The Green Bank Telescope
OOF Processing

David Frayer (GBO)

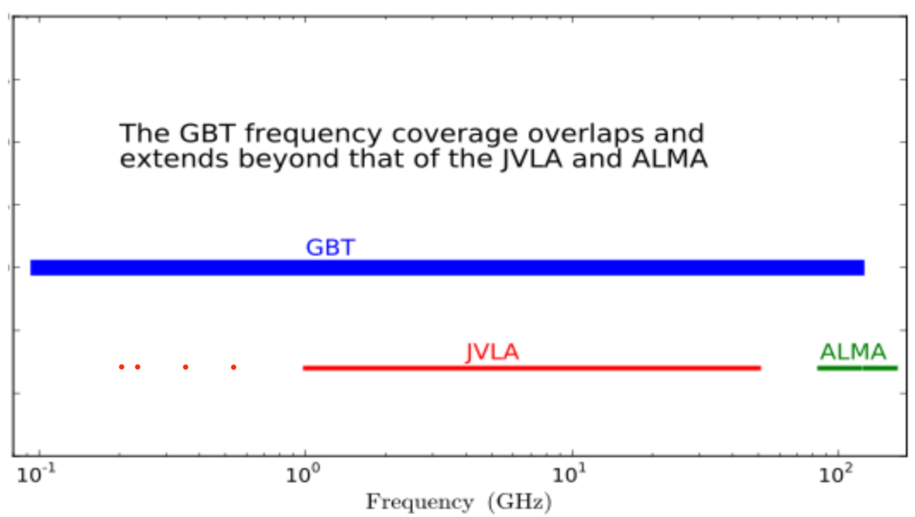
- Argus Instrument Scientist
- 4mm Instrument Scientist
- GBT PTCS and Observer Support
- Research in the evolution gas in star-forming galaxies.

GREEN BANK OBSERVATORY

NSF

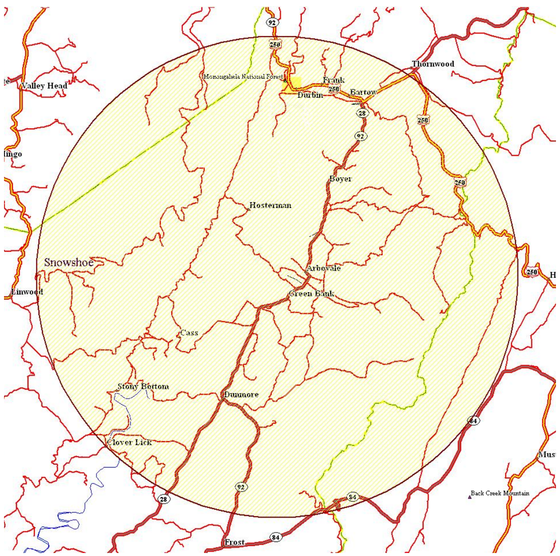
Key Capabilities of the GBT

- 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 (δ≥-46°)
- Location in the National Radio Quiet Zone



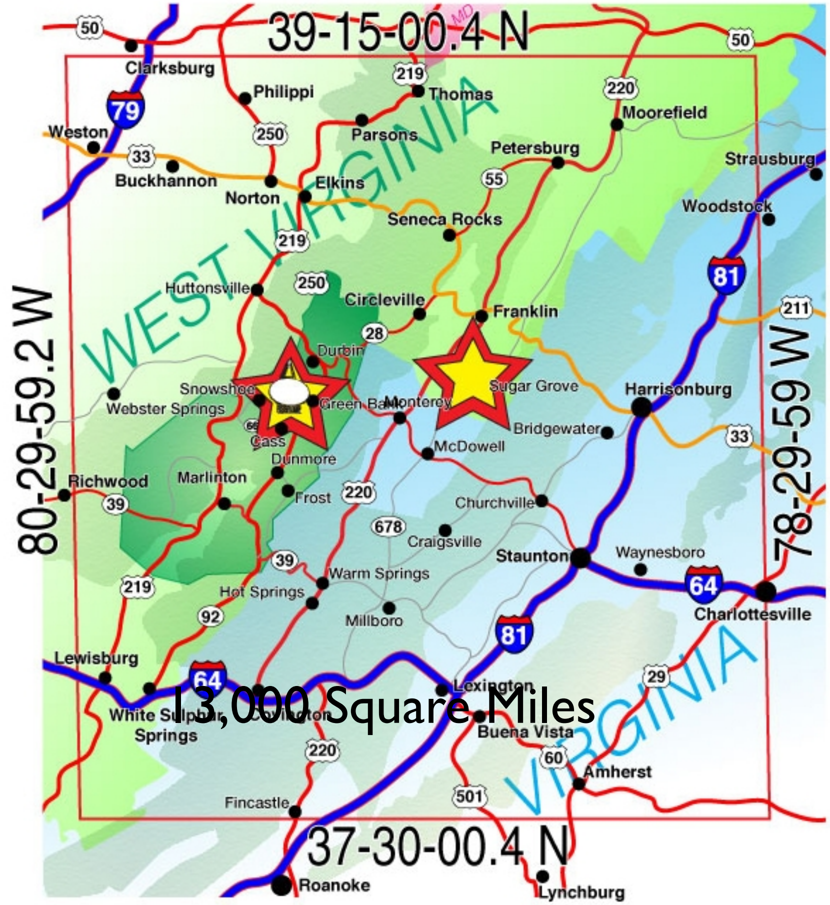
Site protected from Radio Interference

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



Protection within ten miles of the Observatory

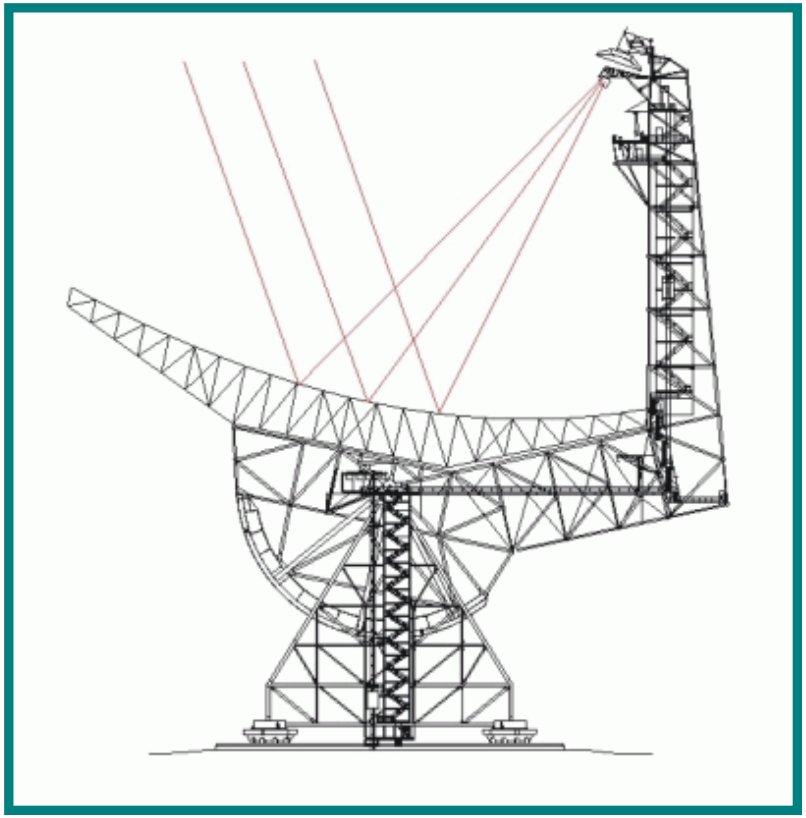
National Radio Quiet Zone
Established by the FCC and NTIA (1957)

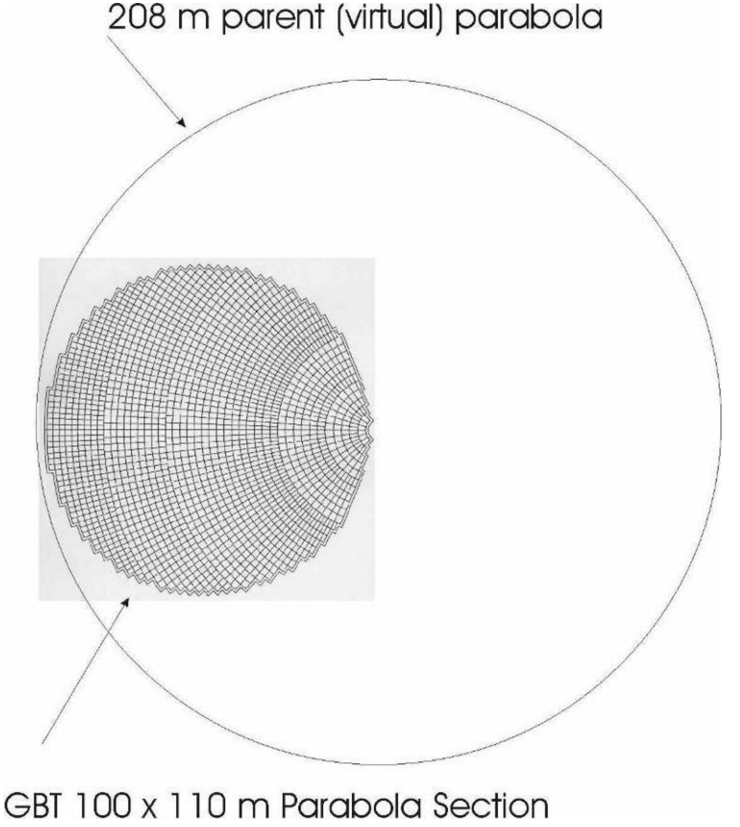


13,000 Square Miles

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)

