Microwave Holography

Richard Prestage

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

Outline of Talk

- Introduction and Specifications

- Types of Microwave Holography:
  - "Traditional" or "with phase" holography
  - "Phase-retrieval" or "out-of-focus" holography [*]
  - Near field with-phase holography

- Examples mainly from GBT, but most radio antennas use some variant of these techniques.

  - [*] "out of focus" now normally performed on bright astronomical point source calibrators.
  - Can be used with near-field beacons (e.g. JCMT)

Homologous Design

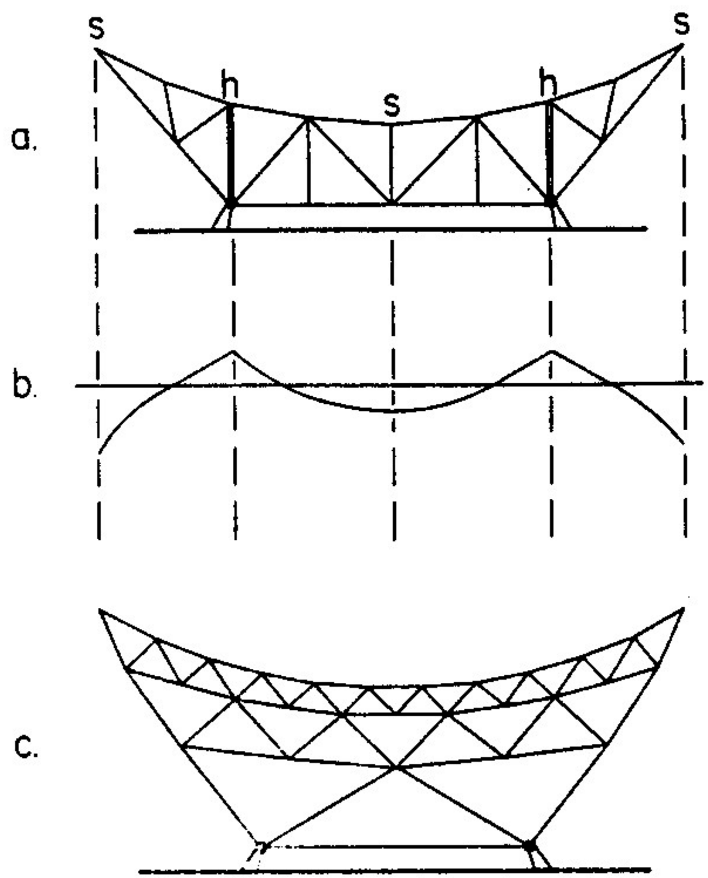
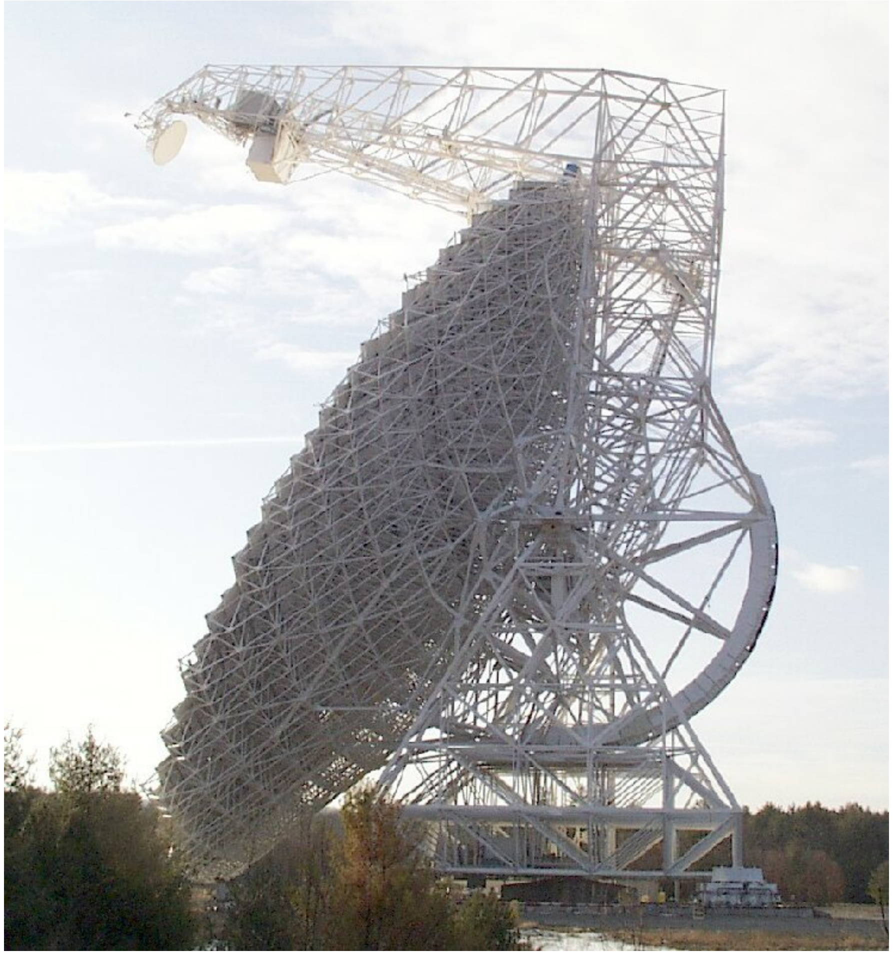


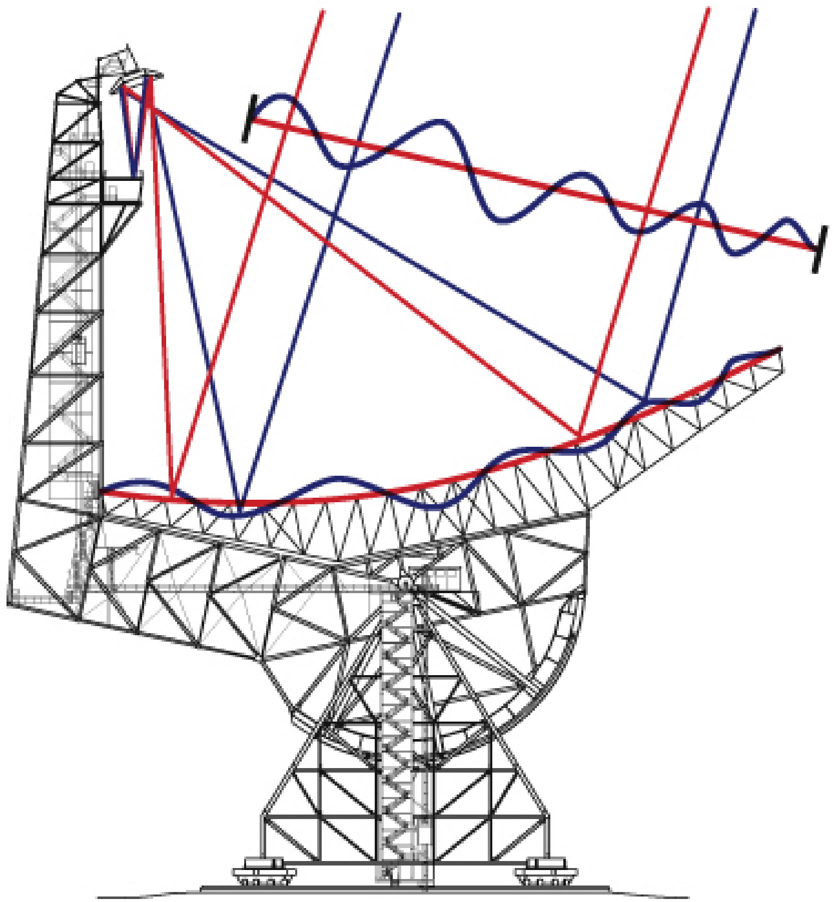
FIG. 7. Equal softness. (a) Conventional design, with hard (*h*) and soft (*s*) surface points. (b) Deformation of this telescope, looking at zenith. (c) Structure, where all surface points have equal softness.

NRAO

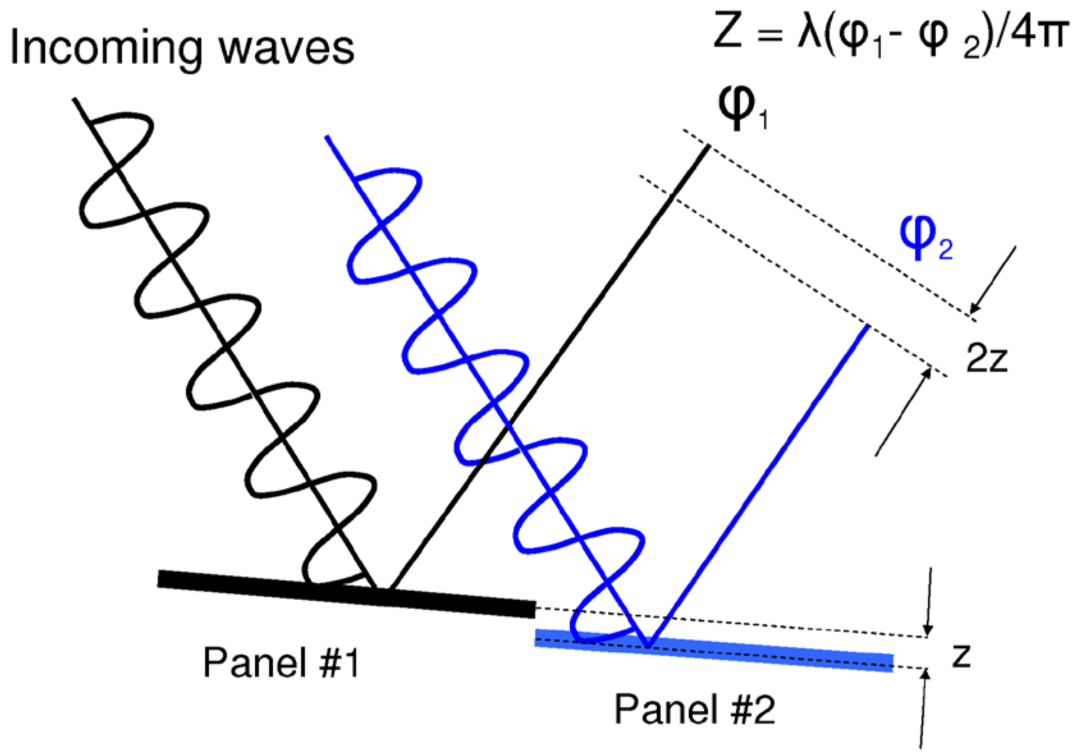
Homologous Design



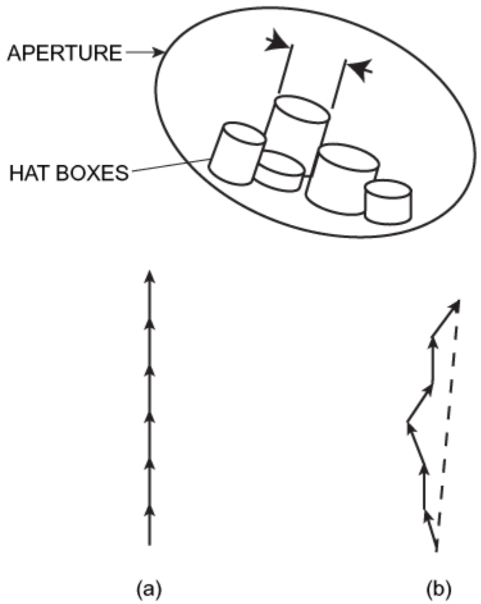
Surface Irregularities

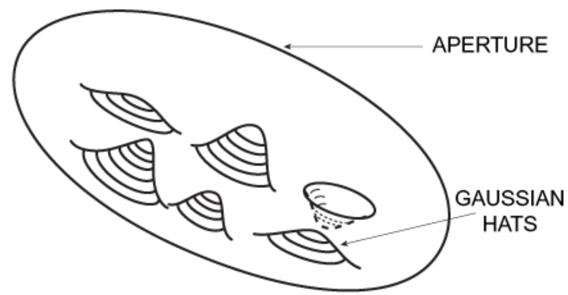


Phase Errors



Phase Losses





Error distribution modeled by Ruze

Ruze formula:

