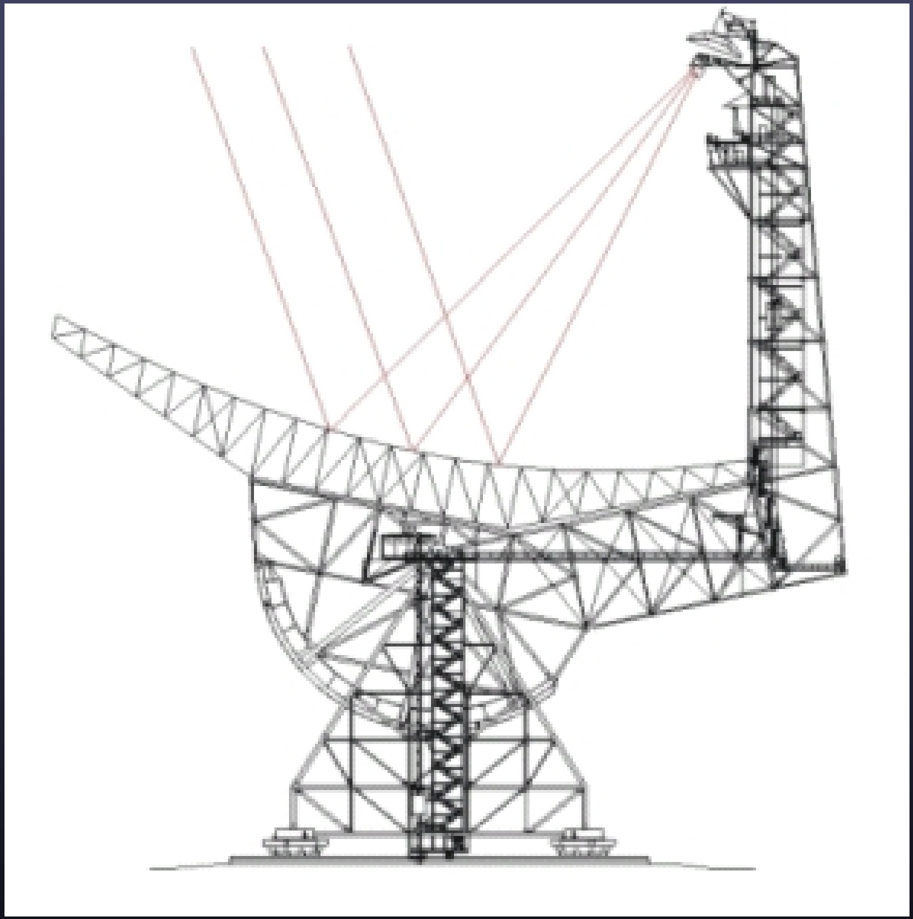
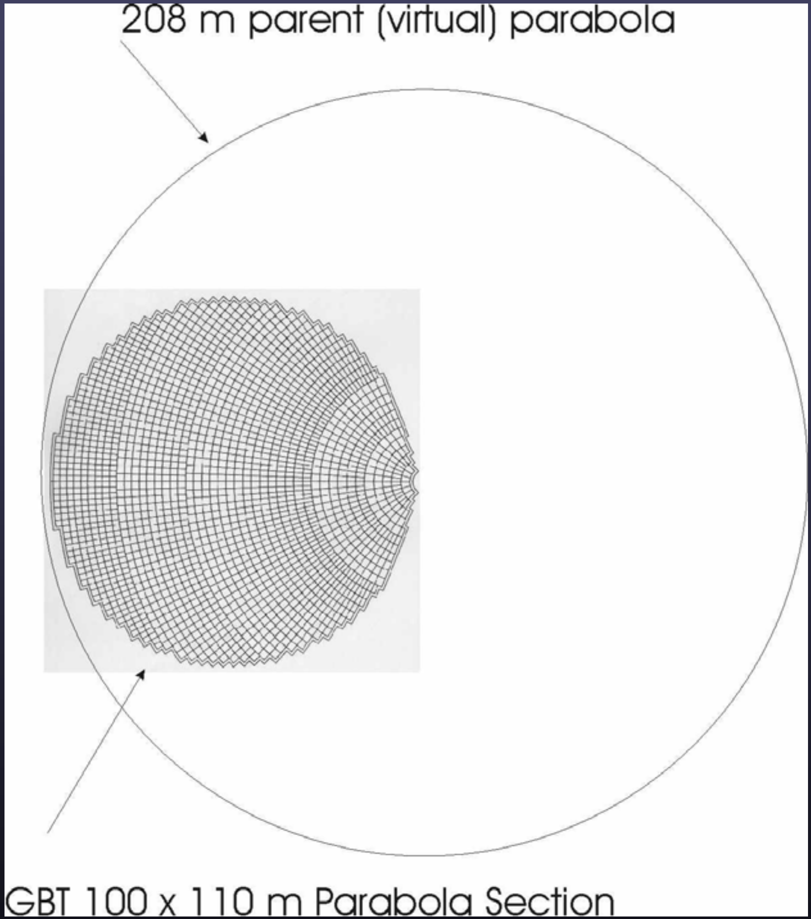
Green Bank Telescope Performance

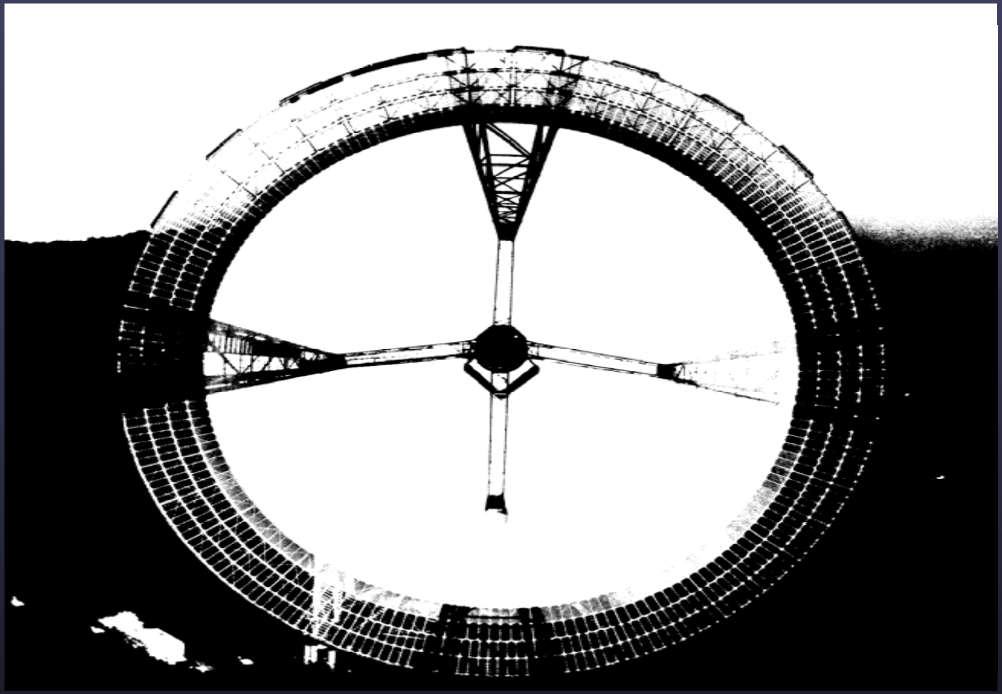
Dana S. Balser

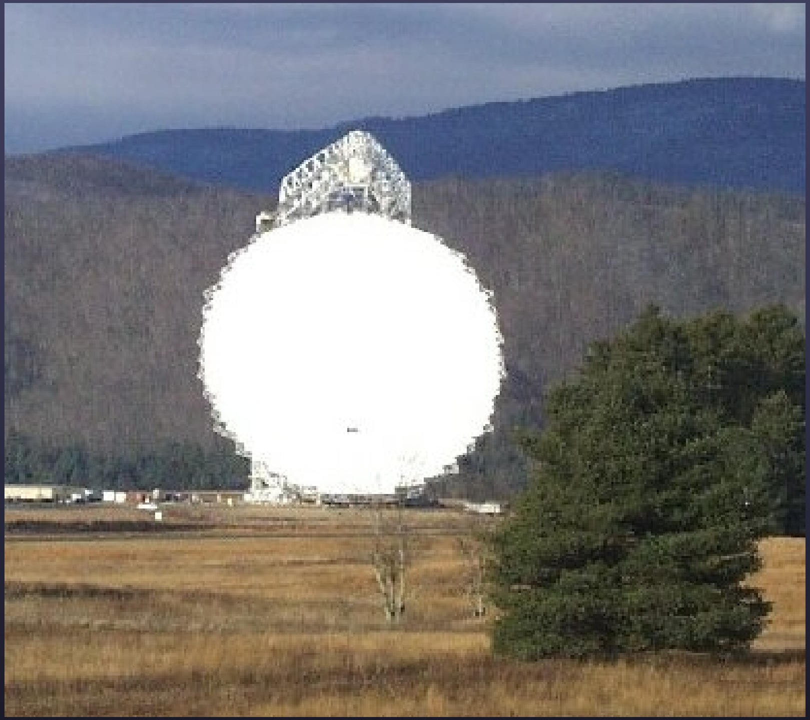
Telescope Structure



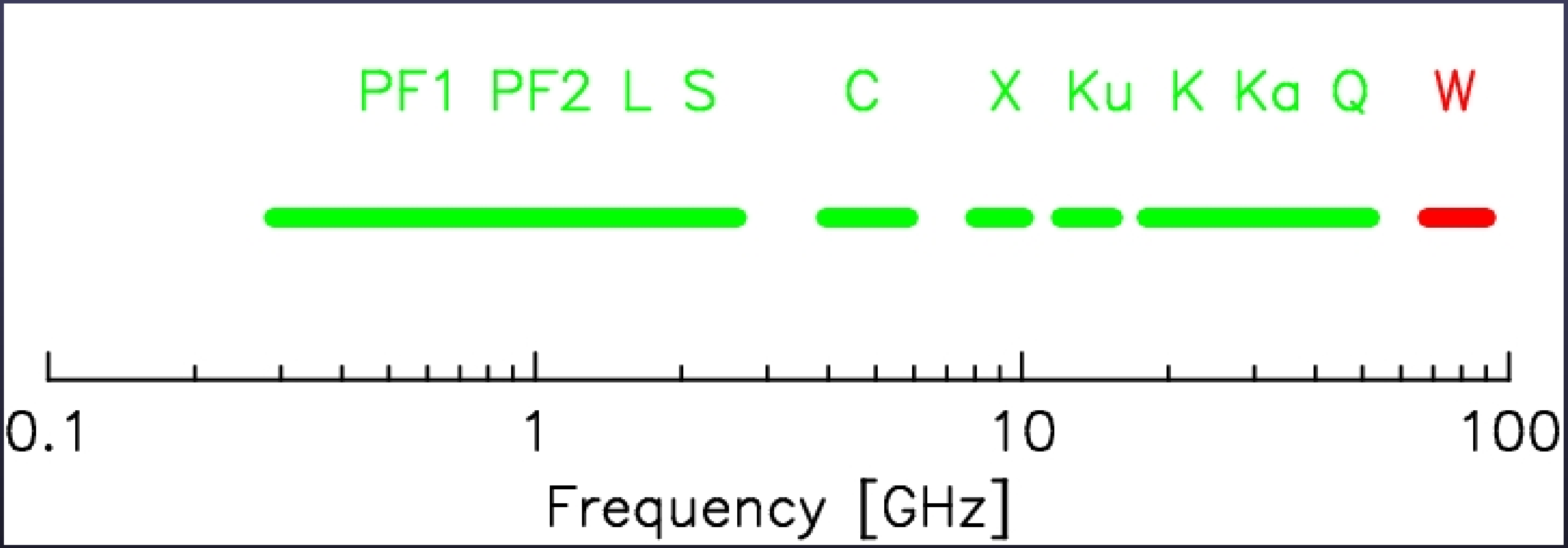


Unblocked Aperture





Frequency Coverage



Telescope Control

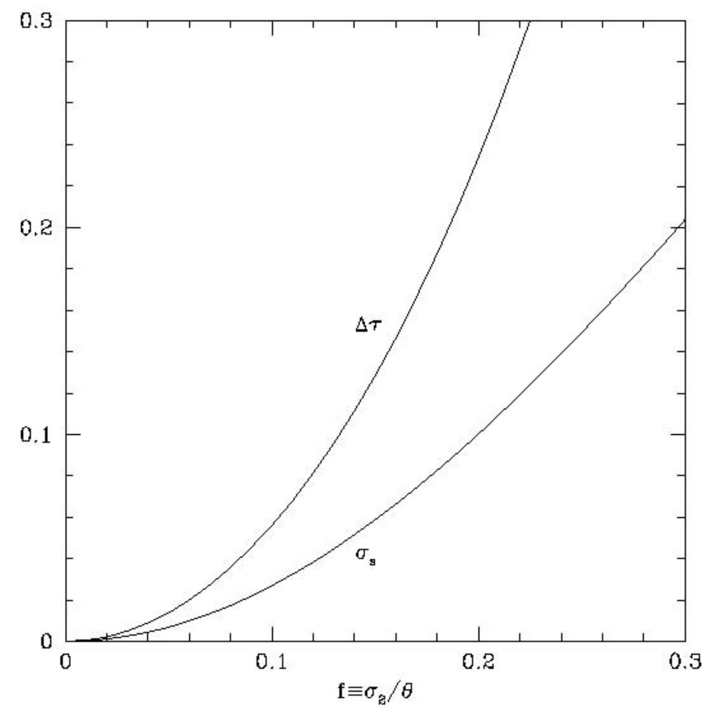
Pointing Requirements

$$g(\rho) = \exp\left[-4\ln 2\left(\frac{\rho}{\theta}\right)^2\right]$$

$$\left(\frac{\theta}{740\ \text{arcsec}}\right) \approx \left(\frac{\text{GHZ}}{\nu}\right)$$

$$\left\langle \rho^2 \right\rangle \equiv \sigma_2^2 = \sigma_{\text{Az}}^2 + \sigma_{\text{El}}^2$$

$$f \equiv \left(\frac{\sigma_2}{\theta}\right)$$



$$\text{Good} \quad (\sigma_s = 5\%) \ \rightarrow f \approx 0.14$$

$$\text{Usable} \ (\sigma_s = 10\%) \rightarrow f \approx 0.20$$

Condon (2003)

Focus Requirements

$$g_a = \exp\left[-4\ln 2\left(\frac{\Delta y_s}{\theta_a}\right)^2\right] \quad \text{Axial}$$

$\theta_a \approx 4\lambda$

Good $(g_a > 0.99) \rightarrow \Delta y_s < \theta_a/16 < \lambda/4$

Usable $(g_a > 0.95) \rightarrow \Delta y_s < \theta_a/8 < \lambda/2$

$$g_l = \exp\left[-4\ln 2\left(\frac{\Delta x_s}{\theta_l}\right)^2\right] \quad \text{Lateral}$$

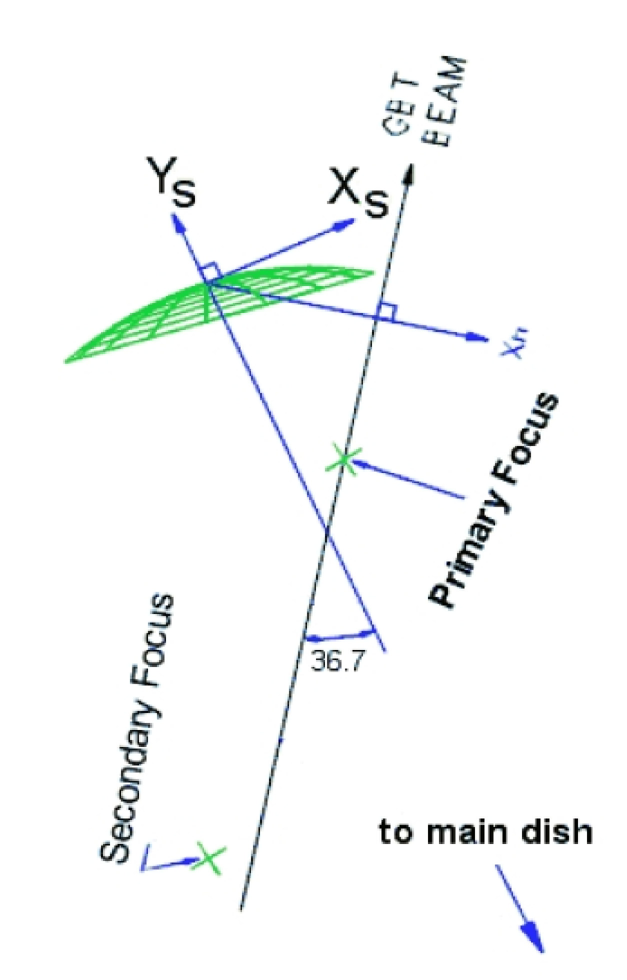
$\theta_l \approx 6\lambda$

Good $(g_l > 0.99) \rightarrow \Delta x_s < \theta_l/16 < \lambda/3$

Plate Scale $\approx 3.7''$ / mm

Q-band: $\lambda = 7$ mm $\rightarrow \Delta x_s < 2.3$ mm

$\rightarrow \theta = 17.3'' \rightarrow f = 0.5$



Srikanth (1990)
Condon (2003)

Surface Requirements

$$\eta_s \approx \exp\left[-\left(\frac{4\pi\varepsilon}{\lambda}\right)^2\right]$$

η_s is the aperture efficiency for the surface.