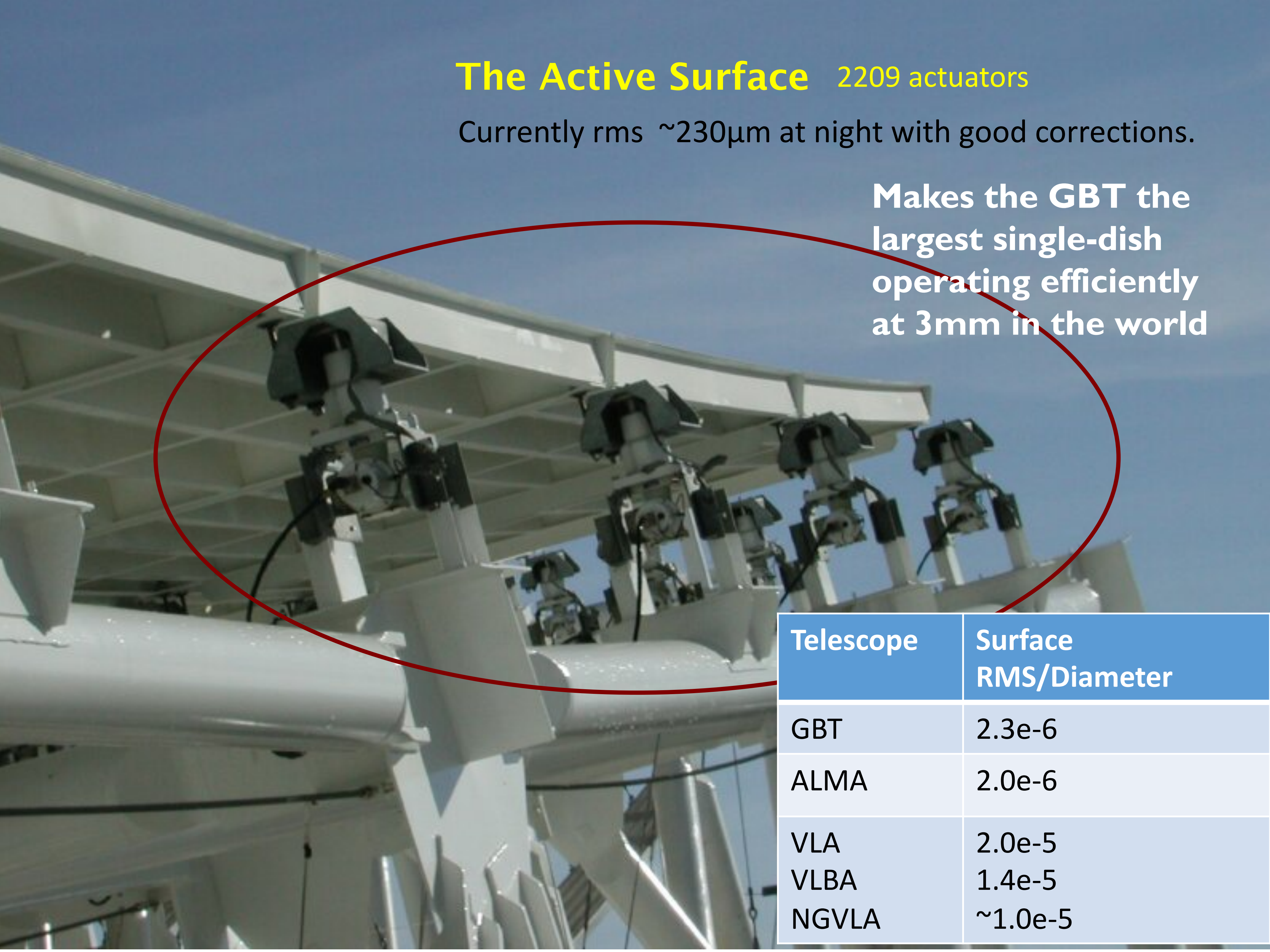




The Active Surface 2209 actuators

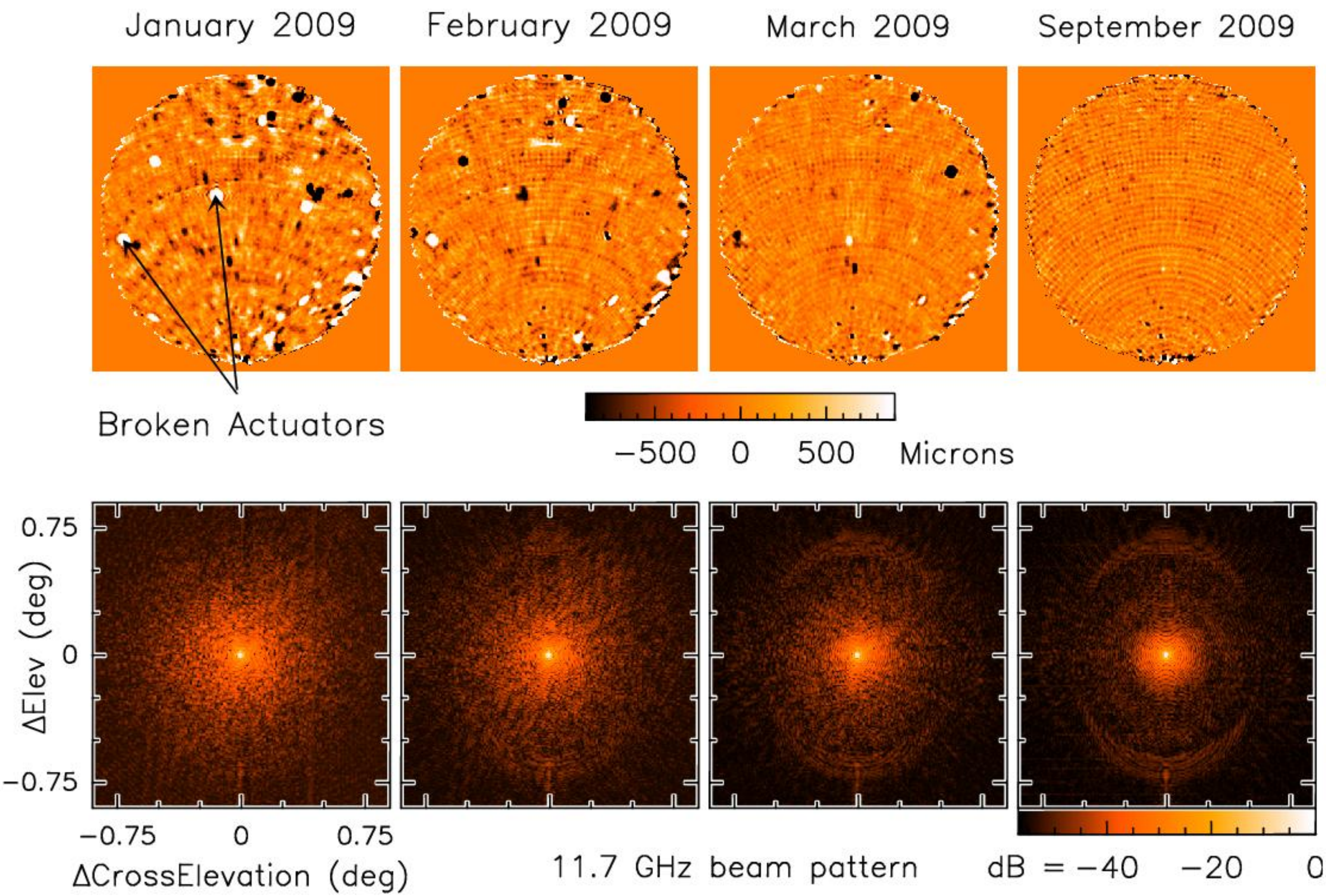
Currently rms ~230µm at night with good corrections.

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



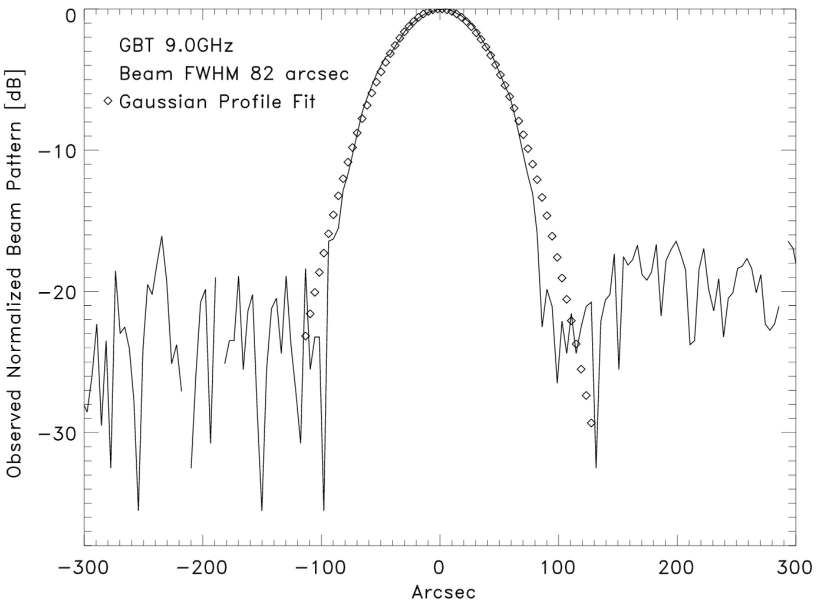
Telescope	Surface RMS/Diameter
GBT	2.3e-6
ALMA	2.0e-6
VLA VLBA NGVLA	2.0e-5 1.4e-5 ~1.0e-5

