Combination of with-phase and phase-retrieval holography at the GBT

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(major contributions by Todd Hunter, Fred Schwab, Steve White, Bojan Nikolic)

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

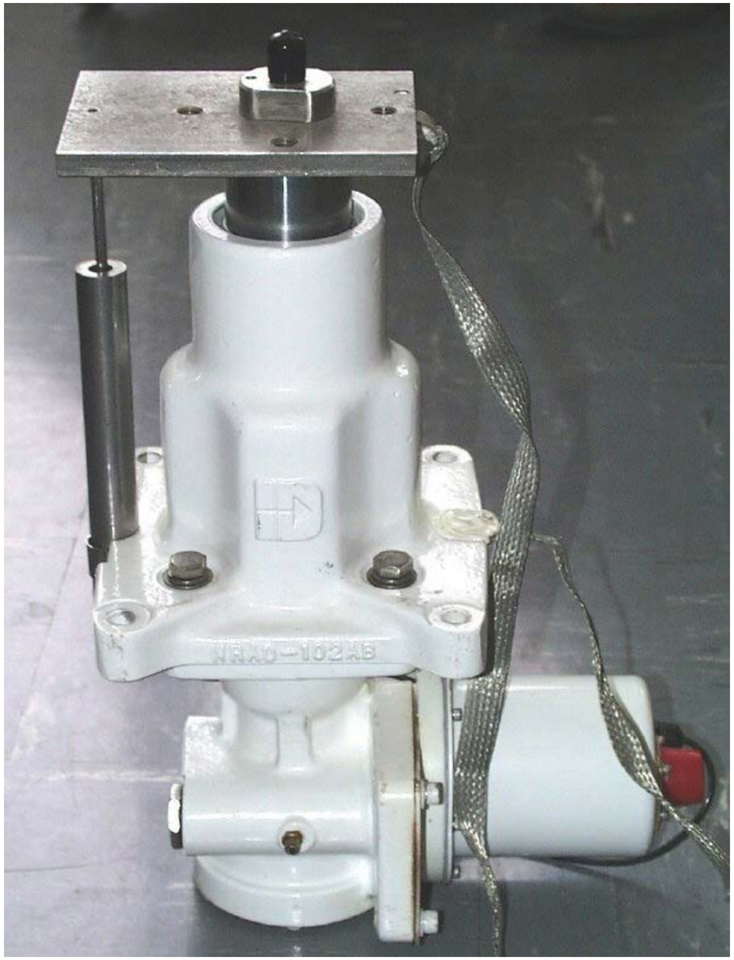
NRAO

GBT Active Surface

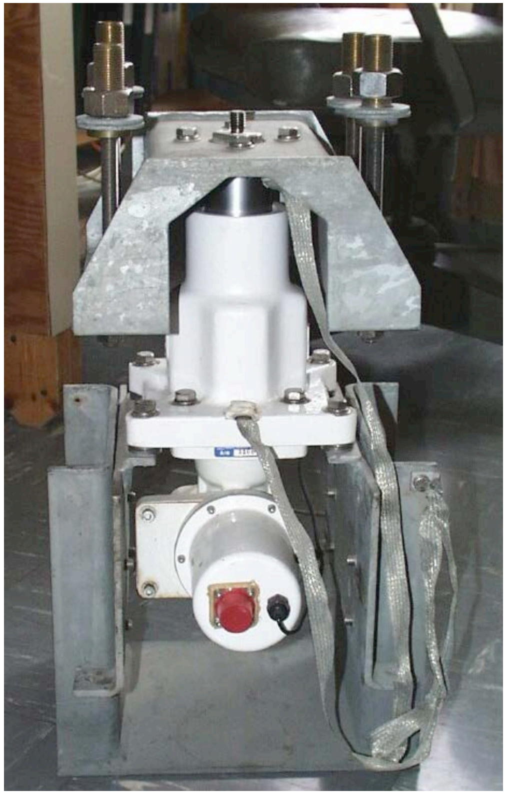
- 2004 panels, 1.57mm 6061 T6 aluminum skins epoxied to rib frame,
- CMM-measured rms < 75 μm (mean=60)
- 2209 actuators (located at panel corner intersections)

Actuator specifications

- Stroke = 51 mm (≈ 4x the requirement)
- Speed = 250 microns /second
- Static load (axial and side) = 481 kg
- Lifetime = 20 years (at 60 meter /year)
- Motor type = DC brush
- Position sensor = LVDT
- Resolution ~ 25 microns
- Repeatability < 50 microns
- Temperature effect ~16 microns rms
- Control system
  - 139 pairs of modules
  - Each with up to 16 actuators



Actuator attached to panel mechanism

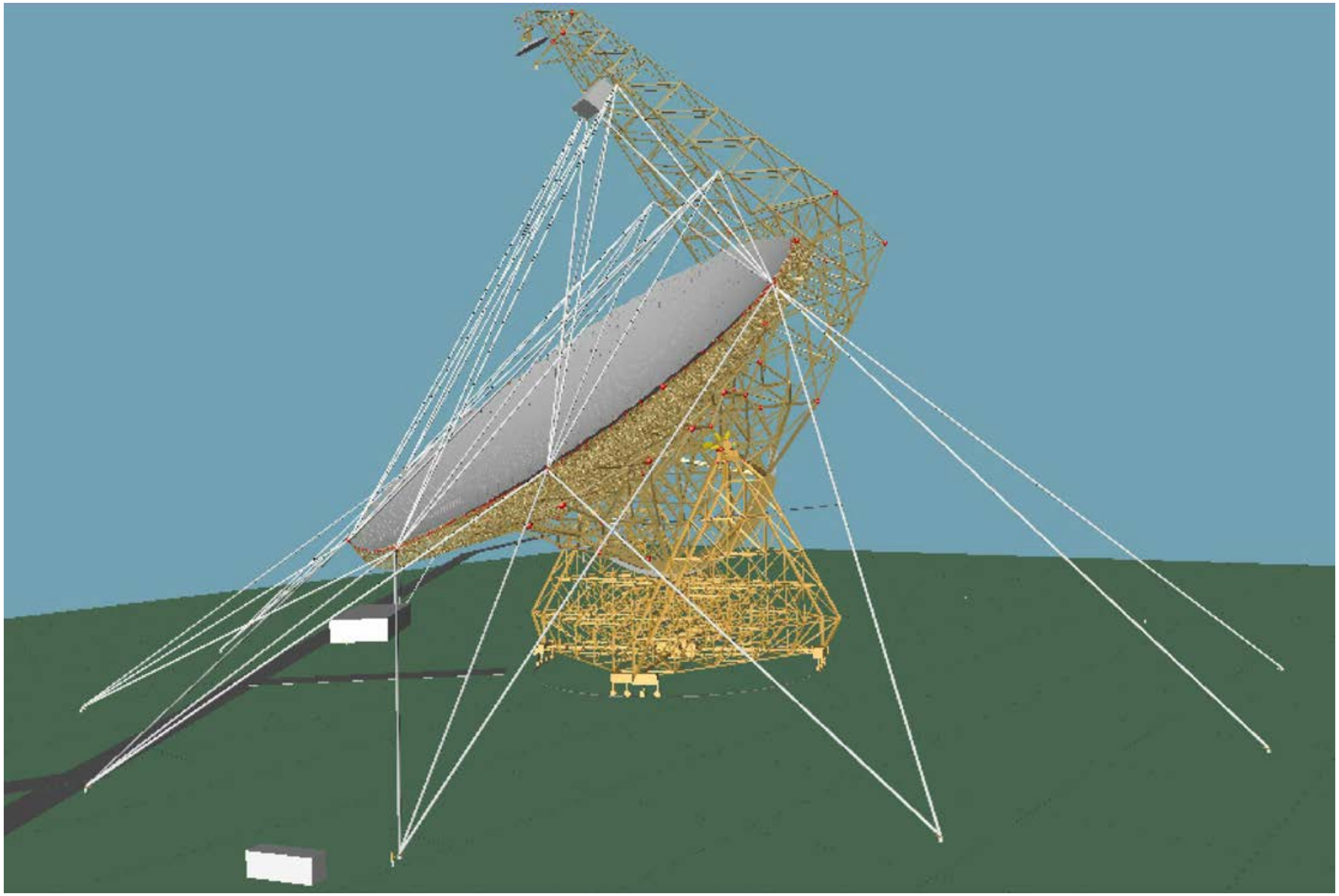


Initial Metrology Plan

- Trilateration to multiple targets using Laser Rangefinders
- Measure absolute position of optics (in a fixed reference frame)
- Required accuracy of LRFs: ~ 100μm

Laser Rangefinders (20 built)