ε is the rms surface error.

$$S_\nu = \frac{2kT_A'}{\eta_a A_g}$$

S_ν is the flux density.

k is Boltzmann's constant.

T_A' is the antenna temperature corrected for the atmosphere.

η_a is the aperture efficiency.

A_g is the geometric primary area.

Good: $\varepsilon < \lambda/16 \rightarrow \eta_s \approx 0.54$

Usable: $\varepsilon < \lambda/4\pi \rightarrow \eta_s \approx 0.37$

Ruze (1966)
Condon (2003)

Repeatable Errors – Pointing

- Telescope misalignments:
  - Azimuth track tilt
  - Horizontal collimation
  - Elevation axle collimation
  - Encoder offsets

- Gravity: assume linear elastic structure

$$\Delta A\ \mathrm{Cos}(E) = d_{0,0} + b_{0,1}\mathrm{Sin}(E) + d_{0,1}\mathrm{Cos}(E) + b_{1,1}\mathrm{Cos}(A)\mathrm{Sin}(E) + a_{1,1}\mathrm{Sin}(A)\mathrm{Sin}(E)$$

$$\Delta E = d_{0,0} + c_{1,0}\mathrm{Sin}(A) + d_{1,0}\mathrm{Cos}(A) + b_{0,1}\mathrm{Sin}(E) + d_{0,1}\mathrm{Cos}(E)$$

Repeatable Errors – Focus

- Gravity: assume linear elastic structure

$$X = A_x + B_x \,\mathrm{Cos}(E) + C_x \,\mathrm{Sin}(E)$$

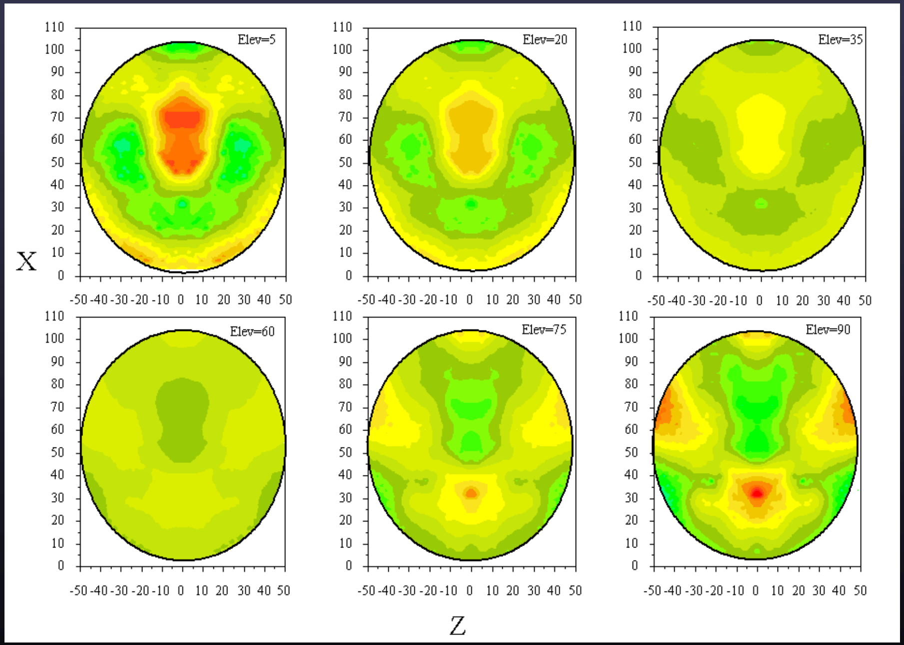
$$Y = A_y + B_y \,\mathrm{Cos}(E) + C_y \,\mathrm{Sin}(E)$$

$$Z = A_z + B_z \,\mathrm{Cos}(E) + C_z \,\mathrm{Sin}(E)$$

Repeatable Errors – Surface

- Gravity:
  - Homologous design (almost)
  - Photogrammetry (50.3 deg) → Zero-point
  - Finite Element Model (FEM)
  - Best Fit Parabola (BFP)

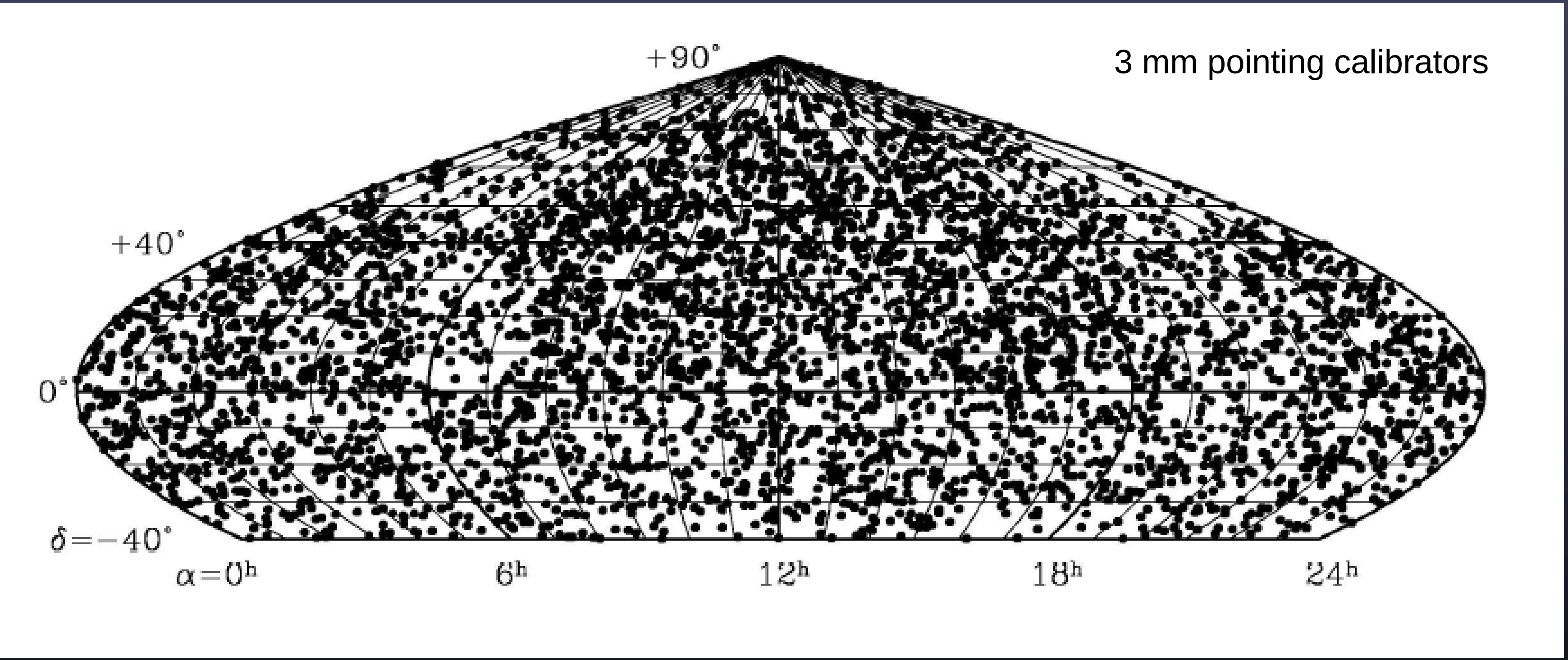
Active Surface: 2004 Panels
2209 Actuators



Point Source Calibrators

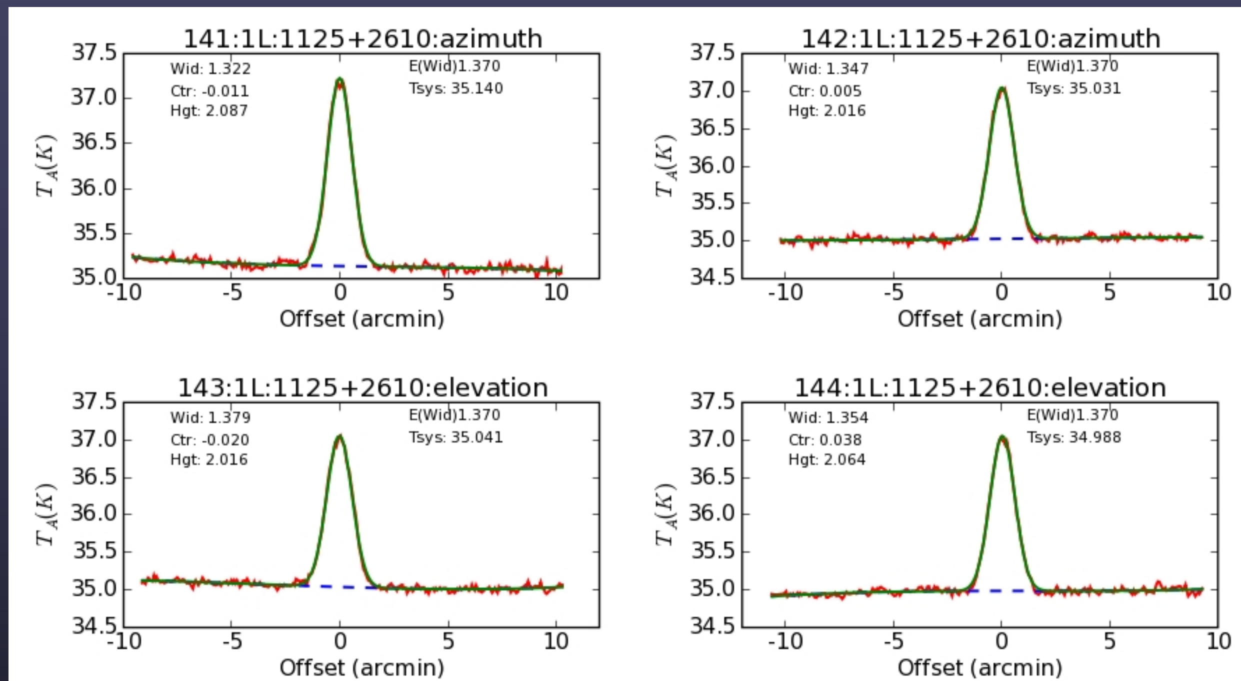
PCALS 4.0: 7108 sources

Two-dimensional rms error < 0.2 arcsec



Condon & Yin (2005)

Pointing Model



Azimuth Series ΔA Cos(E)

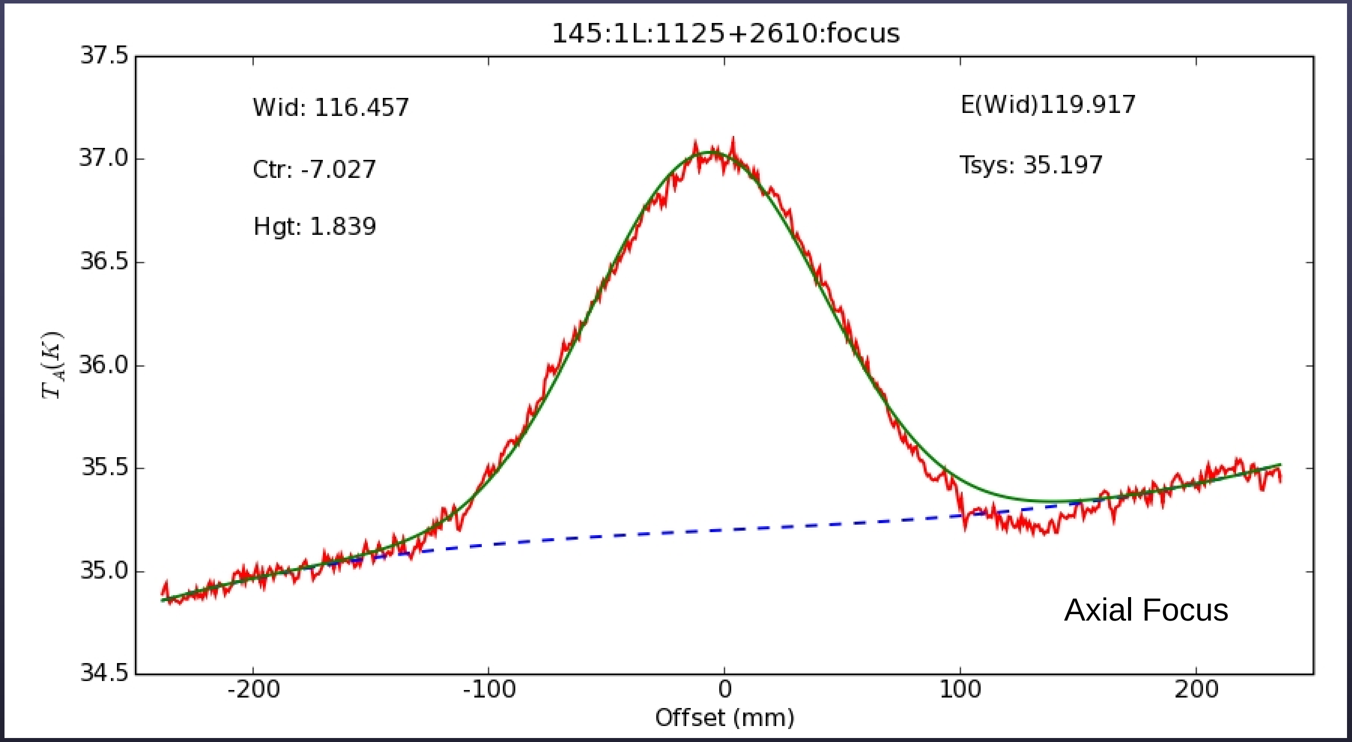
Coeff. (M&C)	Coeff. (TPOINT)	Term	Value (arcsec)	σ (arcsec)	Meaning
$d_{0,0}$	–CA	1	–29.82	6.221	Horizontal Collimation
$b_{0,1}$	–NPAE	Sin E	–3.57	4.451	El Axle Collimation
$d_{0,1}$	–IA	Cos E	–11.71	4.943	Az Zero
$b_{1,1}$	AW	Cos A Sin E	+2.20	0.422	Zenith E-Tilt
$a_{1,1}$	AN	Sin A Sin E	+2.97	0.431	Zenith N-Tilt

Elevation Series ΔE

Coeff. (M&C)	Coeff. (TPOINT)	Term	Value (arcsec)	σ (arcsec)	Meaning
$d_{0,0}$	IE	1	–758.47	6.226	El Zero
$c_{1,0}$	–AW	Sin A	–2.20	0.422	Zenith E-Tilt
$d_{1,0}$	AN	Cos A	+2.97	0.431	Zenith N-Tilt
$b_{0,1}$	ECES	Sin E	+678.13	4.443	Asymmetric Gravity
$d_{0,1}$	ECEC	Cos E	+795.03	4.925	Symmetric Gravity

