Performance and Properties of the GBT

Richard Prestage for the PTCS Team

GBT High Frequency Science Workshop – 21 September 2015

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

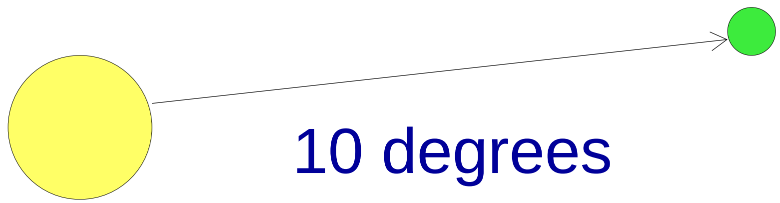
Talk Outline

- Current offset pointing / tracking performance
- Current surface accuracy
- Recent, current and potential future servo upgrades
- Potential new surface measurement system
- Summary
- Call for collaborators!

Offset Pointing and Tracking Accuracy

Offset Pointing / Tracking at 3 mm

1) Point on bright quasar



2) Track source of interest

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

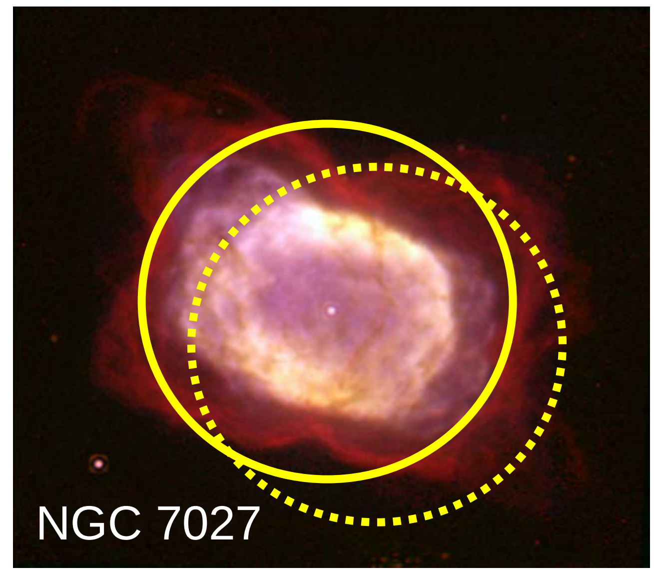
$$\left(\frac{\theta}{740\ \text{arcsec}}\right) \approx \left(\frac{\text{GHZ}}{\nu}\right)$$

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

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

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

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



At 115 GHz, beam size = 6.5”, so the tracking requirement for 10% error = 1.3” rms

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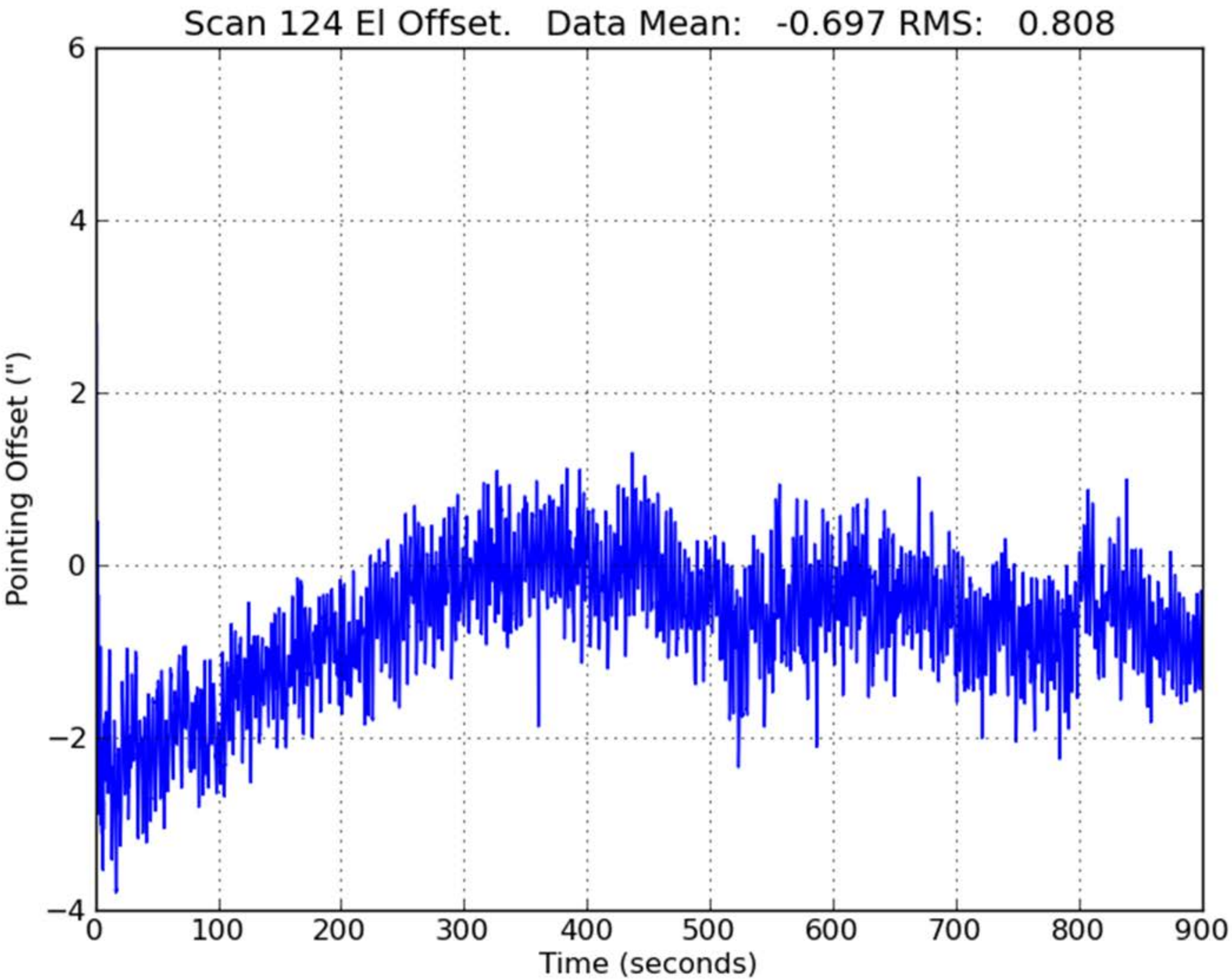
Slide after Todd Hunter

Offset Pointing / Tracking at 3 mm



Offset Pointing / Tracking at 3 mm

- Recently replaced 22-bit BEI encoders with 26-bit Heidenhains

- Best (benign time-time) performance before encoder upgrade:
  - 1.7" (just acceptable for 90 GHz)

- Now, potentially (not yet measured):
  - $\leq$ 1" offset pointing, plus $\leq$ 1" tracking over ~ 30 min
  - **Extremely close to 115 GHz specification!**

- Under non-ideal conditions, performance degrades due to thermal and wind effects
- Thermal deformations compensated for by pointing/focus
- Wind effects are (primarily) "feed arm sway"

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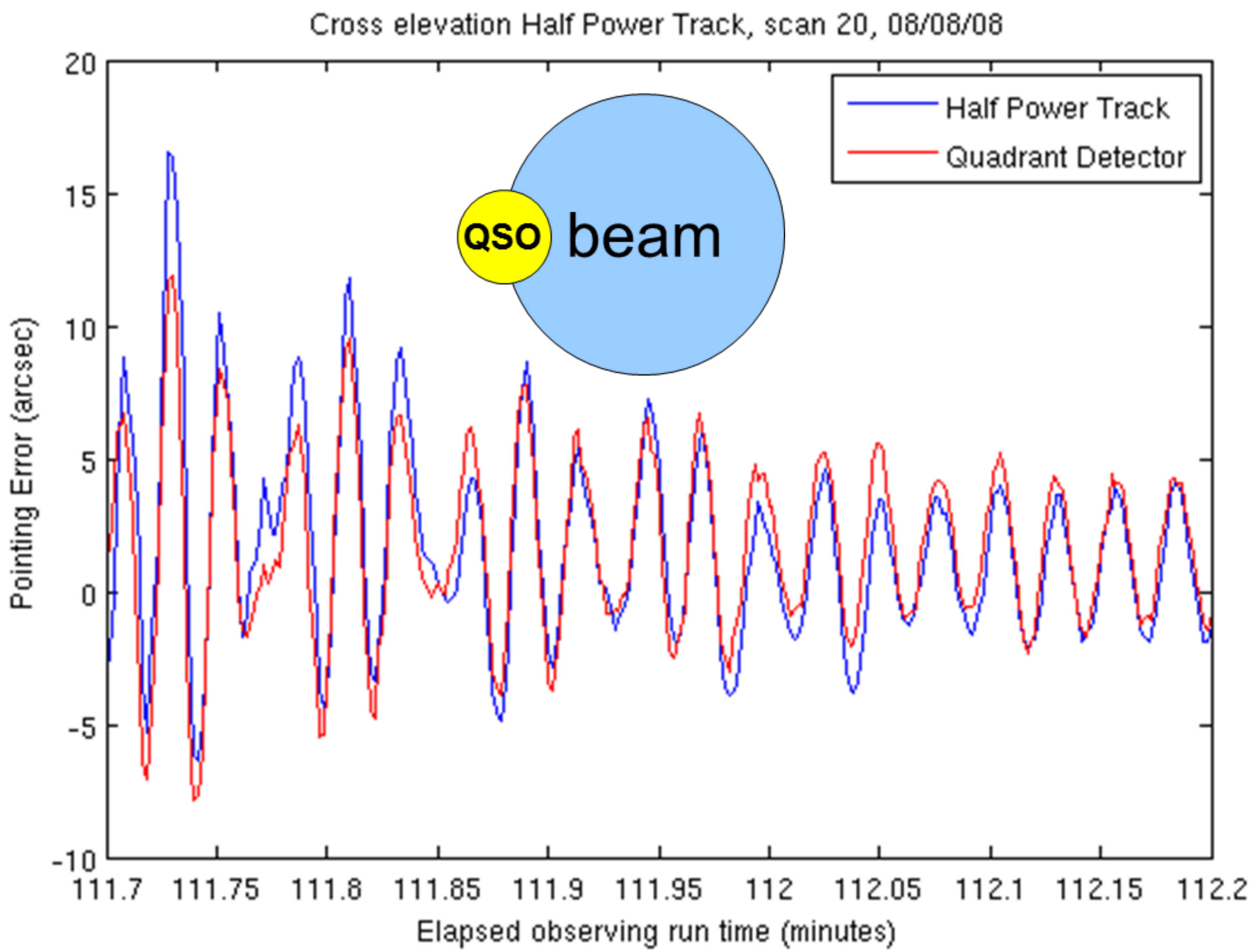
Monitoring feed-arm sway with the QD



