The ALMA Antennas

From Specification to Science

Jeff Mangum

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

NRAO

ALMA Development Timeline

- September 10, 1982: MMA Memo #1, "The Concept of a Millimeter Array" by F. N. Owen
  - "The purpose of this report is to summarize the concept of a millimeter wave array which NRAO might build in the next 5 to 10 years."
  - "Much of the science that a millimeter array would produce would come from spectral line observations."
  - "The concept has started with a Wye shaped array with at least 15 antennas. Antennas of 10 meter diameter seem to be the largest practical size."
  - "The antennas should be capable of operating at 100 GHz most of the time and at 230 GHz under the best conditions."
  - "Wide bandwidths (1 to 5 GHz) and low system temperatures would be necessary for the desired sensitivity."
  - "Cost Estimate for Millimeter Array:"
    - Telescopes: $11.0 M
    - Receivers: $7.5 M
    - Correlator, IF, LO: $4.0 M
    - Computers: $1.5 M
    - Site: $3 M
    - Transporters: $1 M
    - Management: $2 M
    - Contingency & Etc.: $6 M
    - **TOTAL = $36 M**

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ALMA Development Timeline (Cont.)

- February 10-11, 1983: NSF Review on the "future of millimeter astronomy" reviews NRAO contribution which describes the science that one could do with a "millimeter array"
- October 1, 1984: MMA Memo #25: "Are We Thinking Boldly Enough?" by M.A. Gordon
  - "…our millimeter array [concept] may prove to be too conventional to win funding in tight economic times."
  - "…I argue that we should design the Array to be truly unique."
  - "My solution is to put the array in the southern hemisphere."
- 1985 through 1995: MMA Design Development
  - 40 8m antennas
  - Operate up to 345 GHz
- 1999: MOU between NRAO and ESO for the joint development of a millimeter array in Chile
- 2002-2004: Two prototype antennas evaluated at the VLA site
- February 25, 2003: North America / Europe bilateral agreement to construct and operate ALMA
- September 2004: North America / Europe / Japan trilateral agreement to construct and operate an enhanced Atacama Large Millimeter / submillimeter Array (ALMA)

ALMA Key Science Goals

- Detect CO or CII in a normal galaxy like the Milky Way at a redshift of 3 in less than 24 hours
- Image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars in the nearest (d = 150 pc) molecular clouds
- Provide precise high-dynamic range images at an angular resolution of 0.1 arcsec

ALMA Design

- Continuous Frequency Coverage: 100 to 1000 GHz
- >6600 m^2 Collecting Area
- Baselines: 15 m to 16 km
- Ability to Process 16 GHz of Bandwidth
- 24 Hour Operation
- Continuum Sensitivity: 0.05 to 1 mJy in 60 seconds
- Spectral Line Sensitivity: 7 to 62 mJy in 60 seconds at 1 km/s resolution

ALMA Site

- Chilean Andes at altitude 5050 m (Array Operations Site: AOS)
- Operations Support Facility (OSF) at 2900 m

A Brief History of the ALMA Antennas

- 2000: ALMA US and EU each procure prototype antennas to test viability of ALMA antenna performance specifications
  - 2000 February 18: Purchase order for VertexRSI antenna signed
- 2001 May 14: Antenna Evaluation Group (AEG) is formed
  - International group of antenna testers tasked with evaluating the prototype antennas
- 2001 June: Outfitting of ALMA Test Facility (ATF) at VLA site begins
  - 2002 November: ALMA US prototype antenna able to position in (Az,El)
- 2003 January: Testing of ALMA US prototype antenna at ATF begins
  - 2003 January: First radiometric measurements (1mm and 3mm) made with ALMA US prototype antenna
  - 2003 March: Provisional acceptance of ALMA US prototype antenna
  - 2003 April-July: Holographic measurements of ALMA US prototype antenna
  - 2003 October: Full acceptance of ALMA US prototype antenna
  - 2003 November: First astronomical image (Saturn at 3mm) with ALMA US prototype antenna
  - 2004 January: ALMA EU prototype antenna able to position in (Az,El)
- 2004 February: Testing of ALMA EU prototype antenna at ATF begins
  - 2004 January-February: Holographic measurements of ALMA EU prototype antenna
- 2004 May 28: Prototype antenna testing ends
  - 2004 May 28: Executive report describing evaluation results issued to ALMA, NRAO, and ESO management
  - 2004 December 12: Final reports describing surface accuracy, pointing, and fast switching performance of ALMA US and EU prototype antennas submitted
- 2004: Production antenna contracts chosen by US and EU

ALMA Antennas

- 54 12m antennas
- ACA adds 12 7m antennas
- Performance Requirements
  - Surface Accuracy: 25µm RMS (20µm goal)
  - Absolute Pointing Accuracy: 2 arcsec all-sky
  - Offset Pointing Accuracy: 0.6 arsec over 2 degree radius
  - Fast Switching
    - 1.5 degree move in 1.5 seconds
    - Settle to 3 arcsec peak pointing error at 1.5 seconds after start of switch
    - Settle to 0.6 arcsec RMS tracking error over 2 to 4 seconds after start of switch
- Path Length Stability: 15µm / 20µm (non-repeatable / repeatable)
- Primary Operating Conditions
  - T_{amb} = -20 to +20 C
  - $\Delta T_{amb} \leq$ 0.6 / 1.8 C over 10 / 30 minute durations
  - $V_{wind} \leq$ 6 / 9 m/s (day / night)

ALMA Key Science Goals Rely on High Performance Antennas

Key Science Goal	Antenna Spec
High Dynamic Range Imaging at 0.1 arcsec resolution	Pointing, Surface, Path Length, Fast Switching
Detect High-Redshift Galaxies	Pointing, Surface, Path Length, Fast Switching
Imaging at 100 to 1000 GHz	Pointing, Surface, Path Length, Fast Switching

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ALMA Antennas Delivery Status

- 41 antennas delivered and integrated
  - North American (Vertex): 21 of 25 (last antenna delivered by 2012-10-01)
  - European (AEM): 7 of 25
  - East Asian (Melco): 4 of 4 (12m) and 9 of 12 (7m)
- 36 antennas in use at the AOS (April 2012)

Vertex and AEM Production Antennas

Property	***Vertex***	***AEM***
Base/Yoke	Insulated Steel	Insulated Steel
BUS	Al honeycomb with CFRP plating, 24 sectors, open back, covered with removable GFRP sunshades	Solid CFRP plates, 16 closed-back sectors glued and bolted together
Receiver Cabin	Insulated steel with INVAR cone interface to BUS	CFRP; direct-connection cabin to BUS
Base	3-point support; bolt connection with foundation	3-point support; bolt connection with foundation
Drive	Gear and pinion	Direct-drive with linear motors
Brakes	Integrated on servo motor	Hydraulic disk
Encoders	Absolute (BEI)	Incremental (Heidenhain)
Panels	264 panels, 8 rings, machined Al, open-back, 8 adjusters (3 lateral/5 axial) per panel	120 panels, 5 rings, Al honeycomb with replicated Ni skins. Rh coated, 5 adjusters per panel
Apex/Quadripod	CFRP structure, "+" configuration	CFRP structure, "x" configuration
Focus Mechanism	Hexapod (5 DOF)	Hexapod (5 DOF)
Total Mass	~107 tonnes	~100 tonnes
Mass Dist. (El/Az)	50%/50%	35%/65%

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Early Science

The Antennae Galaxies

Blue = visible (HST)
Red = CO 1-0 (Band 3)
Yellow = CO 3-2 (Band 7)

