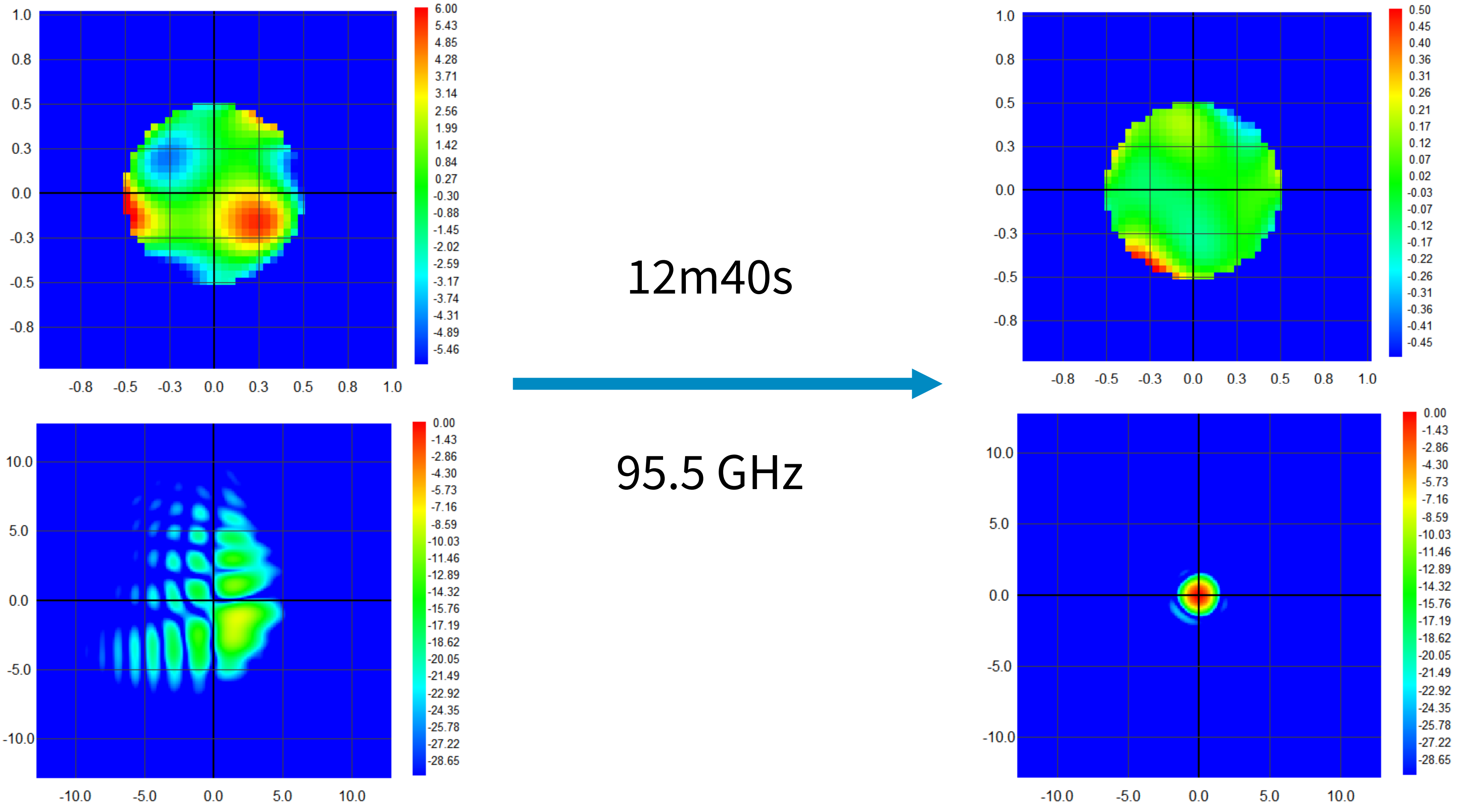
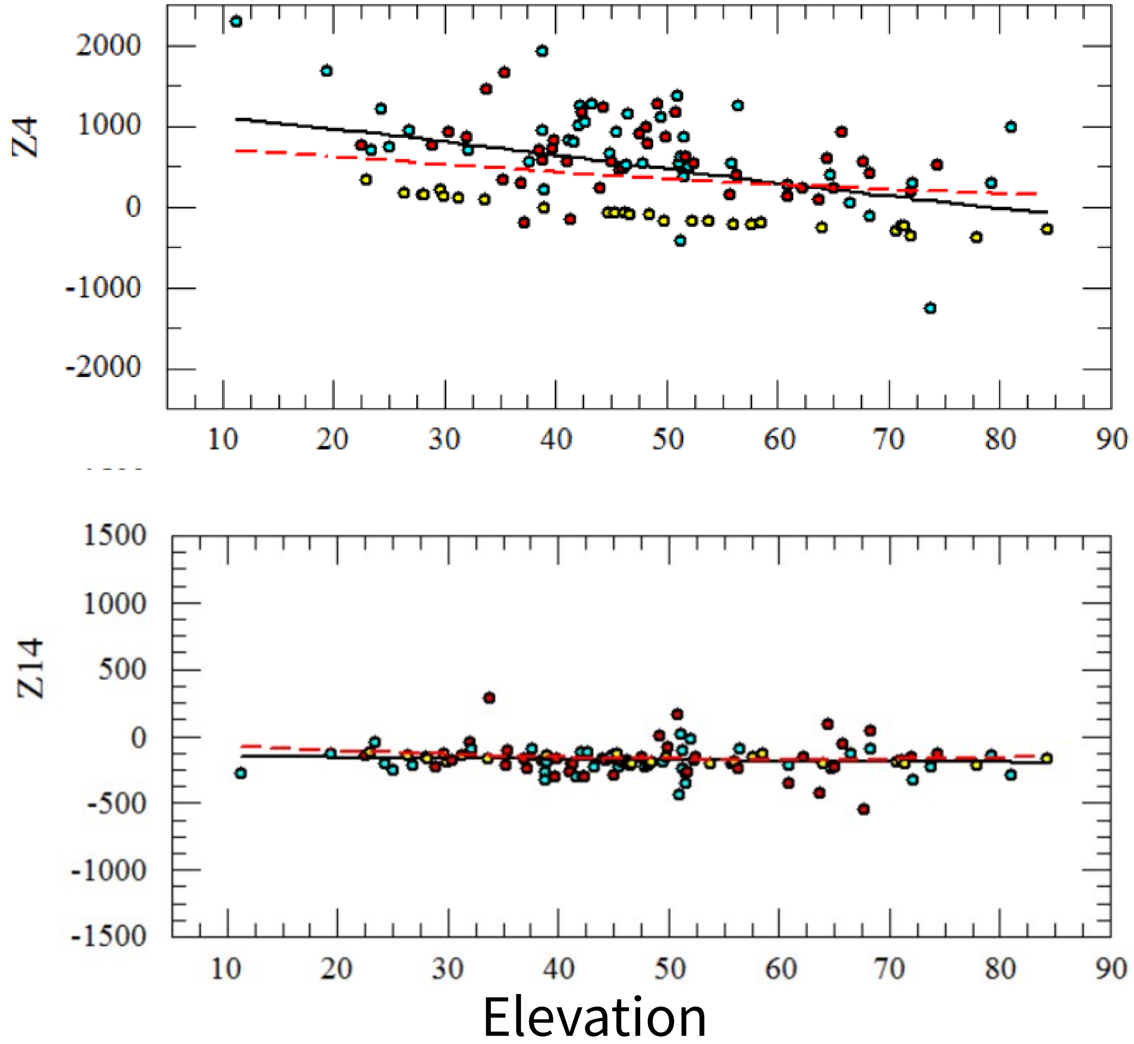

12m40s
95.5 GHz
1.0
0.8
0.5
0.3
0.0
-0.3
-0.5
-0.8
-0.8 -0.5 -0.3 0.0 0.3 0.5 0.8 1.0
6.00 5.43 4.85 4.28 3.71 3.14 2.56 1.99 1.42 0.84 0.27 -0.30 -0.88 -1.45 -2.02 -2.59 -3.17 -3.74 -4.31 -4.89 -5.46
0.50 0.45 0.40 0.36 0.31 0.26 0.21 0.17 0.12 0.07 0.02 -0.03 -0.07 -0.12 -0.17 -0.22 -0.26 -0.31 -0.36 -0.41 -0.45
10.0
5.0
0.0
-5.0
-10.0
-10.0 -5.0 0.0 5.0 10.0
0.00 -1.43 -2.86 -4.30 -5.73 -7.16 -8.59 -10.03 -11.46 -12.89 -14.32 -15.76 -17.19 -18.62 -20.05 -21.49 -22.92 -24.35 -25.78 -27.22 -28.65



PTCS Memo 76: “The Updated 2014 Gravity Model”

Results from 109 AutoOOF over 1 year

“The high-order Zernike terms tend to show a low dispersion that may suggest these terms are relatively insensitive to thermal effects. The terms that have the largest thermal scatter are Z4, Z5, and Z10. The Z4 term appears particularly sensitive to varying conditions with an rms scatter of more than 500 µm. If the thermal variations primarily only effect the lower order terms, it may be possible to speed up the derivation of the thermal Zernikes by taking short daisy, circle, or spiral scans instead of the full, time-consuming maps currently used by AutoOOF”

$Z_{GBT,n} = A \cdot \sin(E) + B \cdot \cos(E) + C$

$$1 - G/G_0 \propto rms^2$$

TABLE 2:

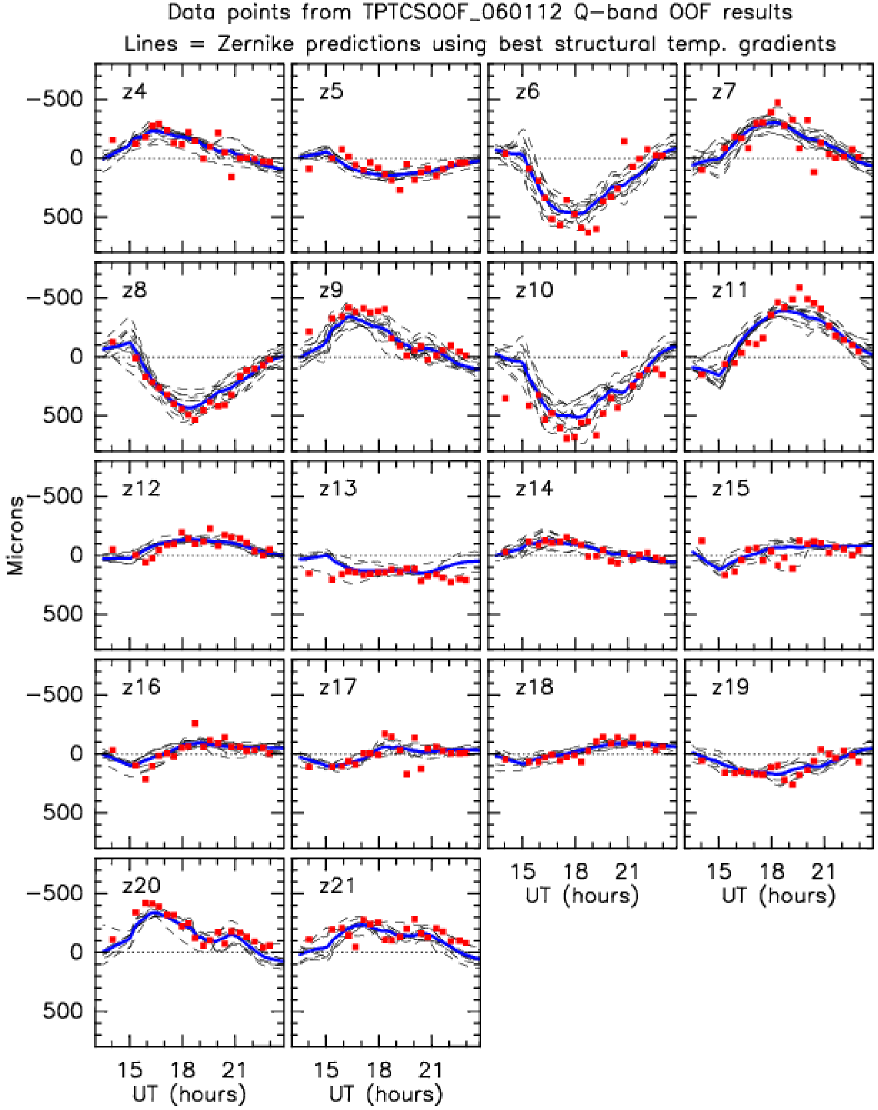
Z	A	B	C	σ_A	σ_B	σ_C	rms
4	-697.71	697.91	550.68	905.87	775.82	1137.56	517.55
5	0.0	0.0	-282.34	----	----	314.38	314.38
6	0.0	0.0	-206.22	----	----	182.95	182.95
7	0.0	0.0	23.06	----	----	217.58	217.58
8	0.0	0.0	95.99	----	----	153.50	153.50
9	588.39	1305.77	-1063.37	341.03	292.07	428.25	194.84
10	0.0	0.0	-98.51	----	----	280.25	280.25
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	0.0	0.0	-178.06	----	----	106.93	106.93
15	0.0	0.0	29.32	----	----	168.00	168.00
16	0.0	0.0	79.20	----	----	168.57	168.57
17	0.0	0.0	-75.06	----	----	92.41	92.41
18	0.0	0.0	-212.43	----	----	81.72	81.72
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