ε = rms surface error

$\eta_p = \exp[(-4\pi\varepsilon/\lambda)^2]$

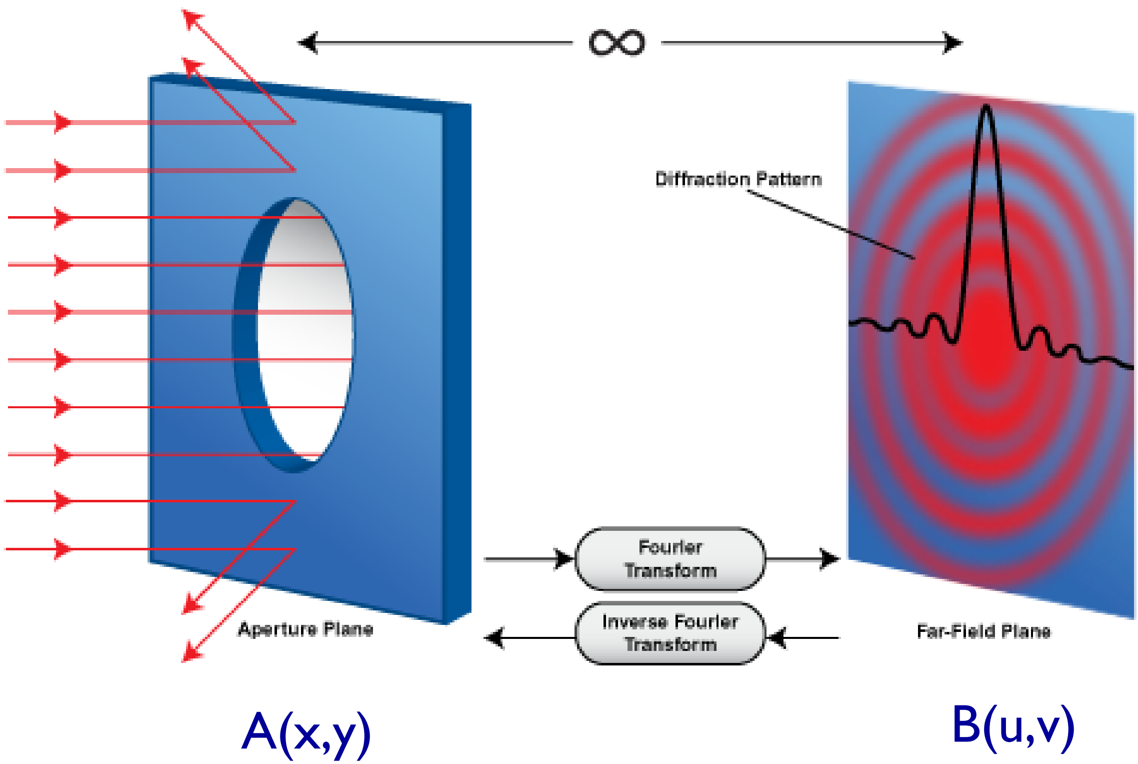
"pedestal" $\theta_p \sim D\theta/L$

Traditional spec: η_a down by 3dB for $\varepsilon = \lambda/16$

"acceptable" performance (forward gain does not decline with wavelength) $\varepsilon = \lambda/4\pi$

NRAO

Fourier Transform Relationship



Far-field beam pattern is Fourier transform of aperture plane electric field distribution

Goal of Microwave Holography

- Measure far field amplitude and phase –
  - Or something related to that
- Perform the inverse Fourier Transform
  - Phase of the electric field in the aperture plane
- Relate that to a mechanical displacement at the actuator
- Characterize (non-active surface) or adjust the surface to obtain best possible rms surface error

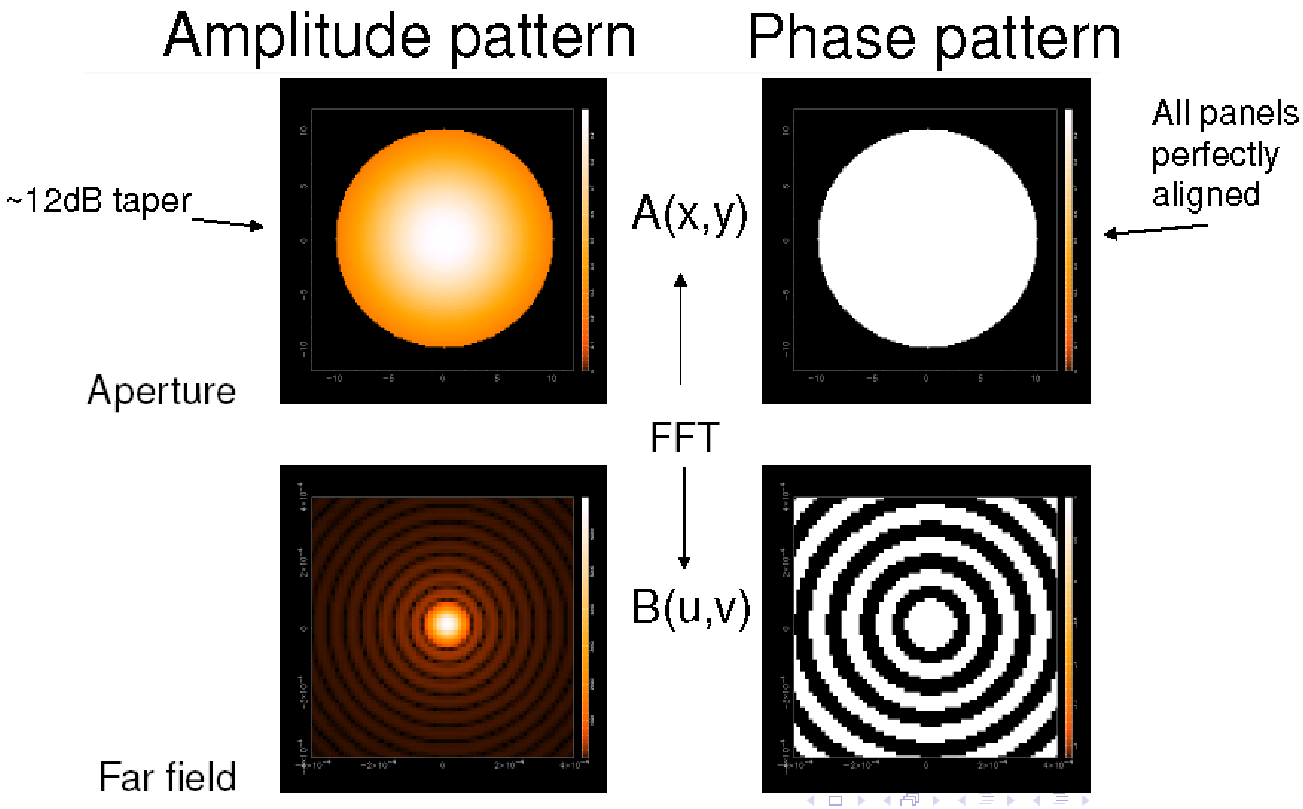
NRAO

Traditional (phase-reference) holography

- Dedicated receiver to look at a geostationary satellite
- Second dish (or reference antenna) provides phase reference
- Measure amplitude and phase of far-field beam pattern
- Fourier transform to determine amplitude and phase of aperture illumination

- Standard Technique which has been in use for ~ 35 years (see e.g. Bennett et al. 1976).

An Ideal Radio Telescope



$$B(u,v) = \Sigma A(x,y) \exp[2\pi j(xu+yv)]$$

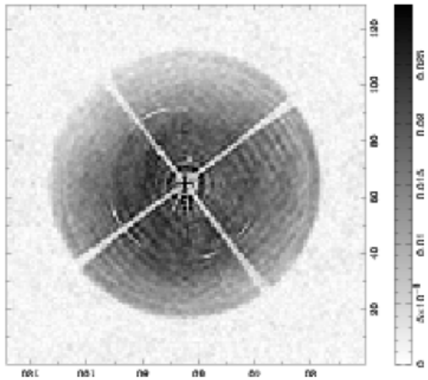
where B = beam, A = aperture
u,v are angles; x,y are distances

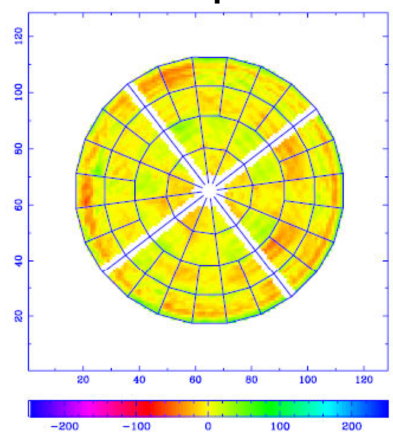
A Real Radio Telescope

Amplitude pattern

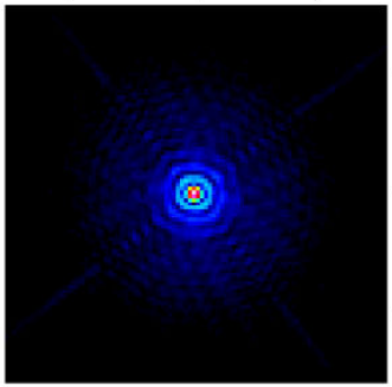
Phase pattern

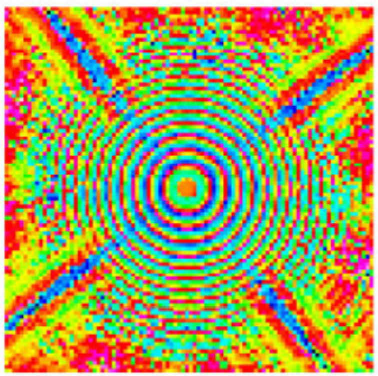
aperture





FFT





Phase Reference Holography

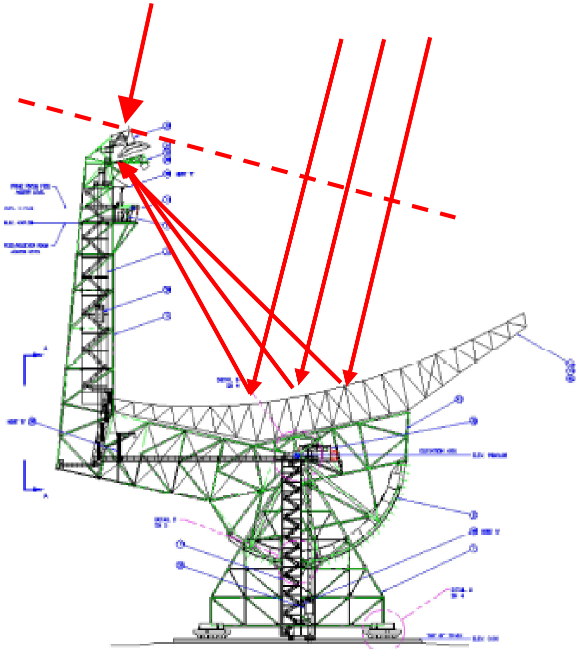
- Advantages:
  - Can be performed at reasonable elevation angles.
  - High spatial resolution over the dish.
  - High accuracy (~60μm for GBT system).
- Disadvantages:
  - Generally can only be performed at one elevation.
  - Long (hours) data acquisition time.
  - Requires dedicated hardware
  - Receiver requires unusually high dynamic range (70dB).