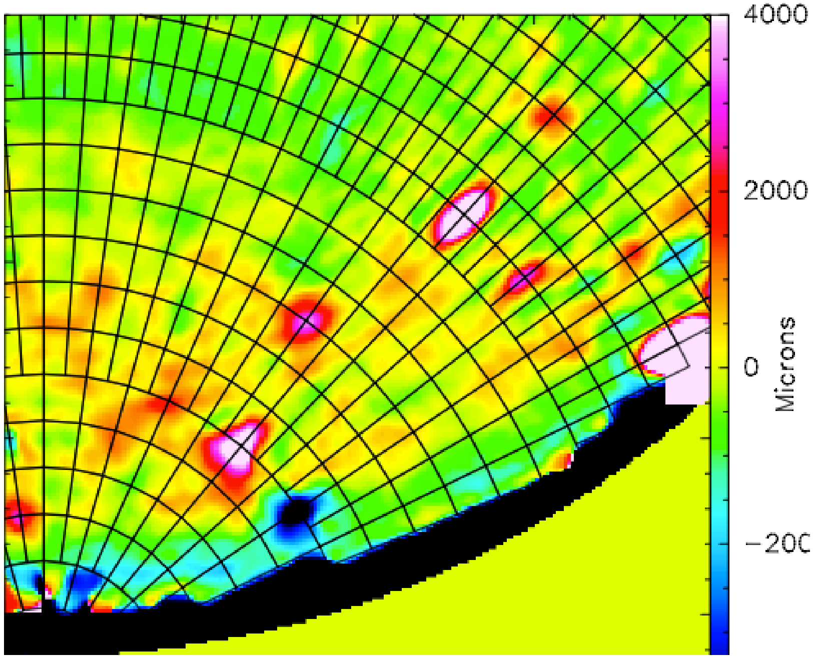
LRF Configurations

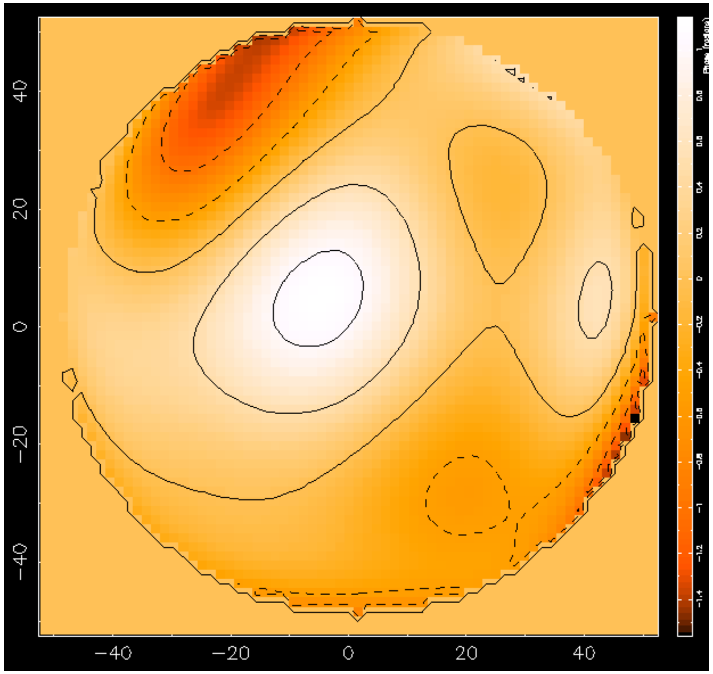


Concerns with LRF Performance

- How to measure Group Index of Refraction
- Geometry of system: "long skinny triangles"; relaying coordinate systems
- System Integration Concerns
- Difficulty of integrating LRF usage into GBT control software, and astronomical (incremental, differential) improvements to pointing and surface adjustments

Alternative – Traditional + OOF Holography



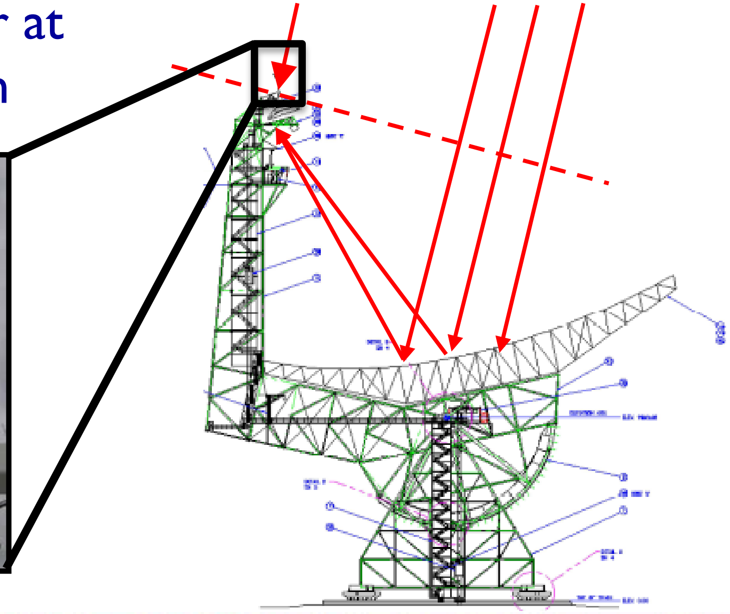


High-resolution interferometric holography

- Technique is > 30 years old (Bennett et al. 1976)
  - Measure complex beam pattern (phase and amplitude)
  - Fourier transform to get phase and amplitude of E field on aperture
  - Convert phase to surface error, and apply mechanical corrections
- 2 Receivers: room-temp. LNBs, 10kHz filters, Hilbert transform correlator

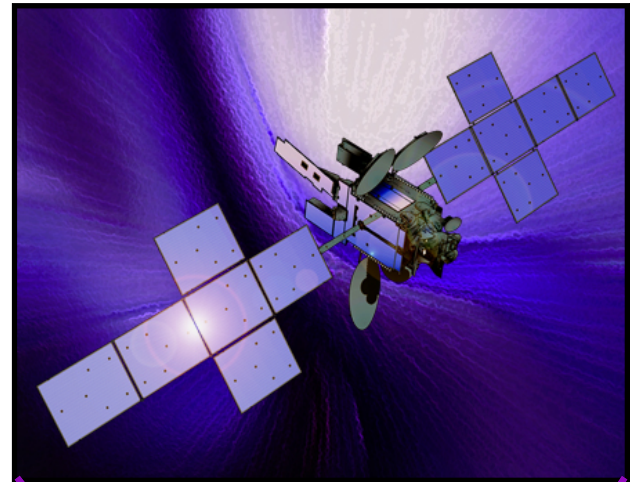
Main receiver in Gregorian turret

Reference receiver at top of feed arm

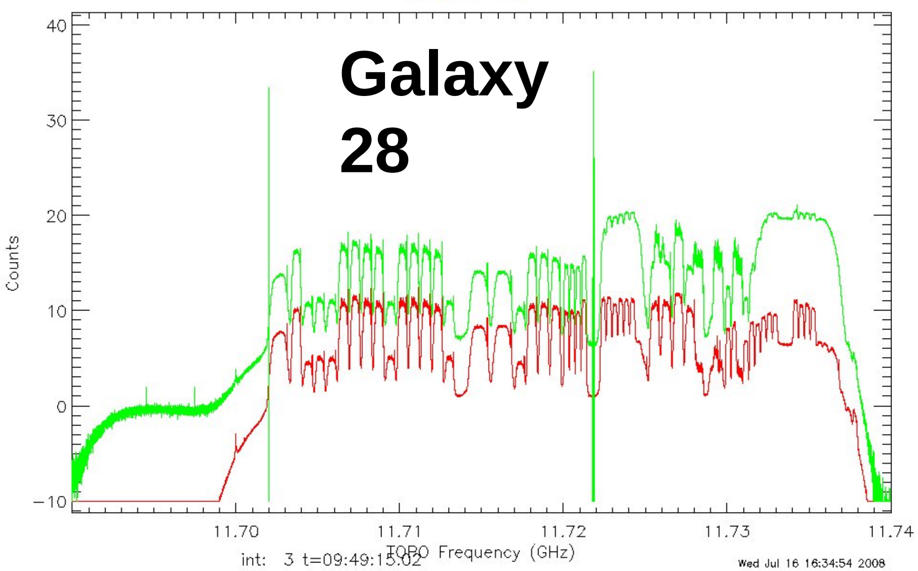


Satellite target

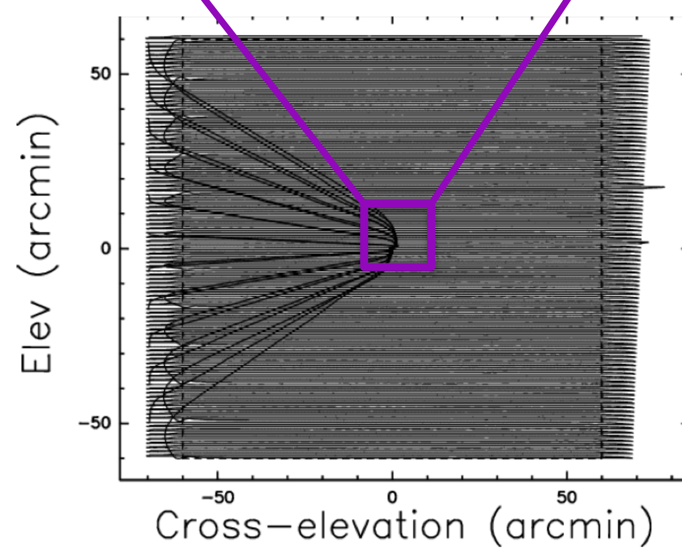
- Galaxy 28 = geostationary TV broadcaster
- Elevation = 44° , well-behaved orbit
- 11.702 GHz CW beacon (stable to < kHz)
- Effective flux density ~ 10^6 Jy in 10 kHz filter
- Typical system phase stability (receiver + atmosphere) = 2° in 36 msec integrations
- Corresponds to 70 microns surface rms