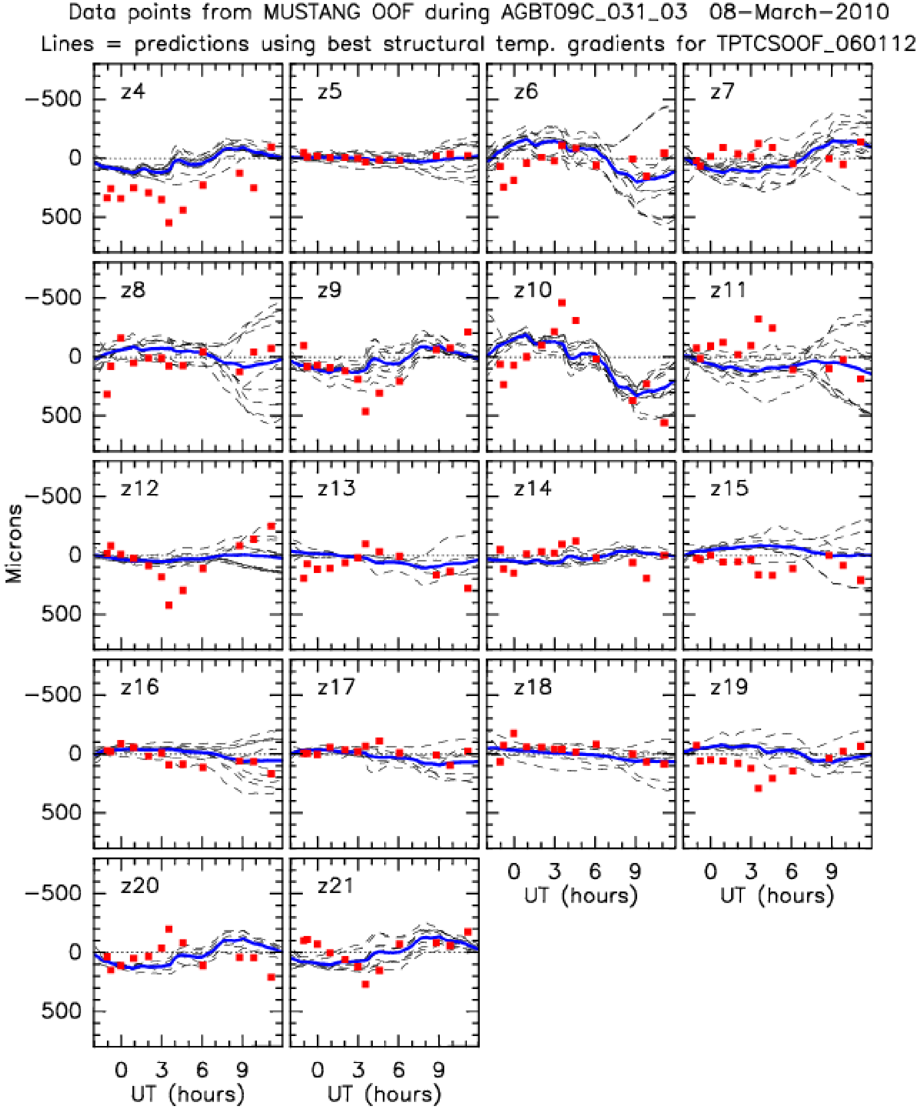
Fun Facts:

- Red : Large thermal component
- Green : No gravity component
- Blue : FEM Model is good
- Our focus tracking model for X can be improved ($Z_{GBT,9}$ – vertical coma - is not flat) – probably inconsequential

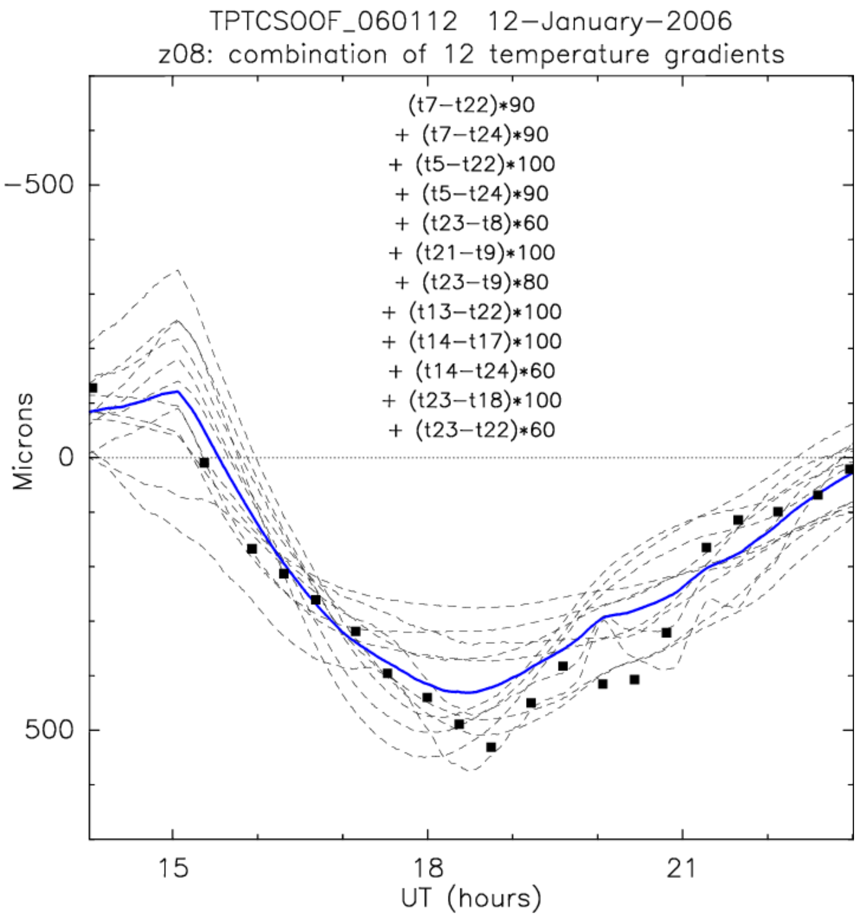
Daytime Zernikes

- Todd Hunter:
- https://safe.nrao.edu/wiki/bin/view/GB/PTCS/DaytimeOOFJan2006





Alternative #1: Use Existing Temperature Sensors

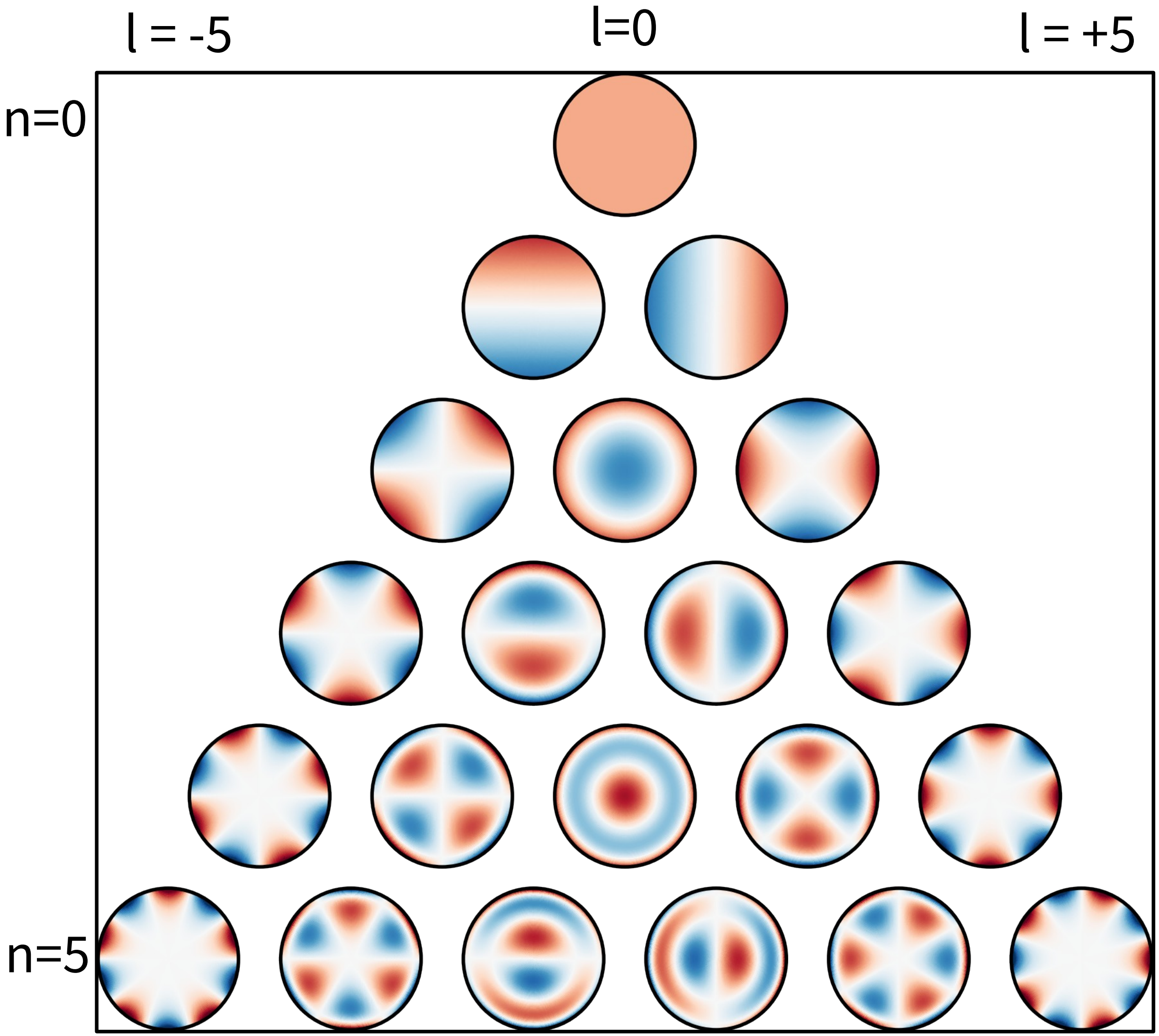


Pros: If this can be developed, then we would not have to take time out to measure the surface at night or during the day!

Cons: Need to dedicate staff time with no guarantee of success

Hybrid? AutoOOF every ~2 hours to reset surface and temperature sensors to estimate changes between OOFs?

Todd Hunter:
https://safe.nrao.edu/wiki/bin/view/GB/PTCS/DaytimeOOFJan2006



Describe errors in the aperture plane, not the optical surface

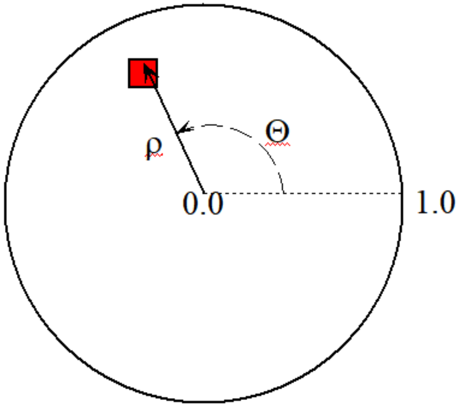
Fun Facts:

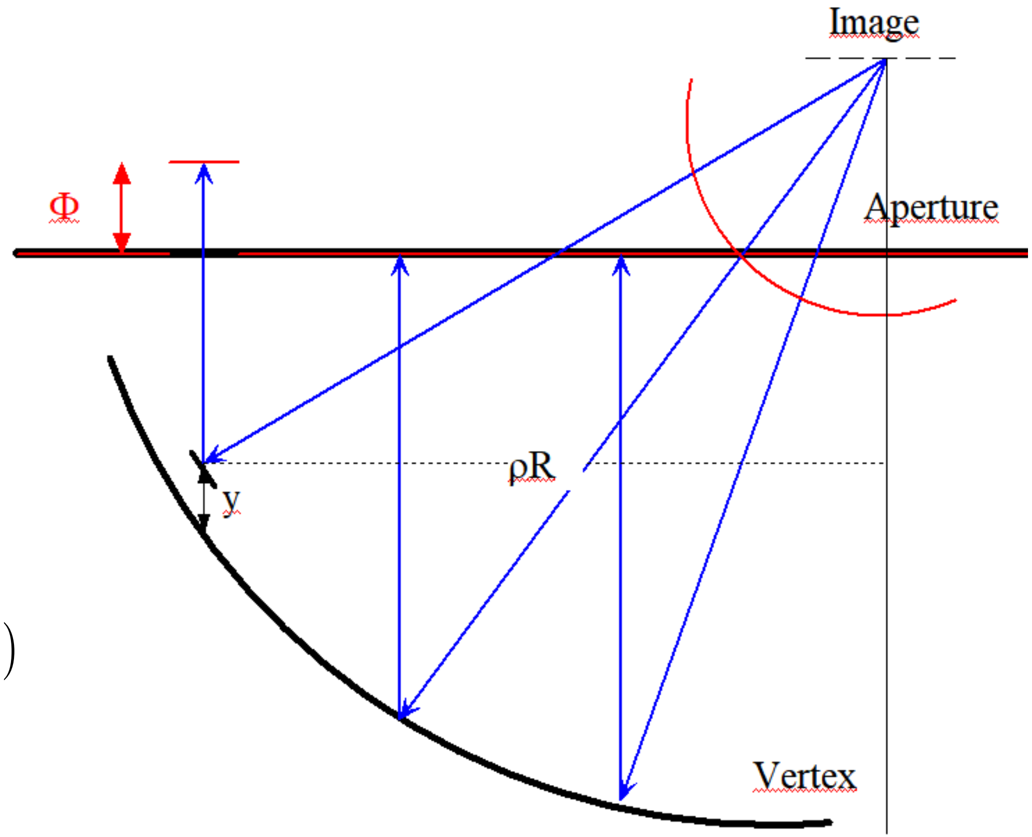
- Six different naming conventions in the literature (The GBT created its own numbering system)
- Normalized to 1 or π?

$$\int_0^{2\pi}\int_0^{1} Z_n Z_m \rho \, d\rho \, d\Theta \qquad \begin{matrix} 0 \text{ if } n \neq m \\ \pi \text{ if } n = m \end{matrix}$$