Feed-arm sway as a function of wind speed

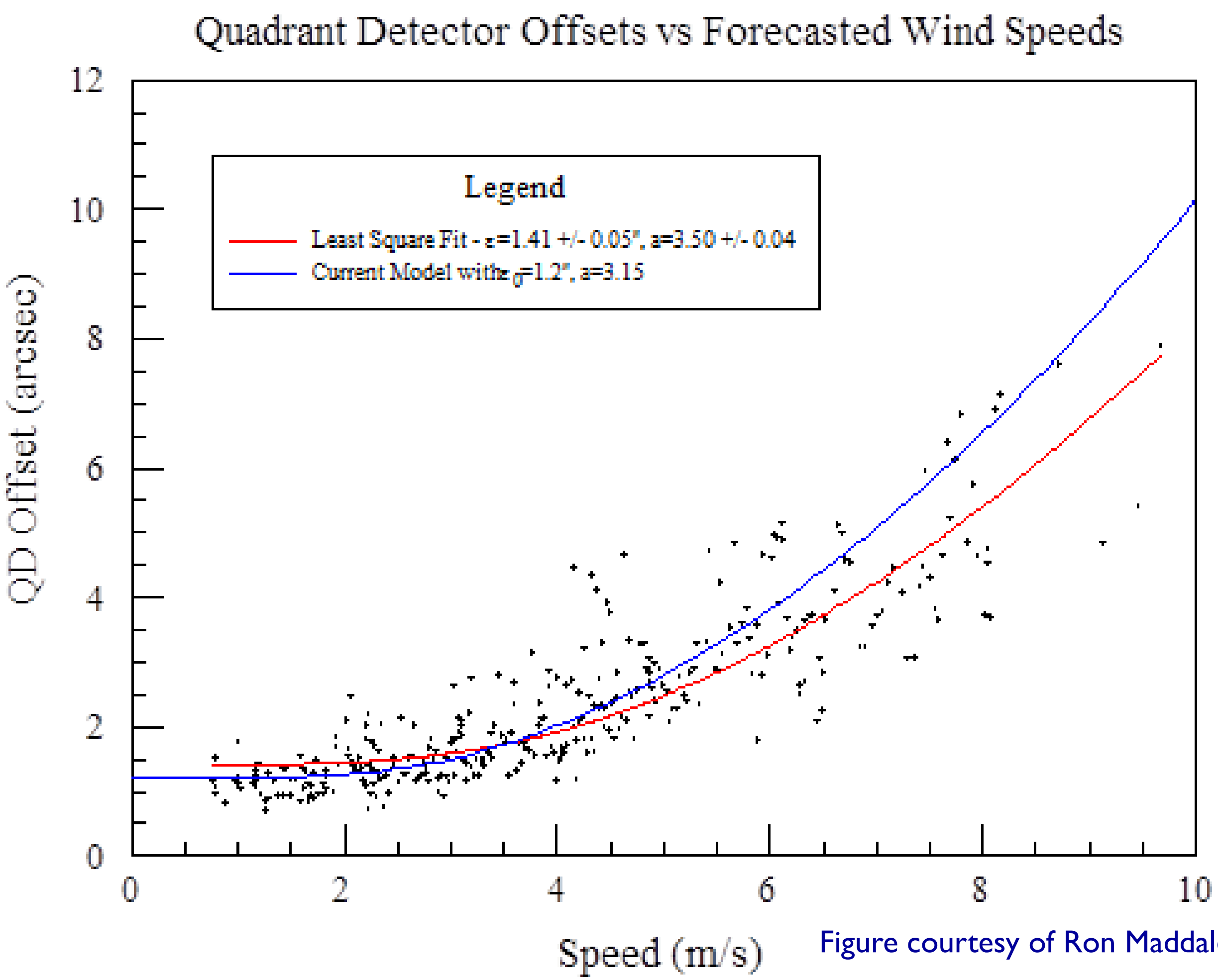
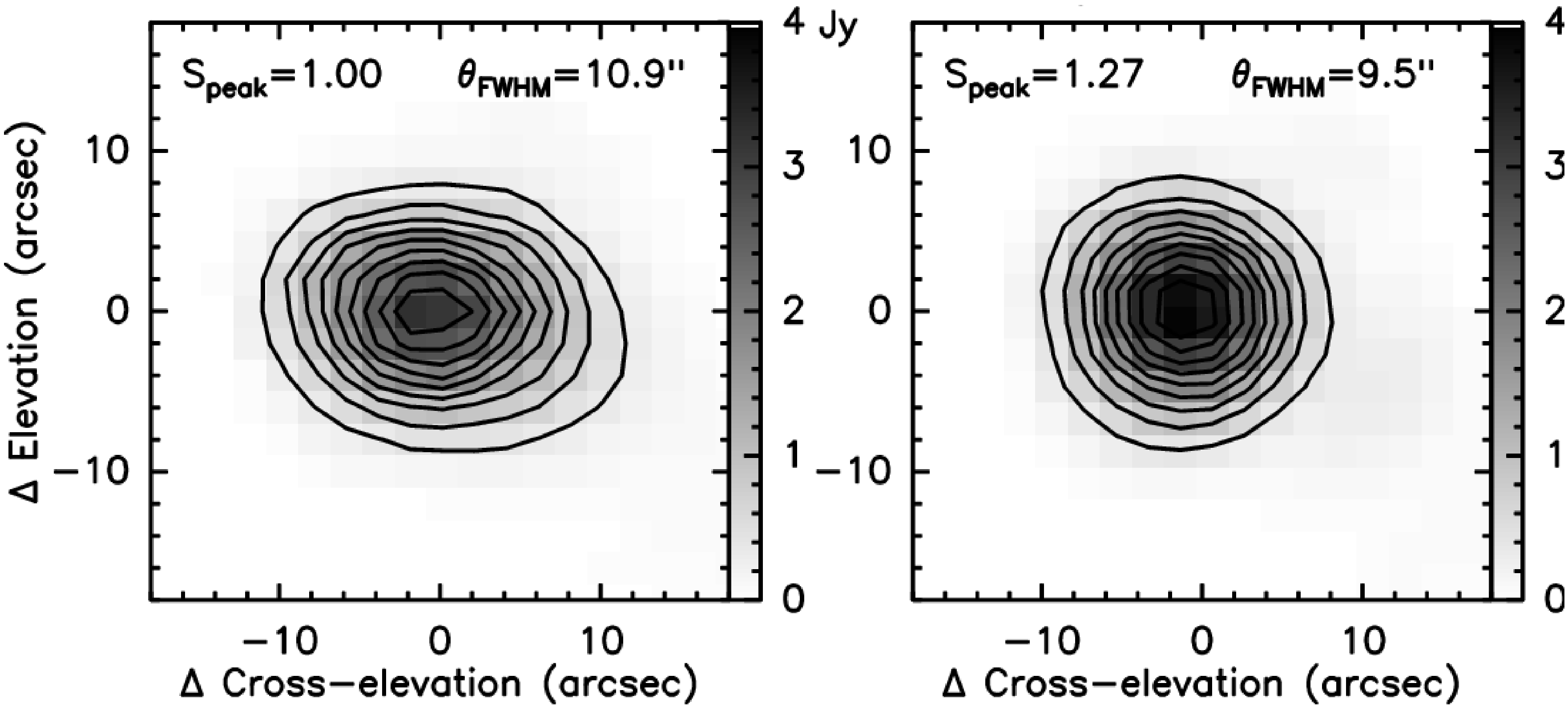


Figure courtesy of Ron Maddalena

For array detectors, correct off-line



MUSTANG images of a bright quasar obtained on a windy (≈ 6 m s^{-1}) night combining several scans with a total integration time of about 20 minutes. Beam size under ideal conditions is 9.0” ((Ries et al., 2011)

Summary offset pointing / tracking performance

- Under benign (no-wind) night-time conditions:
  - ≤ 1" offset pointing, plus ≤ 1" tracking (~ 1.5" total)

- Current DSS equation:

$$\sigma_{tr}^2 = \sigma_0^2 + \left(\frac{s}{a}\right)^4$$

$$\sigma_0 = 1.3'' \quad a = 3.5\, ms^{-1}\, arcsec^{-2}$$

= 2.5" @ 5 m s^{-1} (11 mph)
= 8" @ 10 m s^{-1} (22 mph)

Current Surface Accuracy

Surface Requirements for 3mm

- Aperture efficiency given by:
  - $\eta_{aperture} = \eta_{surface} \times \eta_{illumination} \times \eta_{spillover} \times \eta_{blockage}$

