High Frequency GBT Corrections

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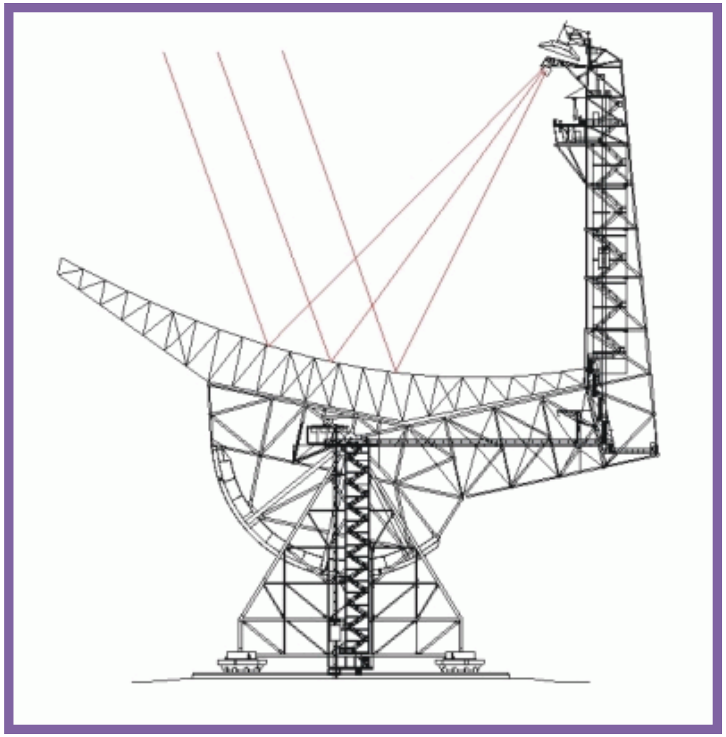
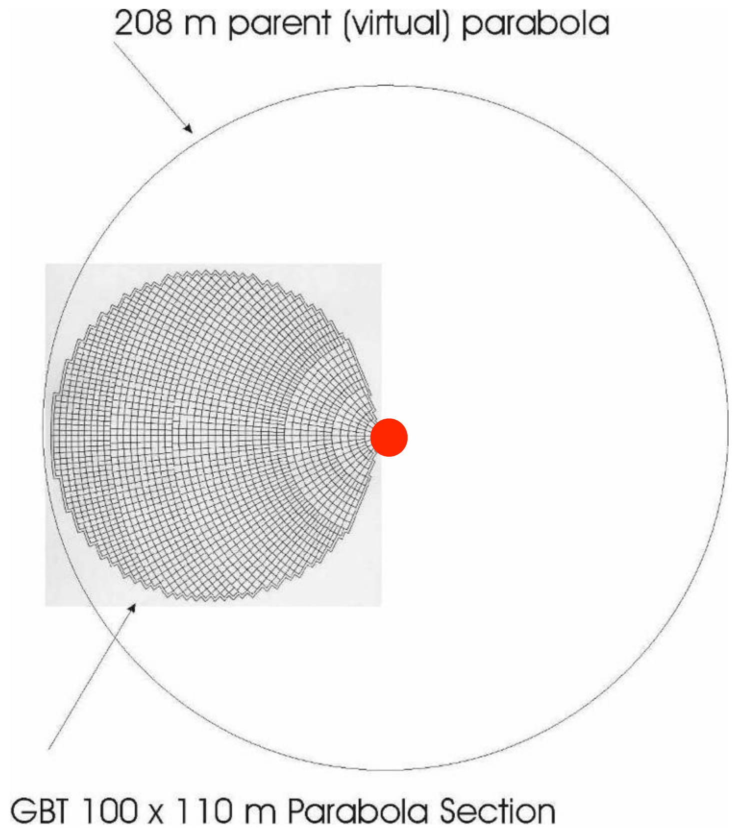
GBT Telescope Optics

- 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)

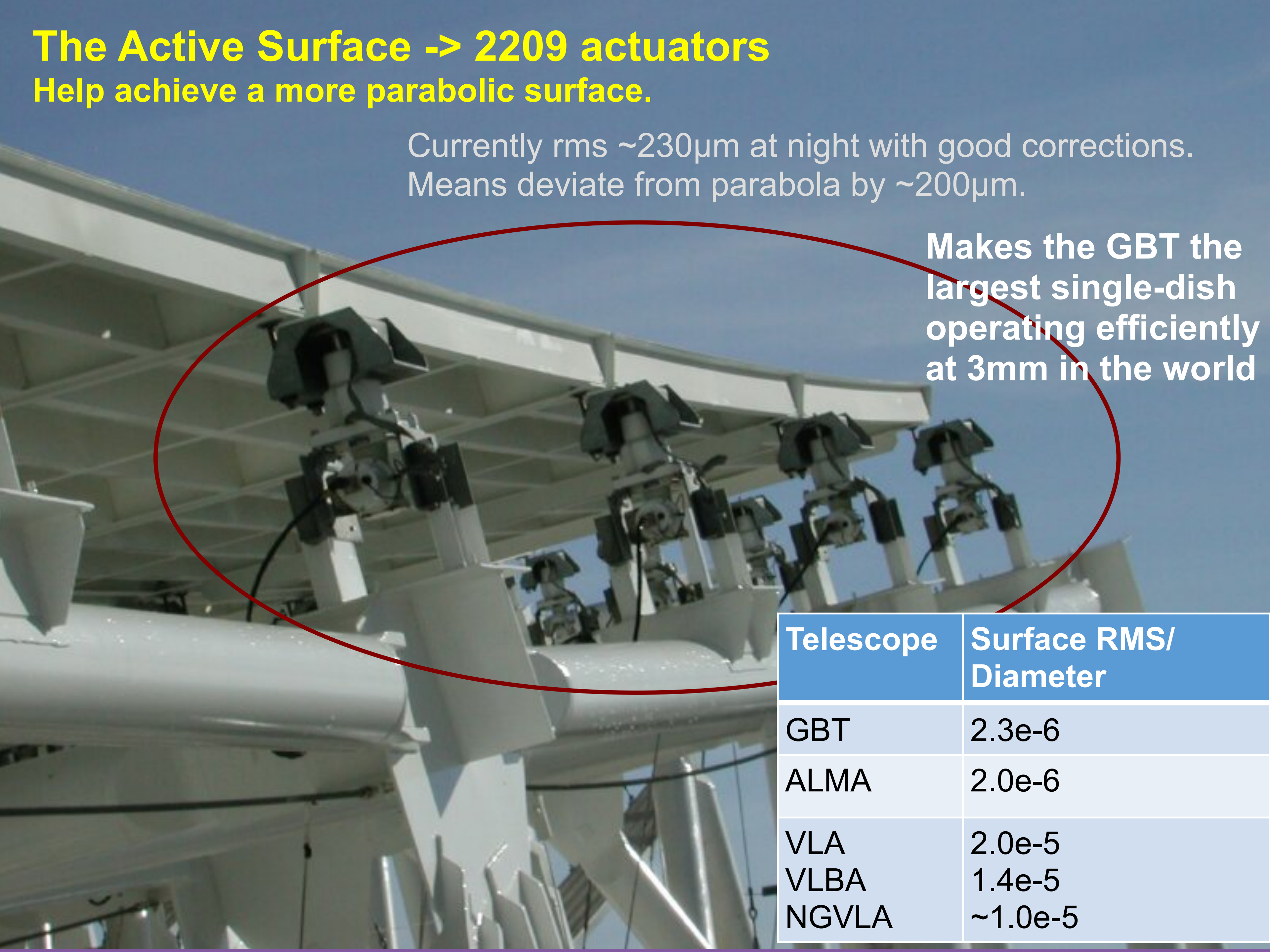




The Active Surface -> 2209 actuators

Help achieve a more parabolic surface.

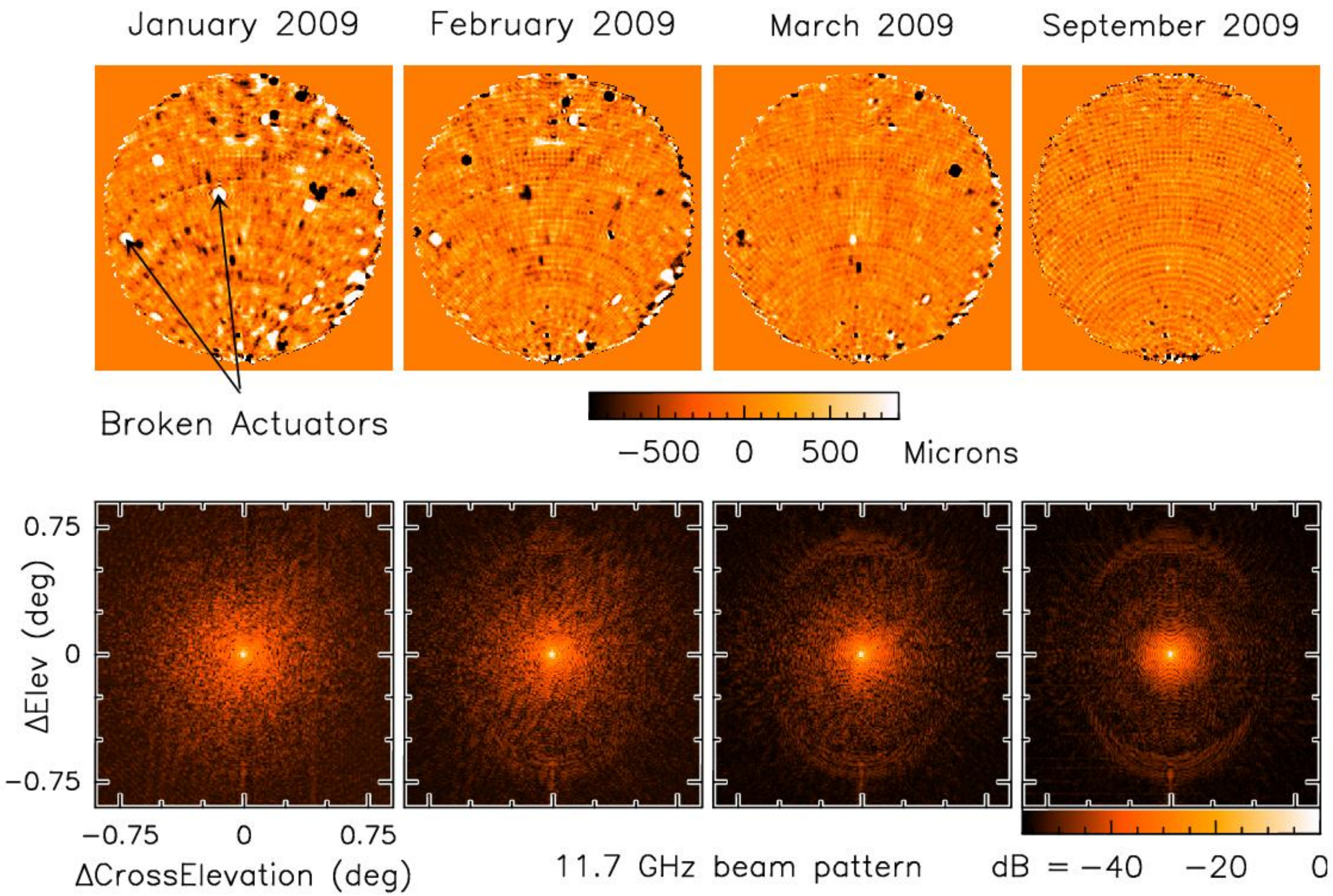
Currently rms ~230μm at night with good corrections.
Means deviate from parabola by ~200μm.



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

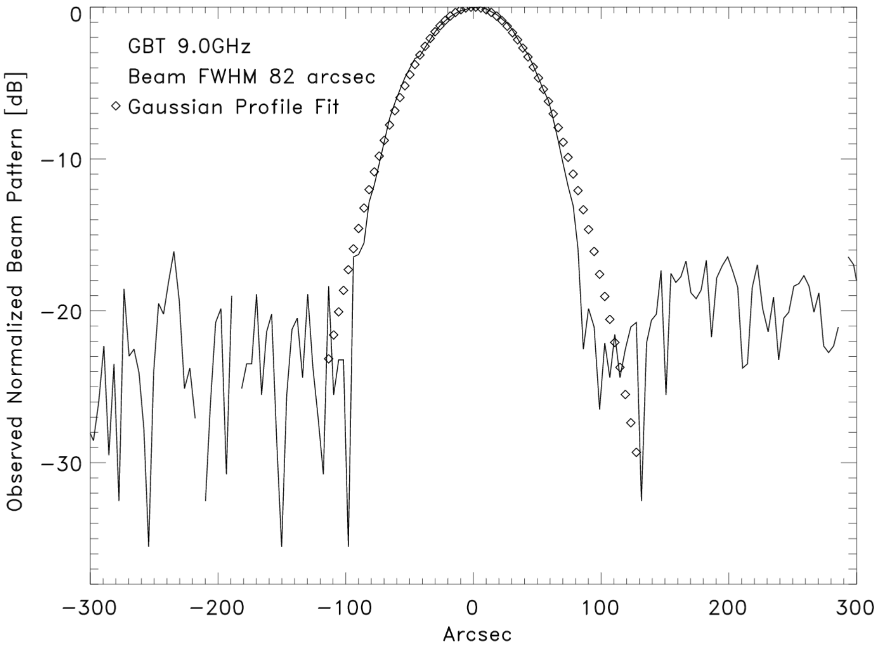
Telescope	Surface RMS/ Diameter
GBT	2.3e-6
ALMA	2.0e-6
VLA VLBA NGVLA	2.0e-5 1.4e-5 ~1.0e-5

Improvements to Active Surface in 2009

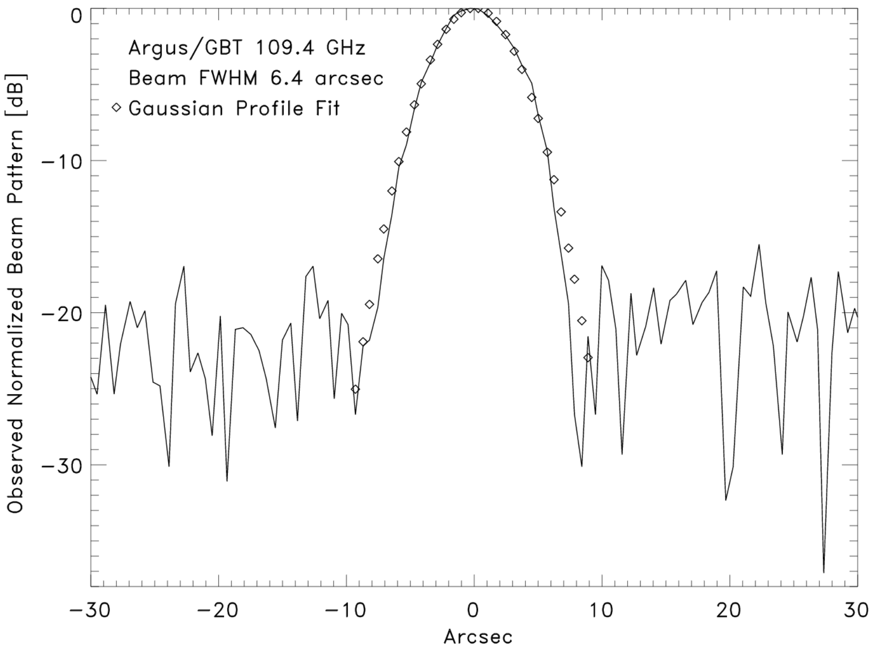


The GBT Achieves its Theoretical Beam at 110 GHz

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

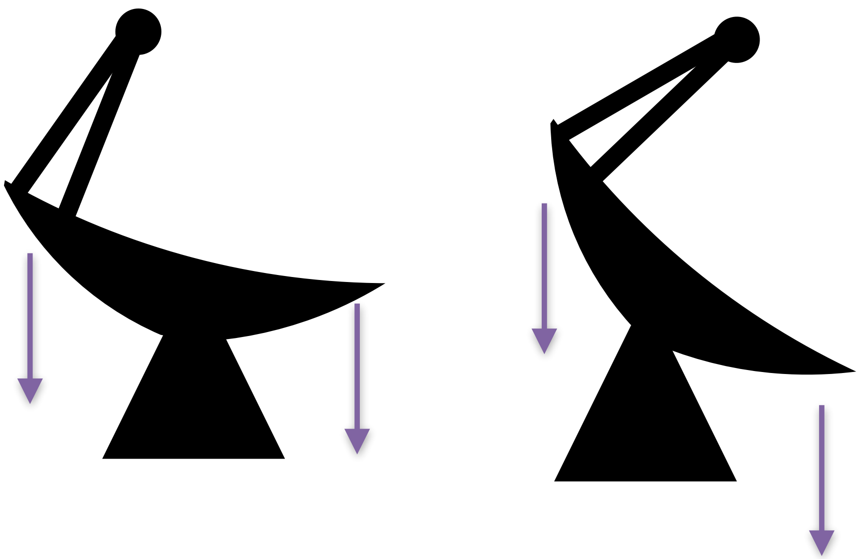


GBT/Argus 109.4 GHz

What can cause deviations from perfect parabola and theoretical beam?