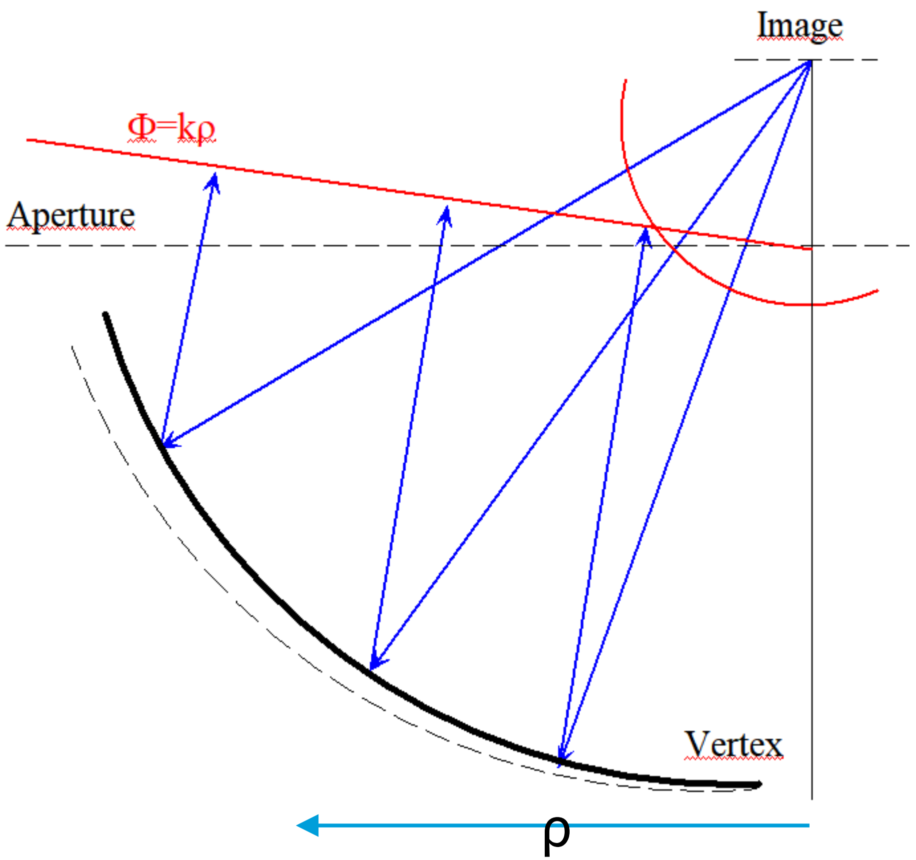
$$\Phi(\rho,\Theta)=C_0^0\cdot Z_0^0(\rho,\Theta)+C_1^{-1}\cdot Z_1^{-1}(\rho,\Theta)+C_1^1\cdot Z_1^1(\rho,\Theta)+\ldots$$

$$\Phi(\rho,\Theta)=\sum C_n^l\cdot Z_n^l(\rho,\Theta)+small\ scale\ aperture(panel)\ errors$$

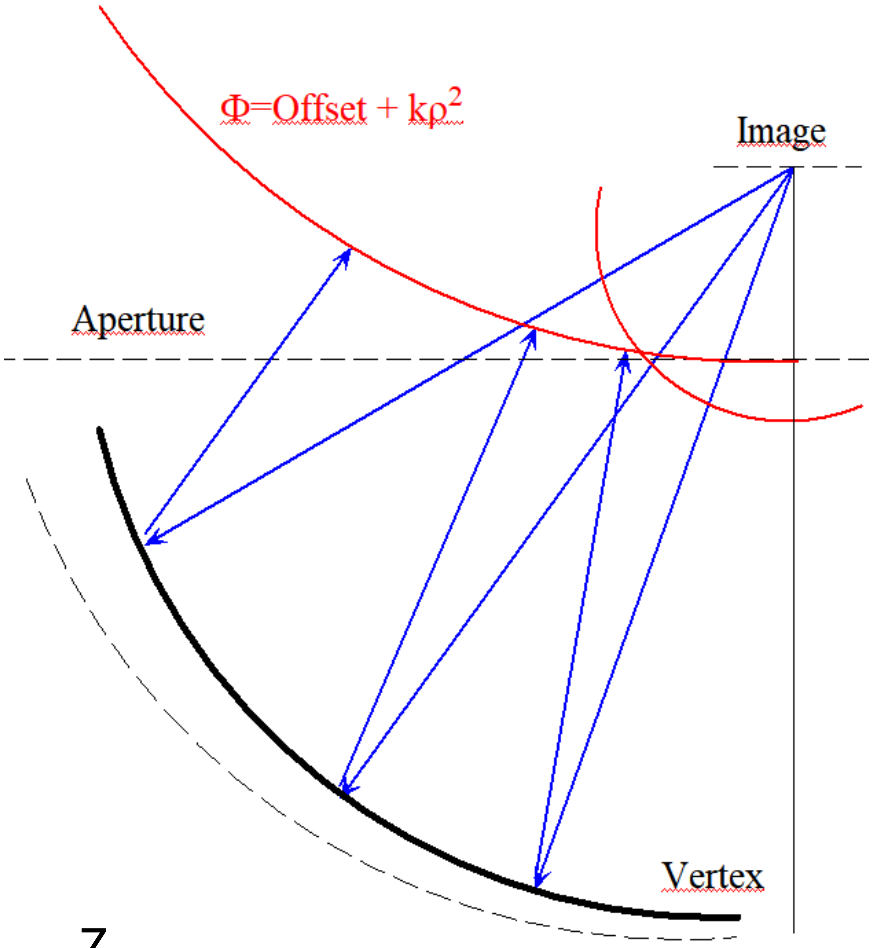




$$\Phi(\rho,\theta)=2\pi\frac{y}{\lambda}\cdot\left(1+\frac{F_{eff}-R^2\rho^2/4F_{eff}}{F_{eff}+R^2\rho^2/4F_{eff}}\right)$$



$Z_{GBT,2}$ or $Z_{GBT,3}$



$Z_{GBT,5}$

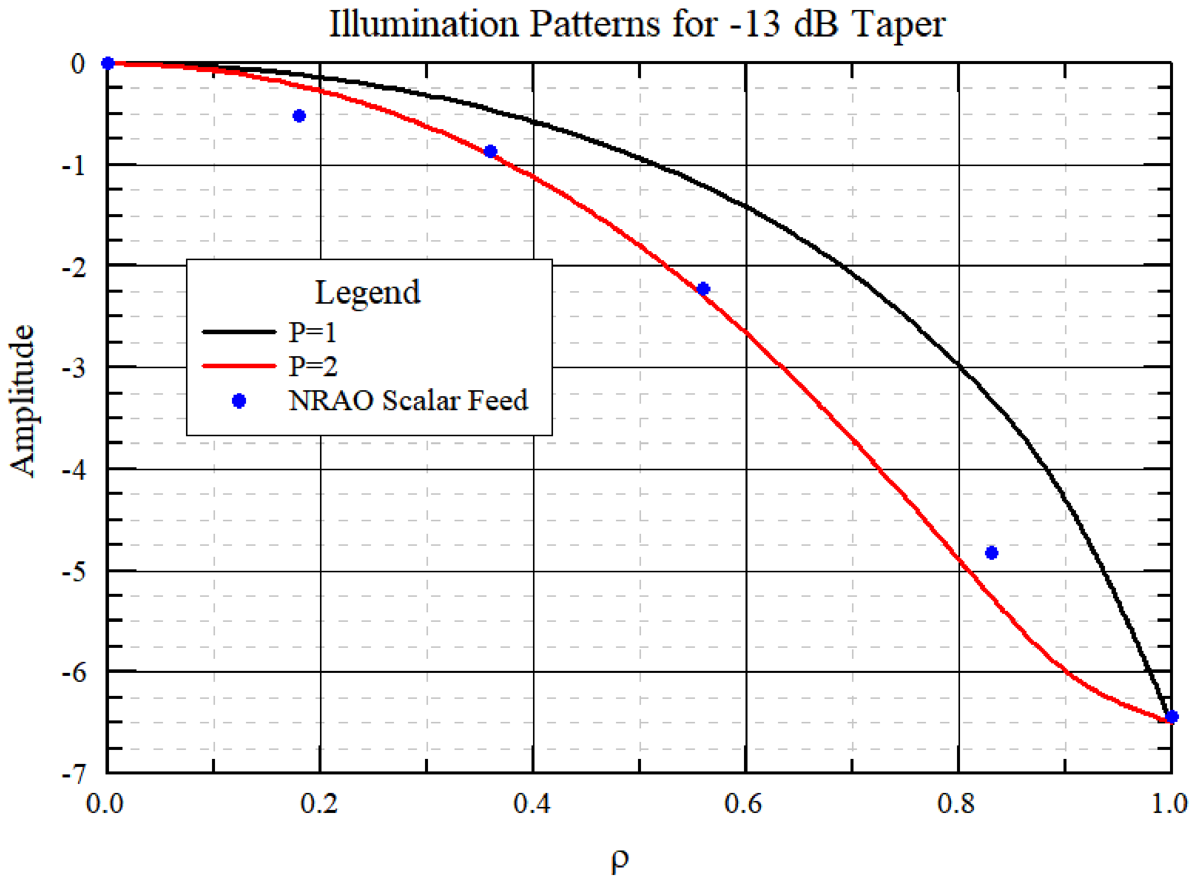
$$E_a(\rho,\Theta) = \text{electric field amplitude across aperture plane} = \sqrt{\text{feed illumination}}$$

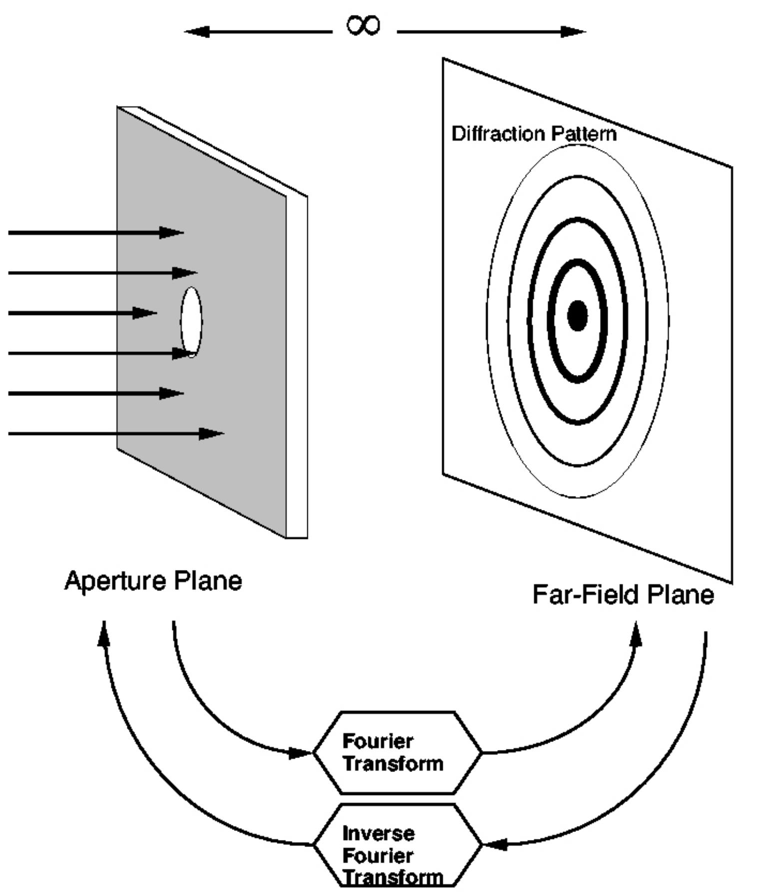
$$Beam(\Delta xEl, \Delta El) = \frac{\left| \int_0^{2\pi} \int_0^1 E_a(\rho,\Theta)\, e^{i\{\Phi(\rho,\Theta) + 2\pi[\Delta xEl \cdot \cos\Theta + \Delta El \cdot \sin\Theta]\rho D/\lambda\}}\, \rho\, d\rho\, d\Theta \right|^2}{\left| \int_0^{2\pi} \int_0^1 E_a(\rho,\Theta)\, \rho\, d\rho\, d\Theta \right|^2}$$

$$G/G_0 = Beam(0,0) = \frac{\left| \int_0^{2\pi} \int_0^1 E_a(\rho,\Theta)\, e^{i\Phi(\rho,\Theta)}\, \rho\, d\rho\, d\Theta \right|^2}{\left| \int_0^{2\pi} \int_0^1 E_a(\rho,\Theta)\, \rho\, d\rho\, d\Theta \right|^2}$$

