps.

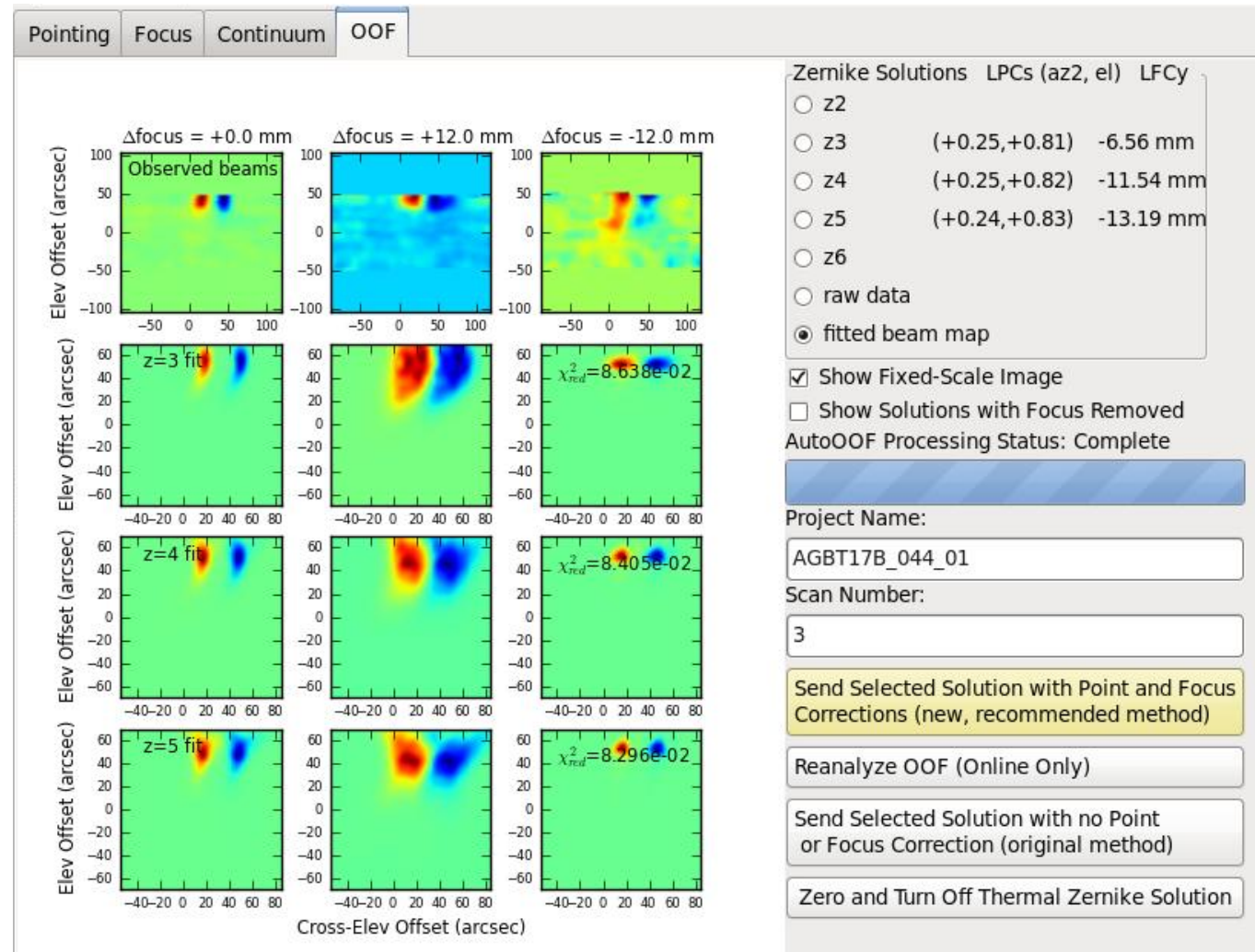


Beam Maps of Example Bad OOF

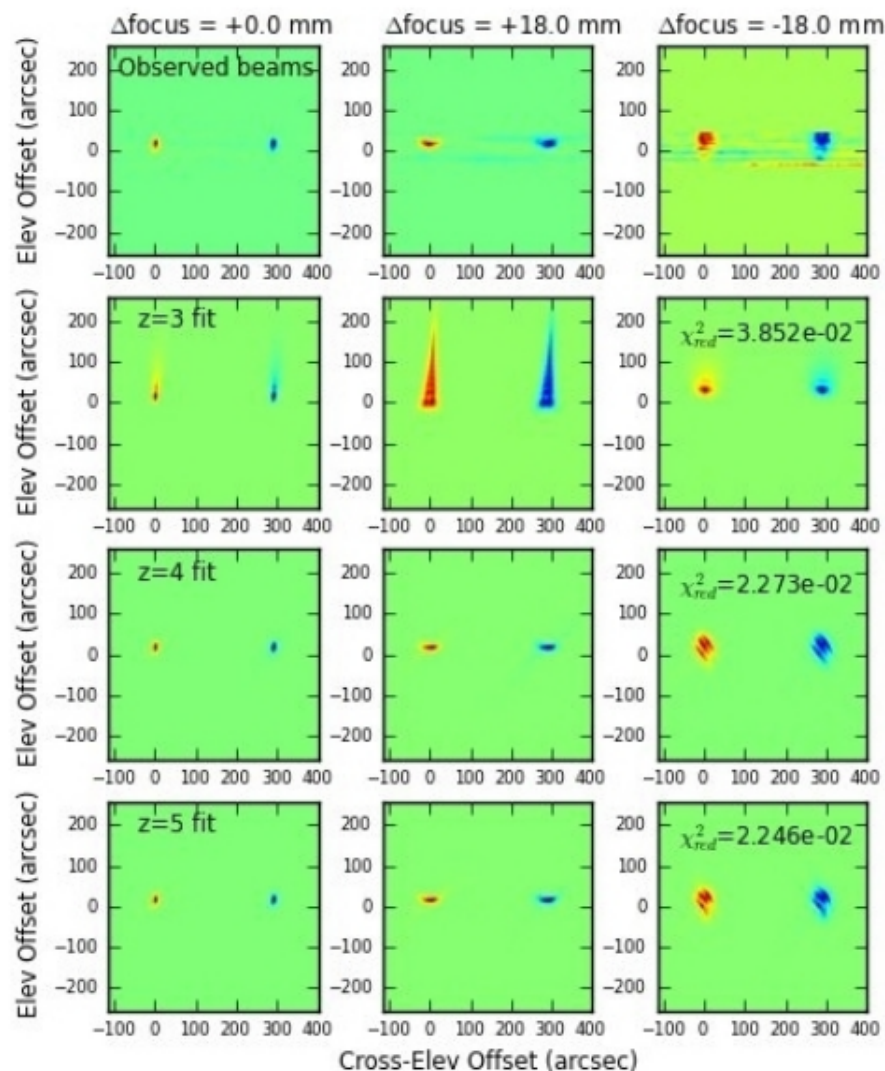
The “observed” beams should not be streaks or very elongated. This can happen in windy conditions.

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 beam maps 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).

Cleo Status Window

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 **FSW1ENOCAL**

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