Balser et al. (2002)

Focus Model



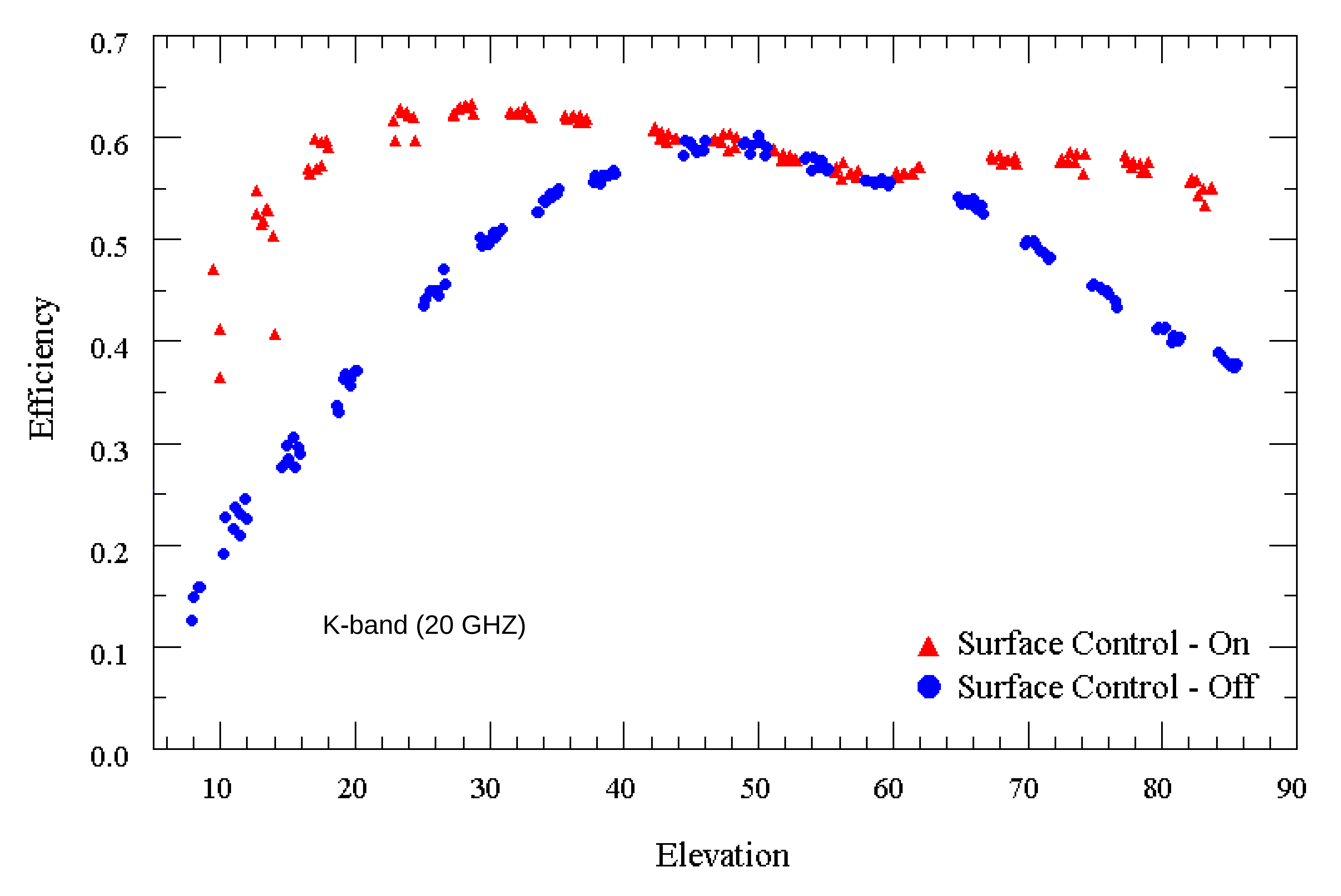
$$X = 212.55 - 301.98\,\mathrm{Cos}(E) - 25.55\,\mathrm{Sin}(E)\ \mathrm{mm}$$

$$Y = -148.39 + 183.74\,\mathrm{Cos}(E) + 9.96\,\mathrm{Sin}(E)\ \mathrm{mm}$$

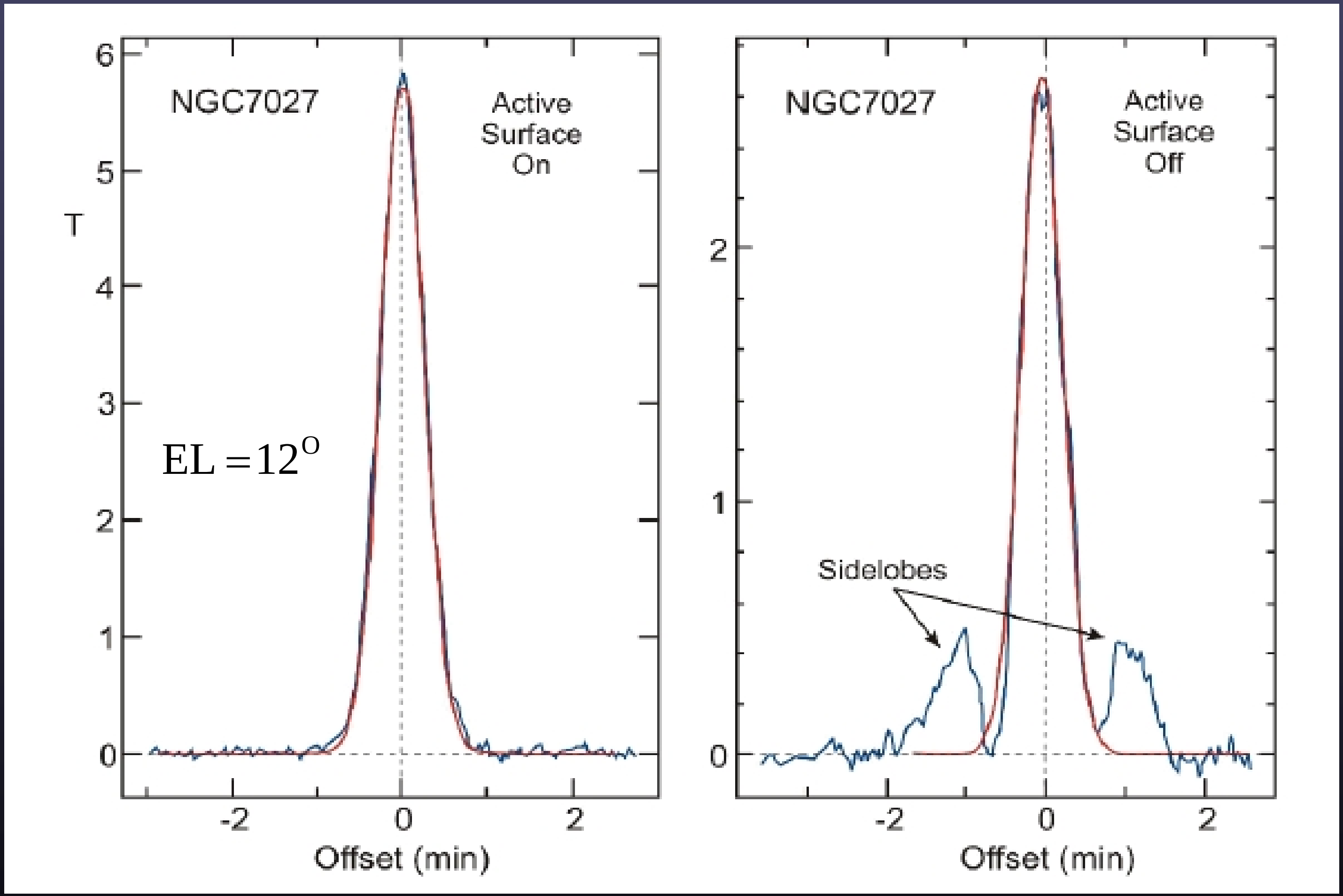
$$Z = 9.56 + 11.18\,\mathrm{Cos}(E) - 21.86\,\mathrm{Sin}(E)\ \mathrm{mm}$$

Ghigo et al. (2001)

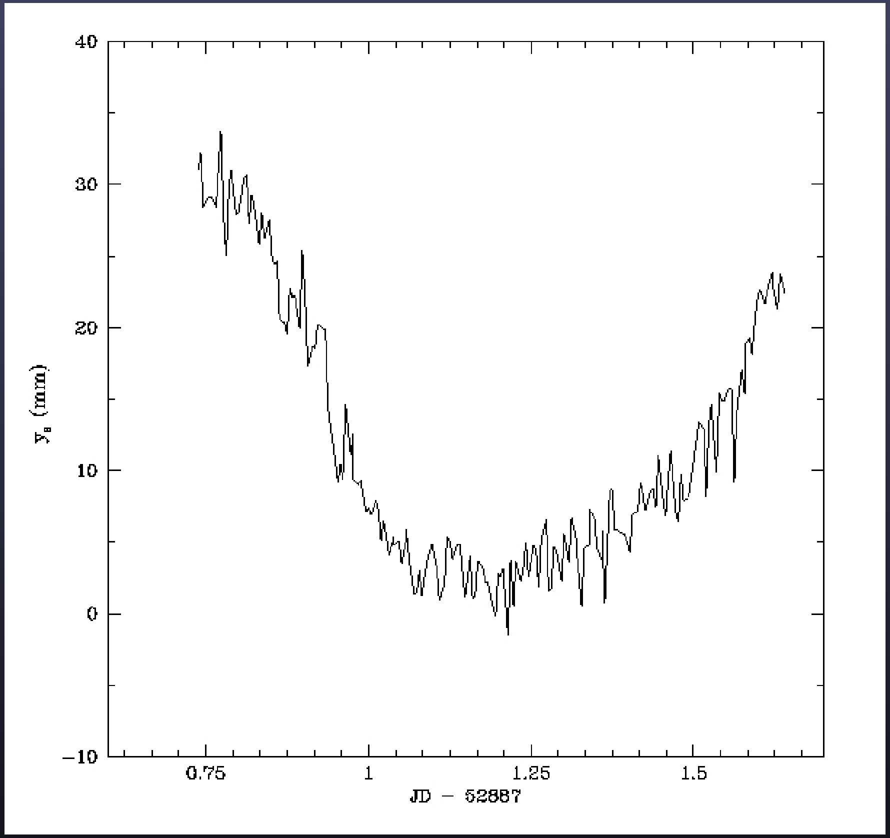
Finite Element Model – Gain Elevation Curve



Finite Element Model – Sidelobes



Non-repeatable Errors – Thermal

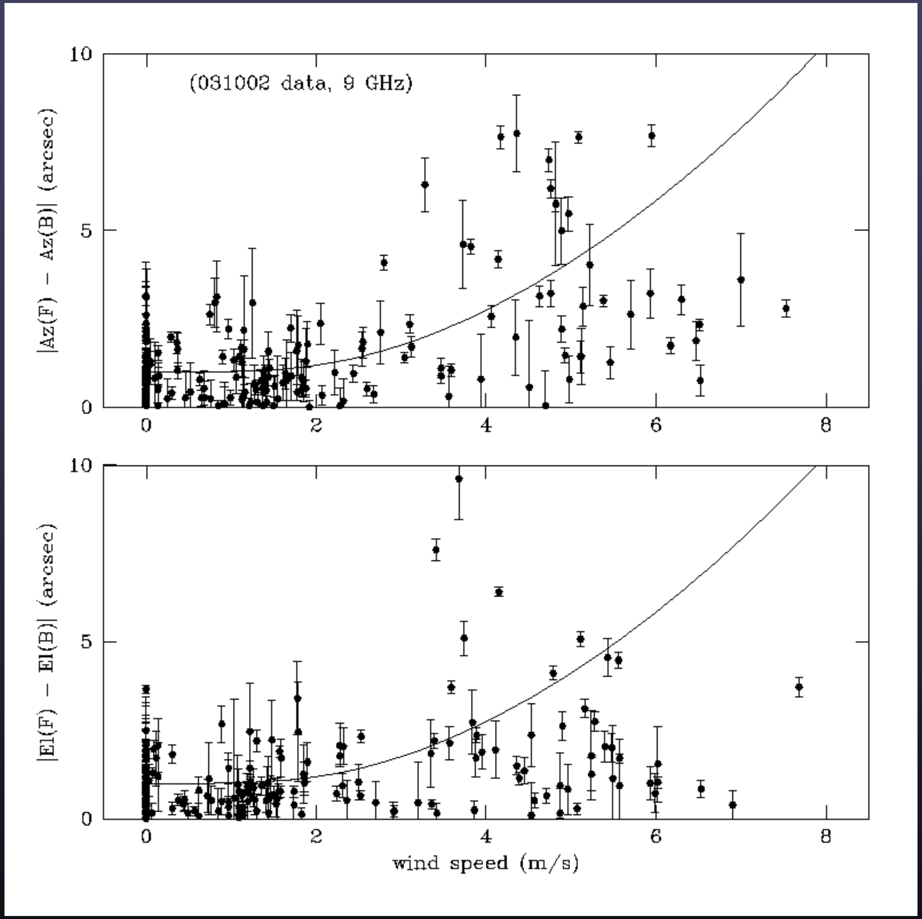


30 mm $\rightarrow \lambda/3$ at a frequency of 3 GHz

30 mm $\rightarrow 3\lambda$ at a frequency of 30 GHz

Usable $(g_a > 0.95) \rightarrow \Delta y_s < \theta_a / 8 < \lambda / 2$

Non-repeatable Errors – Wind



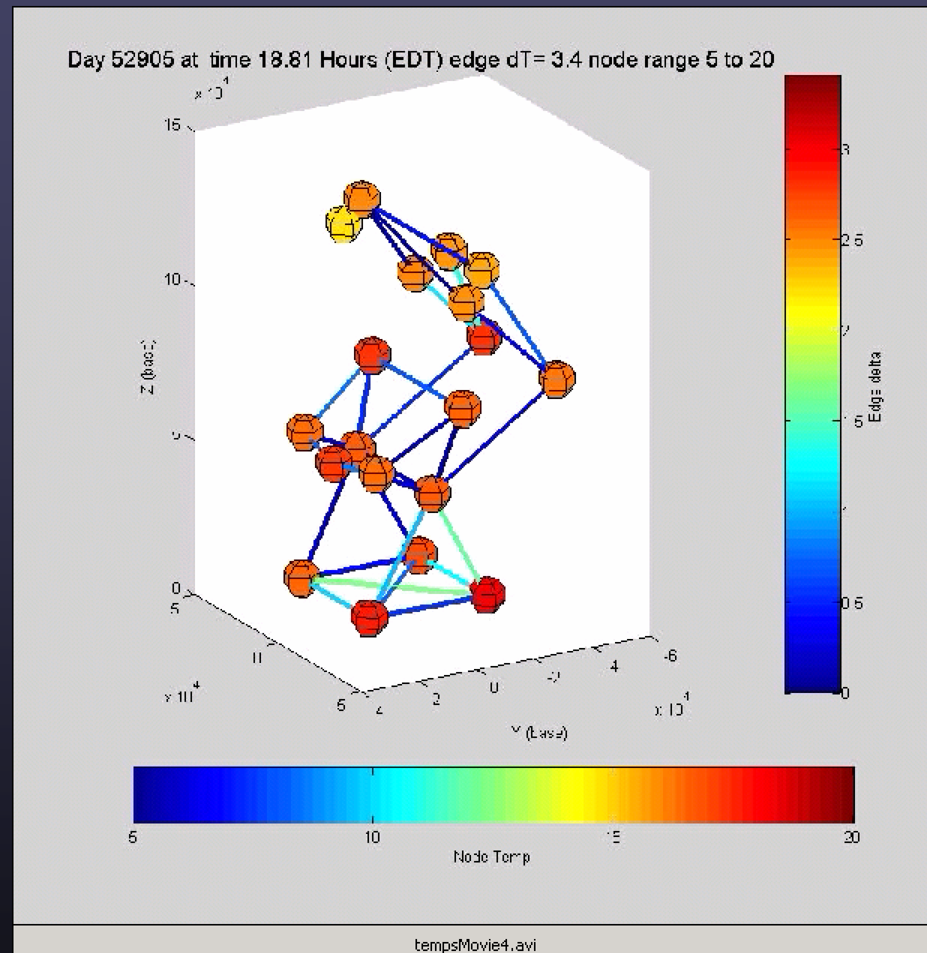
$$\sigma_1(\text{wind}) \approx 0.16\left[\frac{s}{\text{m s}^{-1}}\right]^2 \quad \text{arcsec}$$

$$\sigma_2(\text{wind}) \approx \sqrt{2}\,\sigma_1(\text{wind})$$

$$\approx 8'' \text{ at } s = 6 \text{ m s}^{-1} \rightarrow f = 0.22 \text{ at } 20\,\text{GHz}$$