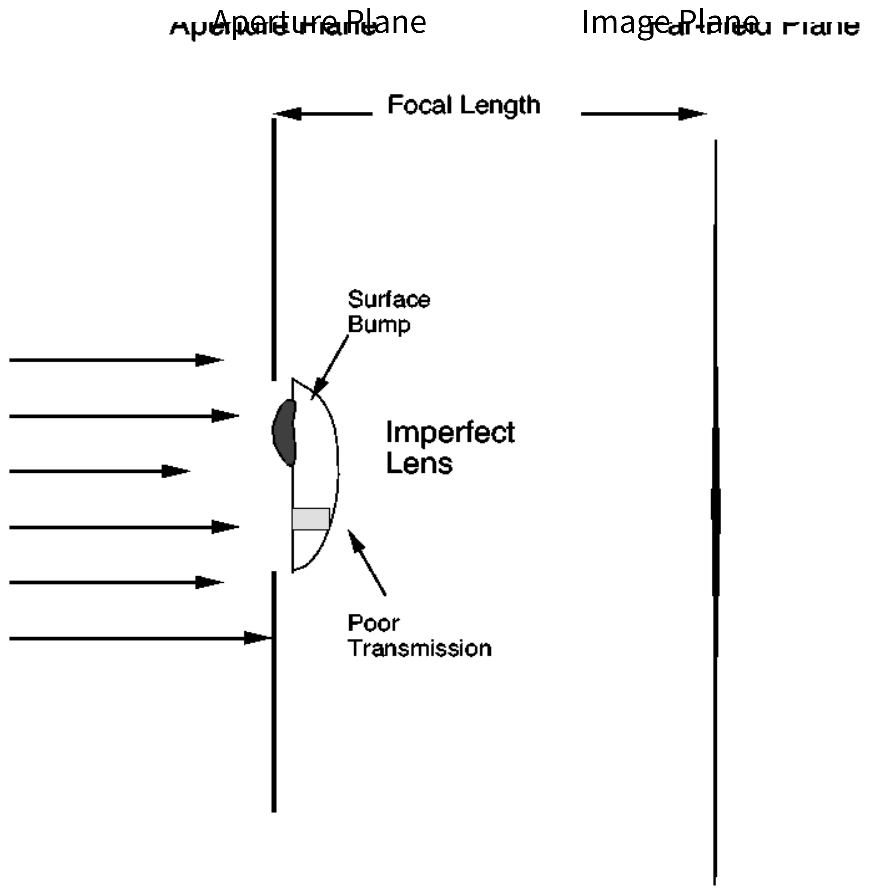
In effect, Z's are not orthogonal

$$G/G_0 \sim 1 - \frac{\left| \iint E_A(\rho)\Phi(\rho,\Theta) \right|^2}{\left| \iint E_a(\rho) \right|^2} \sim 1 - \frac{\left| \iint E_a(\rho) \cdot smallscale \right|^2}{\left| \iint E_a(\rho) \right|^2} - \frac{\left| \iint \sum C_n^l \boldsymbol{E_A(\rho) Z_n^l(\rho,\Theta)} \right|^2}{\left| \iint E_a(\rho) \right|^2} + \ldots$$

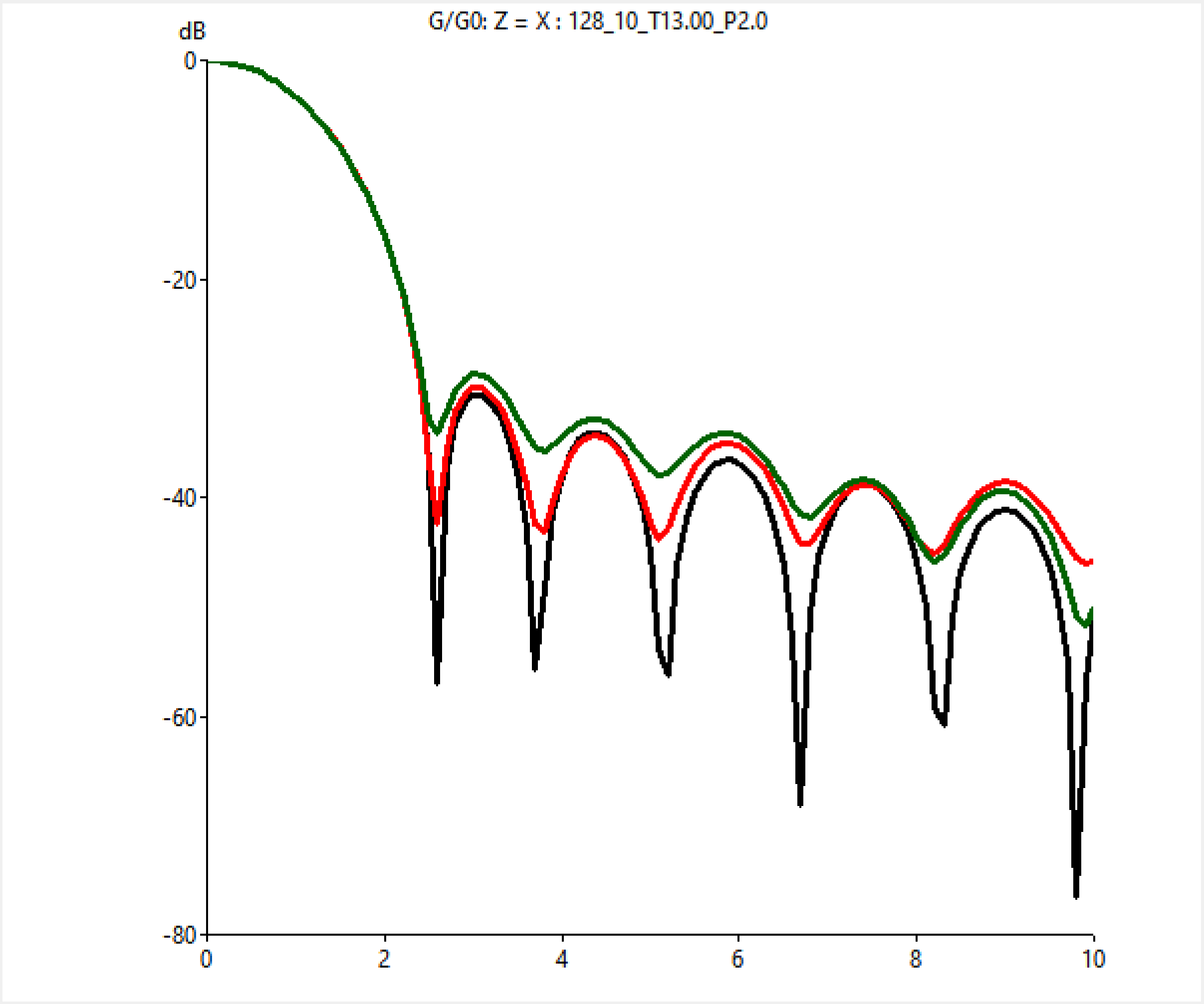

Illumination Patterns for -13 dB Taper
Legend
P=1
P=2
NRAO Scalar Feed
Amplitude
ρ
0
-1
-2
-3
-4
-5
-6
-7
0.0
0.2
0.4
0.6
0.8
1.0



An aperture creates a diffraction pattern in the far-field. From the diffraction pattern you can calculate what the aperture is like.



Diffraction Pattern Altered by Errors in Aperture or in Lens



- Black : No errors
- Red : Gaussian ‘bump’ 10-m FWHM
- Green : Gaussian ‘bump’ 25-m FWHM

AutoOOF : resolution of 16m for 7th order , 20m for 5th order

AutoOOF maps need a dynamic range >> 1000 & sufficient S/N to measure accurately details in the 3rd sidelobes

Alternative #2: Use Existing Holography Receiver

To measure large-scale errors, measure only the inner sidelobes:

- Viable continuum sources may be common at 12 GHz (slew times same as for AutoOOF)
- Otherwise, typically 2min 30sec more overhead than AutoOOF for a slew to a geostationary satellite.
- Maps will be about 14’ x 14’ to derive 7th-order Zernikes, 10’ x 10’ for 5th-order Zernikes
- If strips take 30 sec, maps will take ~4 to 8 min.
- Instantaneous data reduction – 32 IFT of length 16 & multiregression LSQ fit (i.e., invert a 21x21 or 36x36 matrix) – Simple to write.

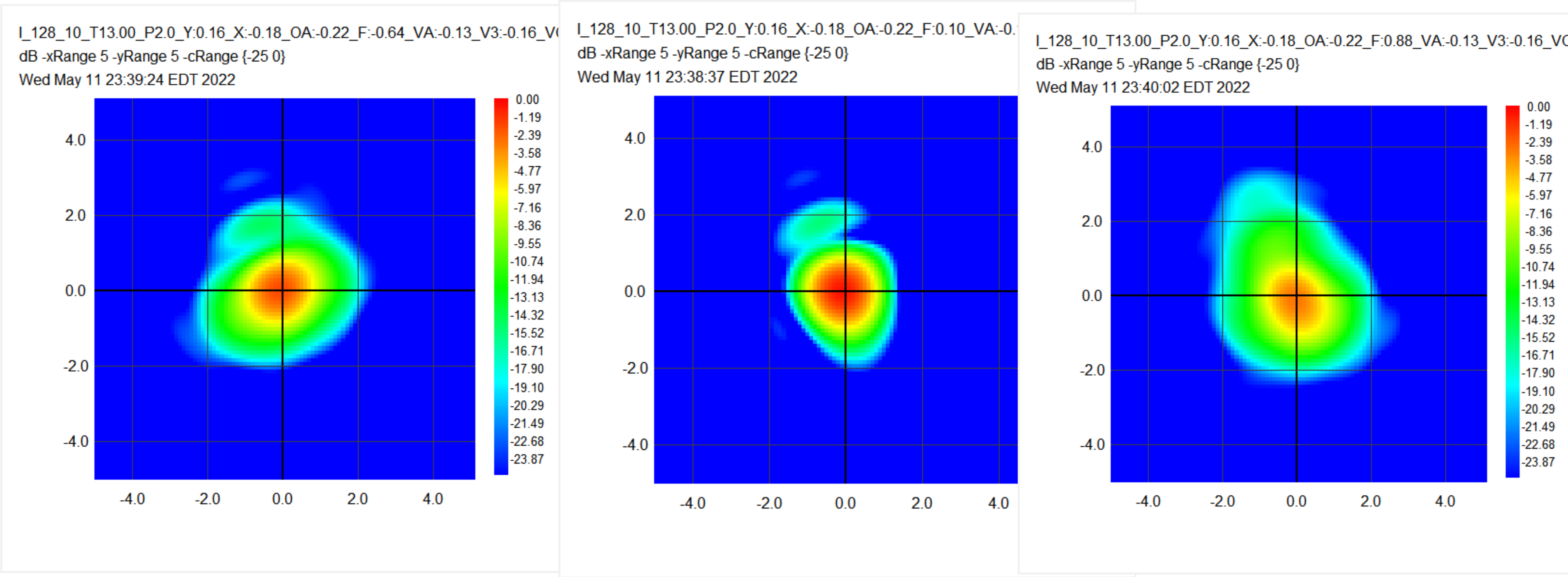
Estimated total time, with overhead for slewing, will typically be 10 min

- Requires having the receiver, which is about the size of a carry-on bag, mounted at all times. **Either:**
  - **Mount in a new hole in the turret, or**
  - **Weather-seal and mount on top of the turret or on the roof of the receiver room**

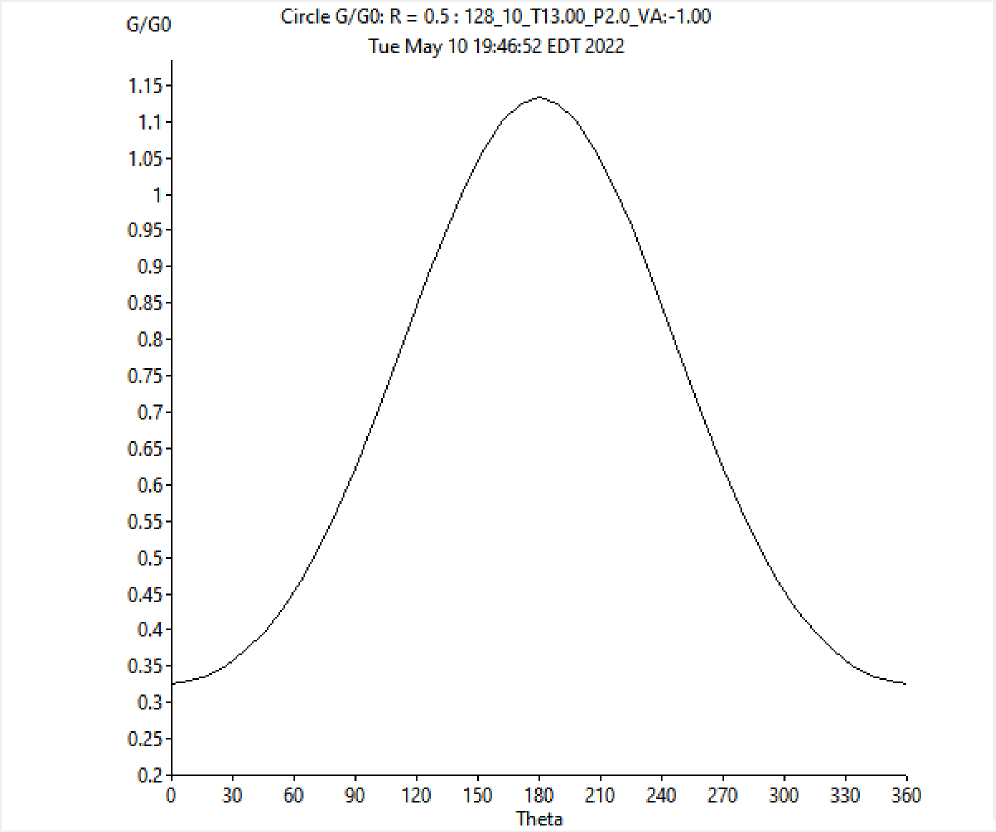
Alternative #3: Circle or Spiral Pointing

