

The GBT Precision Telescope Control System

Kim Constantikes



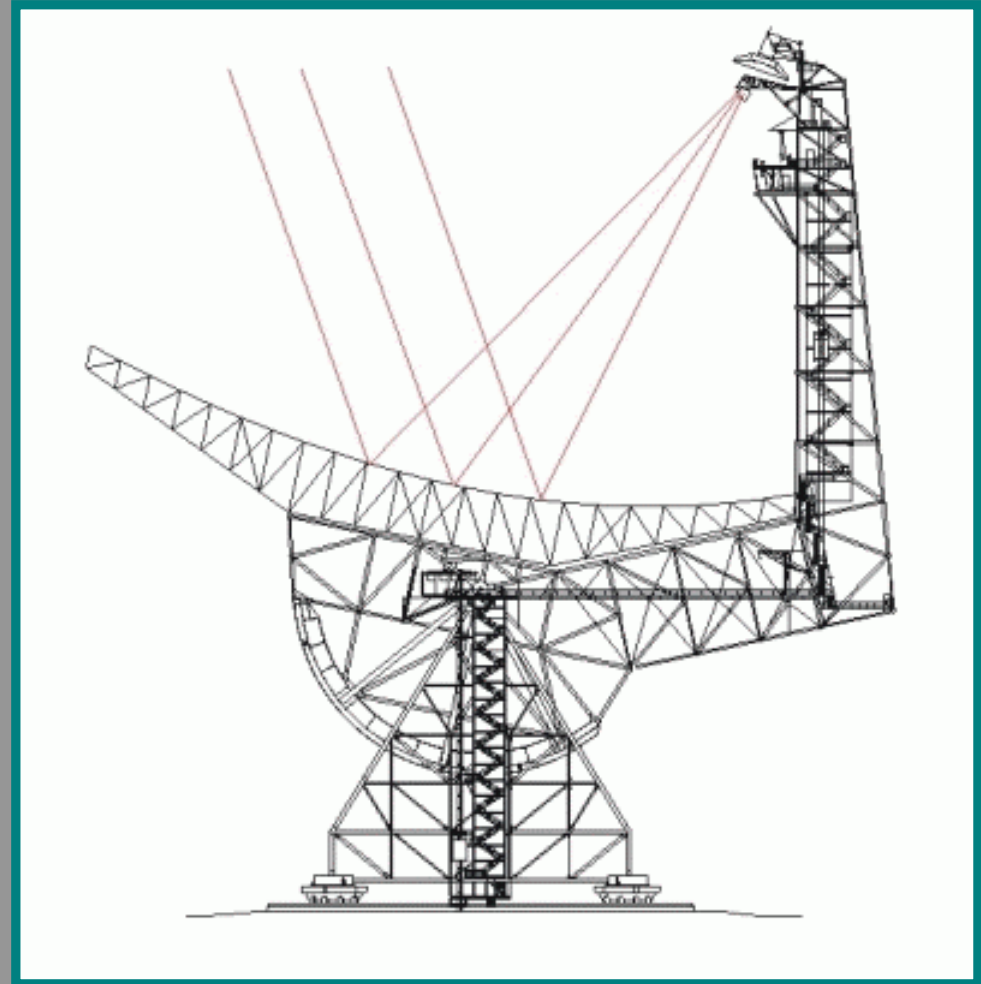
Ohio University
May 24, 2004

Overview



- The Green Bank Telescope
- Scientific Requirements and Objectives
- The Real Telescope
- Instrumentation
- Next Steps

Telescope Structure and Optics





Telescope Structure and Optics

- Offset-Gregorian design
- Operation to 115 GHz, 40 GHz winter 2003-2004
- Optics: 110 m x 100 m of a 208 m parent paraboloid
 - Effective diameter: 100 m
 - Off axis feedarm
 - F/D ~ 0.6
- Elevation Limit: 5°
- Slew Rates: Azimuth - 40°/min; Elevation - 20°/min
- Main Reflector: 2004 actuated panels with 68 μm rms.
 - Total surface: rms 400 μm
- FWHM Beamwidth: $740''/f(\text{Ghz})$
- Prime Focus: Retractable boom
- Gregorian Focus:
 - 8-m elliptic subreflector with 6-degrees of freedom
 - Rotating Turret with 8 receiver bays
- Typical 20-60 K T_{sys} , maximum efficiency 70-75%, NEDT 1 mK to 1 μK

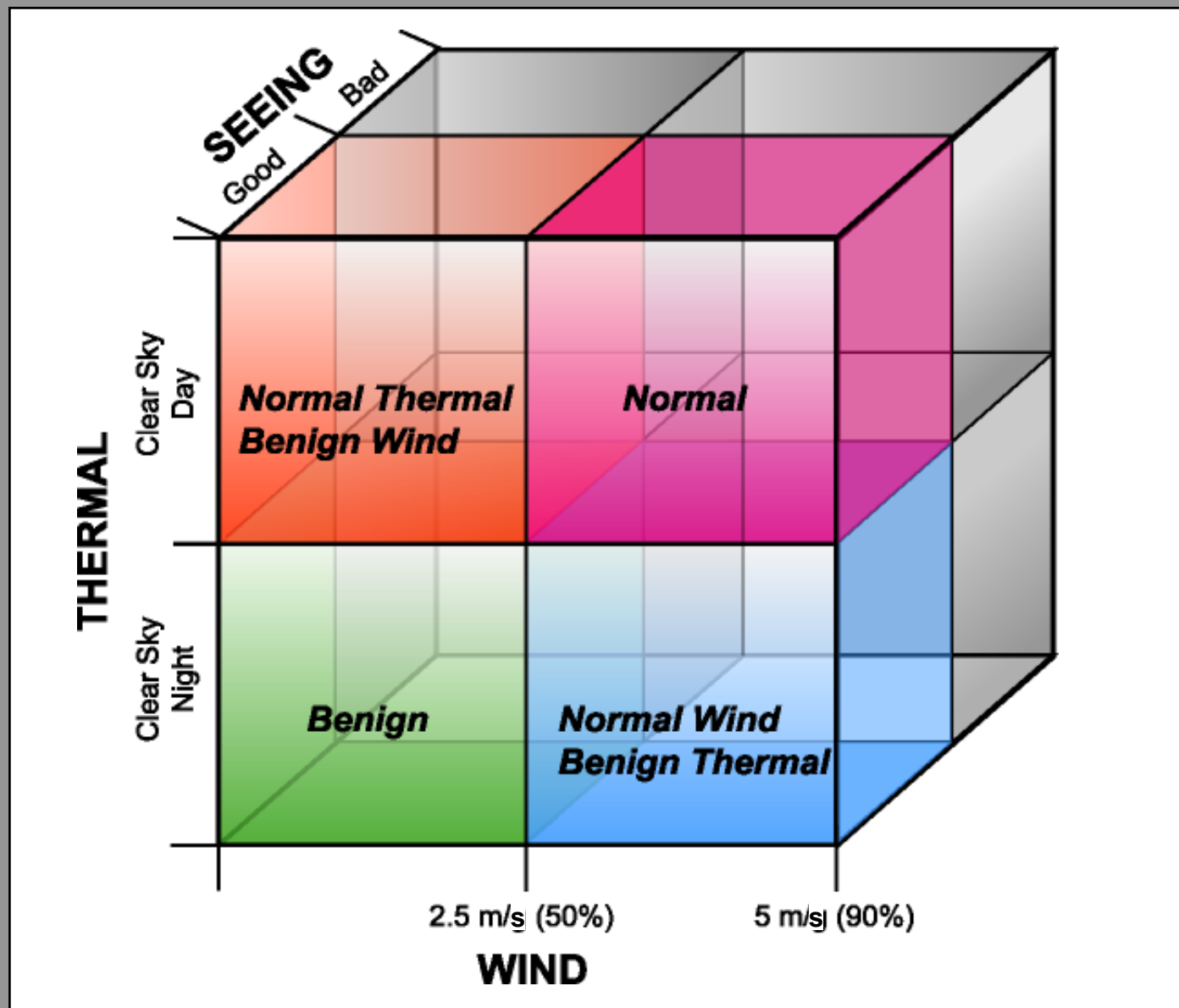
Scientific Requirements



Table 1. PTCS Specifications and Constraints

Parameter	$\nu = 52$ GHz	$\nu = 86$ GHz	$\nu = 115$ GHz	Units	Notes
Wavelength λ	5.8	3.5	2.6	mm	
FWHM beam θ	14.2	8.6	6.4	arcsec	Eq. 1
“Usable” offset tracking σ_2	2.8	1.7	1.3	arcsec	Eq. 6
current wind $ v $	3.0 (6.6)	2.3 (5.2)	2.0 (4.5)	m s^{-1} (mph)	Eqs. 6, 12, 13
requirement wind $ v $	3.5 (7.8)	2.5 (5.6)	2.5 (5.6)	m s^{-1} (mph)	
“Good” offset tracking σ_2	2.0	1.2	...	arcsec	Eqs. 7 and 12
current wind $ v $	2.5 (5.6)	1.9 (4.3)	...	m s^{-1} (mph)	Eqs. 7, 12, 13
requirement wind $ v $	2.5 (5.6)	2.5 (5.6)	...	m s^{-1} (mph)	
Calibrator accuracy $\sigma_2(\text{cal})$	0.7	0.3	0.3	arcsec	Eq. 8
Tracking time Δt	0.5	0.5	0.5	hours	Eq. 11
Blind azimuth pointing σ_A	4.3	2.6	1.9	arcsec	Eq. 16
Blind pointing gradient $ \Delta E /\text{rad}$	10.8	6.5	7.0	"/rad	Eq. 18
“Usable” effective ϵ	0.46	0.28	0.21	mm	Eq. 21
“Usable” focusing $ \Delta y_s $	2.9	1.7	1.3	mm	Eq. 23
“Good” effective ϵ	0.36	0.22	...	mm	Eq. 20
“Good” focusing $ \Delta y_s $	1.4	0.9	...	mm	Eq. 24

PTCS / High Frequency Environmental Envelope



Scientific Requirements



- Efficiency/Collimation: Aperture error $\sim < 1/16\lambda$
 - Maximize flux collected from unresolved source
 - Minimize background confusion, e.g., bright source in sidelobe
 - Best spatial sampling for mapping, e.g., think of beam shape as spatial impulse response
- Pointing
 - Minimize calibration uncertainty of unresolved source intensity
 - Maximize collected flux
 - Accurate enough to find calibrator (blind)
 - Offset good enough over $\sim 5^\circ$ to find program source
 - Track stable over one-half hour



Pointing Coefficients

Table 2. GBT Pointing Coefficients

Component Motion	Effect on Pointing
Primary focal length increase	-1.9 arcsec mm ⁻¹
Primary Y rotation	+1.77 arcsec arcsec ⁻¹
Primary X translation	+2.7 arcsec mm ⁻¹
Primary Y translation	-1.9 arcsec mm ⁻¹
Primary Z translation	-1.9 arcsec mm ⁻¹
Subreflector X translation	-3.8 arcsec mm ⁻¹
Subreflector Y translation	+2.9 arcsec mm ⁻¹
Subreflector Z translation	+2.1 arcsec mm ⁻¹
Subreflector X rotation	+0.15 arcsec arcsec ⁻¹
Subreflector Y rotation	+0.13 arcsec arcsec ⁻¹
Feed X translation	+1.05 arcsec mm ⁻¹
Feed Y translation	-1.05 arcsec mm ⁻¹
Feed Z translation	-0.25 arcsec mm ⁻¹

Feed arm tip moves ~ 400mm as elevation changes from horizon to zenith:
 ~ 300 arcsec of elevation pointing
 ~ 100 mm of focus shift
 > 2 orders of magnitude improvement needed!