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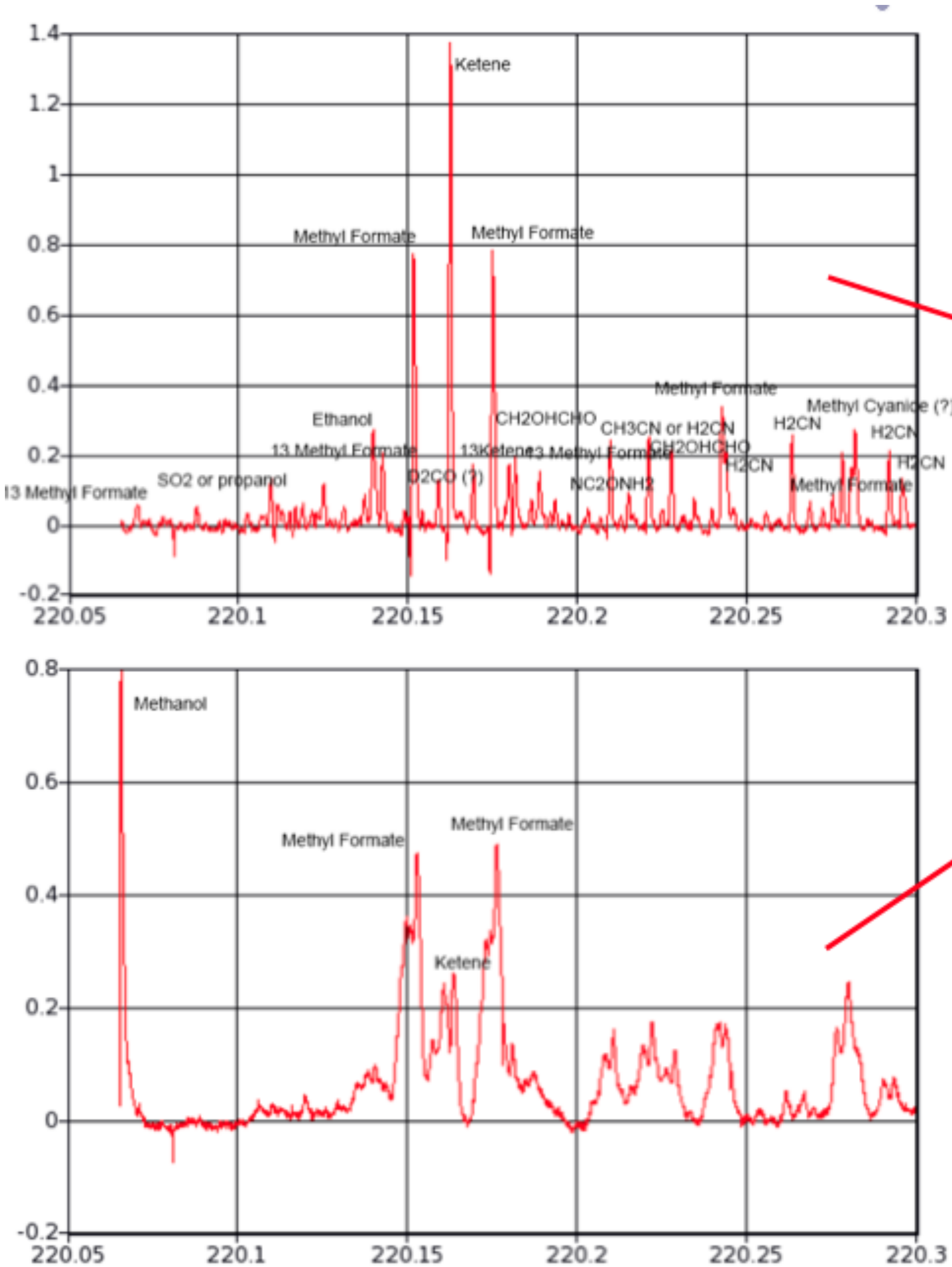
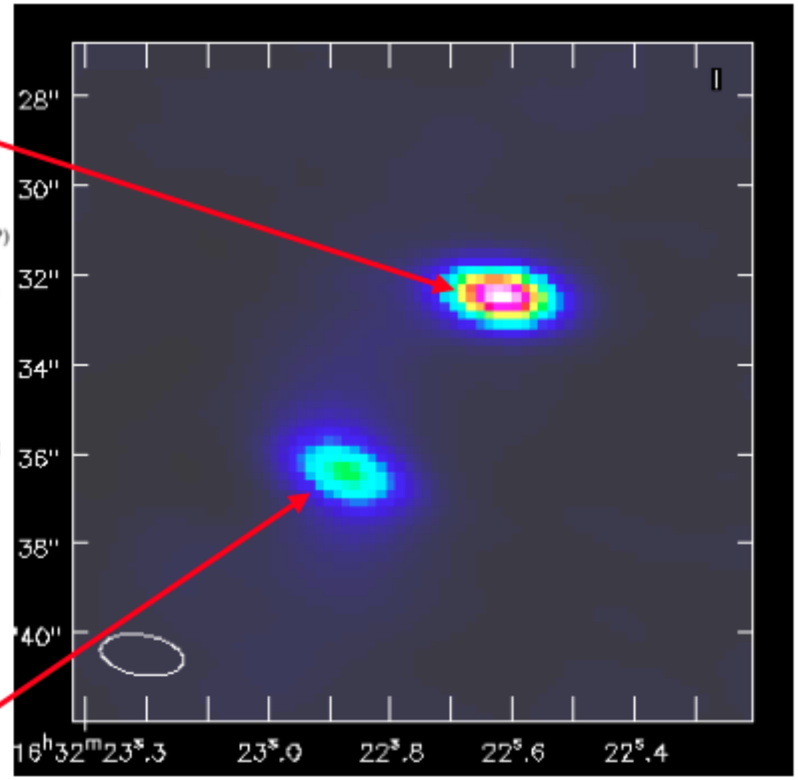
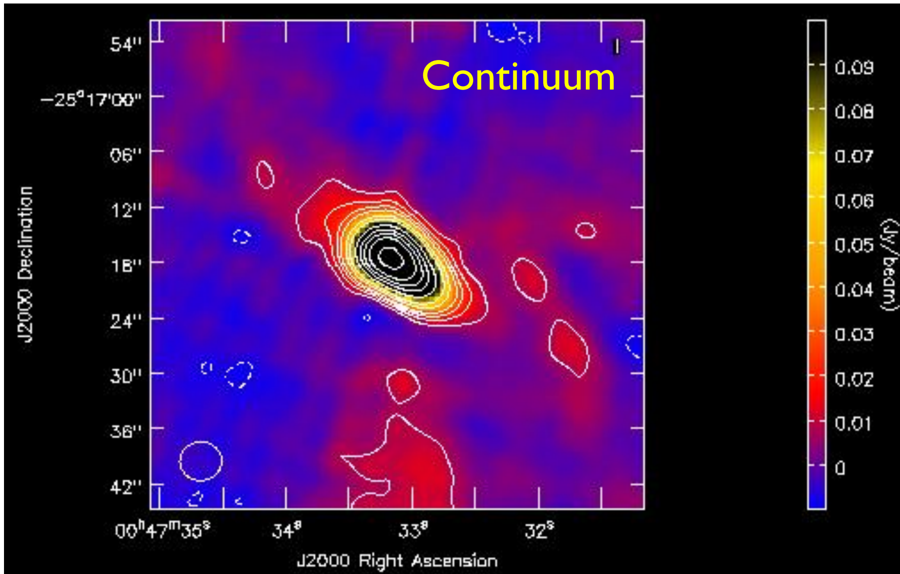
Early Science



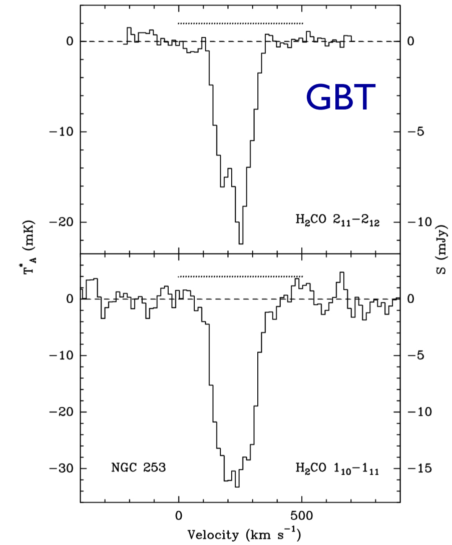


IRAS16293

Why Pointing Is Important

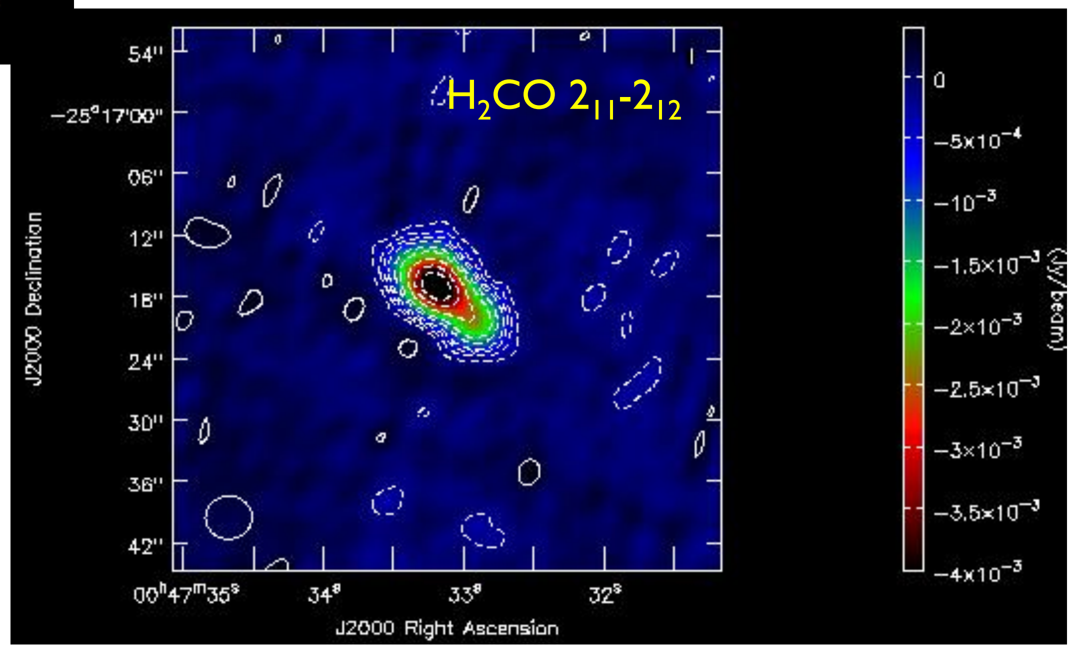


NGC253
$H_2CO\ 2_{11}$-2_{12} (14.48 GHz)
JVLA DnC Array (θ_b = 5 arcsec)
FWHM ≅ 200 arcsec



Pointing Errors:

- Limit dynamic range to i.e. < 300:1 when σ_p ≅ 0.02 FWHM (0.6 arcsec at 230 GHz; Braun 1989, MMA Memo 54)
- "Blurr" images
- Re-distribute flux from compact to extended structures
- JVLA at 2 cm: 0.02*FWHM ≅ 4 arcsec



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The ALMA Test Facility (ATF)

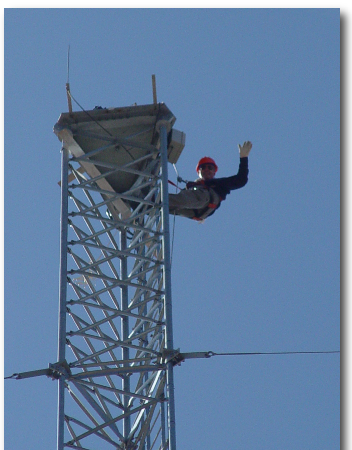
The AEG

- Jeff Mangum (NRAO)
- Jaap Baars (ESO/MPIfR)
- Albert Greve (IRAM)
- Robert Lucas (IRAM)
- Ralph Snel (Lund University)
- Pat Wallace (RAL)

XAVIER GALLEGOS/Tucson Citizen

Astronomer Jaap Baars is continually studying the skies.

Jack Meadows



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ALMA NA Antenna IPT

Antenna Testing Division

- Art Symmes (NA IPT Lead)
- Nicholas Emerson
- Kevin Flaim
- David Hunter
- Martin Mundnich
- Derek Harris
- Tony Rodriguez

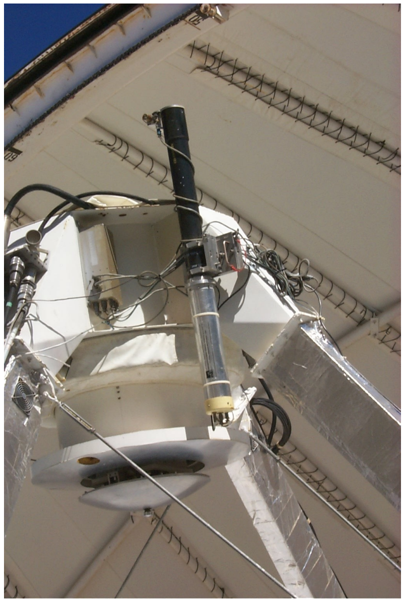
Pointing

Techniques and Systems Used:

- Optical Pointing Telescope (OPT)
- 1 and 3 mm Radiometry
- Accelerometer System