- For the GBT:
  - off-axis design: $\eta_{blockage} = 1$
  - 14dB taper: $\eta_{spillover} = 0.9895$; $\eta_{illumination} = 0.707$
  - Ruze formula: $\eta_{surface} = \exp(-(4\pi\sigma/\lambda)^2)$

- GBT specification on surface rms, $\sigma \leqq (\lambda / 4\pi)$:
  - i.e. $\eta_{surface} = 1/e = 0.367$

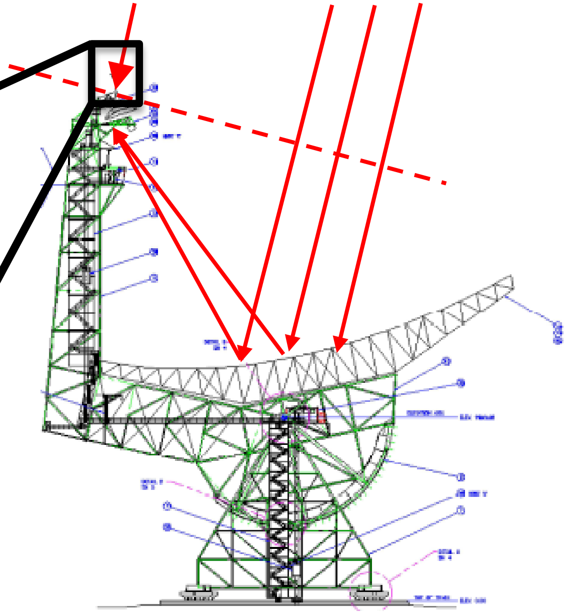
- For 115 GHz we need:
  - $\sigma \leqq 210$ μm rms

Surface Measurement: High-resolution with-phase holography

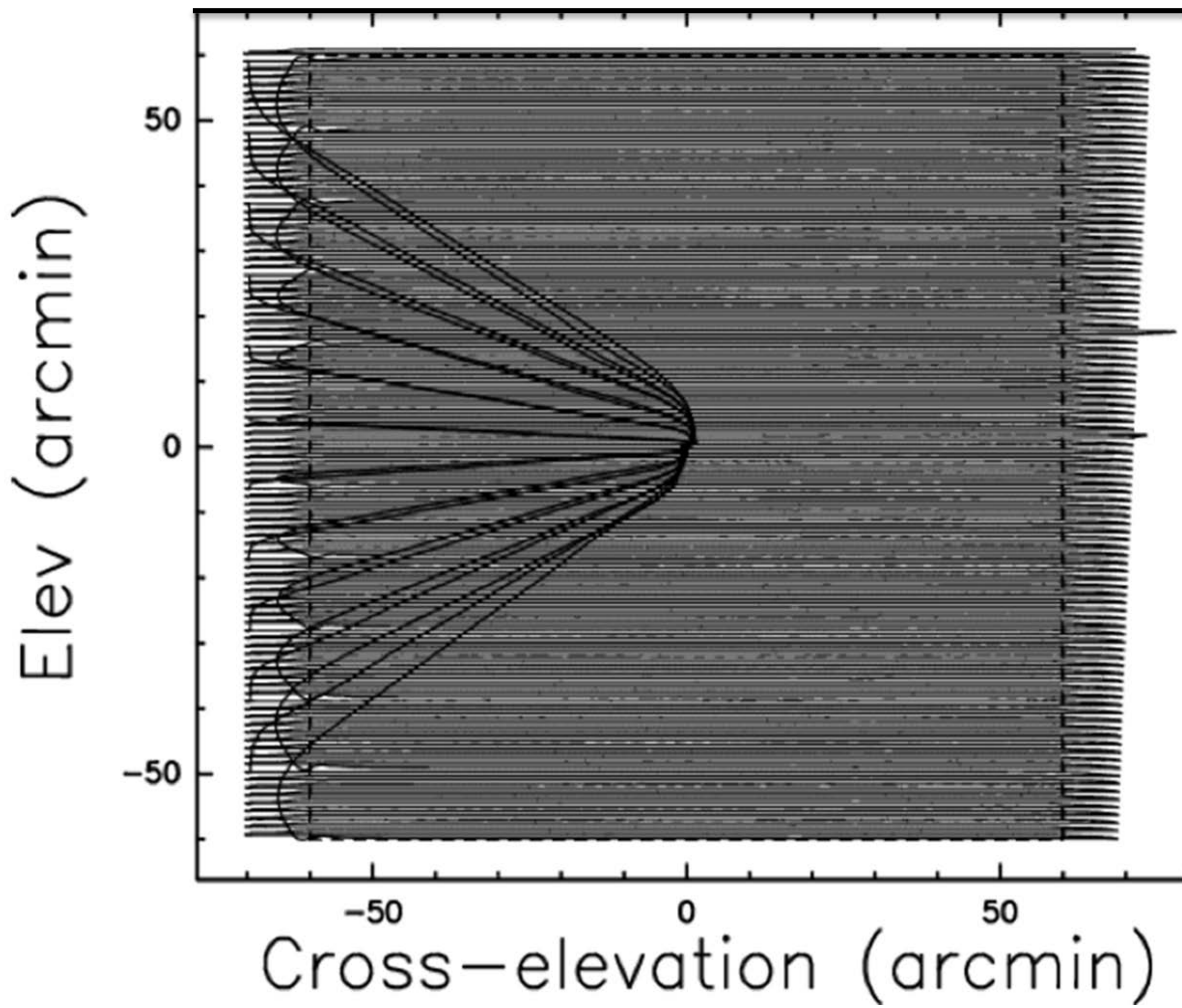
- Technique is > 30 years old (Bennett et al. 1976)
  - Measure complex beam pattern (phase and amplitude)
  - Fourier transform to get phase and amplitude of E field on aperture
  - Convert phase to surface error, and apply mechanical corrections
- 2 Receivers: room-temp. LNAs, 10kHz filters, Hilbert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

Main receiver in Gregorian turret

Reference receiver at top of feed arm



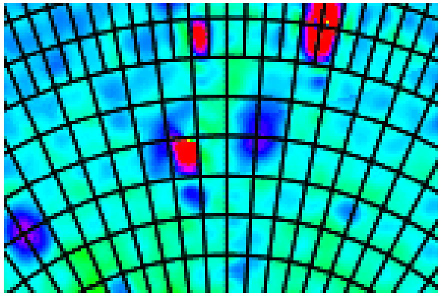
Scan Pattern (2° x 2° Map)



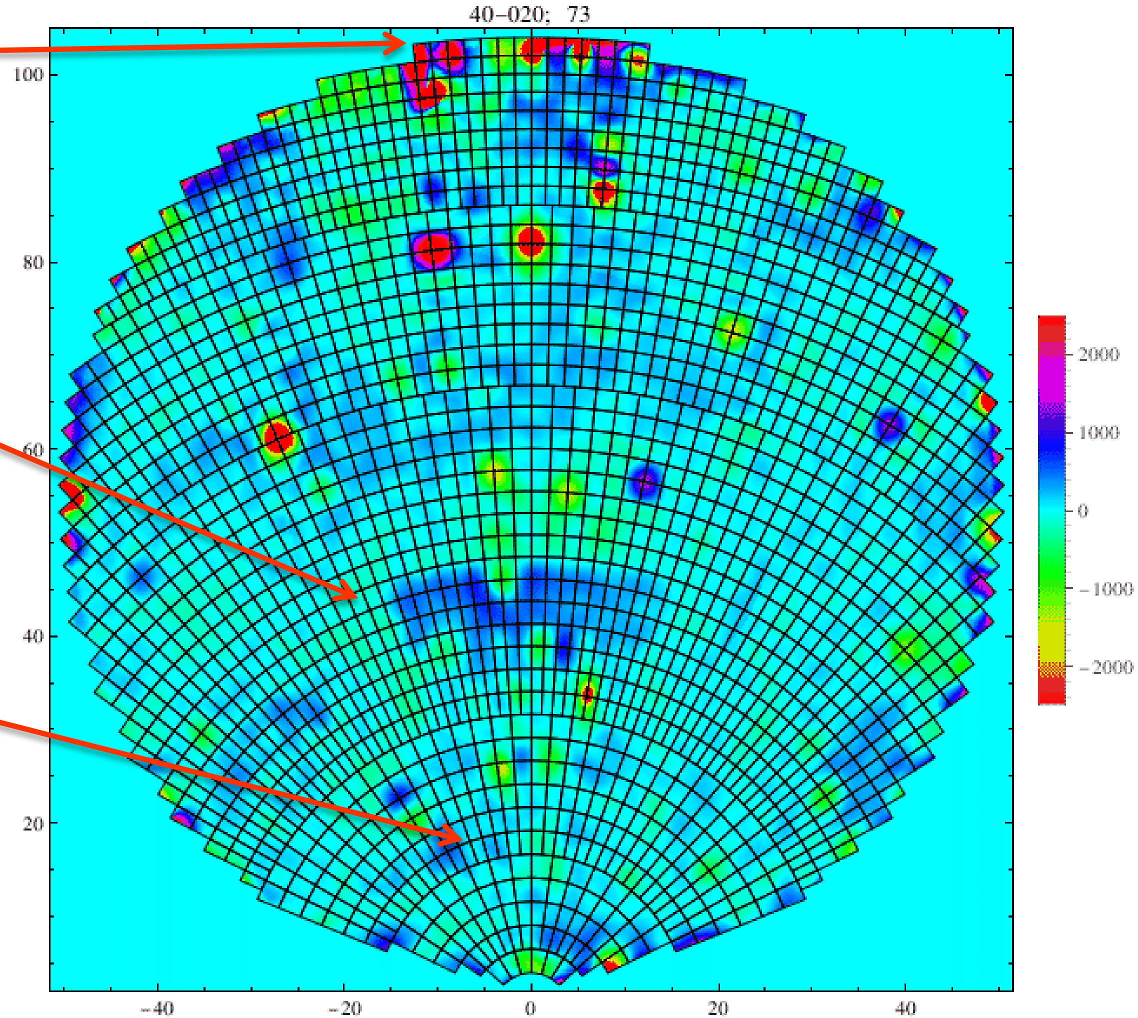
Recent (not ideal) Results

Non-repaired actuators (due to structural inspections)

Patch of 128 bad actuators (now fixed power supply problem)



Ice damage



Surface Measurement: Low-resolution "OOF" holography

- 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.