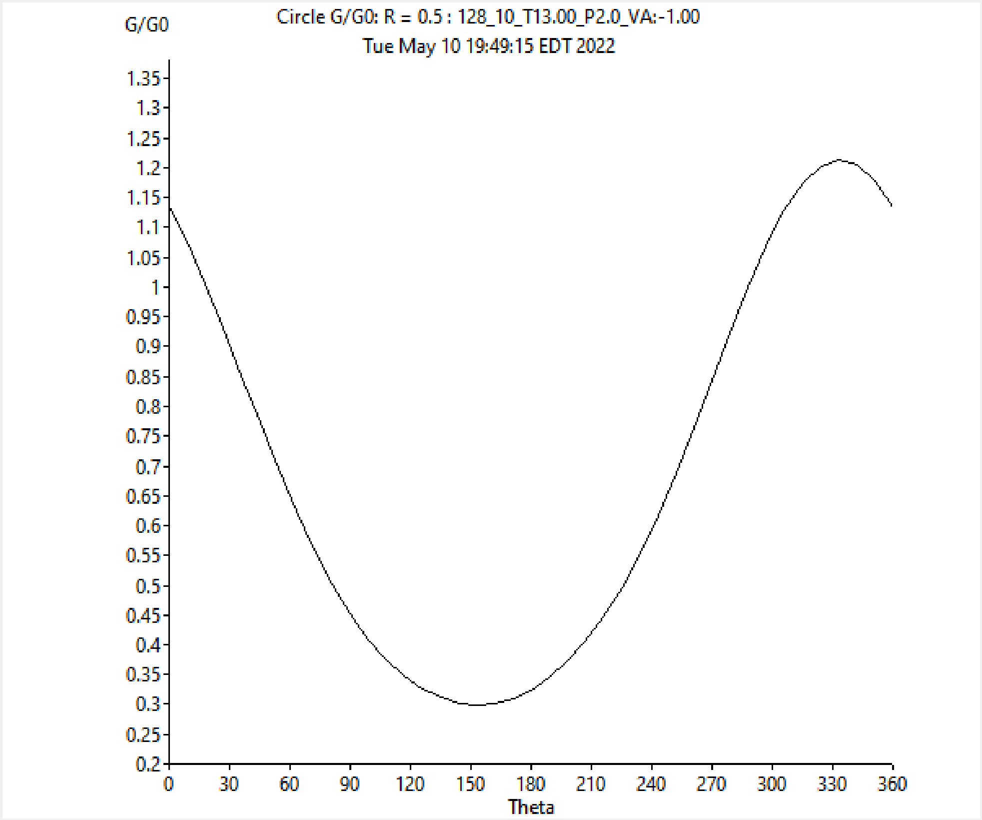
Condon (2012): "Circular Pointing Scans"

http://www.gb.nrao.edu/ptcs/ptcspn/ptcspn74/ptcspn74.pdf



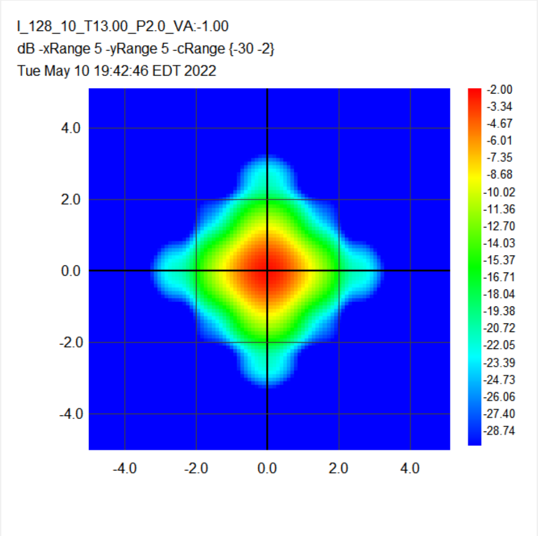
Pointing – Two Examples

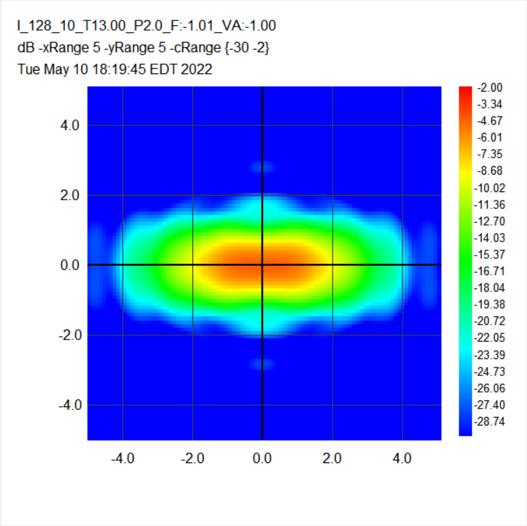


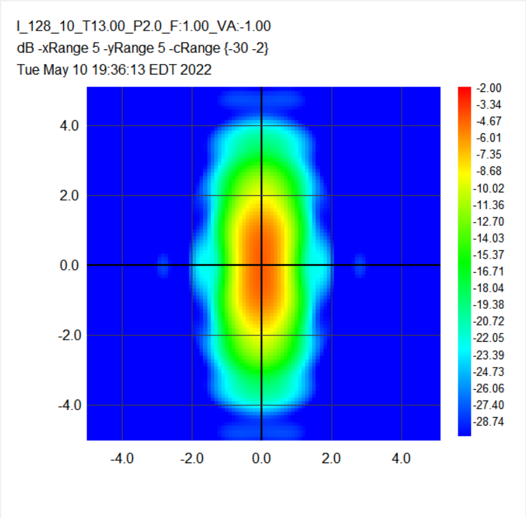


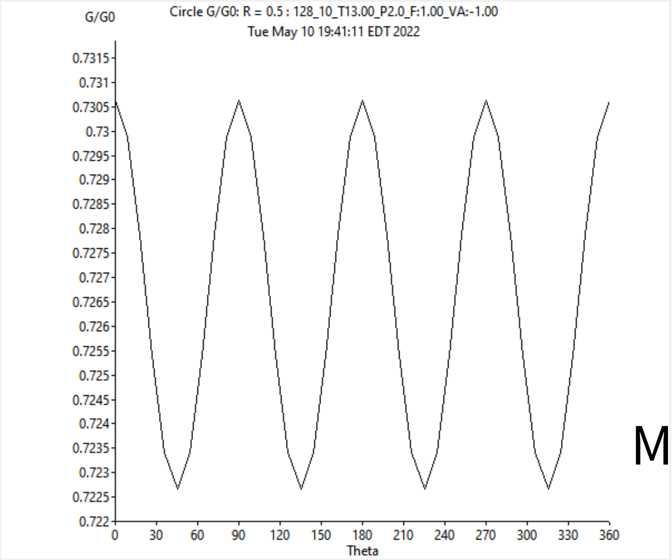
Magnitude →→ $(Z_{GBT,2}^2 + Z_{GBT,3}^2)$; phase →→ $Z_{GBT,2}/Z_{GBT,3}$