Phase Reference Holography

- Basic method:
  - Measure complex beam pattern via interferometry
  - Fourier transform to get phase and amplitude of E-field
  - Convert phase to surface error
- GBT Ku-band holography system re-commissioned (December 2008):
  - Two room-temp. LNBs, 10 kHz filter and digital correlator
  - New DROs with Digital PLLs (stability)
  - Linux backend, sample rate = 28 Hz
  - Allows 200-column, 2° x2° maps in 3 hours

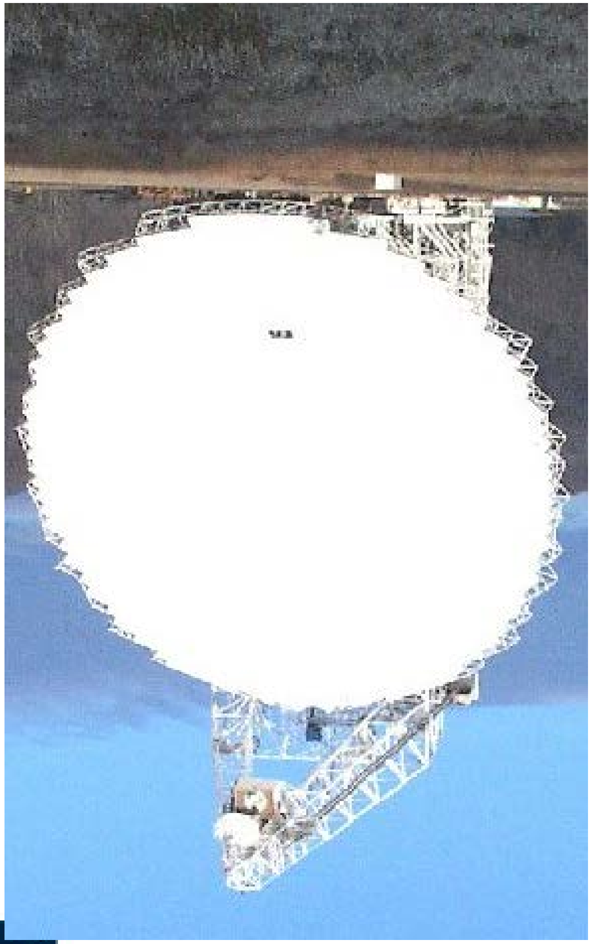
Reference horn at top of feedarm

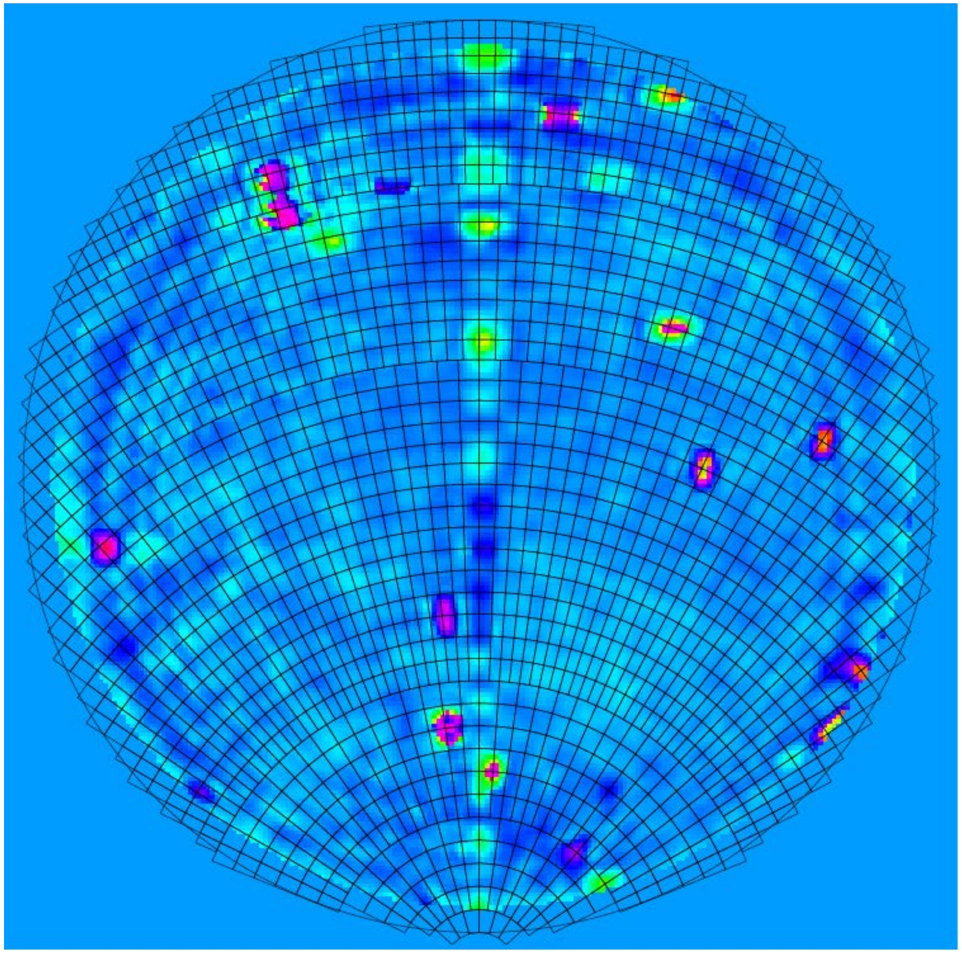
Main receiver in Gregorian turret



NRAO

Holography Map Showing Panel Locations





Near-Field (Beacon) Holography

- Similar to traditional with-phase holography.
- Use a radio beacon in the near-field (Fresnel region) of the antenna under test.
- Use of near field causes a rapid variation of phase across the aperture (Baars et al. 2007).
  - Largely corrected for by displacing the feed from the primary focus.
  - Residual correction applied to the aperture phase distribution after the Fourier transform.
- Higher order terms collected into a variable ε:

$$A(x,y) \propto \int B(u,v) \exp\{ik(ux+vy)e^{-ik\varepsilon} du dv$$

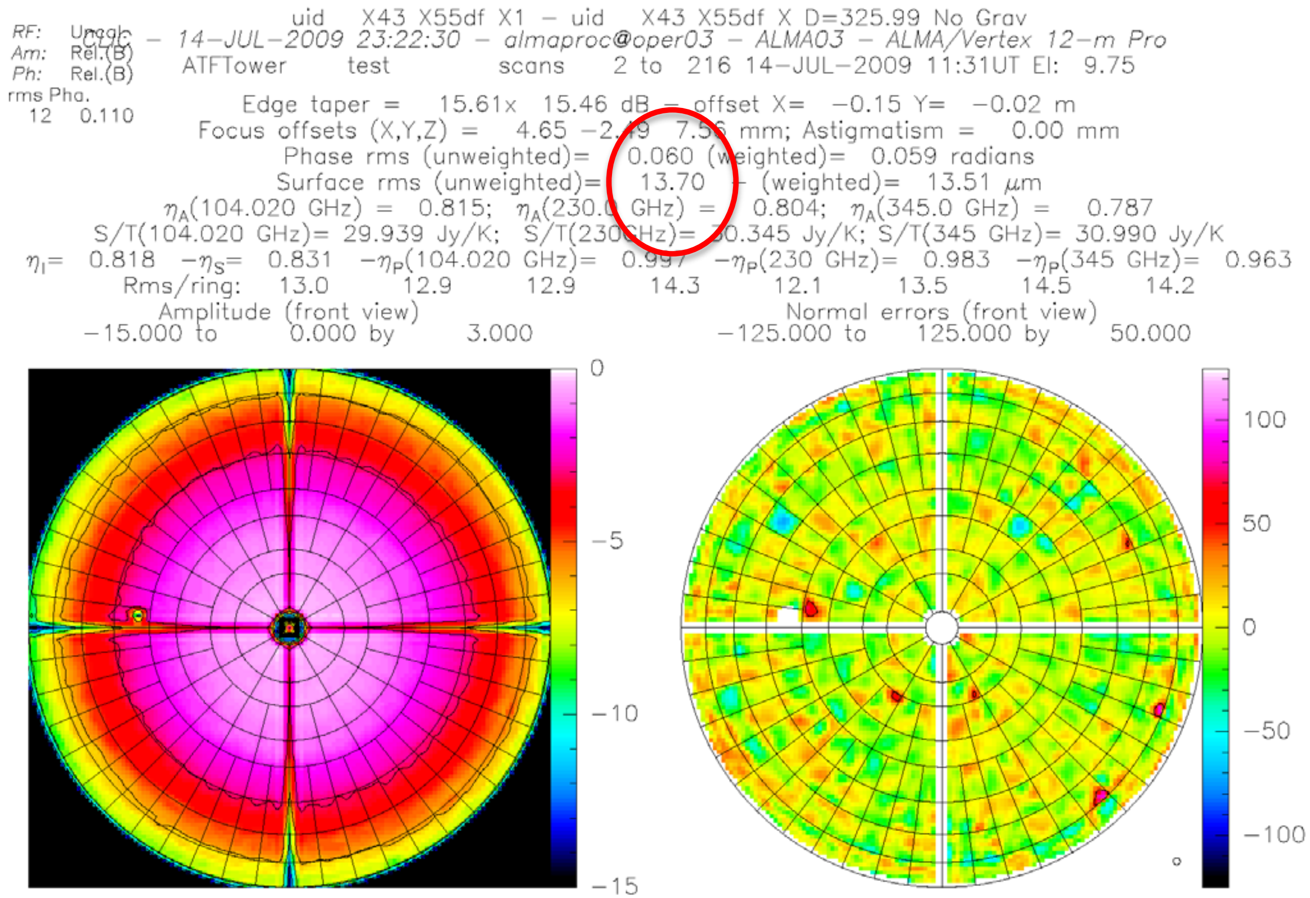
- The terms in ε “modify” the direct Fourier transform

Near-Field(Beacon) Holography

- Advantages:
  - Nearby beacon allows high S/N, high-resolution maps
  - Maps can be obtained relatively quickly (less than one hour)
  - Beacon can be chosen to have convenient frequency/location
- Disadvantages:
  - Maps obtained at a single, low elevation
  - Requires dedicated hardware
  - Possibility of multiple reflections from ground or near-by structures

NRAO

Near-field (Beacon) Holography

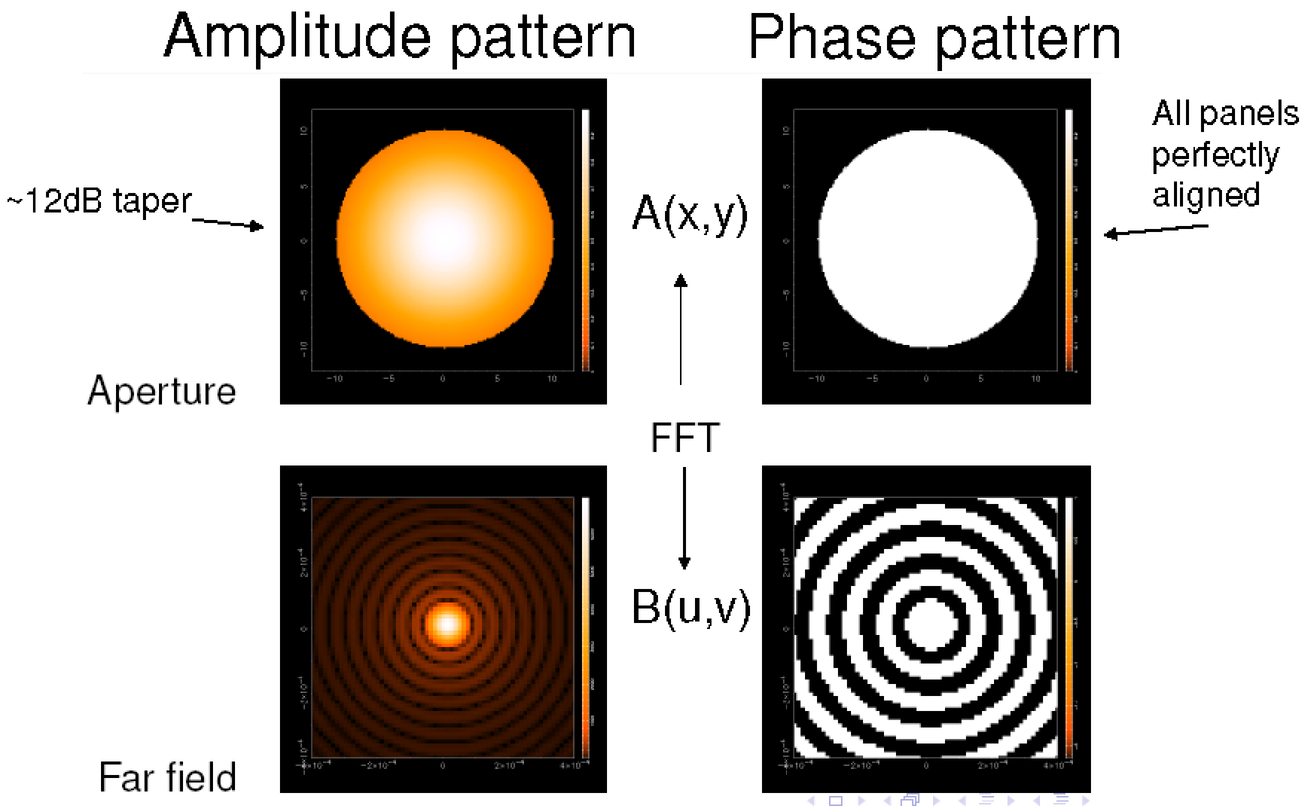


Phase Retrieval (Out of Focus) Holography

- Measure power only (instead of amplitude and phase) of far-field beam pattern on bright astronomical calibrator
- Without the amplitude/phase, cannot do the inverse Fourier transform to get aperture plane values.
- Instead *assume* aperture amplitude and phase; do forward transform to predict beam pattern.
- Iteratively adjust aperture phase, varying phase until predicted beam map is in good agreement with observed map.