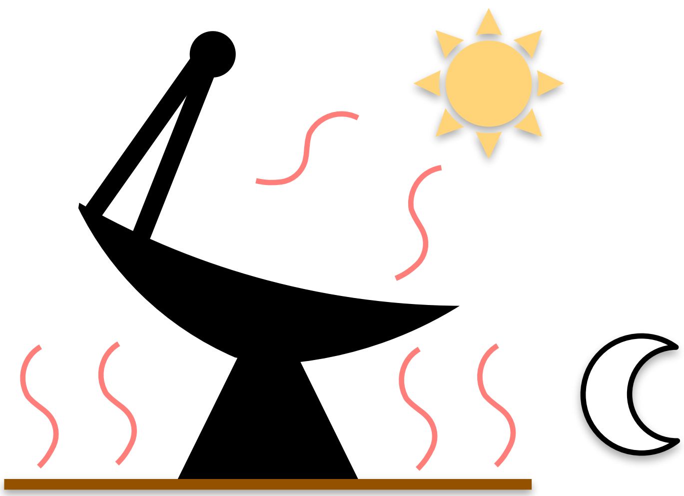
Deformations caused by:

Gravity



Changes with elevation

Differential Heating

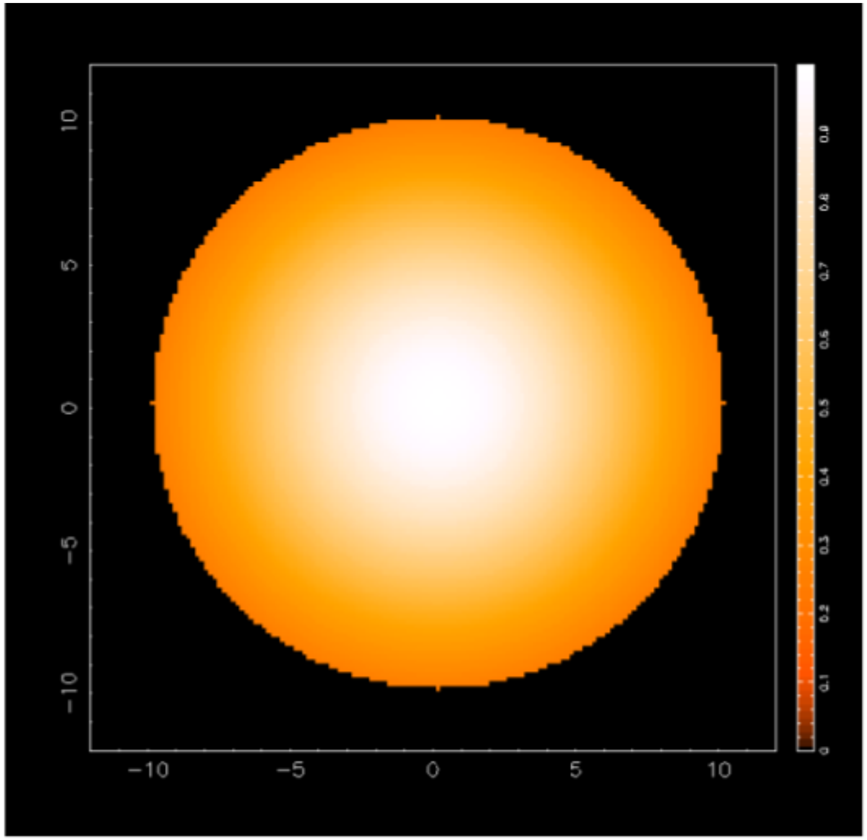


Why do these deformations matter at high frequency and not at low frequency?

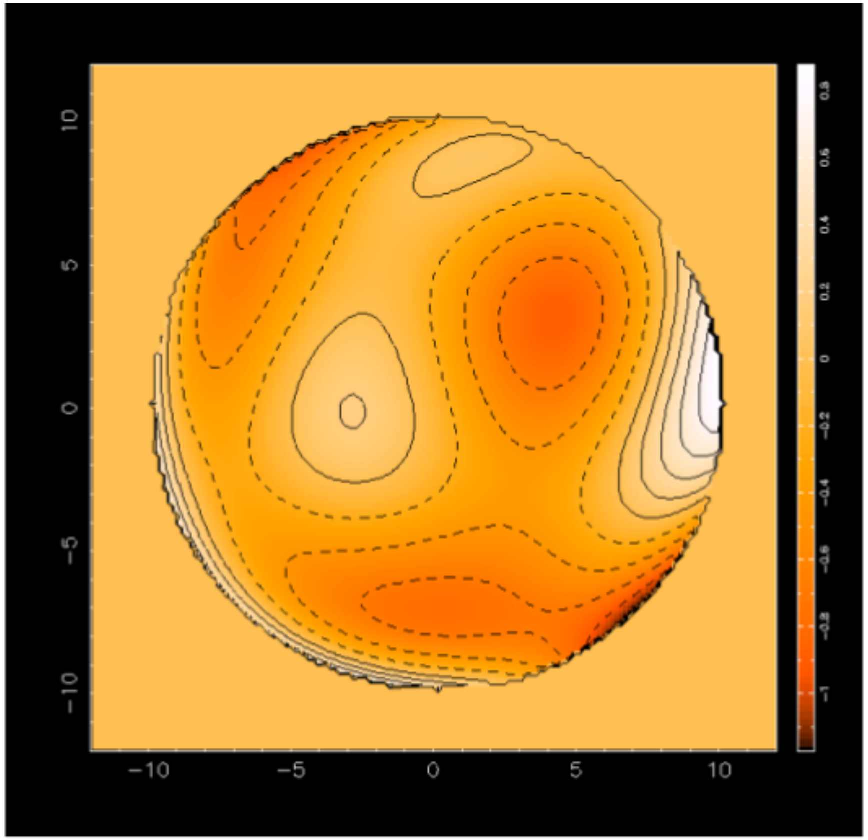
Quite simply, in the mm range this is where these deviations in the dish are larger than the wavelength.

A Surface with random large-scale errors

Receiver Response
(Taper/Apodisation/…)



Surface Errors
(Projected to an imaginary surface)



Model Surface Using Zernike Polynomials

Set of orthogonal polynomials that are used to reconstruct geometric features across a circular aperture.

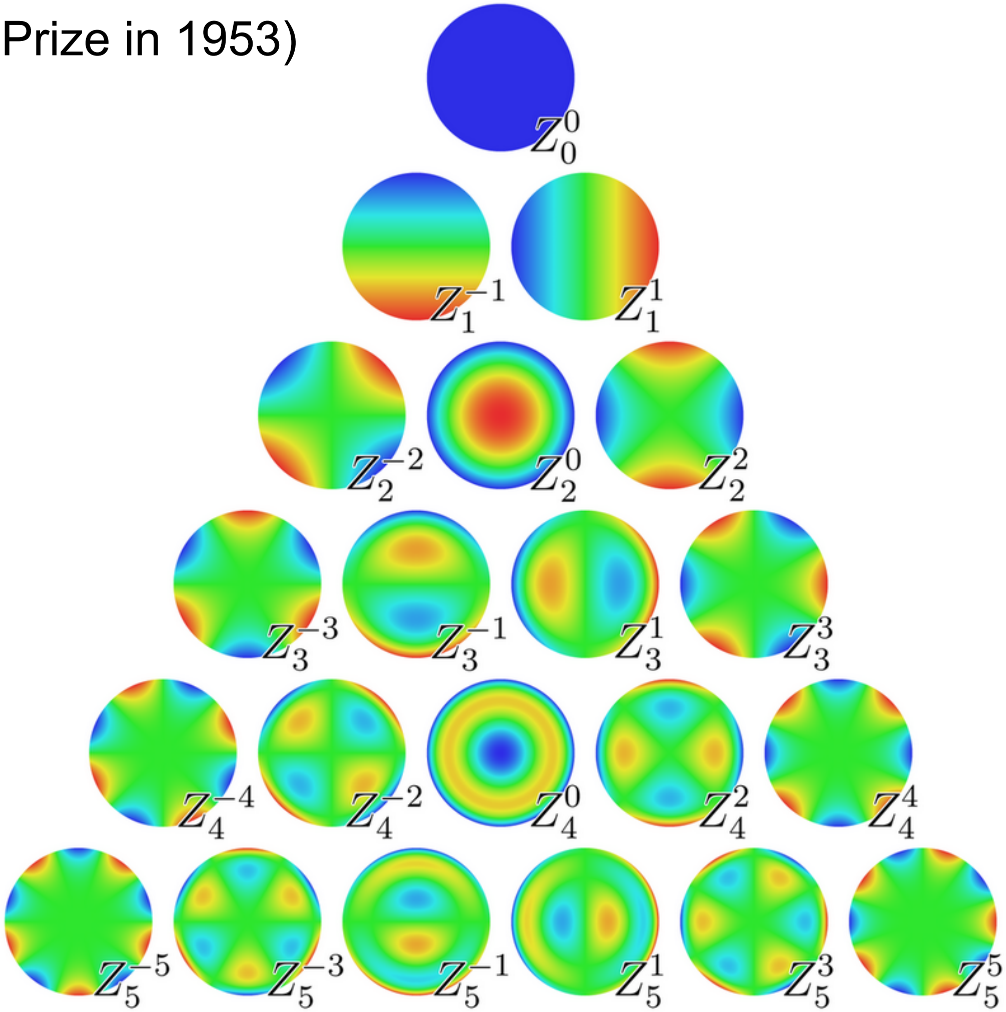
Derived by Frits Zernike in 1934 (Nobel Prize in 1953)

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

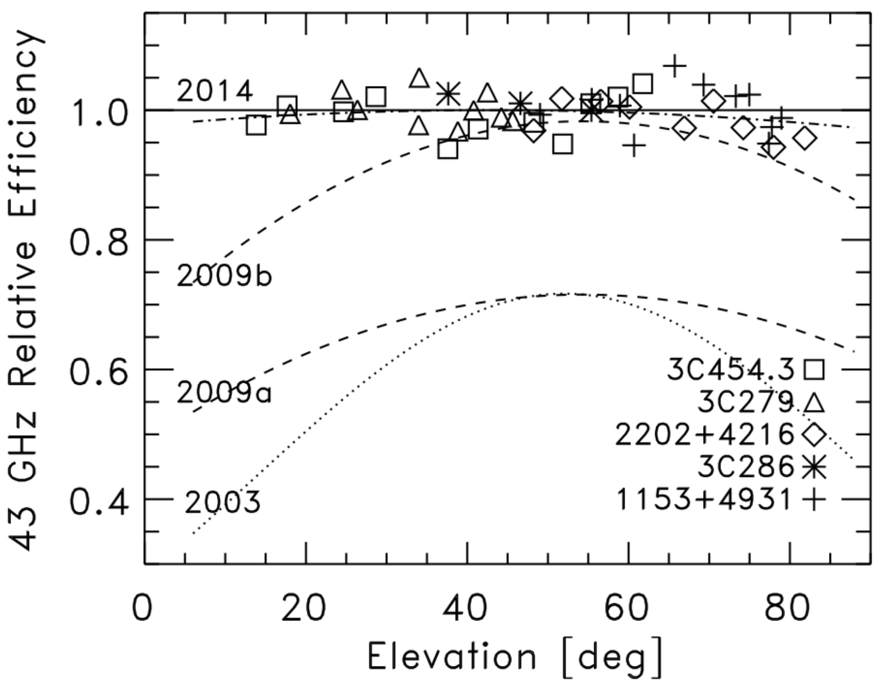
Each Zernike parameter fitted as a function of elevation:

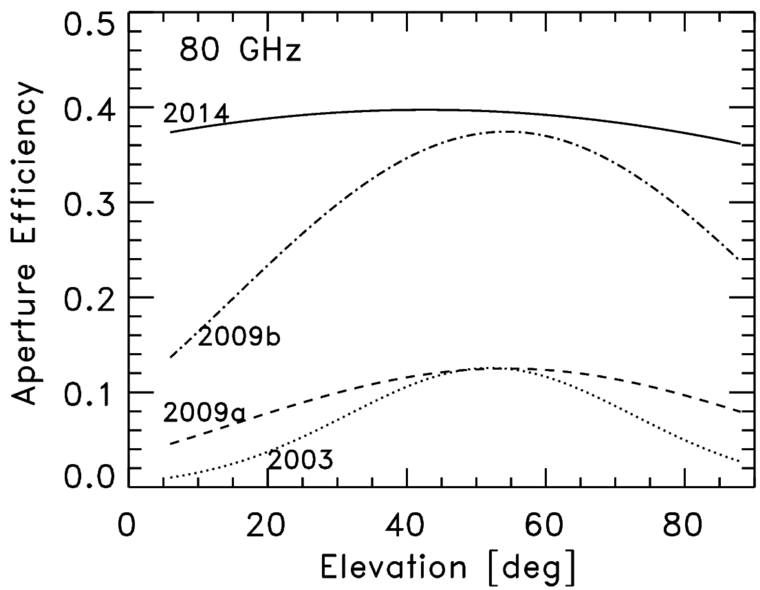
$$Z_n = A_n \sin(el) + B_n \cos(el) + C_n$$

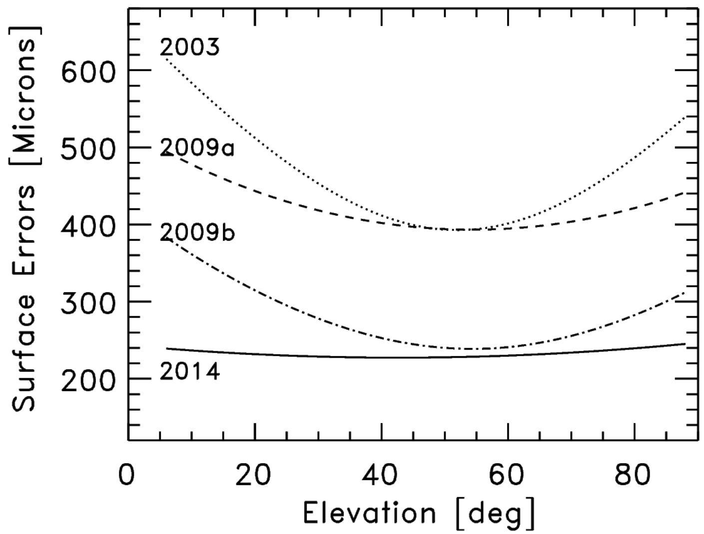
The updated 2014 gravity model improved telescope performance (PTCS PN#76)

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 Gravity Model + Active Surface







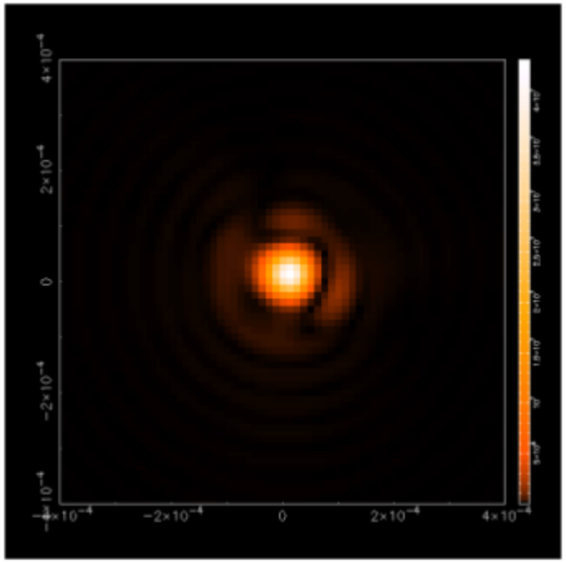
Improvements to the gravity model in 2014 yields a flat gain curve with elevation and has significantly improved the GBT performance at high-frequency (GBT Memo#301)