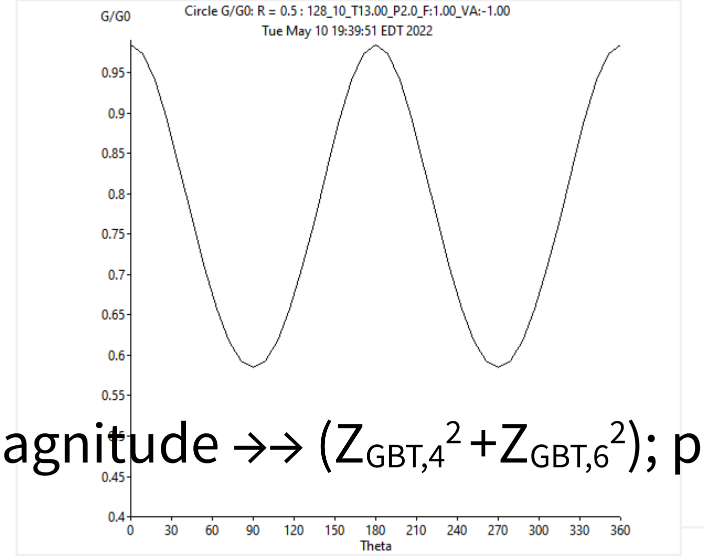
Astigmatism : In and Out of Focus

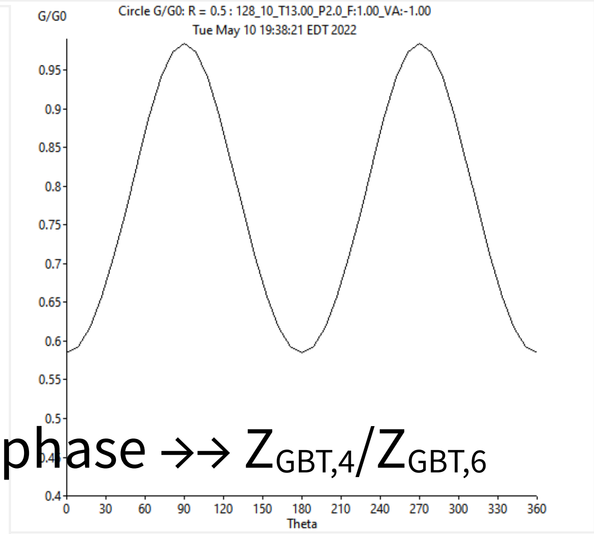






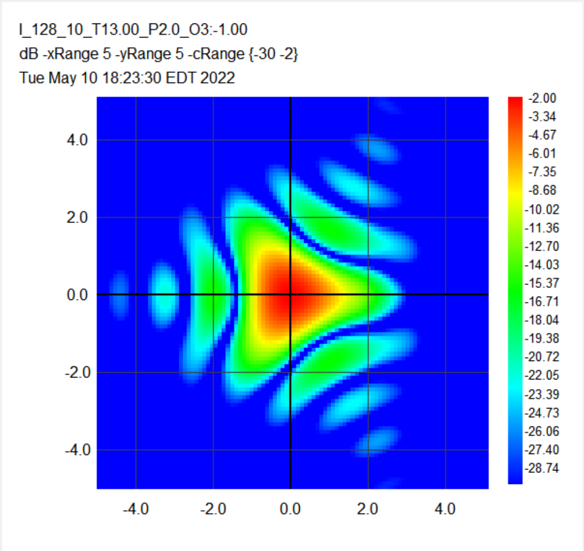


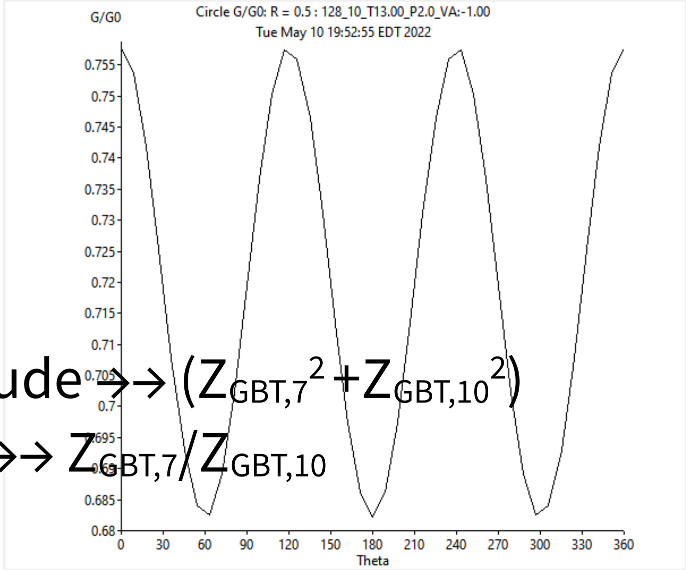




Magnitude →→ $(Z_{GBT,4}^2 + Z_{GBT,6}^2)$; phase →→ $Z_{GBT,4}/Z_{GBT,6}$

Trefoil

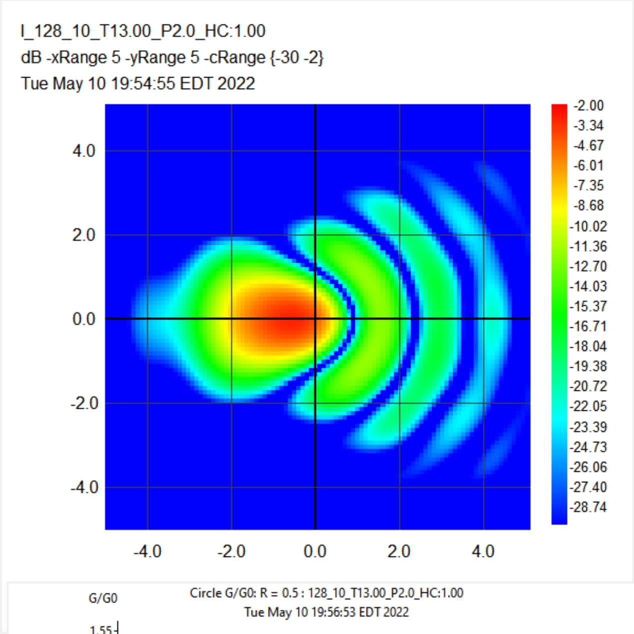


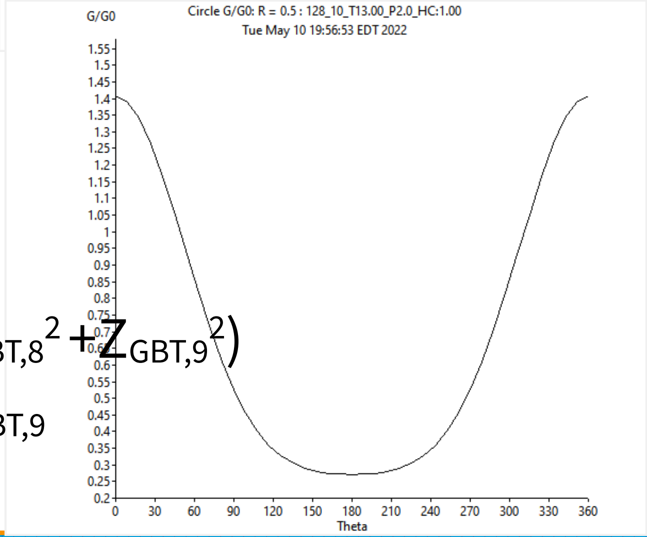


Magnitude →→ $(Z_{GBT,7}^2 + Z_{GBT,10}^2)$

Phase →→ $Z_{GBT,7}/Z_{GBT,10}$

Coma

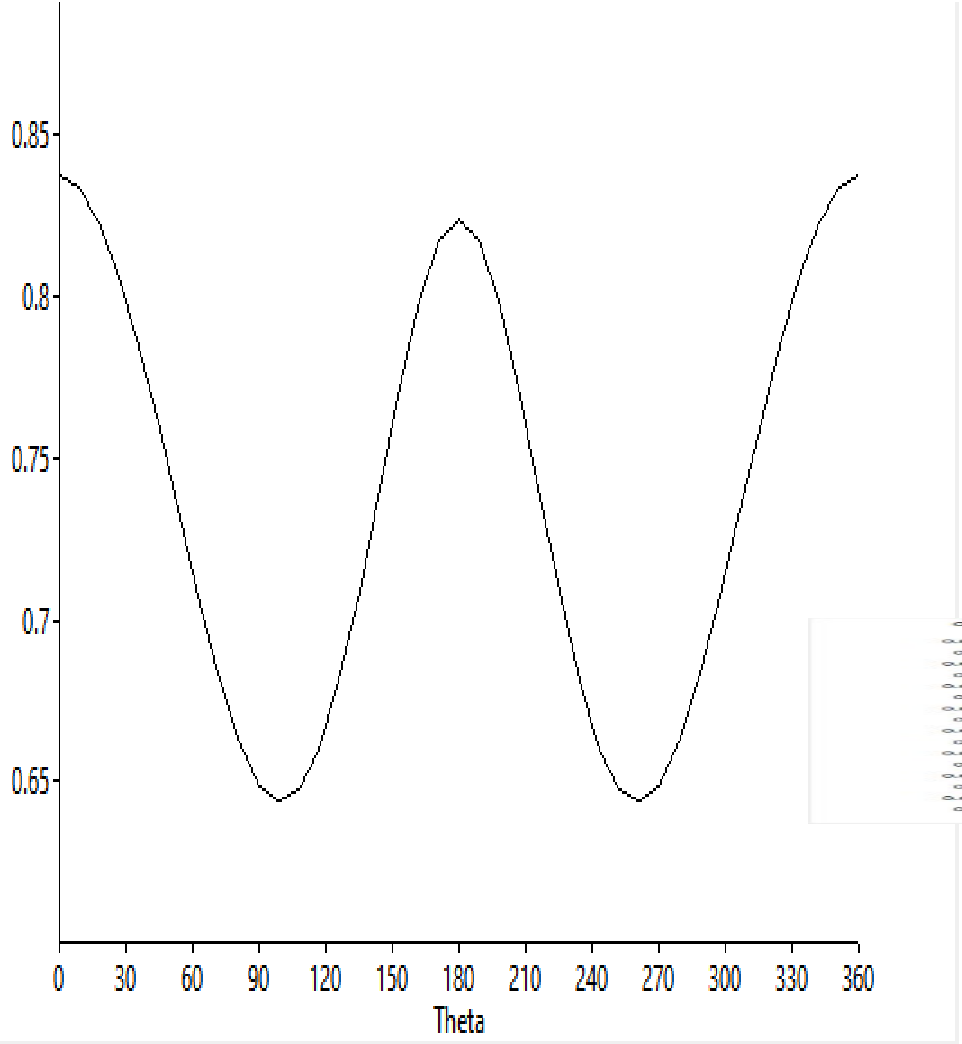


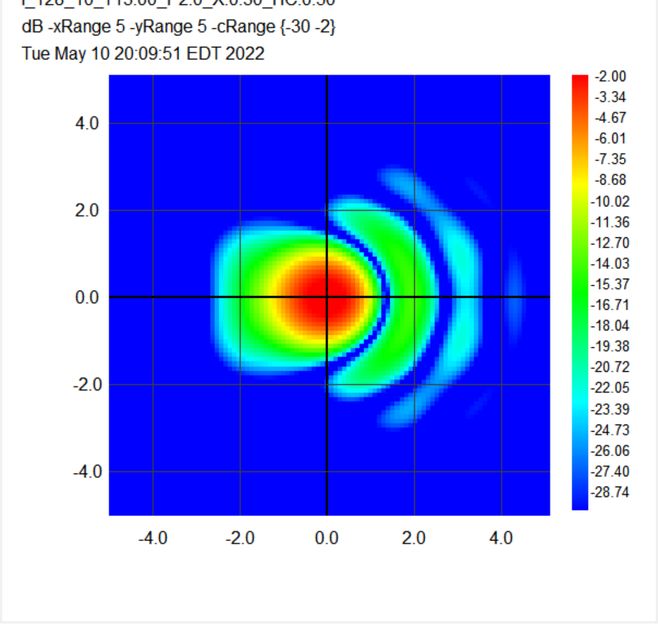


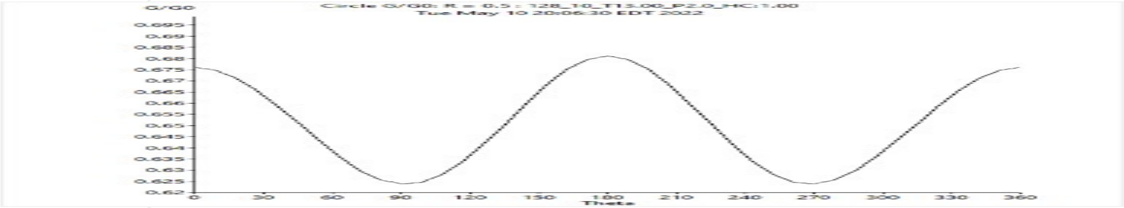
Magnitude →→ $(Z_{GBT,8}^2 + Z_{GBT,9}^2)$

Phase →→ $Z_{GBT,8}/Z_{GBT,9}$

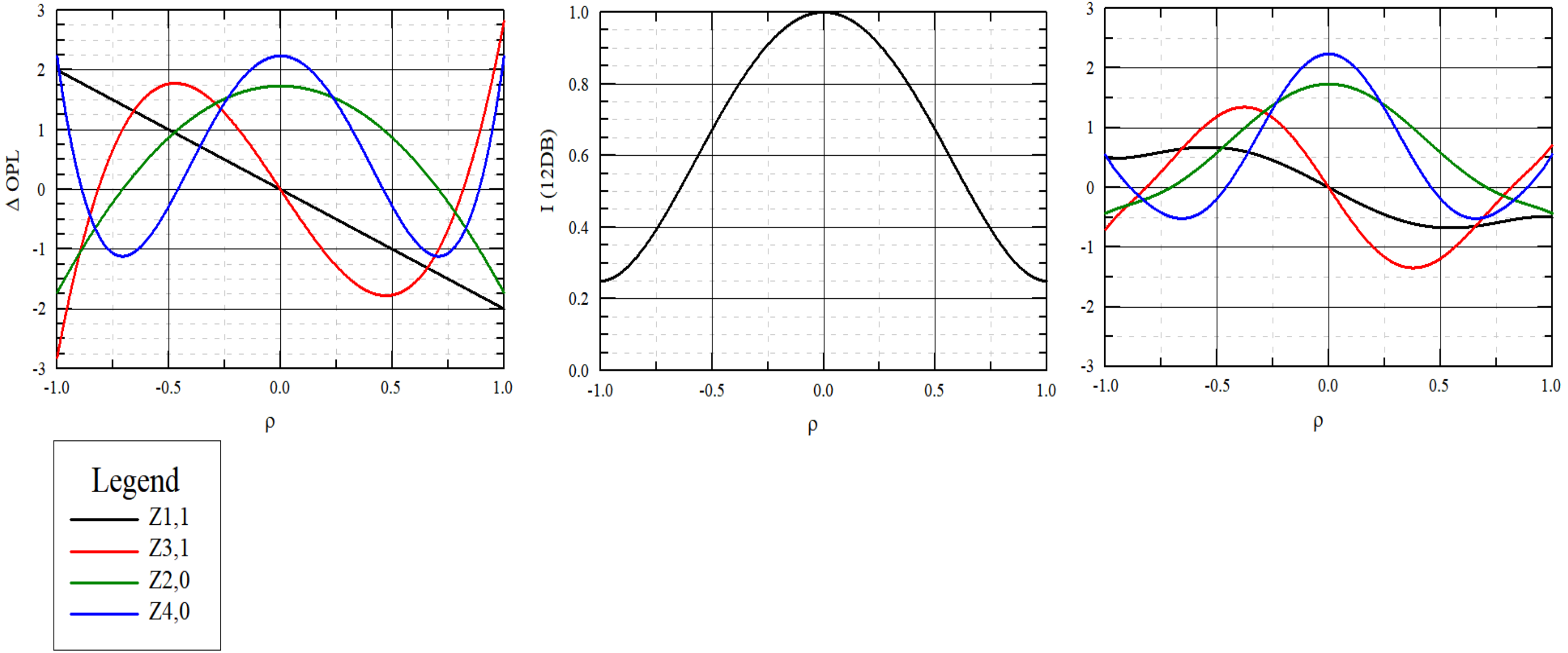
Examples of Coma + Pointing







Feed Illumination pattern and ‘Effective’ Zernikes



Circle Pointing

- Some Zernikes are effectively not orthogonal:

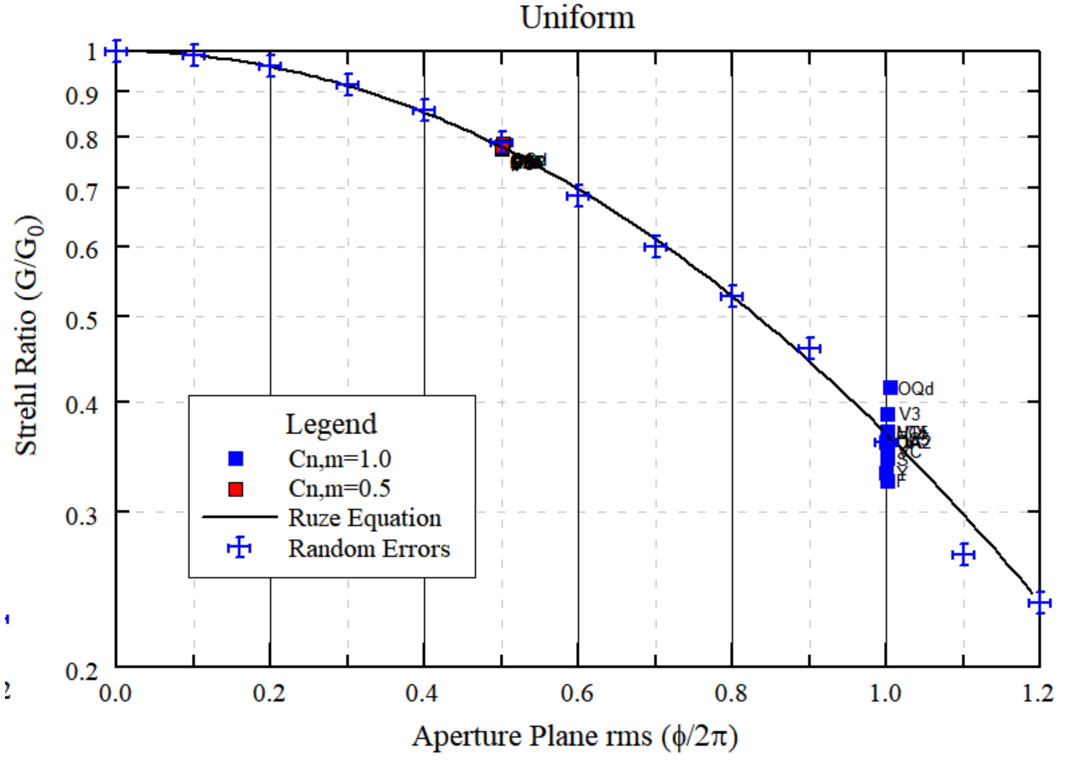
  $Z_0^0, Z_2^0, Z_4^0, Z_6^0 \ldots.$

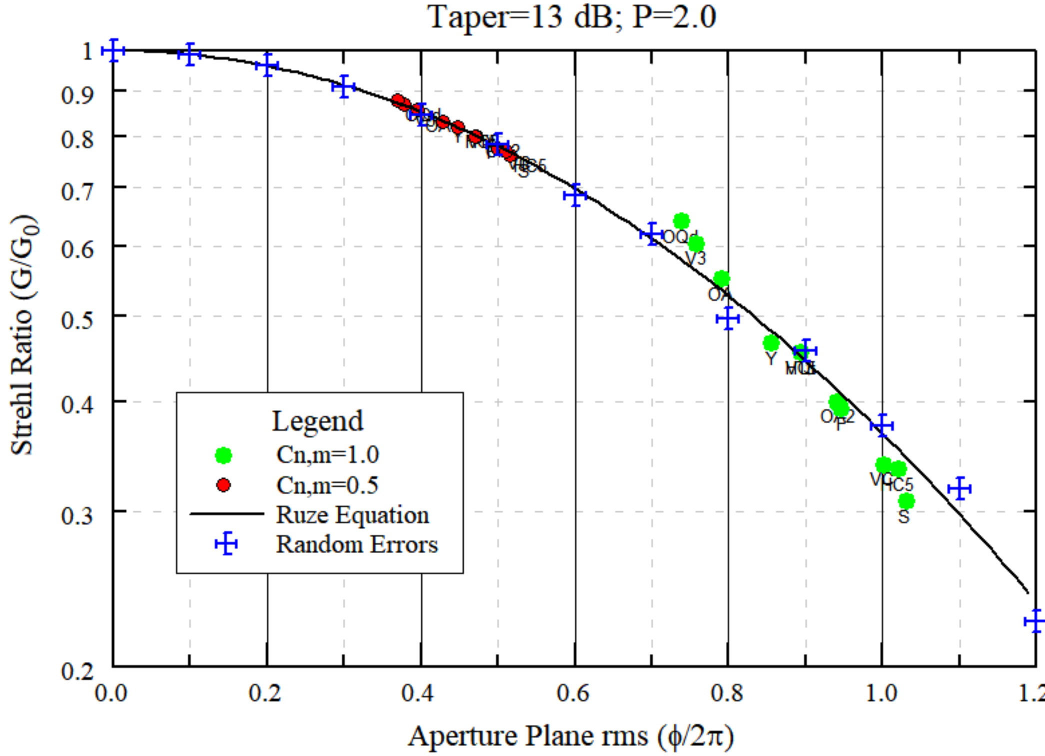
- Aberrations from different Z's become *more* correlated in the image plane (e.g., coma & pointing; spherical & defocus)
- Works better with spirals that go out to 2^{nd} or 3^{rd} sidelobes – buts that's what AutoOOF is doing
- Probably would determine not enough low-order aberrations to be an effective technique.