Improvements to Surface in 2009

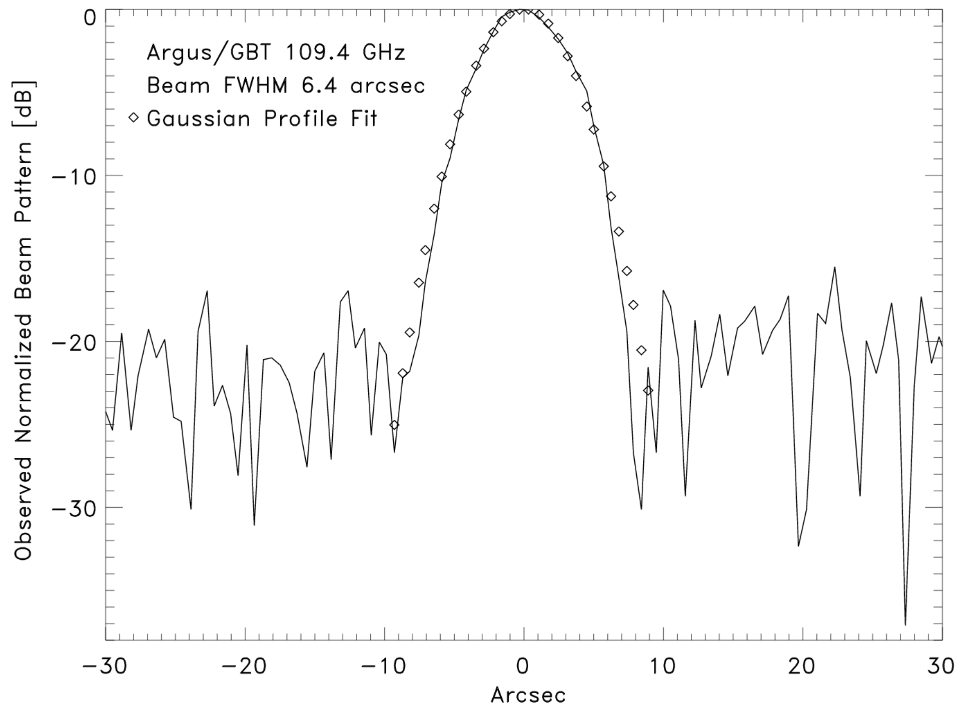


The GBT Achieves its Theoretical Beam at 110 GHz

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

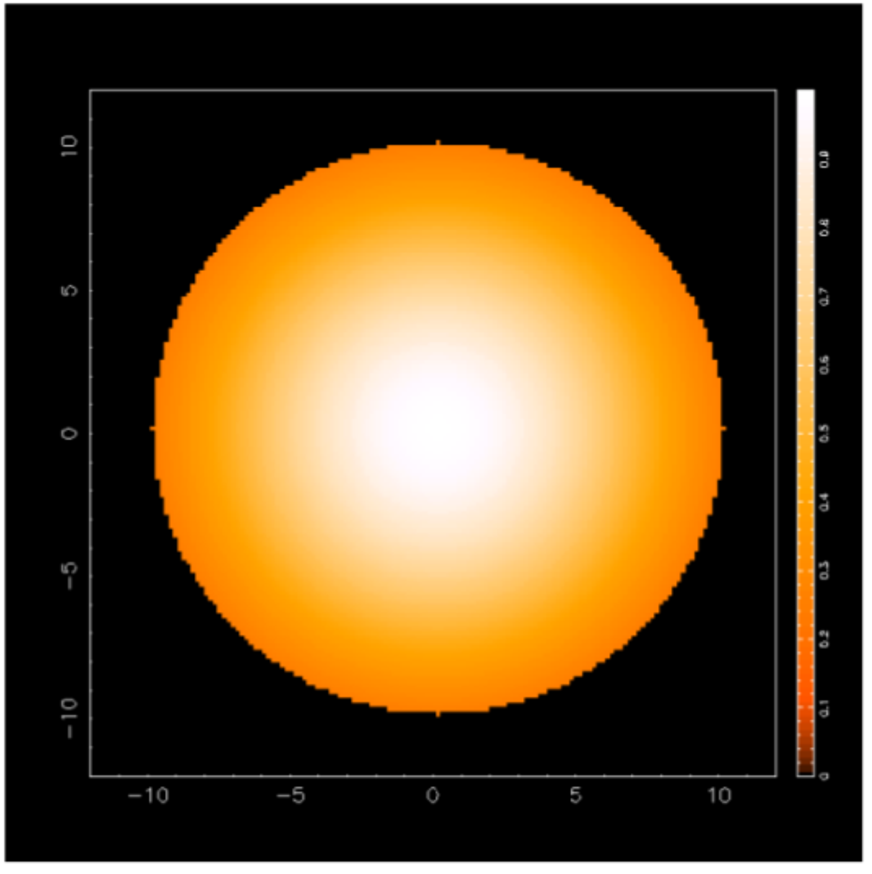


GBT/Argus 109.4 GHz

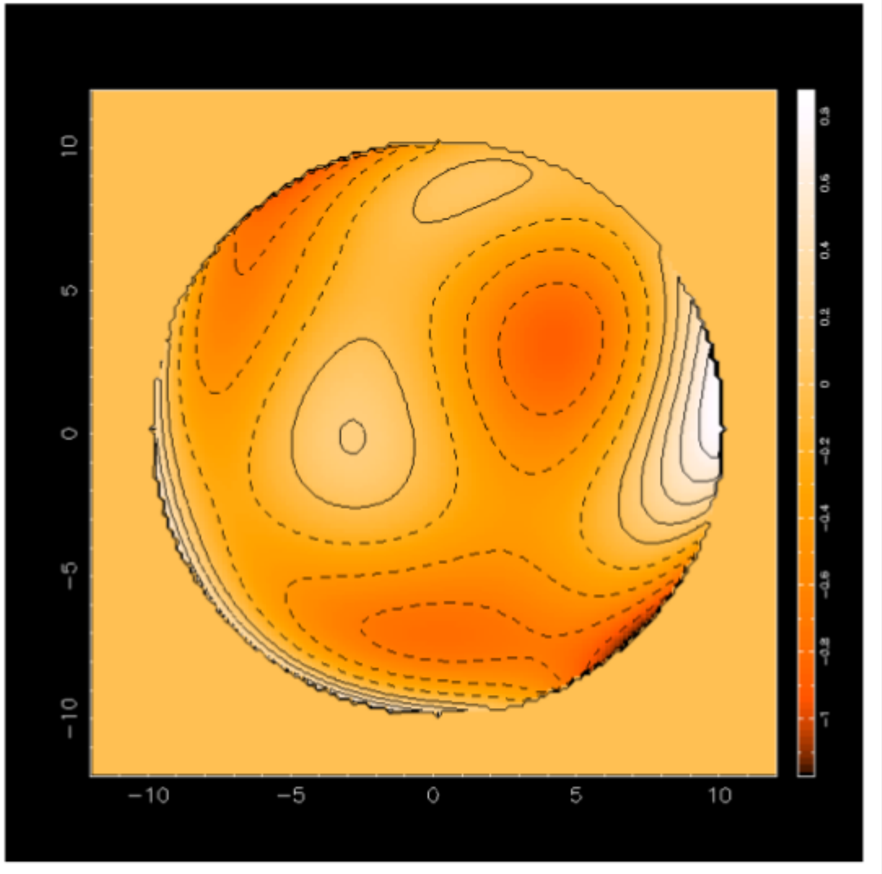
Unblock GBT aperture ➔first side-lobe predicted at -27dB

A surface with random large-scale errors

Receiver Response
(Taper/Apodisation/...)



Surface Errors
(Projected to an imaginary surface)



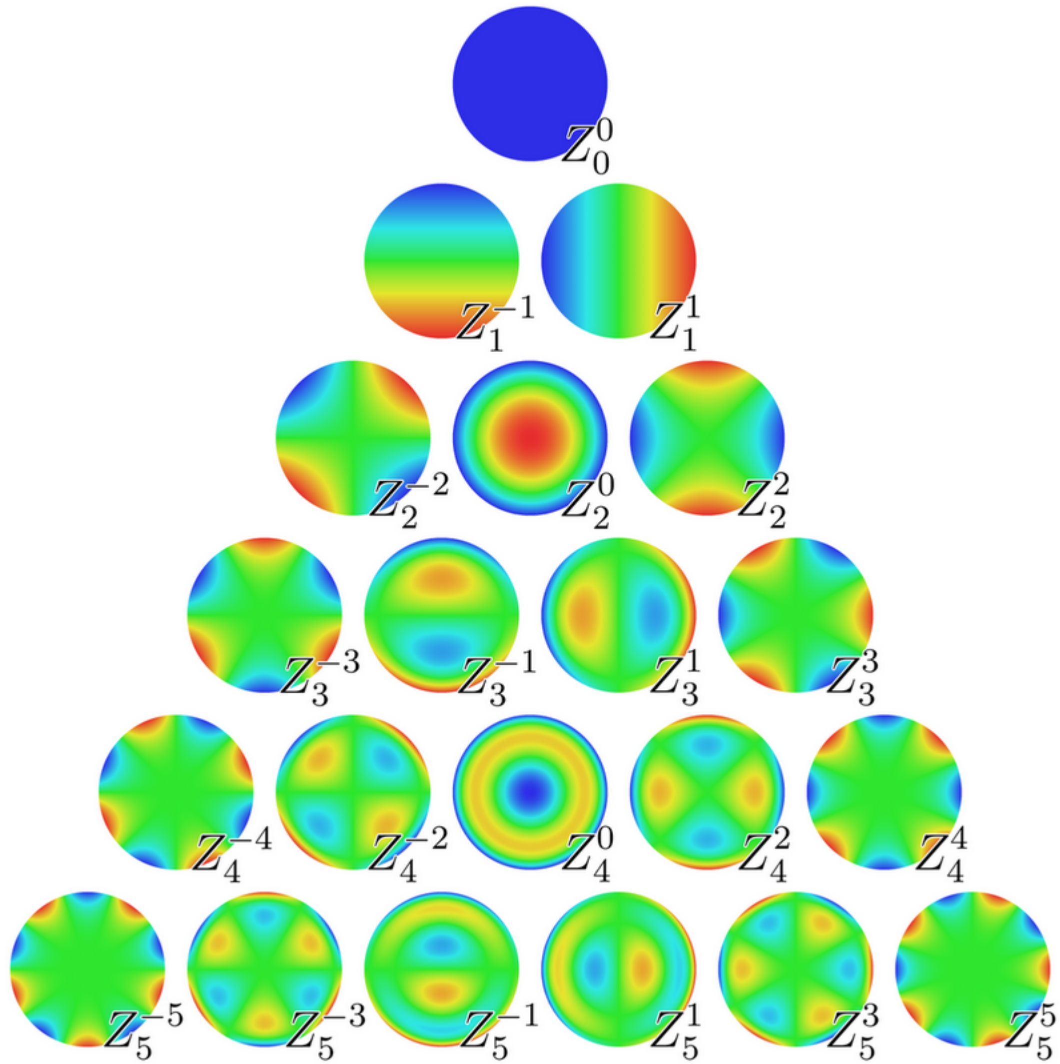
Model Surface Using Zernike Polynomials

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:

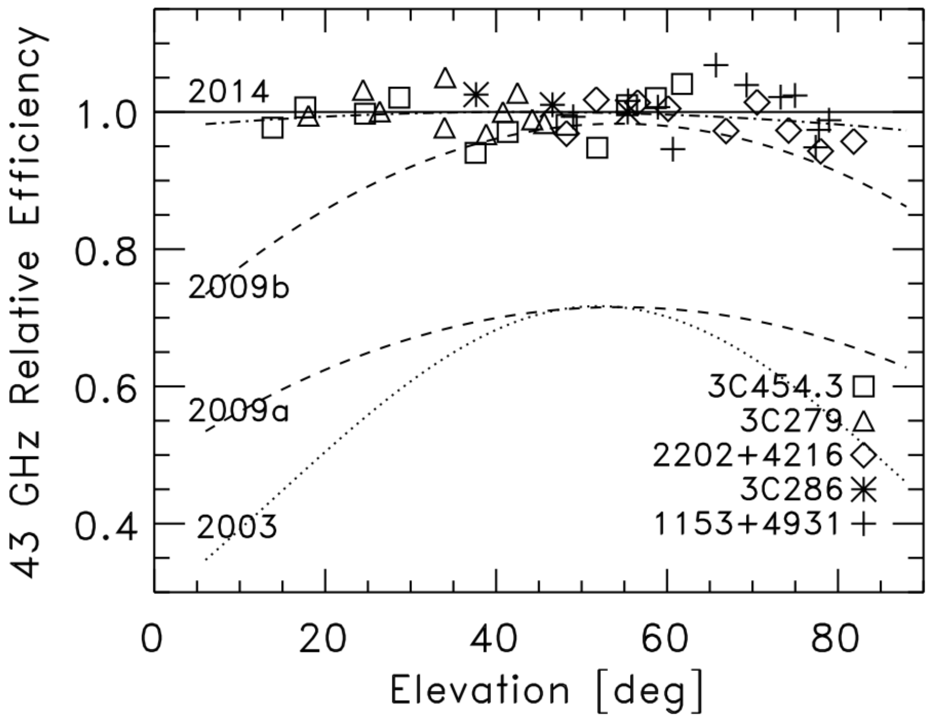
$$Z_n = A_n \sin(el) + B_n \sin(el) + C_n$$

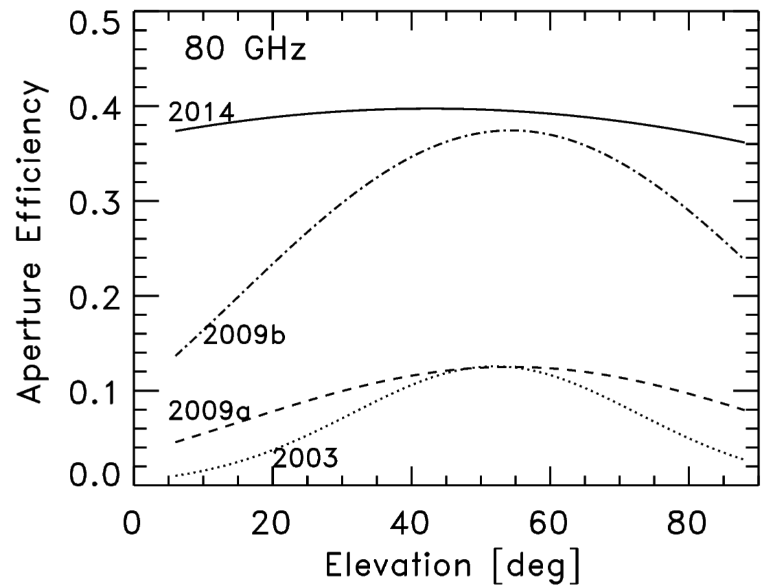
The updated 2014 gravity model improved telescope performance (PTCS PN#76)

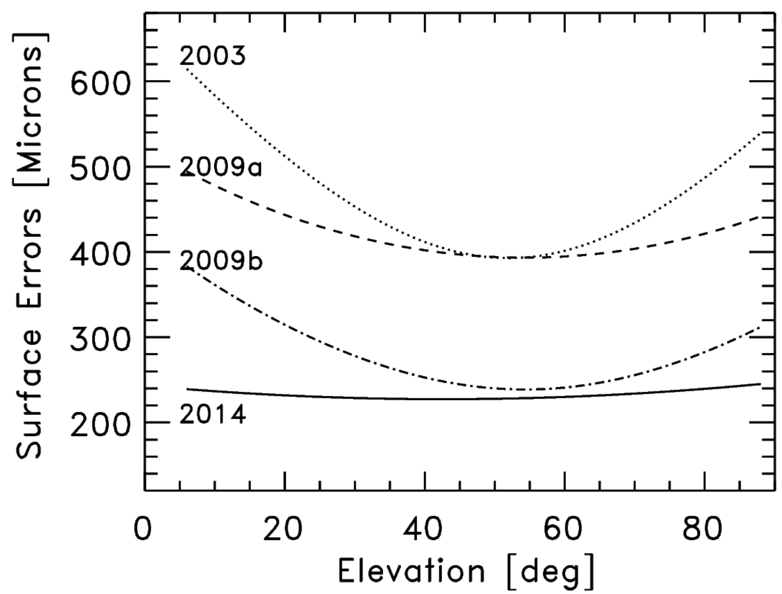
TABLE 1:

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



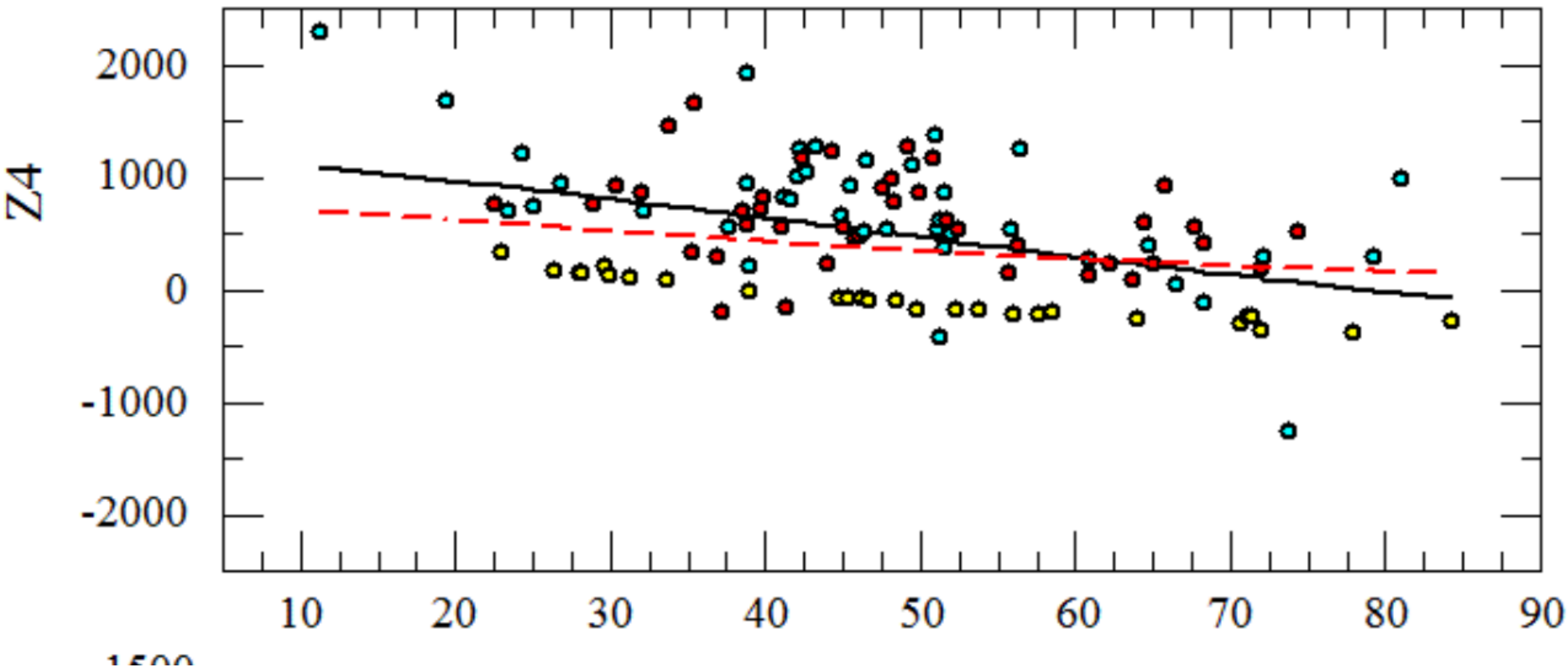




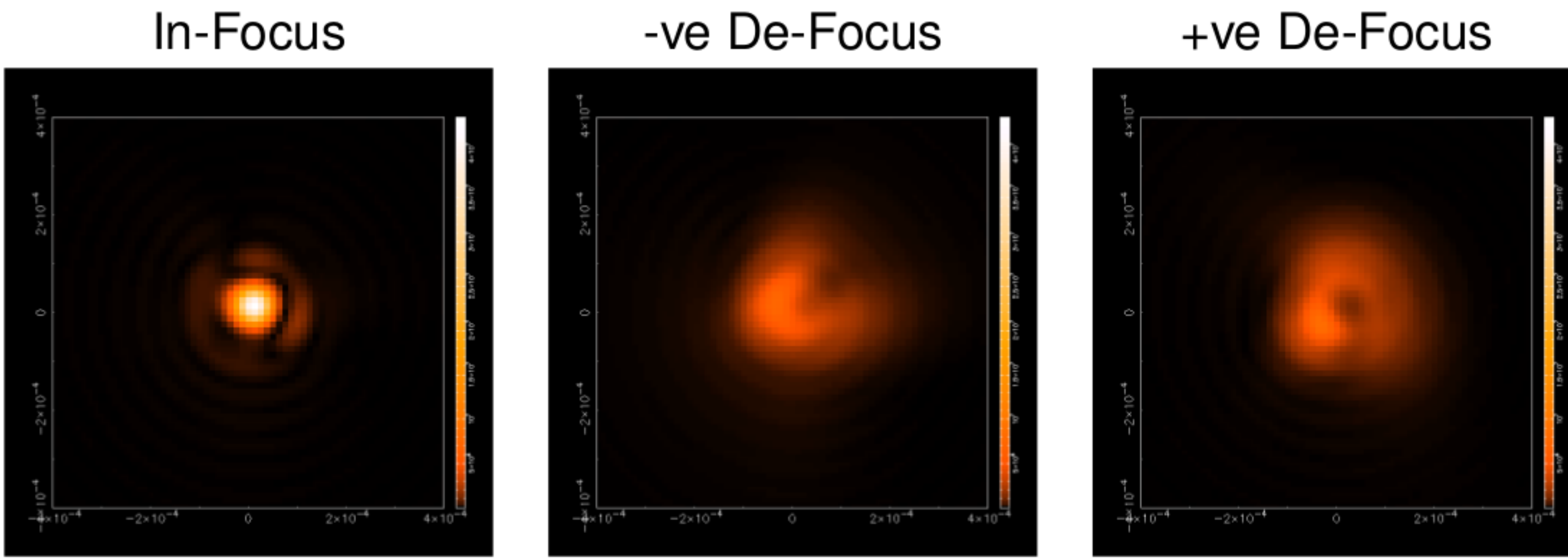
Improvements to the Zernike-Gravity model in 2014 yields a flat gain curve with elevation and has significantly improved the GBT performance at high-frequency (GBT Memo#301)

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

Zn(total) = Zn(gravity) + Zn(thermal)

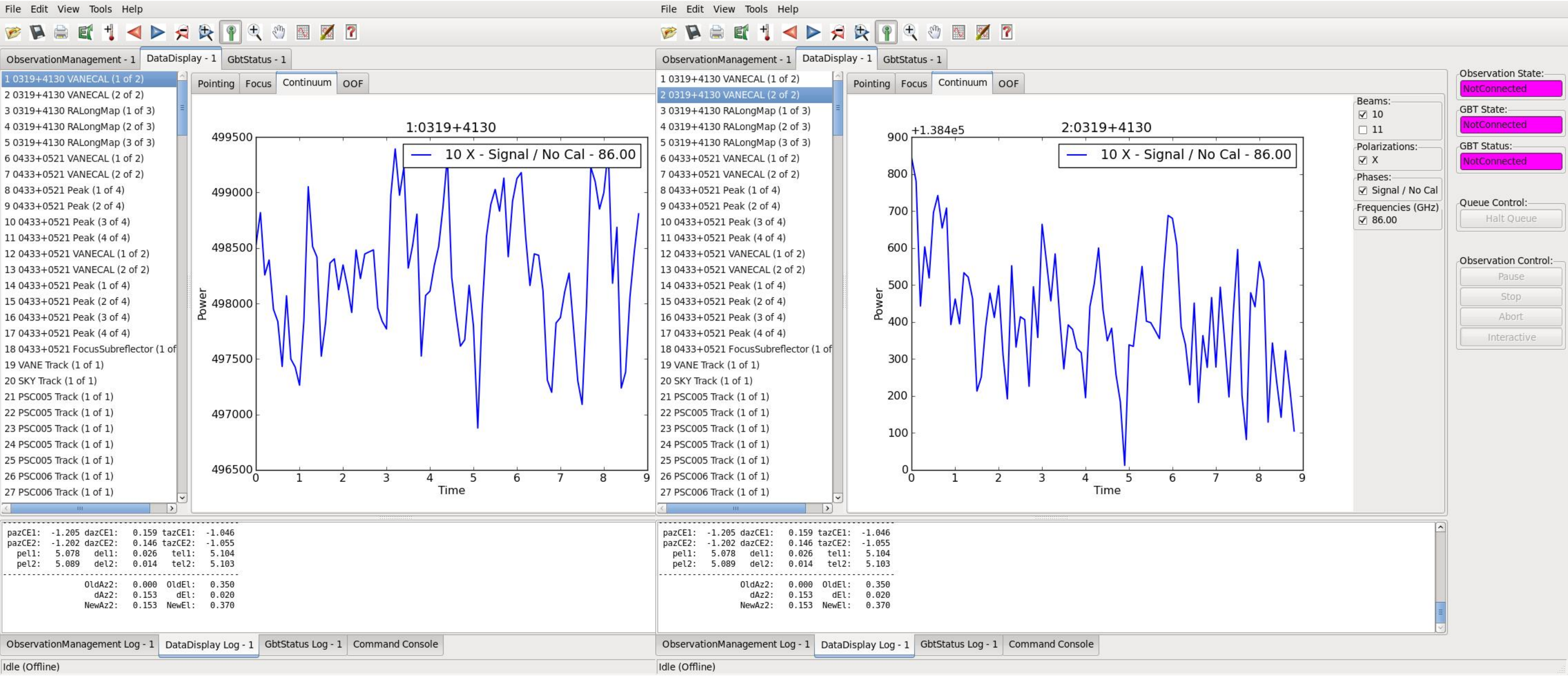


Use Out Of Focus (OOF) mapping observations of bright point sources to derive Zernike parameters