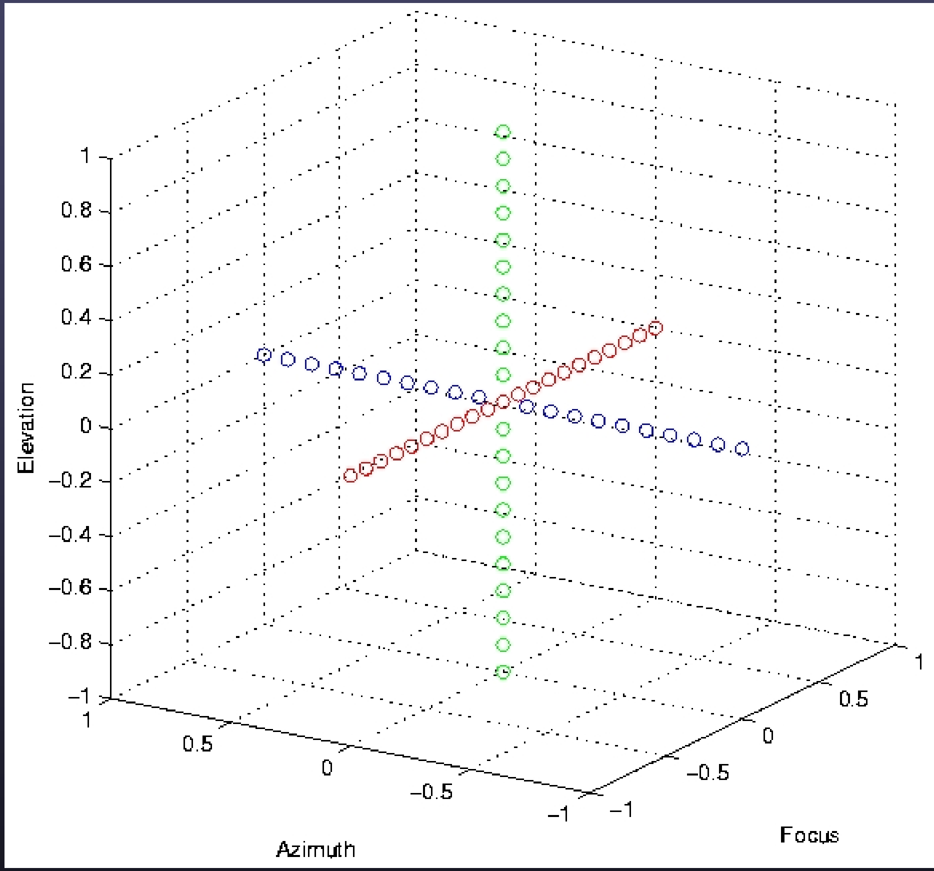
$$\text{Usable } (\sigma_s = 10\%) \rightarrow f \approx 0.20$$

Thermal Pointing and Focus Corrections



Constantikes (2003)

Data Collection and Quality



Jack Scan

All-sky Observations
Single Source Track

Up-Down at Night → Gravity
NCP Source → Temperature

Gaussian Fits (Az, El, Focus)

Polarization (LCP – RCP)

Direction (Forward – Backward)

Thermal Model – Focus

$$\Delta\tilde{F}\left(\phi, T_i^{(f)}\right) = M^{(f)} \times \begin{bmatrix} T_1^{(f)} \\ . \\ . \\ . \\ T_6^{(f)} \\ 1 \\ \sin(\phi) \\ \cos(\phi) \end{bmatrix} = M^{(f)} \times T^{(f)}$$

Constantikes (2003)

Term	Coefficient	Min-Max	Significance	Parameter
M_1	1.086	13.1	14.3	SR-Pri
M_2	-0.697	6.2	-4.3	VFA-Pri
M_3	3.981	15.6	62.0	HFA
M_4	-7.326	0.9	-6.8	BUS V1
M_5	-0.688	12.1	-8.3	BUS V2
M_6	-2.576	12.1	-31.2	BUS F
M_7	-180.630	0.0	0.0	Offset
M_8	66.189	.7	43.1	sin term
M_9	196.949	0.6	110.8	cos term

Thermal Model – Azimuth

$$\Delta A\left(\phi,\theta,T_i^{(a)}\right)=M^{(e)}\times\begin{bmatrix} T_1^{(a)} \\ . \\ . \\ . \\ T_4^{(a)} \\ 1 \\ \sin(\phi) \\ \cos(\phi) \\ \cos(\theta)\sin(\phi) \\ \sin(\theta)\sin(\phi) \end{bmatrix}=M^{(a)}\times T^{(a)}.$$

Constantikes (2003)

Term	Coefficient	Min-Max	Significance	Parameter
M_1	5.5862	4.0	22.4	Alidade
M_2	-8.0331	2.7	21.3	HFA
M_3	-1.6289	2.4	3.8	BUS
M_4	1.3683	2.0	2.8	VFA
M_5	3.4124	0.0	0.0	CA, d(0,0)
M_6	1.3223	0.7	1.0	NPAE, b(0,1)
M_7	3.5152	0.9	3.0	IA, d(0,1)
M_8	-2.4960	1.9	4.8	AW, b(1,1)
M_9	-1.3360	1.8	2.5	AN, a(1,1)

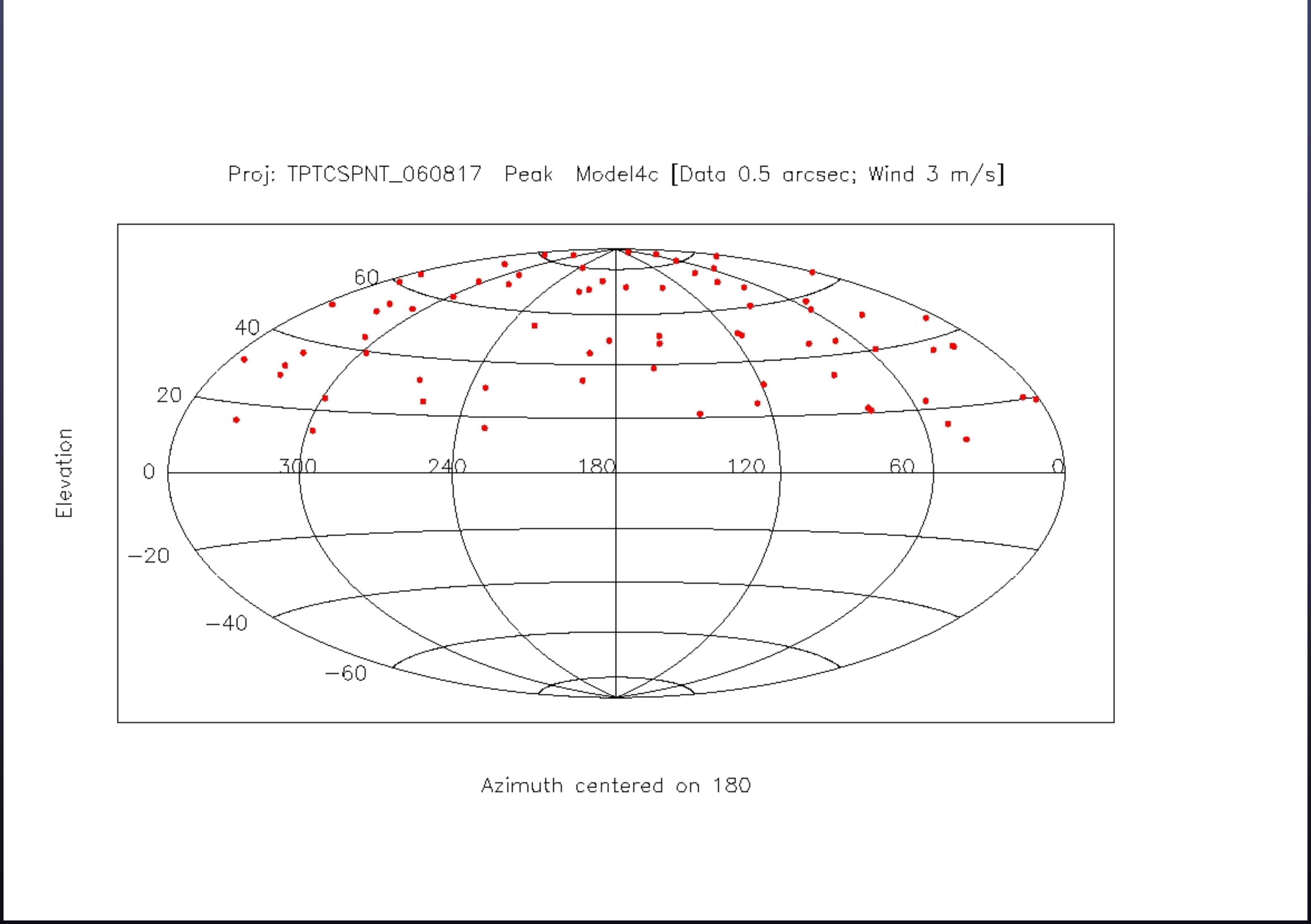
Thermal Model – Elevation

Constantikes (2003)

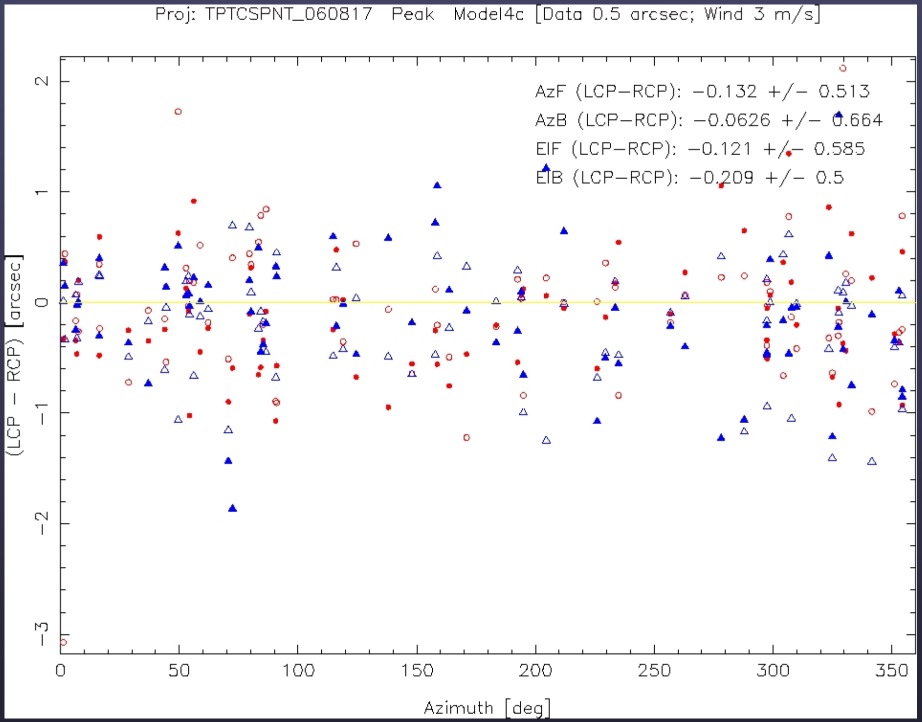
$$\Delta E\left(\phi,\theta,T_i^{(e)}\right) = M^{(e)} \times \begin{bmatrix} T_1^{(e)} \\ . \\ . \\ . \\ T_4^{(e)} \\ 1 \\ \sin(\phi) \\ \cos(\phi) \\ \sin(\theta) \\ \cos(\theta) \end{bmatrix} = M^{(e)} \times T^{(e)}.$$

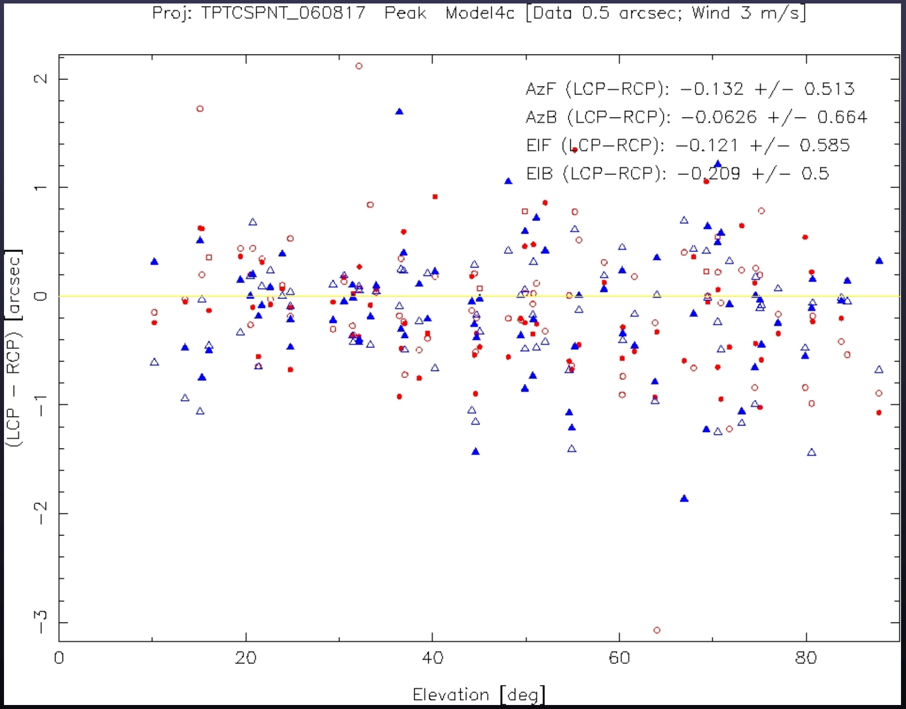
Term	Coefficient	Min-Max	Significance	Parameter
M_1	-4.6455	1.2	-5.3	BUS
M_2	1.7830	15.6	-27.8	HFA
M_3	4.4488	5.9	26.4	VFA
M_4	-8.4477	1.6	-14.0	Alidade
M_5	62.2218	0.0	+0.000	-IE,d(0,0)
M_6	-55.8624	0.7	-62.792	HZCZ,b(0,1)
M_7	-22.8268	0.9	-38.216	HZSZ,d(0,1)
M_8	2.4960	2.0	+2.169	-AW,c(1,0)
M_9	-1.3360	2.0	-1.750	AN,d(1,0)