2° x2° map, 200 rows 3.5 hours

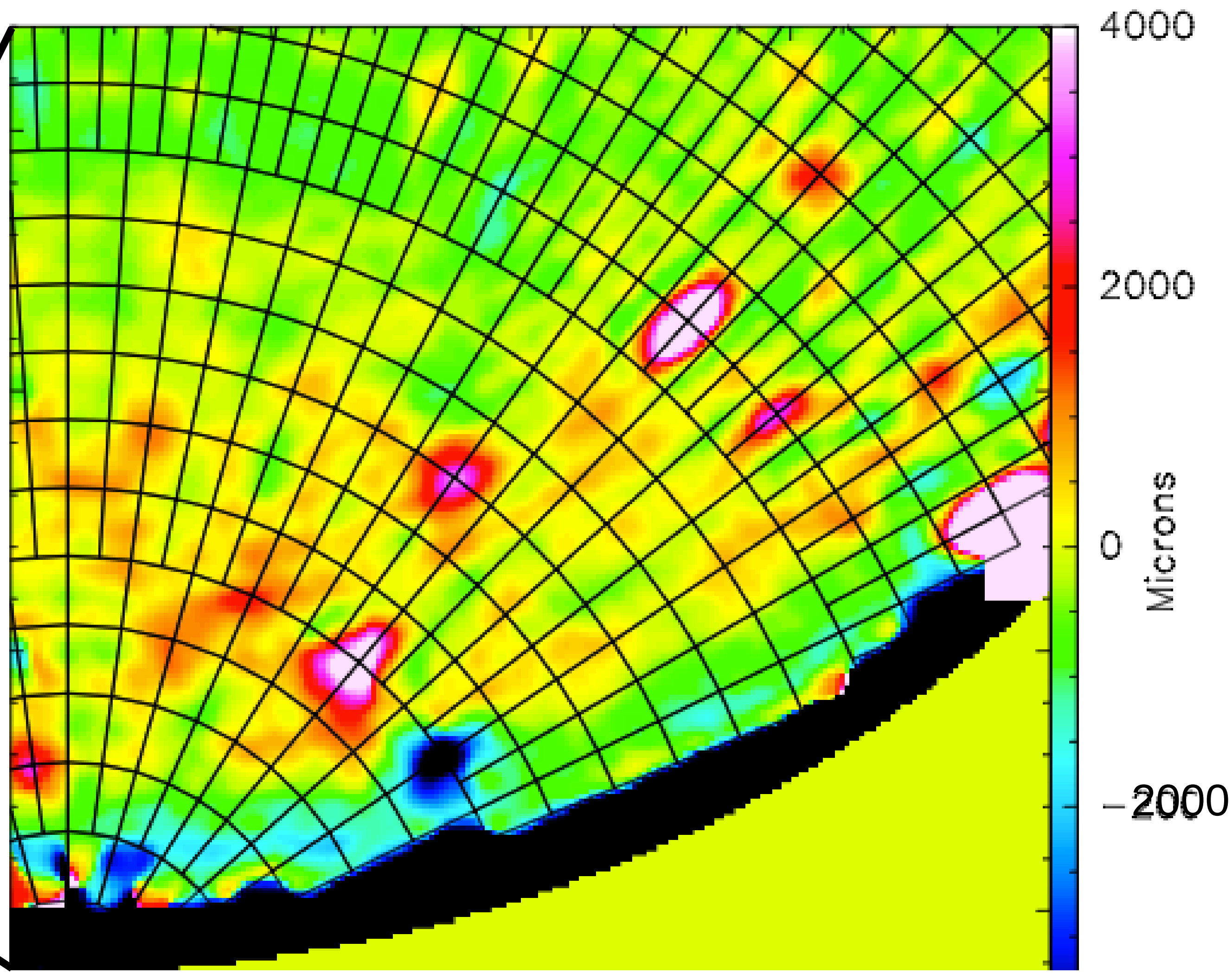


50 MHz

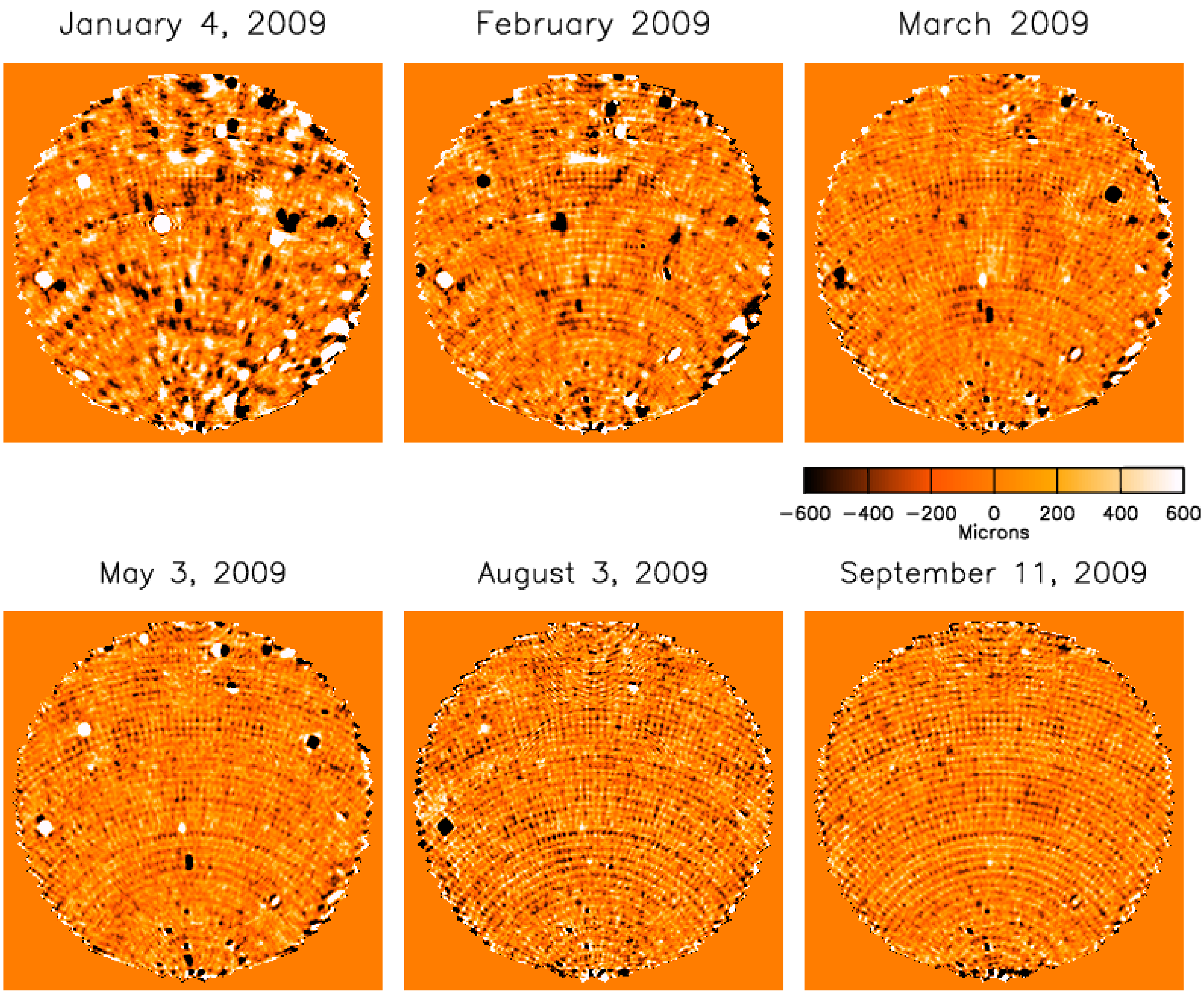


High-resolution interferometric holography

- Actuator "influence function" revealed



Progress in surface adjustments (2009)