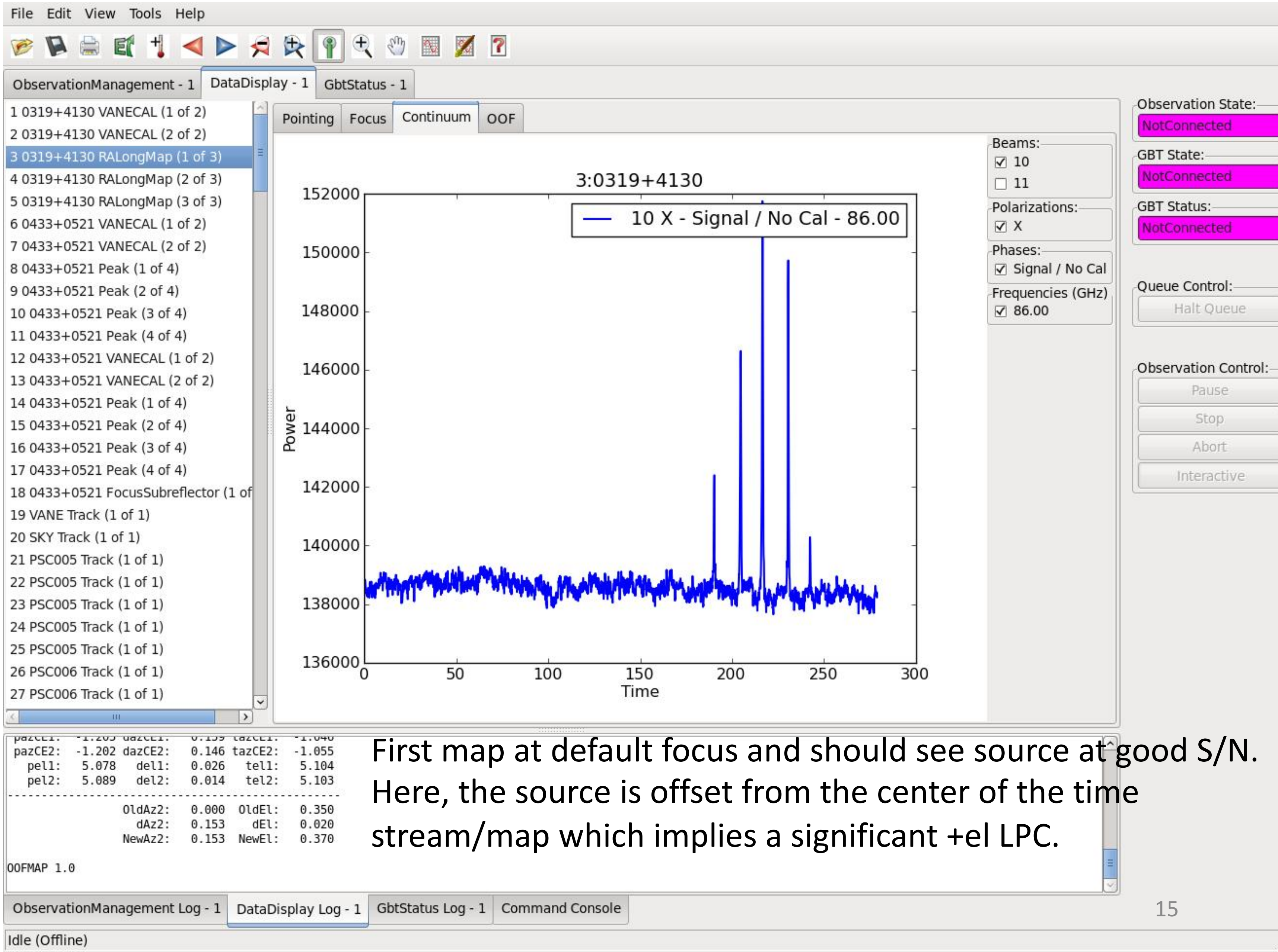
Example Argus AutoOOF Observations:

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



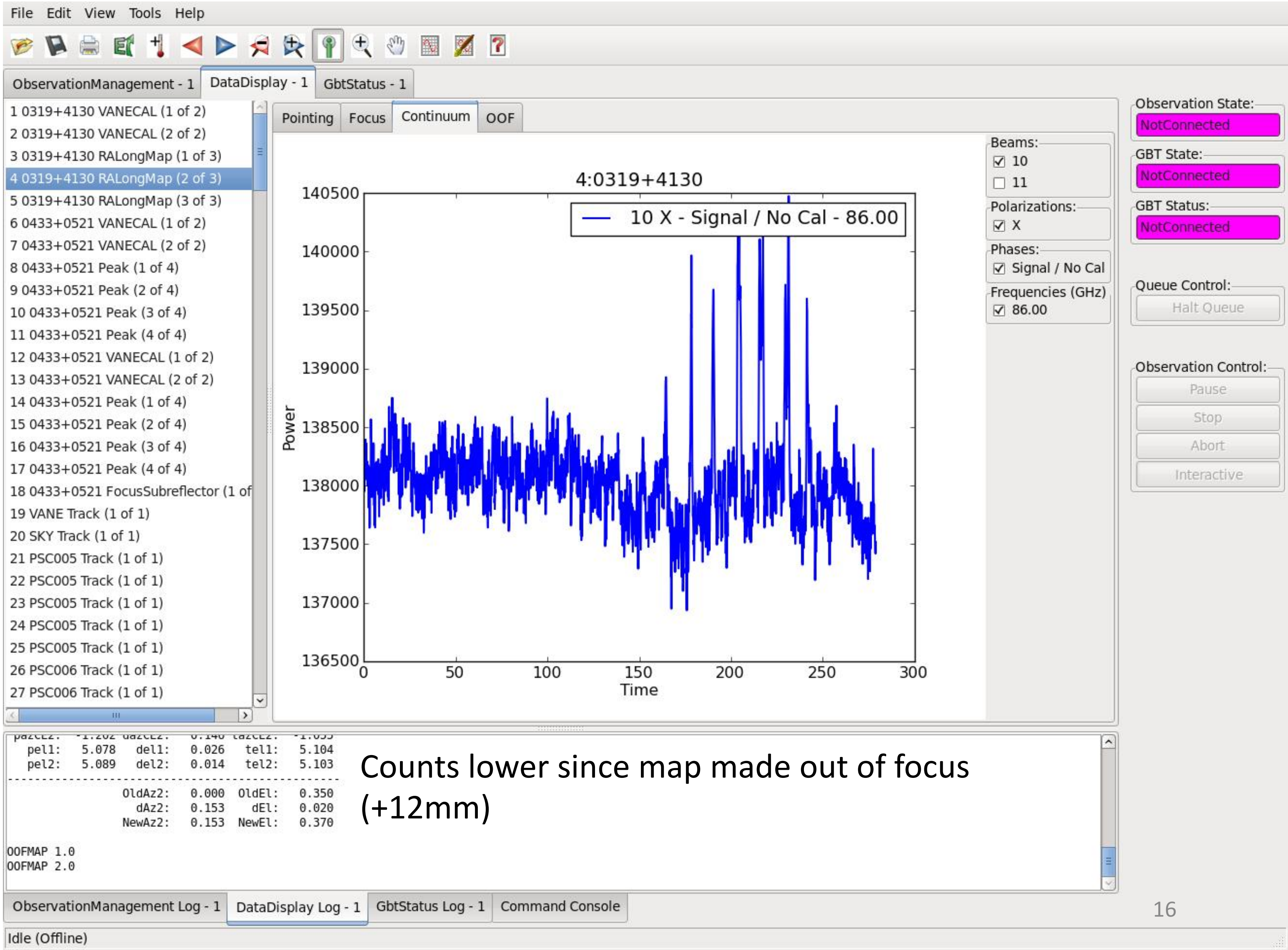
Vanecal scans with the DCR – first scan is with VANE (4.985e5 counts) and second scan is on SKY (1.354e5+500 counts). Tsys~Twarm(SKY/(VANE-SKY)) = 104 K for Twarm~270. **Should have VANE/SKY>~3 in good conditions**.

(scan 3) Argus OOF map-1 data



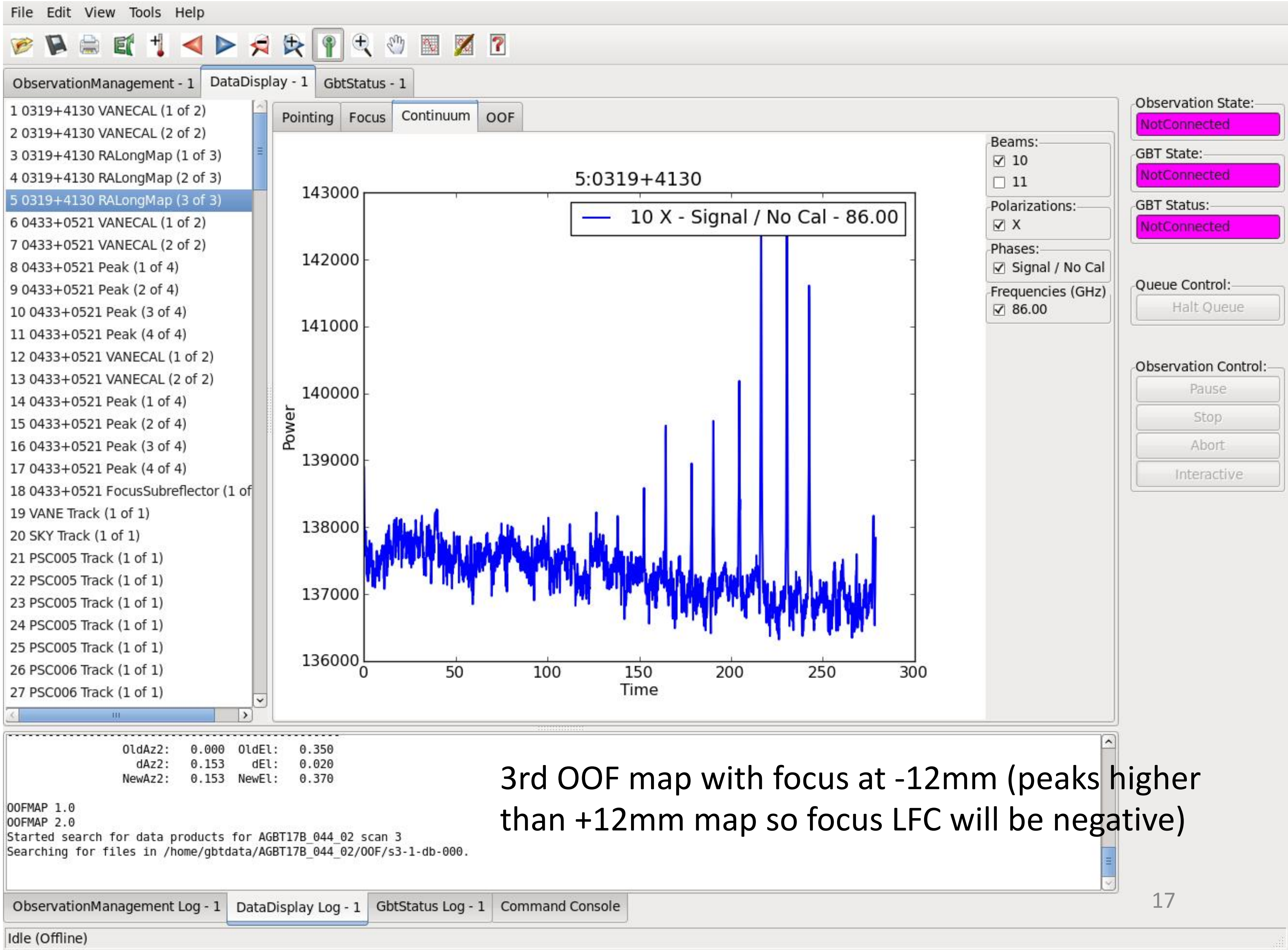
First map at default focus and should see source at good S/N. Here, the source is offset from the center of the time stream/map which implies a significant +el LPC.