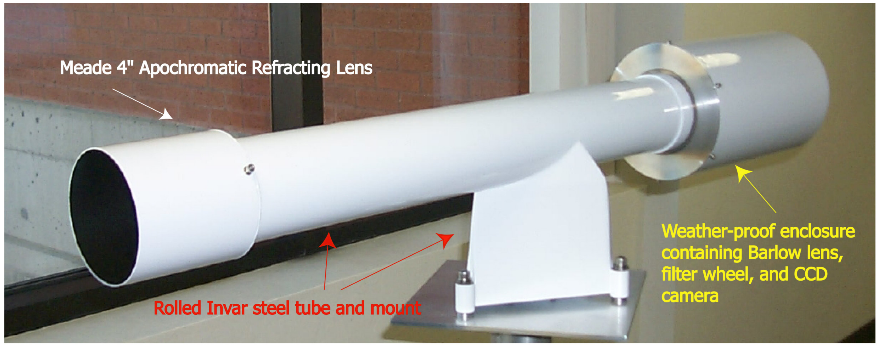
Optical Pointing Telescopes

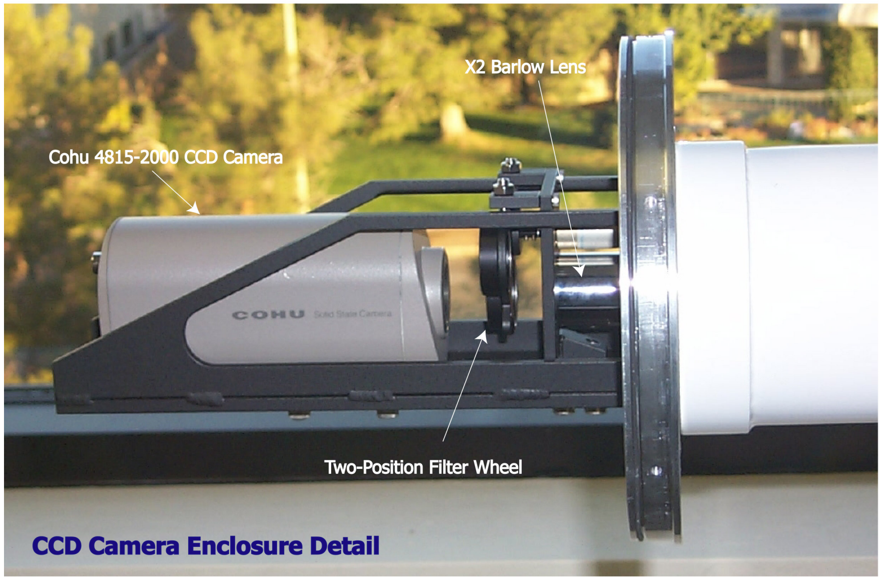
- Prototype OPTs developed at NRAO Tucson 2000-2002
  - Based on NRAO 12m and Hat Creek OPT systems
  - Two OPTs constructed and used to characterize prototype antennas 2002-2004
  - Used to characterize pointing performance on production antennas:
    - DV01-DV09
    - DA41-DA49
- Production OPTs
  - Based on prototype OPT experience
  - ALMA specification
  - Contracted to ACE (Tucson)
  - Two systems delivered to-date

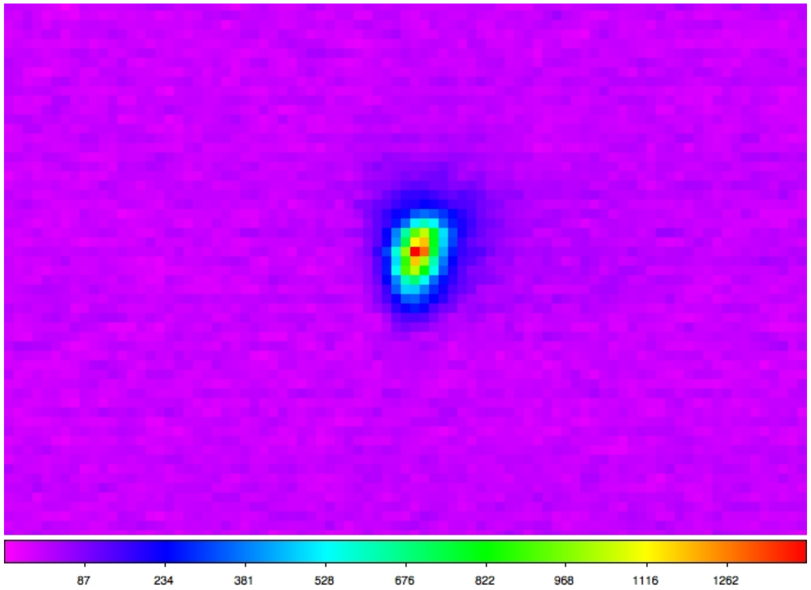


NRAO 12m OPT

Prototype Optical Pointing Telescopes



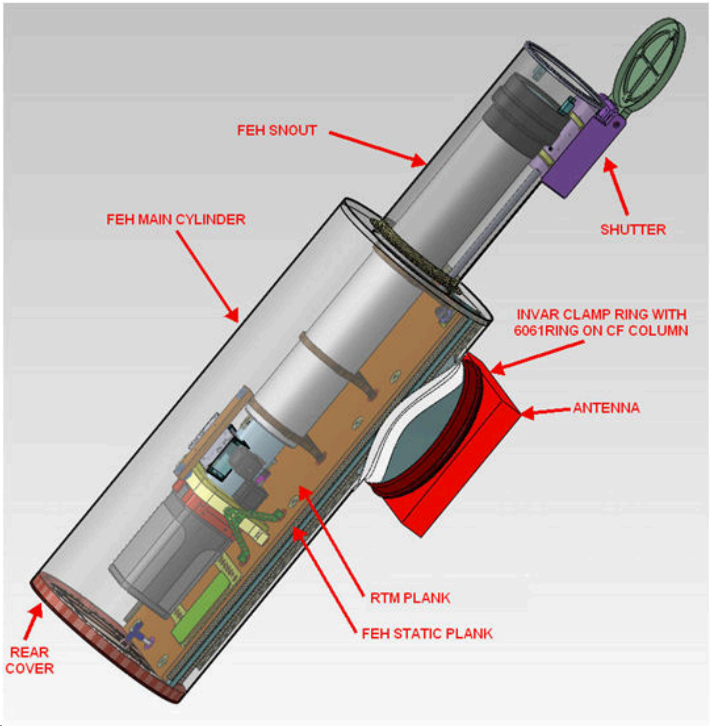


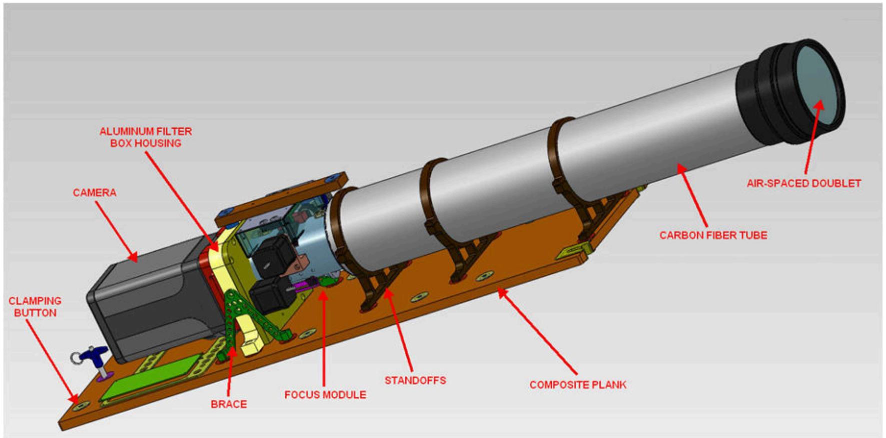


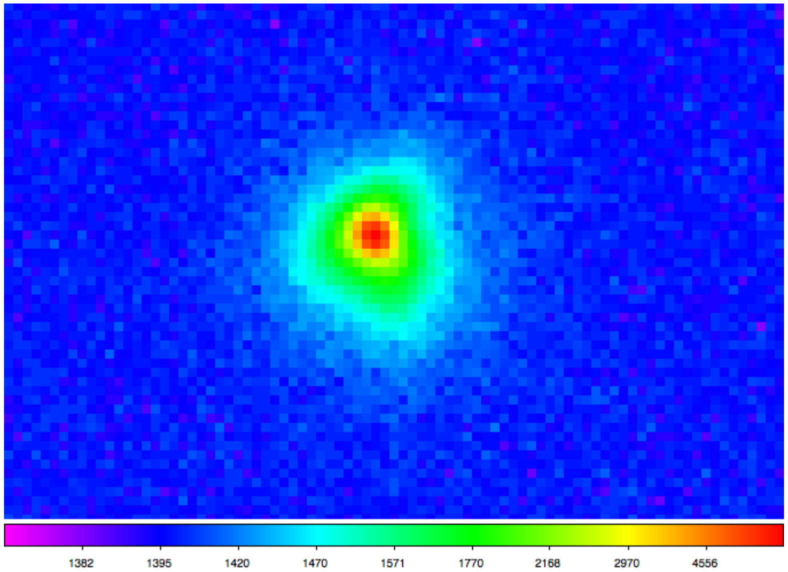
- D = 4 inches (Meade 102ED)
- f = 920 mm
- Effective plate scale = 1.12 arcsec
- FOV = 12 x 9 arcmin
- Limiting magnitude = 9 (in 5 sec)

Production Optical Pointing Telescopes

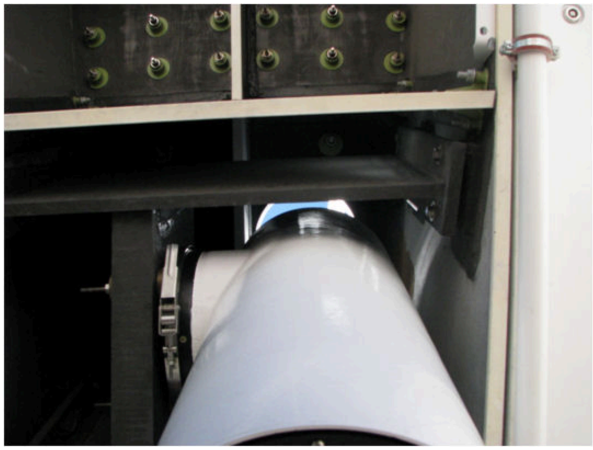
- Orion 120mm f7.5 lens (f = 900mm)
- 5x Barlow lens
- Princeton Instruments Photomax 1024 CCD camera
- FOV ≈ 8.5 x 8.5 arcmin
- Effective plate scale ≈ 0.5 arcsec
- Limiting magnitude > 10 (in 1 second)