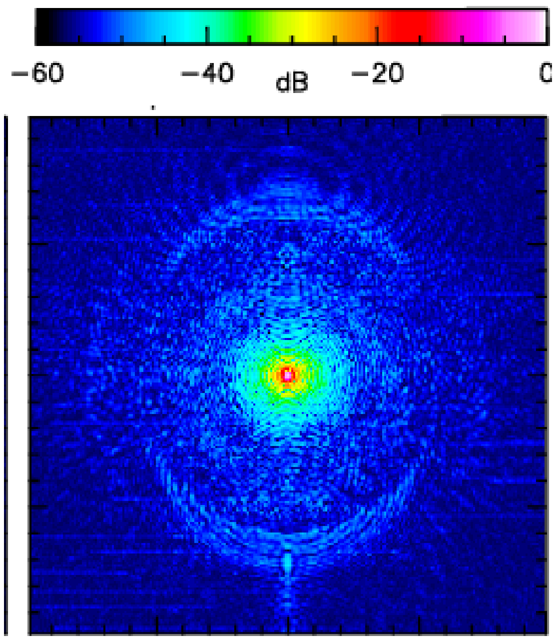


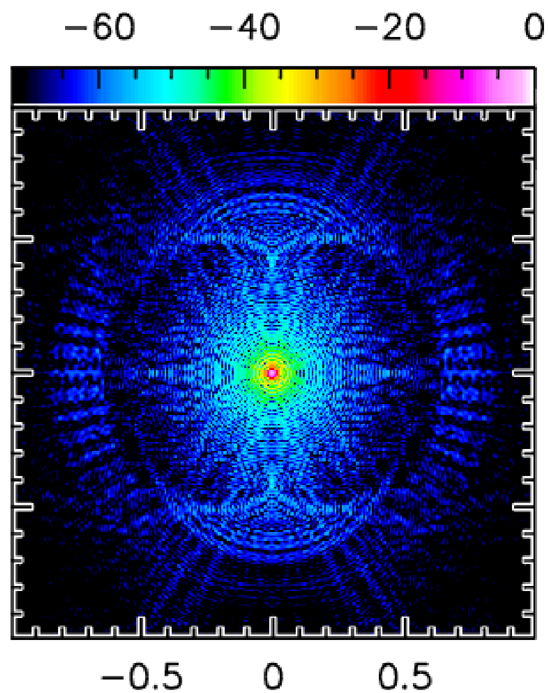
Identification of "twin arc" pattern

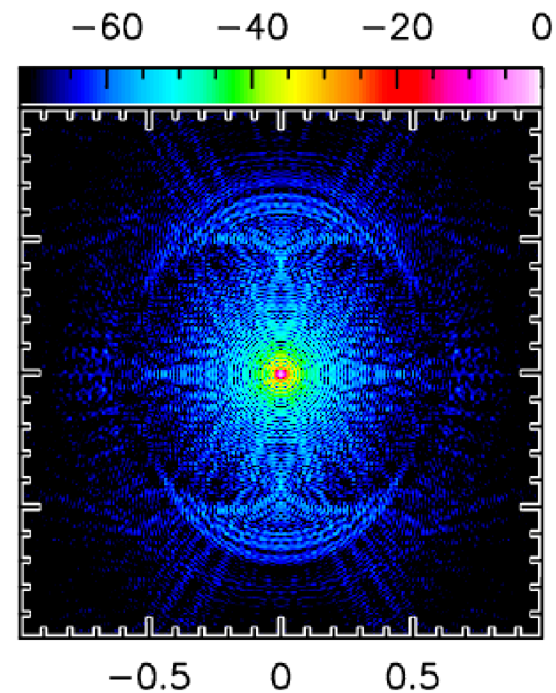
Observed beam

Predicted beam

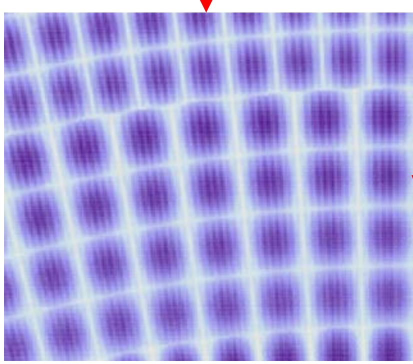
gravity error   -2° C thermal



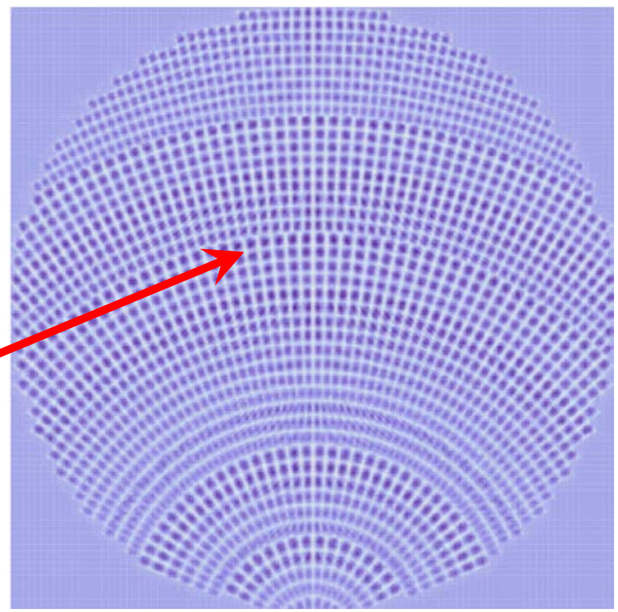




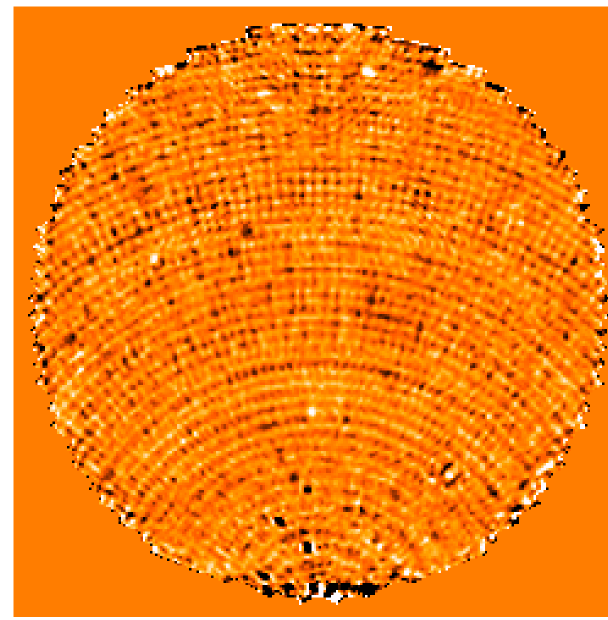
Shape of individual panels (gravitational and thermal sag) is the dominant pattern



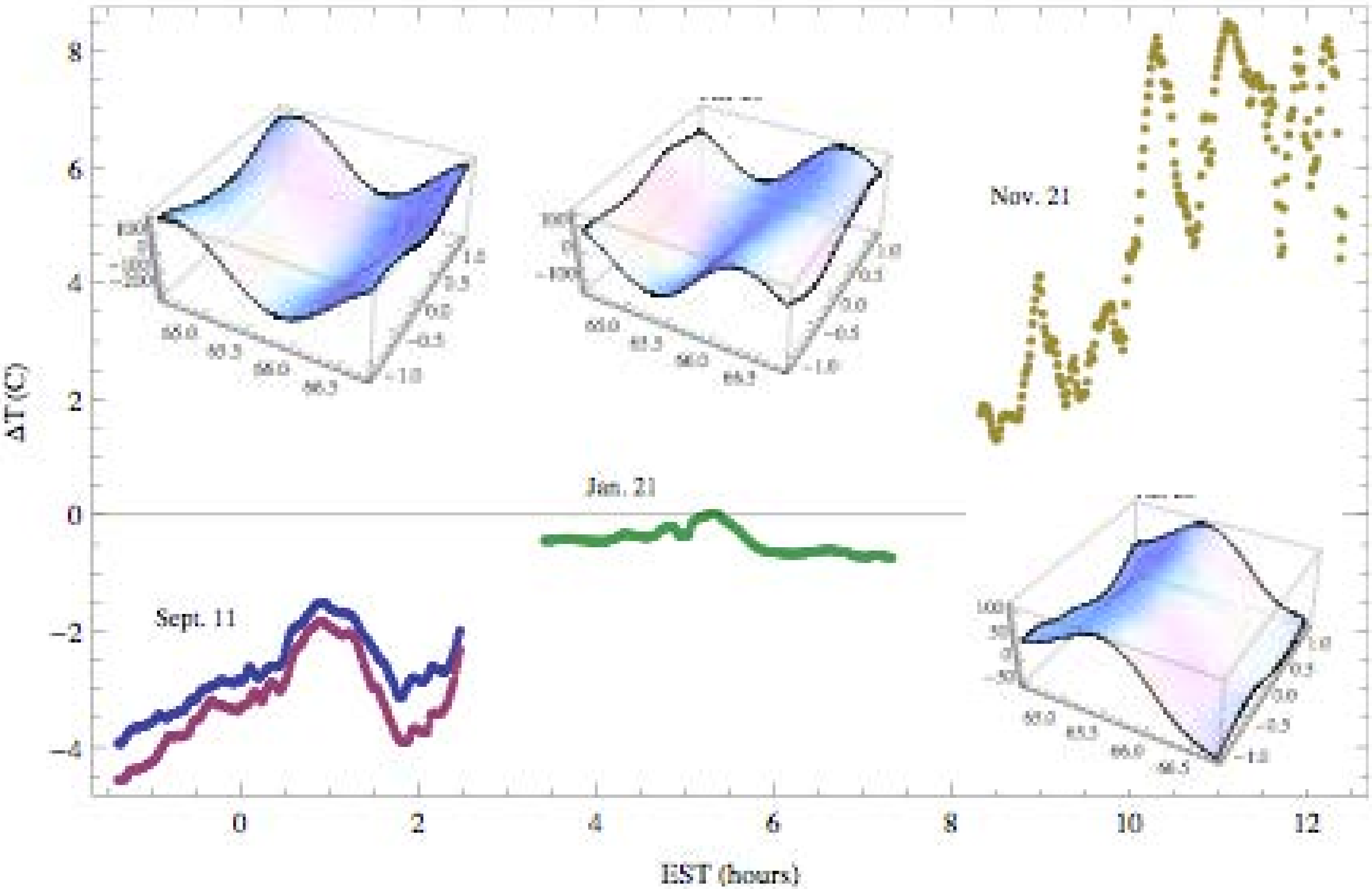
FEM model



Observed surface



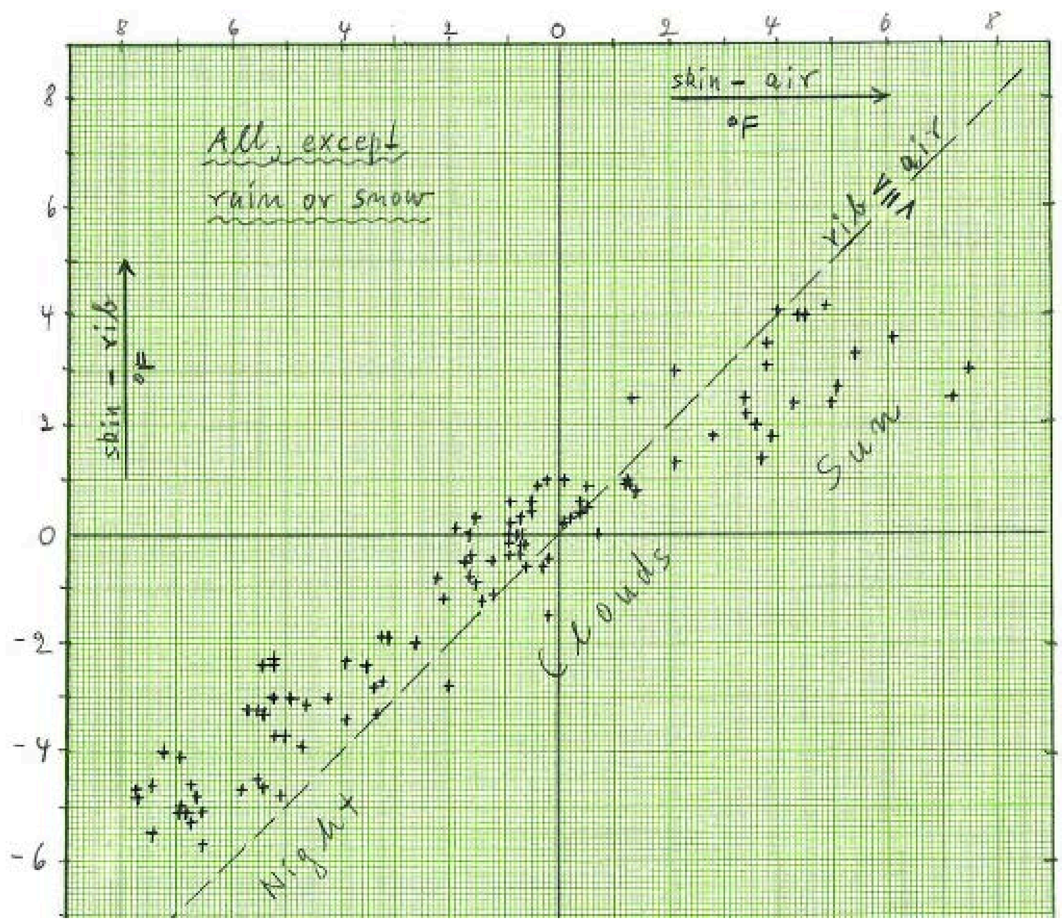
Tier-averaged panel profiles for tier 26