GREEN BANK OBSERVATORY

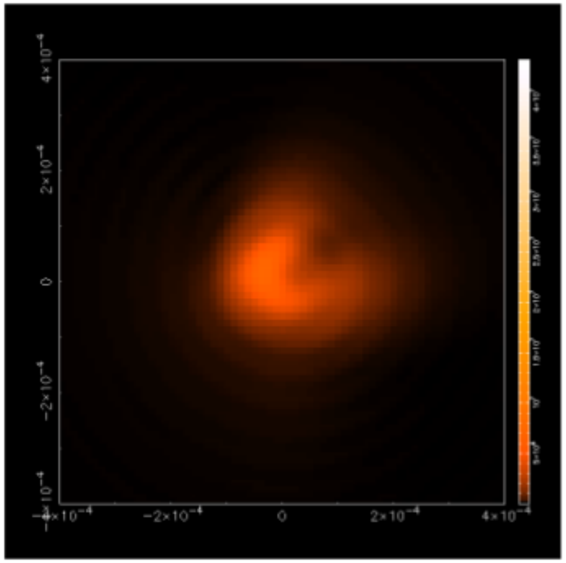
Surface Improvements with OOF

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

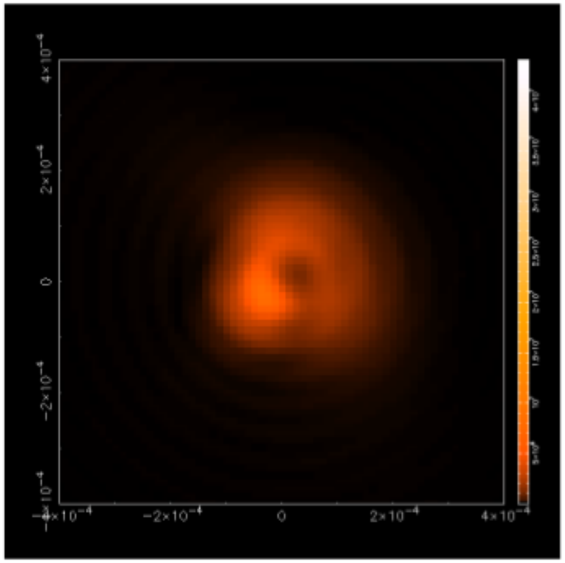
In-Focus



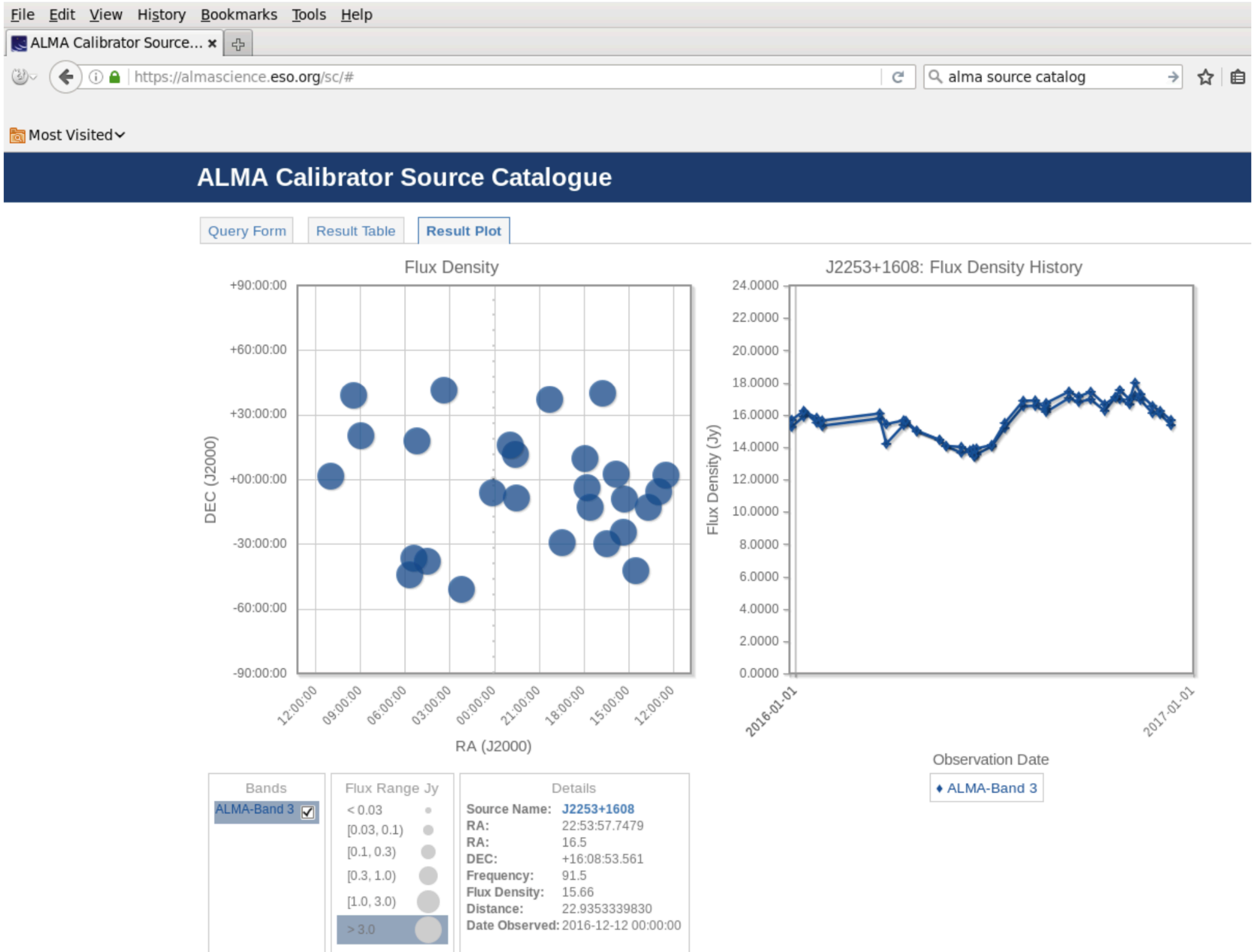
-ve De-Focus



+ve De-Focus



ALMA Calibrator Source Catalogue



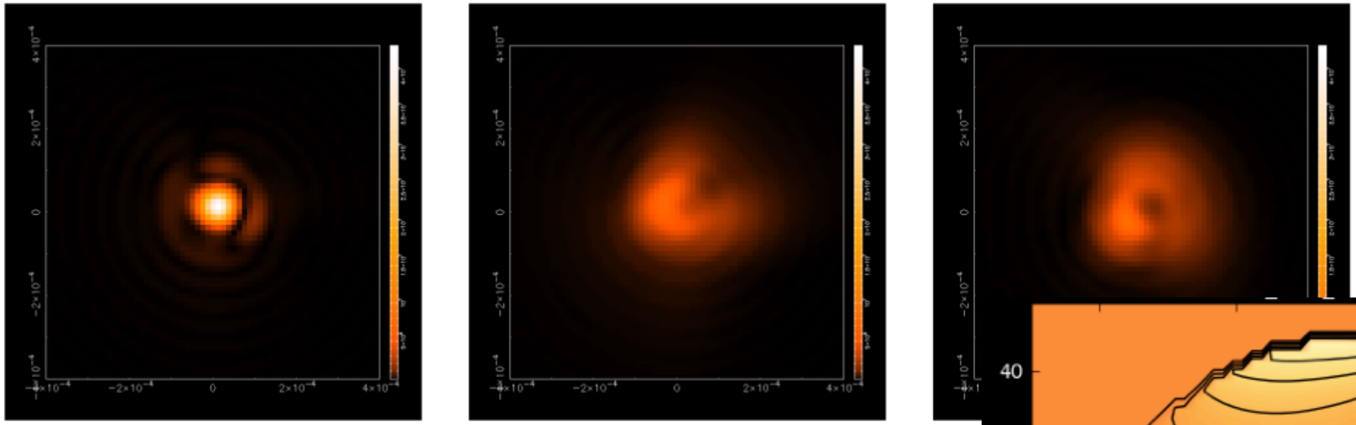
Surface Improvements with OOF

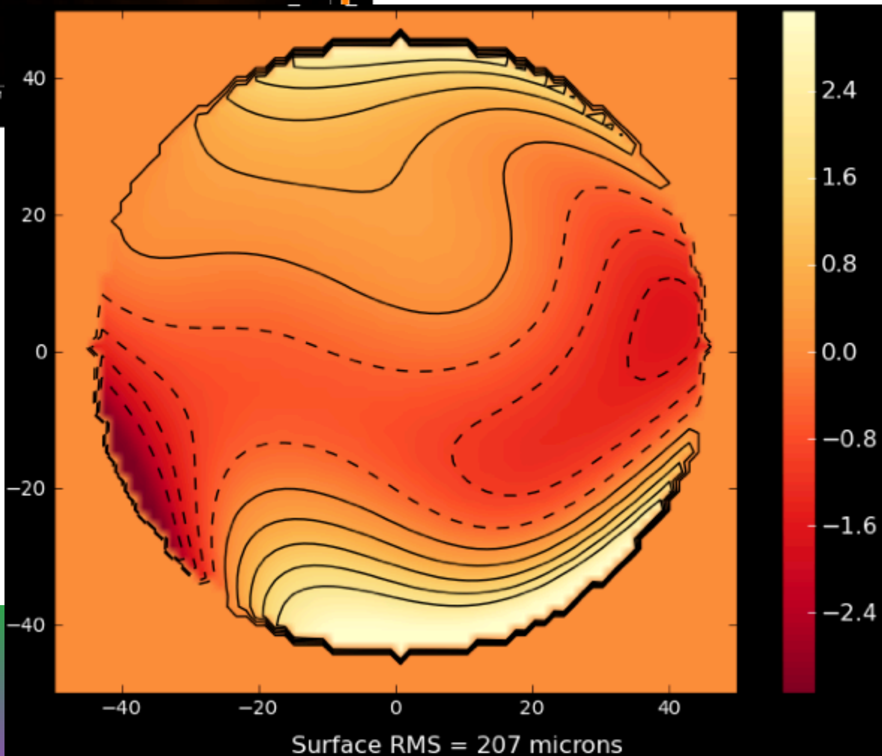
Out Of Focus (OOF) - AutoOOF - active surface (RMS + map), pointing (Az,El), focus corrections (mm)

In-Focus

-ve De-Focus

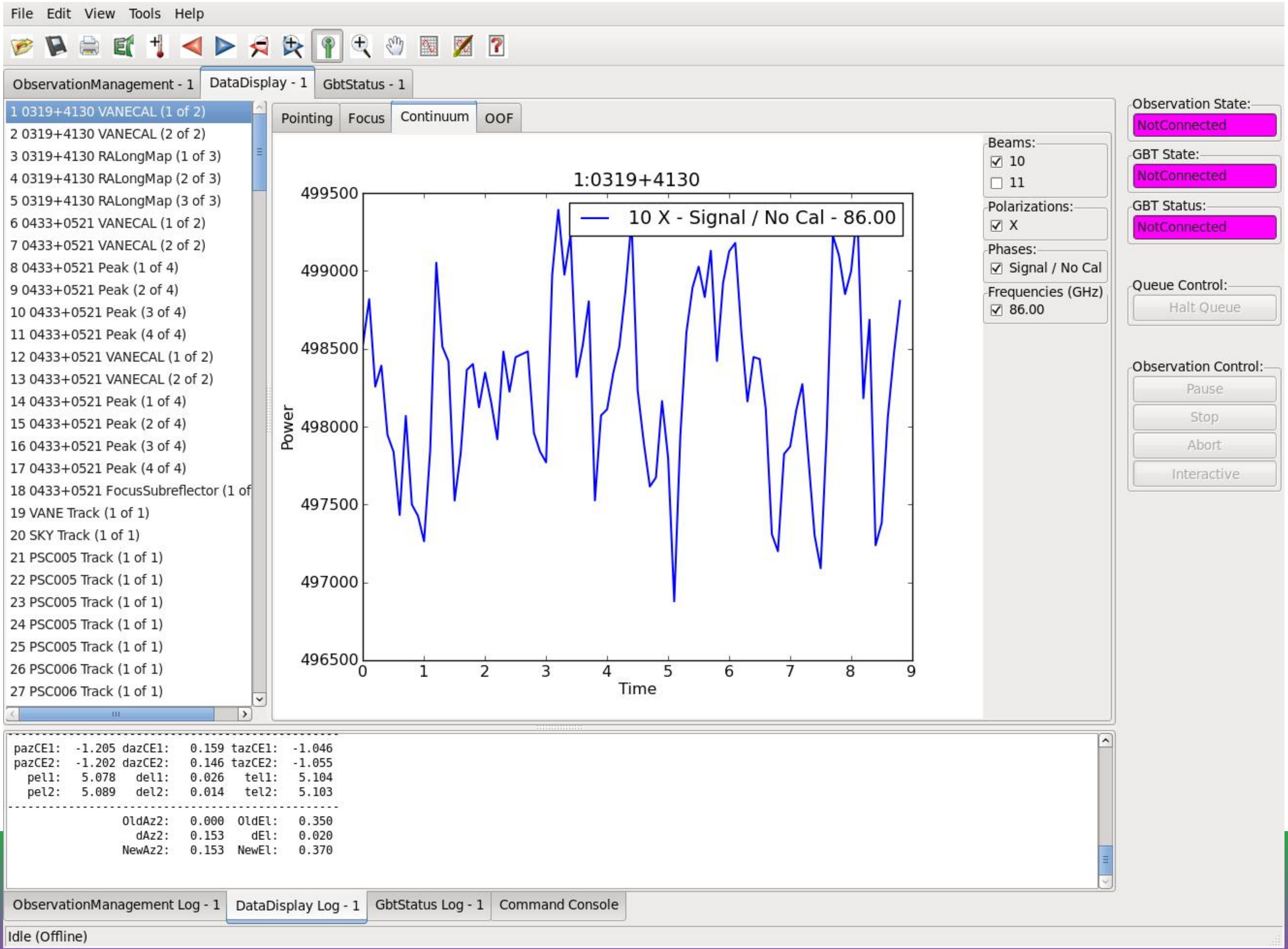
+ve De-Focus





Example of Argus AutoOOF Observations:

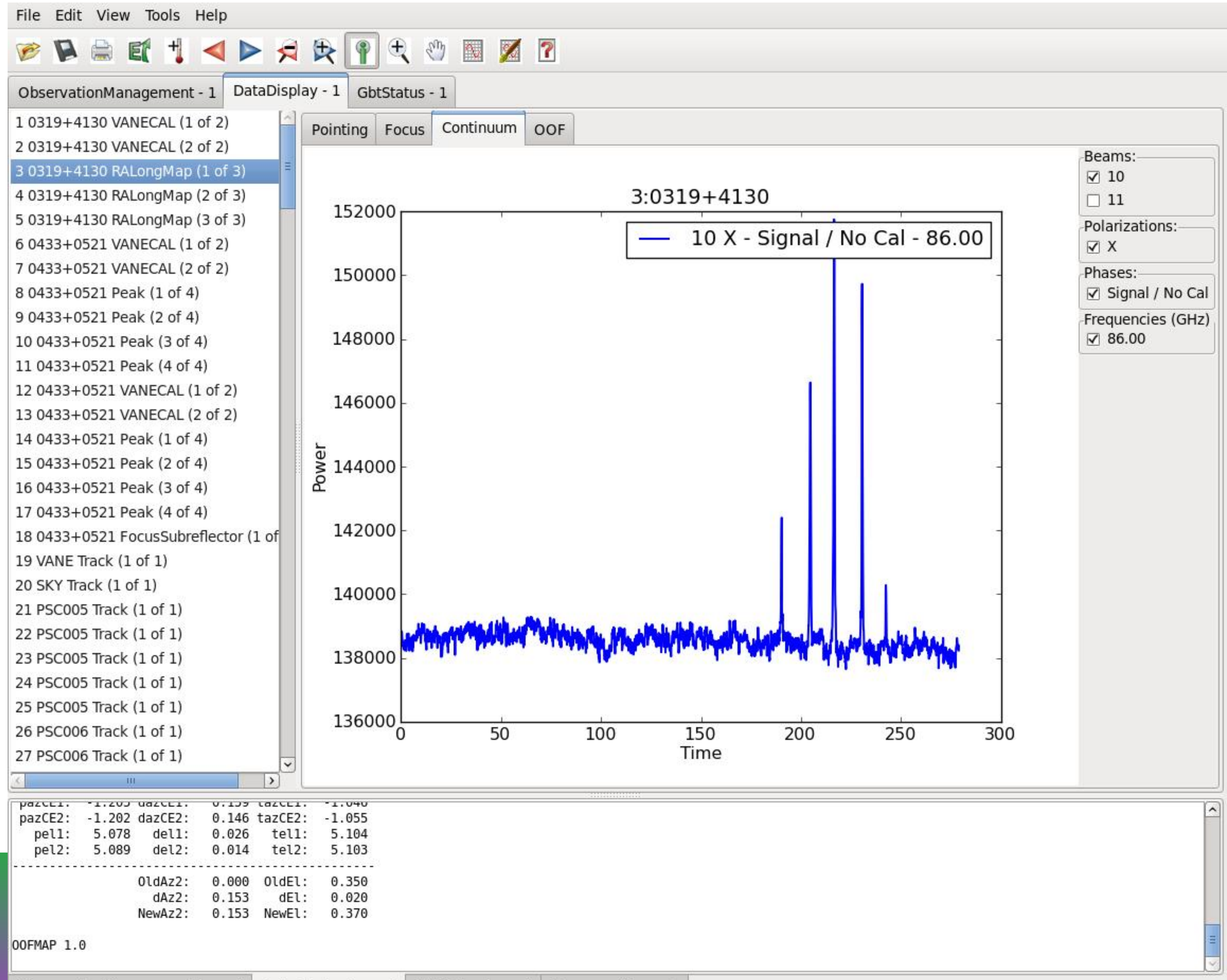
Early Scans - setup



Example of Argus AutoOOF Observations:

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

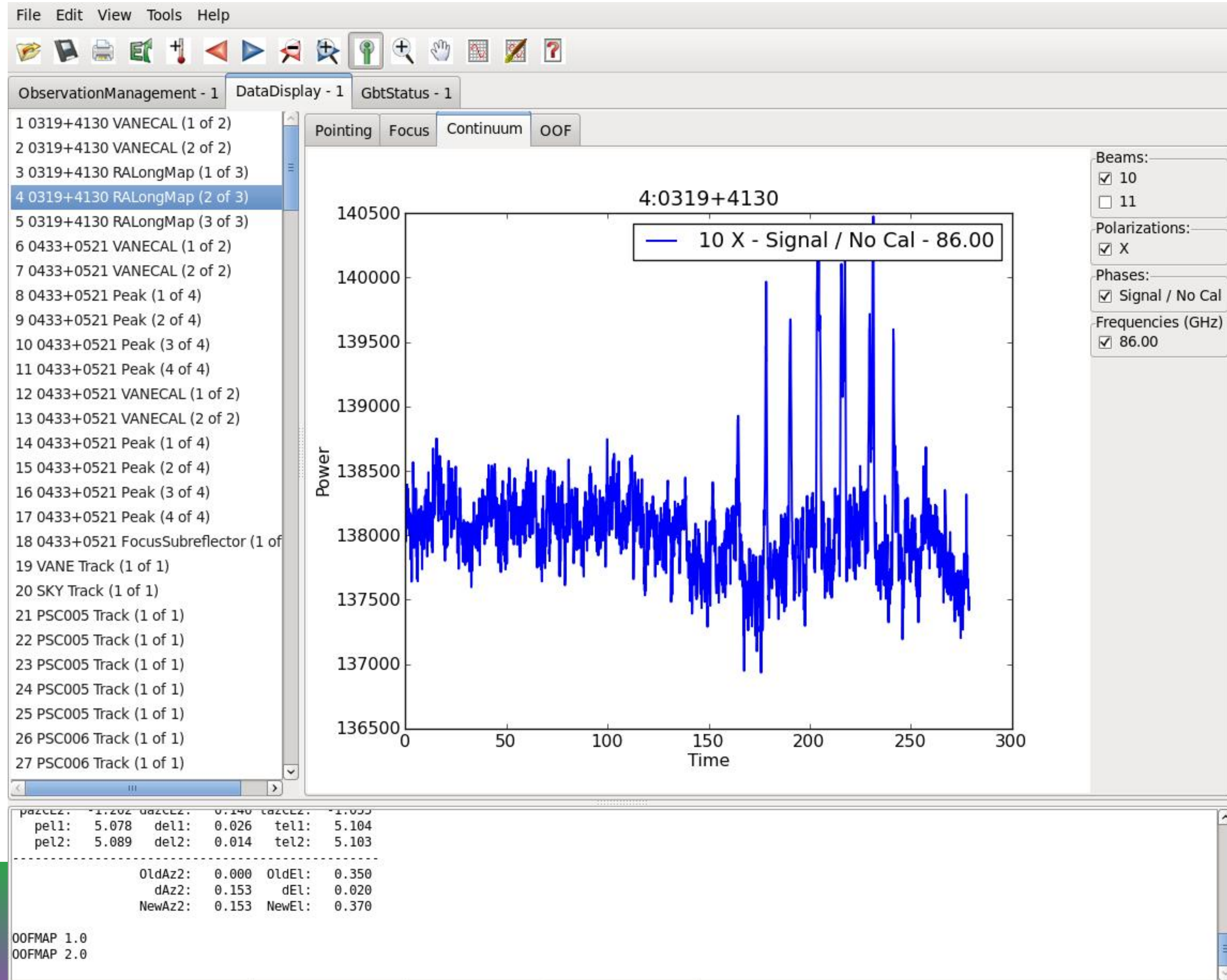
First map at default focus and should see source at good S/N.



Example of Argus AutoOOF Observations:

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

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

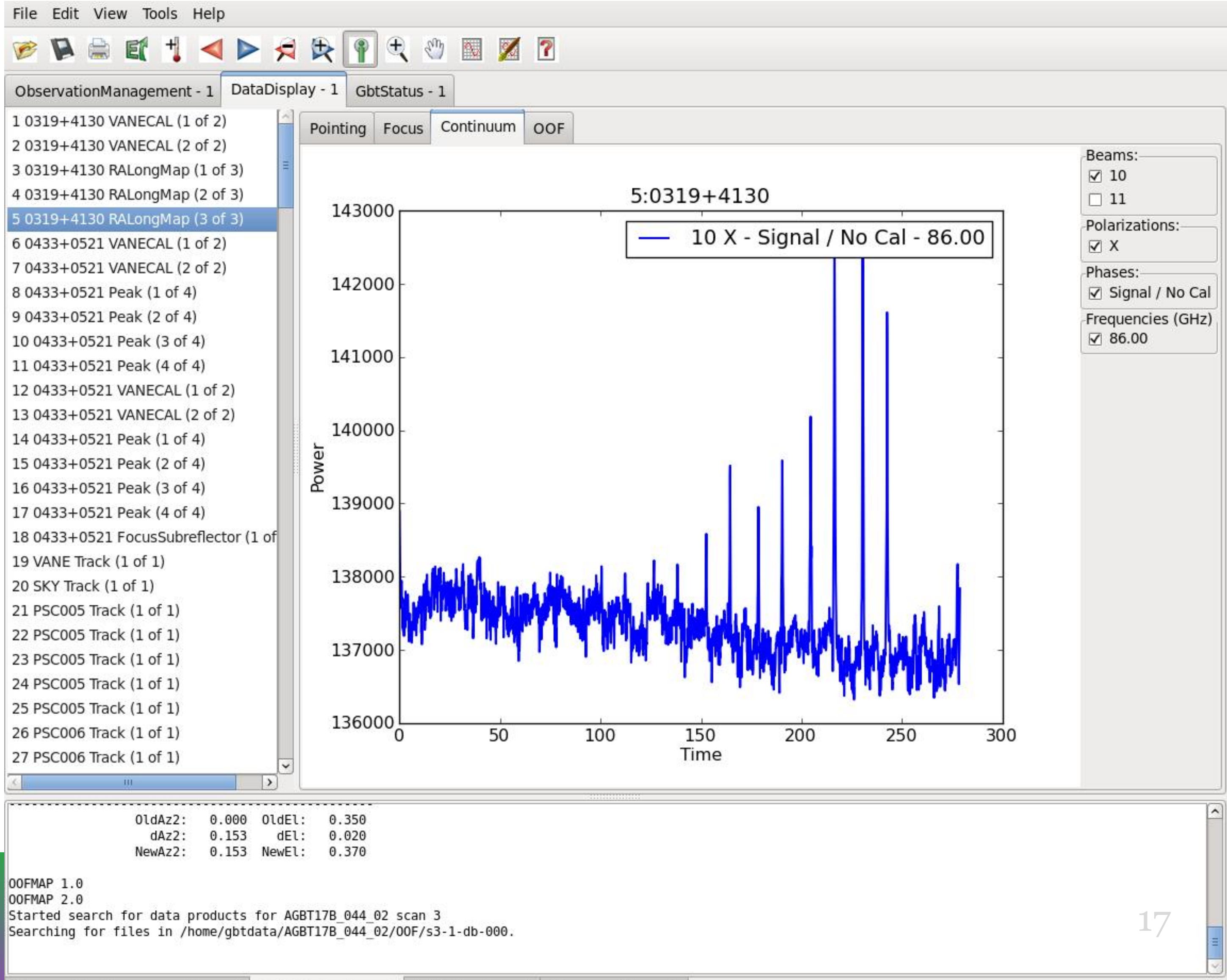


Example of Argus AutoOOF Observations:

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

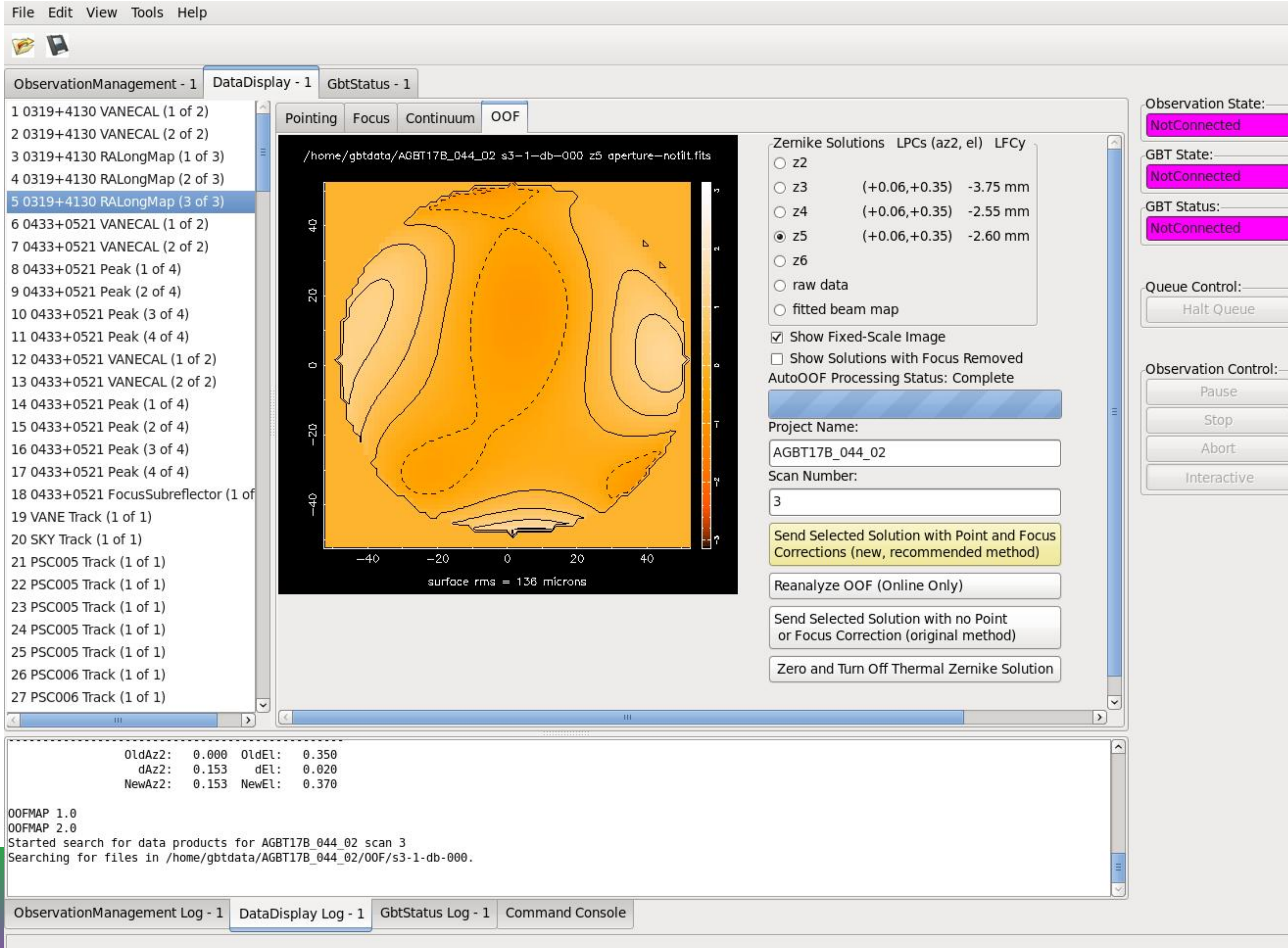
3rd OOF map with focus at -12mm

peaks higher than +12mm map so focus LFC will be negative



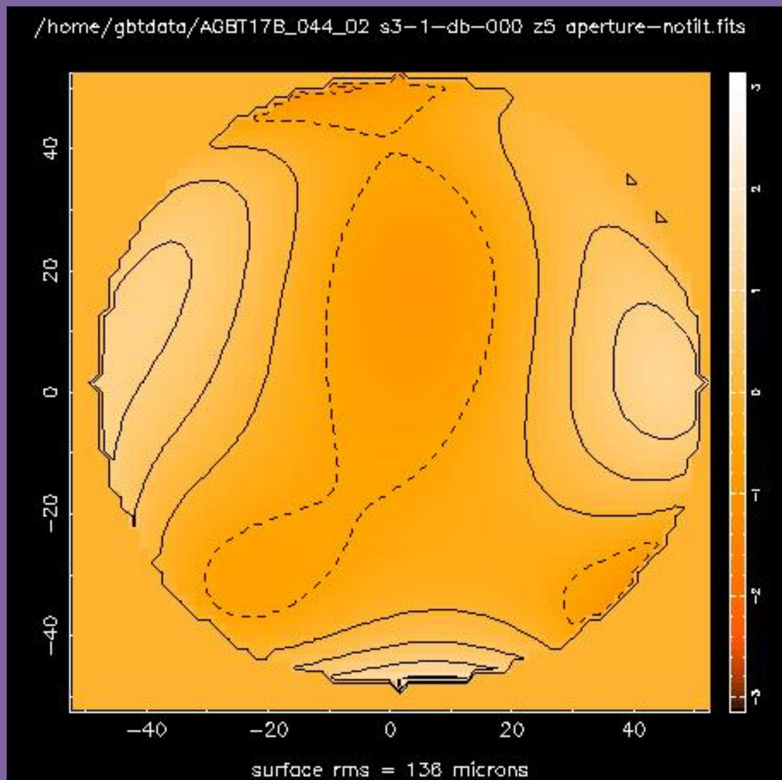
AutoOOF Solutions

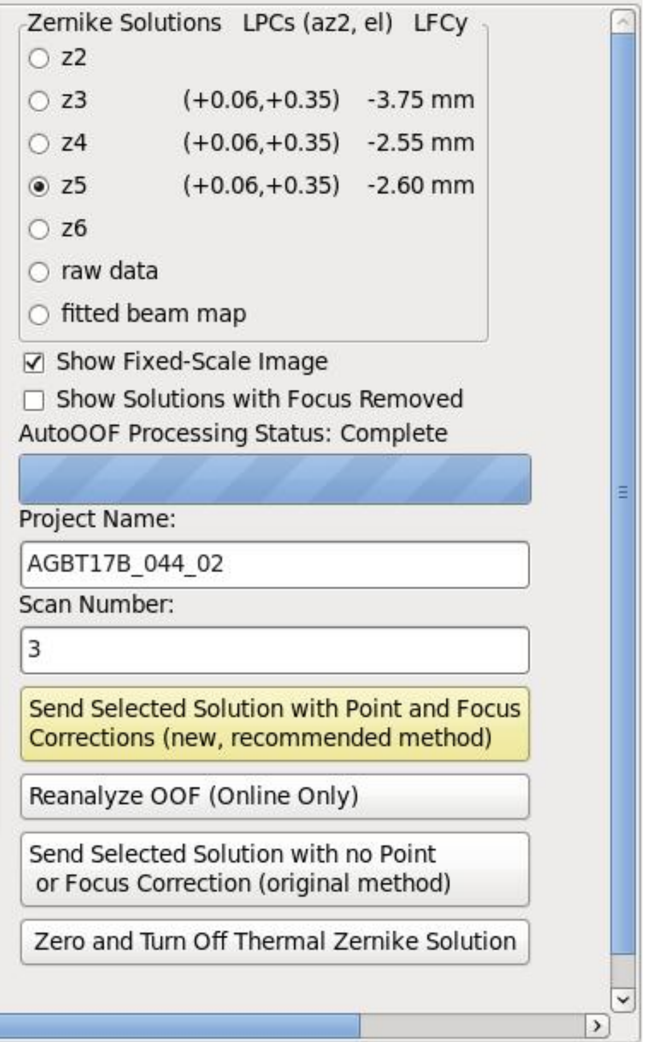
20 min to complete



AutoOOF Solutions

Surface Map

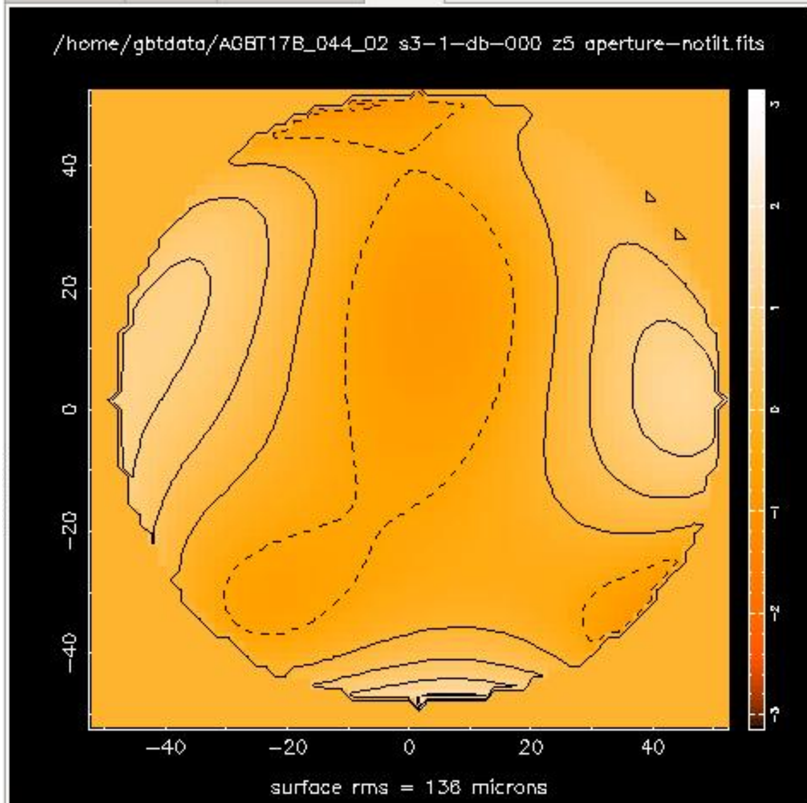




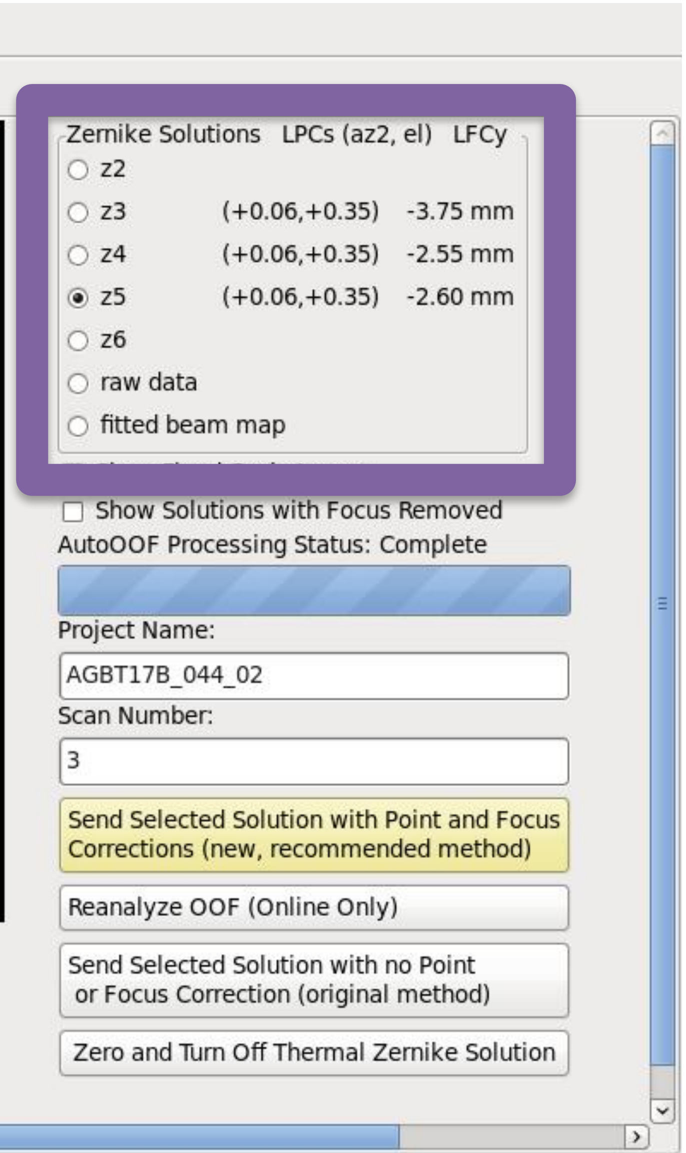
Be weary of “rms” >350 microns
(which happens in windy conditions)