Entire pointing error budget is:
 0.32 mm subreflector X translation, or
 0.41 mm subreflector Y translation, etc.



- 2003
 - Develop and test methods for astronomical characterizations of structure- pointing and efficiency- and collect data
 - Improvements in gravity model
 - Develop instruments and algorithms for thermal corrections, test and refine
 - Develop algorithms and test existing laser rangefinder system
- 2004
 - Implement additional instrumentation
 - Develop additional algorithms, test
 - Emphasize slow perturbations: Available servo bandwidth < 1 Hz (subreflector), dominant effects are ~ 0.1 Hz or less.
 - Have new pointing and surface corrections in place for winter 2004-2005: Objective of “good” 52 GHz, “Usable” 86 GHz

Pointing Degradation Mechanisms:

Most are slow, < 0.1 Hz

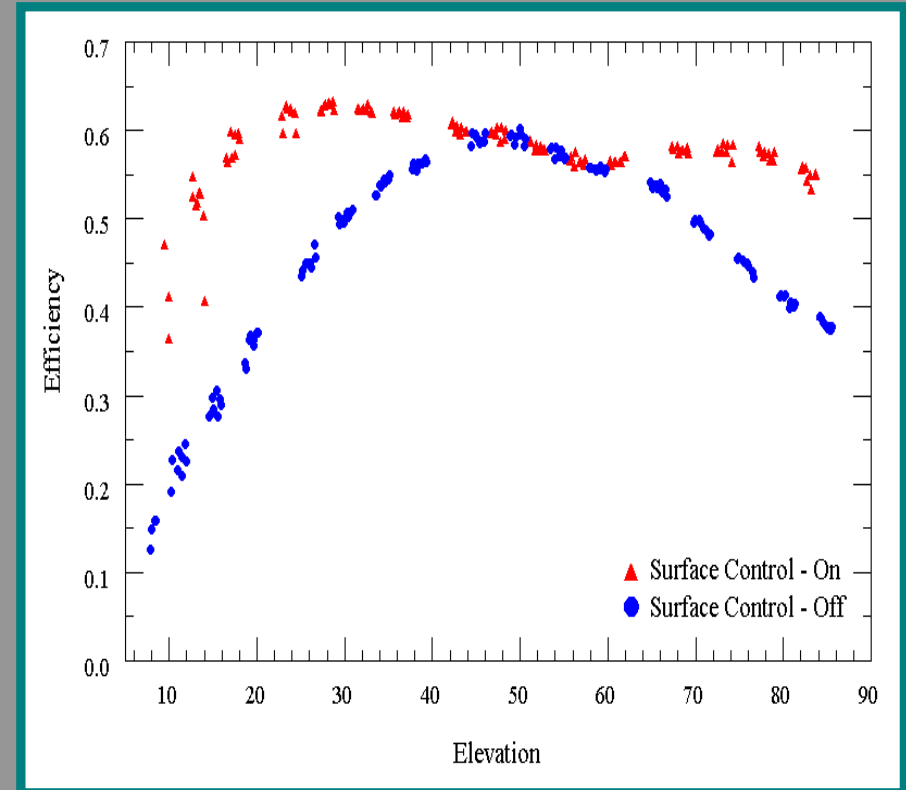
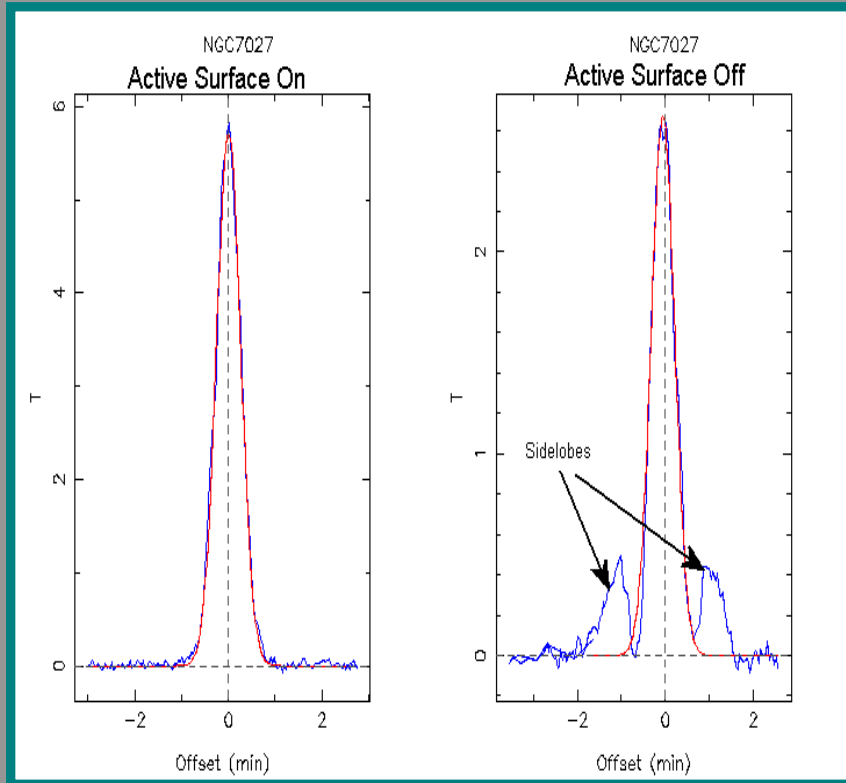


- Gravitational distortions, alignment:
 - Structure is linear (stress tensor), powerful constraint!
 - Compensate with “Traditional” pointing model: sin/cos of az,el (2-D Fourier series in general, “Condon Series”)
- Thermal distortions (mostly gradient):
 - Mechanical design is “homologous”. Diurnal focus variation ~ 40 mm, elevation variation ~ 30 arcsec, worst transient around sunup, large effects persist to hours after sundown
- Wind load distortions:
 - Predicted and measured pointing effects up to 10’s of arcsec
- Structural vibrations (particularly at “jerky” scan start)
 - 10’s of arcsec
- Azimuth track bumps, elevation anomaly ~ 5 arcsec
- Servo errors, response to perturbations (wind, bumps) ~ 1-2 arcsec
- Miscellaneous at ≤ 1 arcsec: Bearing wobble, encoder error...
- Anomalous refraction at high frequencies



- Efficiency:
 - Uncompensated gravitational distortions, i.e., structural finite element model prediction errors
 - Uncompensated thermal distortions of back-up structure (also causes focus error)
 - Primary panel shape errors
 - Secondary figure errors
 - Mis-collimation
- Polarization
 - Squint and Squash
 - Coupling

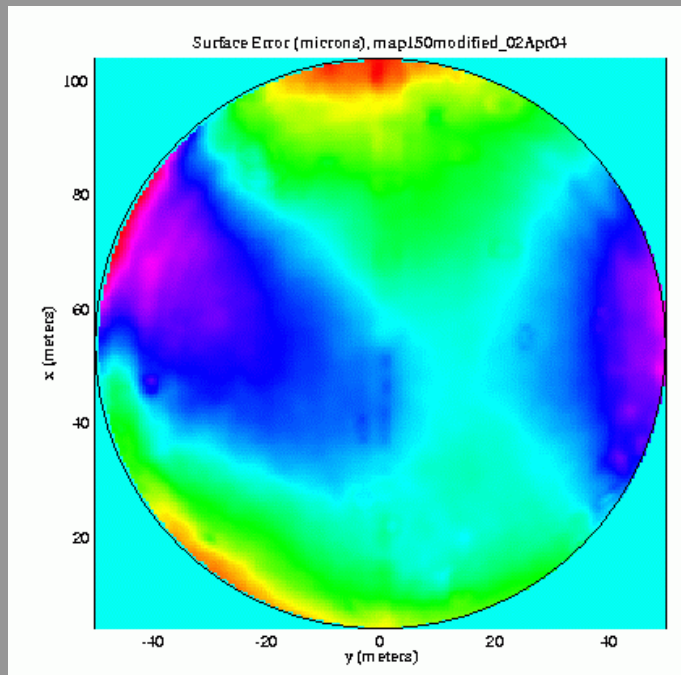
The Real vs. Ideal GBT: Efficiency and Beam Shape



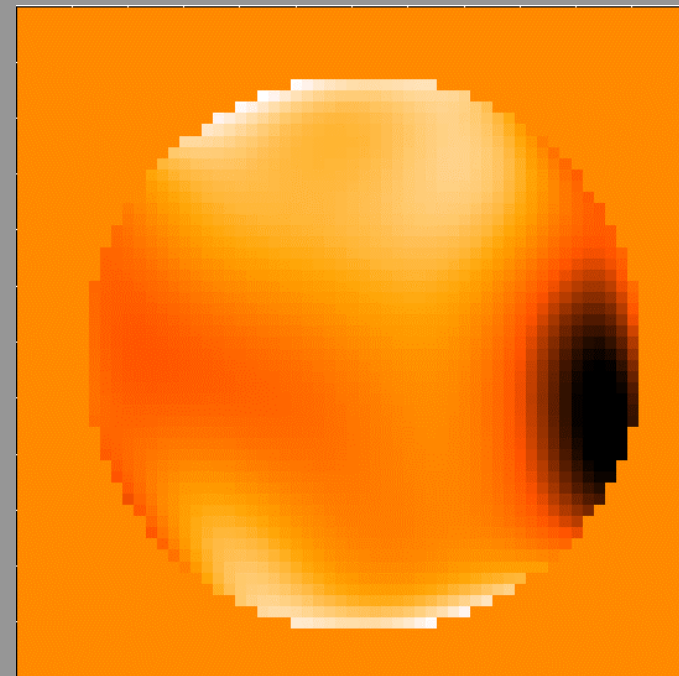
Holography Results



- Surface errors $\sim 300\text{-}400\mu\text{m}$ rms; dominated by large scale errors.
- Traditional and “oof” measurements; consistent but complimentary results.
- Efficiency improvements of $\sim 30\text{-}50\%$ by quick, easy large-scale adjustments.