- ***Extremely powerful technique! Everyone should try it!***

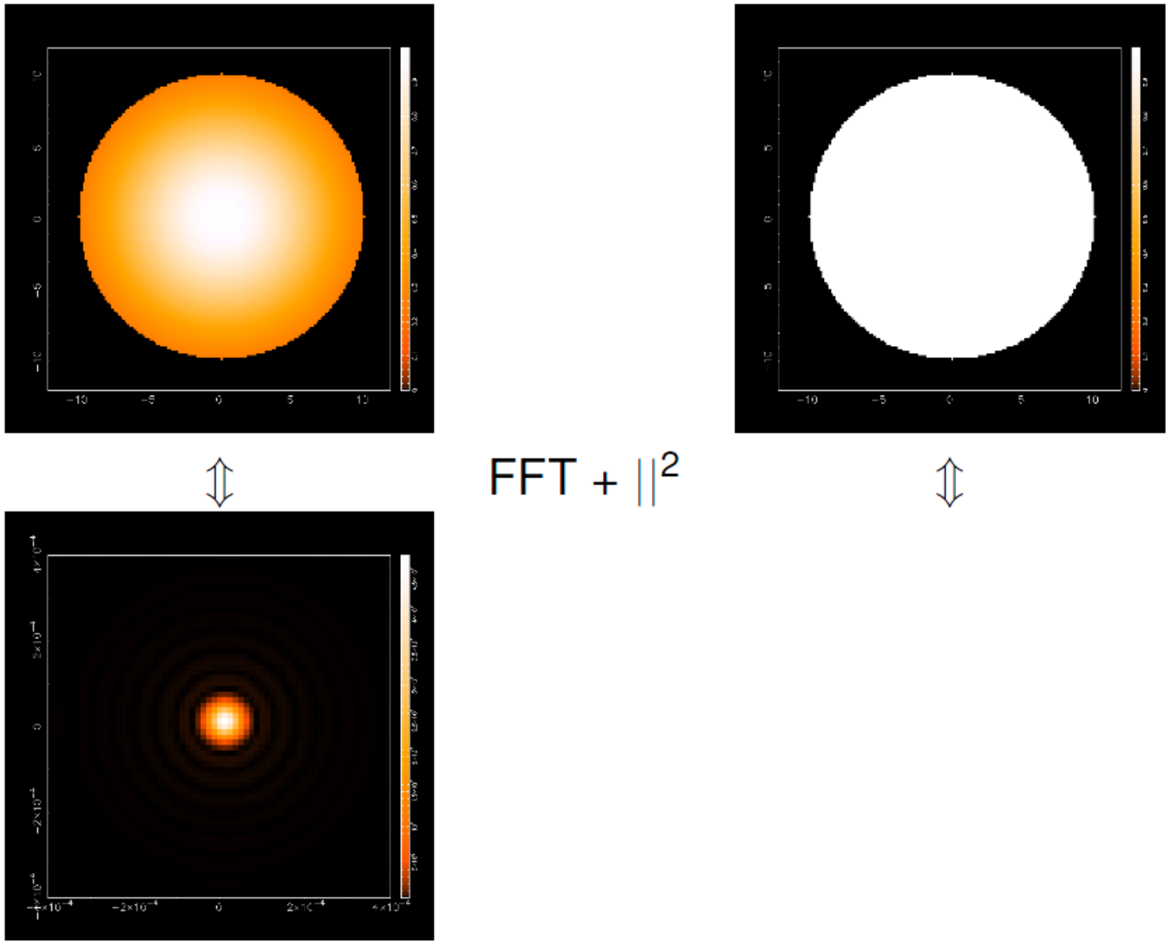
An Ideal Radio Telescope



$$B(u,v) = \Sigma A(x,y) \exp[2\pi j(xu+yv)]$$

where B = beam, A = aperture
u,v are angles; x,y are distances

Phase Retrieval (Out of Focus) Holography



Phase Retrieval (Out of Focus) Holography

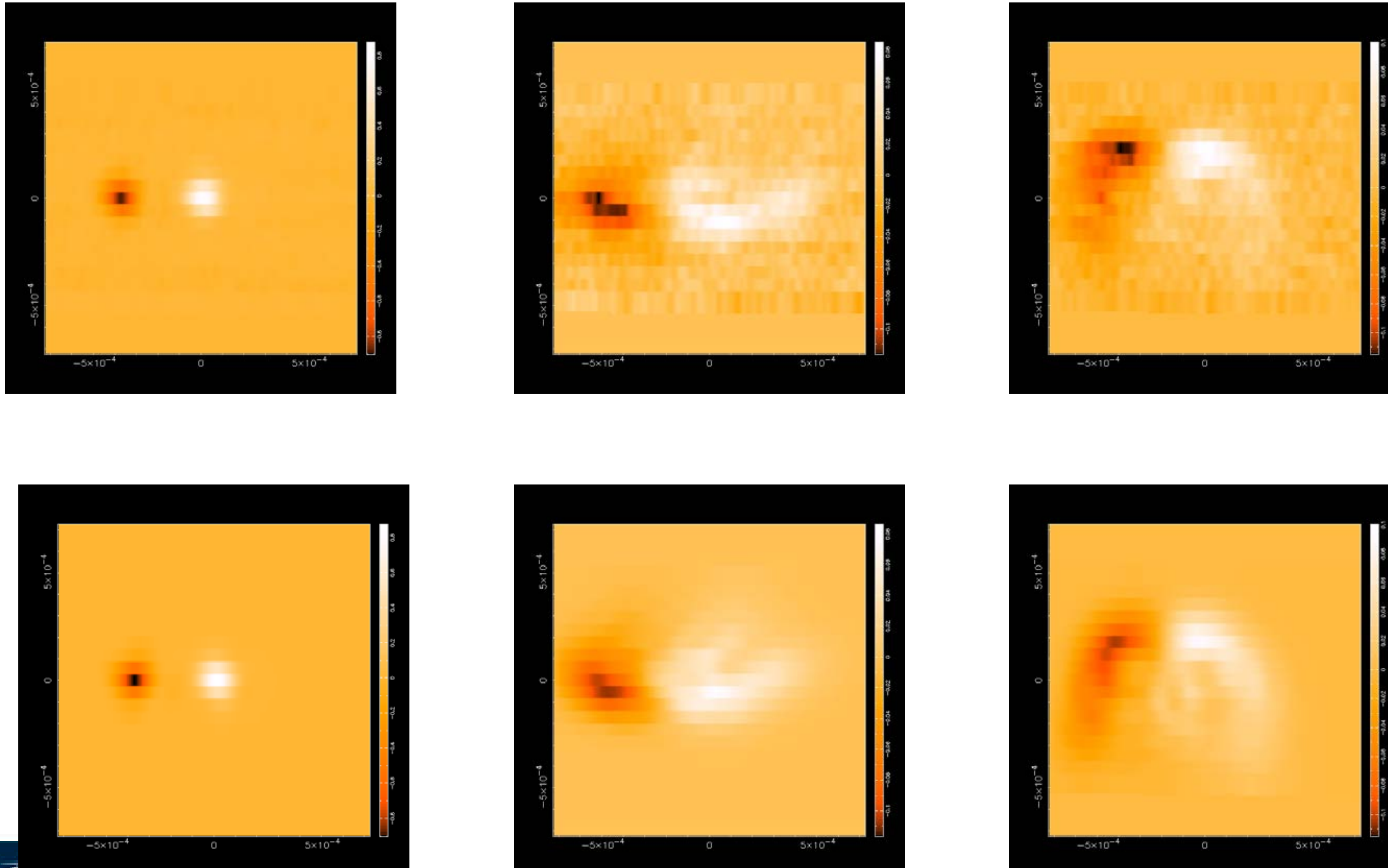
- Advantages:
  - Uses same receiver as used for astronomical measurements
  - That receiver usually works; no need for a reference
  - Measure the complete optical aberrations in the telescope
  - Rapid maps (< five minutes)
    - As a function of elevation
    - As a function of time
- Disadvantages:
  - Low spatial resolution (cannot resolve individual actuators)

Technique

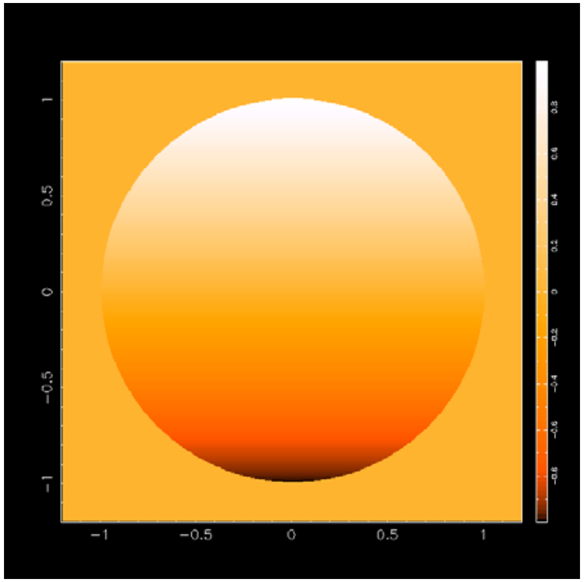
- Make three Nyquist-sampled beam maps, one in focus, one each ~ five wavelengths radial defocus
- Model surface errors (phase errors) as combinations of low-order Zernike polynomials. Perform forward transform to predict observed beam maps (correctly accounting for phase effects of defocus)
- Sample model map at locations of actual maps (no need for regridding)
- Adjust coefficients to minimize difference between model and actual beam maps.

NRAO

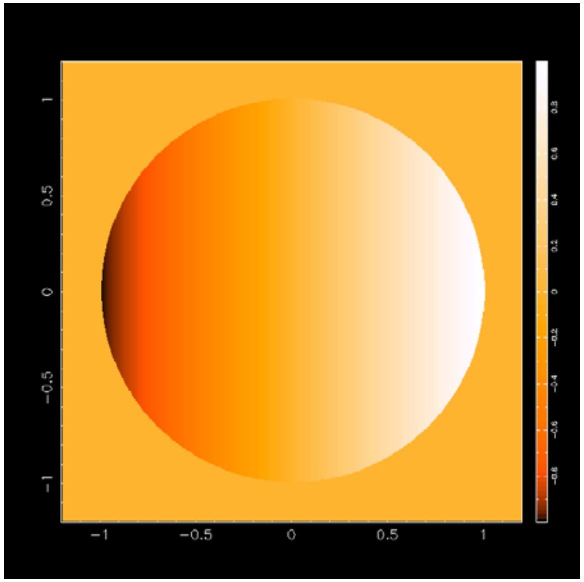
Typical "before" data (rms = 370 µm)