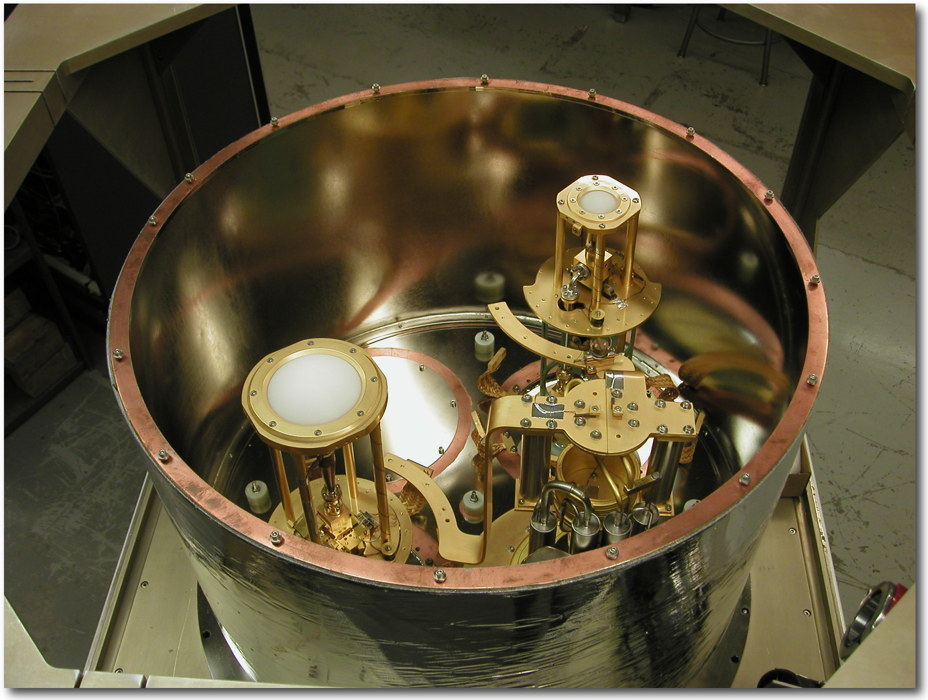


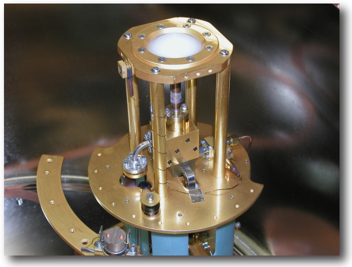
Production Optical Pointing Telescopes

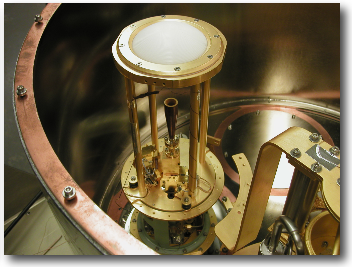


Production OPT installed in the BUS of the ALMA NA Production Antenna

Evaluation Frontend System

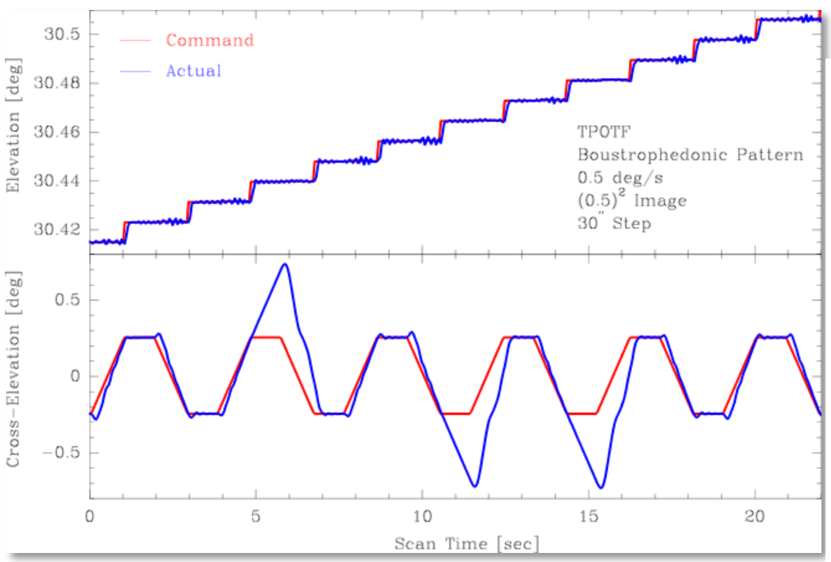






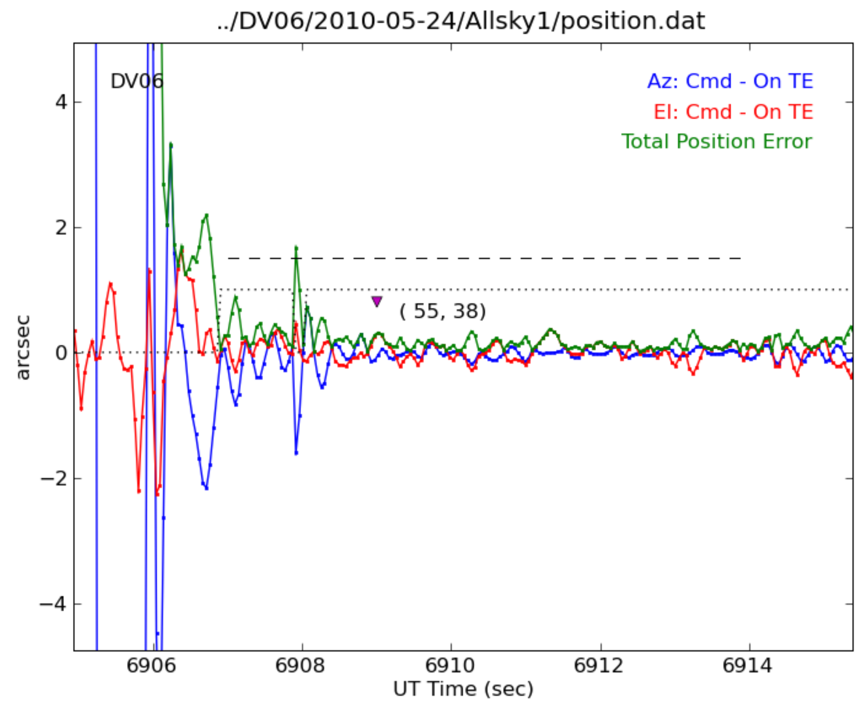
CANAnalyzer

- Developed by Fritz Stauffer at ATF
- Monitors command/response antenna position each TE (48 ms)