Rest Freq **89188.5247** Velocity **/**

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

Dynamic Corrections

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

ActiveSurface **VEGAS**

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

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**

Az, El LPCs

Focus YFC

Active Surface ON with Thermal corrections from OOF

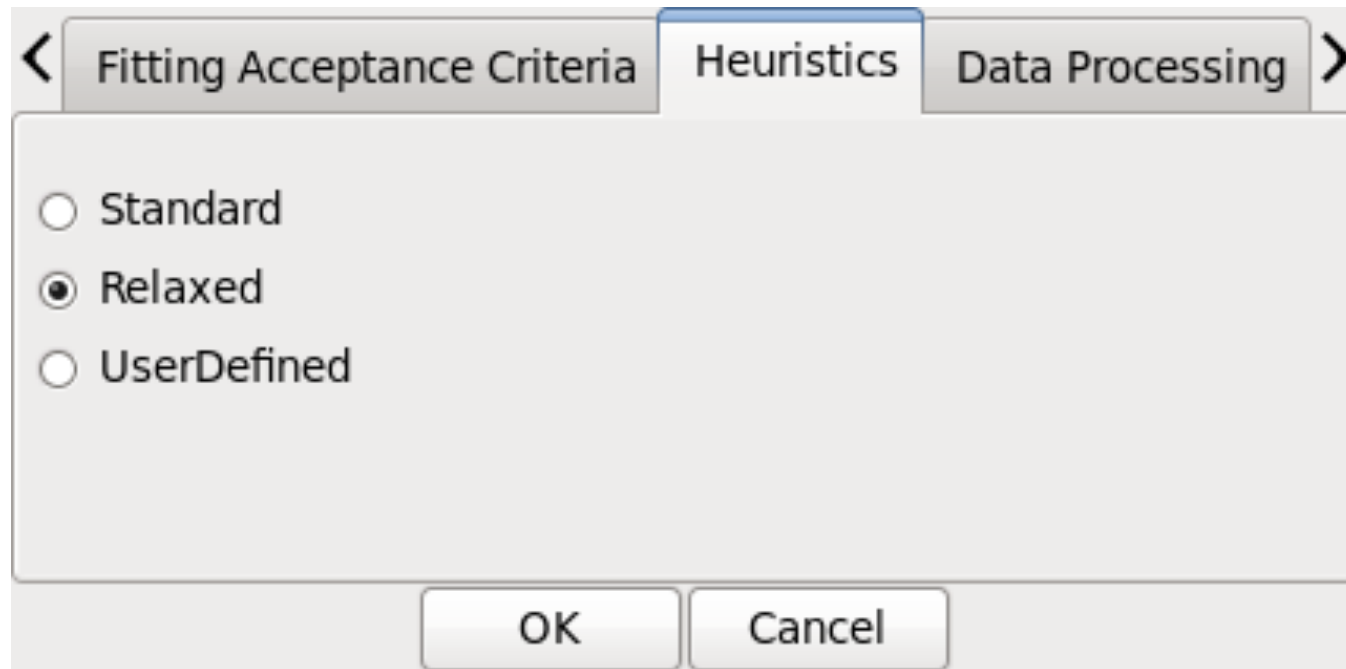
VEGAS balance values on sky: ~-20(+/-3)