Zernike Polynomials n = 1

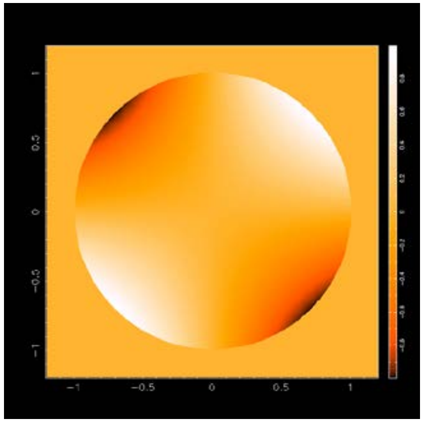


Vertical pointing

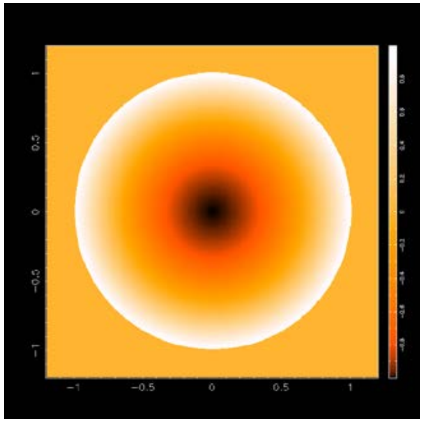


Horizontal pointing

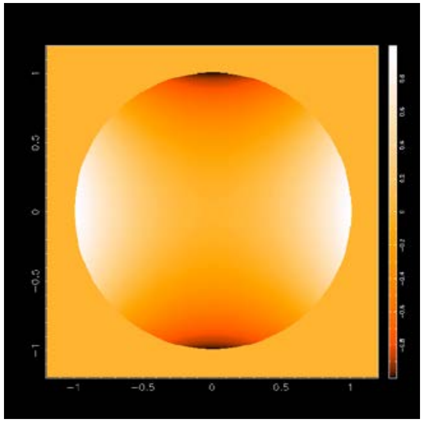
Zernike Polynomials n = 2



X Astigmatism

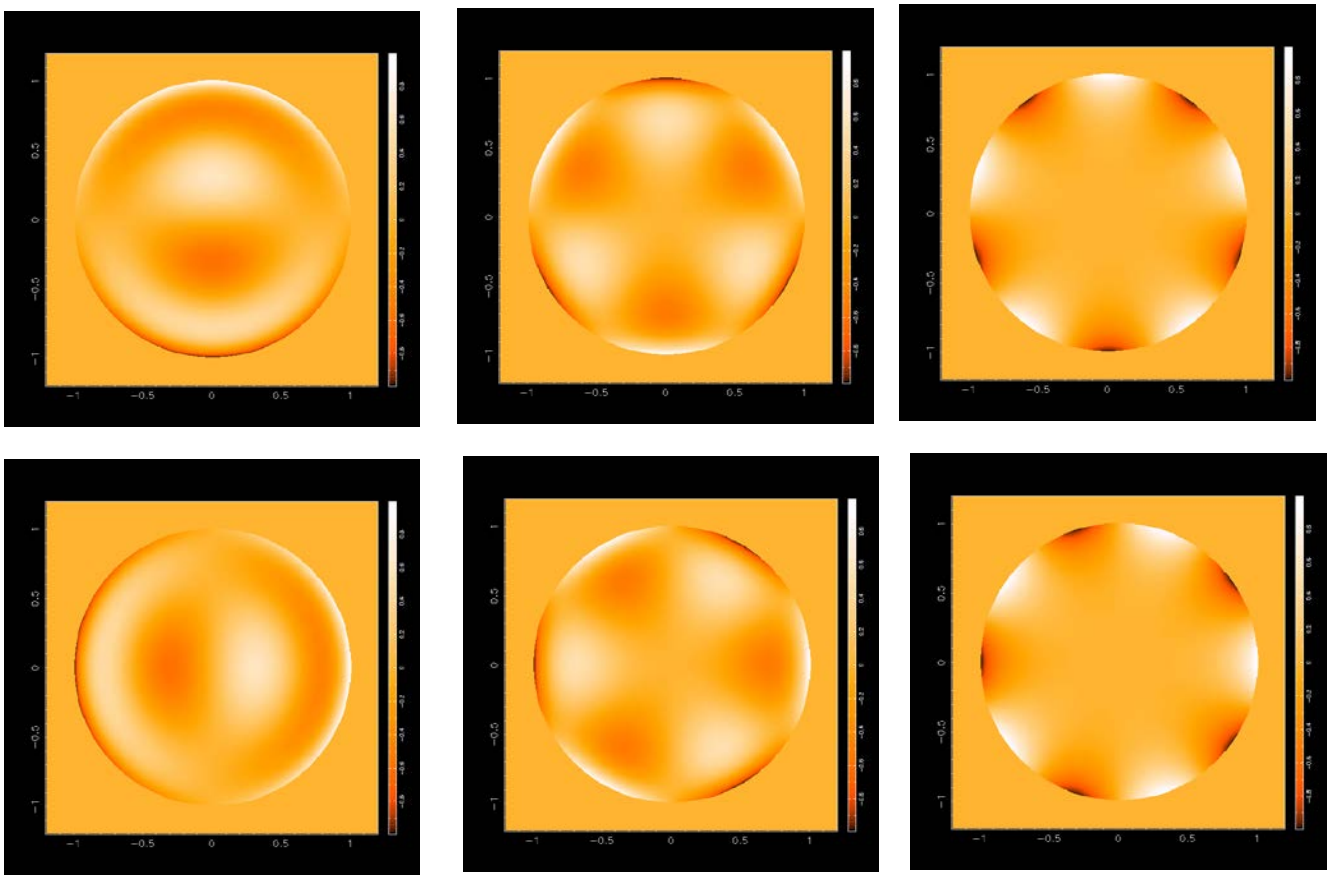


Focus

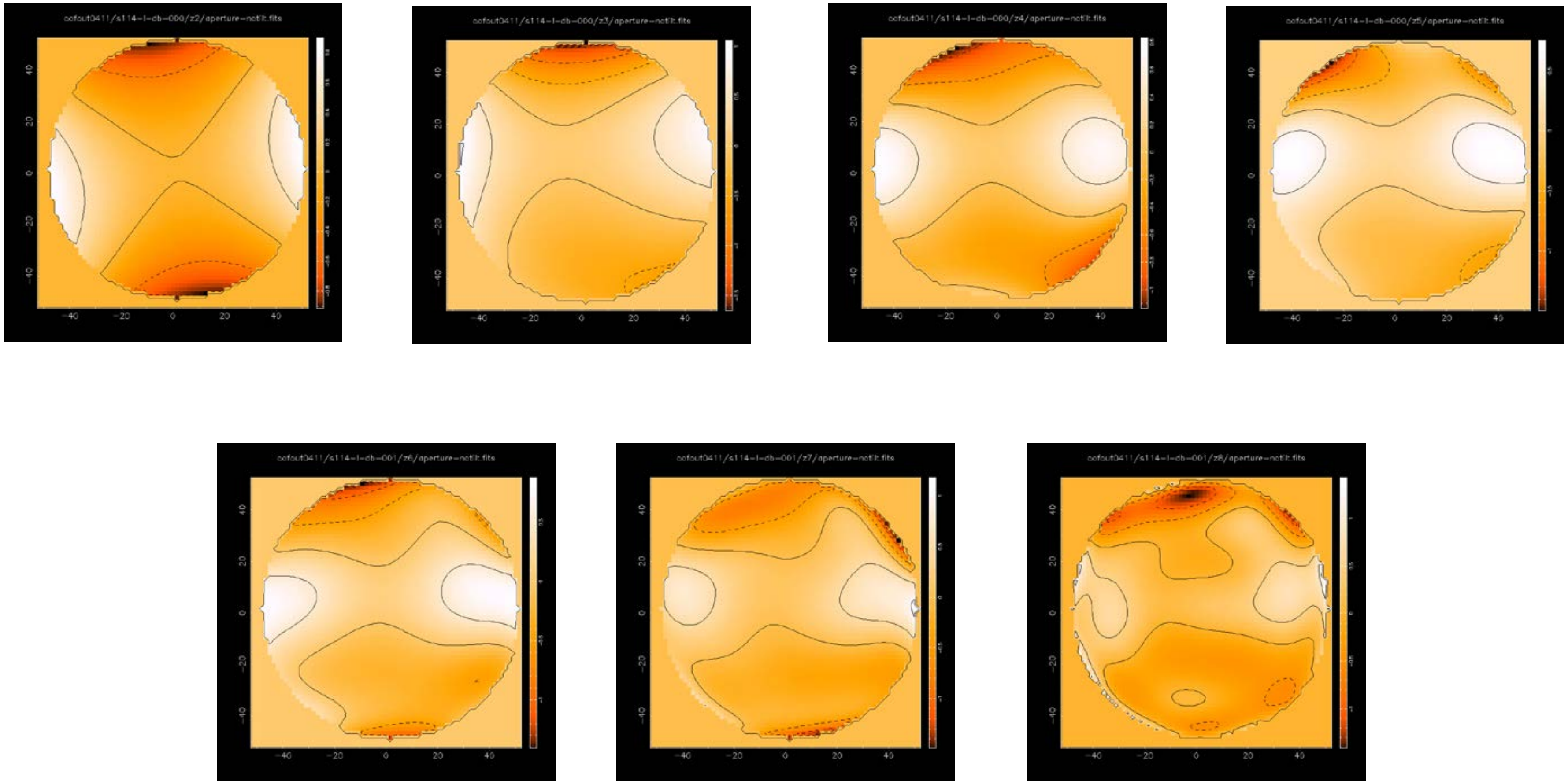