150 x 150 pixel 12GHz traditional map

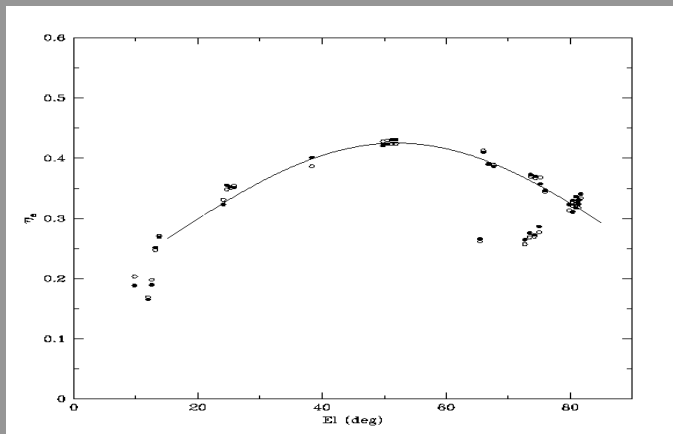


43GHz (SiO maser) OOF map

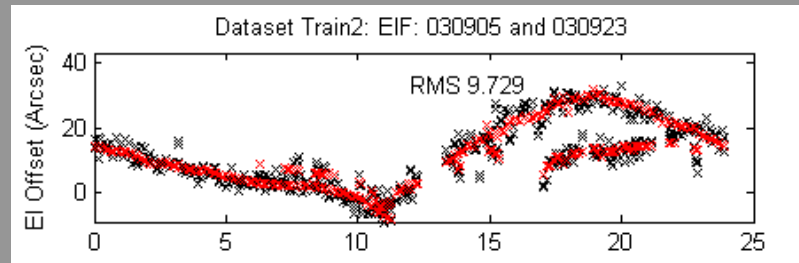
PTCS Technical Achievements



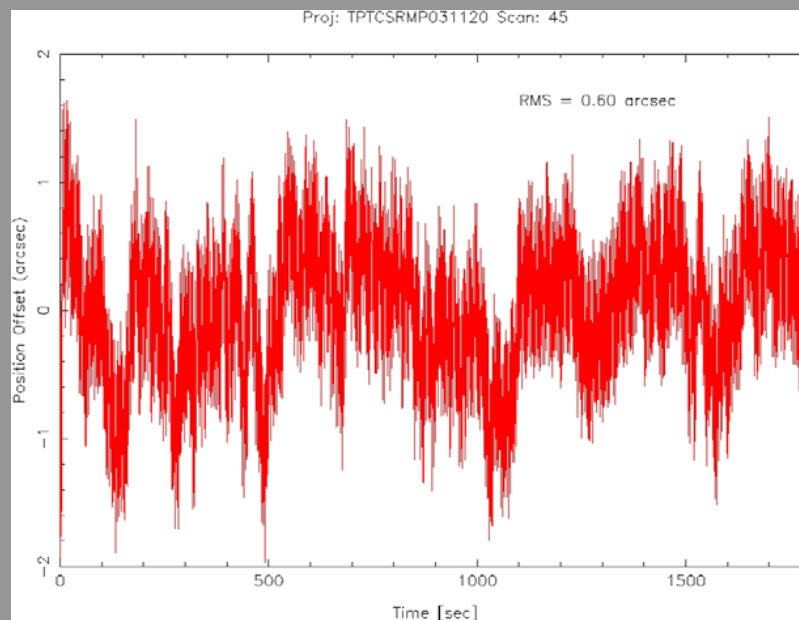
- Successfully passed two design reviews
- Delivered Q Band (43GHz) performance:
 - Blind pointing < 4" radial rms
 - Offset pointing < 2.7" radial rms
 - Focus < 2.5 mm rms
 - 43% peak efficiency



43GHz gain-elevation curve

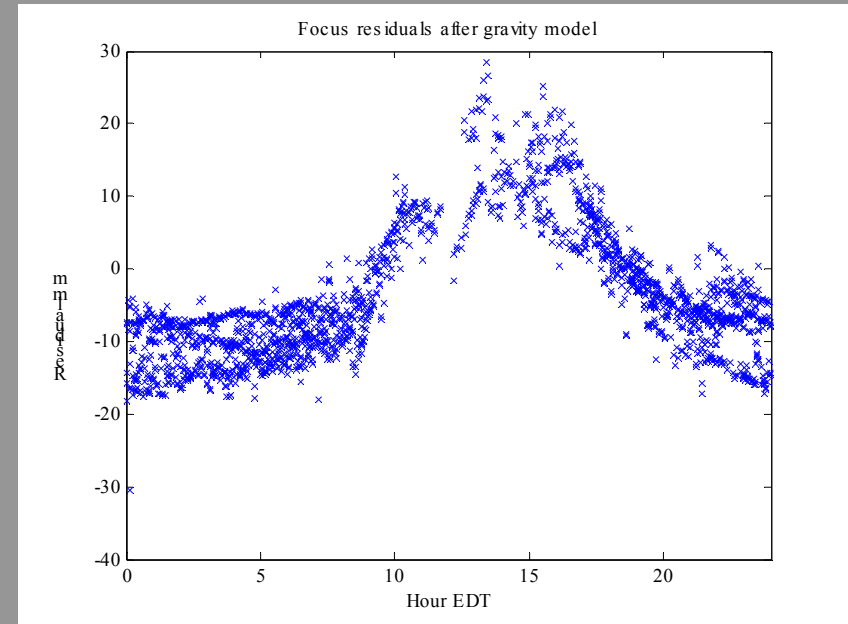
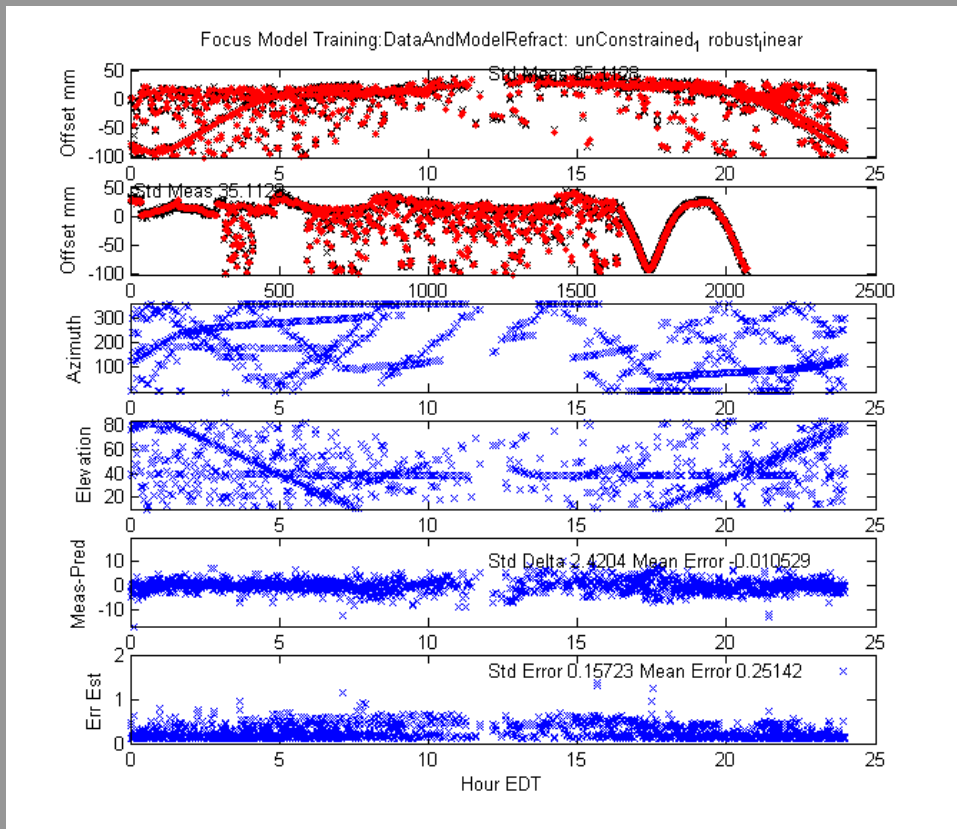


Dynamic pointing corrections



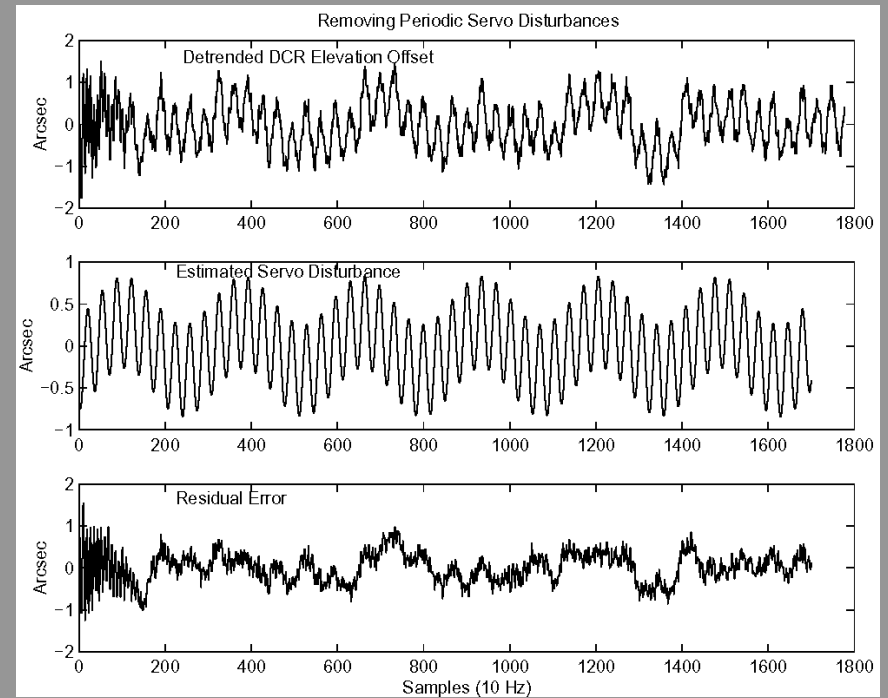
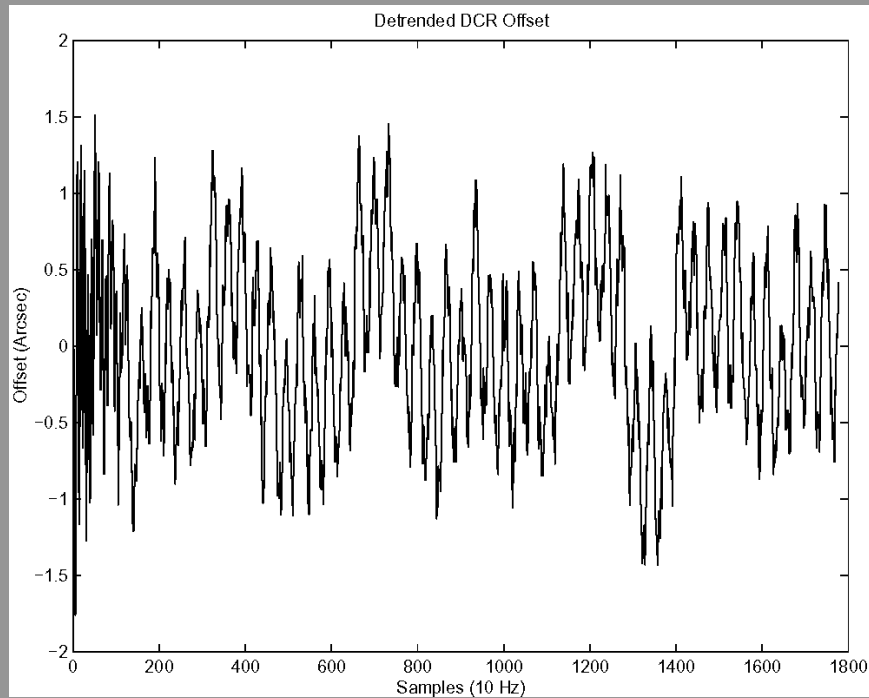
Half-hour $\frac{1}{2}$ power track, $\sigma_2 \sim 1''$