Observing Strategies: 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”



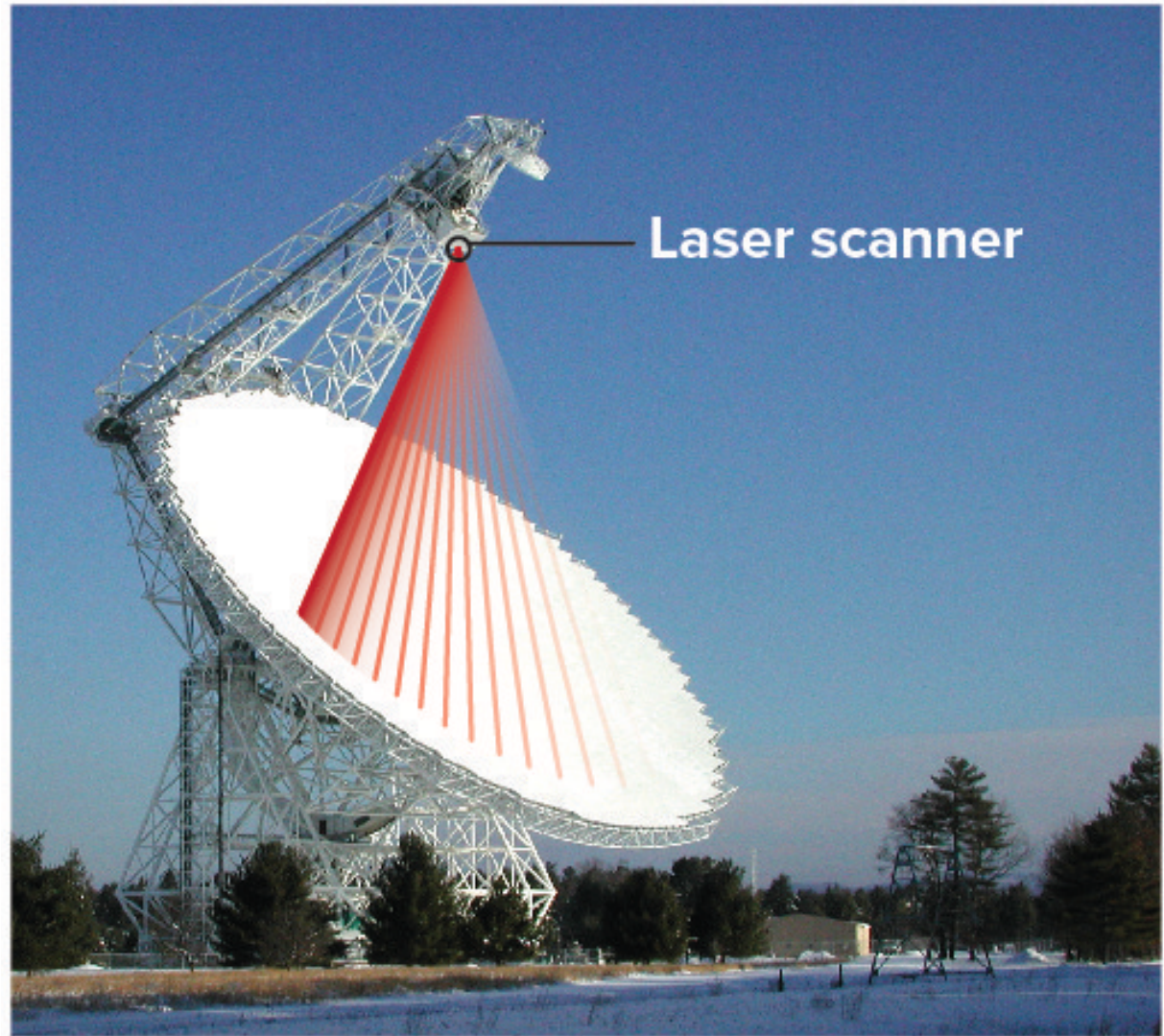
LASSI: Laser Antenna Surface Scanning Instrument