(scan 4) Argus OOF map-2 data



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

(scan 5) Argus OOF map-2 data



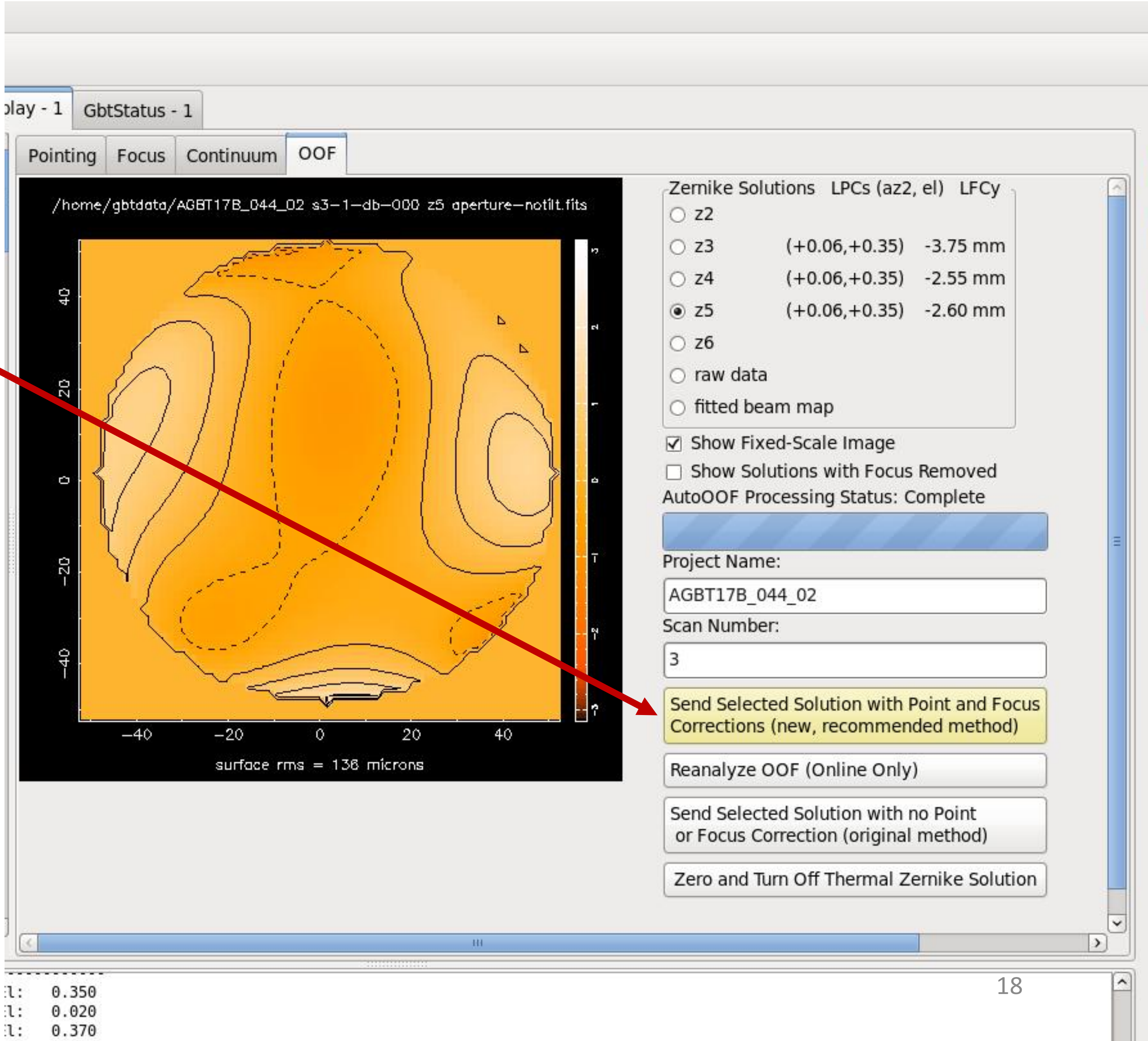
3rd OOF map with focus at -12mm (peaks higher than +12mm map so focus LFC will be negative)

AutoOOF Solutions

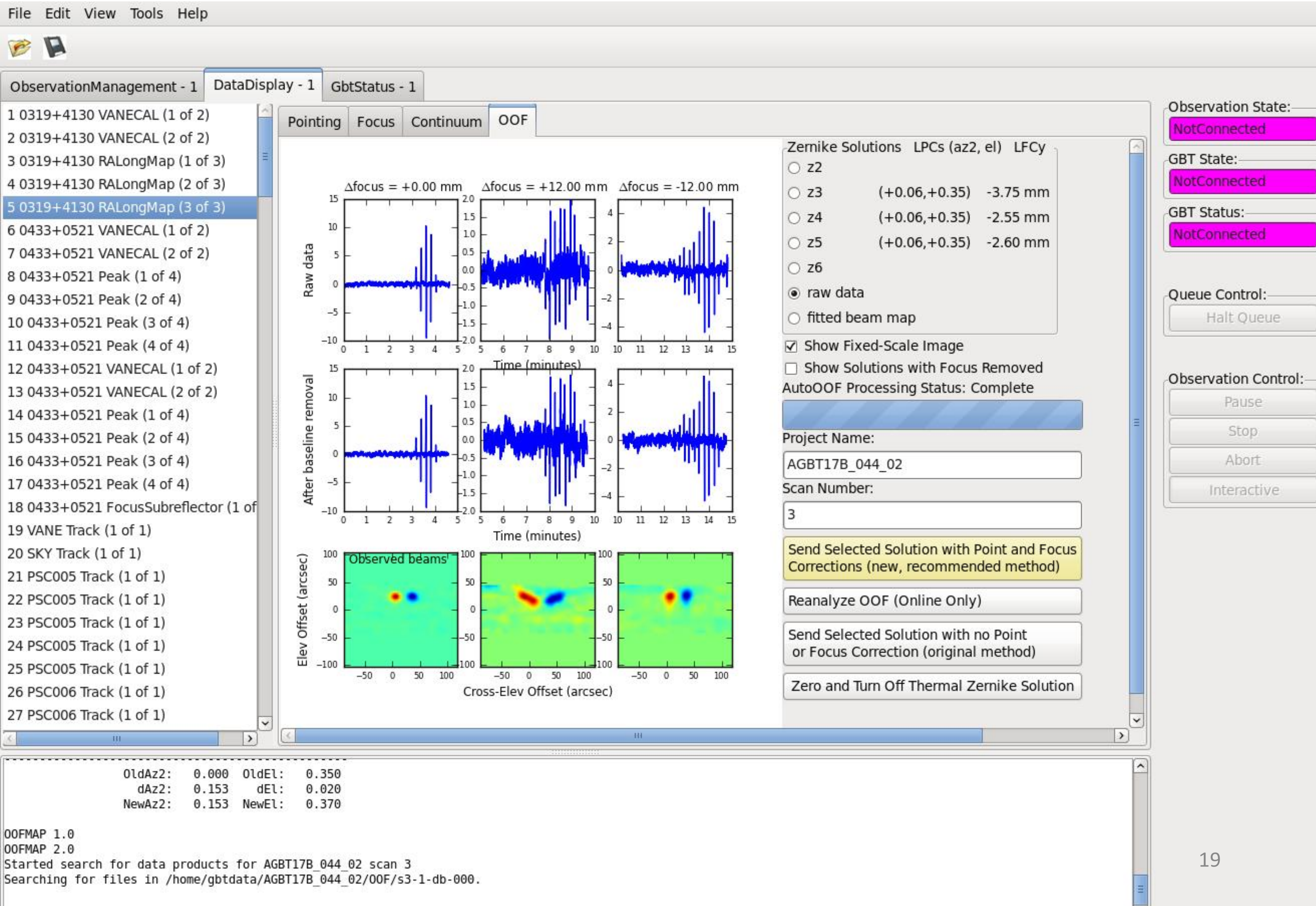
Click yellow button after OOF processing to send corrections to GBT and turn on the thermal zernike's.

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

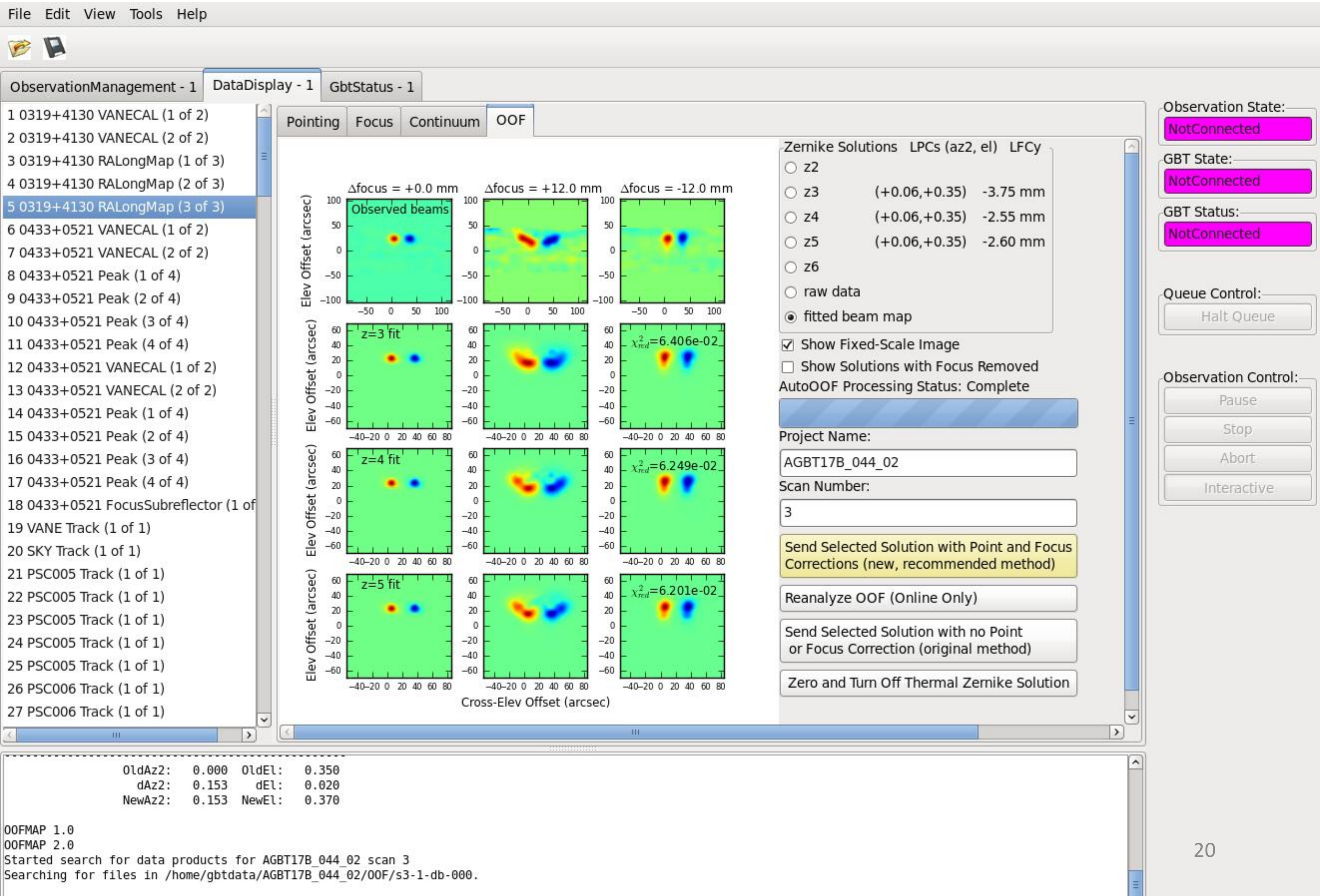
Be weary of "rms" >350 microns (which happens in windy conditions)