S. von Hoerner (January 1971)

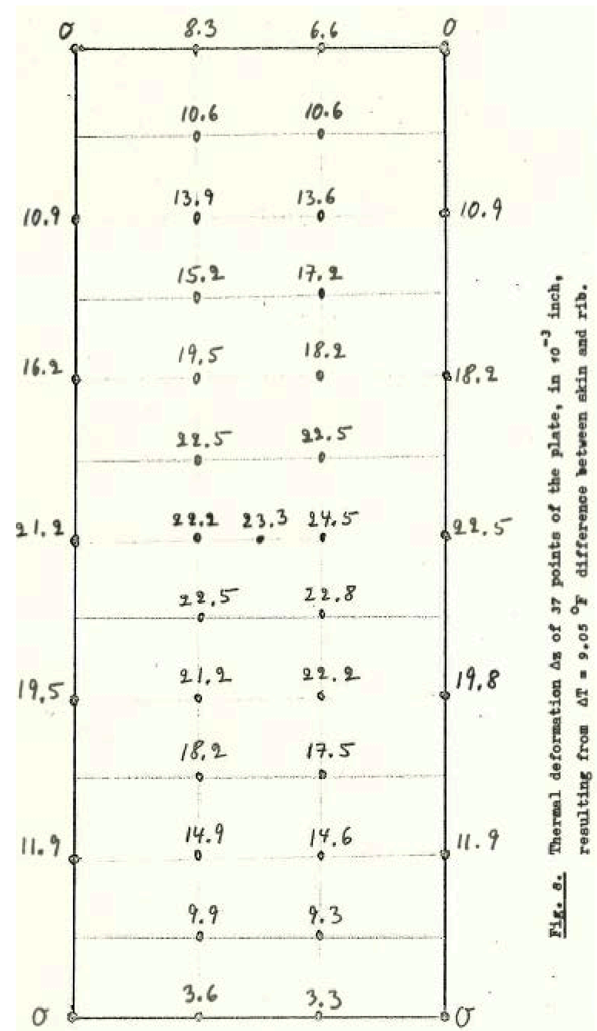
Measured panel temperature gradients

T (skin) – T (rib)



T (skin) – T (air)

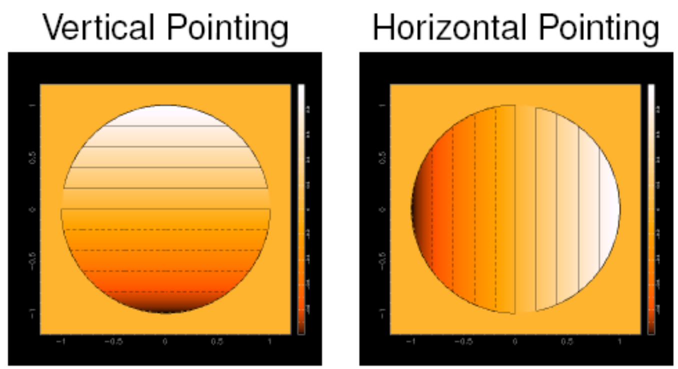
Panel deflection (mils)



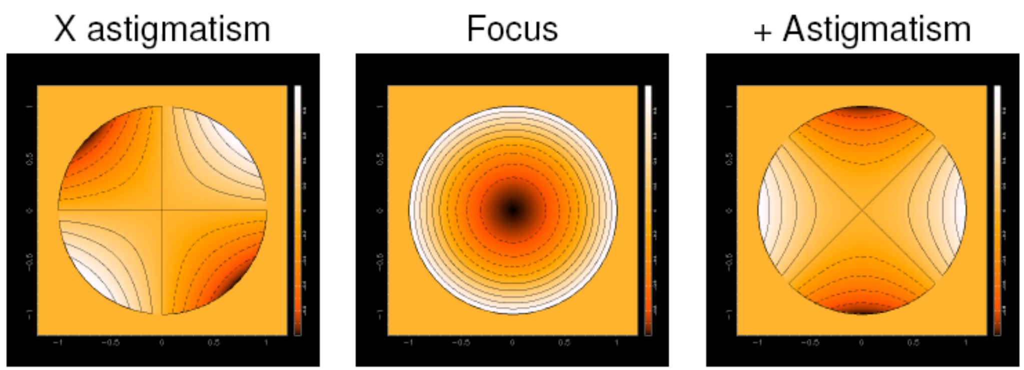
“Out-of-focus” (OOF) Holography

Any telescope surface pattern can be conveniently expressed as a sum of Zernike patterns. GBT active surface can apply up through n=7 (36 terms).

n=1

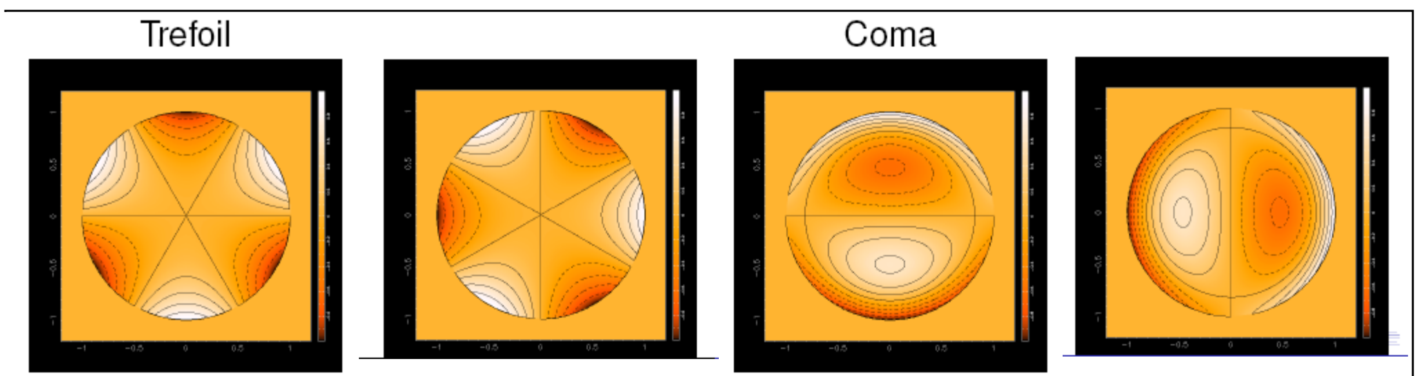


n=2

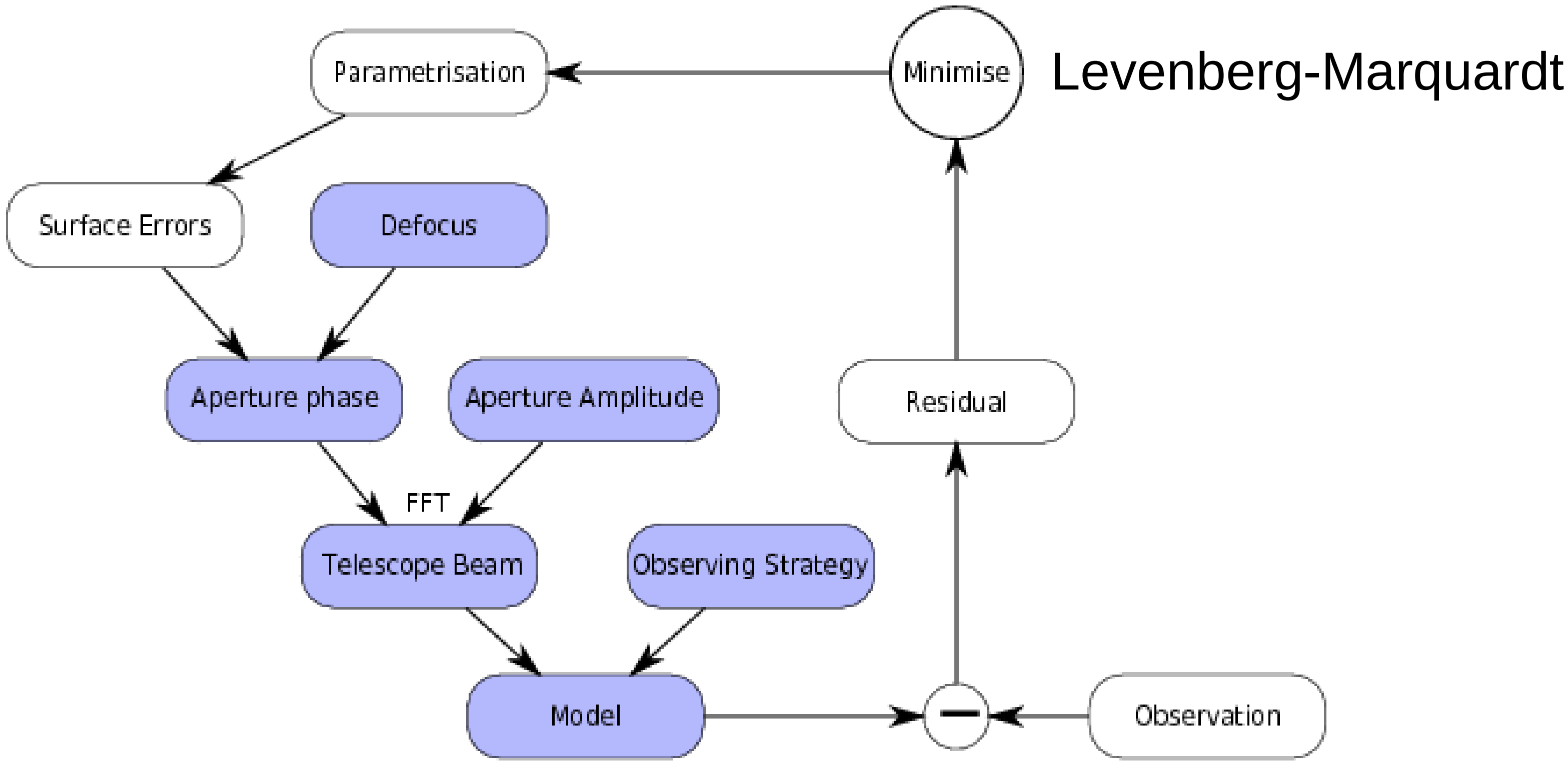


But not quite orthonormal (due to the receiver illumination taper)