A Terrestrial Laser Scanner

- emits laser signals to calculate distances based on the time delay of the returned laser pulses

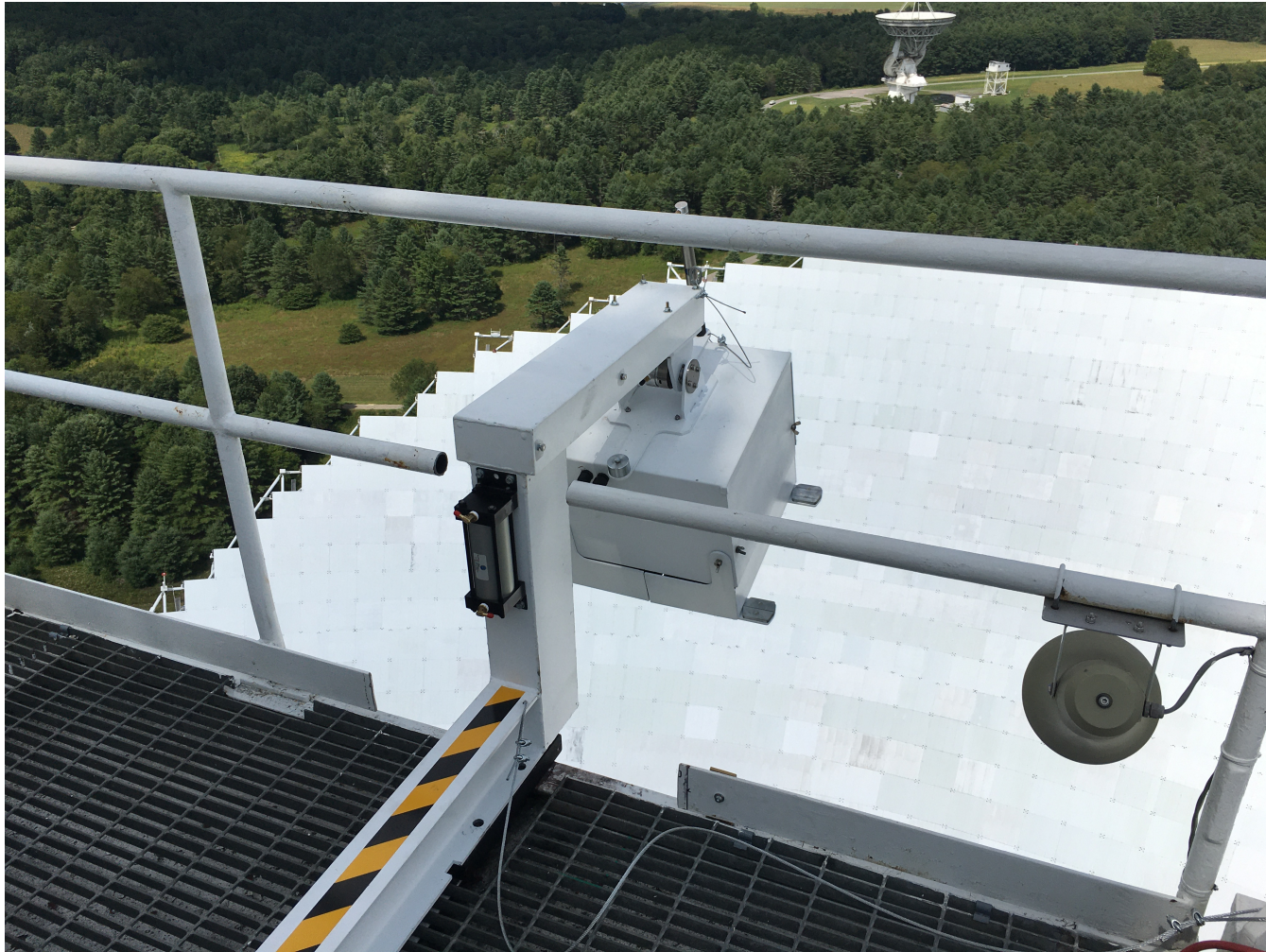
Opens up more day time observing for high frequency