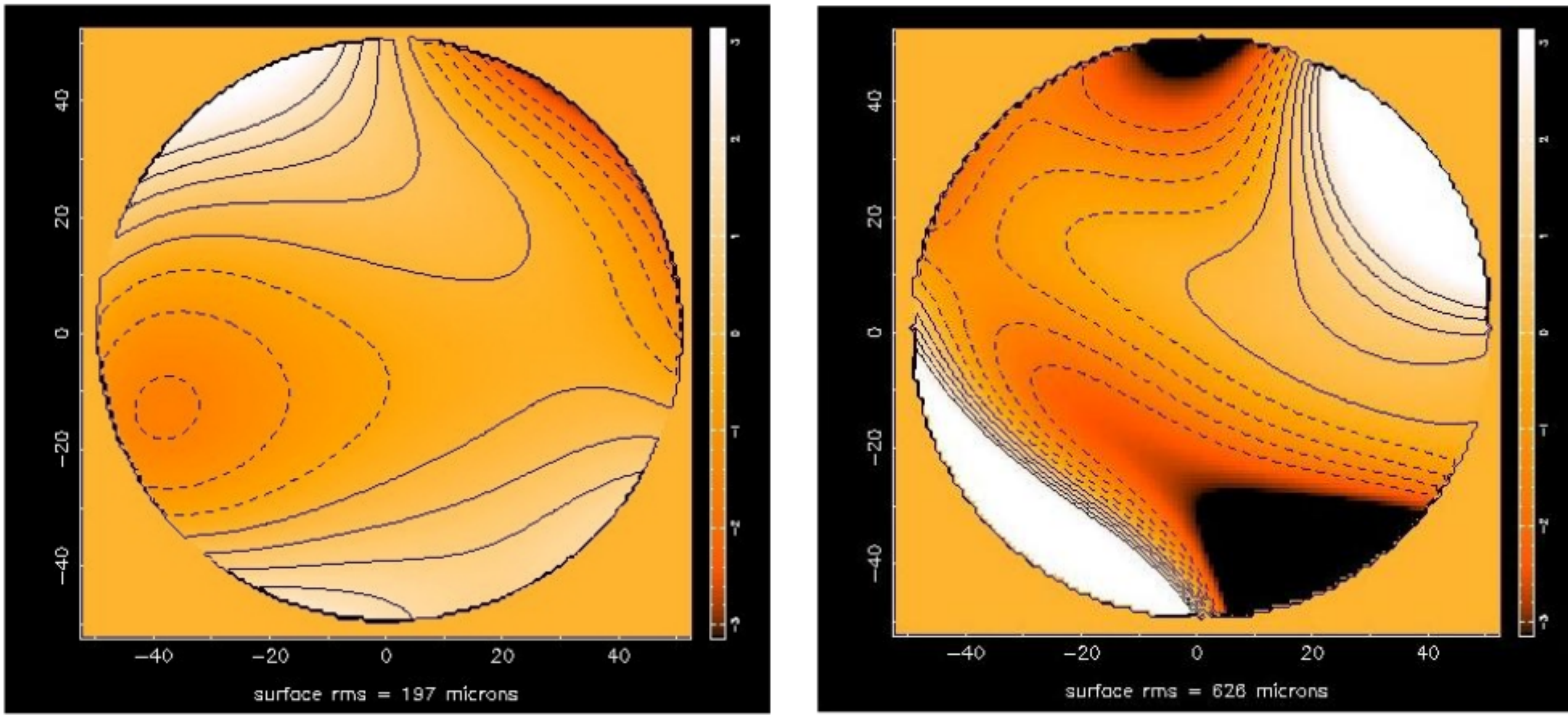
AutoOOF "Raw data"



AutoOOF Beam Fits



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

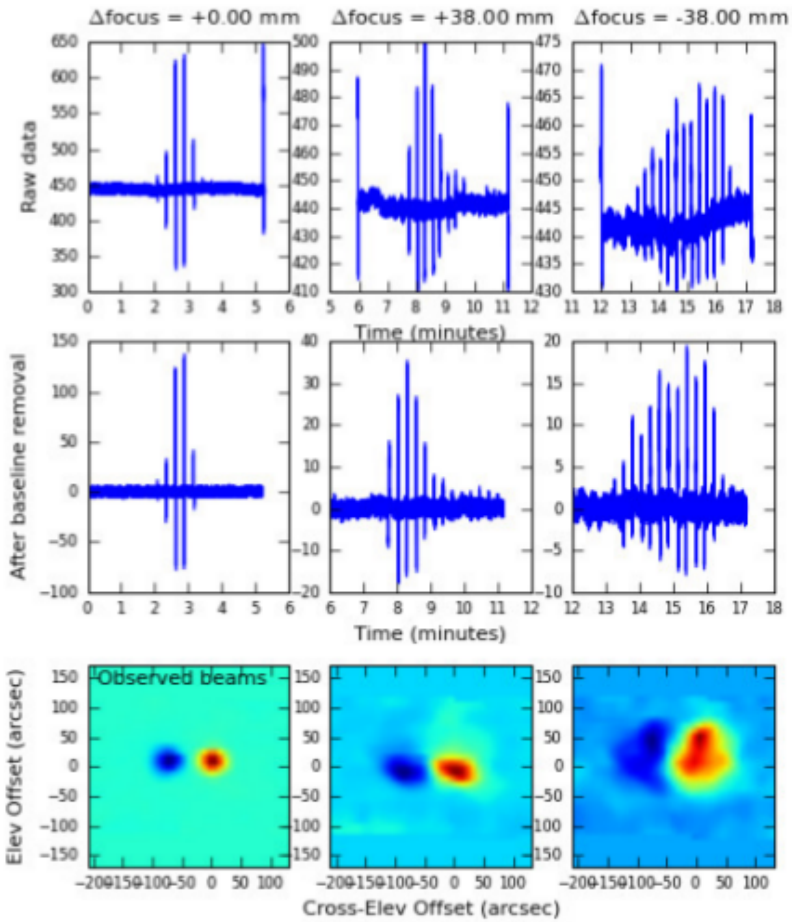


(a) Acceptable OOF solution.

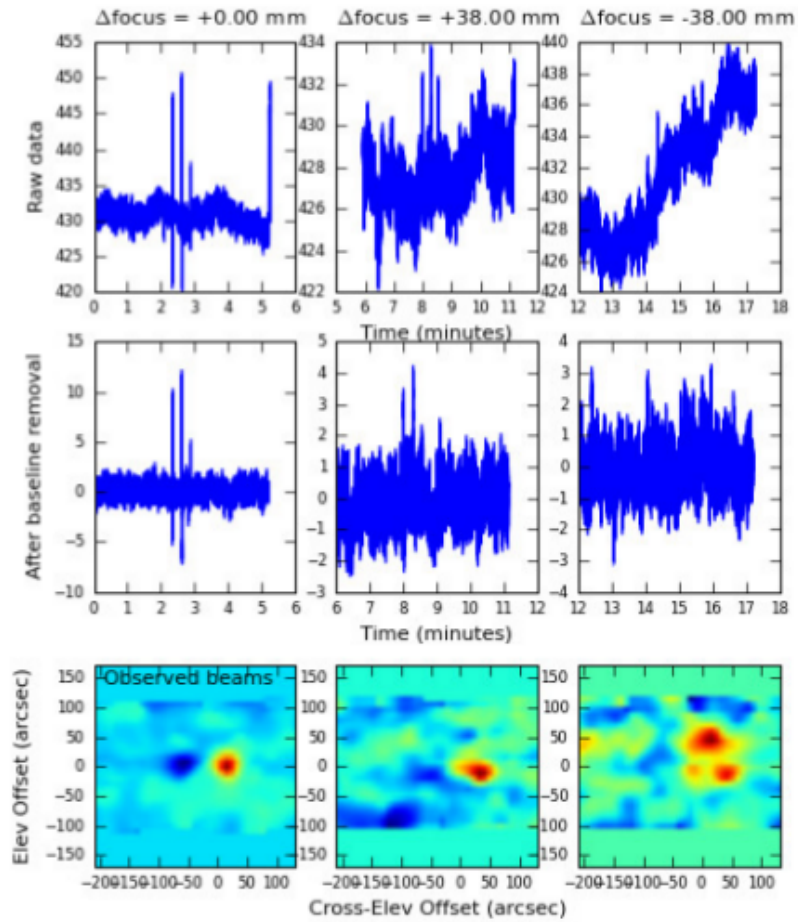
(b) Unacceptable OOF solution.

Figure 5.8: Figure 5.8a shows broad features (±1.5 radians of phase) with a surface rms of 197 μm. Figure 5.8b shows steep contour lines (±15 radians of phase) and a surface rms of 626 μm. 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.



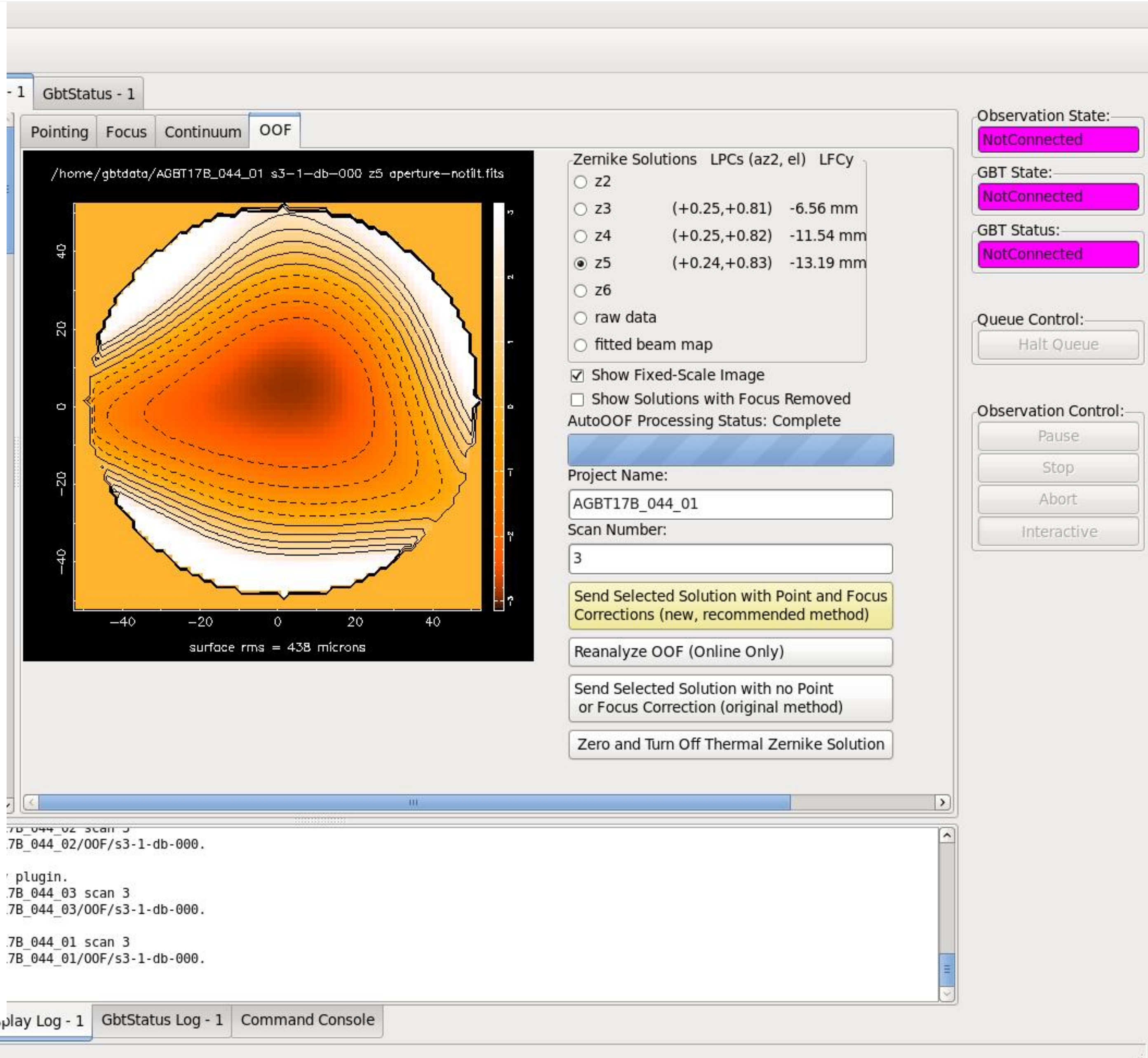
(b) A plot of raw OOF data on a source which is too faint.

Example of a Bad OOF

In this case observations were done in the keyhole at >85deg and OOF "rms" 438um with a large implied focus and EL pointing offset.