Fun Fact: For anything other than a uniform illumination: Different Zernikes produce different gain loss for the same value. For our 'standard' 13dB tapers

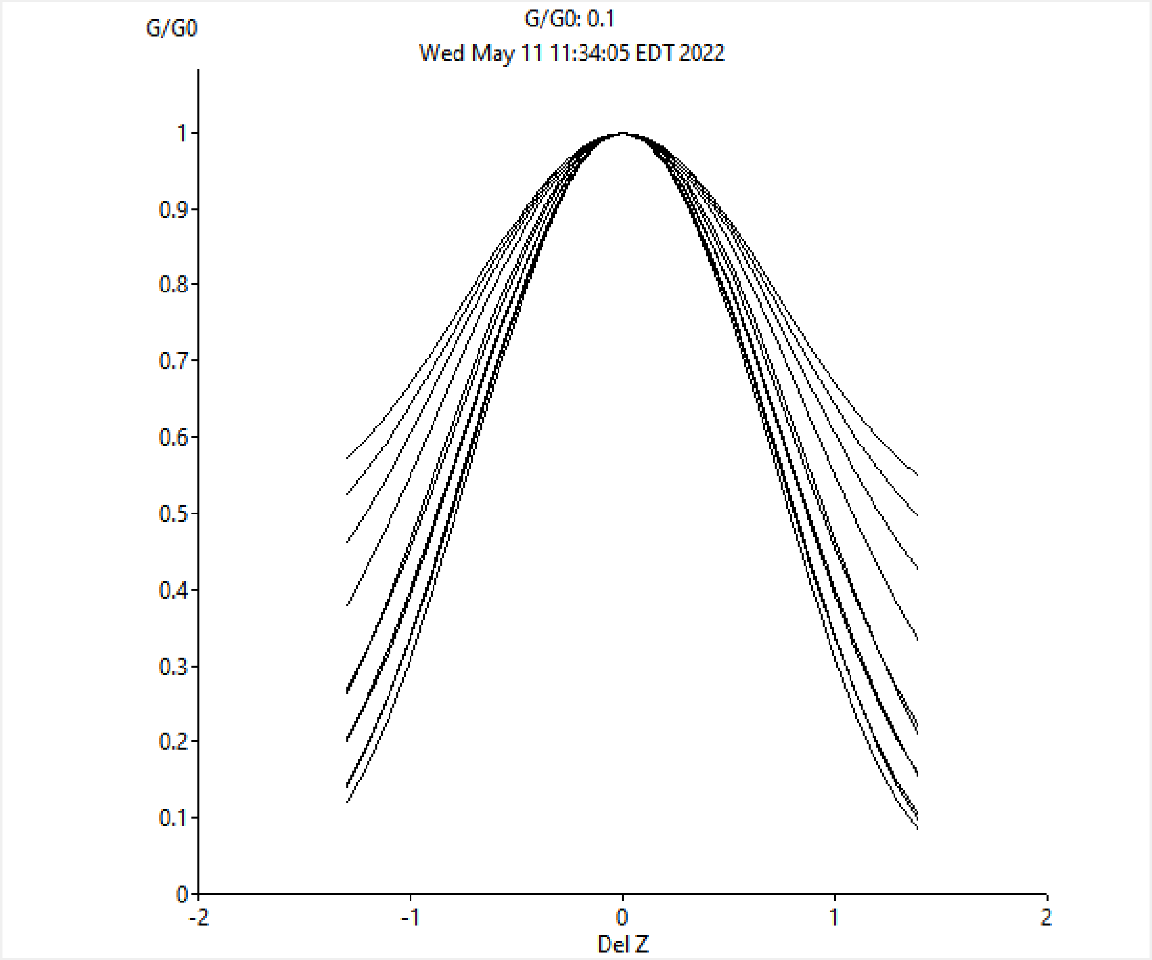
$Z_{GBT,13}$ = 1.0 produces G/G_0 = 0.3

$Z_{GBT,10}$ = 1.0 produces G/G_0 = 0.6

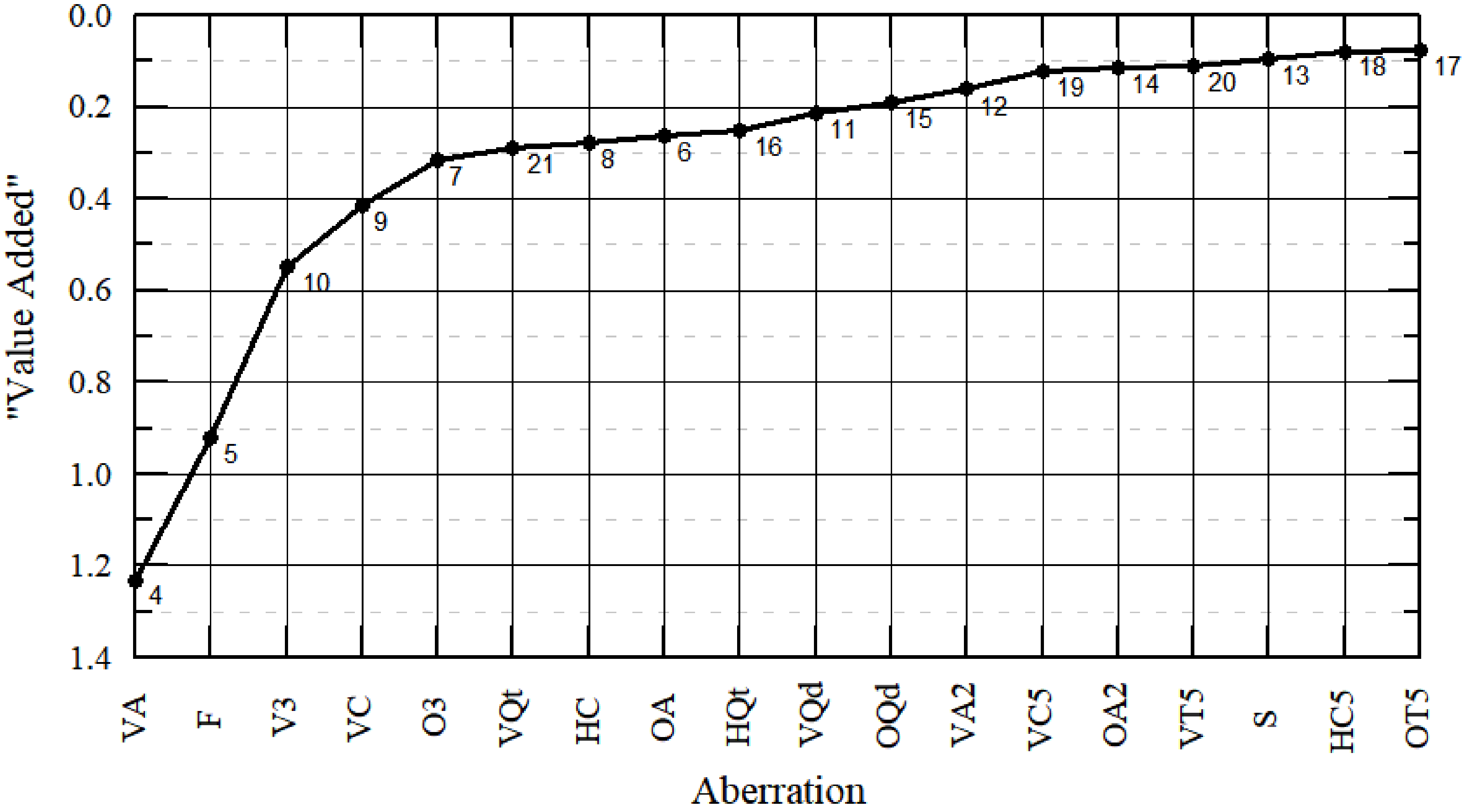




Zernike ‘Sensitivities’



PTCS Memo 76 combined with the ‘sensitivity’ of each Zernike



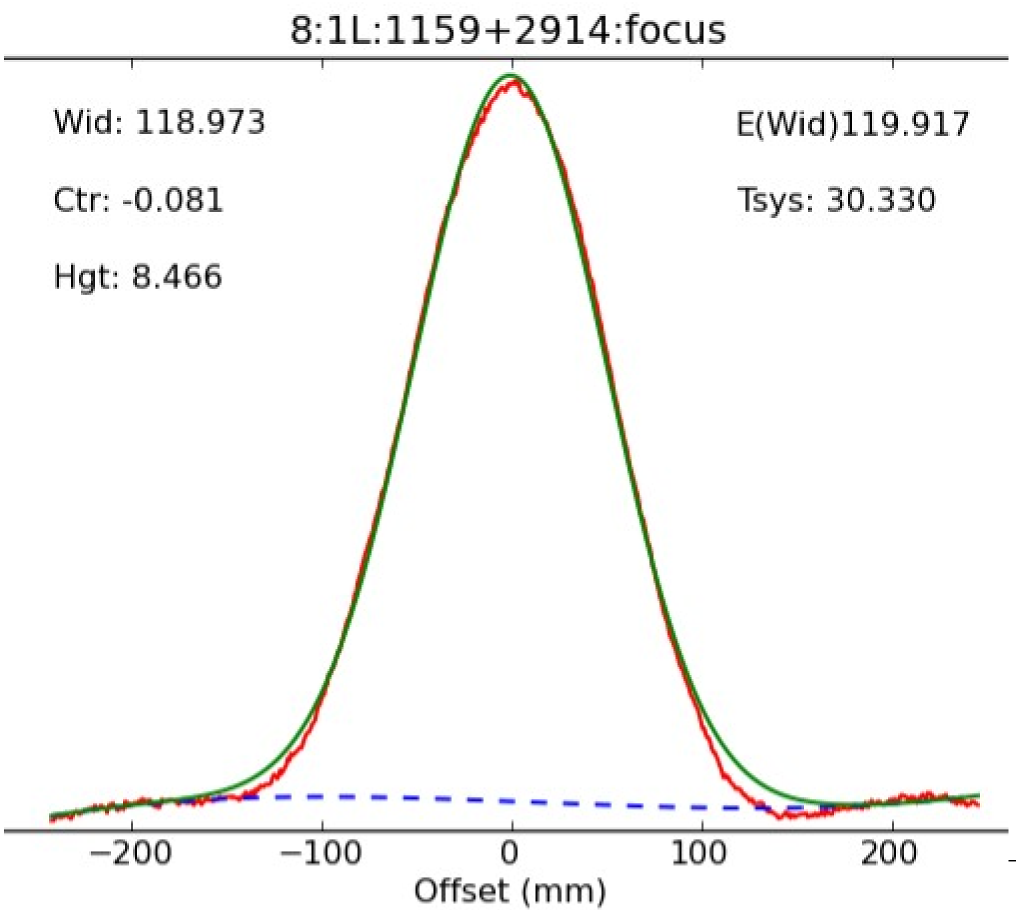
Zernikes sorted by importance (nighttime)

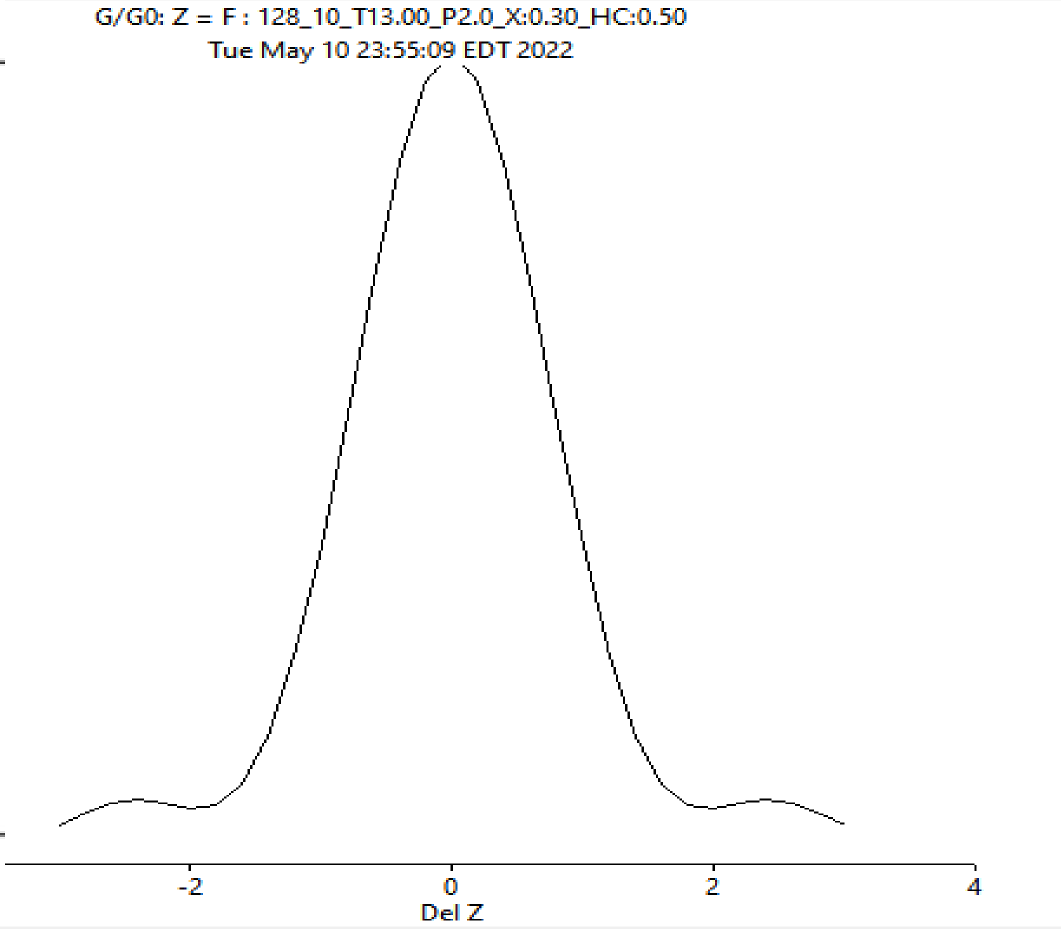
PTCS Memo 76

Aberration	GBT #	rms (μm)
VA	4	518
F	5	314
V3	10	280
O3	7	218
VC	9	195
VQd	11	188
OA	6	183
VQt	21	174
HQt	16	169
OQd	15	168
HC	8	154
VA2	12	136
VT5	20	111
OA2	14	107
VC5	19	102
OT5	17	92
S	13	91
HC5	18	82