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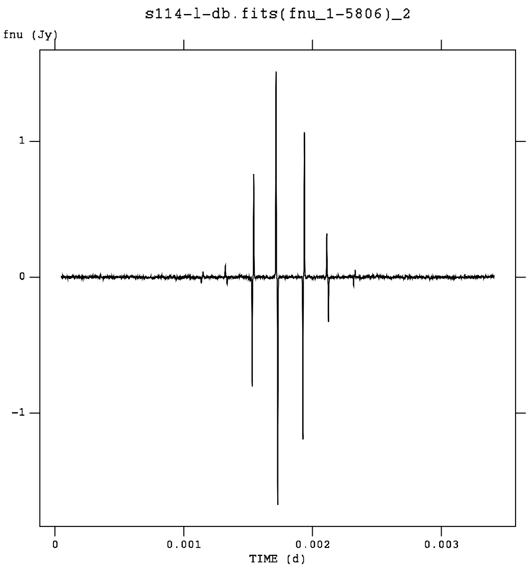
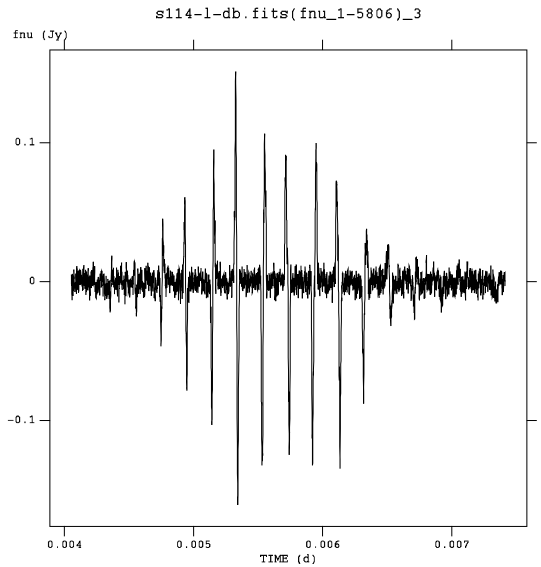
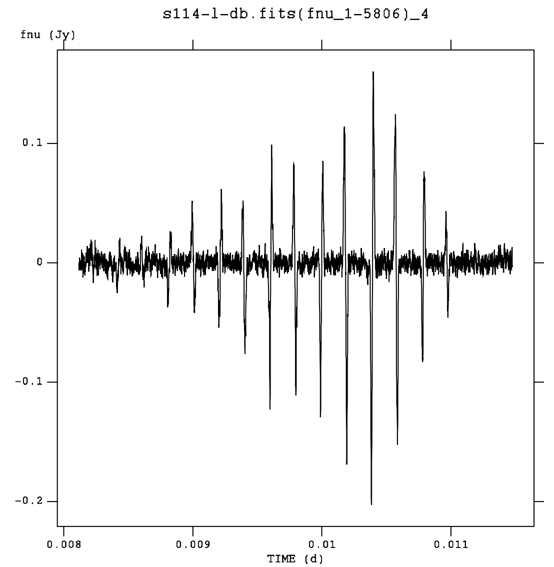
Typical data







Q-band (43 GHz)

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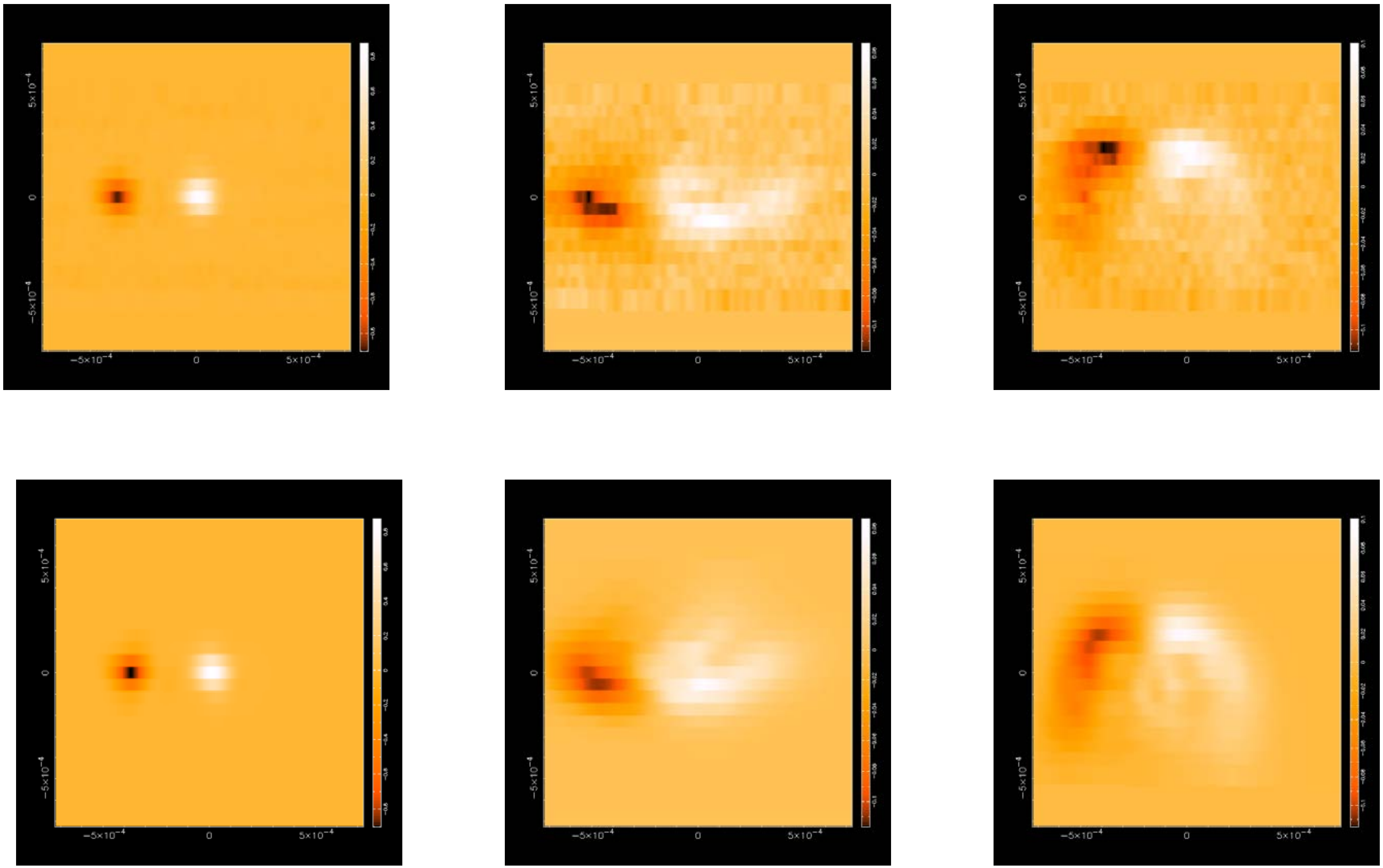
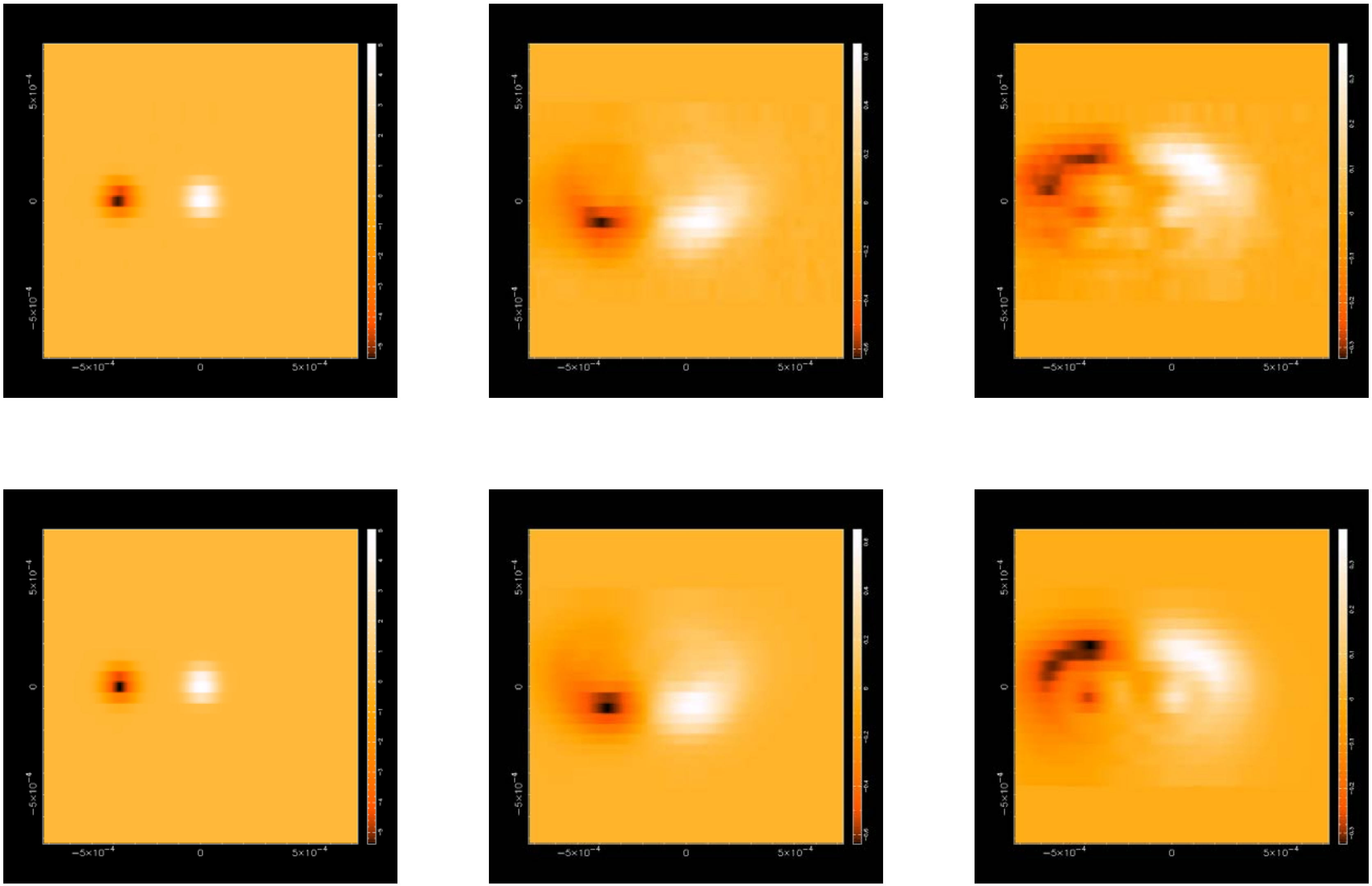
Typical data: before (rms = 370 μm)