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

Check the raw data and fitted beam maps.



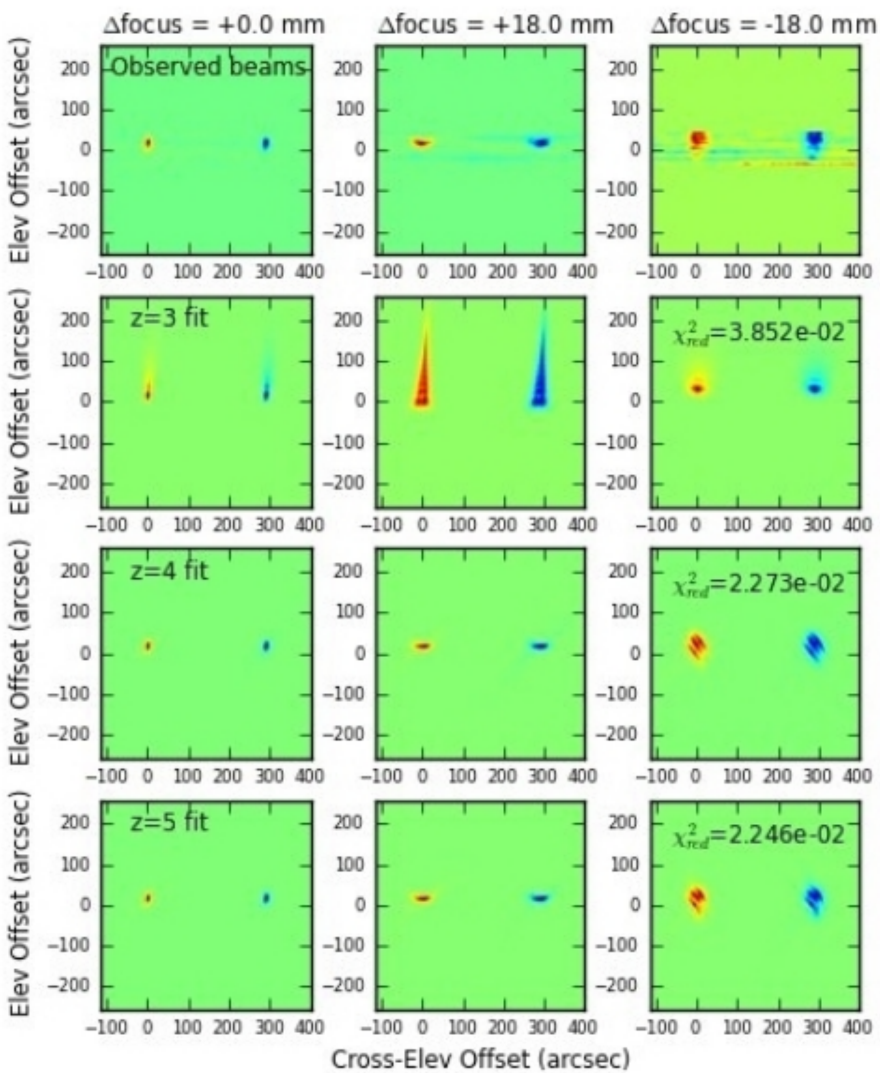
Beam Maps of Example Bad OOF

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)



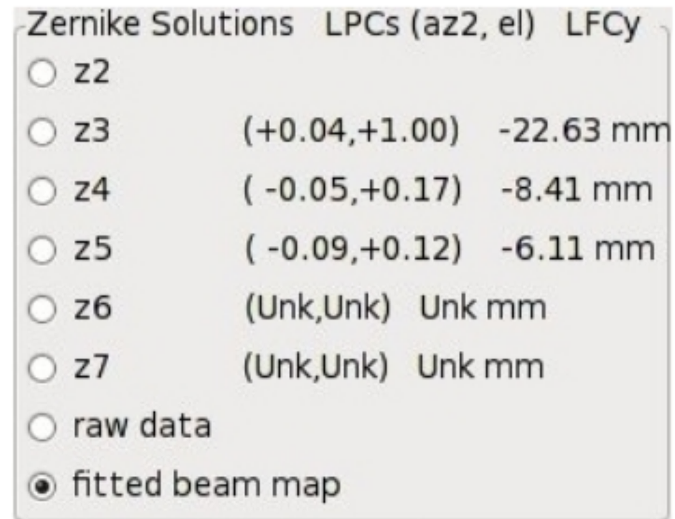
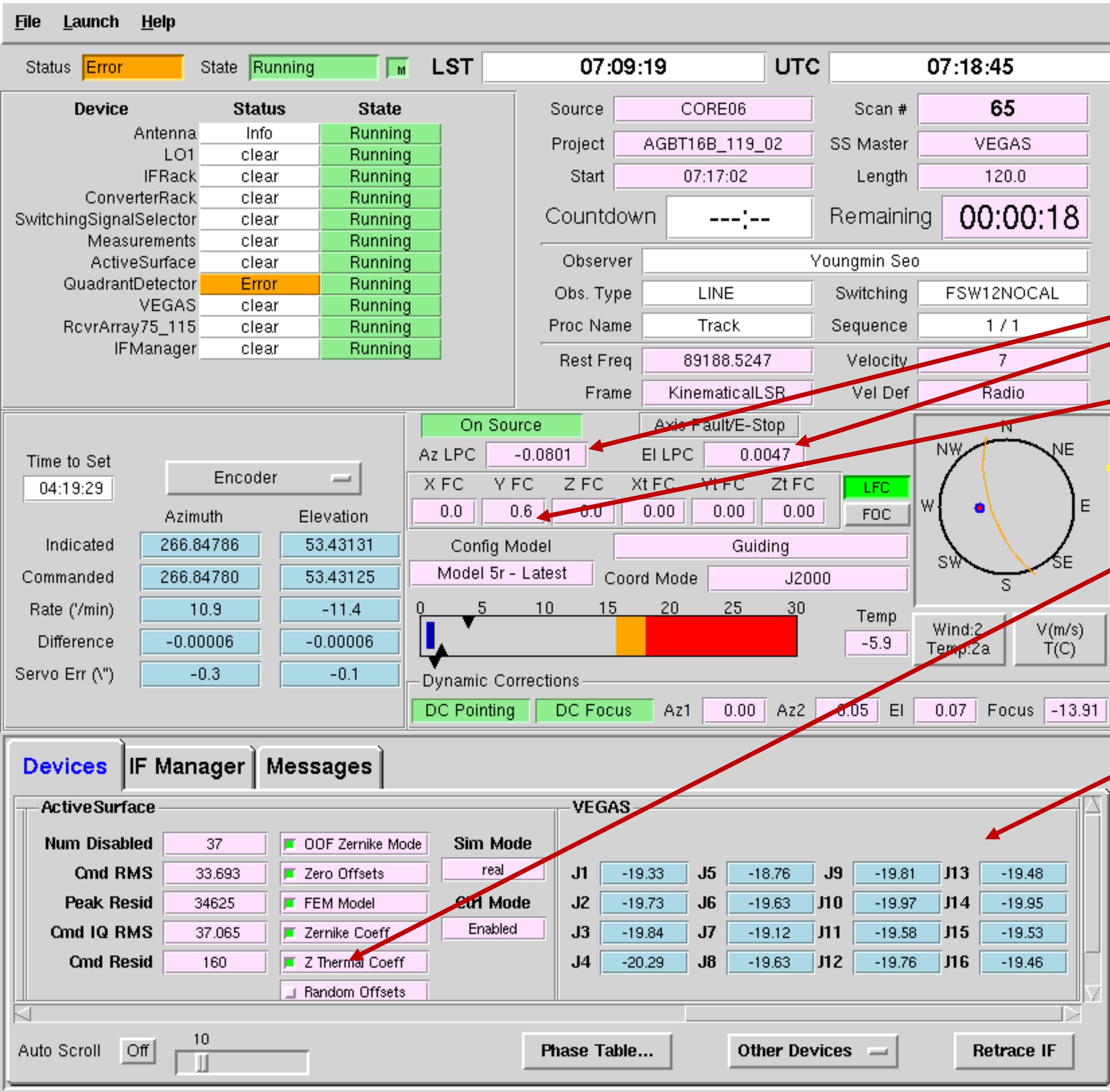


Figure 5.10: The AutoOOF fitted beam maps (left). The observed beams are plotted on the top row with the z3, z4 and z5 fits to the observed beams plotted below. The z3 solution (2^{nd} row down) shows an obvious artifact and should not be used. Also note the significant jump in LPCs and the LFC between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

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

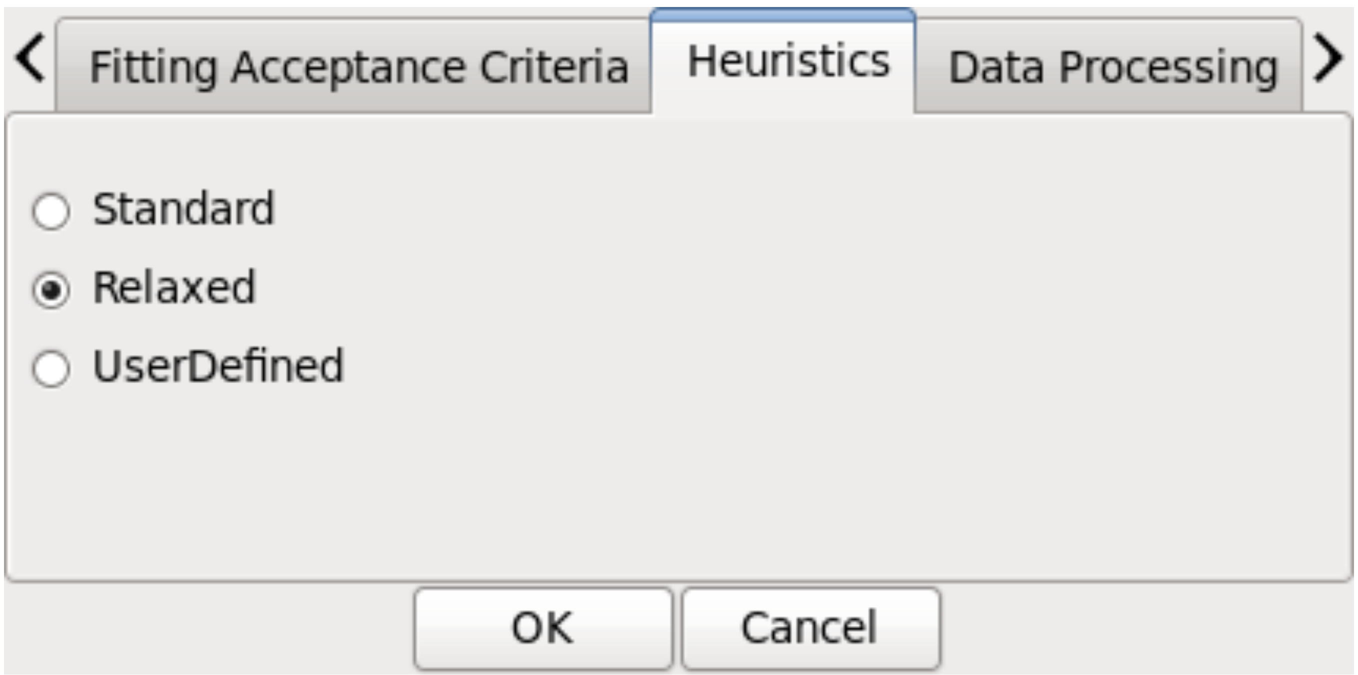
Observing: Antenna Optimization

- 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	Snu (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: 5º
  - Can observe 85% of the entire Celestial Sphere
- Slew Rates: Azimuth - 40º/min; Elevation - 20º/min