Performance – Blind Pointing



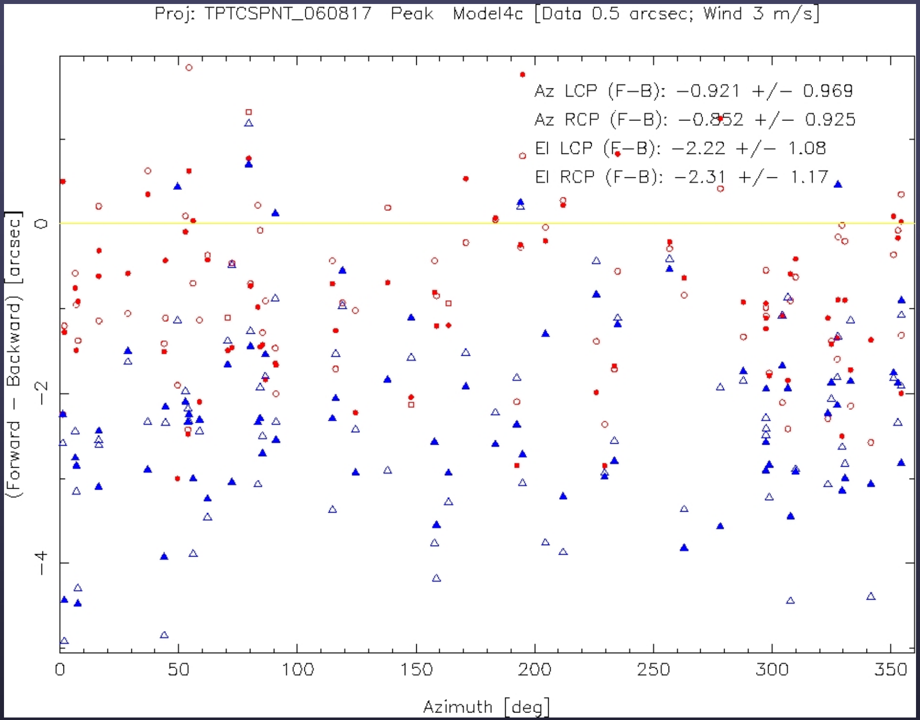
Pointing Data Quality – Polarization

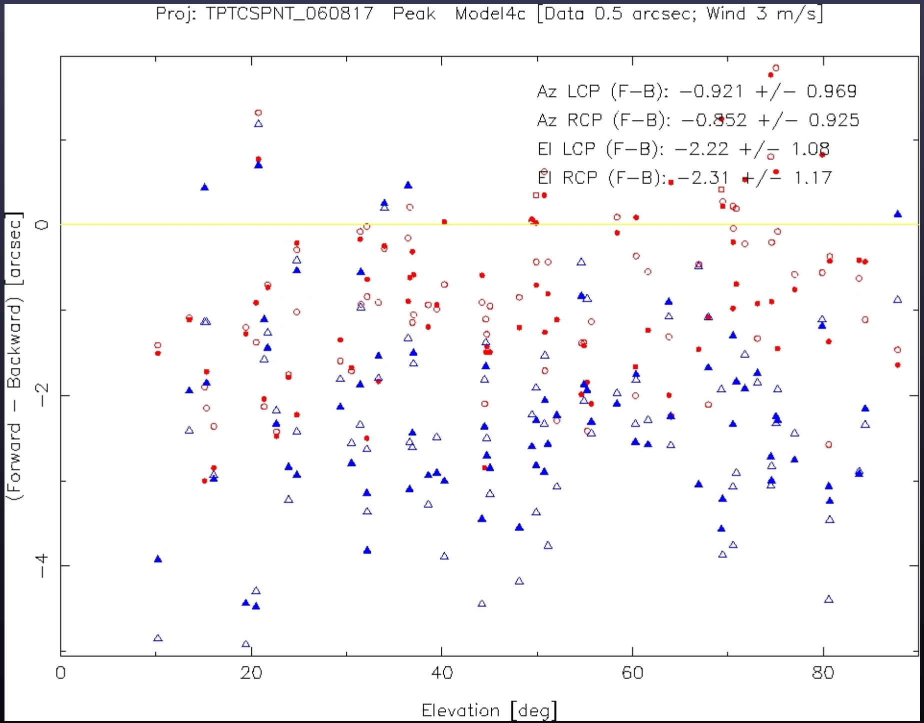




$[\mathrm{LCP} - \mathrm{RCP}] = -0.13 \pm 0.57\ \mathrm{arcsec}$

Pointing Data Quality – Direction

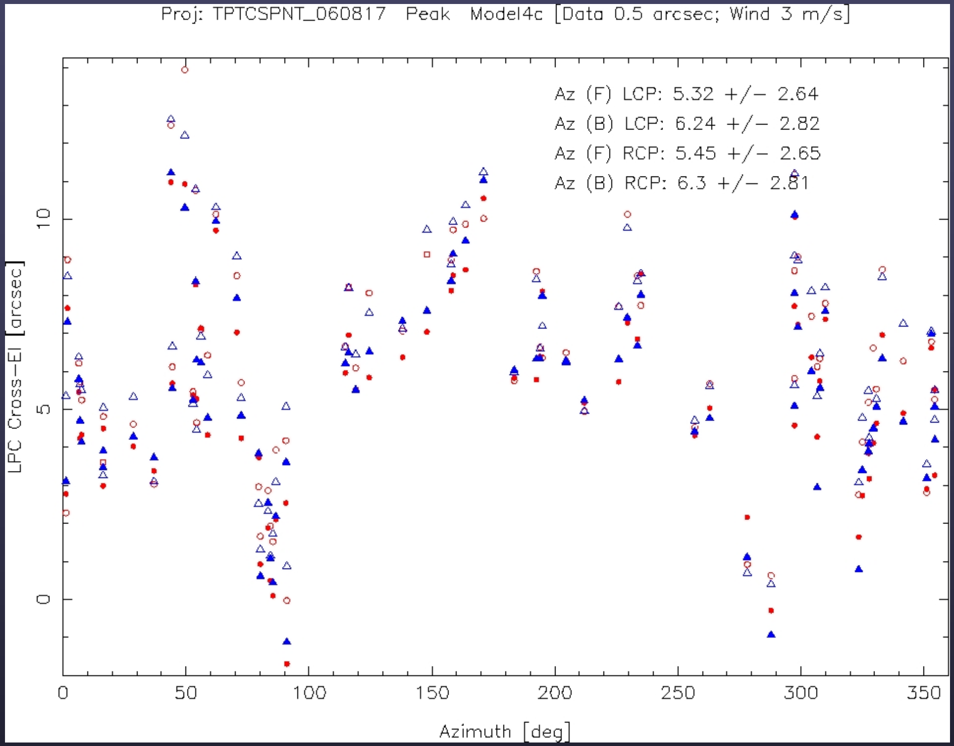


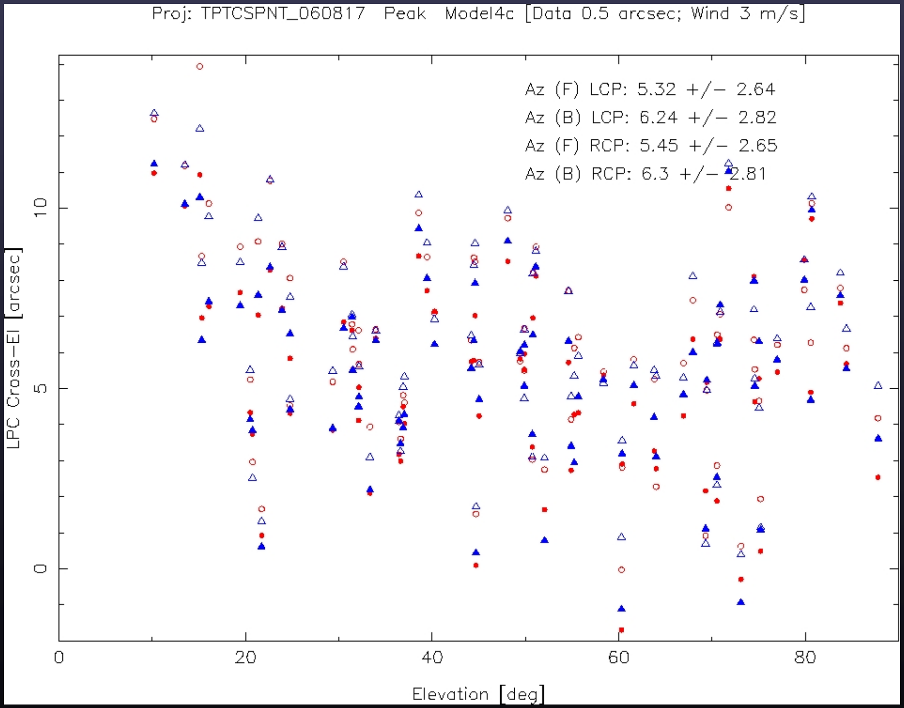


$$[\mathrm{F - B}]_{\mathrm{Az}} = -0.89\ \mathrm{arcsec}$$

$$[\mathrm{F - B}]_{\mathrm{El}} = -2.3\ \mathrm{arcsec}$$

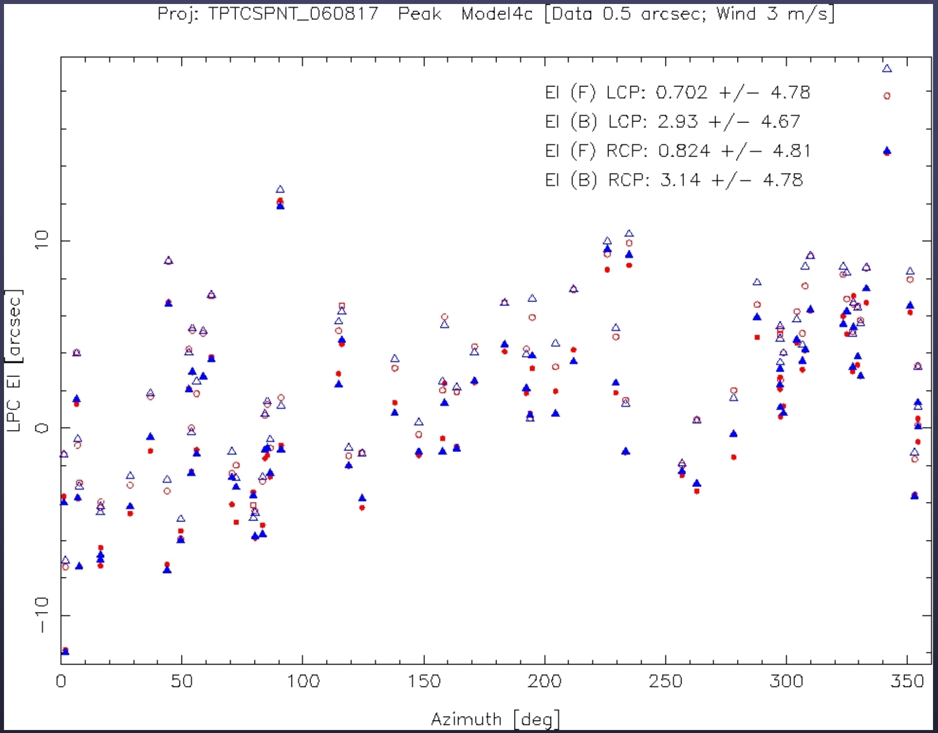
Cross-Elevation Uncertainty



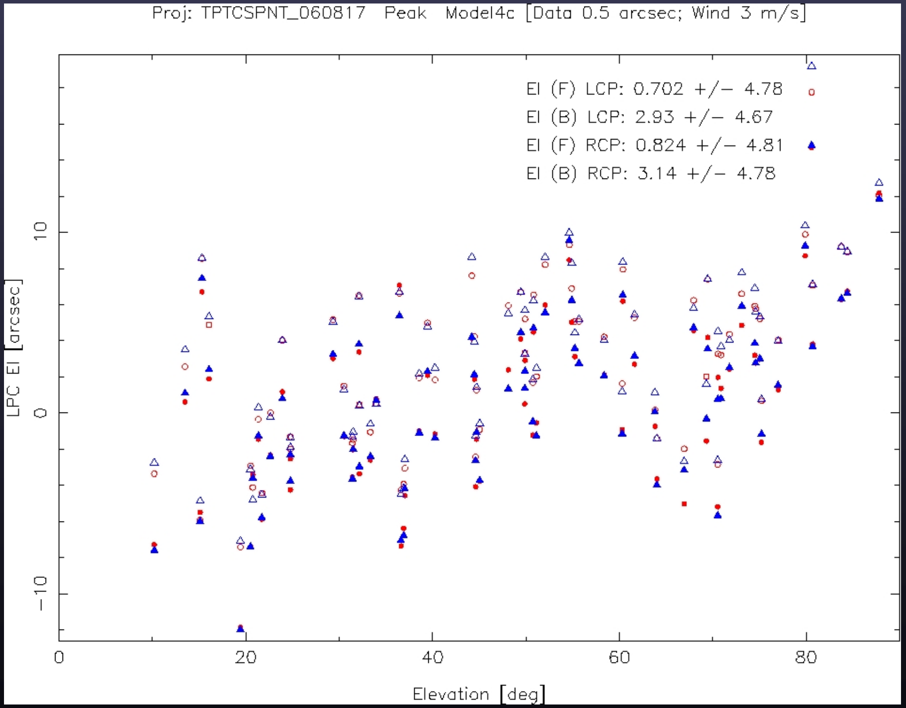


$$\sigma[\Delta A\ \mathrm{Cos}(E)] = 2.7\ \mathrm{arcsec}$$

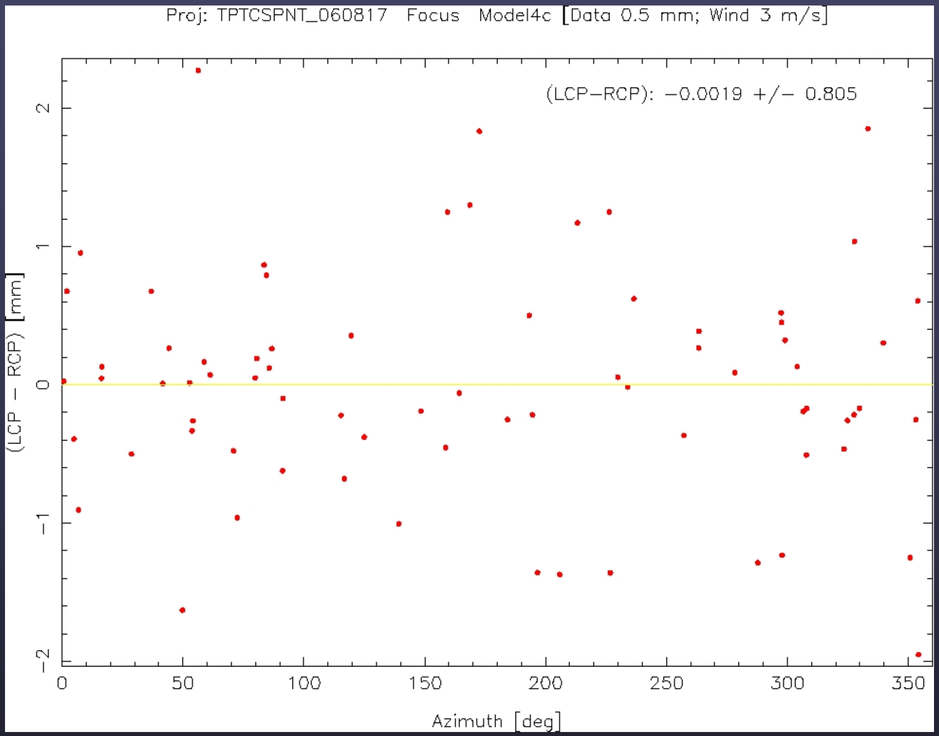
Elevation Uncertainty

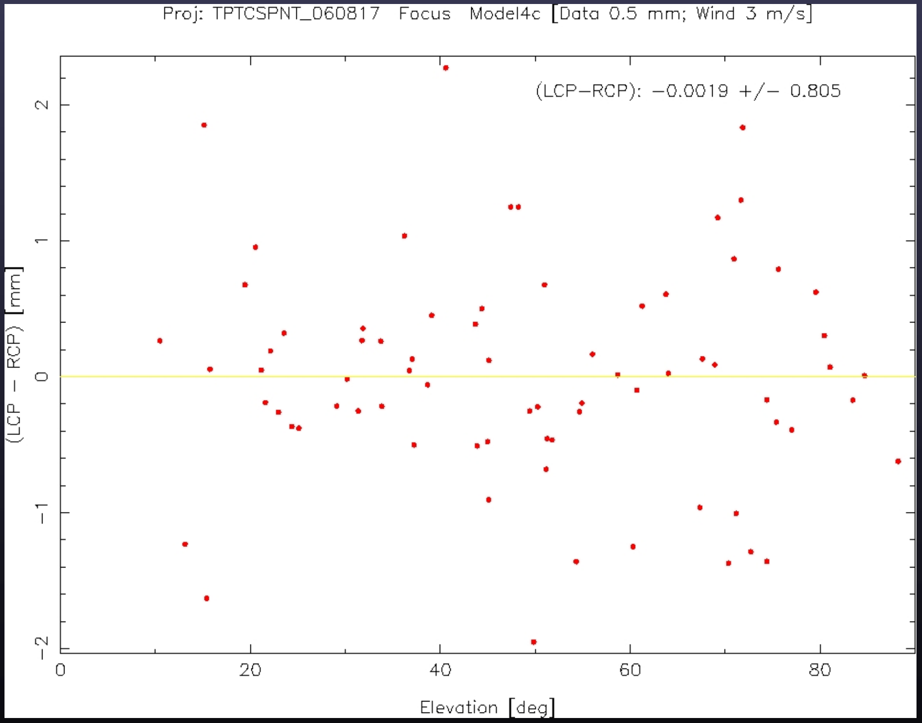


$$\sigma[\Delta E] = 4.8 \text{ arcsec}$$



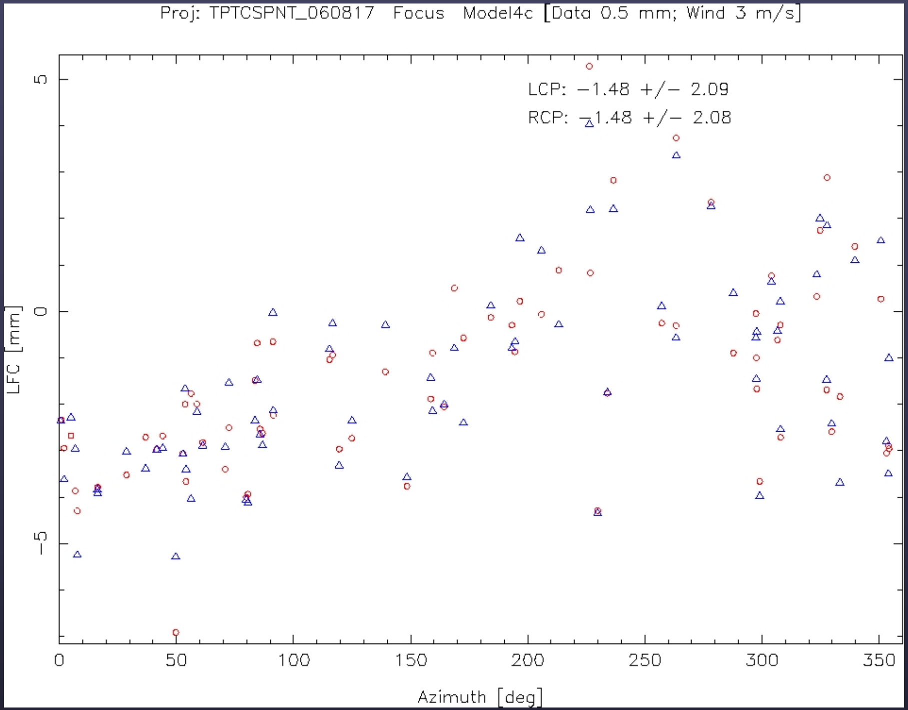
Focus Data Quality – Polarization