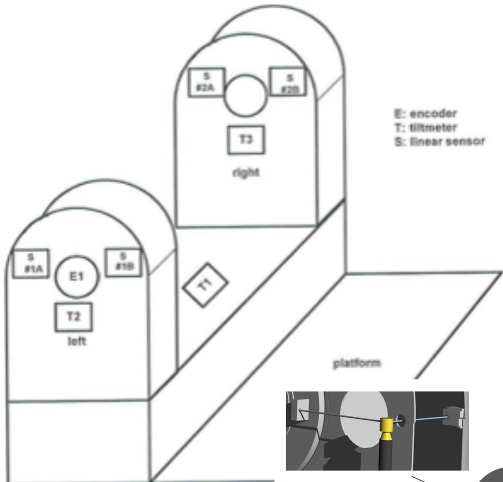
ATF

ALMA

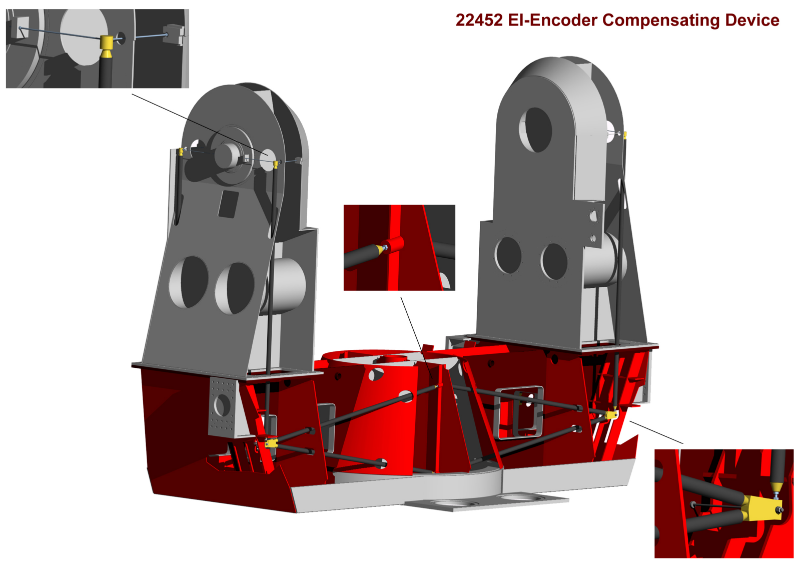


Vertex Metrology System

Tiltmeter(s) and Linear Sensors



22452 El-Encoder Compensating Device



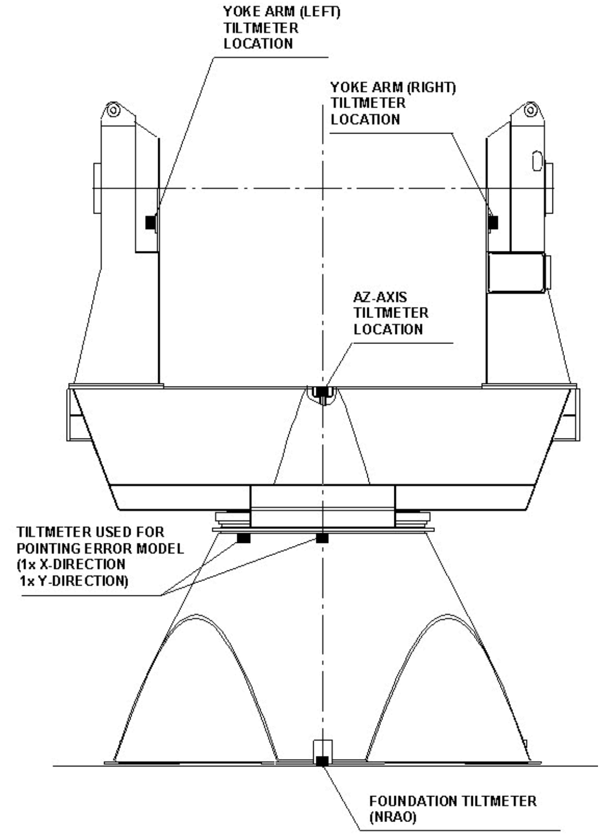
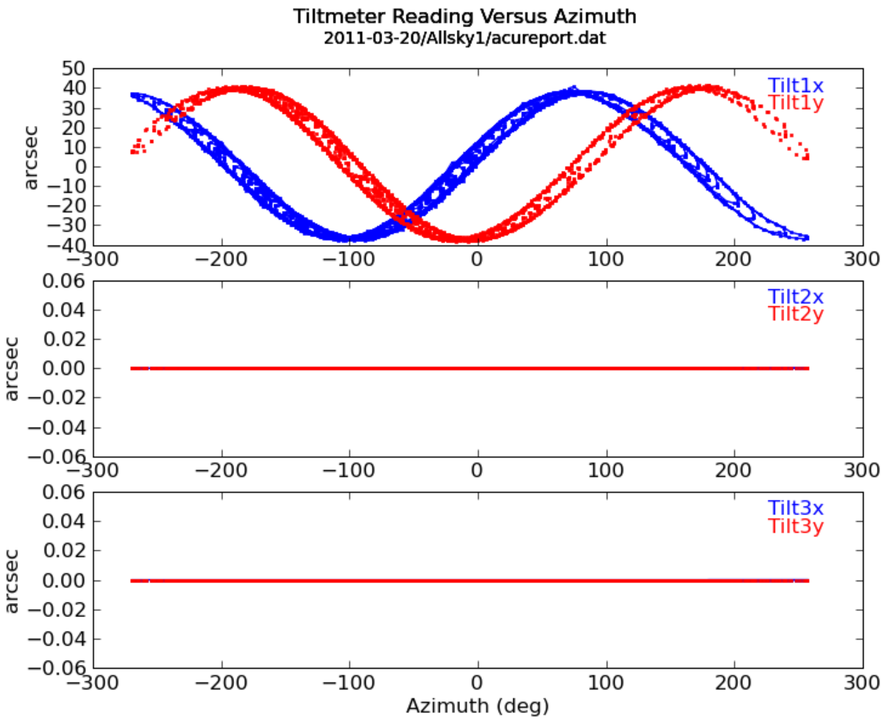
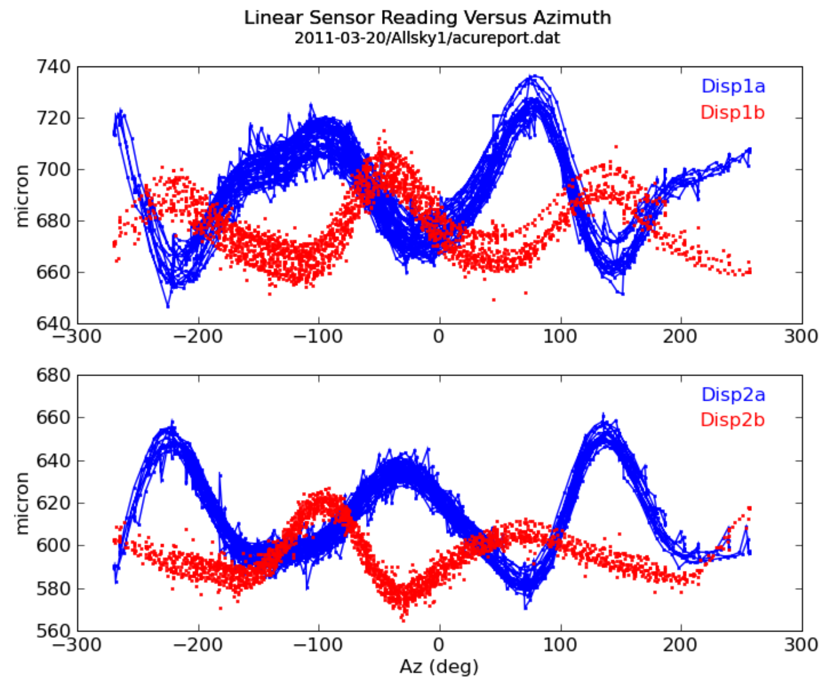