AutoOOF Solutions

Zernike, LPCs (arcmin), LFC (mm)



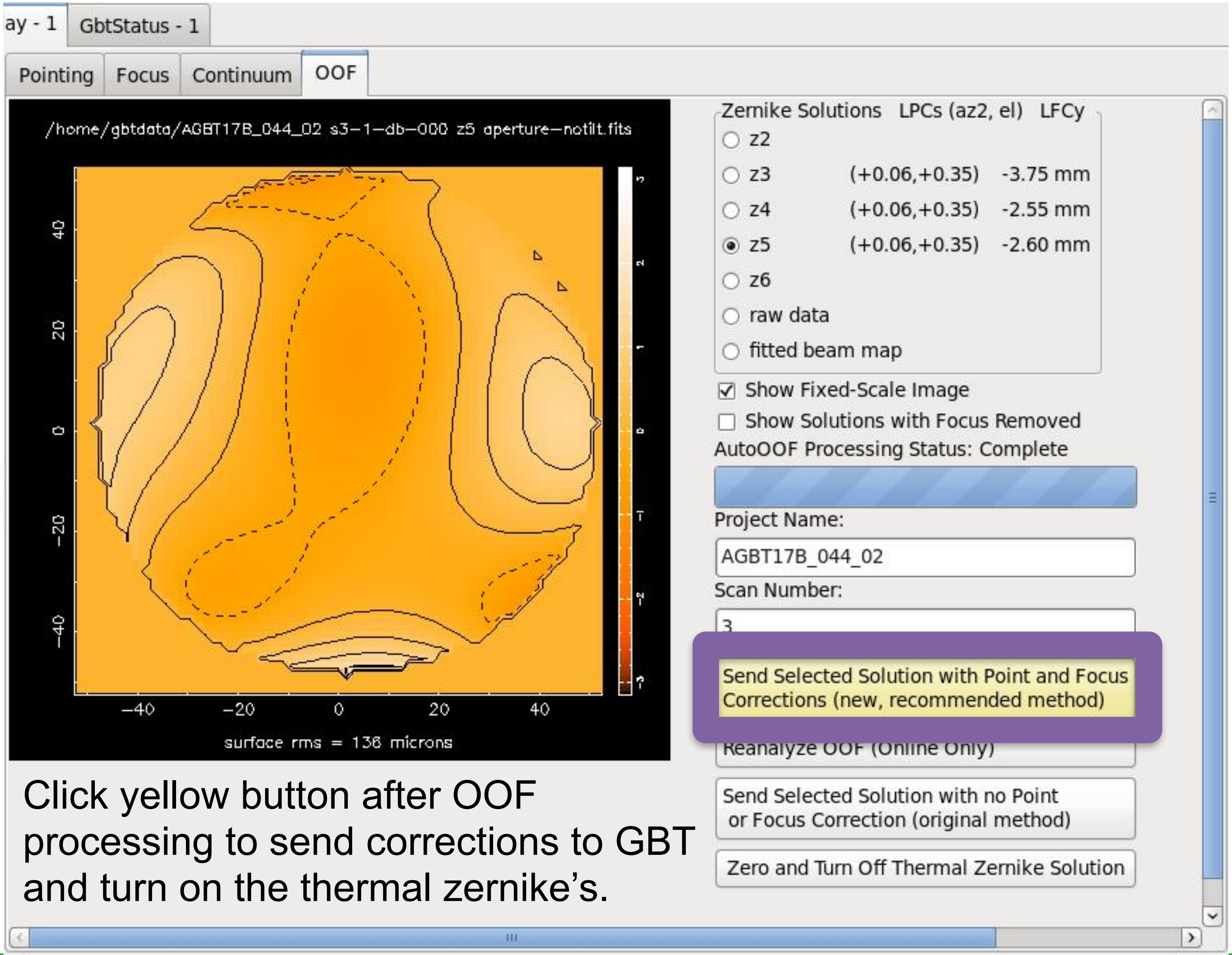
Typically pick between z4,z5,z6 based on residual rms and beam fits (z5 default). LFC a few mm.



GREEN BANK OBSERVATORY

AutoOOF Solutions

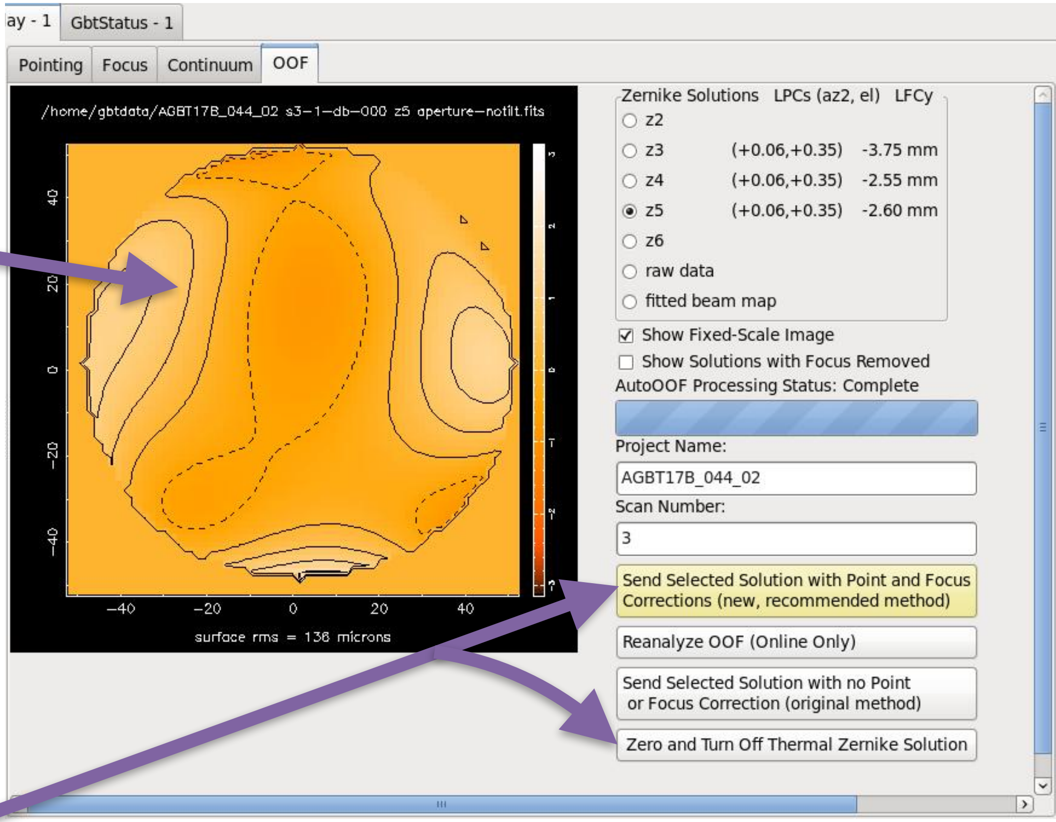
Send solutions



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

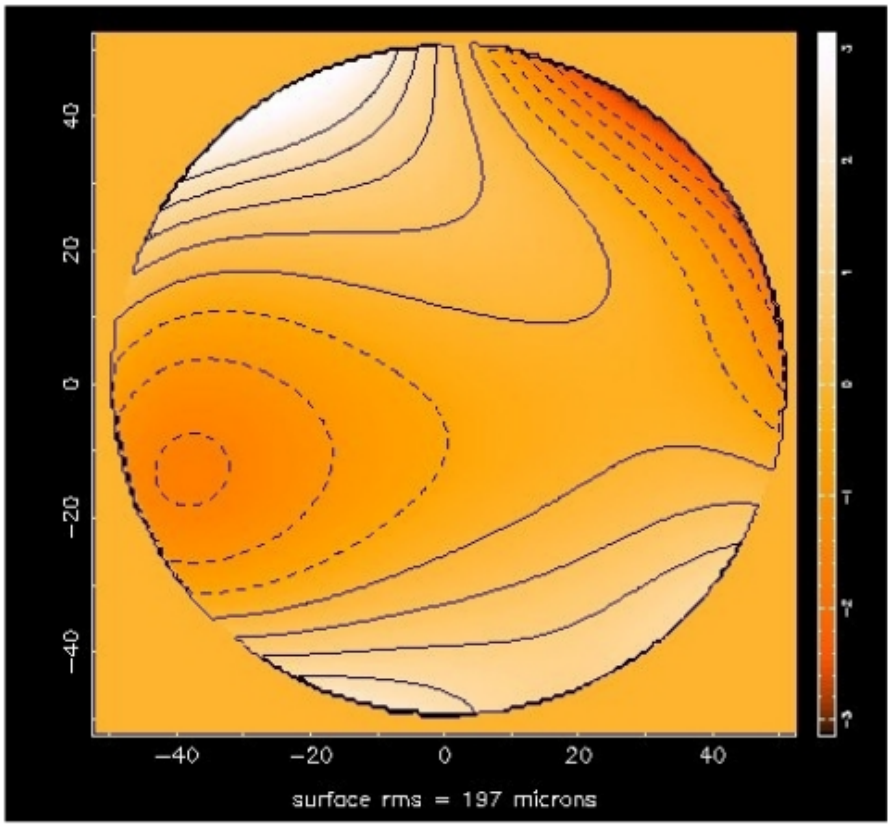
AutoOOF Solutions

- OOF image - displays the measured Δ's from the current surface to the computed optimal surface from the OOF measurements. The algorithm takes raw data, fits Zernikes to that data, and produces the Δ map (the combination of these Zernikes builds the surface corrections).
- $z_{tot} = z_{grav} + z_{thermal}$
    - OOF measures the z_{tot} at the elevation of your OOF target, refers to models for z_{grav} and then derives $z_{thermal}$
    - $z_{thermal}$ is the difference between measured z_{tot} and the models (z_{grav}).
        - Thus the solutions are often called "Zernike Thermal Solutions" or "Thermal Coefficients" for short

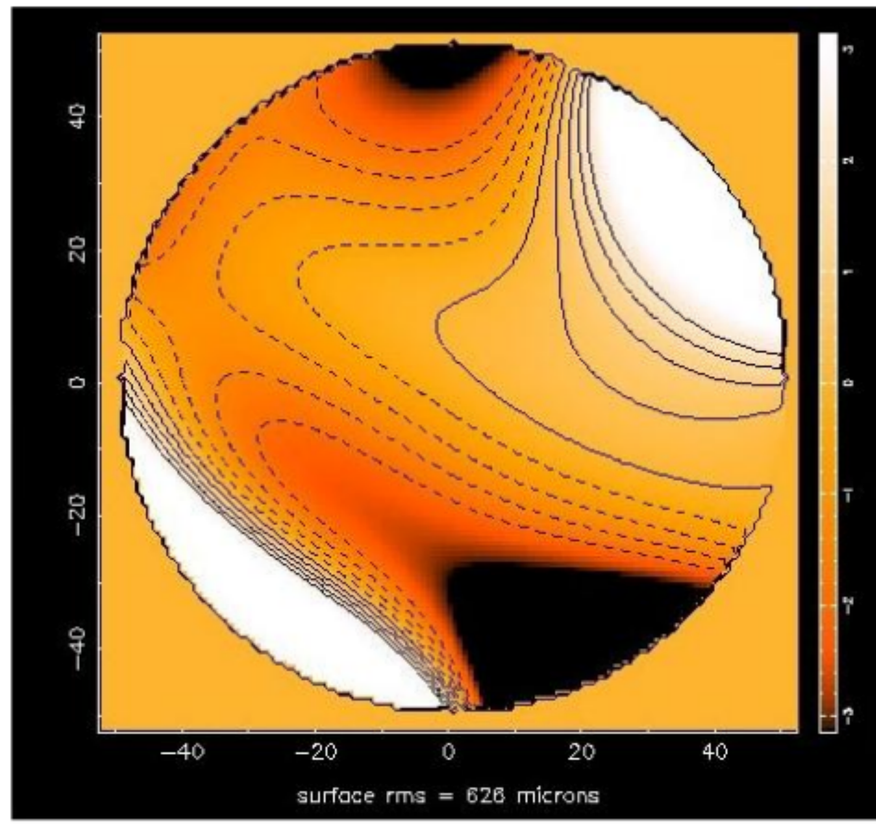


AutoOOF Example Solutions

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



(a) Acceptable OOF solution.

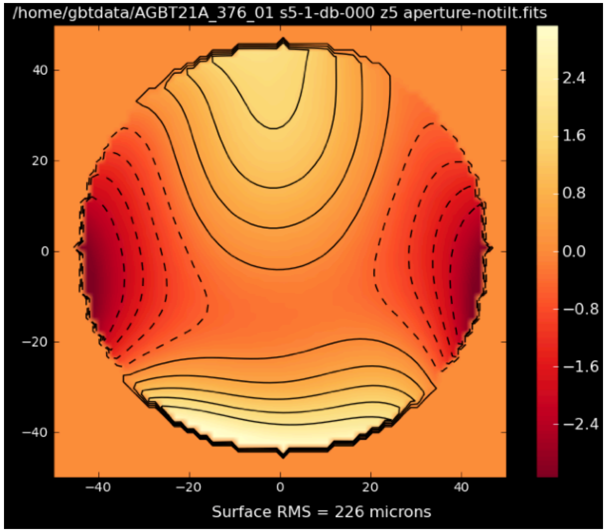


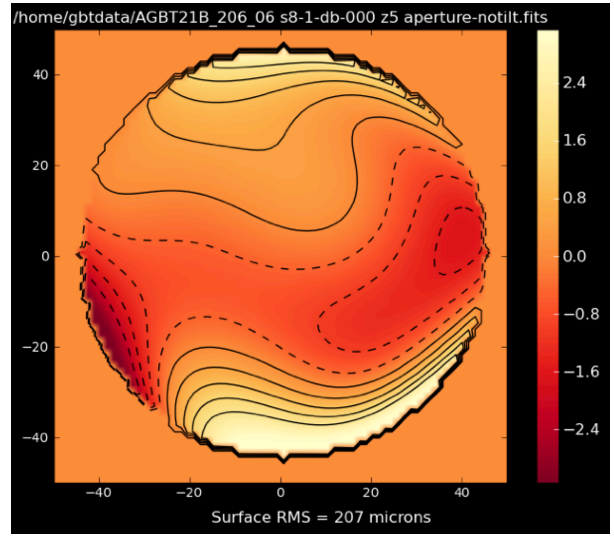
(b) Unacceptable OOF solution.

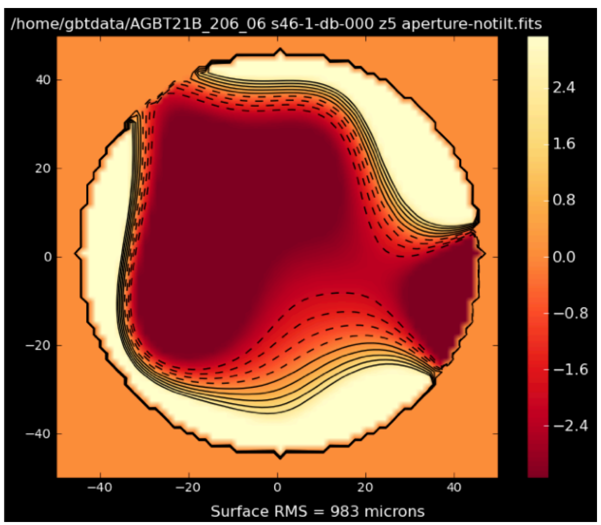
Figure 5.8: Figure $\boxed{5.8a}$ shows broad features (±1.5 radians of phase) with a surface rms of 197 μm. Figure $\boxed{5.8b}$ shows steep contour lines (±15 radians of phase) and a surface rms of 626 μm. This is likely the result of poor quality raw data and should not be used.