Processing time takes 6 minutes (compared to the 20-30 minutes for OOF scans)

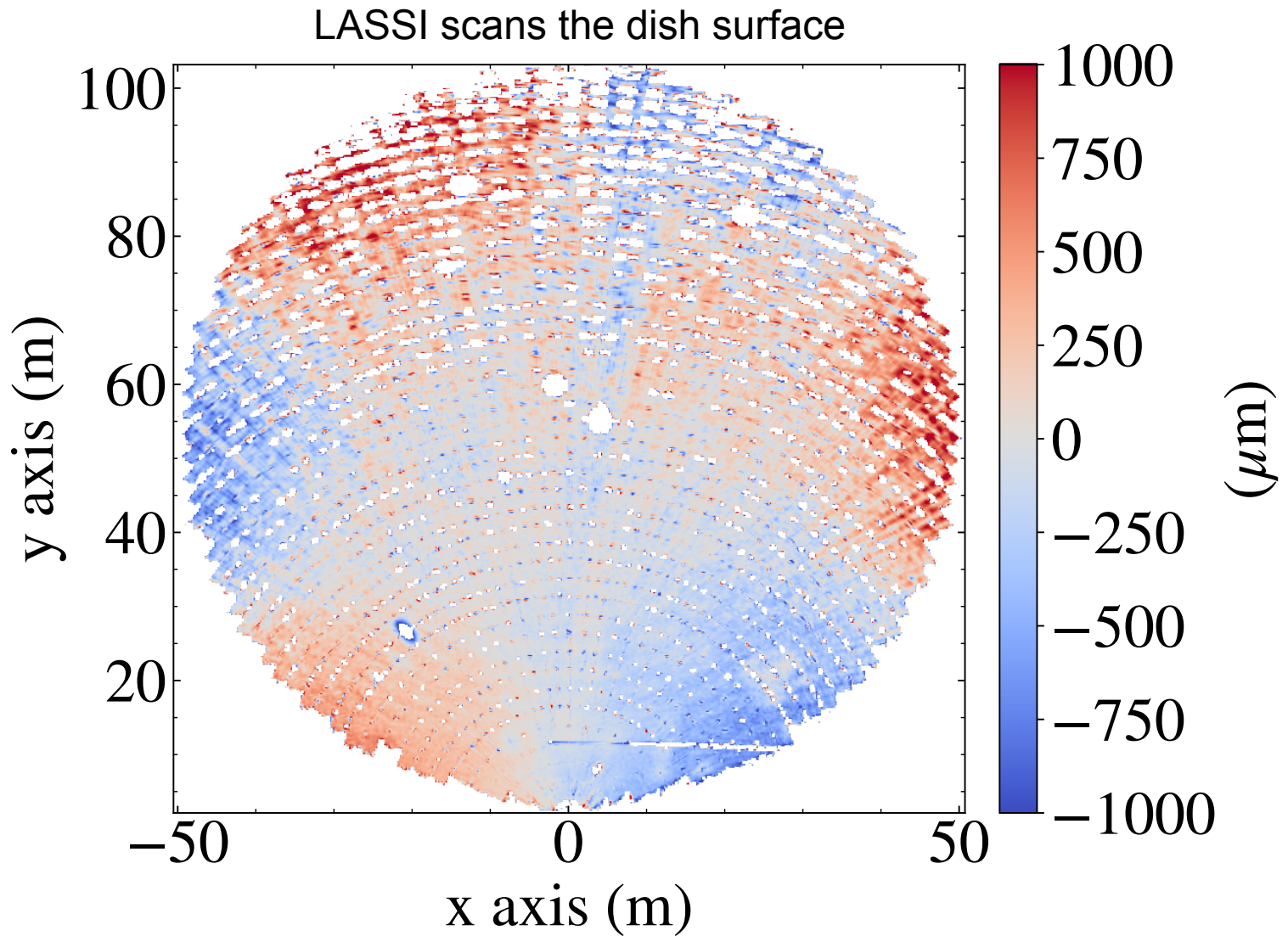


LASSI: Laser Antenna Surface Scanning Instrument

Photo of LASSI installed on the GBT



LASSI: Laser Antenna Surface Scanning Instrument





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