Figure: Tiltmeter Mounting Locations

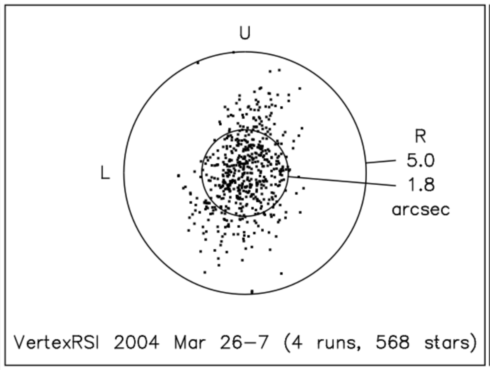
Metrology System

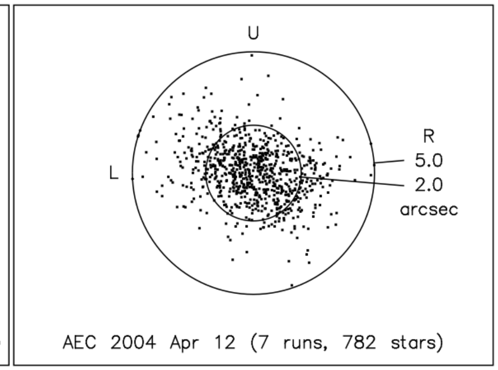




All-Sky Optical Pointing Results

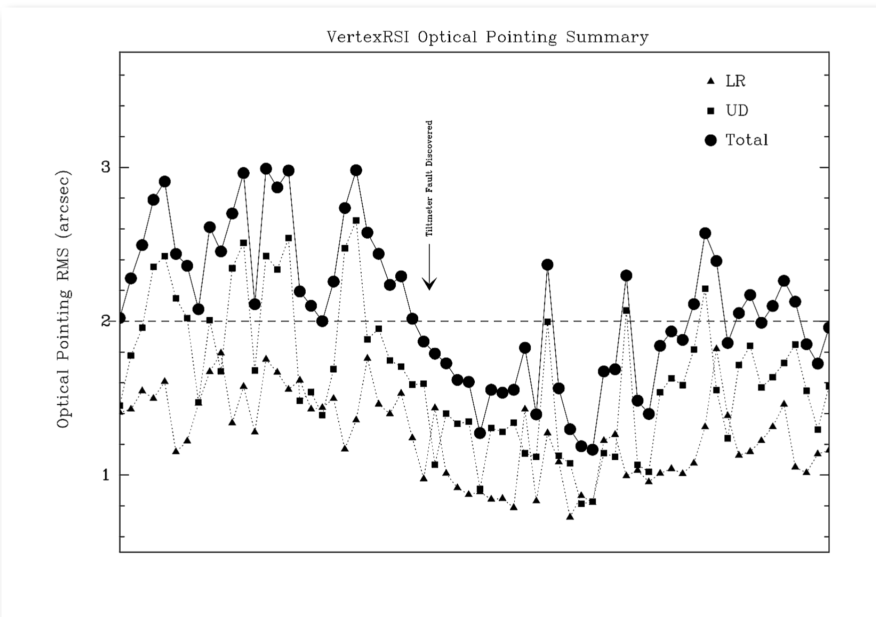
Prototype Antennas

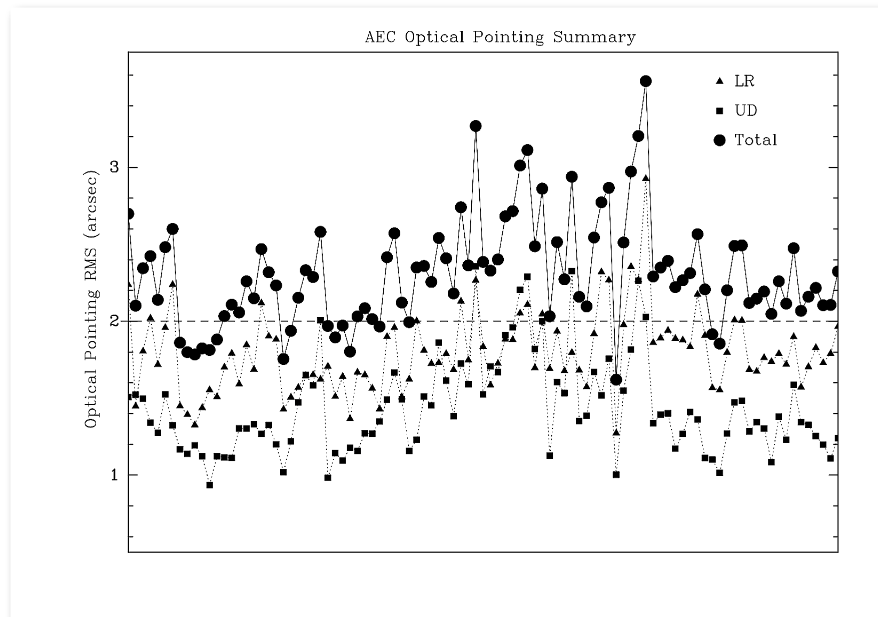




VertexRSI

AEC



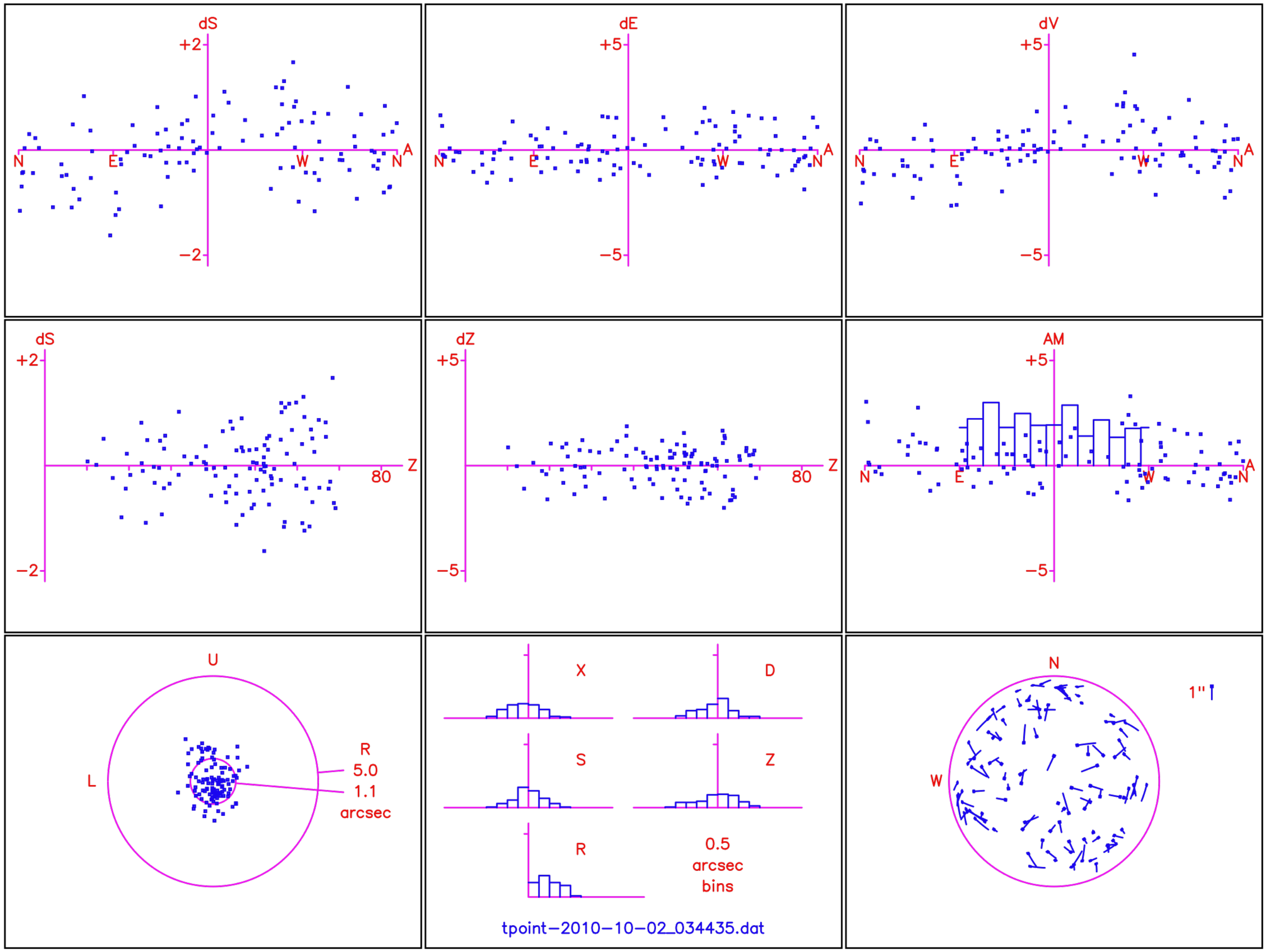


Pointing Performance Summary

Prototype Antennas

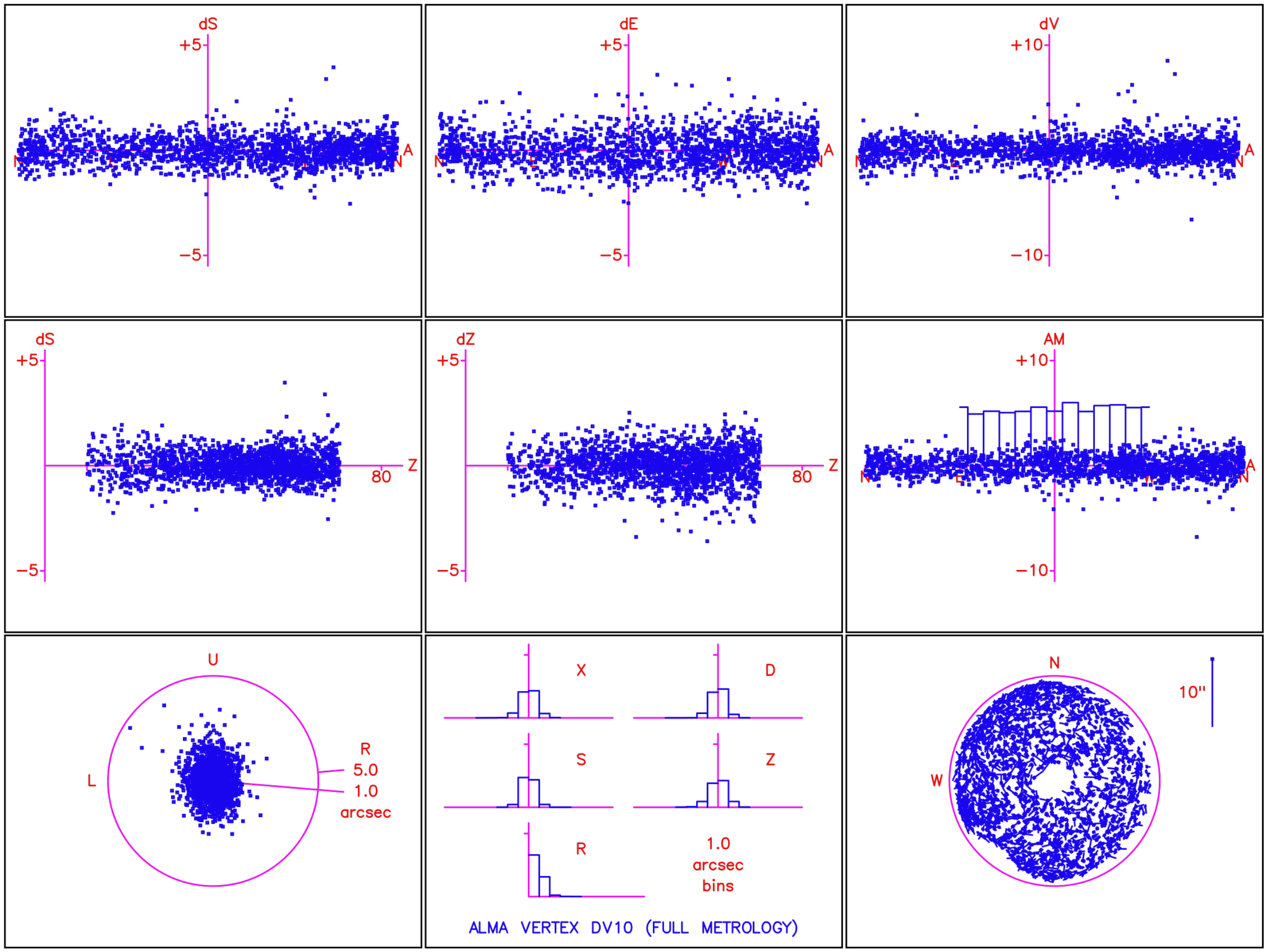
System/Technique	AEC (arcsec)		VertexRSI (arcsec)	
	Absolute	Offset	Absolute	Offset
Optical	2.0-2.6	0.3-0.8	1.3-1.8	0.3-1.1
Radiometric	<4	<0.5	<4	<0.9
Accelerometer (10 sec)	…	0.29±0.09 (spread) ±0.05 (wind)	…	0.58±0.15 (spread) ±0.08 (wind)
Accelerometer (15 min)	…	0.50±0.13 (spread) ±0.02 (extrapolation) ±0.11 (wind)	…	0.94±0.26 (spread) ±0.05 (extrapolation) ±0.20 (wind)

Sample All-Sky Pointing Measurement



Production Antennas

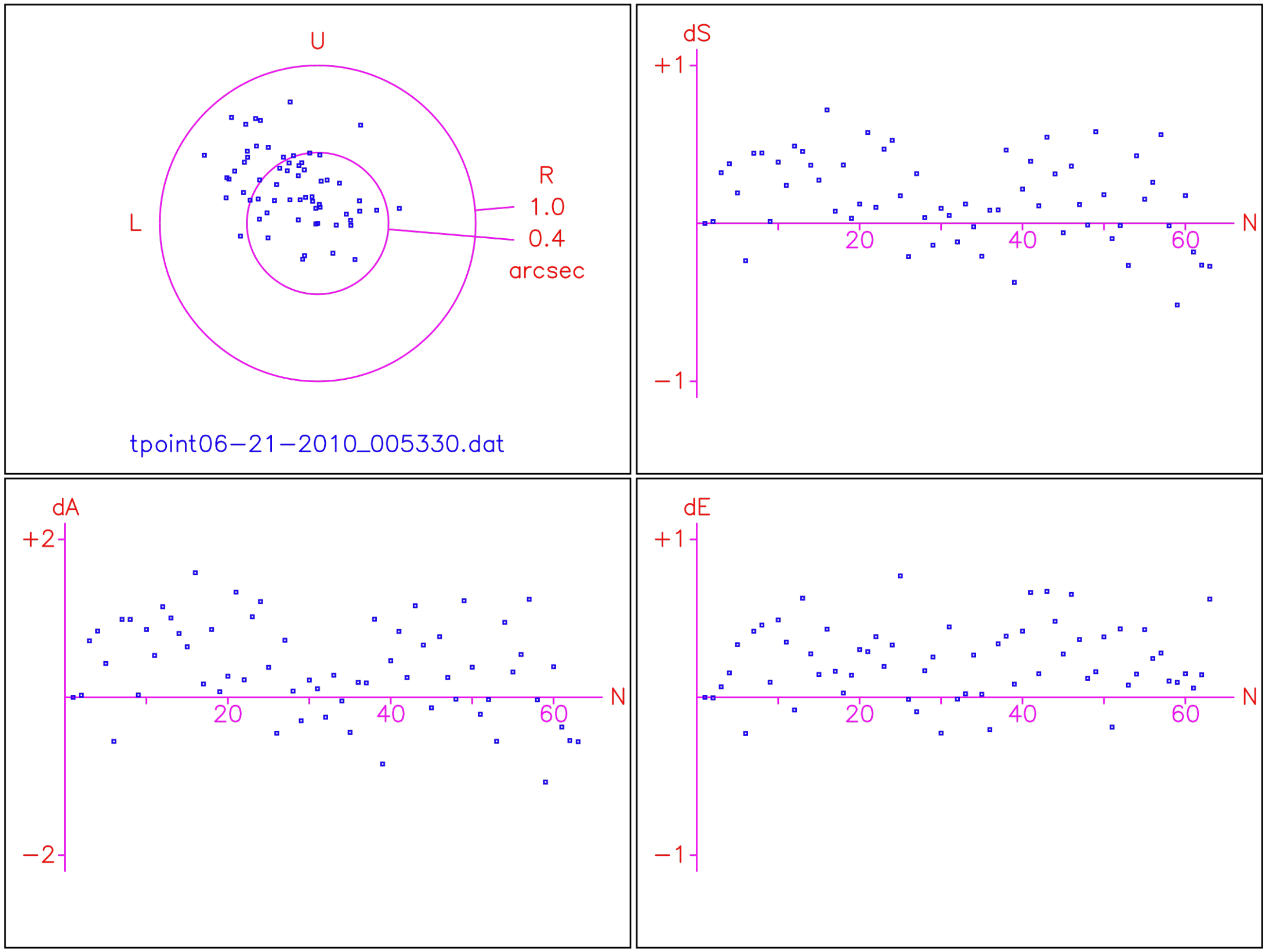
Cumulative All-Sky Pointing Measurement Residual for DV10