Typical data: after (rms = 80 μm)



Estimated error budget

- Small-scale errors:
  - panel manufacturing plus gravity error: 127 μm
  - residual actuator error: 80 μm
  - panel corner setting error: 80 μm
  - panel-scale thermal errors: 100 μm
  - subreflector: 75 μm
  - total small-scale error: 80+80+127+100+75 = 211 μm
- Large-scale thermal error: 100 μm
- **Total error: 211+100 = 235 μm**

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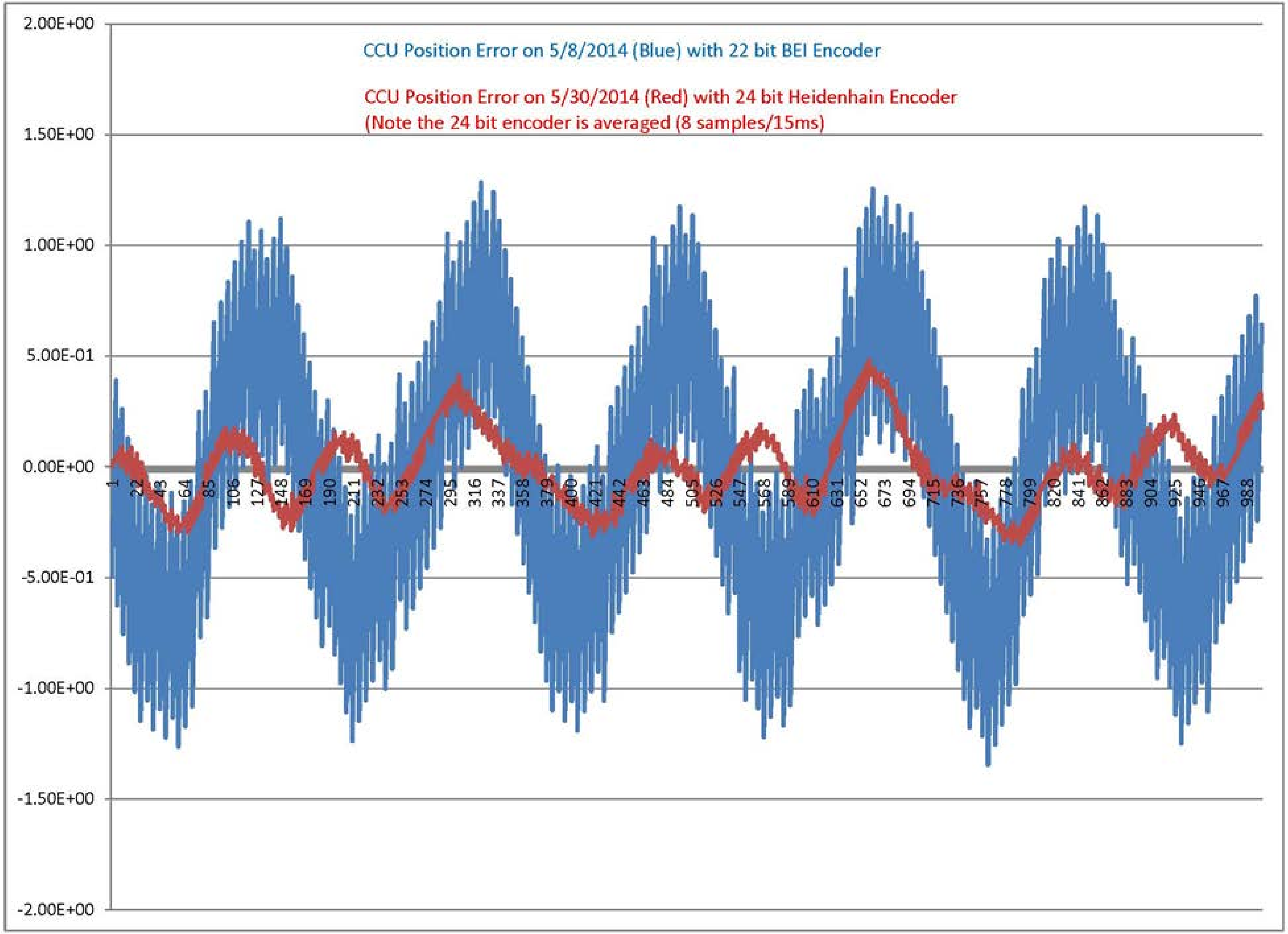
Current and Potential Servo Improvements

Encoder Replacement (Complete)



Servo / Motor Control System Upgrade (Ongoing)

- Primarily a required maintenance upgrade
  - Existing system is > 20 years old, and obsolete
- Replacing existing custom, wire-wrap "rate loop" cards with modern, PCB, plug-compatible version
  - Controls the (analog) velocity loop
  - Controls the individual motors (torque bias; faulted motors…)
- Replace the current VxWorks / VME, proprietary "Central Control Unit", with an open-source, Linux / PC version
  - Initial installation; replicate current functionality
  - Replace "lead-lag" servo algorithm with PID algorithm
  - Replace analog rate loop with digital rate loop