Correcting Focus for Thermal Distortions

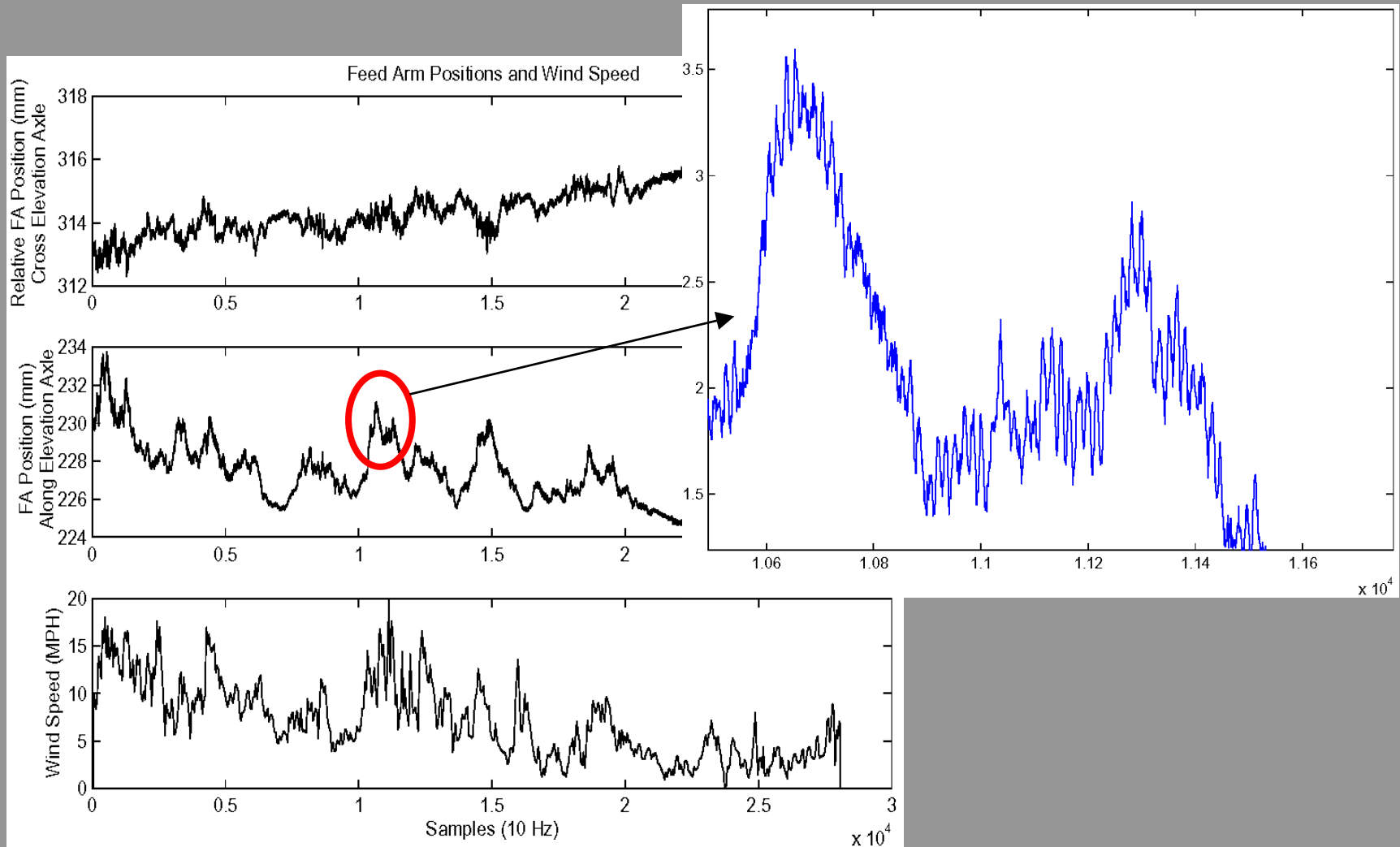


- Corrected via robust linear regression of linearized features:
- Temperature differences
 - Gravity model
 - Wind velocities in alidade-relative frame
- Include k-nearest neighbor estimates of az, el anomalies
- Current best model has 68% at < 2mm

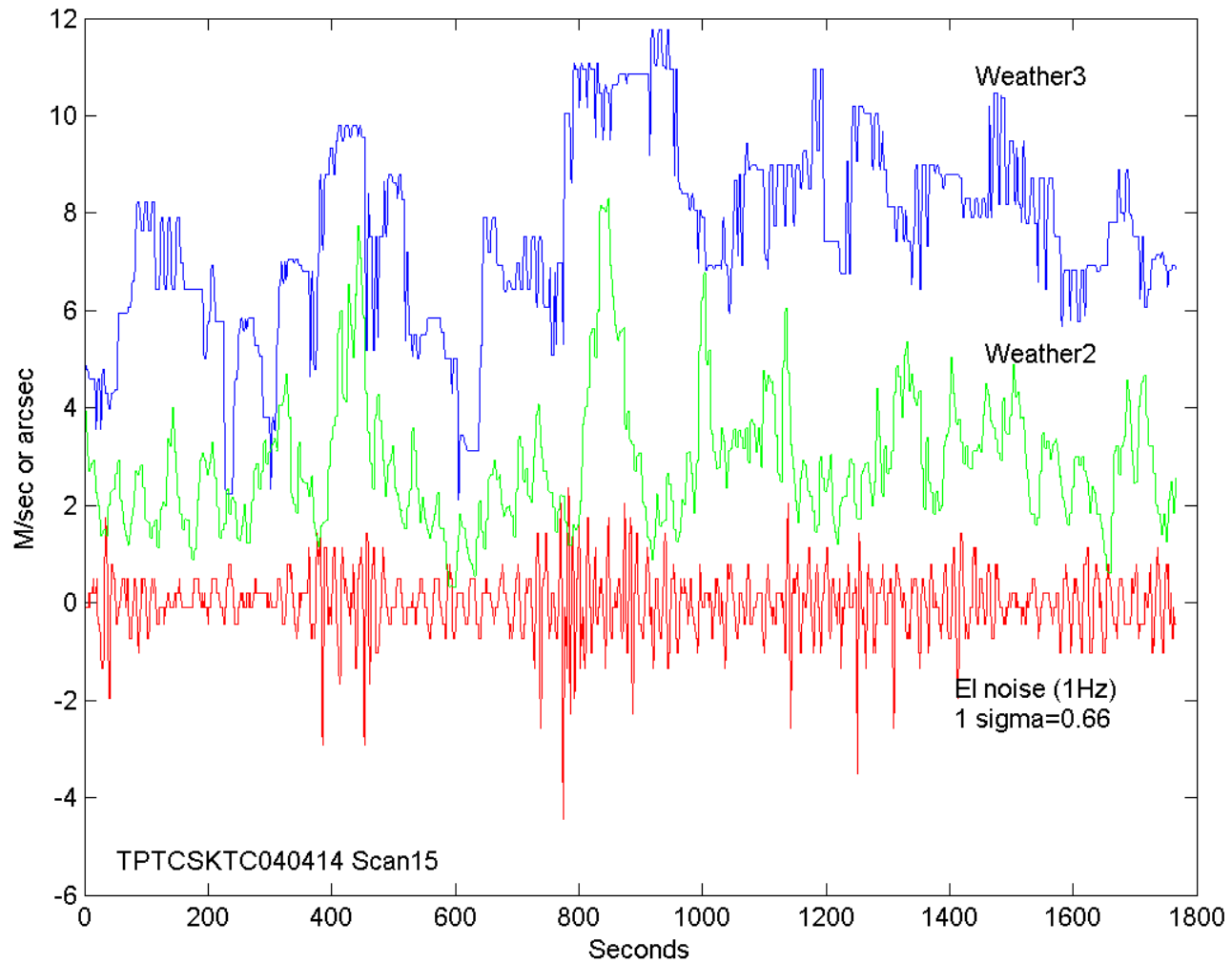
The Real vs. Ideal GBT: Servo Effects and Structure Vibration



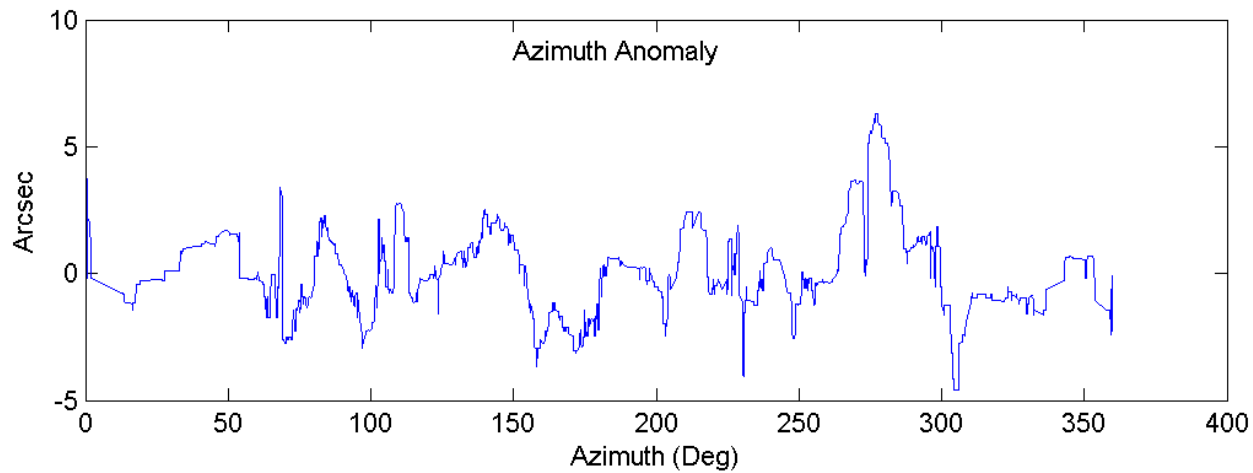
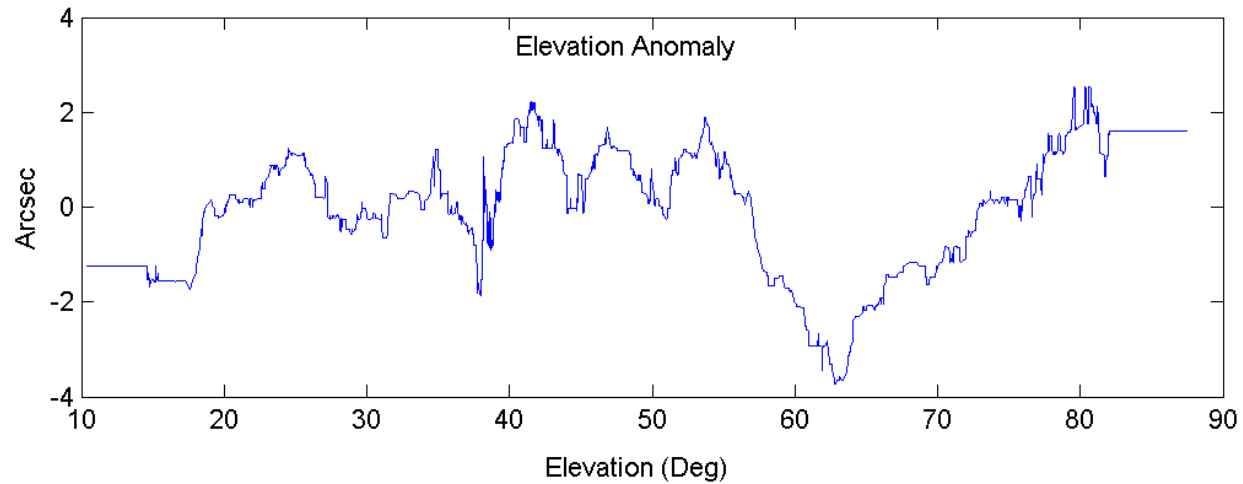
The Real vs. Ideal GBT: Wind Effects