Corrected for Gain Losses at 95.5 GHz

Aberration	GBT#	Relative Importance
VA	4	3.49
F	5	1.23
V3	10	0.61
VC	9	0.48
O3	7	0.35
HC	8	0.29
VQt	21	0.28
HQt	16	0.27
OA	6	0.26
VQd	11	0.24
VA2	12	0.19
OQd	15	0.19
VC5	19	0.13
OA2	14	0.12
VT5	20	0.11
S	13	0.11
HC5	18	0.08
OT5	17	0.08

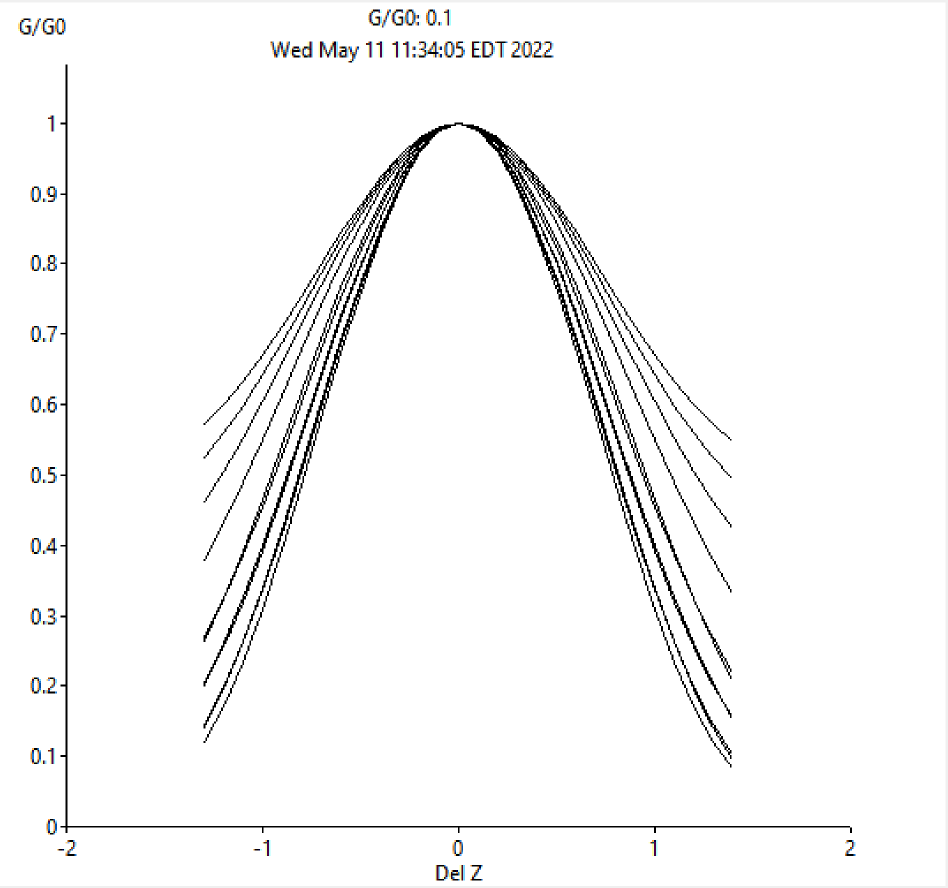

8:1L:1159+2914:focus
Wid: 118.973
Ctr: -0.081
Hgt: 8.466
E(Wid)119.917
Tsys: 30.330
−200
−100
0
100
200
Offset (mm)

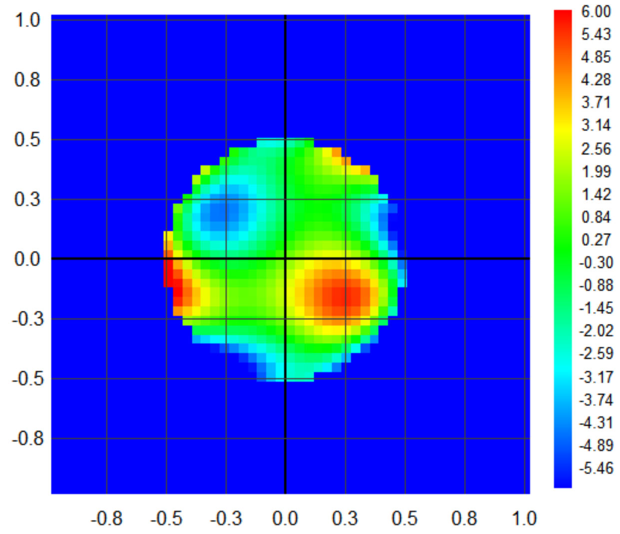

G/G0: Z = F : 128_10_T13.00_P2.0_X:0.30_HC:0.50
Tue May 10 23:55:09 EDT 2022
-2
0
2
4
Del Z

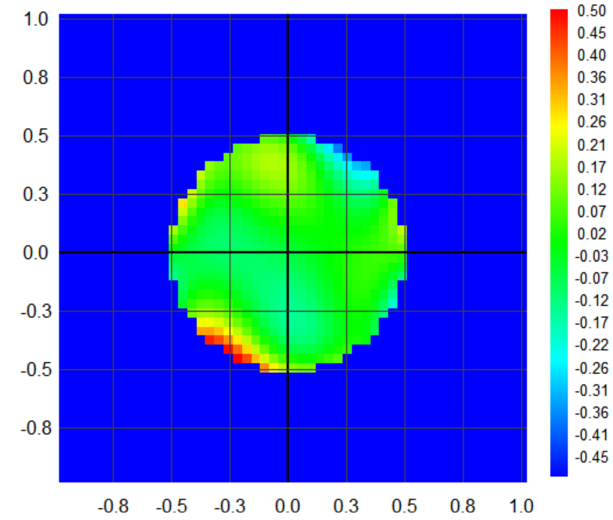
Alternative #4: Auto Maximus

Since AutoPeak determines the value of $Z_{GBT,2}$ and $Z_{GBT,3}$ that maximizes gain, and since AutoFocus determines the value of $Z_{GBT,5}$ that maximizes gain, and we do each of these in separate steps, why not….

…. alter all Zernikes of high importance in separate steps to determine the value at which each one maximizes the gain.



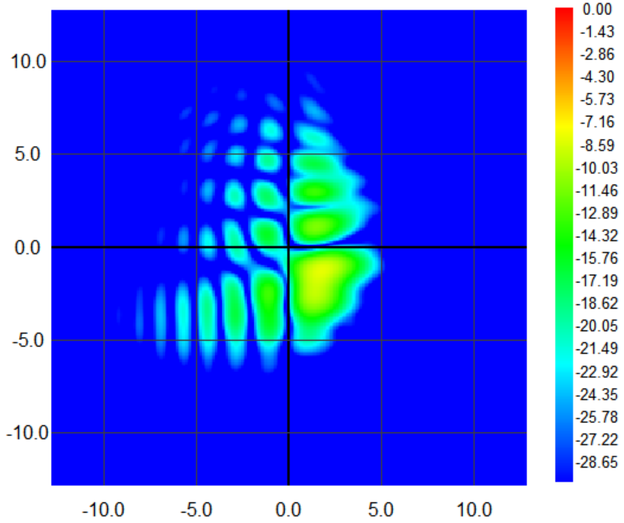


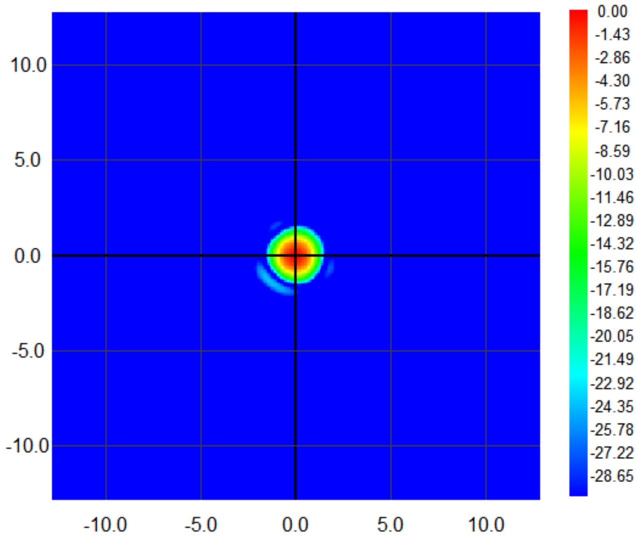


12m40s

$Z_{GBT,N}$ for N=2,3,4,5,7,8,9,10,20,21
Barely acceptable weather

Weighted Aperture Plane rms:
 2.58 to 0.09 radians
 (1300 to 5 µm @ 95.5 GHz)
Gain improvement:
 6.6x
 Within 1% of 'perfect'
1st Sidelobe:
 ??? to -25 dB





Stage 1: Auto Maximus observing sequence

- Change receiver to Ku, Ka, or KFPA if observing with W-band or Argus
- Give user the option to zero out thermal Z's
- Slew to 'off' position for ~10 sec
  - Store average of 10-sec of DCR or CCB samplers as V_{Off}
  - From variance of sampler values, determine if necessary to warn of atmospheric variations
- Observe 'on' source for ~10 sec – store average as V_{On}
  - Determine if source is strong enough and warn user
  - Determine if gain changes (winds, receiver 1/F) are too great and warn user

Stage 2: Auto Maximus observing sequence

- For each ‘trial’
  - For each Z of importance that still needs improvement
    - Move surface to minus maximum derivative of its gain curve
      - V_{-1} = 1 sec of DCR or CCB sampler values
    - Move surface to plus maximum derivative of its gain curve
      - V_{+1} = 1 sec of DCR or CCB sampler values
    - Two-parameter (height and center) LSQ Gaussian fit to

      $V_{-1}-V_{Off}$, $V_{On}-V_{Off}$, $V_{+1}-V_{off}$
    - Move surface for that Z by the result of the LSQ fit
    - If adjustment small, mark this Z as needing no further improvement

Stage 3: Auto Maximus observing sequence

- At end of each trial, observe for ~1 sec and store a new V_{on}
- Report improvement in gain = $V_{on,new}$ / $V_{on,previous}$
- Stop if either:
  - Reached maximum number of trials
  - No more Z's need improving
  - Improvement in V_{on} was too small
  - V_{on} degraded (reverts to results of previous trial)
- Otherwise go on to the next trial

Disadvantages of Auto Maximus

- To do all Z's up to 5th order (21) requires the same amount of time as an AutoOFF
- Will not improve those Z that we designate as not having an important-enough thermal component
  - We know for nighttime observing
  - Must verify which Z's have thermal components during daytime observing
- Sometimes will miss when weather conditions or winds are not appropriate
- Requires a few hours of test time at moderate frequencies in very good weather
  - To measure 'gain' curves that are then scaled to the user's wavelength
  - To determine a better estimate for how long it takes to move actuators
- For Argus & W-Band, solution won't converge when errors are the expected extreme
  - Use a lower-frequency receiver (Ku, Ka, KFPA, with Ka+CCB the best)
  - Convergence is faster when using a lower-frequency receiver anyway

Maybe a hybrid system will work best (e.g., Maximus + Temperature sensors?)

Advantages of Auto Maximus

- Simulator allows us to try different scenarios, weather conditions, errors in assumed feed taper, ….
- Data acquisition, reduction software (almost) exists.
- Z normalization, or lack thereof, is irrelevant
- Works even if $Z_{GBT,N}$ is not what we think it is
  - Doesn't matter if we are using surface or aperture rms
- (non)Orthoganality irrelevant
- No overhead from starting/stopping scans
- No Az/El motions other than one move: Off to On
- Data reduction happens during observing
- Measures pointing and focus as well
- Maybe a good way to extend life of actuators
- Great success even when wavelength is 3x longer than that of an observer's science

- In first minute, warns if wind, atmospheric fluctuations, or T_A are insufficient
- Automatically stops when it finds further progress won't improve G
- If surface is already good, stops after ~6 min
- Measures and reports improvement in gain for each 'trial' (every few minutes)
- Necessary dynamic range is only a few (vs >1000 for AutoOOF)
- Works with weaker sources than AutoOOF (~half-power points vs 4th sidelobe)
- For the 'important' Z's, seems to provide a large-scale surface that is better than what AutoOOF is said to provide.