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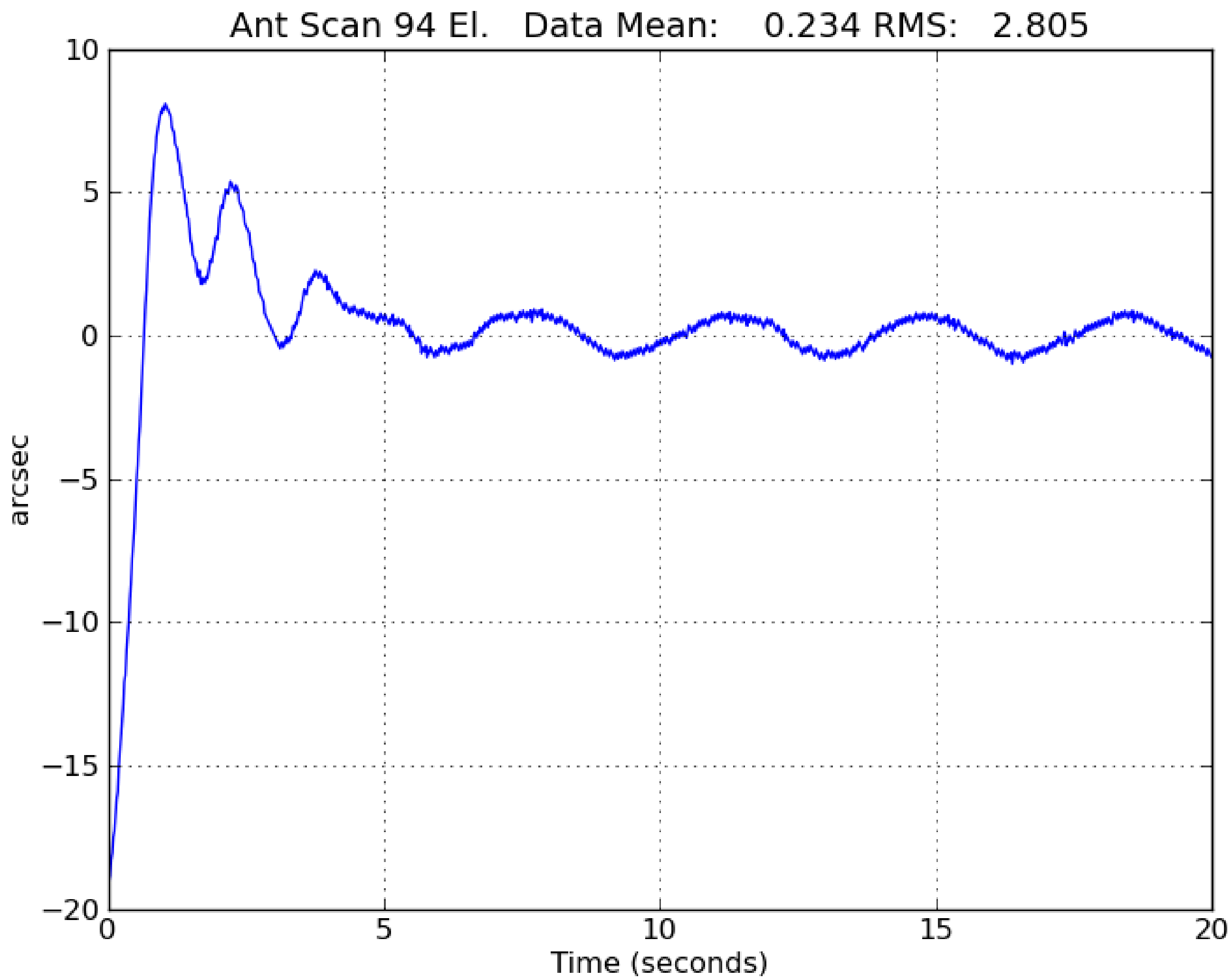
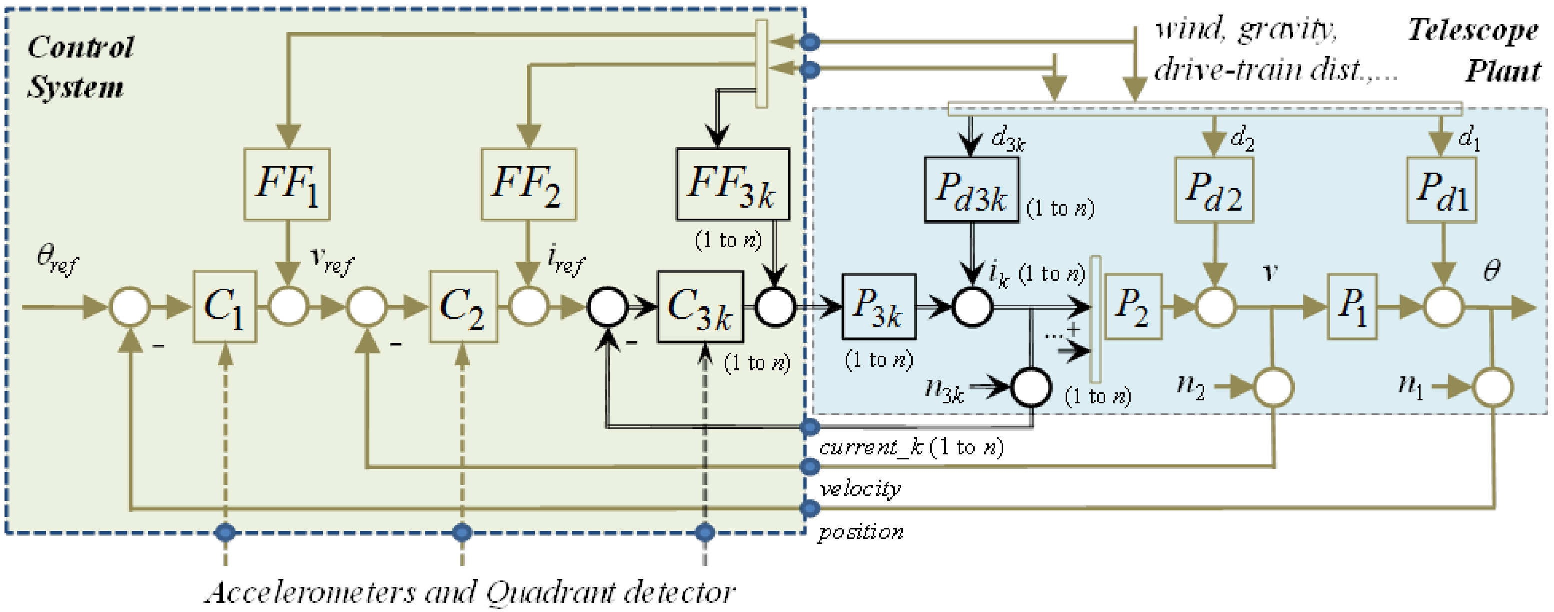
Servo / Motor Control System Upgrade (Ongoing)



Servo / Motor Control System Upgrade (Proposed)

- Develop a modern control system replacement for main drive and subreflector servos
- Collaboration with Case Western Reserve University (Prof.Mario Garcia-Sanz, Trupti Ranka)
- High-fidelity plant model based on improved FE model (Art Symmes)
- Develop "Observers" using additional sensor data (quadrant detectors, accelerometers)
- Improve wind rejection, damp feed-arm vibration
- Compensate for "feed arm sway" (timescales of ~ seconds) using the subreflector

New Servo Architecture



This project is not funded!

Potential Surface Improvements

Leica ScanStation P40

System Accuracy	
Accuracy of single measurement ˆ	
Range accuracy	1.2 mm + 10 ppm over full range
Angular accuracy	8" horizontal; 8" vertical
3D position accuracy	3 mm at 50 m; 6 mm at 100 m
Target acquisition ˆˆ	2 mm standard deviation at 50 m
Dual-axis compensator	Liquid sensor with real-time onboard compensation, selectable on/off, resolution 1", dynamic range ±5', accuracy 1.5"

Distance Measurement System				
Type	Ultra-high speed time-of-flight enhanced by Waveform Digitising (WFD) technology			
Wavelength	1550 nm (invisible) / 658 nm (visible)			
Laser class	1 (in accordance with IEC 60825:2014)			
Beam divergence	< 0.23 mrad (FWHM, full angle)			
Beam diameter at front window	≤ 3.5 mm (FWHM)			
Range and reflectivity	Minimum range 0.4 m			
		Maximum range at reflectivity		
		120 m	180 m	270 m
	P30	18 %	–	–
	P40	8 %	18 %	34 %
Scan rate	Up to 1'000'000 points per second			
Range noise ˆ	0.4 mm rms at 10 m 0.5 mm rms at 50 m			
Field-of-View Horizontal Vertical	 360° 270°			
Data storage capacity	256 GB internal solid-state drive (SSD) or external USB device			
Communications/ Data transfer	Gigabit Ethernet, integrated Wireless LAN or USB 2.0 device			
Onboard display	Touchscreen control with stylus, full colour VGA graphic display (640 × 480 pixels)			
Laser plummet	Laser class 1 (IEC 60825:2014) Centring accuracy: 1.5 mm at 1.5 m Laser dot diameter: 2.5 mm at 1.5 m Selectable ON/OFF			