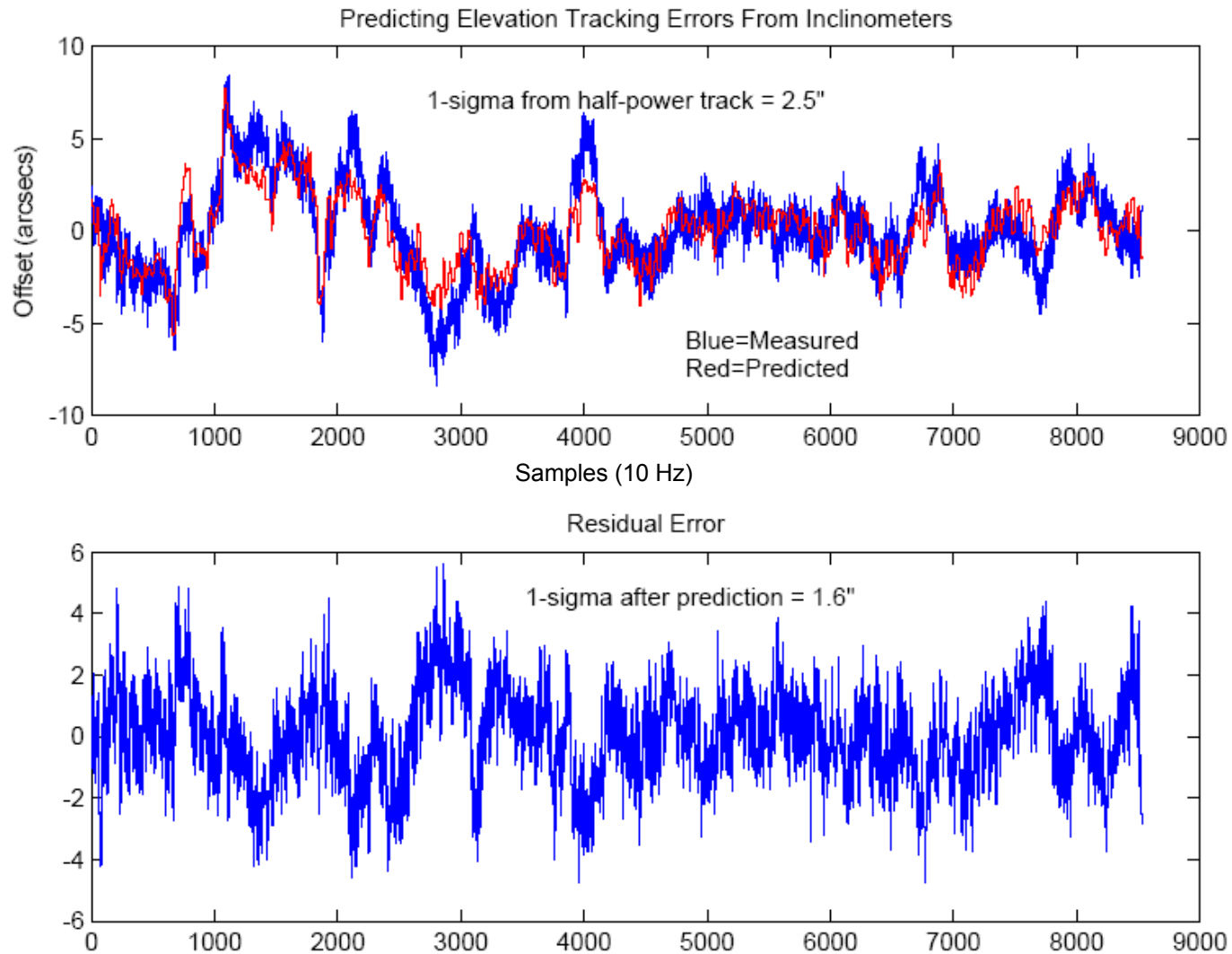
Wind-Servo Disturbance



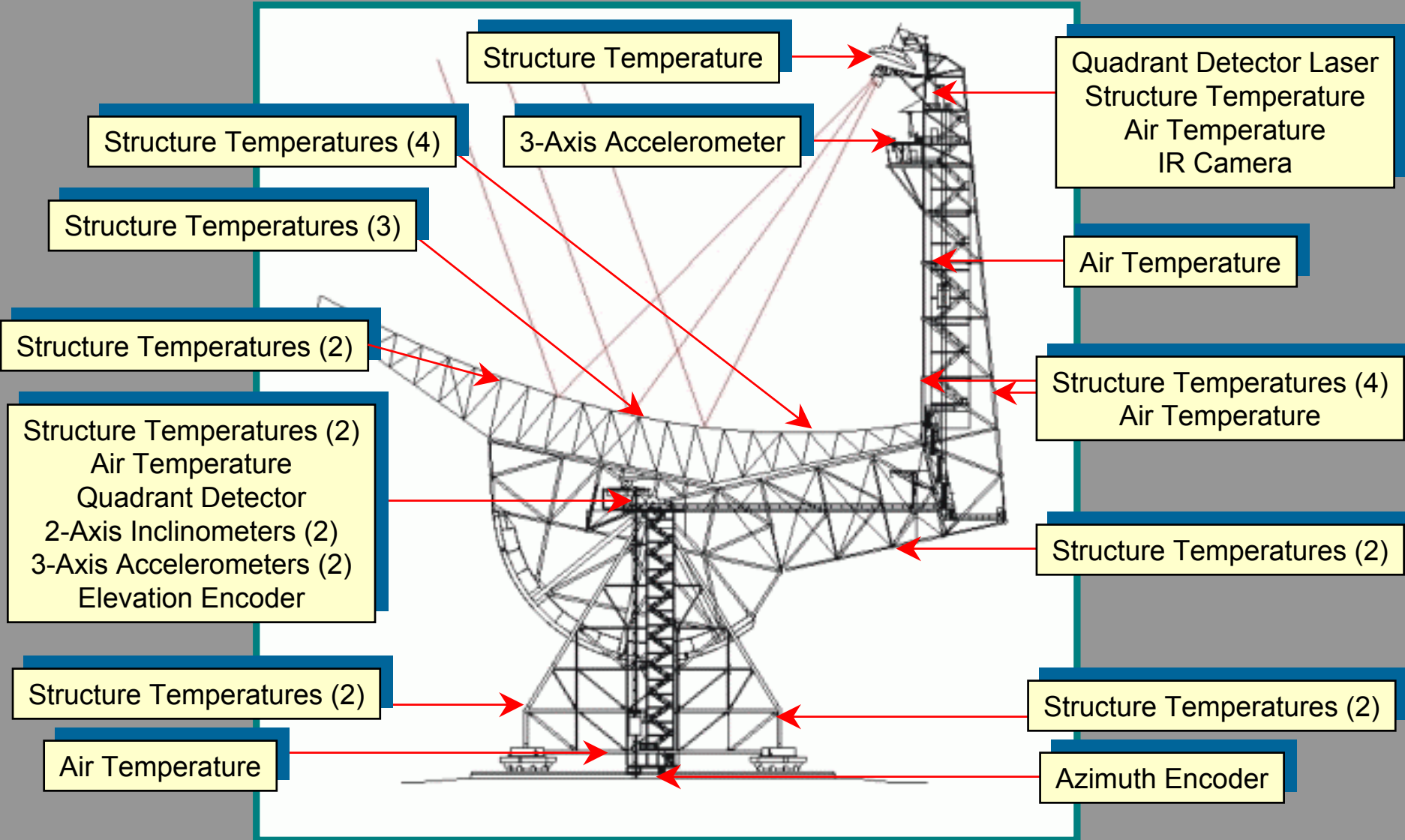
Azimuth and Elevation Anomaly



Predicting Tracking Error From Inclinometers



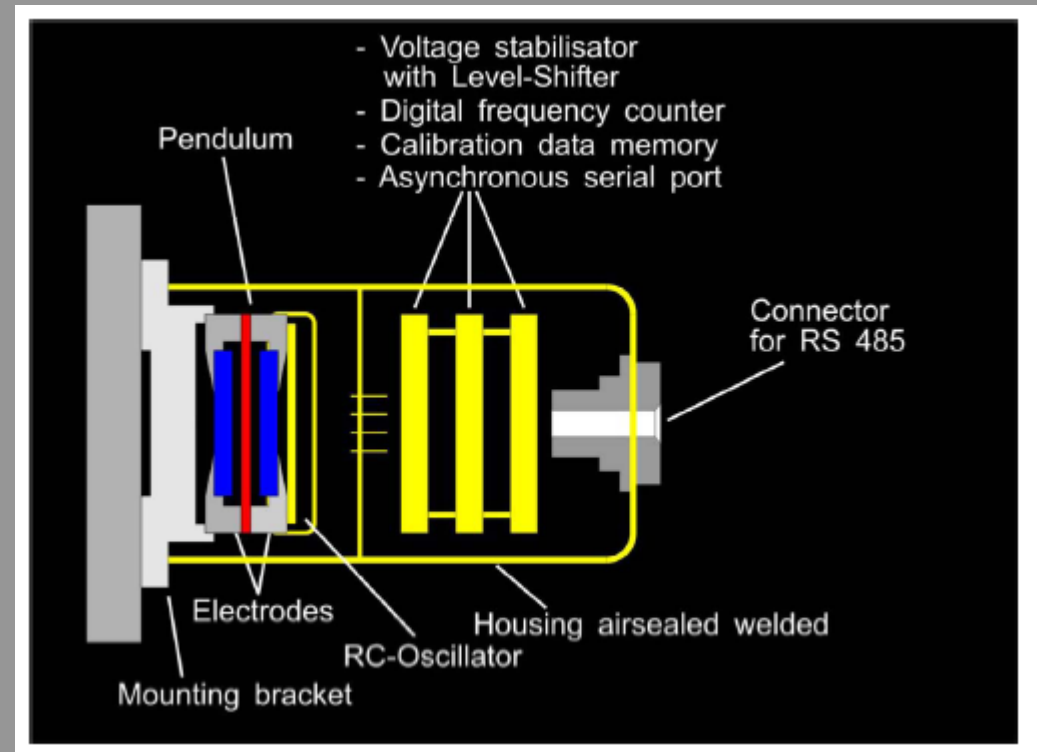
Instrumentation



Inclinometers

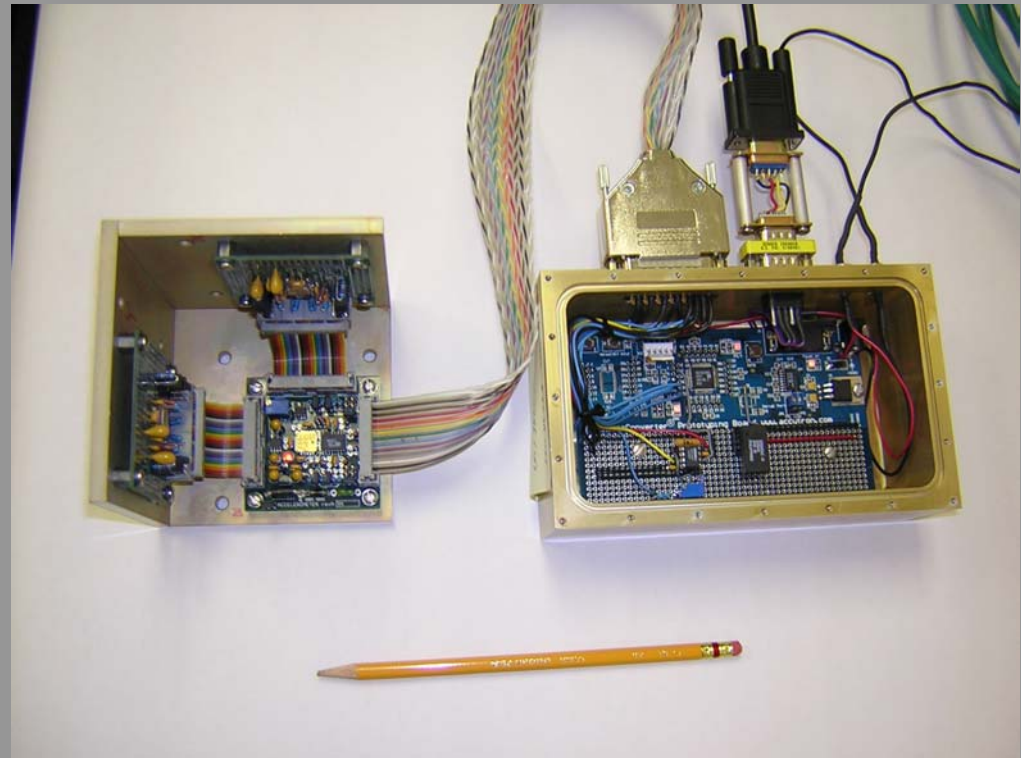
- 2-axis (horizontal plane), both elevation bearings
- 0.1" short-term accuracy, 0.01" resolution
- ~1 sec damping, 17 Hz resonance
- 10 Hz sampling rate

-
- Azimuth track maps
 - Real time measure/correct Az/EI
 - Verify thermal effects
 - Wind force spring balance
 - Structural resonances



Accelerometers

- 3-axis, elevation bearings and receiver cabin
 - MEMS torsion, capacitive readout, nickel