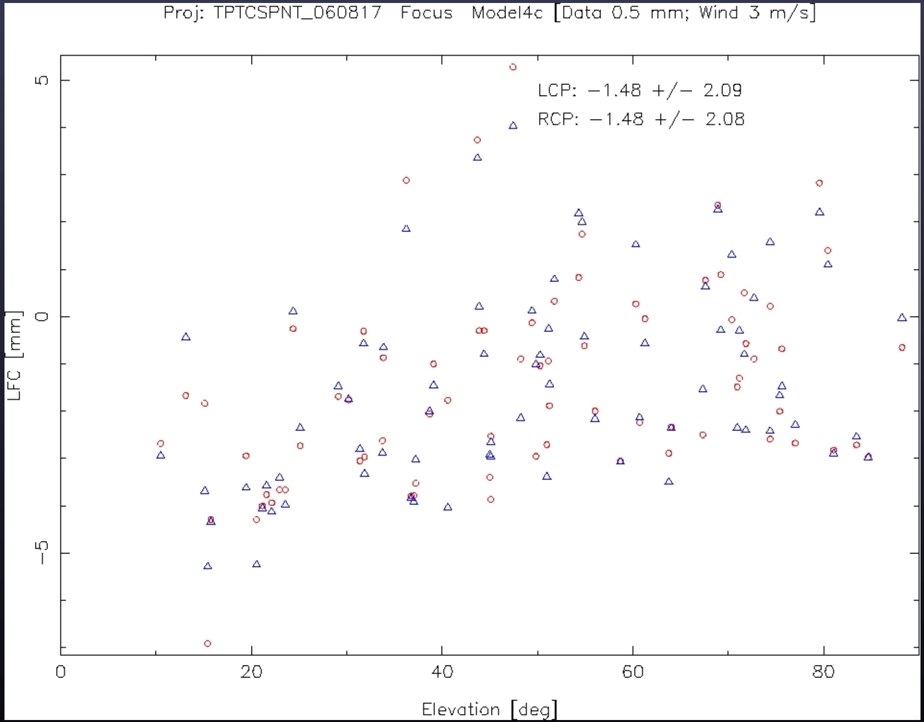




$$[LCP - RCP] = -0.0019 \pm 0.81\,mm$$

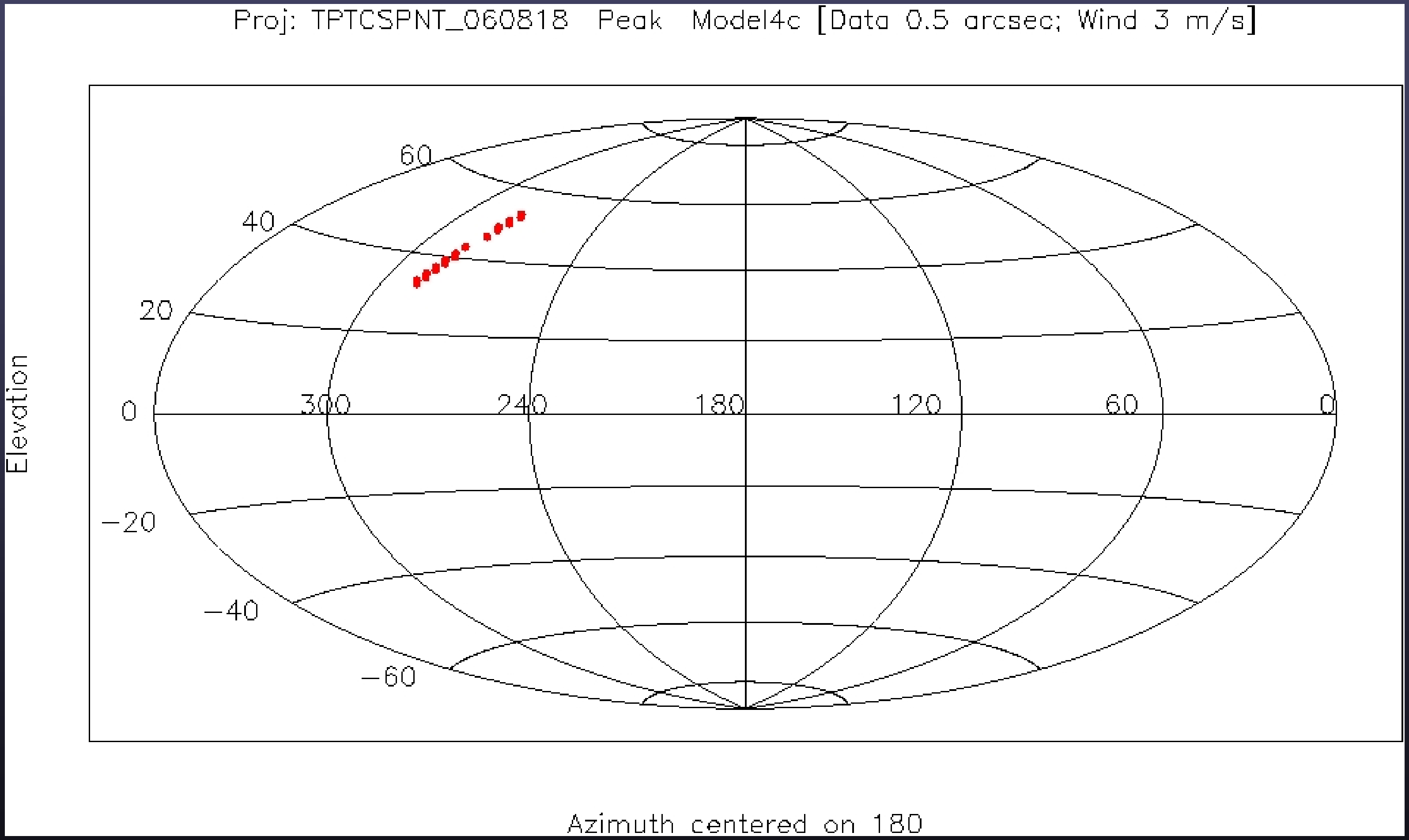
Focus Uncertainty



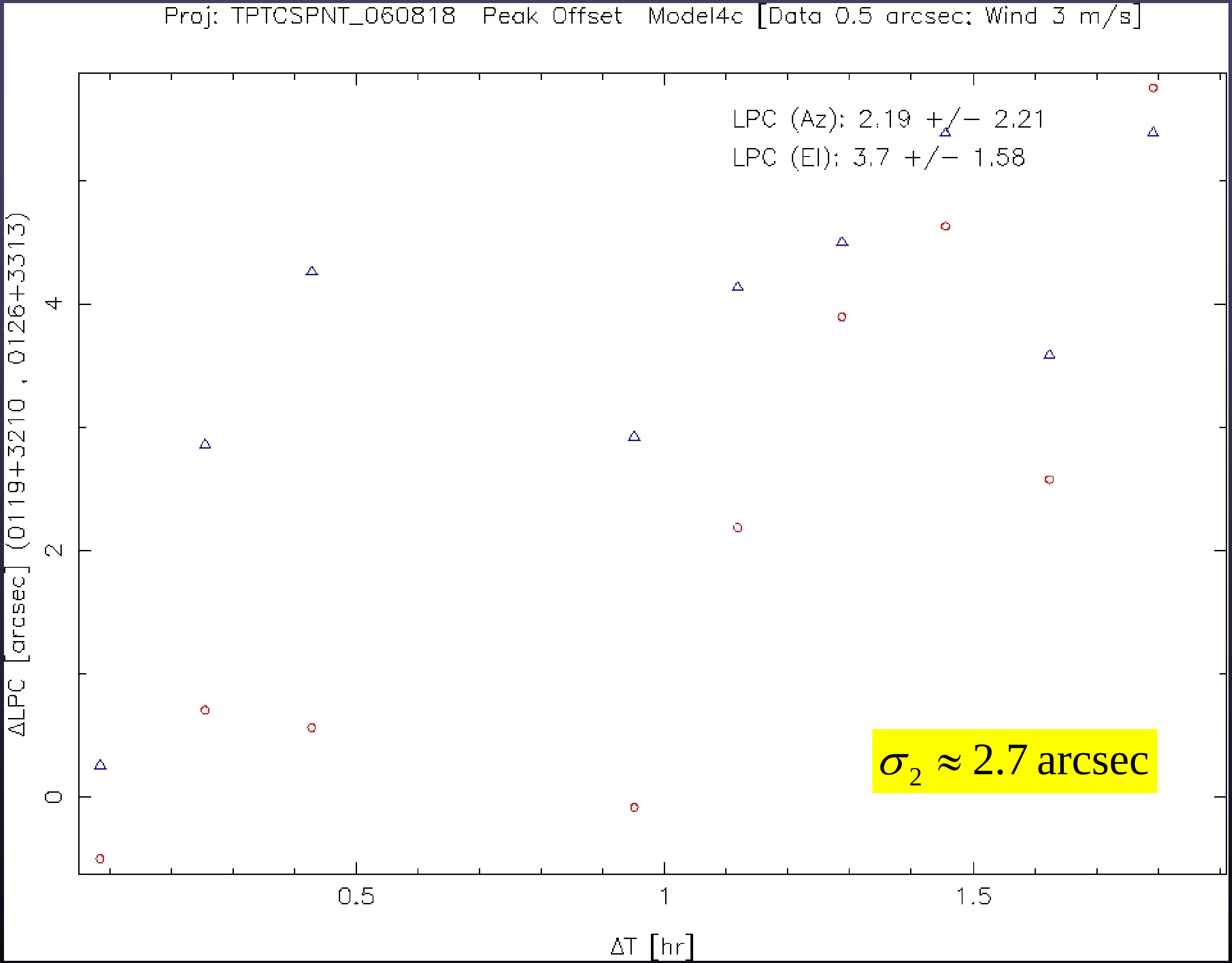


$$\sigma[\Delta f] = 2.1\,\mathrm{mm}$$

Performance – Offset Pointing

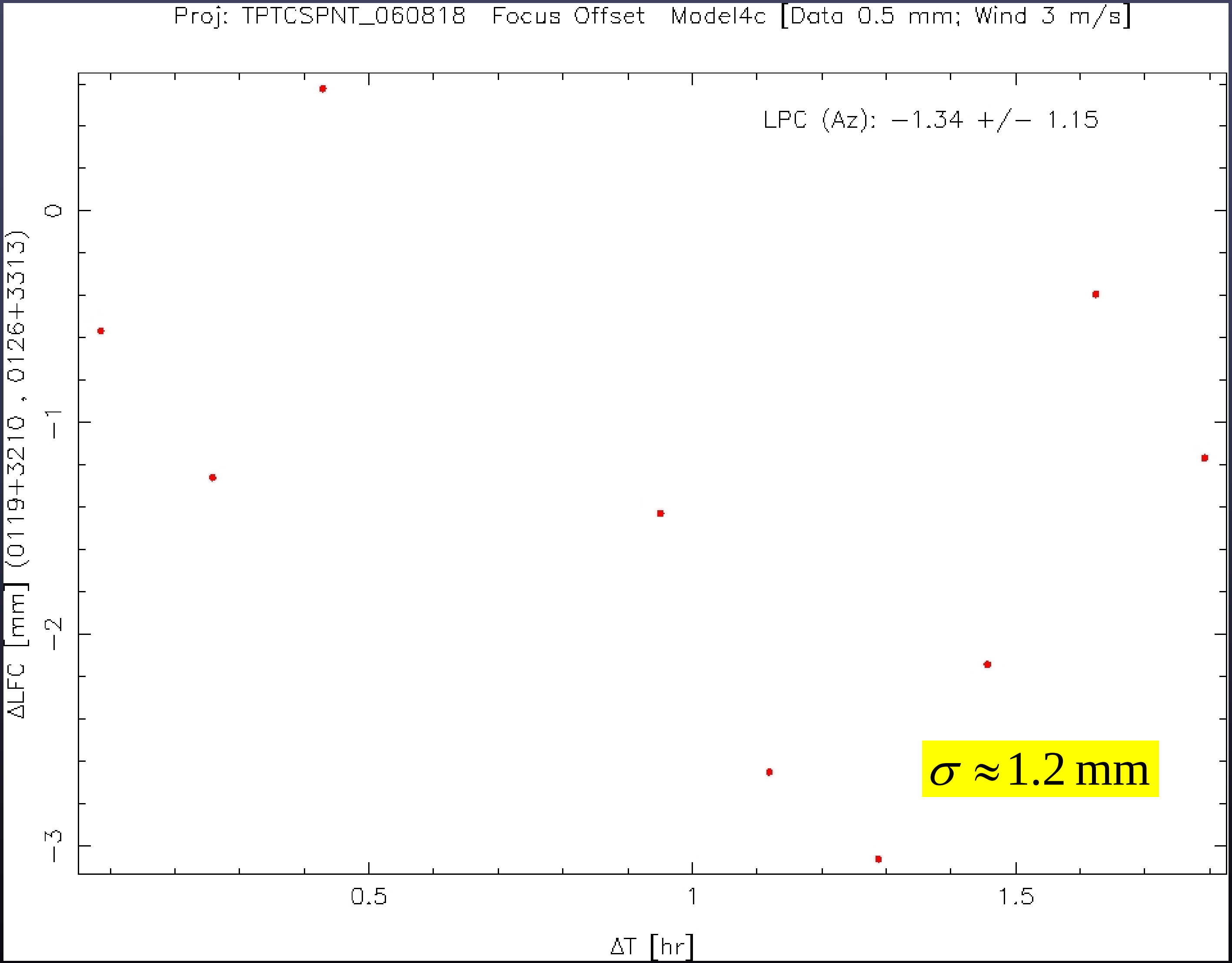


Offset Pointing Uncertainty



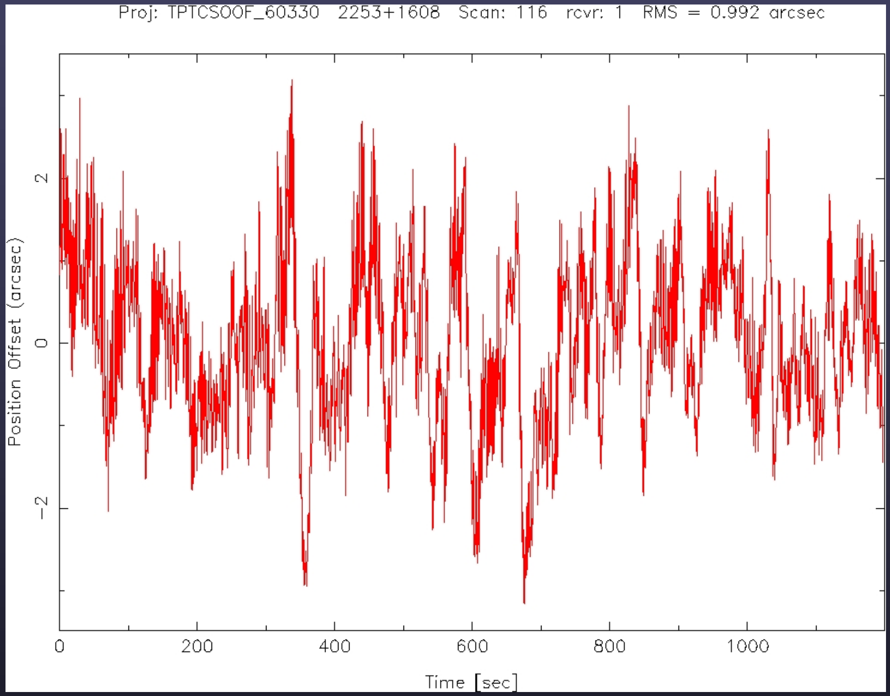
$\sigma_2 \approx 2.7$ arcsec

Offset Focus Uncertainty

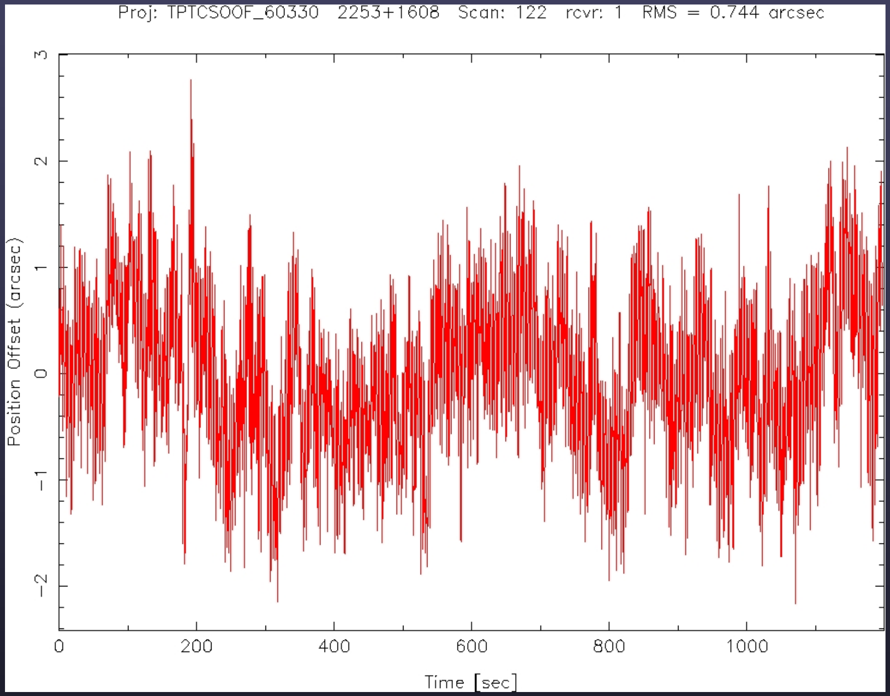


Performance – Tracking

Half-power in Azimuth



Half-power in Elevation

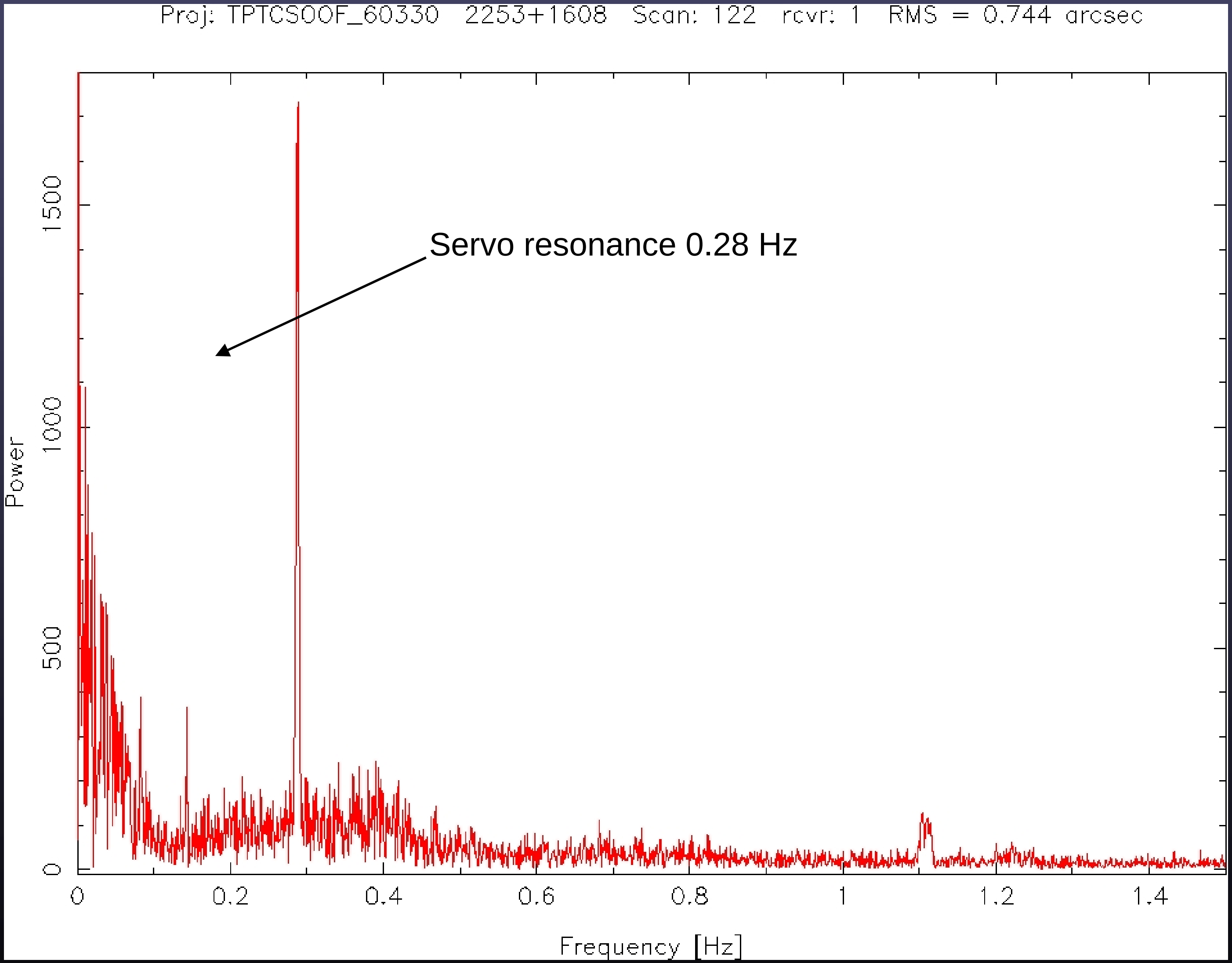


$$(\mathrm{Az}, \mathrm{El}) \approx (99^\circ, 37^\circ)$$
$$(\Delta\mathrm{Az}, \Delta\mathrm{El}) \approx (3.6^\circ, 3.9^\circ)$$
$$\left(\frac{\Delta\mathrm{Az}}{\Delta\mathrm{t}}, \frac{\Delta\mathrm{El}}{\Delta\mathrm{t}}\right) \approx (10.8'/\mathrm{m}, 11.7'/\mathrm{m})$$

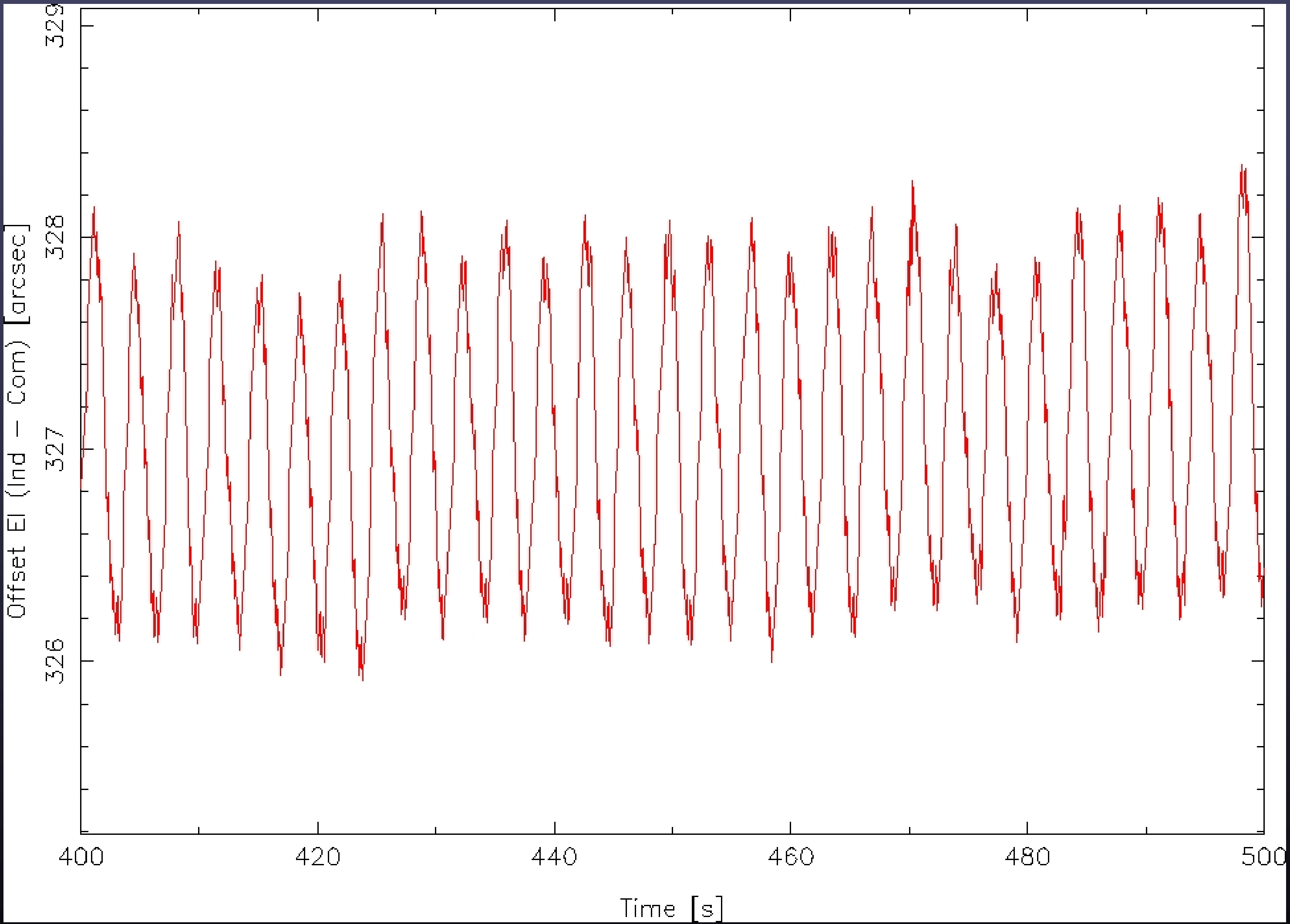