n=3

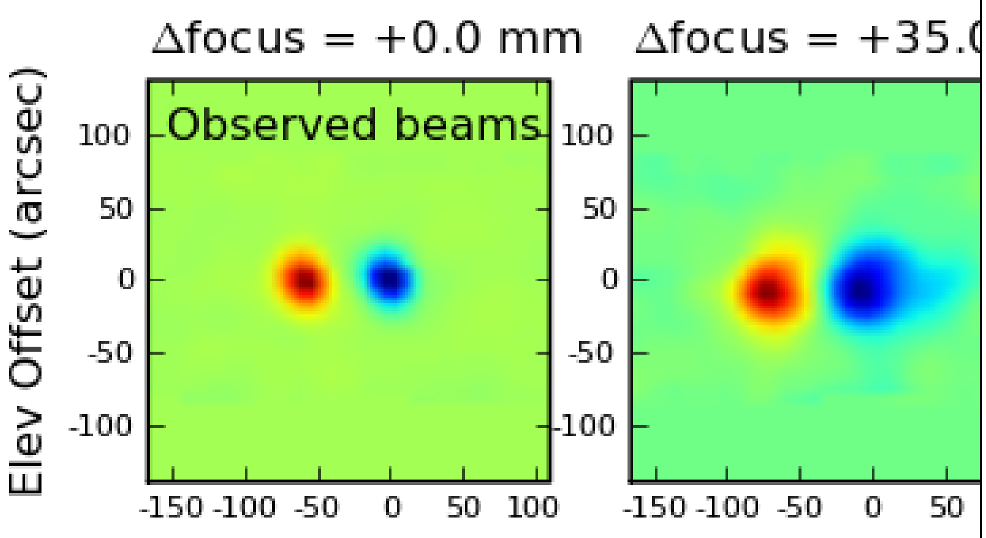


The OOF Holography Algorithm: Forward Model

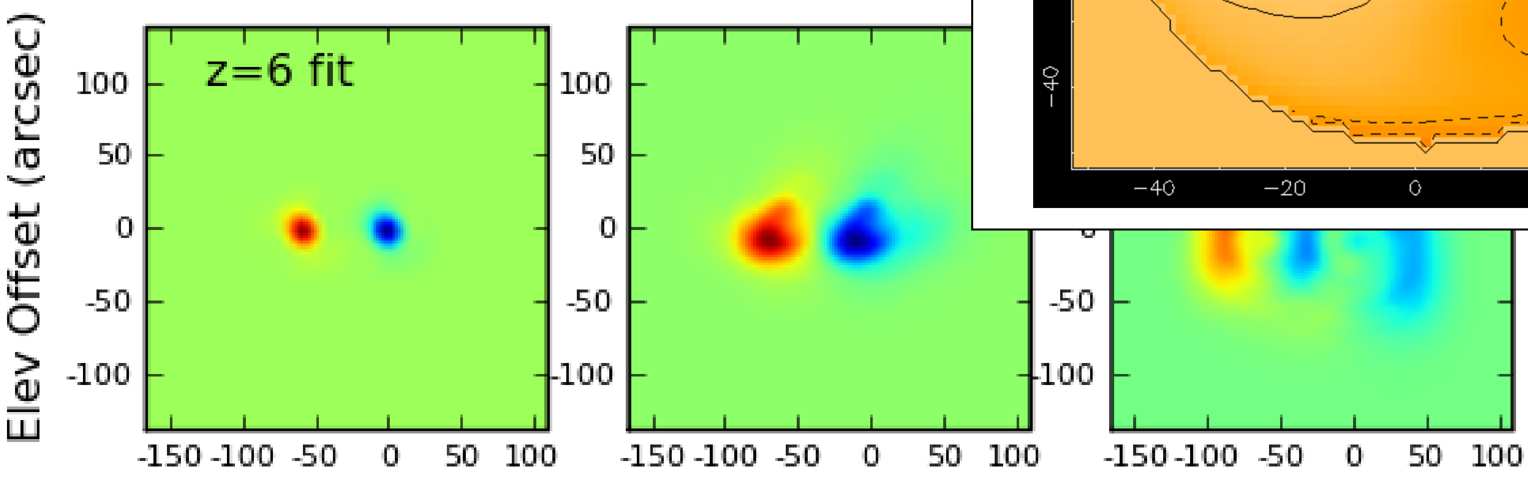


Out-of-Focus (OOF) Holography Technique

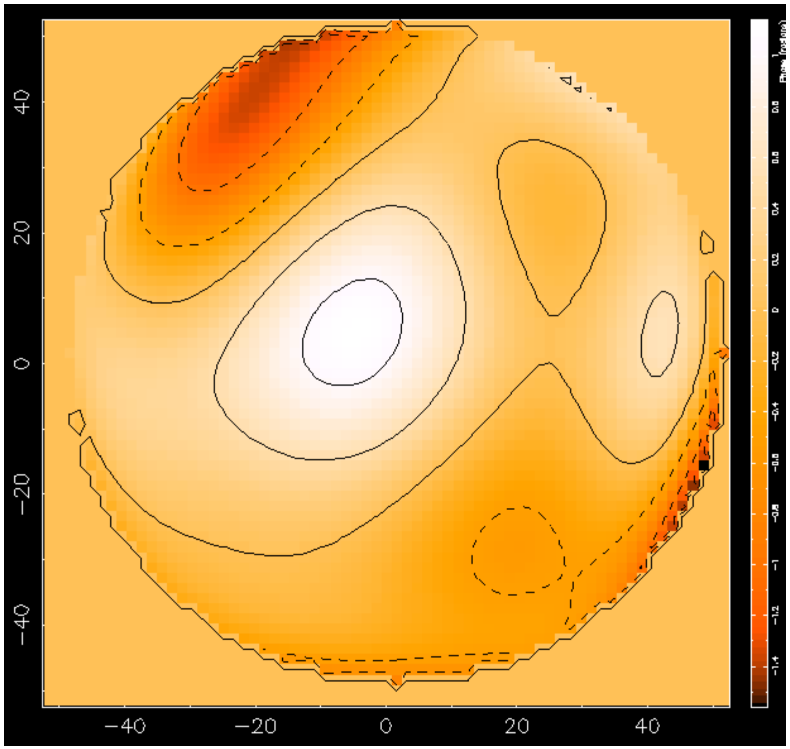
1. Acquire raster maps of a quasar at 3 fo



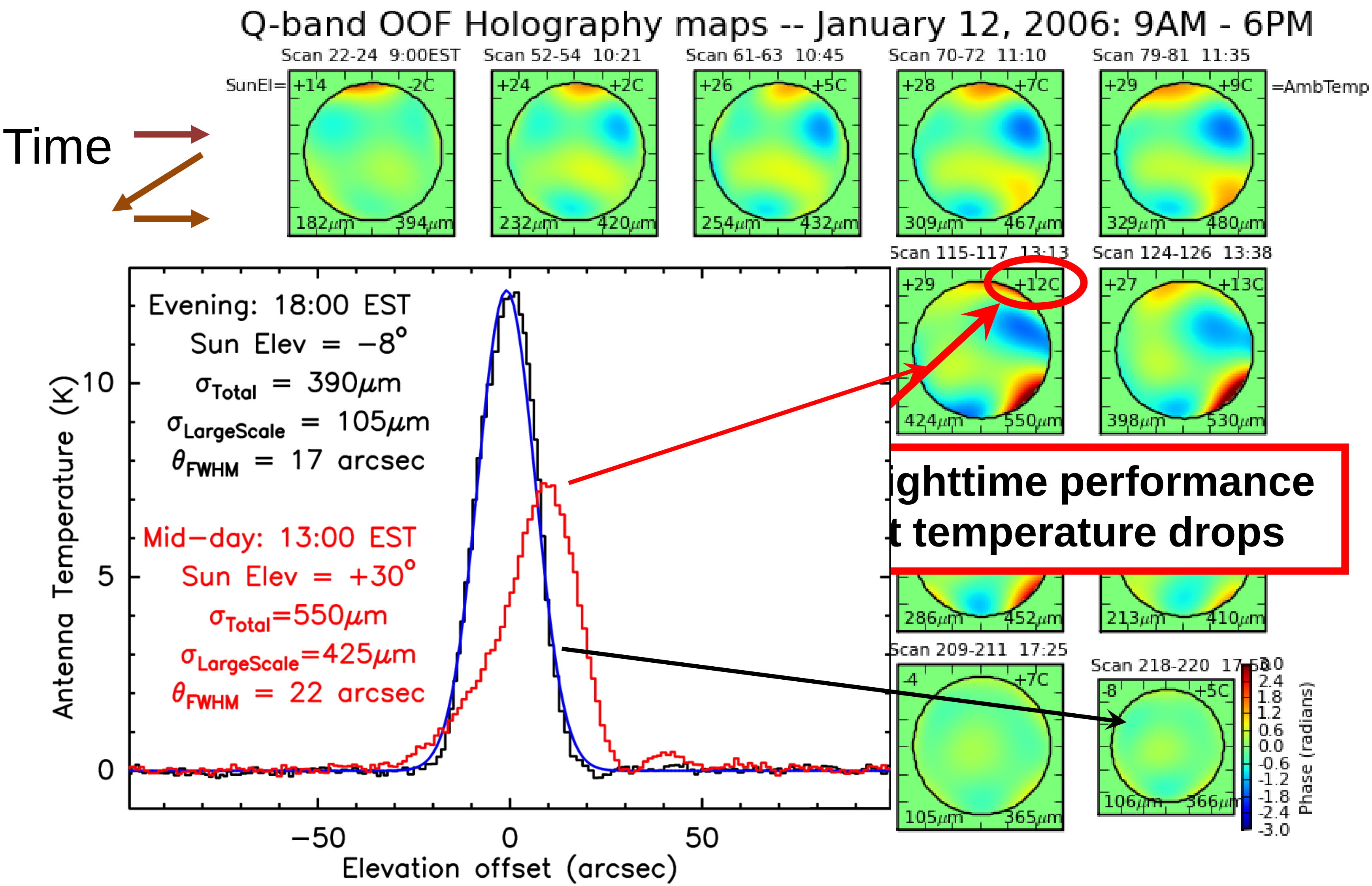
2. Fit with a small number of (5-7) Zernike