 - 2 micro-G/root Hz
 - 10 Hz sampling
 - 1 x 1 x 0.1 G dynamic range
 - 24 x 24 x 16 bit mixed signal ADC/microprocessor
-
- Structural resonances
 - Receiver microphonics
 - Rate-aid inclinometers



Laser Rangefinders



Laser Rangefinders

- 780 nm laser, 0.5 milliradian beam
 - 1.5 GHz CW modulation
 - Goal 100 micron accuracy
 - Variable integration time
 - Steerable beam, ~ 0.3 milliradian resolution
-
- Position by trilateration
 - Primary figure adjustments
 - Collimation
 - Structural model data



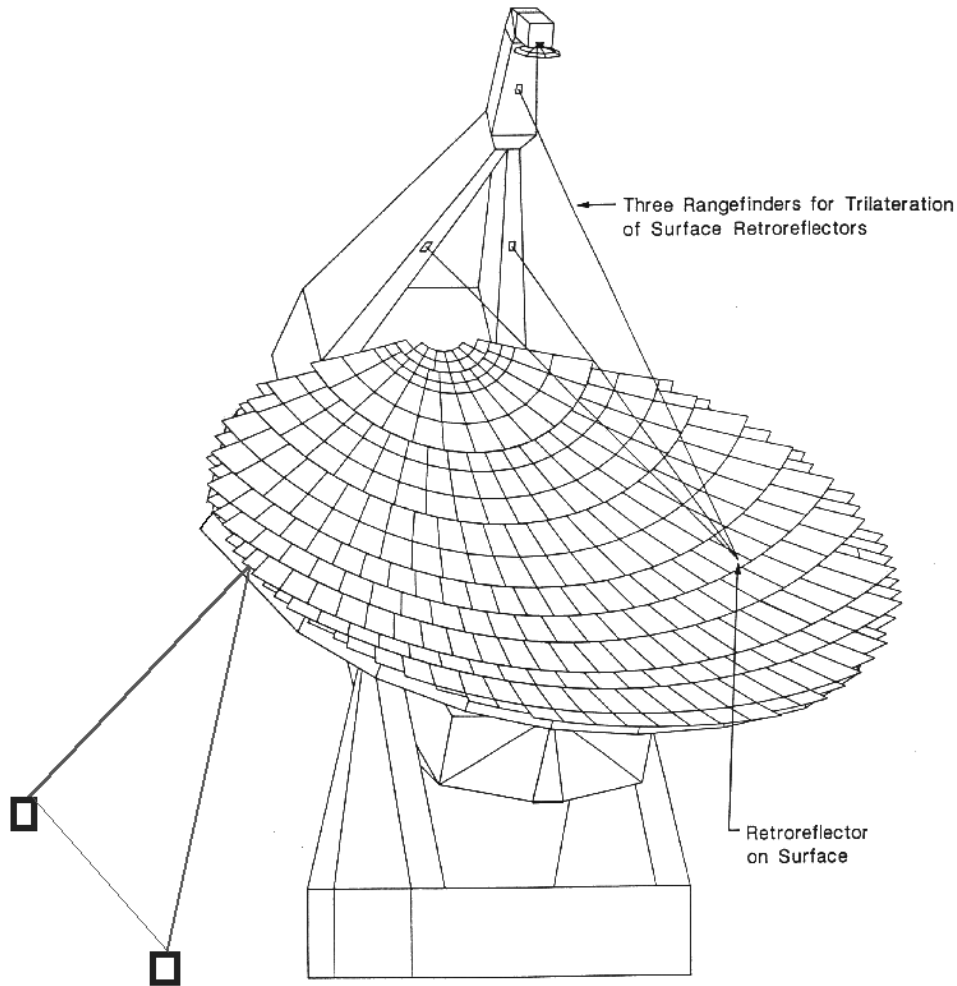
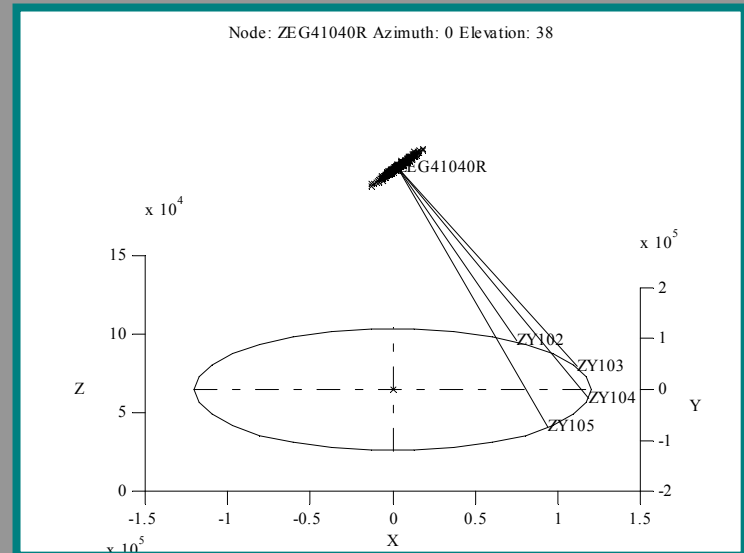
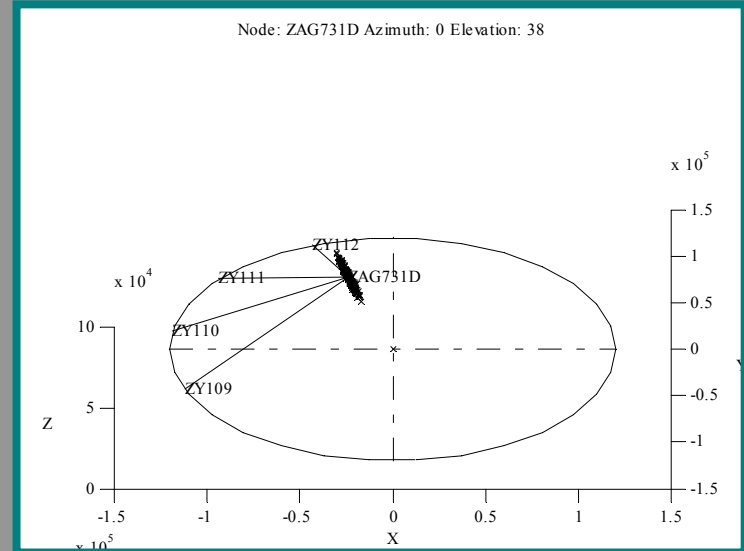


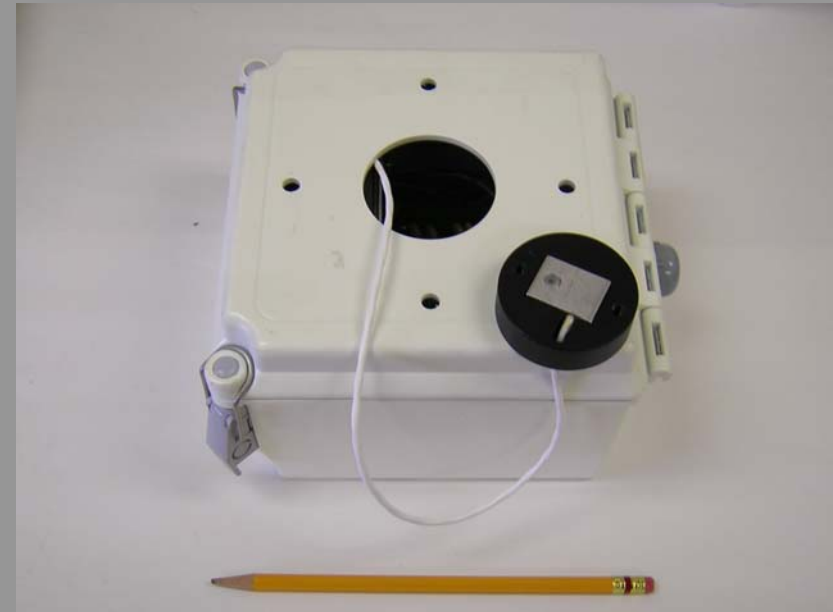
Fig. 1. The geometry of the metrology system.