$$\sigma_2 \approx 1.2 \text{ arcsec}$$

$$(\mathrm{Az}, \mathrm{El}) \approx (105^\circ, 43^\circ)$$
$$(\Delta\mathrm{Az}, \Delta\mathrm{El}) \approx (4.0^\circ, 3.8^\circ)$$
$$\left(\frac{\Delta\mathrm{Az}}{\Delta\mathrm{t}}, \frac{\Delta\mathrm{El}}{\Delta\mathrm{t}}\right) \approx (12.0'/\mathrm{m}, 11.4'/\mathrm{m})$$

Power Spectrum



Servo Error



329
328
327
326
Offset El (Ind - Com) [arcsec]
400
420
440
460
480
500
Time [s]

Performance – Summary

Benign Conditions: (1) Exclude 10:00 → 18:00
(2) Wind < 3.0 m/s

Blind Pointing:
(1 point/focus)

$$\sigma_1(\text{pointing}) \approx 5 \text{ arcsec}$$
$$\sigma(\text{focus}) \approx 2.5 \text{ mm}$$

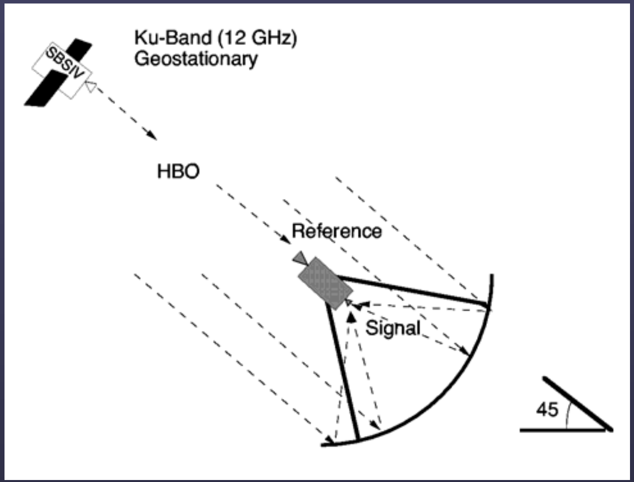
Offset Pointing:
(90 min)

$$\sigma_2(\text{pointing}) \approx 2.7 \text{ arcsec}$$
$$\sigma(\text{focus}) \approx 1.5 \text{ mm}$$

Continuous Tracking:
(30 min)