1863 measurements

Production Antennas

Sample Offset Pointing Measurement Residual



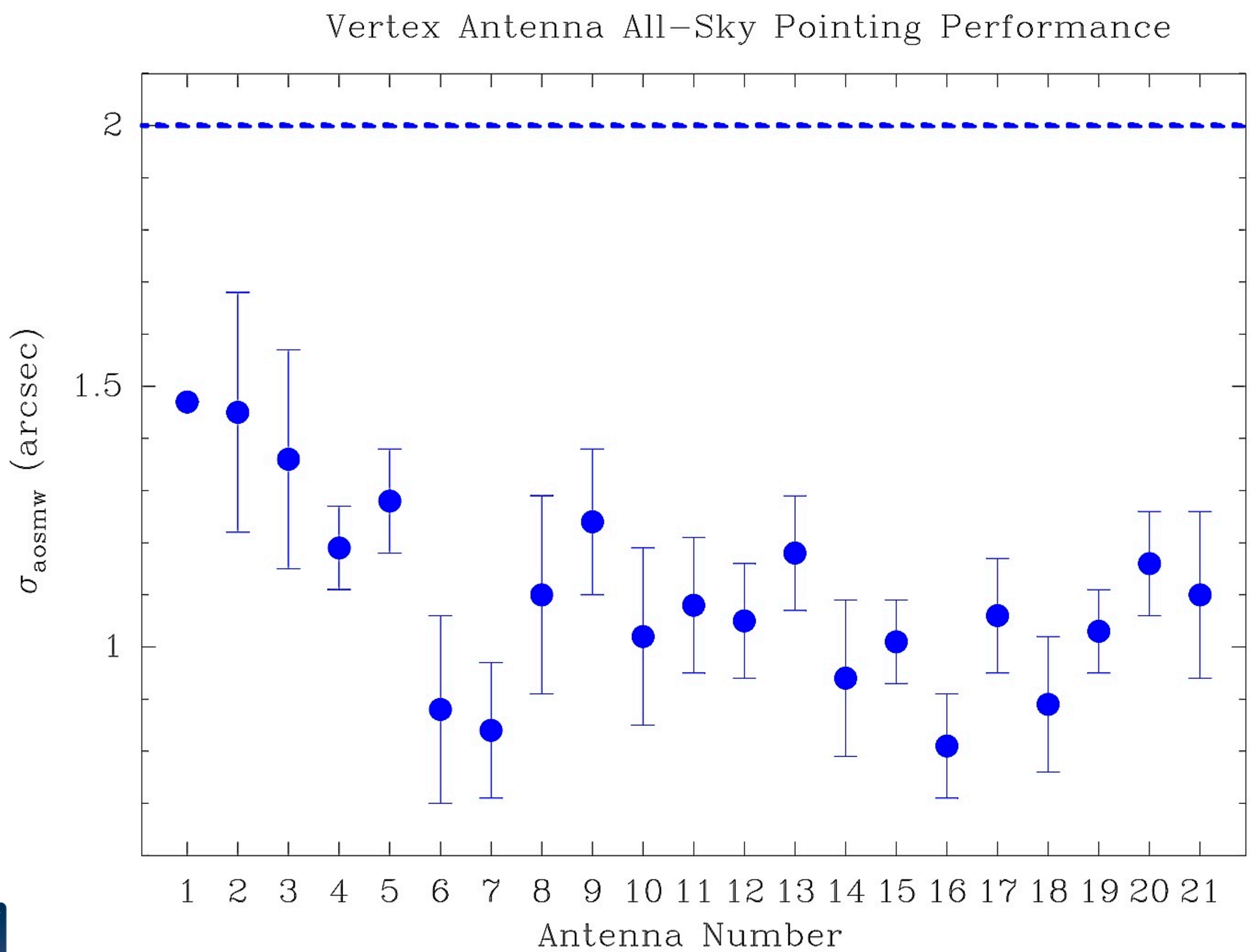
Production Antennas

Vertex Production Antenna All-Sky Pointing Performance

Antenna	Date[a]	N_{meas}	T_{amb} (C)	ΔT (C)	W_s (m/s)	σ_{meas} (arcsec)	σ_{aosmw} (arcsec)
DV01	2009/01/15	57	+8.0 – +22.6	0.3 – 4.2	0.1 – 5.0	1.13	1.47
DV02	2009/04/24	21	+6.4 – +17.0	0.3 – 2.4	0.7 – 3.6	1.35±0.24	1.45±0.23
DV03	2009/09/01	22	+3.5 – +12.2	0.3 – 4.2	1.8 – 5.9	1.38±0.20	1.36±0.21
DV04	2010/02/01	18	+13.8 – +17.3	0.4 – 1.7	1.3 – 4.9	1.12±0.08	1.19±0.08
DV05	2009/10/26	18	+5.0 – +14.5	0.4 – 2.6	1.2 – 4.4	1.22±0.10	1.28±0.10
DV06	2010/06/09	12	+8.7 – +13.3	0.1 – 2.1	0.8 – 8.1	0.94±0.10	0.88±0.18
DV07	2010/04/19	26	+9.4 – +18.4	0.2 – 1.7	1.2 – 5.1	0.77±0.12	0.84±0.13
DV08	2010/07/03	18	+6.7 – +14.2	0.4 – 2.5	1.4 – 5.0	1.09±0.17	1.10±0.19
DV09	2010/07/21	15	-0.3 – +11.1	0.3 – 2.2	1.3 – 2.2	1.21±0.14	1.24±0.14
DV10	2010/10/11	19	+5.8 – +12.5	0.0 – 1.9	2.0 – 6.4	1.01±0.16	1.02±0.17
DV11	2010/12/09	19	+7.4 – +15.1	0.2 – 1.4	1.5 – 4.7	1.06±0.13	1.08±0.13
DV12	2011/01/30	14	+11.3 – +16.0	0.5 – 1.5	1.3 – 6.1	1.00±0.09	1.05±0.11
DV13	2011/03/23	22	+10.8 – +15.2	0.3 – 1.7	1.7 – 5.9	1.14±0.10	1.18±0.11
DV14	2011/05/31	25	+8.9 – +18.0	0.2 – 2.1	2.6 – 6.7	0.91±0.13	0.94±0.15
DV15	2011/07/29	8	+6.0 – +11.7	0.5 – 2.2	1.6 – 5.8	1.11±0.07	1.01±0.08
DV16	2011/08/26	19	+7.8 – +14.5	0.5 – 2.1	3.0 – 5.9	0.82±0.08	0.81±0.10
DV17	2011/10/10	19	+11.2 – +17.9	0.3 – 2.7	1.9 – 6.5	1.02±0.10	1.06±0.11
DV18	2011/12/06	18	+10.8 – +17.4	0.4 – 2.2	1.0 – 5.4	0.83±0.11	0.89±0.13
DV19	2012/01/11	14	+10.0 – +17.7	0.2 – 1.1	0.8 – 4.6	0.96±0.08	1.03±0.08
DV20	2012/04/09	18	+12.4 – +16.7	0.4 – 2.4	1.5 – 5.3	1.10±0.11	1.16±0.10
DV21	2012/05/04	23	+8.1 – +15.1	0.3 – 1.5	1.2 – 5.8	1.07±0.15	1.10±0.16