+ Astigmatism

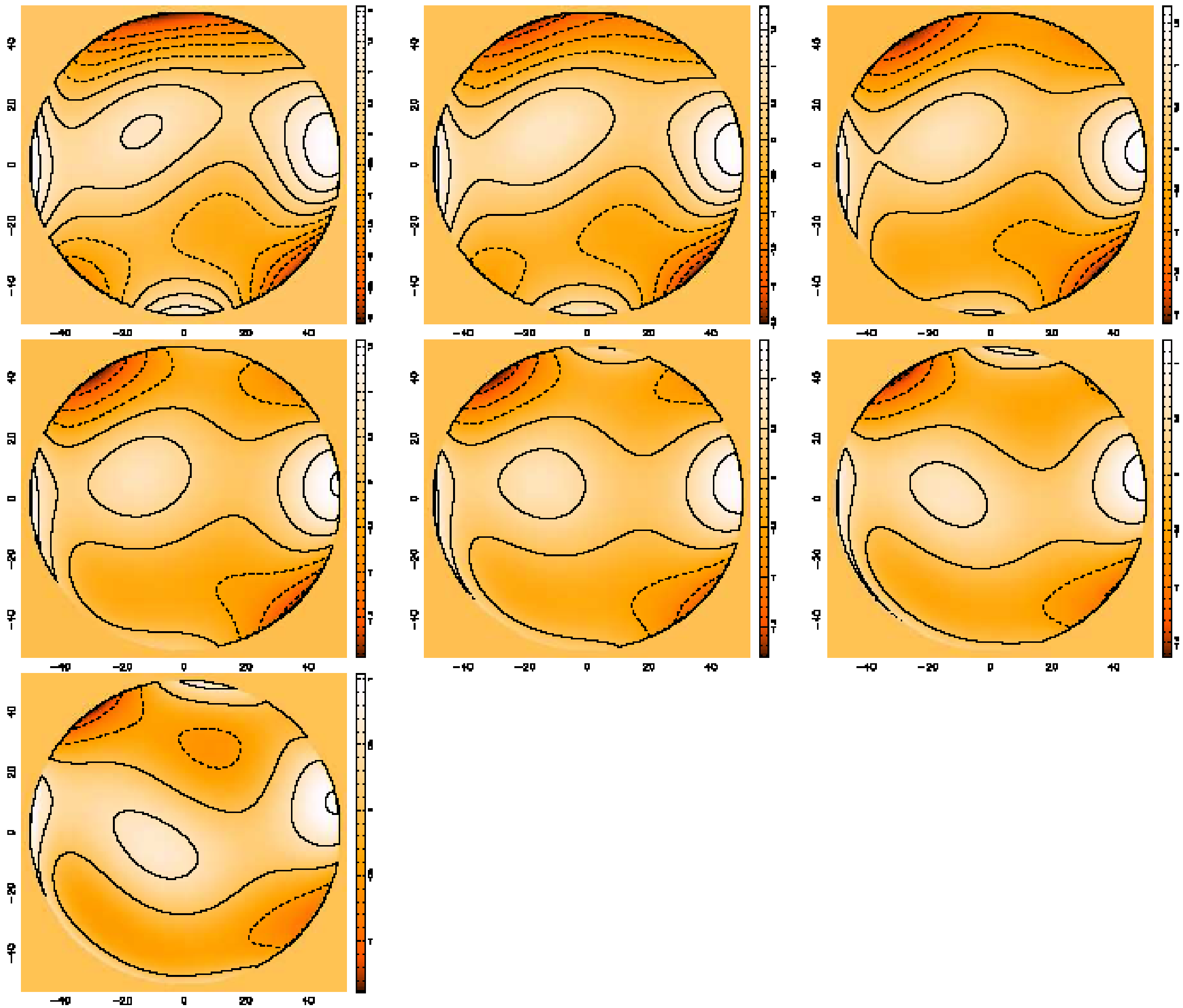
Zernike Polynomials n = 5



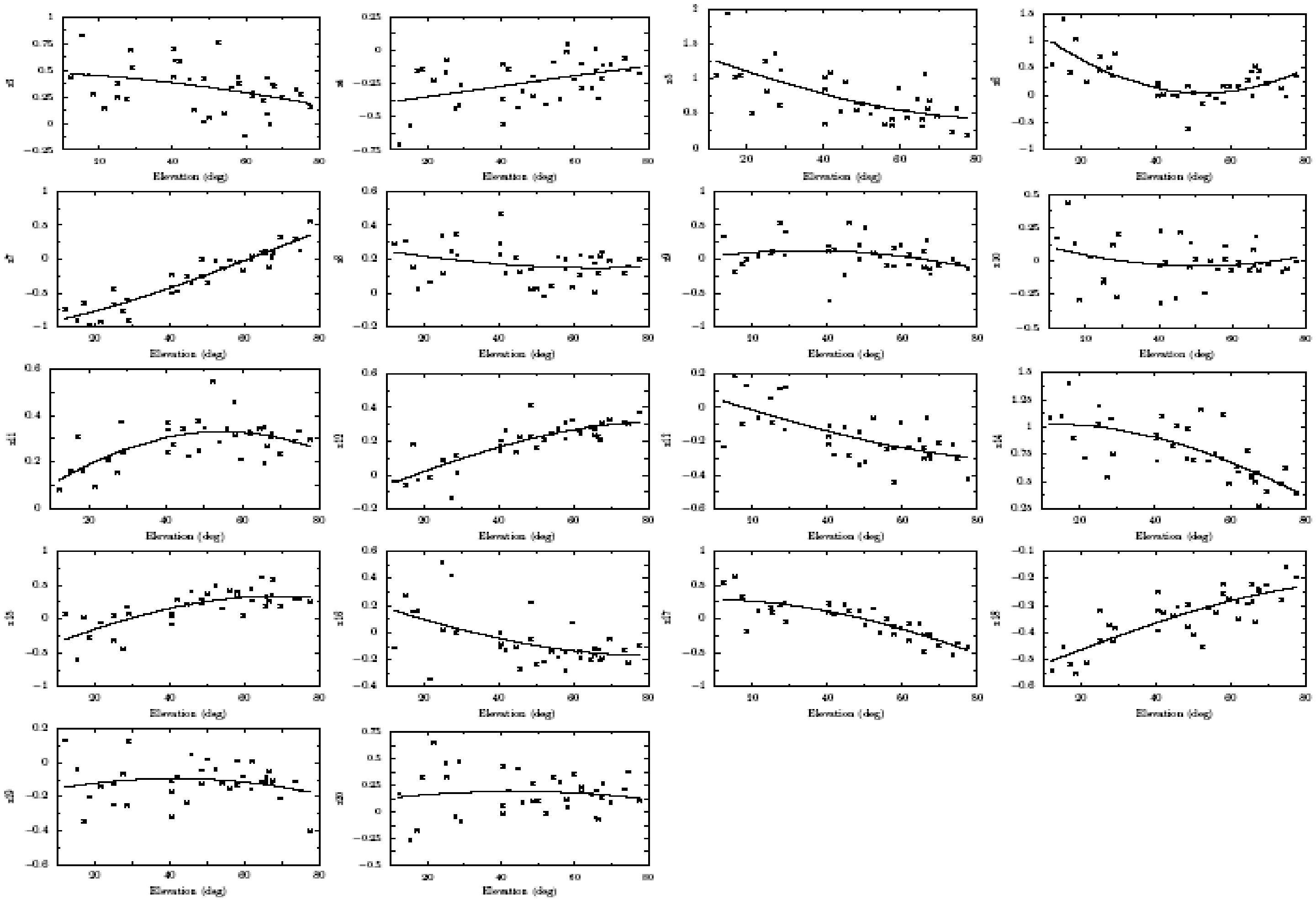
Approximate by adding higher Zernikes



Gravity Model



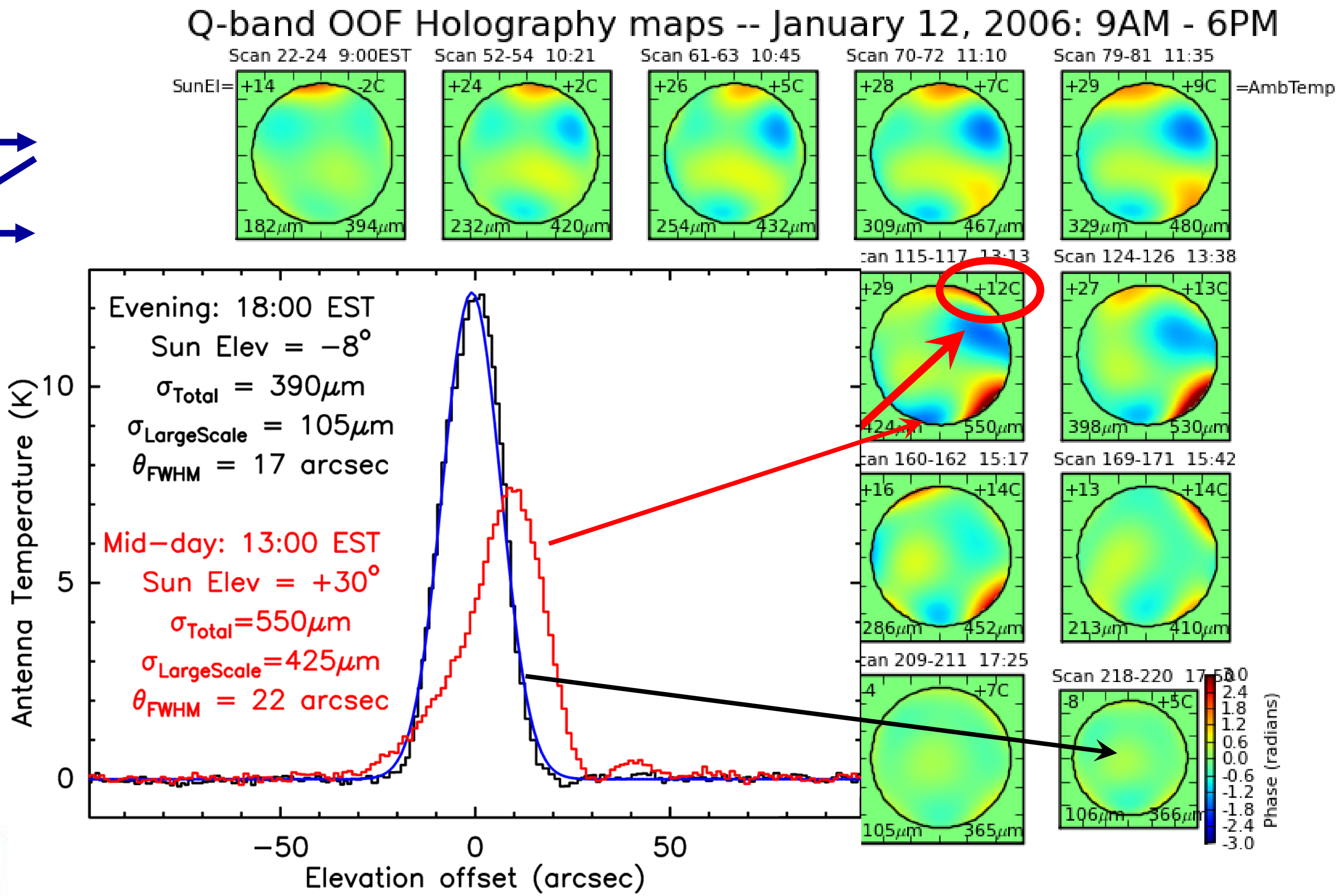
Gravity Model



NRAO

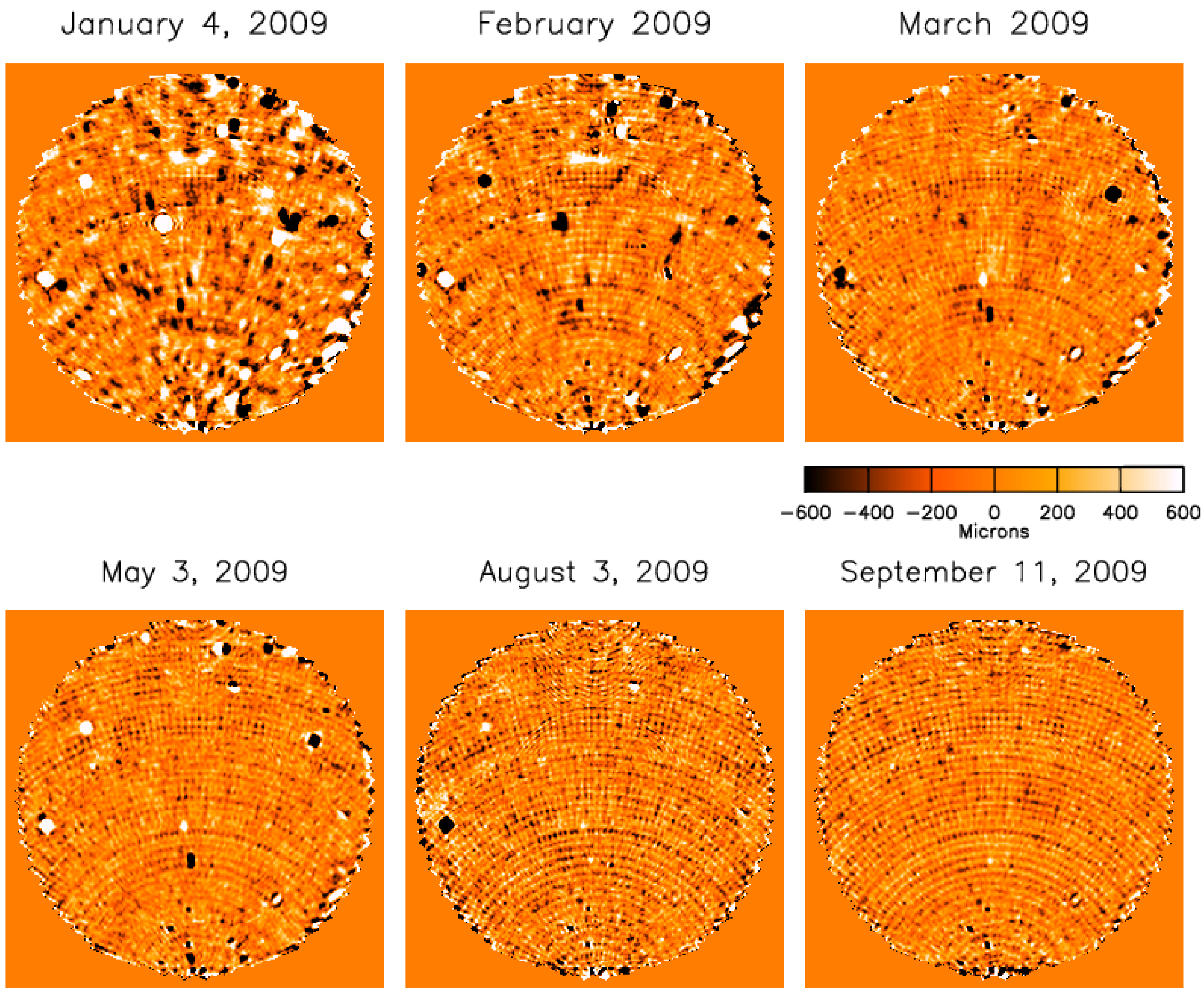
Thermal Distortions due to Solar Heating