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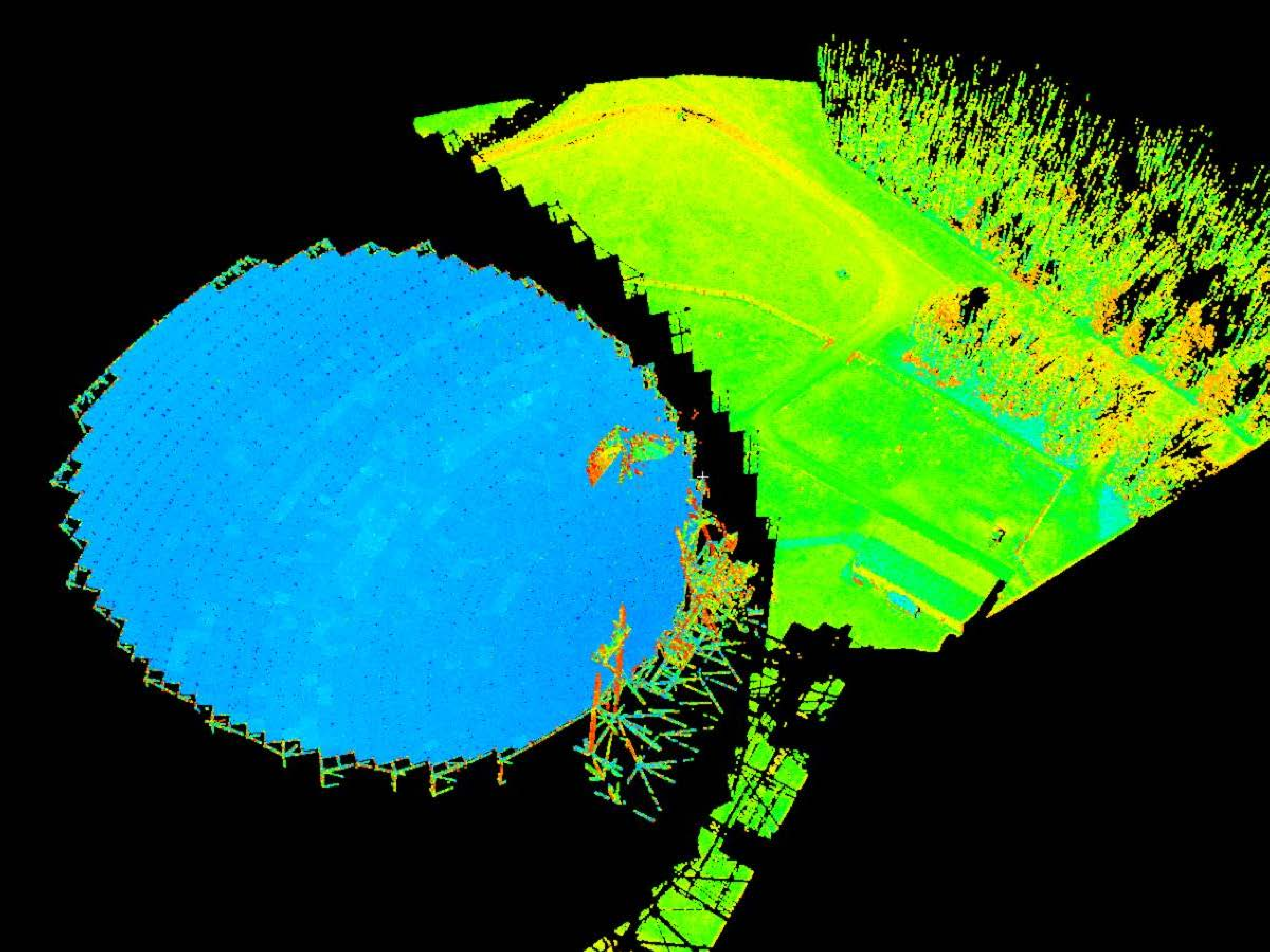
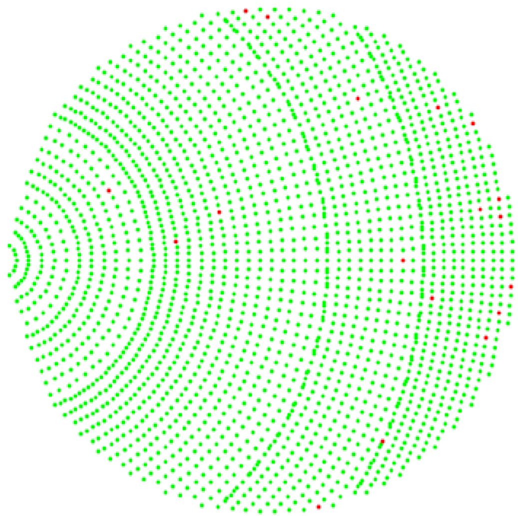
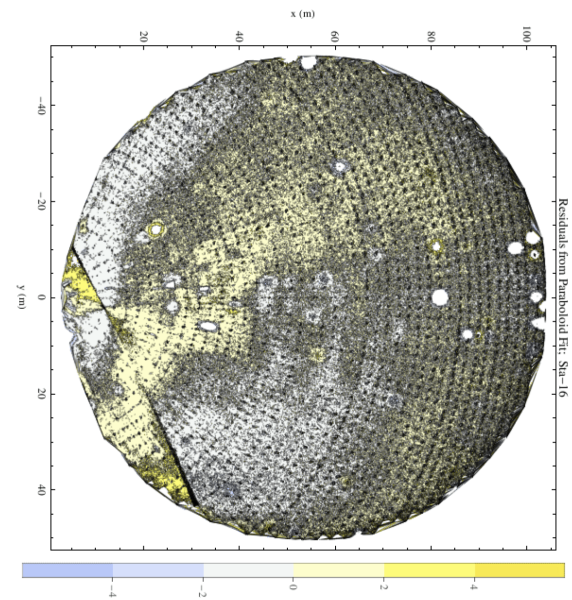
3D accuracy: 6mm @ 100m

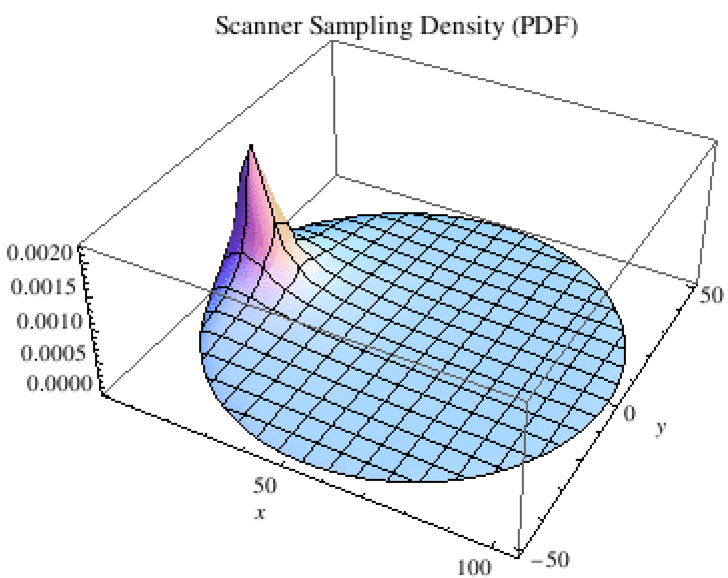
Range noise: 0.5mm @ 50m

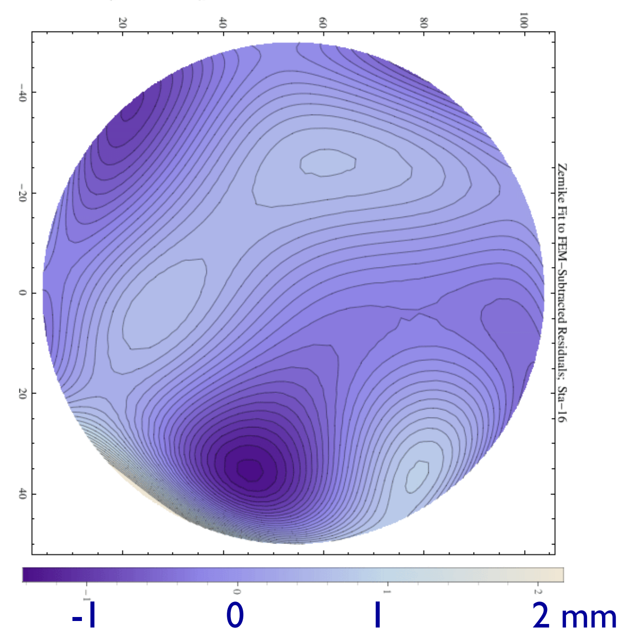


Data Processing (Fred Schwab)









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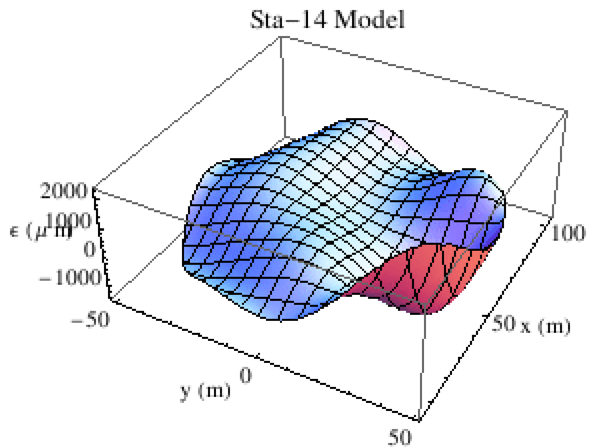