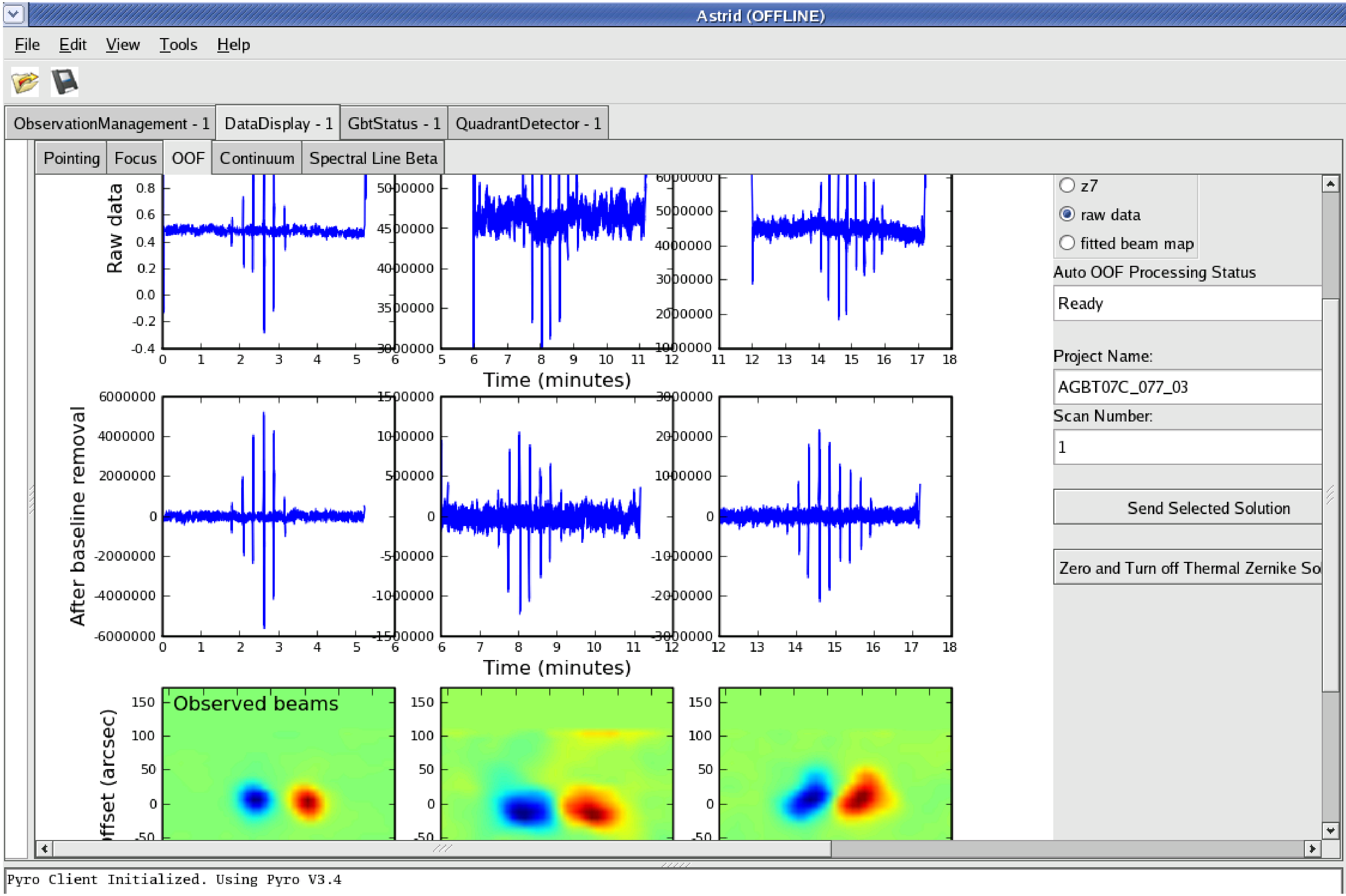


Model is fit to the time stream data. Result is the aperture phase image that can be applied to correct the surface:



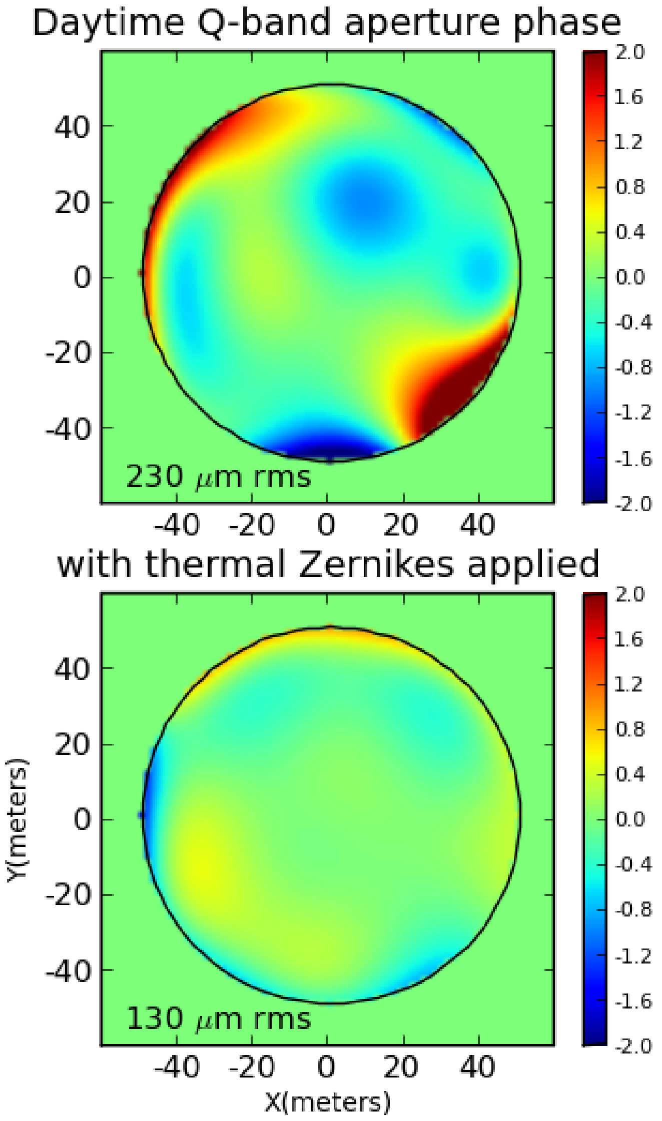
Thermal distortions due to solar heating

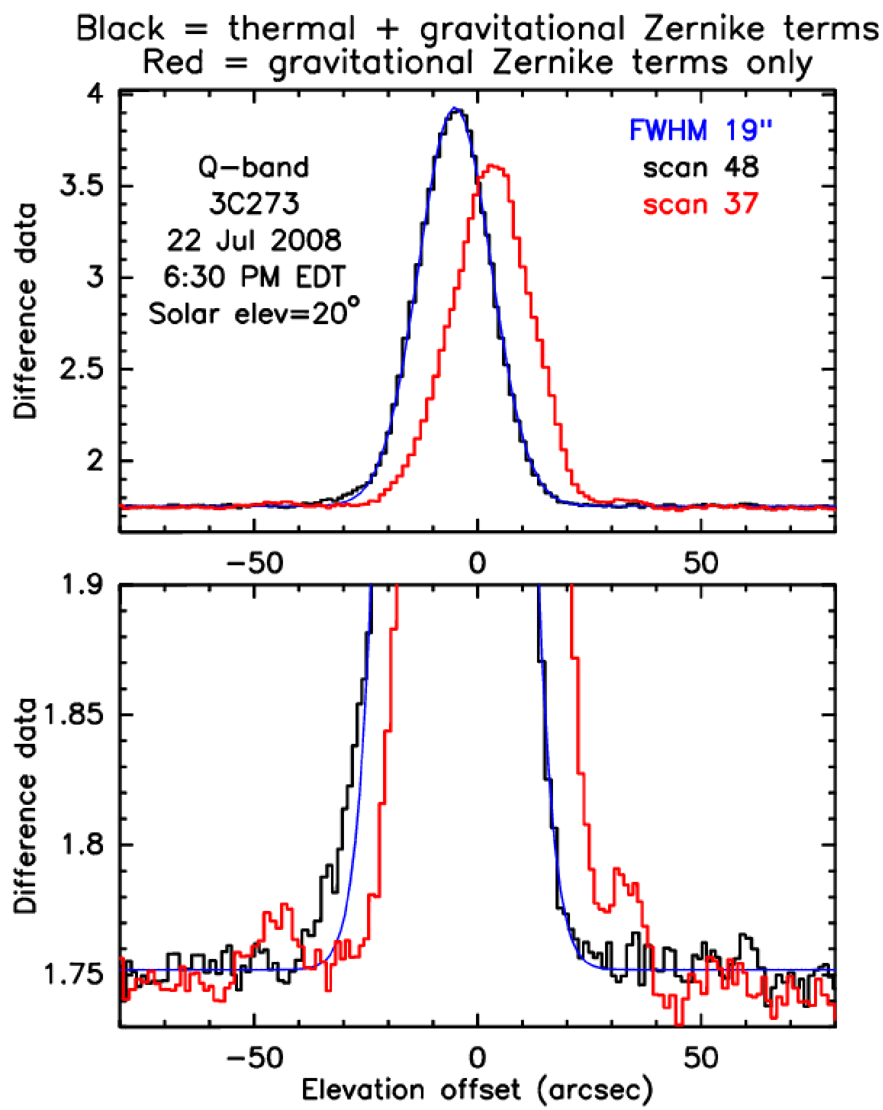




Astrid (OFFLINE)
File Edit View Tools Help
ObservationManagement - 1
DataDisplay - 1
GbtStatus - 1
QuadrantDetector - 1
Pointing
Focus
OOF
Continuum
Spectral Line Beta
Raw data
Time (minutes)
After baseline removal
Time (minutes)
Observed beams
Offset (arcsec)
z7
raw data
fitted beam map
Auto OOF Processing Status
Ready
Project Name:
AGBT07C_077_03
Scan Number:
1
Send Selected Solution
Zero and Turn off Thermal Zernike So
Pyro Client Initialized. Using Pyro V3.4