Time

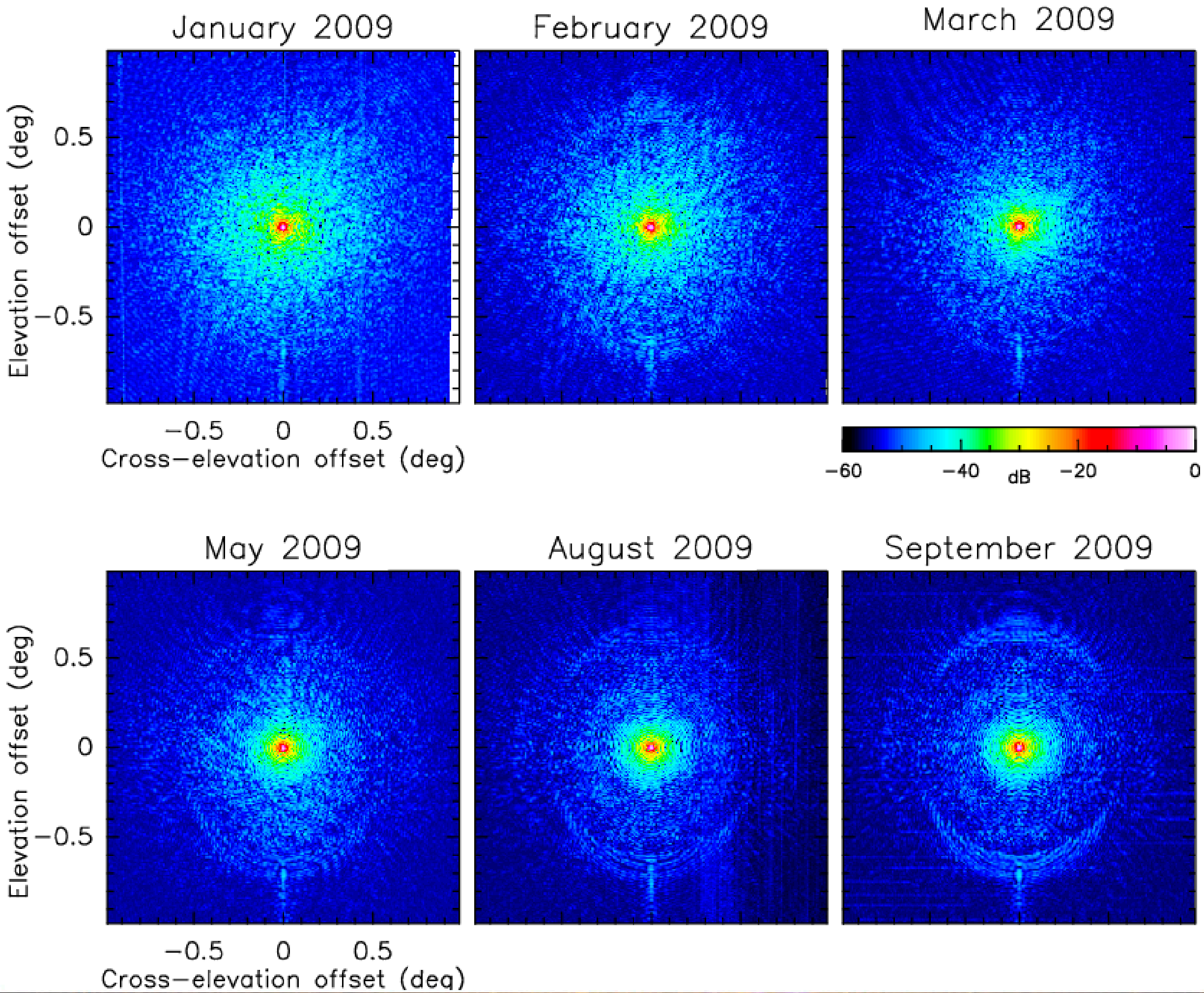


Additional insights from with-phase holography

2009 surface adjustments

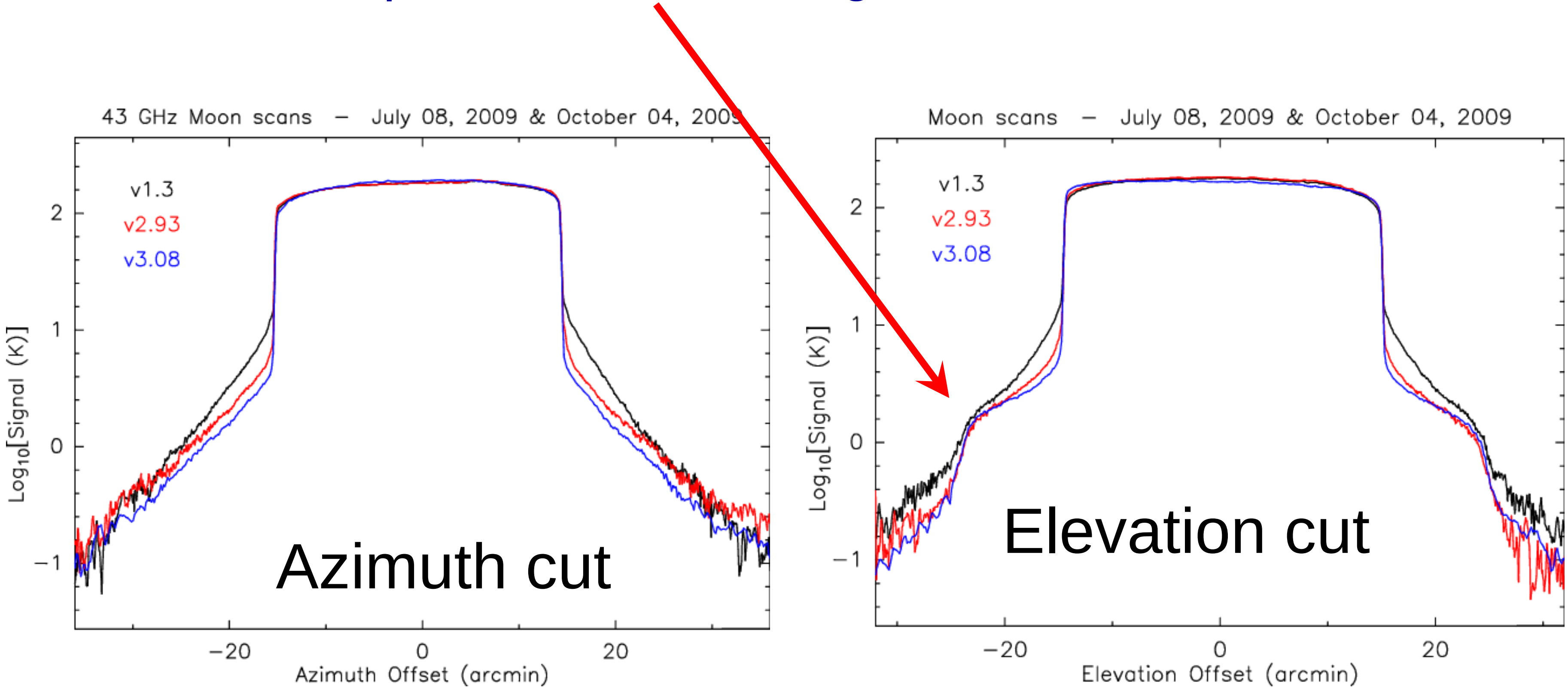


Beam Patterns corresponding to Holography Measurements

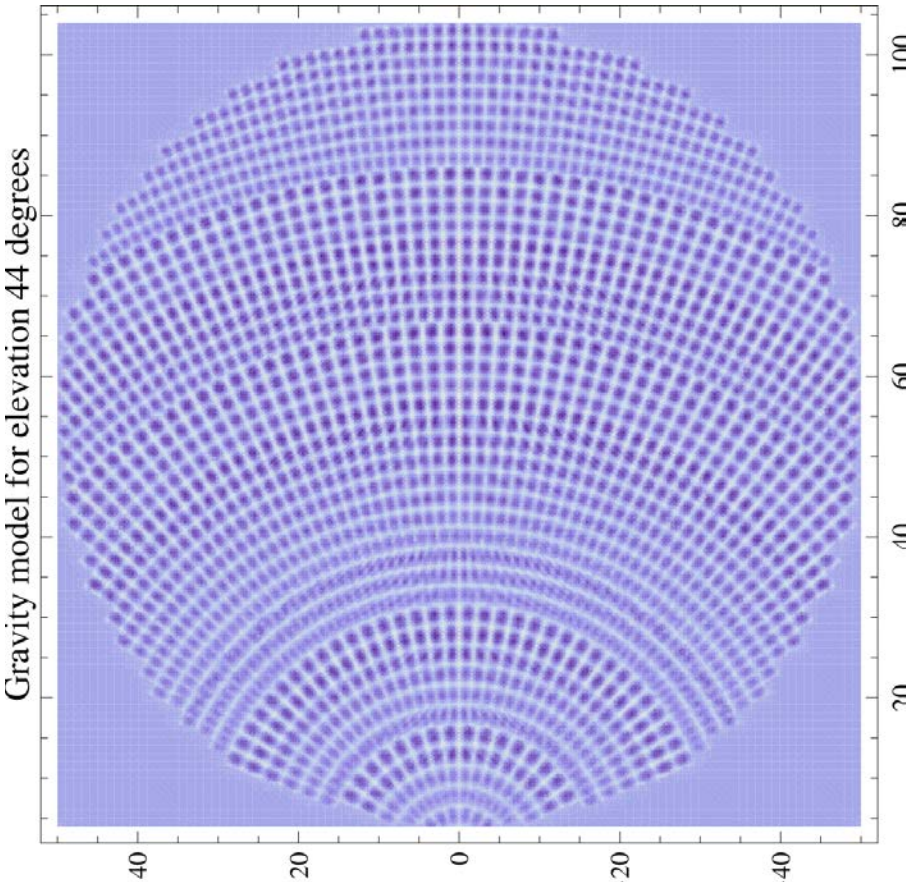


Moon Scans at Q-band (43 GHz)

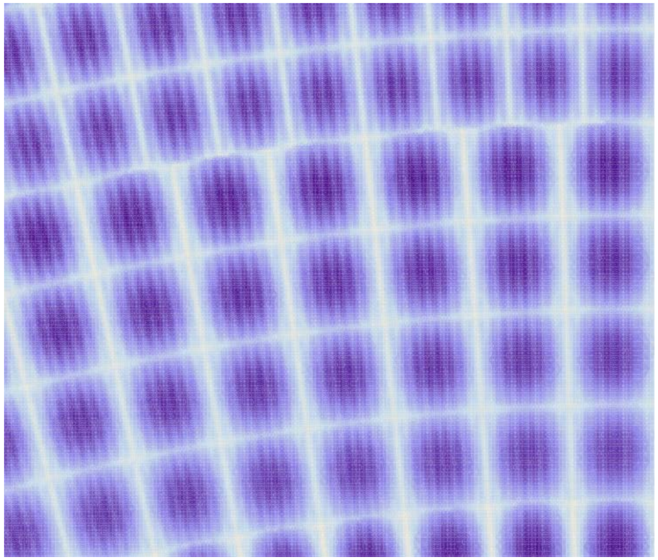
- Reduced sidelobes
- Extra step-like feature emerges in elevation cuts



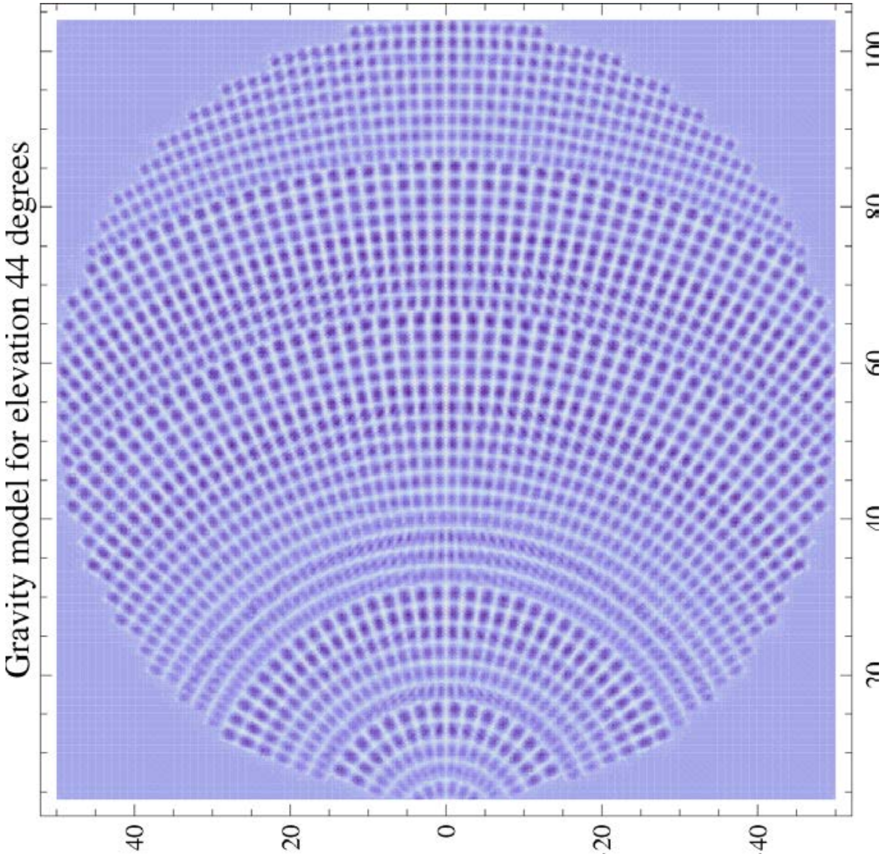
FEM Model of panel gravitational deflection



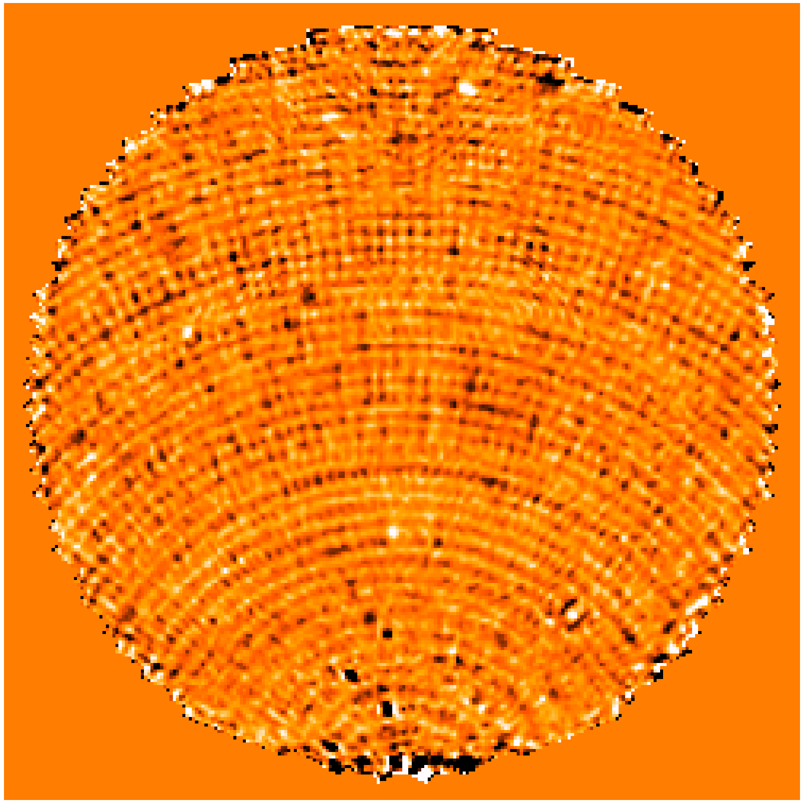
Zoom (showing panel rib structure)