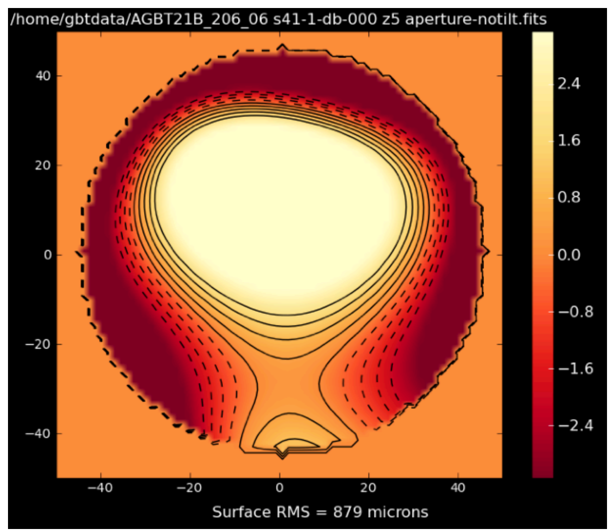
Bad

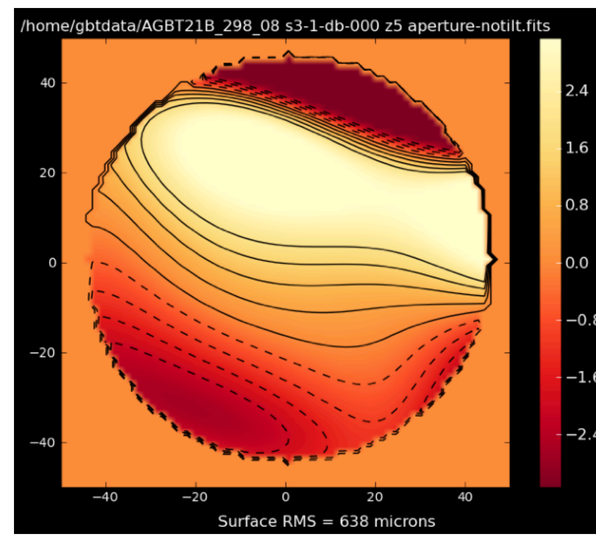
Good


/home/gbtdata/AGBT21A_376_01 s5-1-db-000 z5 aperture-notilt.fits
Surface RMS = 226 microns

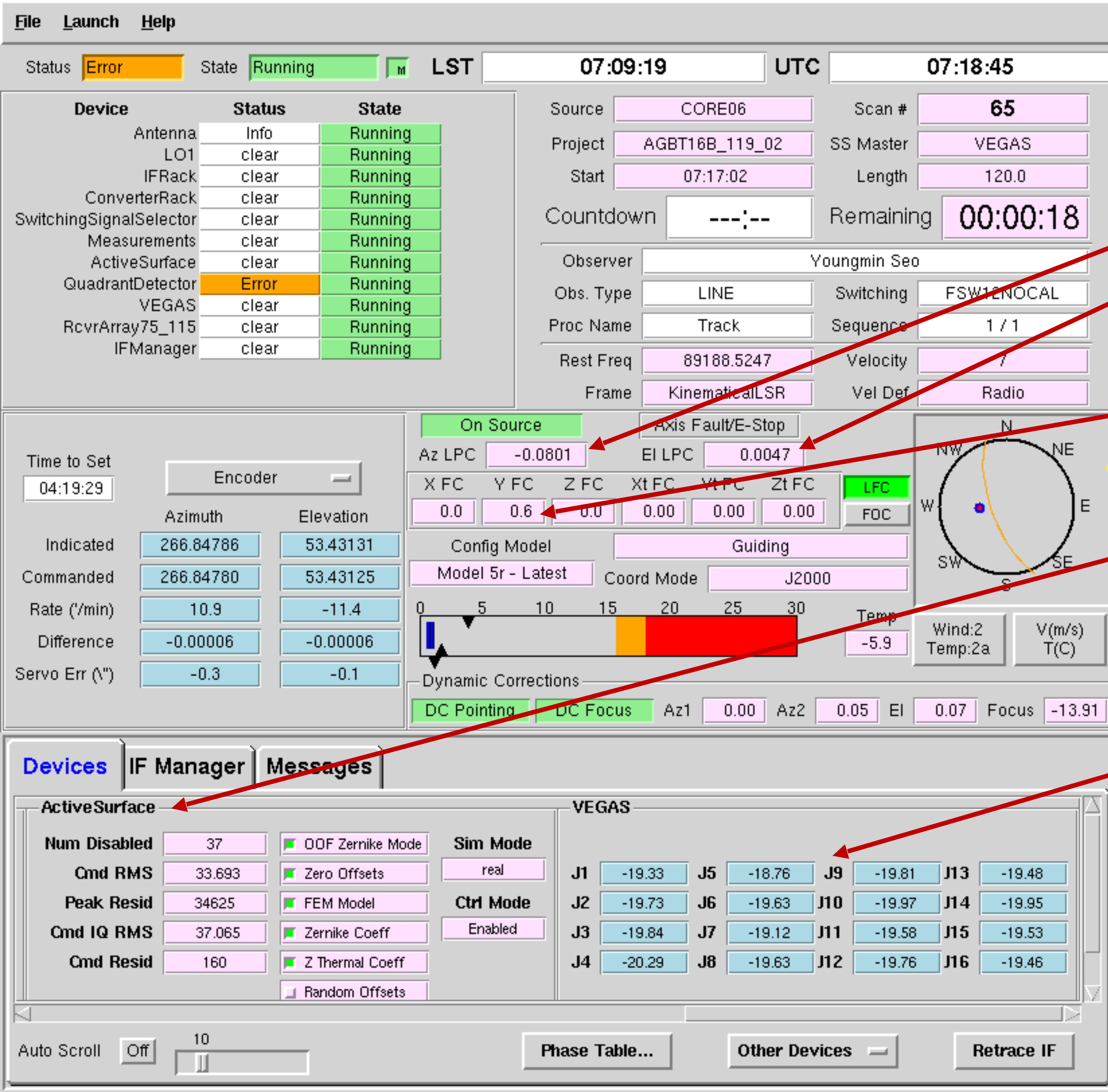

/home/gbtdata/AGBT21B_206_06 s8-1-db-000 z5 aperture-notilt.fits
Surface RMS = 207 microns


/home/gbtdata/AGBT21B_206_06 s46-1-db-000 z5 aperture-notilt.fits
Surface RMS = 983 microns


/home/gbtdata/AGBT21B_206_06 s41-1-db-000 z5 aperture-notilt.fits
Surface RMS = 879 microns


/home/gbtdata/AGBT21B_298_08 s3-1-db-000 z5 aperture-notilt.fits
Surface RMS = 638 microns

Cleo Status Window



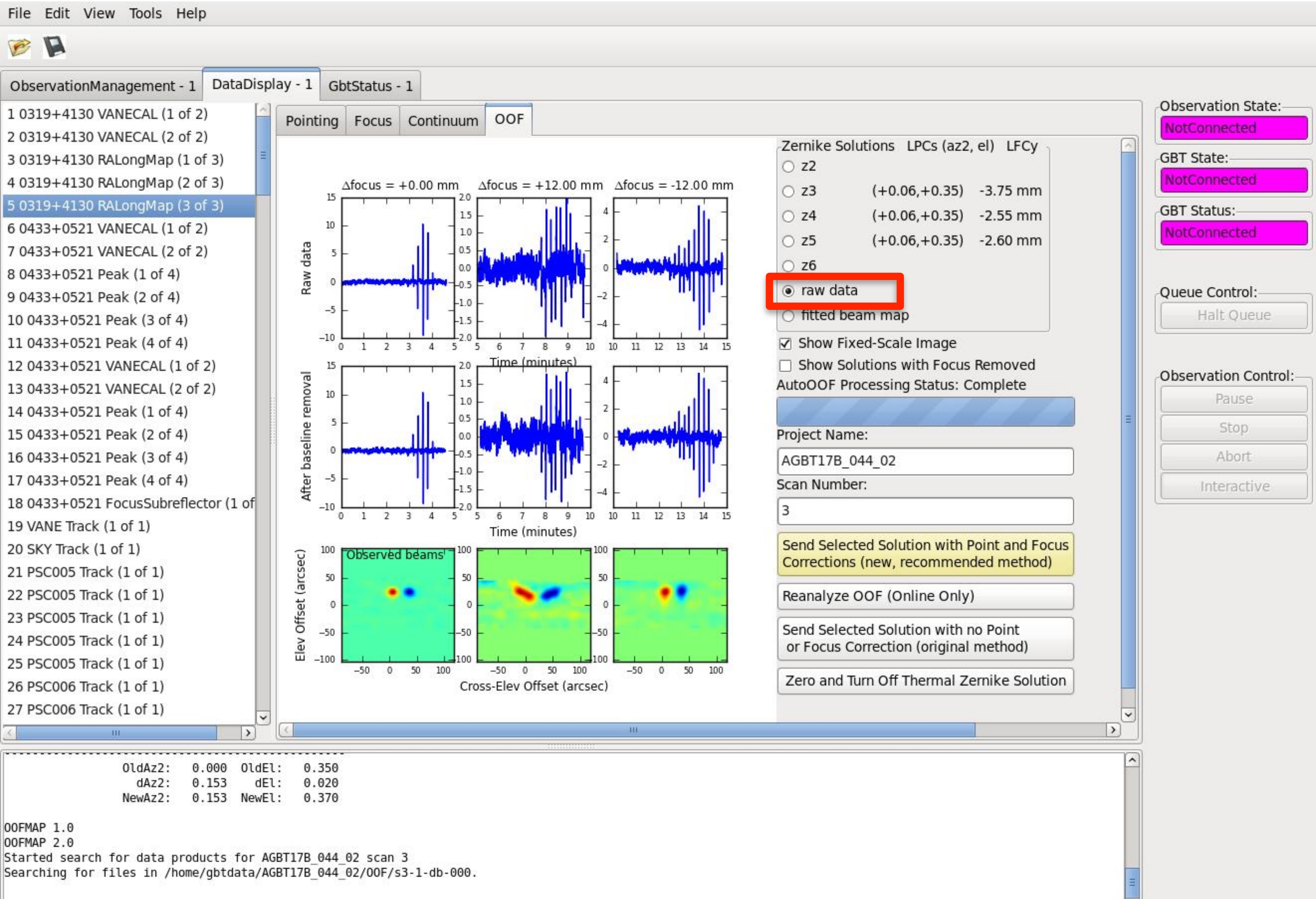
Az,El LPCs

Focus YFC

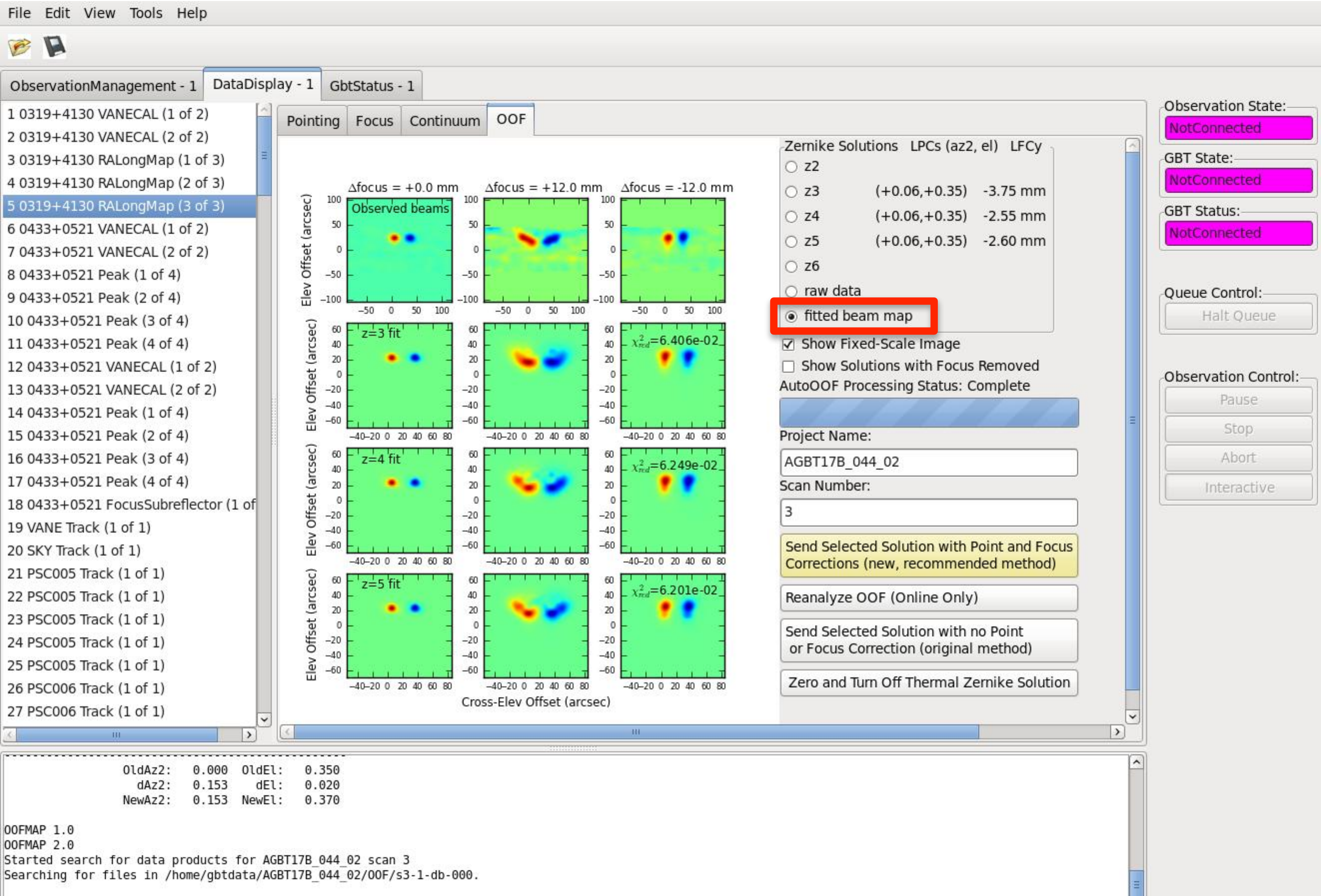
Active Surface ON with Thermal corrections from OOF

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

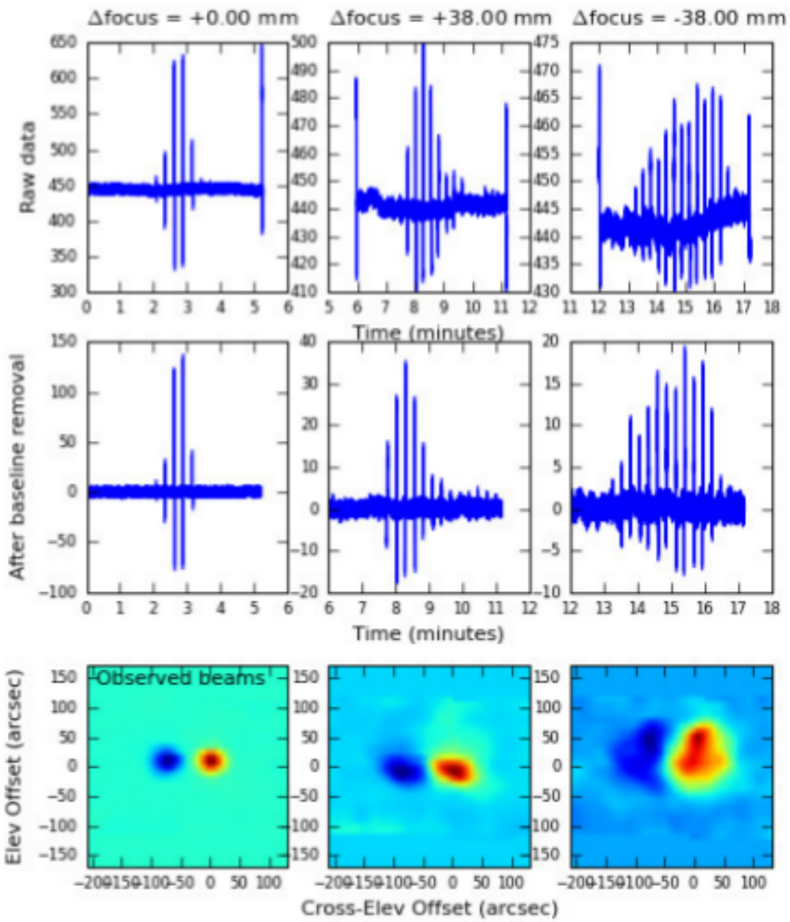
AutoOOF ‘Raw Data’