Example daytime AutoOOF correction





Estimated surface error budget (2010)

- Small-scale errors
  - Panel manufacturing error plus gravity — 127 microns (known)
  - Panel-scale thermal error (nighttime sag) — 100 microns (model)
  - Subreflector surface rms (photogrammetry) — 60 microns (known)
  - Panel setting (actuator + panel corners) — 80 microns (estimated)
  - Actuator repeatability — 50 microns (known)
- Intermediate-scale gravity and thermal errors — 80 microns (estimated)
- Residual large-scale thermal error — 80 microns (known)
- **Total root-sum-squared surface error — 230 microns**

(Surface degrades rapidly during the day with no OOF correction)

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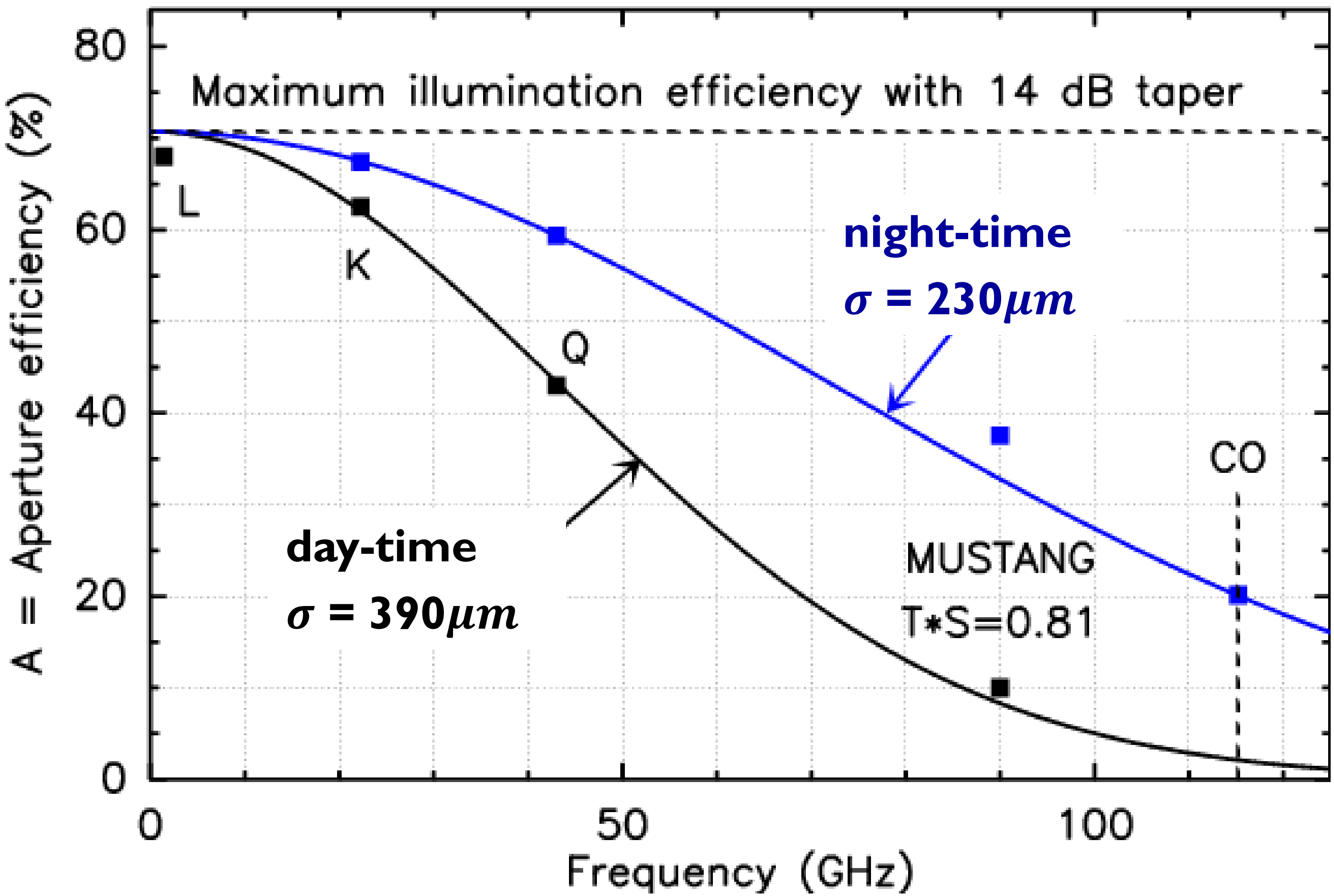
Results



80
60
40
20
0
0
50
100
A = Aperture efficiency (%)
Frequency (GHz)
Maximum illumination efficiency with 14 dB taper
L
K
Q
CO
night-time
$\sigma = 230\mu m$
day-time
$\sigma = 390\mu m$
MUSTANG
T*S=0.81

Future Developments

- “Next Generation” laser rangefinder system
  - Fixed baseline system, range and angle measurements made by instruments mounted on GBT.
  - Relay a fiducial coordinate created at the pintle bearing by high performance inclinometers (like “ALMA reference telescope”)
  - Use a two-tone system with incommensurate frequencies
  - DDS synthesizers
  - MEMS fiber optic switches
- Have a “brass-board” of this, functions well.

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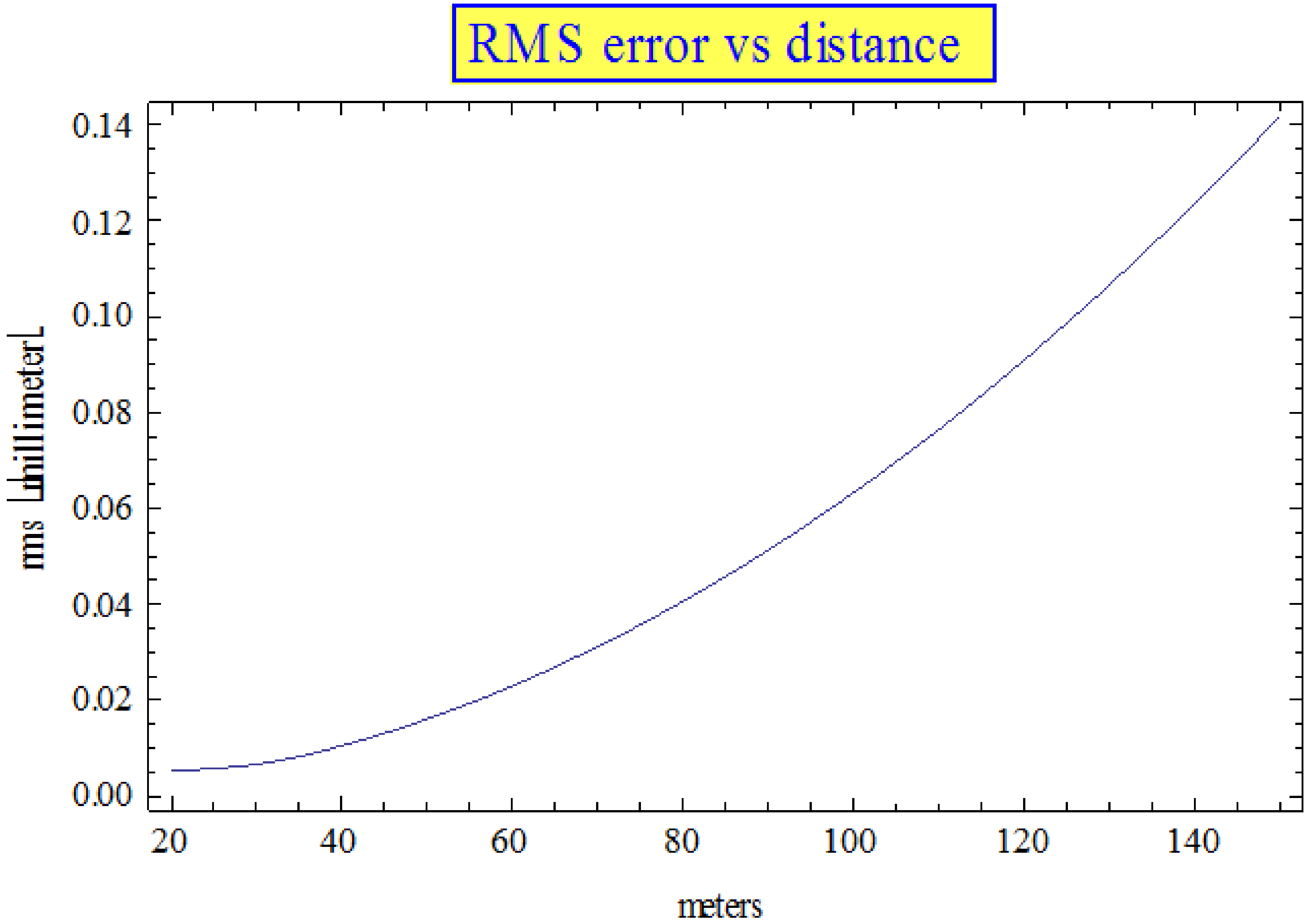
Predicted Results



Alternatives?

Image courtesy of NRAO/AUI