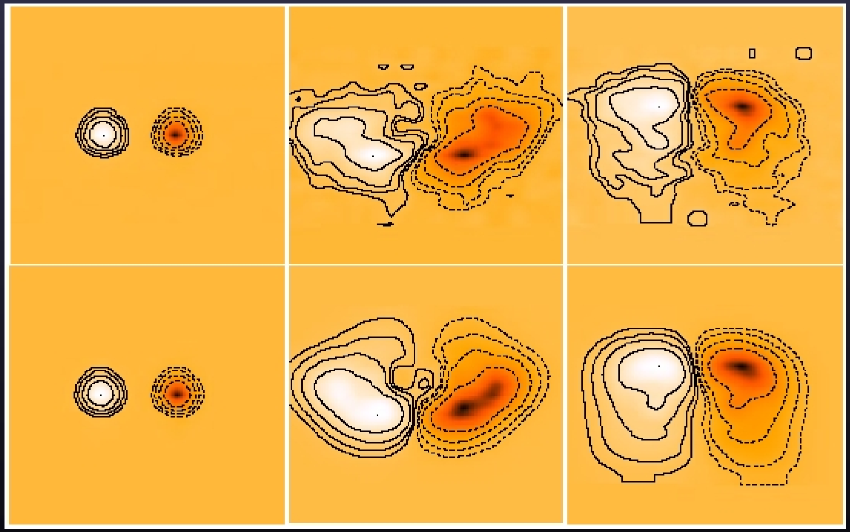
$$\sigma_2 \approx 1 \text{ arcsec}$$

Surface Improvements – Holography



Traditional Holography
(Phase Coherent Holography)

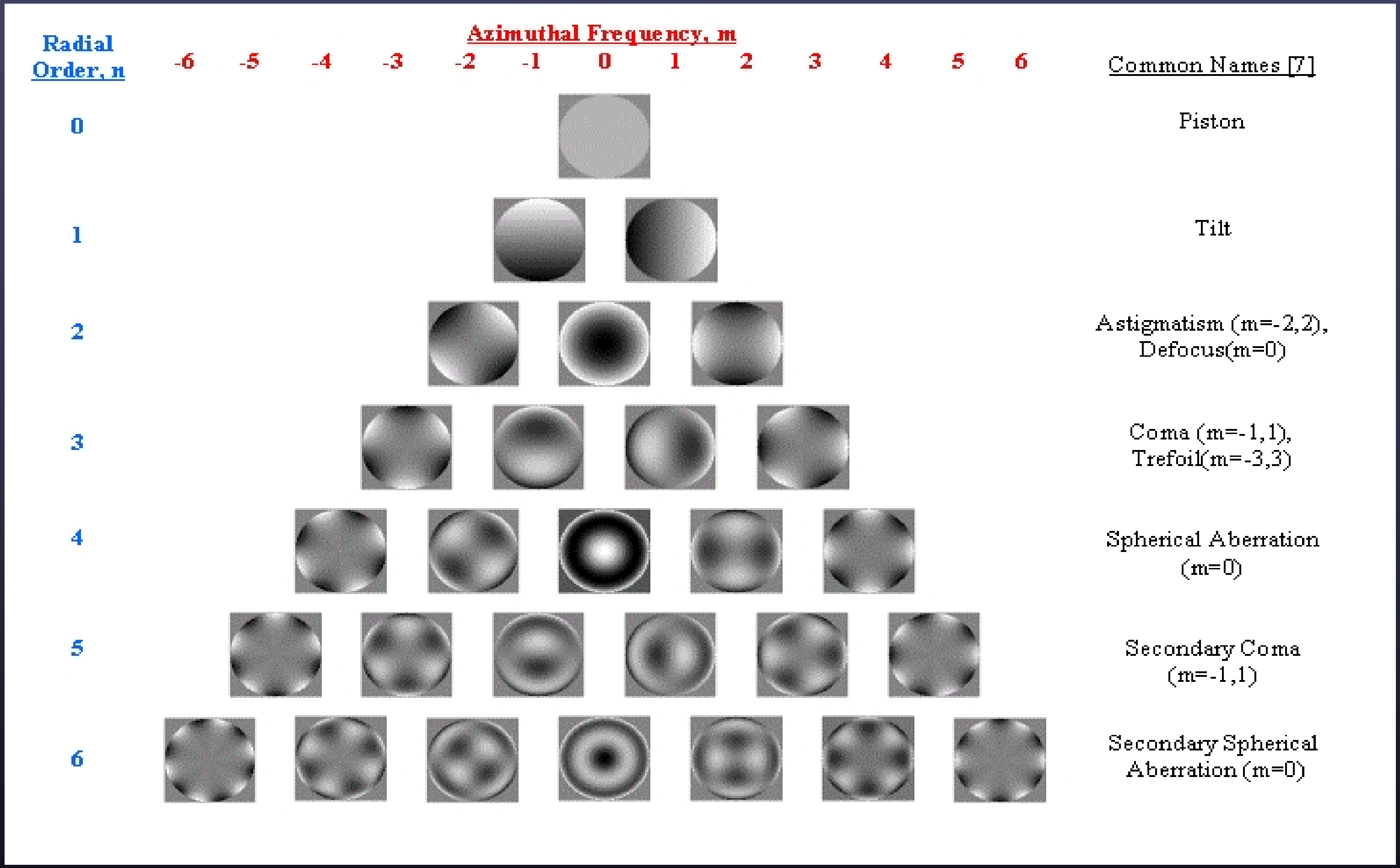
Maddalena



Out-of-Focus Holography
(Phase Retrieval Holography)

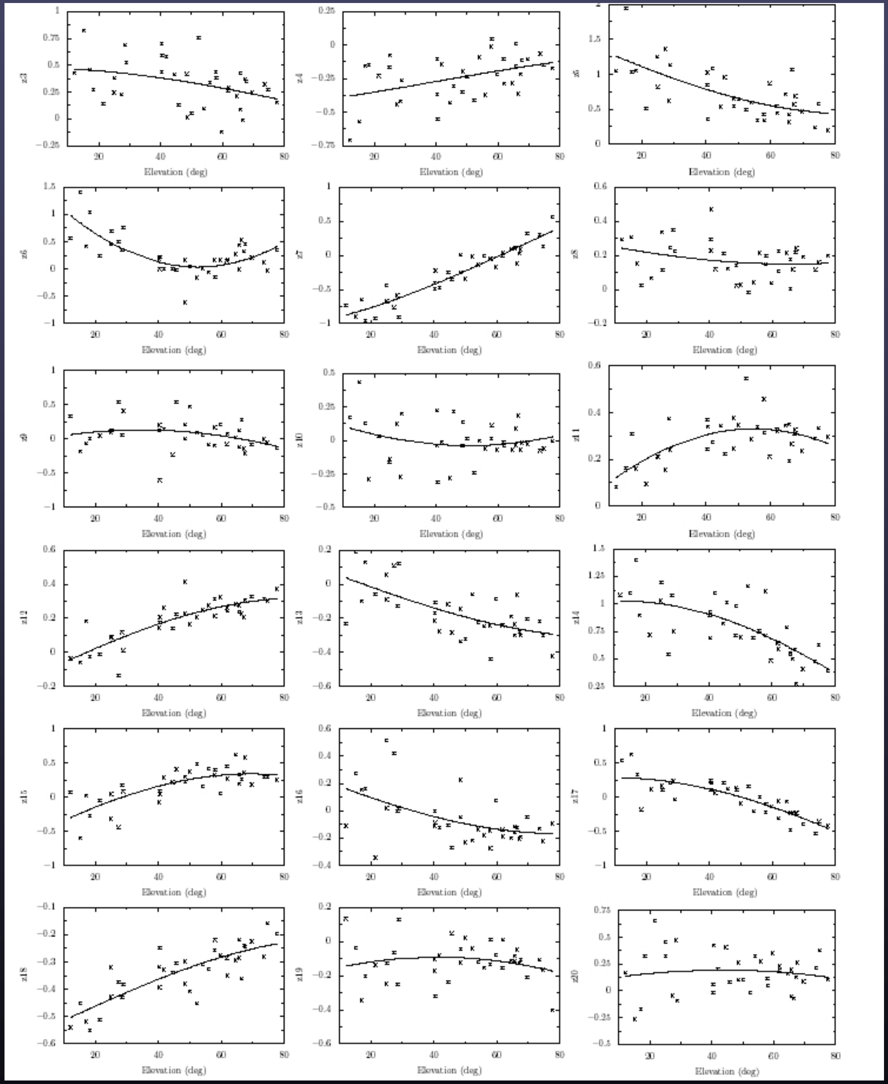
Nikolic et al. (2006)

Zernike Polynomials



Zernike (1934)
Maeda (2003)

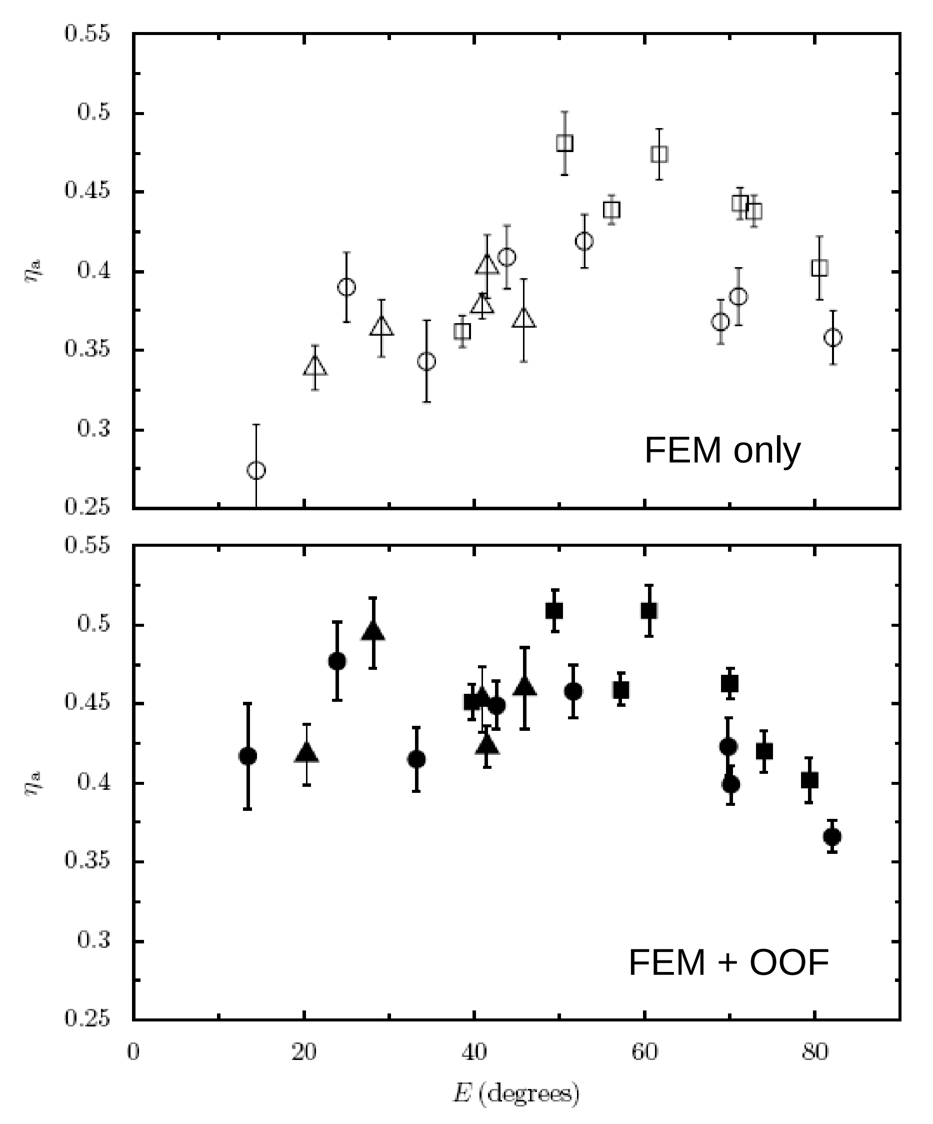
OOF Holography – Gravity



$$z_i(E) = a\,\mathrm{Sin}(E) + b\,\mathrm{Cos}(E) + c$$

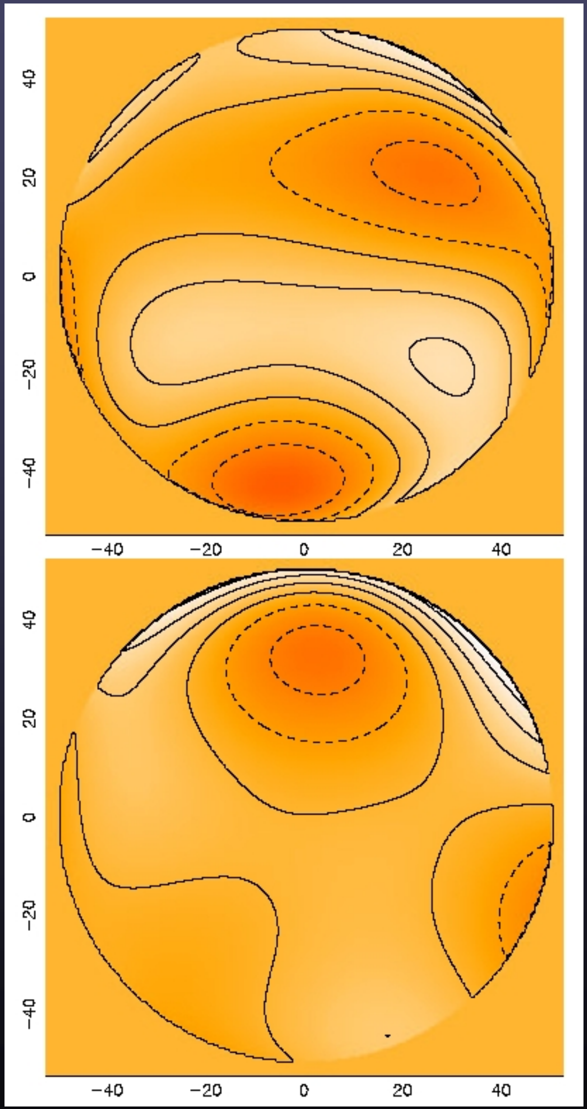
Nikolic et al. (2006)

Gain-Elevation Curve



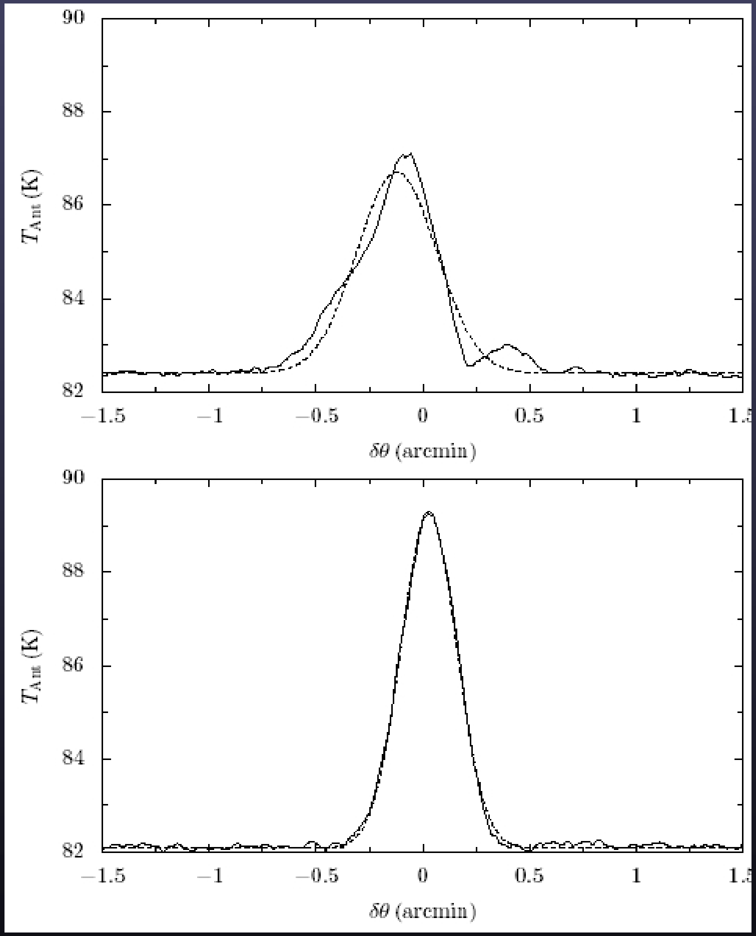
Nikolic et al. (2006)

OOF Holography – Thermal Effects



rms ≈ 330 μm

rms ≈ 220 μm



Summary Surface Performance