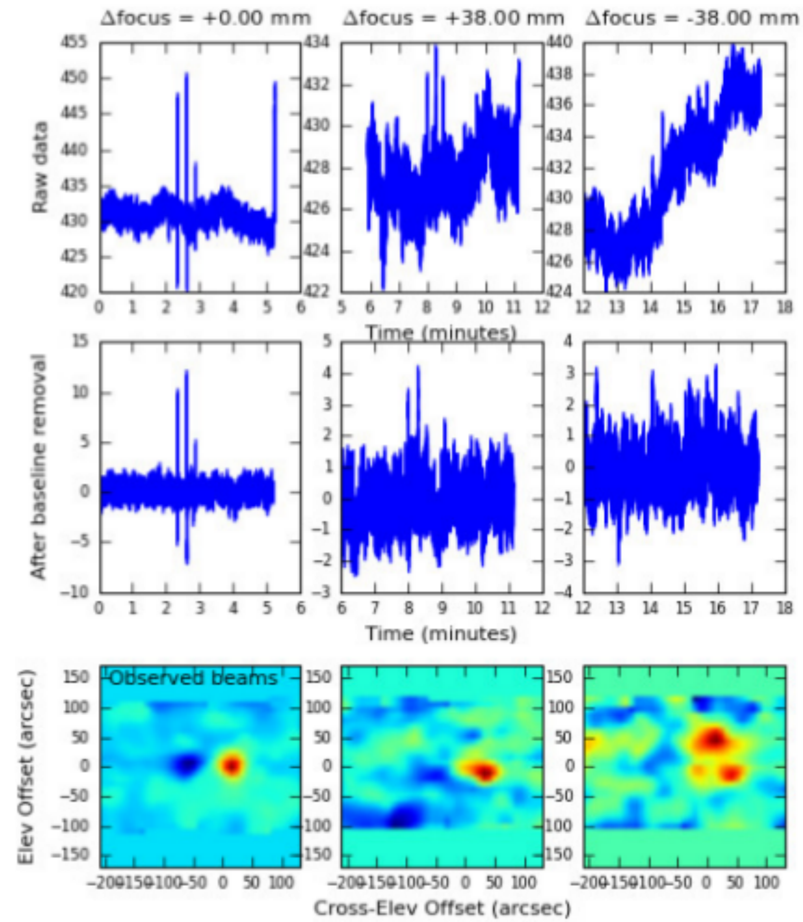
AutoOOF Beam Fits



AutoOOF ‘Raw’ Data Streams



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



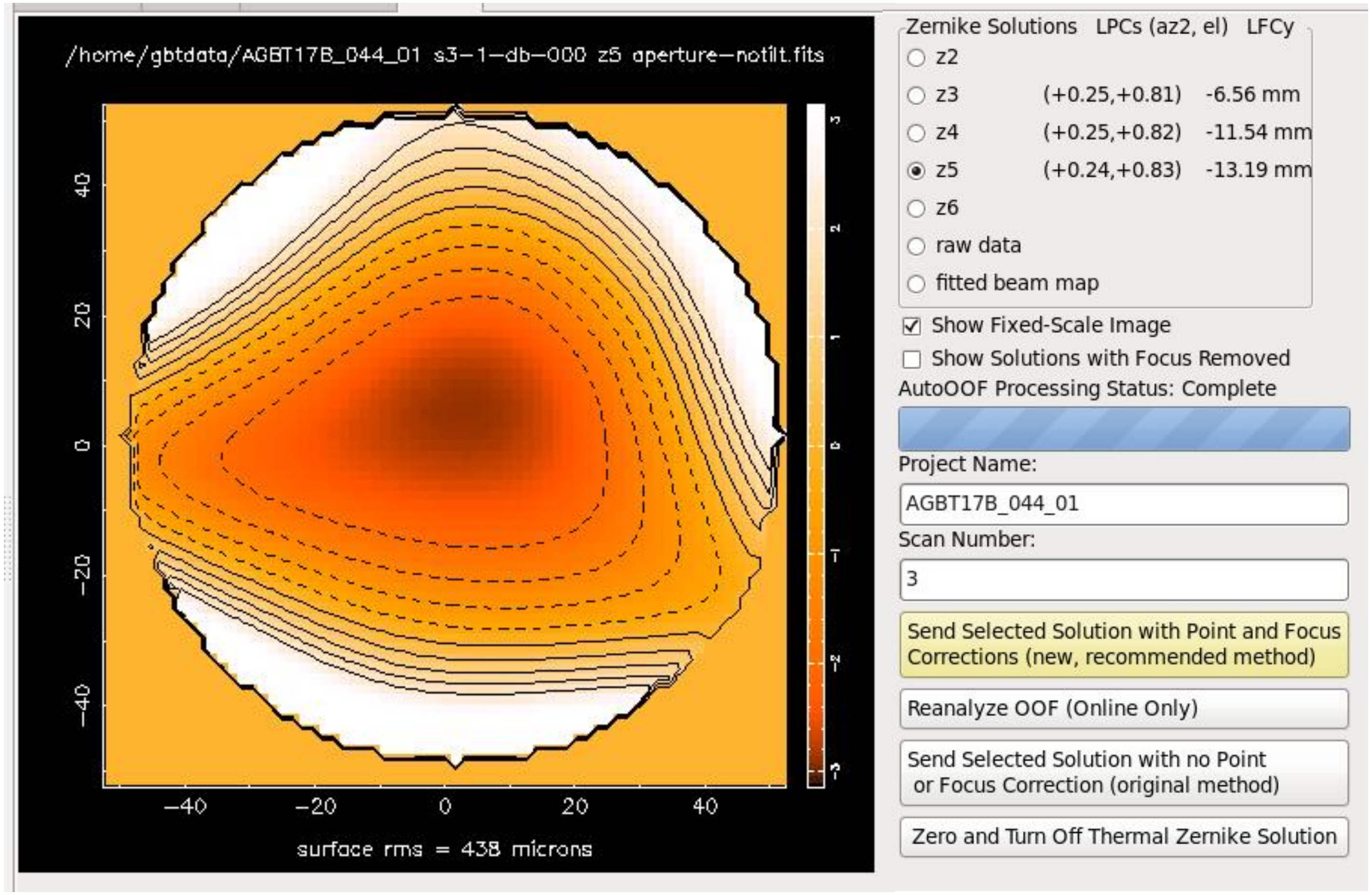
(b) A plot of raw OOF data on a source which is too faint.

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.

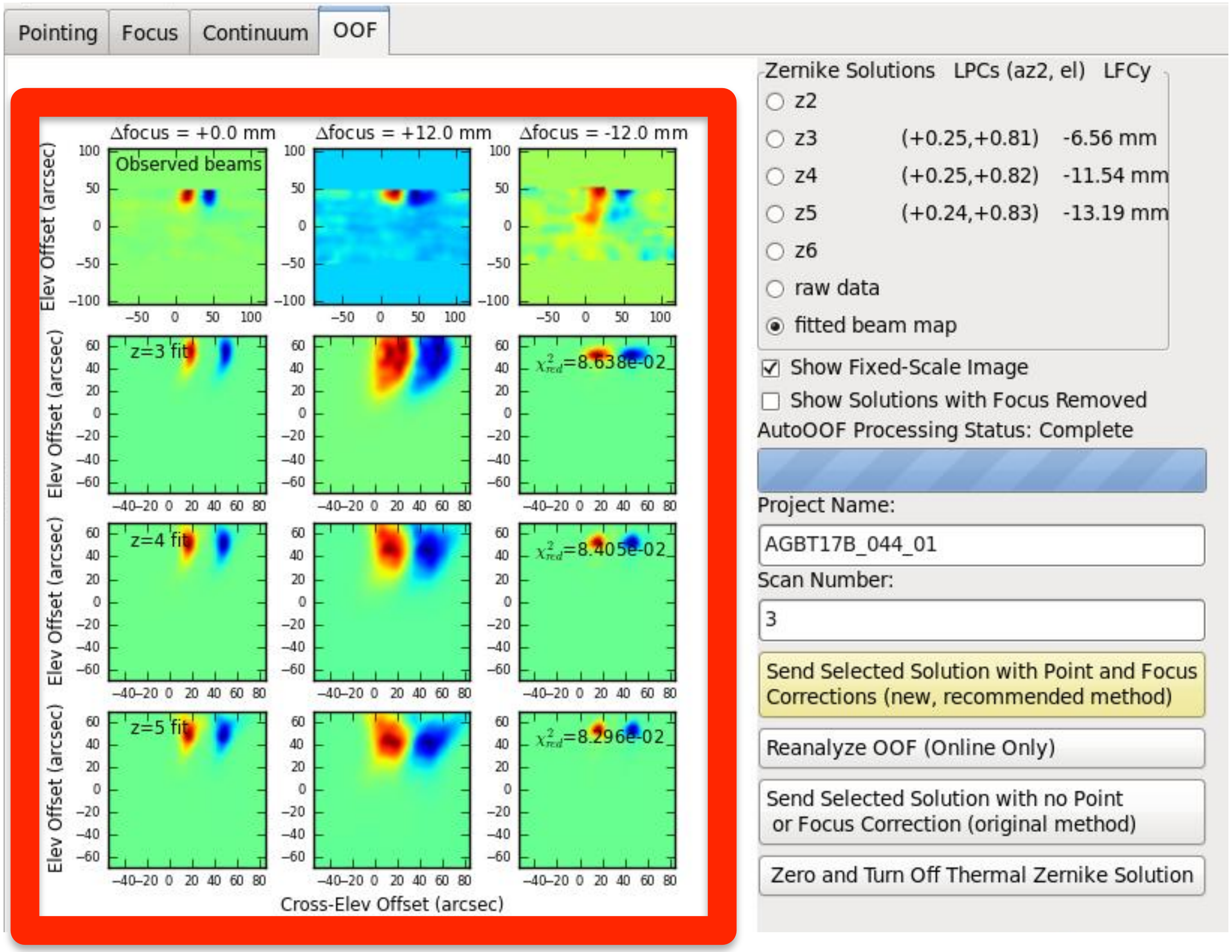
Solution with large rms >400 µm should not be used.

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.

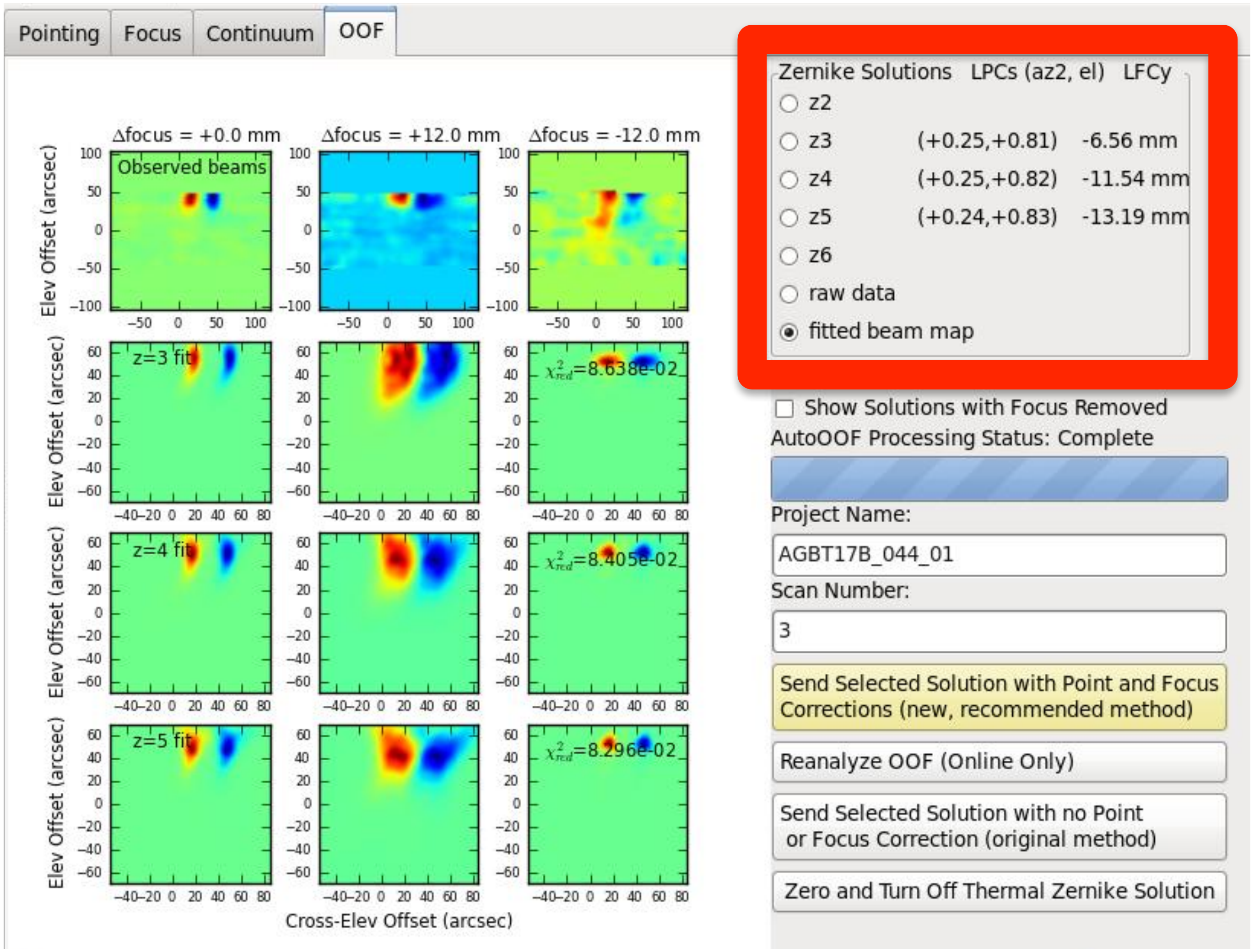


Beam Maps of Example Bad OOF

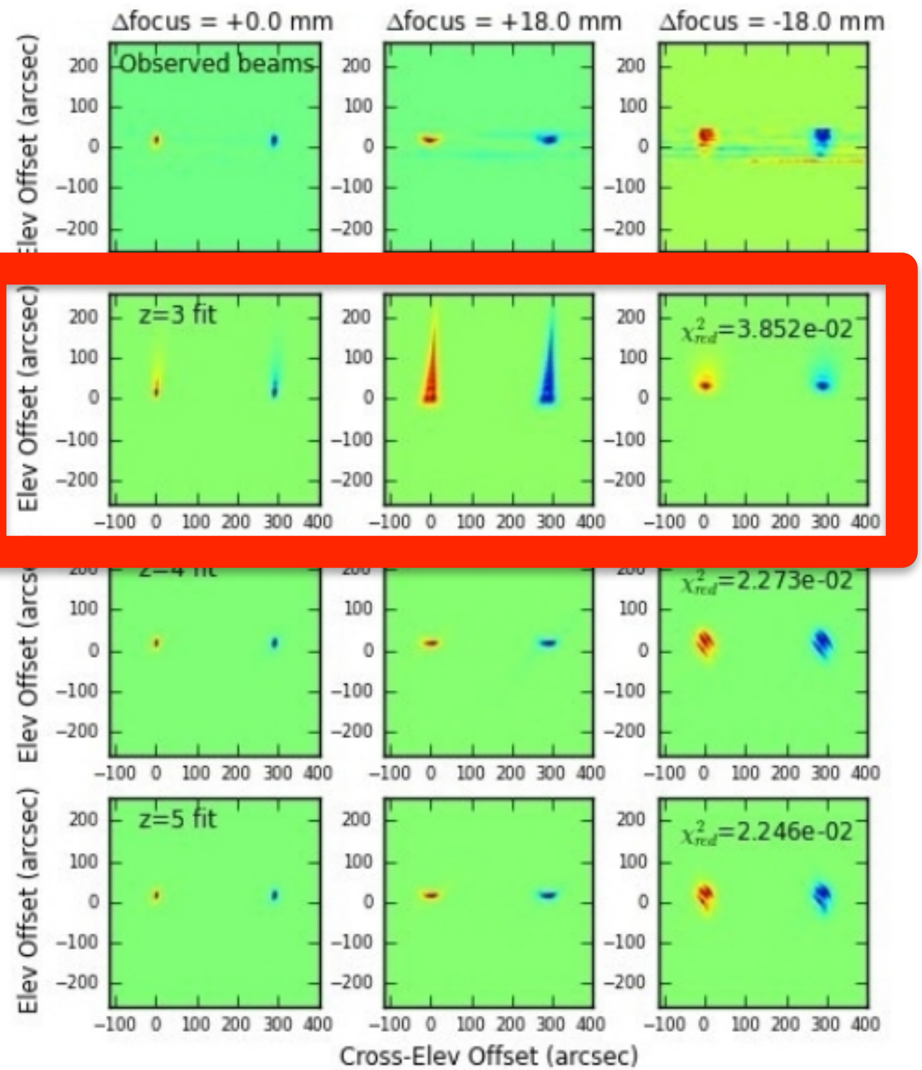
The "observed" beams should not be streaks or very elongated.
This can happen in windy conditions.