Structural/Air Temperature Sensors

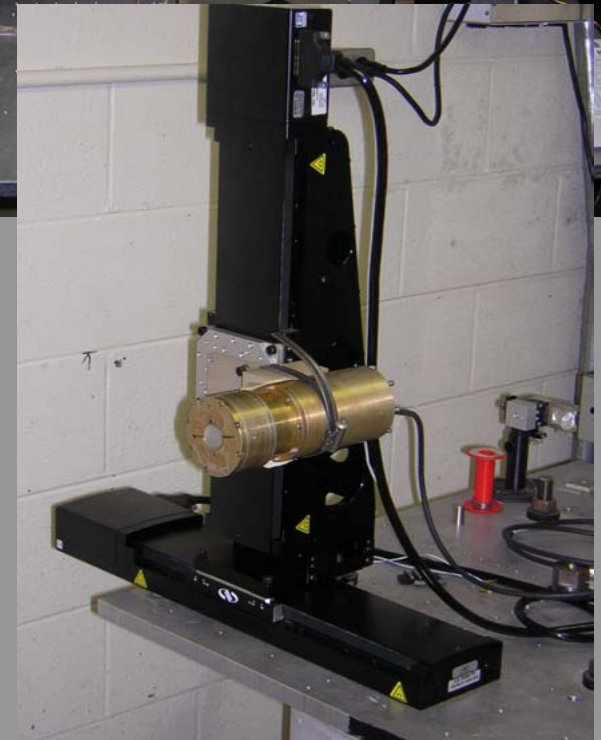
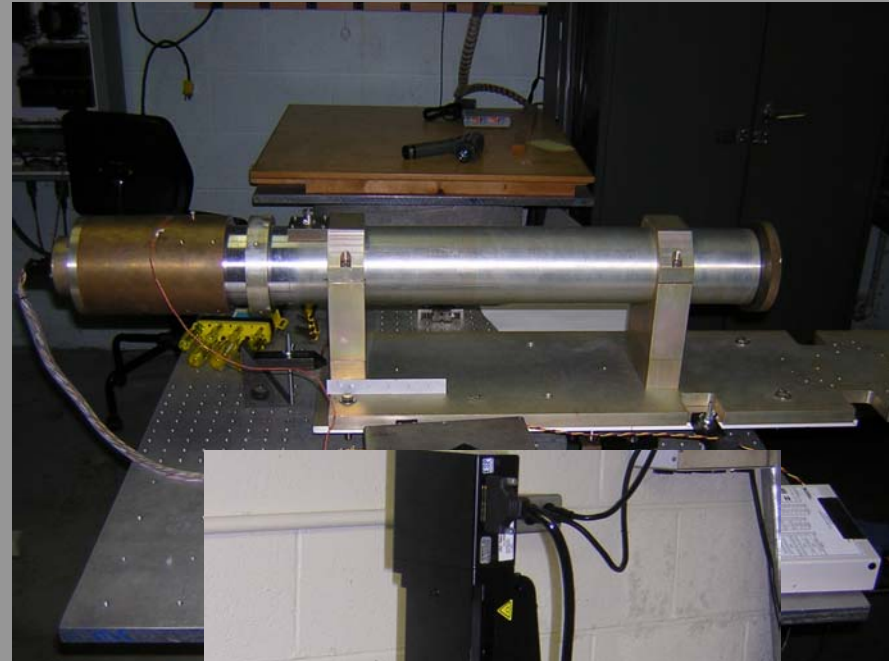
- 0.15 C accuracy, -35 to 40 C
- 0.05 C interchangeable thermistors
- 0.01 C resolution, 1 sec sampling
- 19 structure sensors (soon 23)
- 5 air sensors (forced convection cells, ~ 5 sec time constant)

-
- Structure thermal distortions
 - Vertical air lapse
 - Laser rangefinder group index calculations



Quadrant Detector

- 1 arcsec angle-angle measurements
 - ~5 Hz bandwidth, sampling at 10 Hz
 - Measurement noise ~ 0.2 arcsec (in lab)
 - Good relative measurements on 1/2 hour time scales
 - Degraded by turbulence, index gradients
-
- Feed arm position/motion WRT ~elevation shaft (tipping structure coordinates)
 - Structural resonances





- 160 x 120 8-12 micron uncooled microbolometer array (Inframetrics)
- 0.1 C resolution, accuracy = ?
- Image primary mirror from feedarm
- Primary surface coating black in long wave, Lambertian
- Supporting temperature sensors on two panels, two adjacent locations in back-up structure (BUS)

- Thermal gradients of mirror
- Inferences of BUS gradients
- Combine with OOF maps to refine FEM stiffness estimates of BUS
- Regressions with OOF to get thermal distortions

Weather Stations, Servo Monitor



- Three weather stations
 - Air temp, wind speed/direction, humidity, barometric pressure
 - Two on periphery of compound, one on feed arm tip
- All drives are monitored
 - Currents and tachometers



Current Best Efficiency

- Zernike corrections of primary using OOF maps:
Improved 40° elevation efficiency (Q-band) by ~25 to 40%
- Beam width reduced
- Sidelobes attenuated



Current Best Pointing Models

- Training on all data but test sets
- Test sets: One “Track”, one all-sky run
- Train results: 68th percentile residuals, all elevations, all winds, all hours-
Focus: 2.2 mm, Elevation: 2.6”, Azimuth 3.6”
- Track results: 68th percentile residuals, elevation 20-85, winds < 3.5 m/s, 0000-0800 EDT-
Focus: 0.7 mm
Elevation: 1.9” (6” offset)
Azimuth 2.8” (7” offset)
- All-sky results: 68th percentile residuals, elevation 20-85, winds < 3.5 m/s, 0000-0800 EDT-
Focus: 1.1 mm
Elevation: 2.3” (2” offset)
Azimuth 2.6” (3” offset)



Technical Challenges 2004-2005

- Laser Rangefinders
 - Risk mitigation for other techniques
 - Improved rangefinder pointing
 - Improved ground and feedarm geometries: Larger acceptance angle retros (n=2 glass), cantilevered supports on feedarm
 - Next measurement campaign summer '05
- Utilization of new instruments
 - System ID for inclinometers: Separate vibrations, azimuth drive hunting- attempt real time corrections for azimuth track and wind forces. Possibly directly to half-power track data...
 - IR Thermometry and OOF maps: Combined thermal/gravity enhancements of active surface control
- Better characterization of pointing performance
 - Quantitative offset and track analysis: What are metrics? Can metrics be used for more sophisticated optimizations? Use for Monte-Carlo detection experiment design?

Technical Challenges 2004-2005



- Implement and test new pointing models, including
 - Wind effects
 - Azimuth track effects
 - Elevation anomaly
- Start design of dense temperature sensor infrastructure-
Increase sensors by x10?
- Algorithms for improved trajectory shaping/control
 - Minimization of structure transients
 - Maximize observing time
- Engineering tests of bolometer array may be possible in early spring 2005
 - Great potential for investigating beam shape, optimizing efficiency, speed up OOF mapping.
- Collect/analyze additional astronomical data on pointing, wavefront errors

Technical Challenges 2004-2005



- Thermal-mechanical FEM of BUS
- Characterize main drive controls, investigate new control algorithms- Does modern control approach have advantages?

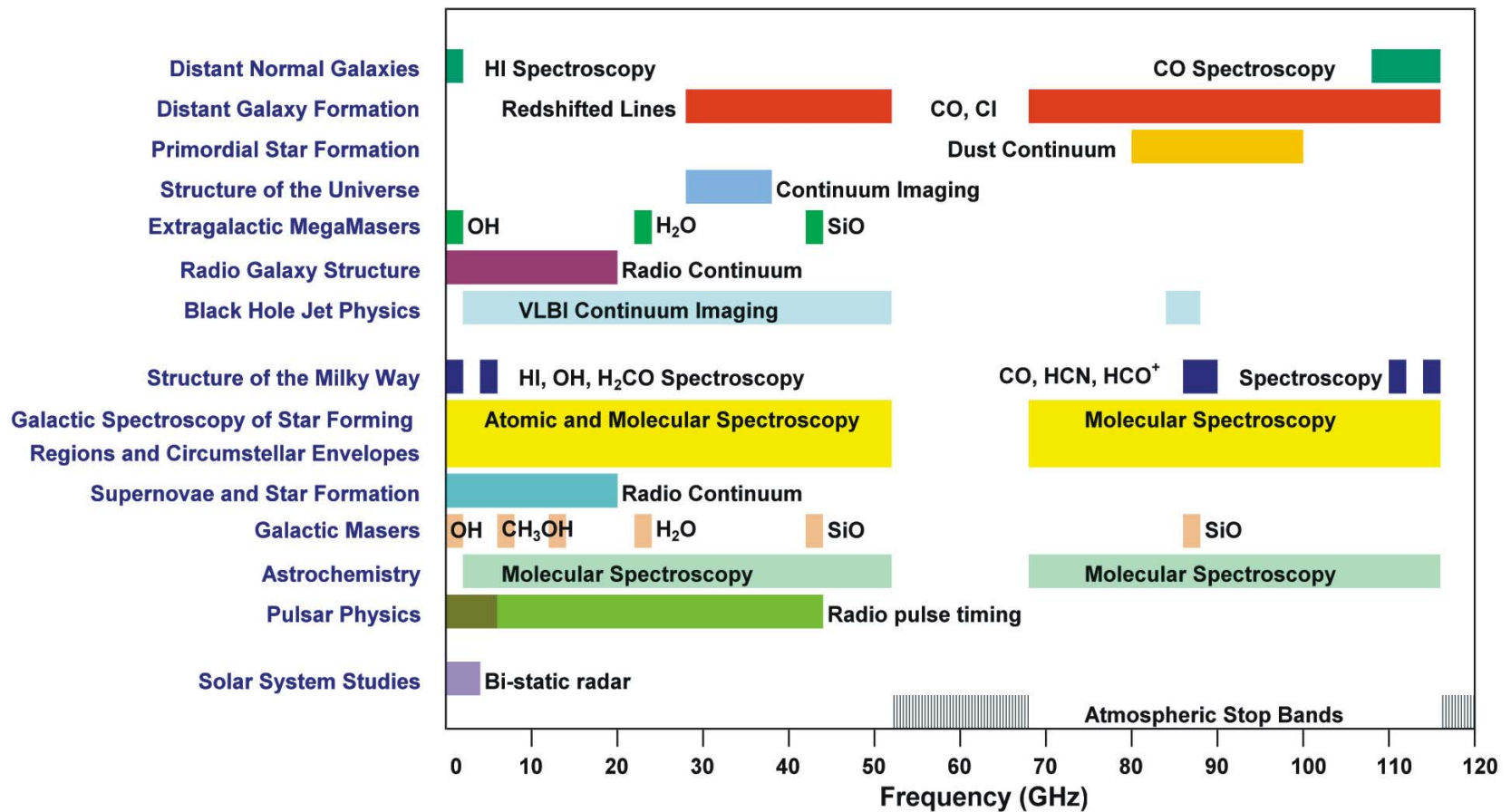
Backups



GBT Science Summary – Frequency Coverage



SCIENCE WITH THE GBT





Predicted Pointing Errors, 5° C Gradient, 5° EI

Loral Tech Memo 52 Table 2-20		EI=5, $\Delta T=5, V_w=0, \text{Sun Az}=180$		
Error Sources	EI Errors (arcsec)		X-EI Errors (arcsec)	
	Repeatable	Nonrepeatable	Repeatable	Nonrepeatable
Mechanical Alignments				
RF/EI Axes Orthogonality	0.0		0.0	
EI/Az Axes Orthogonality	0.0		5.2	
Az Axis Verticality	5.0		0.4	
Structural Deformations				
<u>Reflector</u>				
Wind				
Thermal Gradient		0.3		
<u>Alidade</u>				
Wind				
Thermal Gradient		11.5		
Servo and Drive		0.9		0.3
Miscellaneous				
EI Bearing Wobble	1.0	0.4	0.1	0.0
Az Bearing Wobble	1.0	0.4	0.1	0.0
Encoder Accuracy		1.2		1.2
Encoder Coupling		1.8		2.1
Encoder Referencing	10.0		10.0	
RSS Subtotals	11.3	12.1	11.3	2.4