Model of panel gravitational deflection



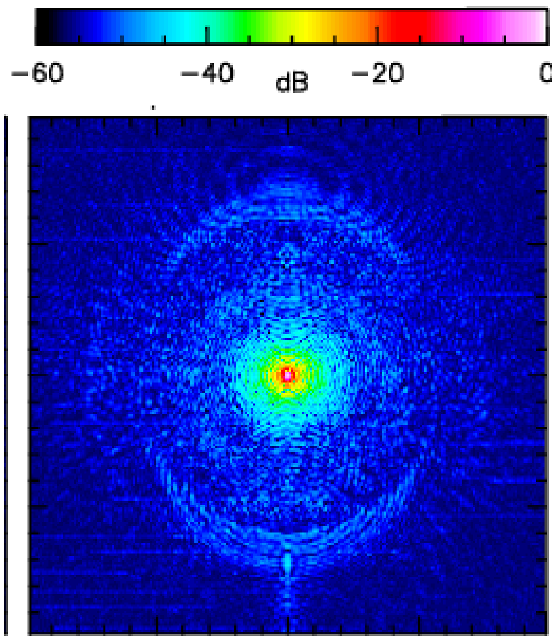
Observed surface error



We got the telescope we paid for…

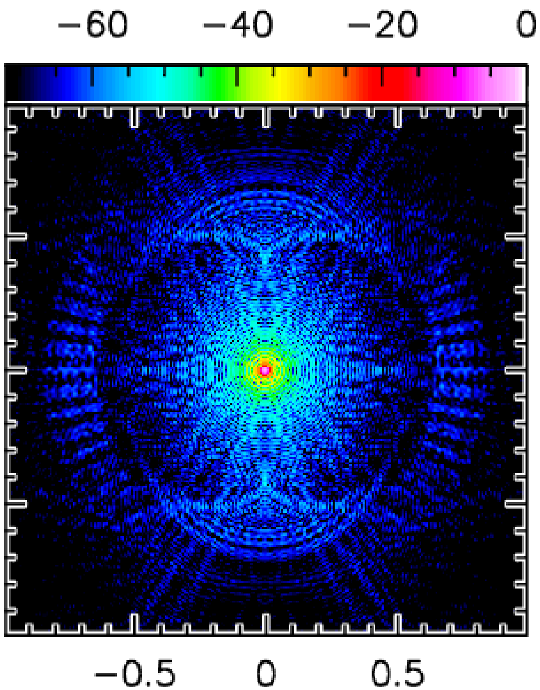
NRAO

Observed beam

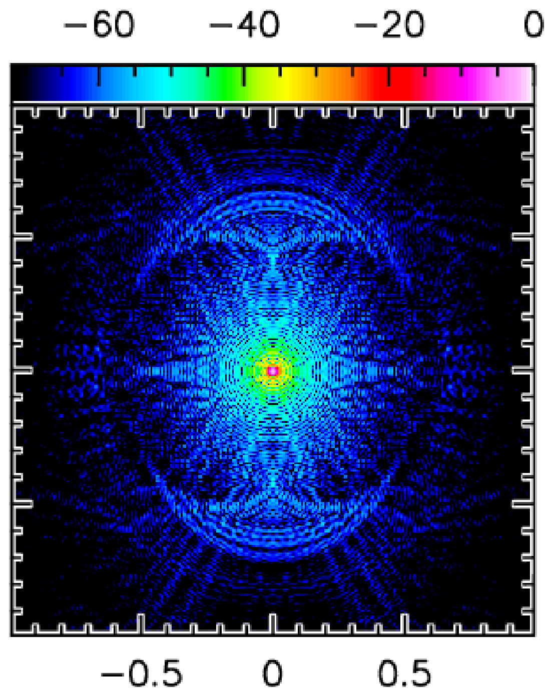


Predicted beam

Gravity error

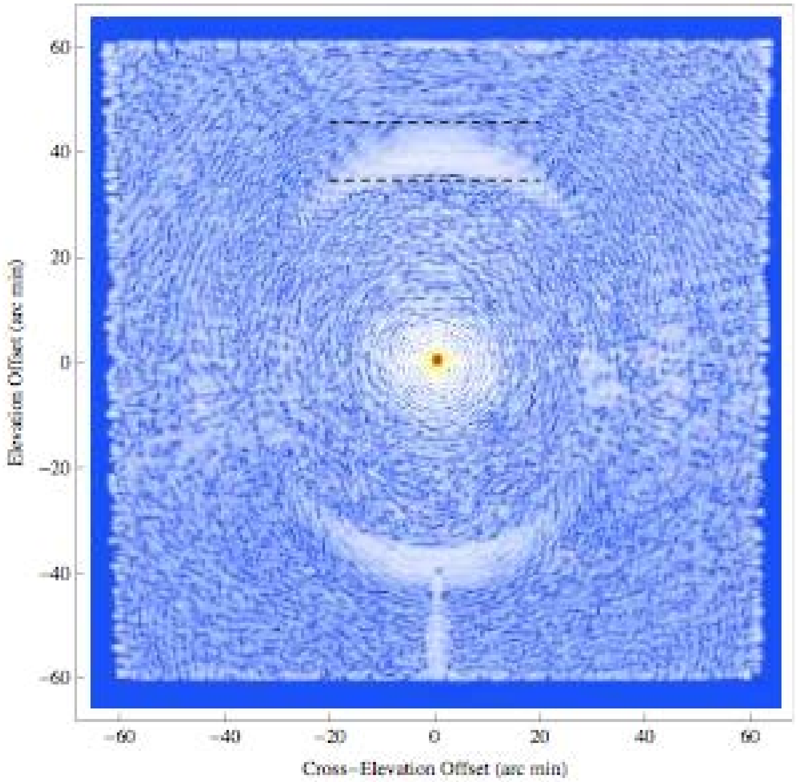


Thermal error (ΔT=2°)

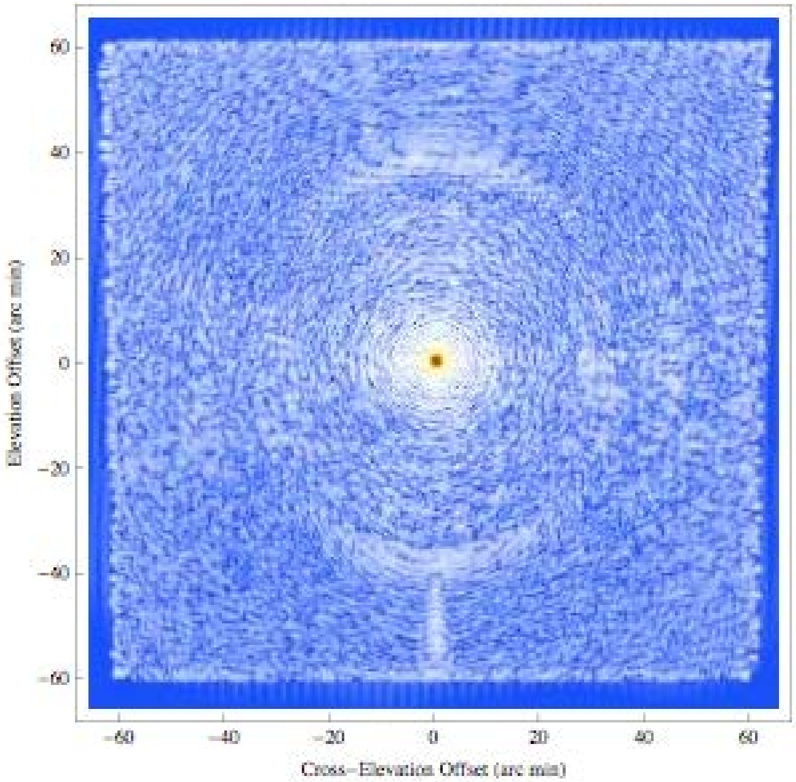


Two nighttime maps

Clear skies (ΔT = -2°)



Cloudy skies (ΔT~0°)

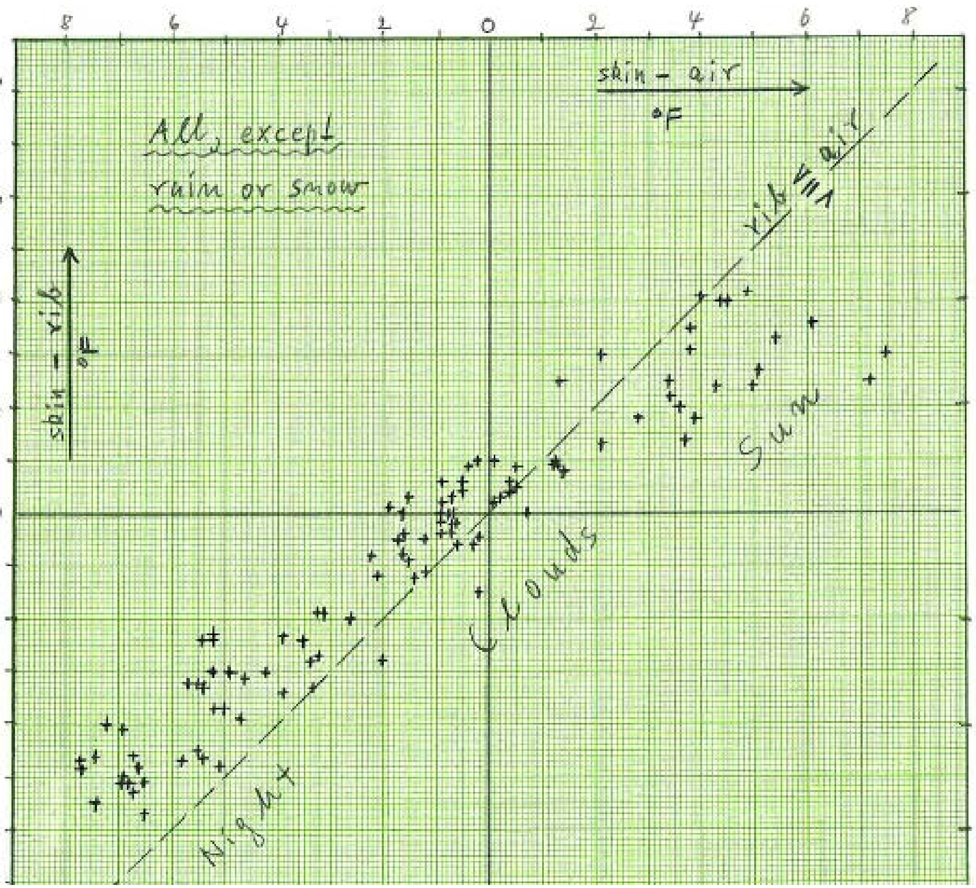


NRAO

S. von Hoerner (January 1971)

Measured panel temperature gradients

T (skin) – T (rib)



T (skin) – T (air)

Panel deflection (mils)

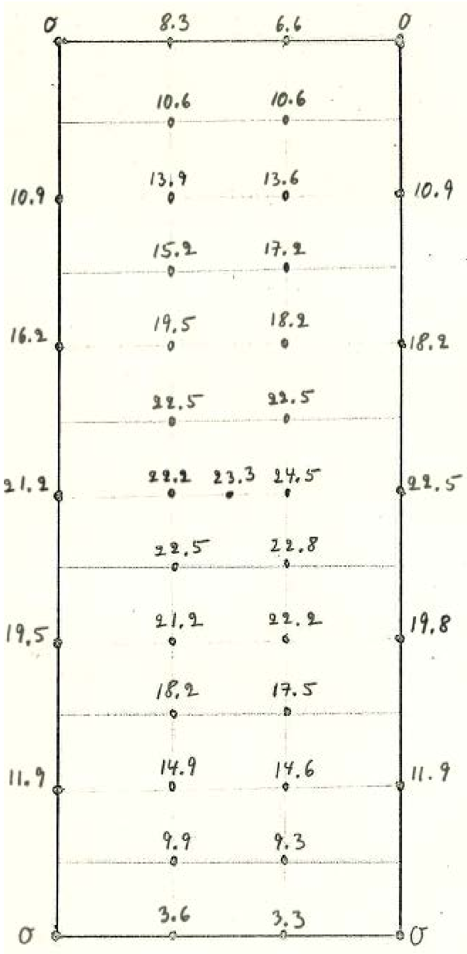


Fig. 6. Thermal deformation Δz of 37 points of the plate, in 10^{-3} inch, resulting from ΔT = 9.05 °F difference between skin and rib.

GBT panel temperature gradients