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)



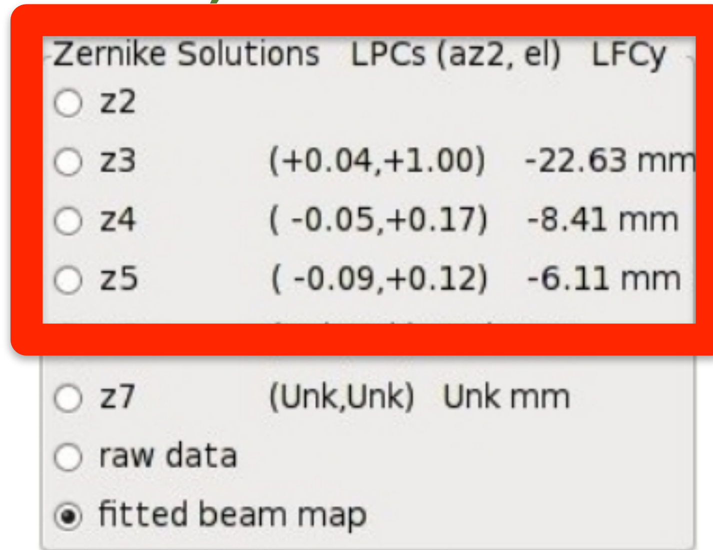


Figure 5.10: The AutoOOF fitted beam maps (left). The observed beams are plotted on the top row with the z3, z4 and z5 fits to the observed beams plotted below. The z3 solution (2^{nd} row down) shows an obvious artifact and should not be used. Also note the significant jump in LPCs and the LFC between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

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

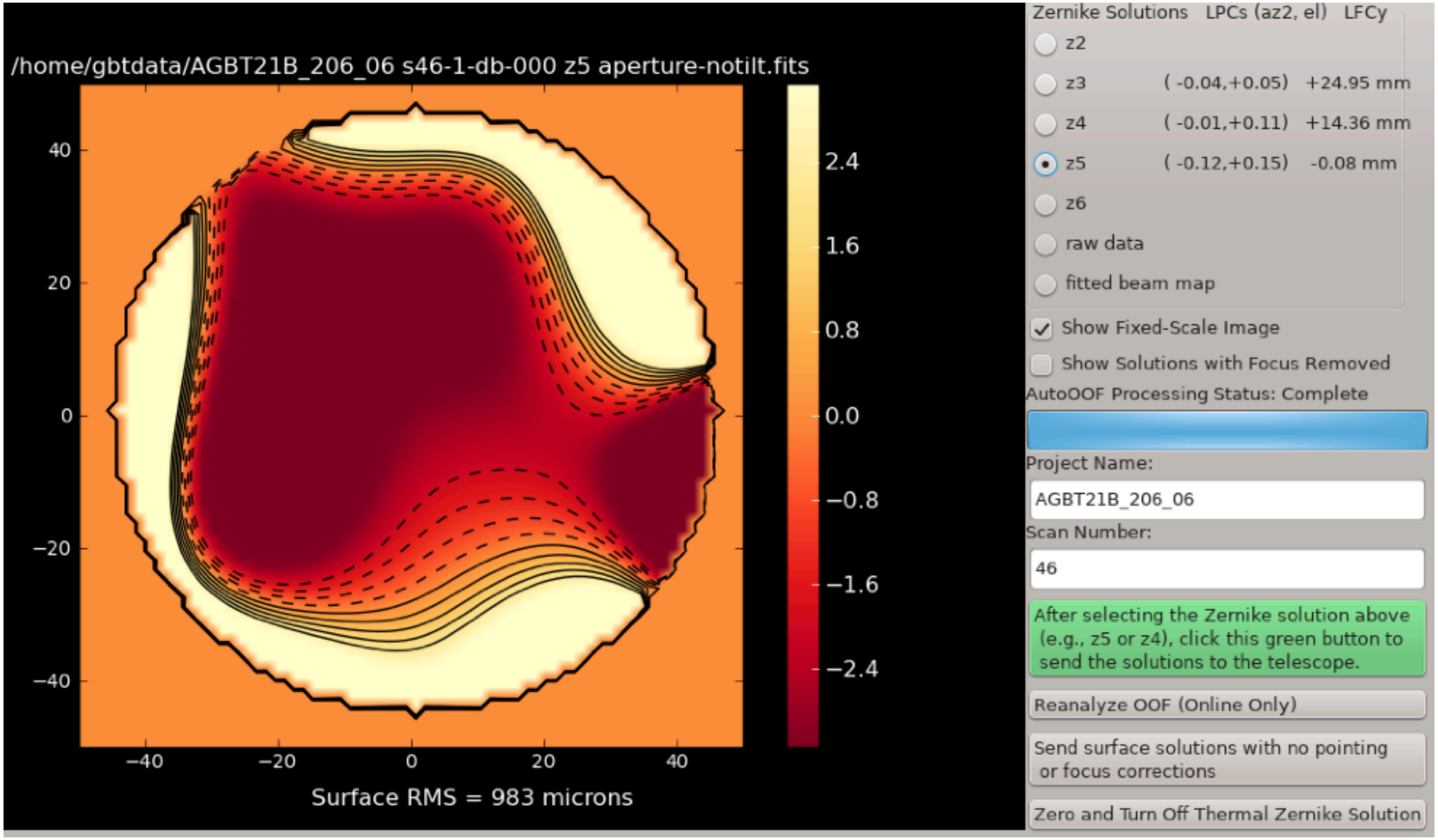
Bad OOF with ARGUS? What do you do?

- 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

- Should point+focus (AutoPeakFocus) every 30min-50min depending on conditions (point+focus takes ~5min)
  - MUSTANG-2 - point every 30 minutes

- AutoOOF (which takes ~20min) is used to correct the surface for thermal effects at night.
  - Not recommended before 21:00 or 22:00
  - Daytime surface changes <1hr time scales
    - Due to these rapidly changing conditions, the AutoOOF solutions (which are on a similar timescale) can cause more harm than good from the AutoOOF. So it is typically not useful to use the “thermal” corrections during the day.
  - OOF solution good for 2-6 hours at night

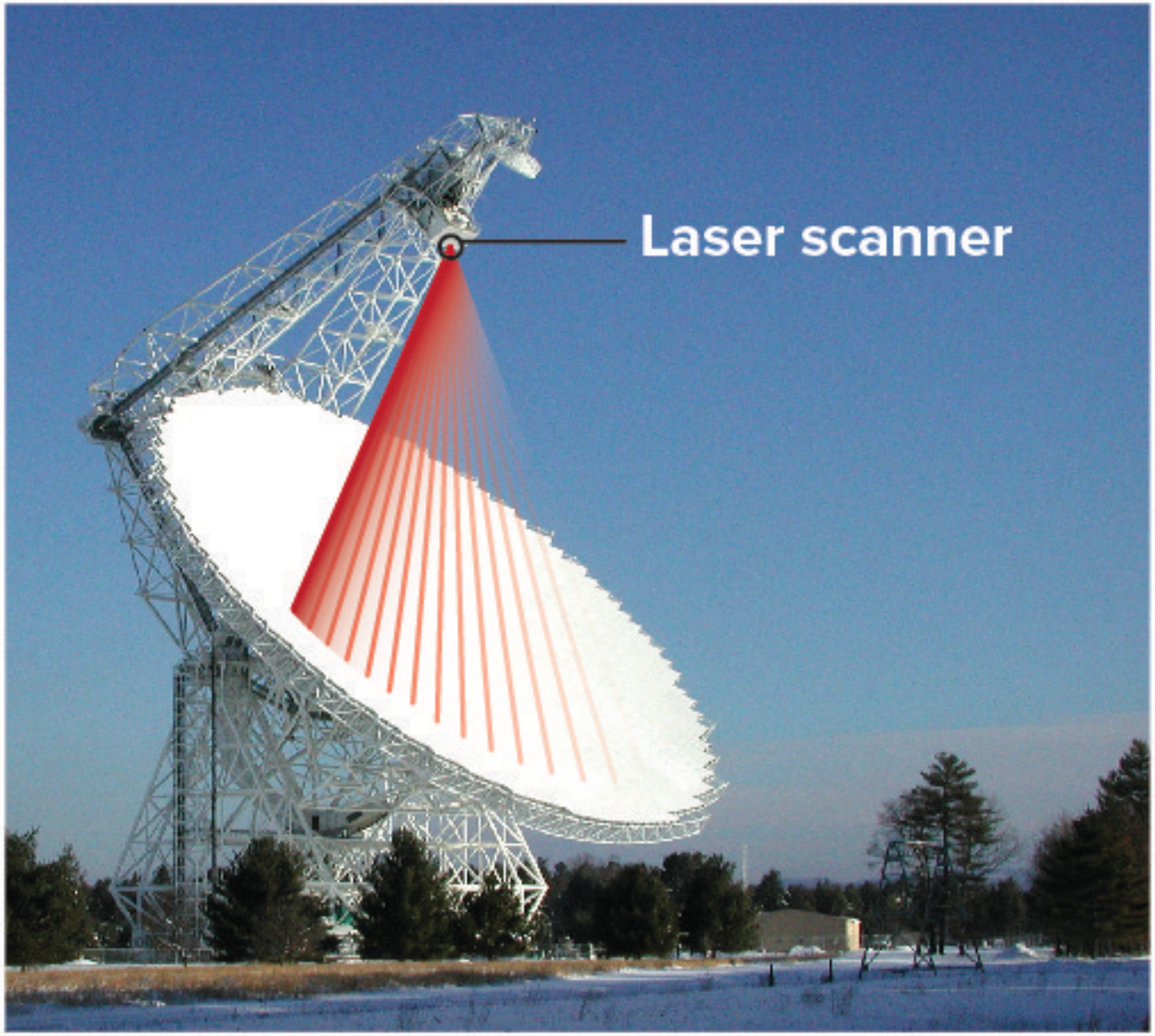
LASSI: Laser Antenna Surface Scanning Instrument

Commercial laser scanner that will scan the dish and detect deviations from previous measurements.

To be used in conjunction with OOF. Not giving an absolute correction but deviations from previous solutions.

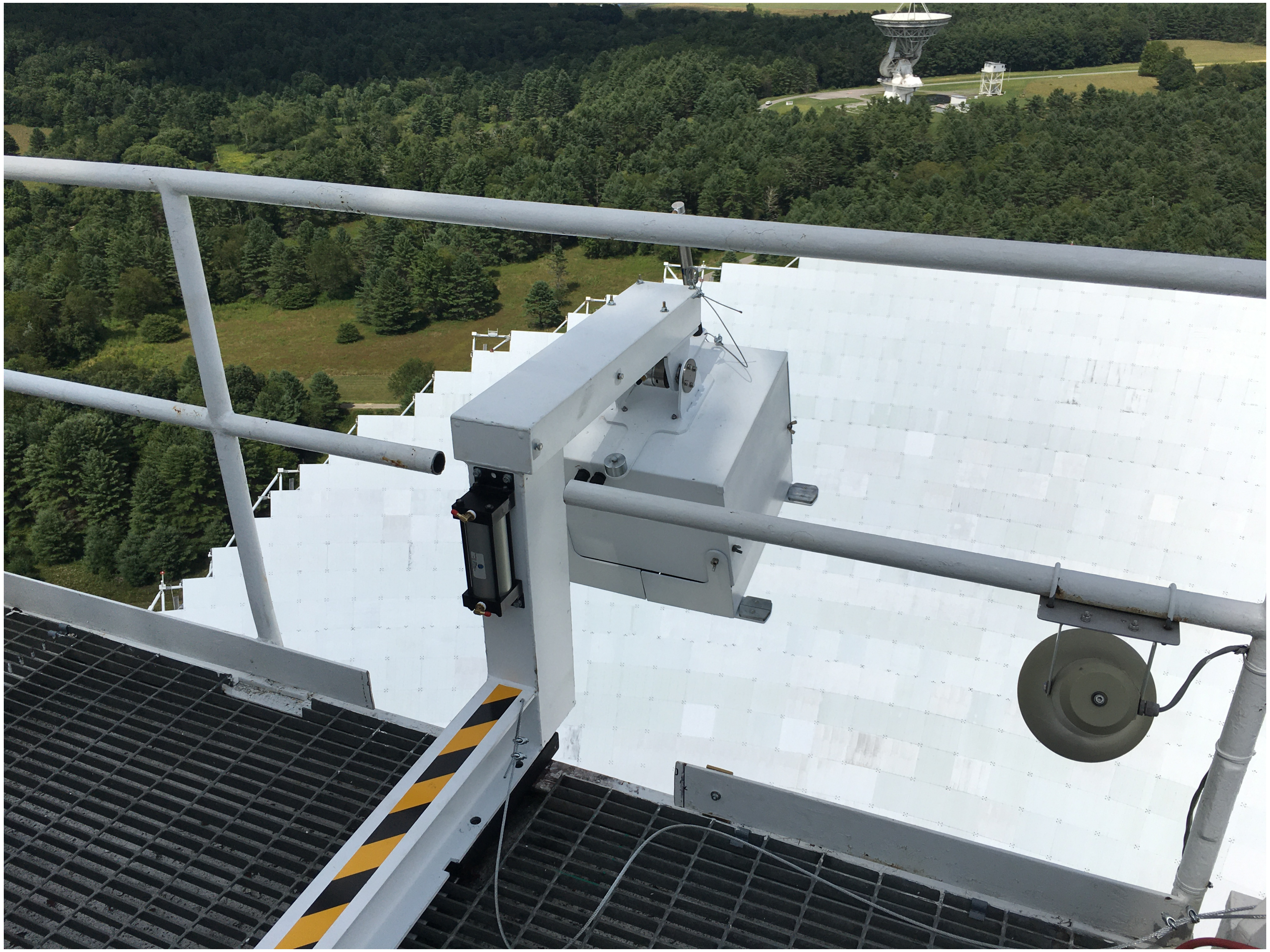
Processing time takes 6 minutes (compared to the 20-30 minutes for OOF scans)

Opens up more day time observing for high frequency.

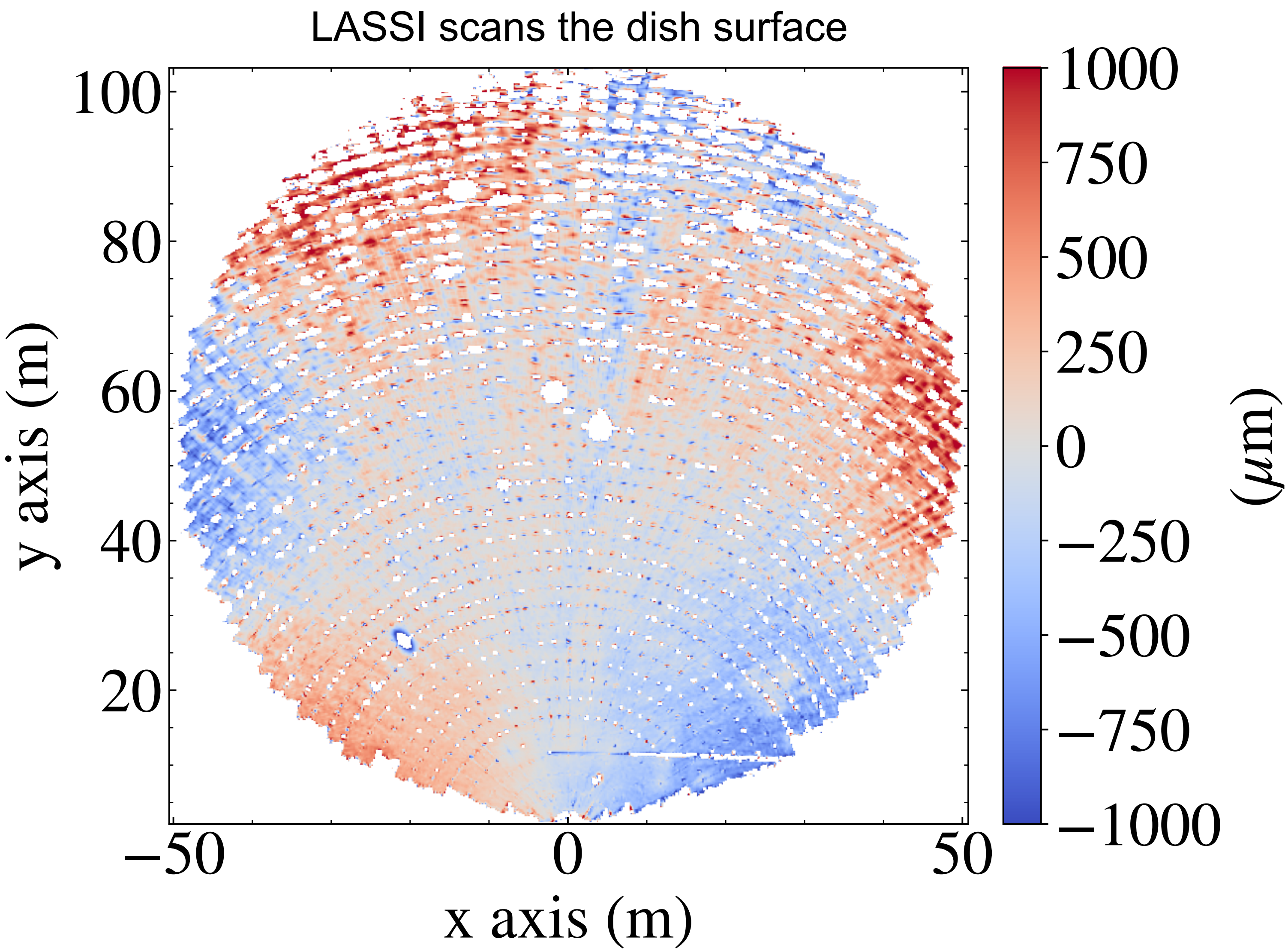


LASSI: Laser Antenna Surface Scanning Instrument

Photo of LASSI installed on the GBT



LASSI: Laser Antenna Surface Scanning Instrument



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