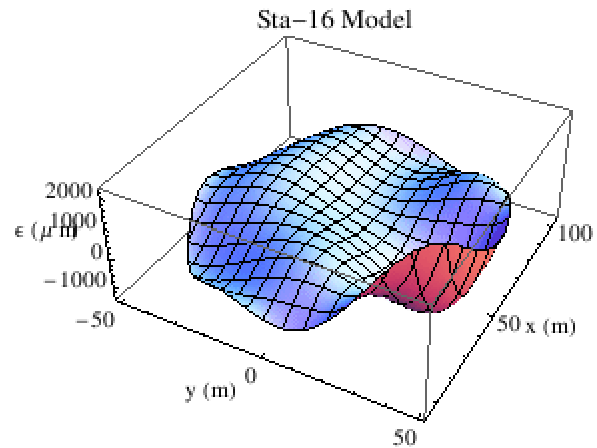

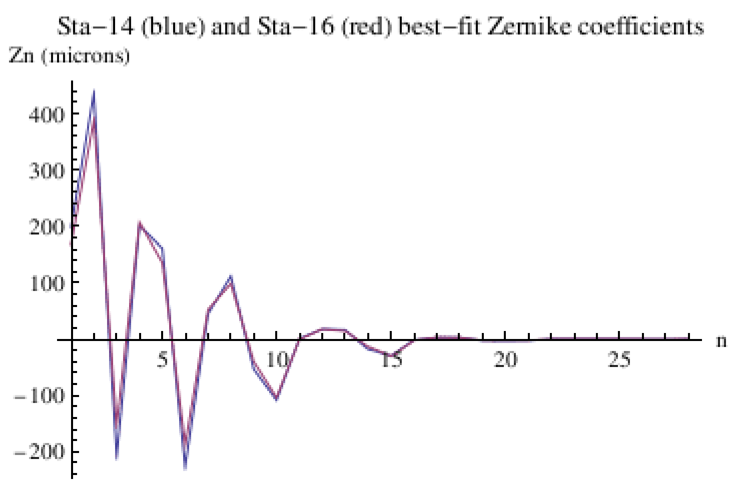

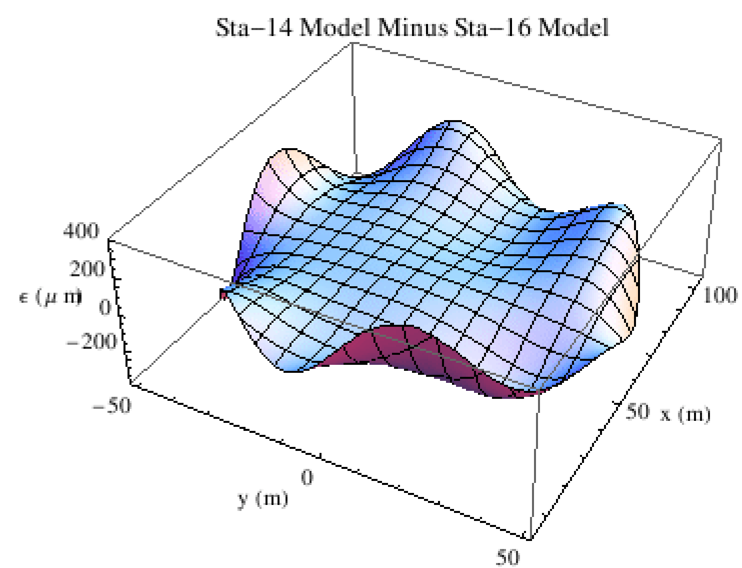

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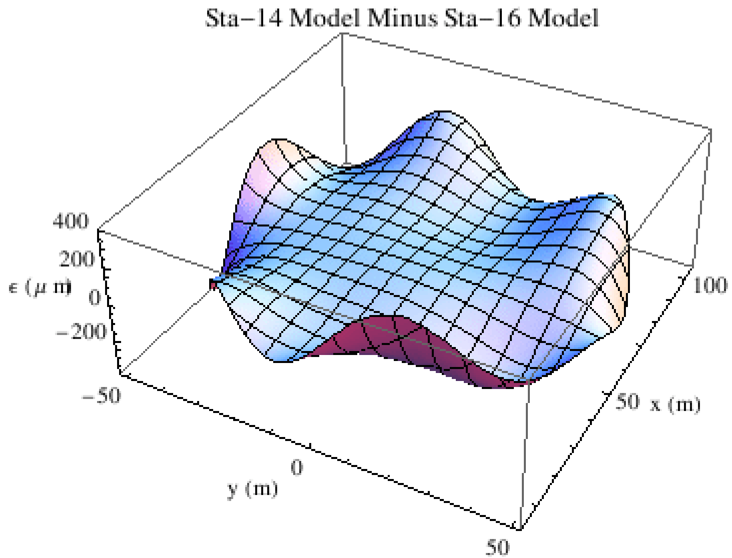
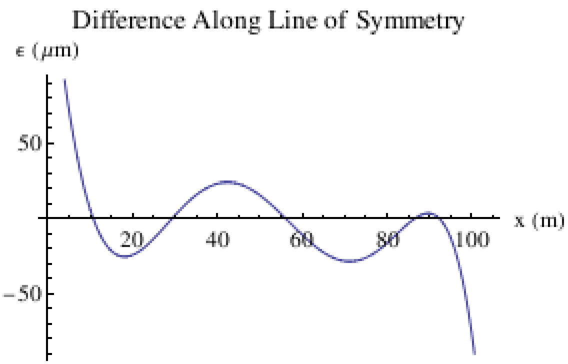
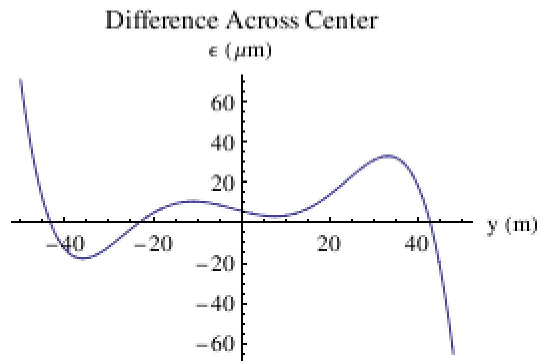


Difference of two successive runs (best case!)





RMS Differences:

- |r| < 50m = 68μm
- |r| < 45m = 48μm
- |r| < 40m = 38μm

RMS of single a measurement: ~ 35μm

RMS of two subsets of the same run ~ 18μm

best case OOF holography: ~ 40μm

Estimated error budget

- Small-scale errors:
  - panel manufacturing plus gravity error: 127 μm
  - residual actuator error: ~~80 μm~~ 50 μm
  - panel corner setting error: 80 μm
  - panel-scale thermal errors: 100 μm
  - subreflector: 75 μm
  - total small-scale error: 80+80+127+100+75 = 211 μm
- Large-scale thermal error: ~~100 μm~~ 30 μm
- Total error: ~~211+100 = 235 μm~~ **~ 200 μm!**

  201 μm

- Current OOF overhead ~ 20 m in 2 hr ~ 17%
- Potential Scan overhead ~ 10 m in 2 hr ~ 8%
- Independent of atmospheric opacity
- Daytime observing becomes possible!

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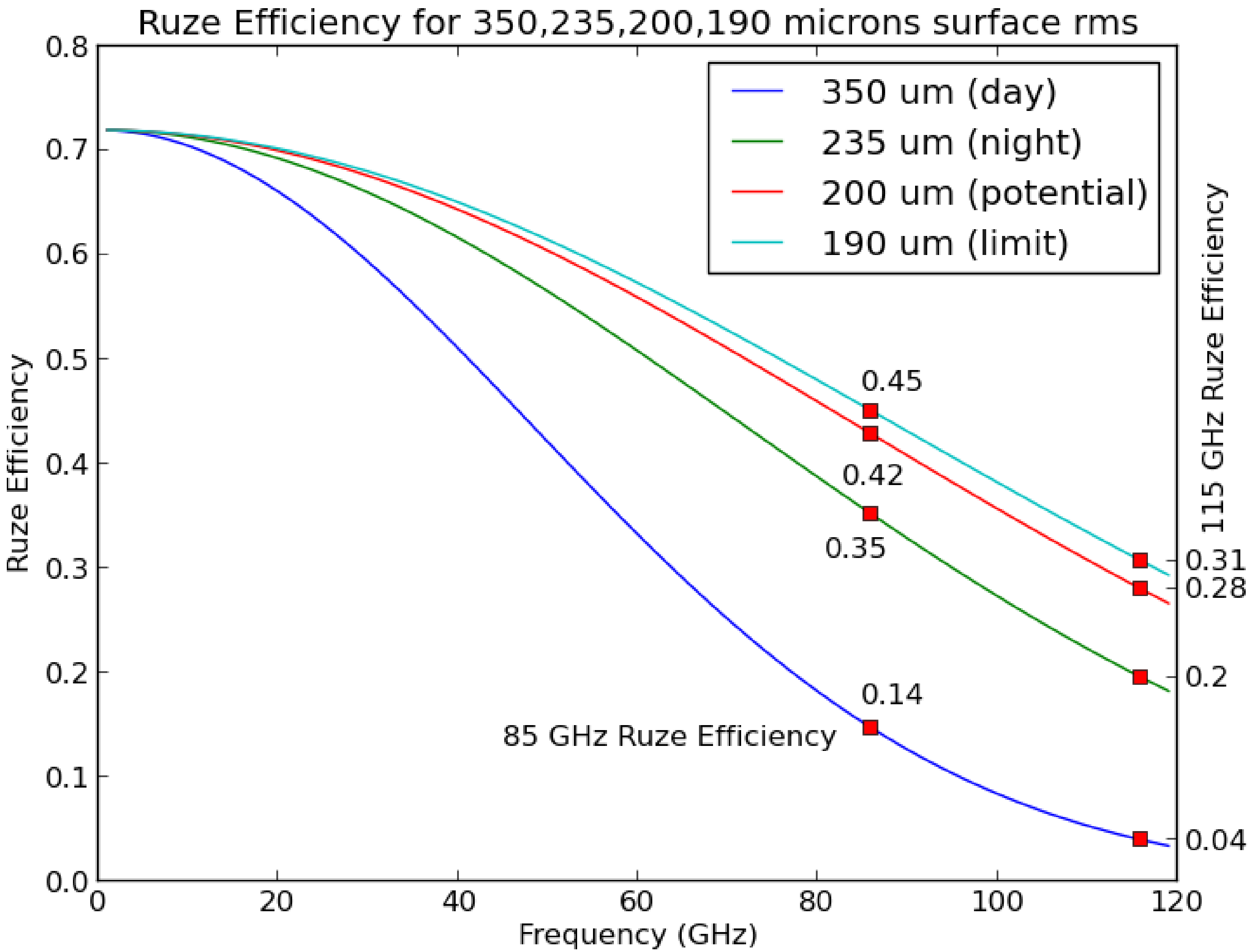
Ruze Efficiency



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Leica ScanStation P40 3D Laser Scanner

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$123,915 online

Save to Shortlist

The Leica Scan - Station P40 offers the highest versatility including long range (up to 885 ft/270m at 34% reflectivity), speed (up to 1 million points per second), and accuracy (3D positional accuracy of 3mm at 50m; 6mm at 100m). Delivering outstanding range, speed and data ... more »

$86,740 with academic discount !

Online stores Reviews Details

Online stores shipping to Green Bank, WV

☐ Free shipping ☐ Refurbished / used

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Sellers	Seller Rating	Details	Base Price	Total Price	
FLT Geosystems	No rating	No tax	$123,915.00 +$26.48 shipping	$123,941.48	Shop

1 - 1 of 1

Performance Summary

Wind	σ_2
Benign Night-time	< 1.5”
5 ms^{-1}	~ 2.5”
10 ms^{-1}	~ 8”

Tracking Accuracy

Surface RMS	$\eta_{surface}$ 85 GHz	$\eta_{surface}$ 115 GHz
350µm	0.14	0.04
235µm	0.35	0.20
200µm	0.42	0.28

Surface Efficiency

Collaborators Needed!

- ***We are currently about to commission three new ~ 3-4mm instruments!***
  - Argus
  - MUSTANG 2
  - U. Mass. / BYU Phased Array Feed + Beamformer

- ***All are being funded by current or recent NSF AST Grants!***

- We need to propose two further Proposals:
  - GBT Servo Improvements (PI Mario Garcia-Sanz, CWRU)
  - New Surface Measurement System (PI – me)

Please come by and talk to me in the next few days!

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Thank you!