Predicted Pointing Errors, 6 m/s wind

Error Sources	EI Errors (arcsec)		X-EI Errors (arcsec)	
	Repeatable	Nonrepeatable	Repeatable	Nonrepeatable
Mechanical Alignments				
RF/EI Axes Orthogonality	0.0		0.0	
EI/Az Axes Orthogonality	0.0		35.3	
Az Axis Verticality	5.0		2.9	
Structural Deformations				
<u>Reflector</u>				
Wind		10.5		
Thermal Gradient				
<u>Alidade</u>				
Wind		1.5		
Thermal Gradient				
Servo and Drive		0.9		0.3
Miscellaneous				
EI Bearing Wobble	1.0	0.4	0.6	0.2
Az Bearing Wobble	1.0	0.4	0.6	0.2
Encoder Accuracy		1.2		1.2
Encoder Coupling		1.8		1.7
Encoder Referencing	10.0		8.1	
RSS Subtotals	11.3	12.3	36.4	2.1

PTCS Project Team



- Richard Prestage: Project Manager, Green Bank Site Deputy Director- Holography, Astronomy
- Jim Condon: Project Scientist- Astronomy, Experimental Design/Analysis
- Kim Constantikes: Project Engineer- Instrumentation, Algorithms, System Design, Pointing, etc.
- ~ 9 Full time participants- 2 software engineers, 2 electrical engineers/technicians, 1 metrologist, 1 mechanical designer
- Plus machine shop, mechanic, etc. support



Winter 04/05 goals

- Usable 86 GHz telescope:
 - 1.7" offset pointing
 - 0.28 mm surface error
 - at night, wind < 2.5 m/s (50%)
- Good 52 GHz telescope:
 - 2" offset pointing
 - 0.35mm surface error
 - extended environment (more sun, wind)

Technical Activities

- Detailed characterization of offset pointing performance.
- Develop detailed error budgets:
 - Attack in cost/benefit order.
- Corrections for wind pointing errors.
- Corrections for azimuth track unevenness.
- Develop instruments/ techniques for combined thermal/ gravity model of primary.

- Laser rangefinder improvements:
 - Pointing and geometry
 - Risk mitigation for alternatives



- Laser Metrology
 - Measure position of all relevant components to ~ 100 microns, infer orientations
 - Currently low-level and long time-line
- Combined Astronomical, Structural Measurements, Models
 - Semi-empirical models driven by indirect measurements
 - E.g, astronomical pointing, linear regressions against suitable parameters: Temperature gradients, wind pressure, etc.
 - E.g., holography and linear structure model (very important!) to refine finite element structure model prediction of primary shape vs. elevation angle.
 - Incremental improvements, small capital investment

Main Drives



- Azimuth: 1 drive/wheel, 4 wheels per truck, 4 trucks
- Elevation: 8 drives (bull gear/pinion)
- 0.3" per bit, azimuth and elevation encoders
- Analog velocity (tach) and torque (current) loops
- Digital position loop 50Hz sampling (10 Hz parabolic demand)
- ~0.3 Hz closed loop bandwidth
($< \sim 0.6$ Hz first structural mode !)
- Current loop lag-compensated, velocity loop lead-lag compensated, position loop type-II with nonlinear compensation for large angle motions
- < 1 " spec tracking error for constant velocity
- Max 20 Deg/min elevation, 40 Deg/min azimuth

Subreflector Drive/Stage, Active Surface Control



- Subreflector/six link “Stewart Platform”
 - Full 6DOF control
 - Magnetostrictive link length encoders
 - Spec xx translation accuracy, yy tilt accuracy
- Active surface
 - 2209 actuators, DC motor drives, LVDTs
 - ~ 25 micron closed loop, ~ 75 micron accuracy (LVDT)
 - Cube retroreflector at near each panel corner

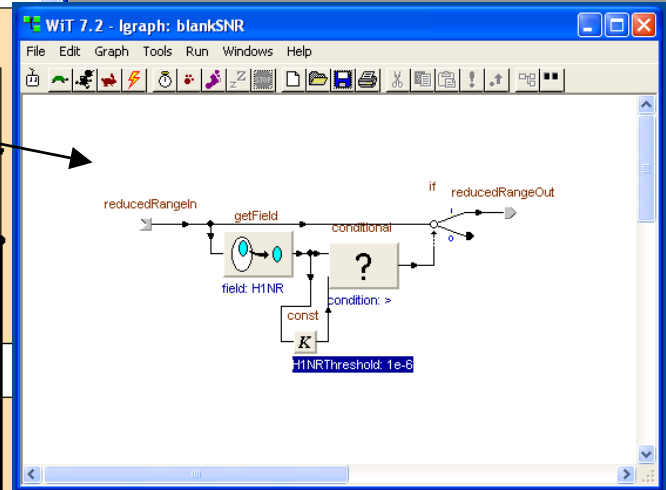
Example: Multilateration with laser rangefinders



Graph state defined by edge data, Matlab engine retains state in global structures

Can probe or break on edges, pause execution, and use full MATLAB IDE in paused state

Hierarchical graphs modularize operators

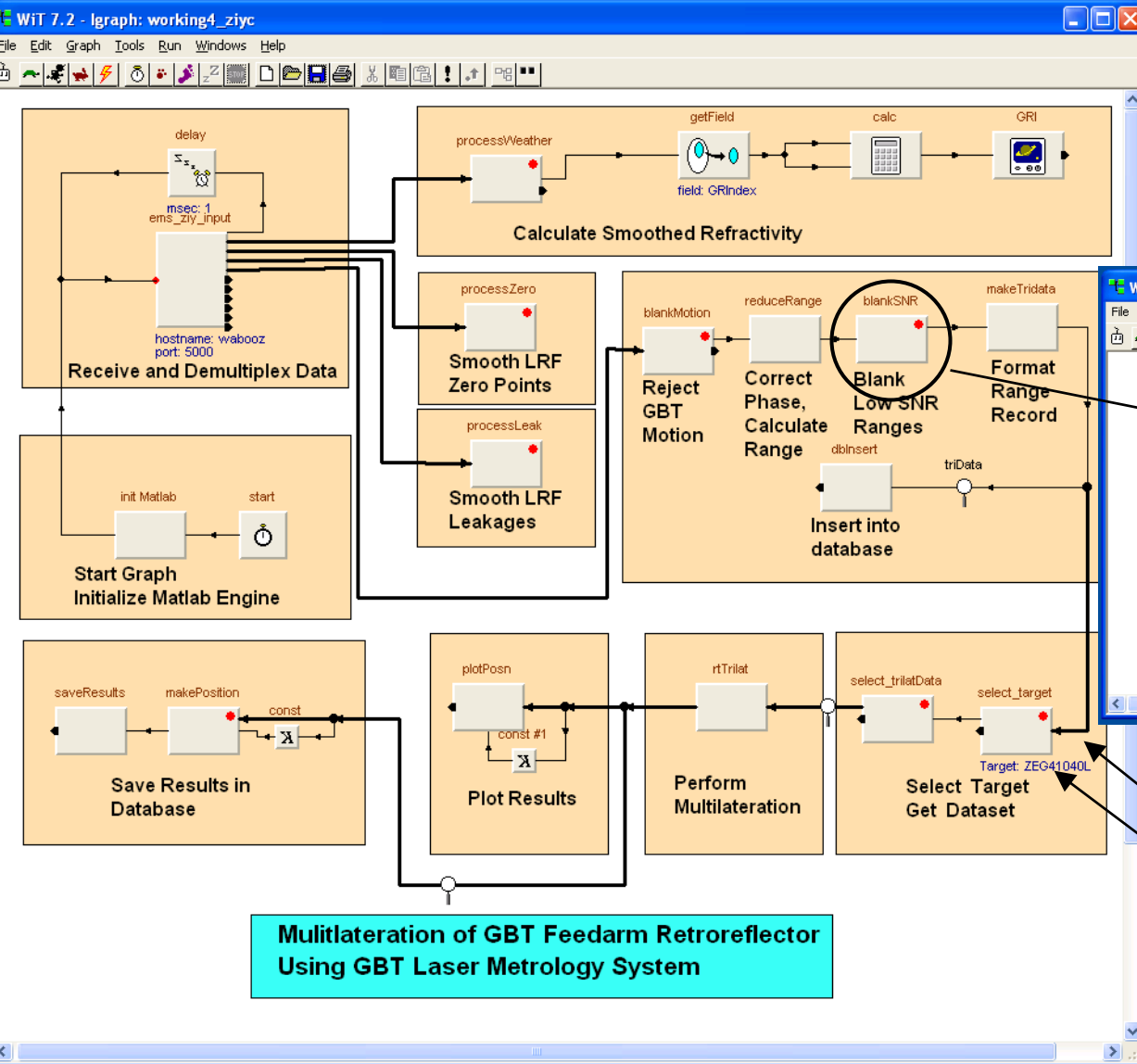


Graph edges carry primitive data types, structures, generic objects

Graph nodes execute when input data are available

Node parameters can be changed on the fly, parameters can be promoted to inputs, etc.

Database operations via ODBC and SQL



Multilateration of GBT Feedarm Retroreflector Using GBT Laser Metrology System

Example: Multilateration with laser rangefinders



EMS_tridata [3]

```

0:
rangefinder ZY111
target ZEG41040L
MJDDate 52887.8
el 38.0428
az 360.087
rma1x -93504.5
rma1y 75262.6
rma1z 354.552
rta1x -3156.13
rta1y 11012.4
rta1z 138224
rhoMeas 176917
rhoPred 176915
H1Counts 0.173177
H1NR 42.3623
LARatio 0.0118075
leak 5.64807
leakStd 0.114759
leakAmp 0.00204482
leakAmpStd 0.000234662
zero 4.13581
zeroStd 0.0327077
Ng 0.000251887

1:
rangefinder ZY108
target ZEG41040L
MJDDate 52887.8
el 38.0429
az 360.087
rma1x -75053.6
rma1y -93656.4
rma1z 352.741
rta1x -3156.16
rta1y 11012.3
rta1z 138224
rhoMeas 187445
rhoPred 187439
H1Counts 0.0977206
H1NR 89.7342
LARatio 0.0407456
leak 4.13993
leakStd 0.0358951
leakAmp 0.00398166
leakAmpStd 0.000142922
zero 3.92366
zeroStd 0.00403883
Ng 0.000251889

2:
rangefinder ZY109
target ZEG41040L
MJDDate 52887.8
el 38.0429
az 360.087
rma1x -111674
rma1y -43639.4
rma1z 350.864
rta1x -3156.14
rta1y 11012.3
rta1z 138224
rhoMeas 183781
rhoPred 183771
                    
```

WIT 7.2 - lgraph: working4_ziyc

Receive and Demultiplex Data

Start Graph Initialize Matlab Engine

Save Results in Database

Figure No. 1: ZEG41040L

delta-X (mm)

delta-Z (mm)

Number of RFs

RMS (mm)

Minutes (EDT)

Multilateration Using