[a] Date of final report

Vertex Production Antenna All-Sky Pointing Performance

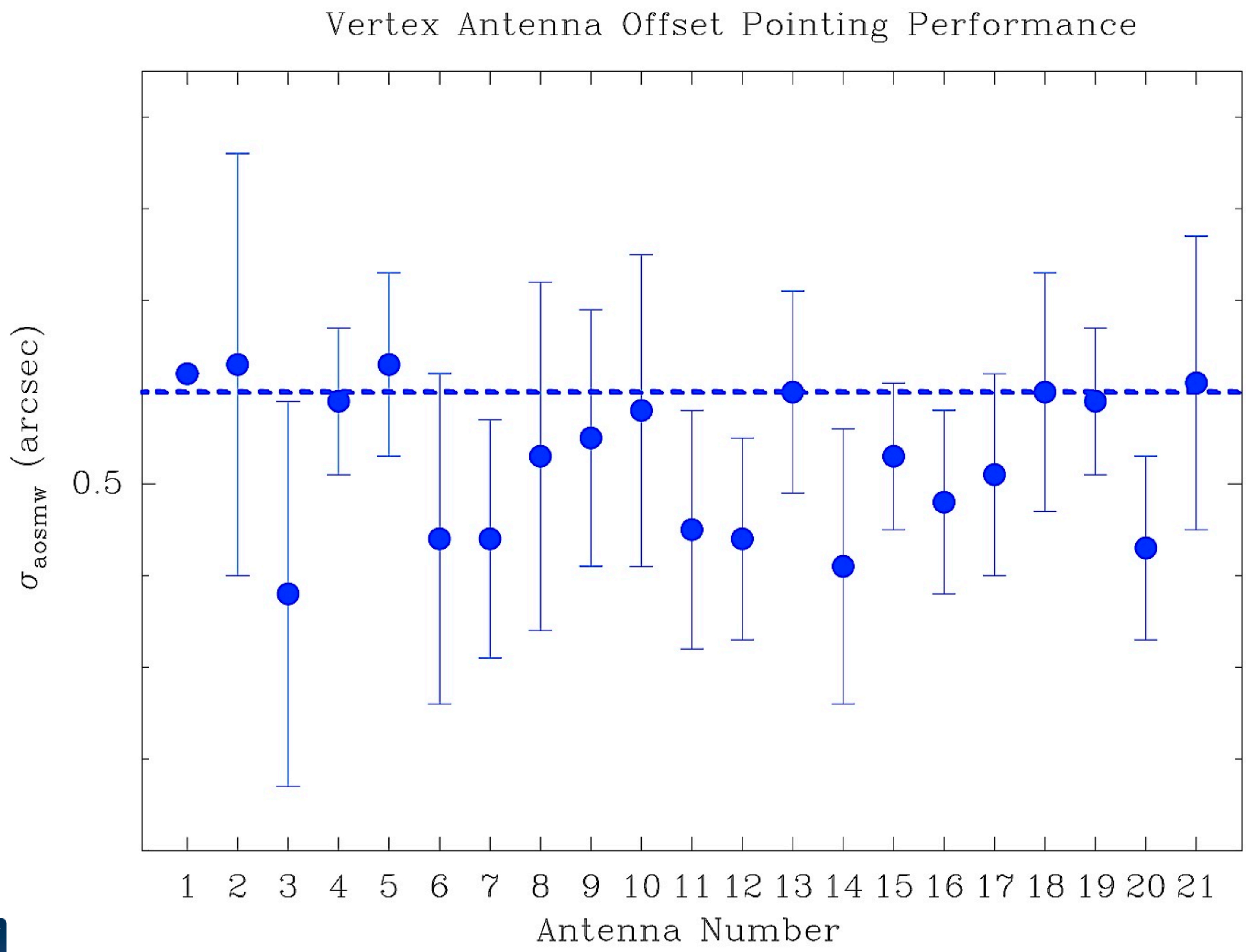


Vertex Production Antenna Offset Pointing Performance

Antenna	Date[a]	N_{meas}	T_{amb} (C)	ΔT (C)	W_s (m/s)	σ_{meas} (arcsec)	σ_{aosmw} (arcsec)
DV01	2009/02/02	40	+11.2 – +17.8	0.1 – 0.8	0.7 – 4.5	0.55±0.11	0.62±0.10
DV02	2009/04/15	29	+8.3 – +13.6	0.2 – 1.3	0.9 – 4.1	0.63±0.14	0.63±0.10
DV03	2009/10/05	36	+4.6 – +10.7	0.2 – 3.6	0.8 – 5.8	0.66±0.17	0.38±0.24
DV04	2010/02/03	30	+13.1 – +17.6	0.2 – 1.3	0.8 – 5.9	0.49±0.13	0.59±0.19
DV05	2009/10/26	30	+7.1 – +15.1	0.2 – 1.4	0.8 – 5.4	0.73±0.18	0.63±0.12
DV06	2010/06/10	32	+7.0 – +14.3	0.2 – 1.0	1.6 – 9.2	0.51±0.13	0.44±0.27
DV07	2010/04/16	26	+11.7 – +17.0	0.0 – 1.7	1.9 – 6.9	0.51±0.13	0.44±0.27
DV08	2010/07/03	26	+8.1 – +15.5	0.2 – 1.6	0.6 – 6.9	0.64±0.22	0.53±0.23
DV09	2010/08/02	27	+4.4 – +11.9	0.2 – 2.2	1.3 – 5.8	0.57±0.16	0.55±0.24
DV10	2010/10/13	25	+4.9 – +14.5	0.0 – 1.0	1.7 – 4.7	0.67±0.16	0.58±0.28
DV11	2010/11/29	28	+9.8 – +16.1	0.2 – 1.3	1.4 – 5.9	0.58±0.11	0.45±0.25
DV12	2011/01/30	25	+12.7 – +17.0	0.2 – 0.9	1.4 – 5.6	0.52±0.11	0.44±0.28
DV13	2011/03/23	32	+10.0 – +16.2	0.1 – 1.7	1.7 – 5.2	0.59±0.16	0.60±0.18
DV14	2011/05/31	54	+8.6 – +16.5	0.1 – 1.5	1.6 – 7.1	0.56±0.17	0.41±0.27
DV15	2011/07/29	45	+5.4 – +14.7	0.2 – 1.6	1.5 – 8.6	0.73±0.25	0.53±0.33
DV16	2011/08/27	40	+5.4 – 11.4	0.2 – 1.0	1.2 – 5.8	0.60±0.13	0.48±0.28
DV17	2011/10/10	30	+9.2 – +17.7	0.1 – 2.5	0.9 – 6.3	0.54±0.13	0.51±0.23
DV18	2011/11/28	27	+9.2 – +15.5	0.1 – 1.1	1.7 – 5.8	0.61±0.15	0.60±0.21
DV19	2012/01/14	29	+9.9 – +17.0	0.1 – 0.8	0.8 – 4.2	0.53±0.15	0.59±0.17
DV20	2012/04/07	32	+12.0 – +17.4	0.1 – 0.9	2.0 – 6.4	0.50±0.14	0.43±0.23
DV21	2012/05/04	29	+5.8 – +14.9	0.2 – 1.0	1.9 – 5.1	0.66±0.16	0.61±0.23

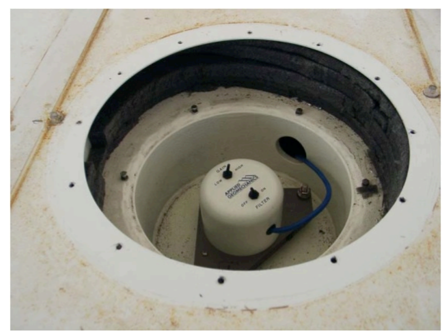
[a] Date of final report

Vertex Production Antenna Offset Pointing Performance



Things We Missed

- A “ghost deformation” due to “pinching” of the feet of the antennas
  - ✓ Interesting though negligible contribution to the all-sky pointing performance discovered while characterizing antenna DV06
- Azimuth encoder hysteresis
  - ✓ Encoder shaft alignment issue diagnosed and solved by antenna DV03
- Tiltmeter measurement dependence on local temperature
  - ✓ Flaw in metrology system design which only exposed itself during observations at the AOS (much wider range in ambient temperature)
  - ✓ Ethanol electrolyte freezing at low temperatures
  - ✓ Replacing methanol-based tiltmeters tested and found to work at low temperature



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Pointing Performance Summary

- Based on a limited set of positioning characterization measurements conducted at the OSF, all Vertex antennas meet the all-sky and offset pointing performance specifications
- Antenna pointing is a process which develops over the lifetime of an instrument

Fast Switching

Techniques and Systems Used

- Radiometer
- Optical Pointing Telescope
- Accelerometer System

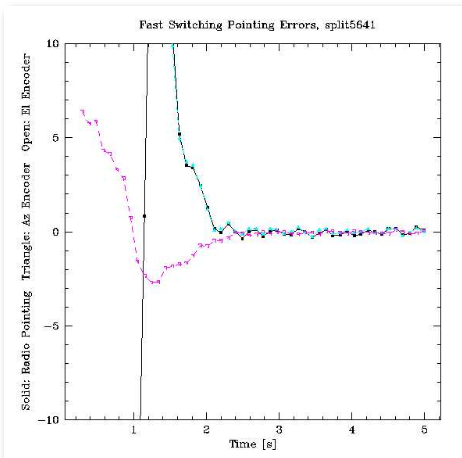
Radiometric Fast Switching Performance

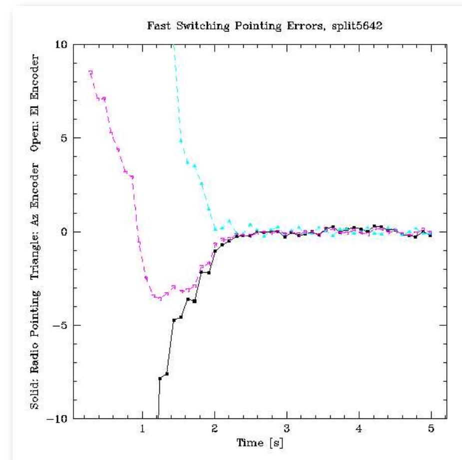
Prototype Antennas

AZ

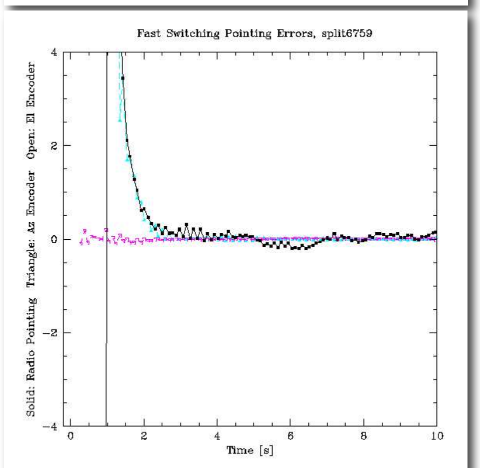
EL

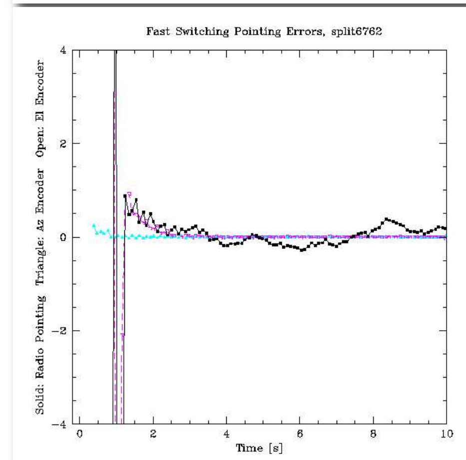
VertexRSI





AEC





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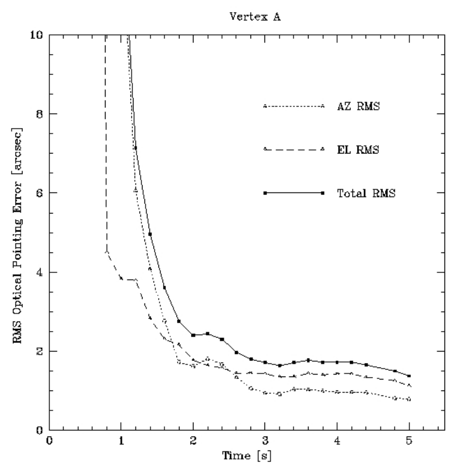
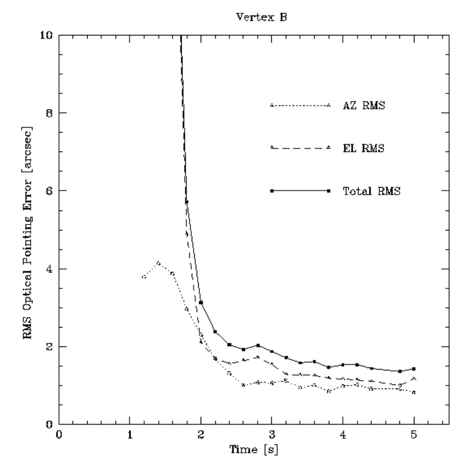
Optical Fast Switching Performance

Prototype Antennas

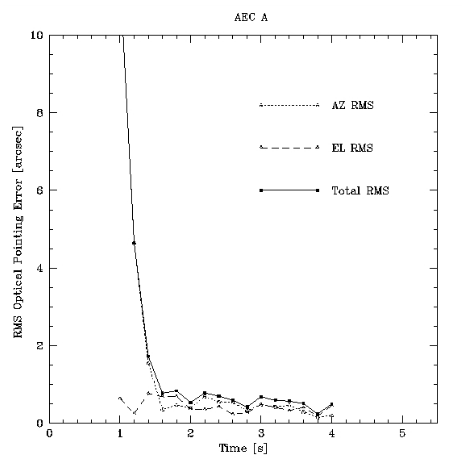
θ_{star} = 0.4 deg

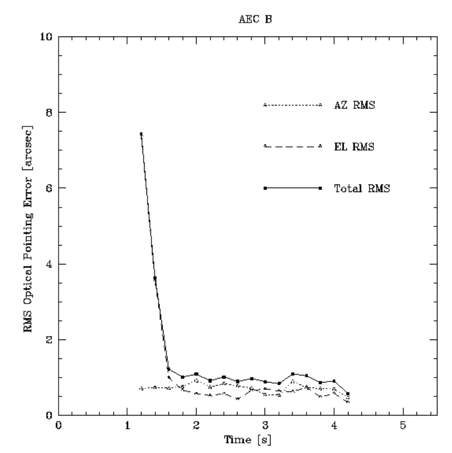
θ_{star} = 1.8 deg





VertexRSI





AEC

NRAO

Fast Switching Performance Summary

Prototype Antennas

System/Technique	***AEC***	***VertexRSI***
Radiometry	1.4-1.8 sec	1.5-1.8 sec
Optical	1.4-1.6 sec	1.5-2.0 sec
Accelerometer	1.5* sec	1.5-1.8 sec

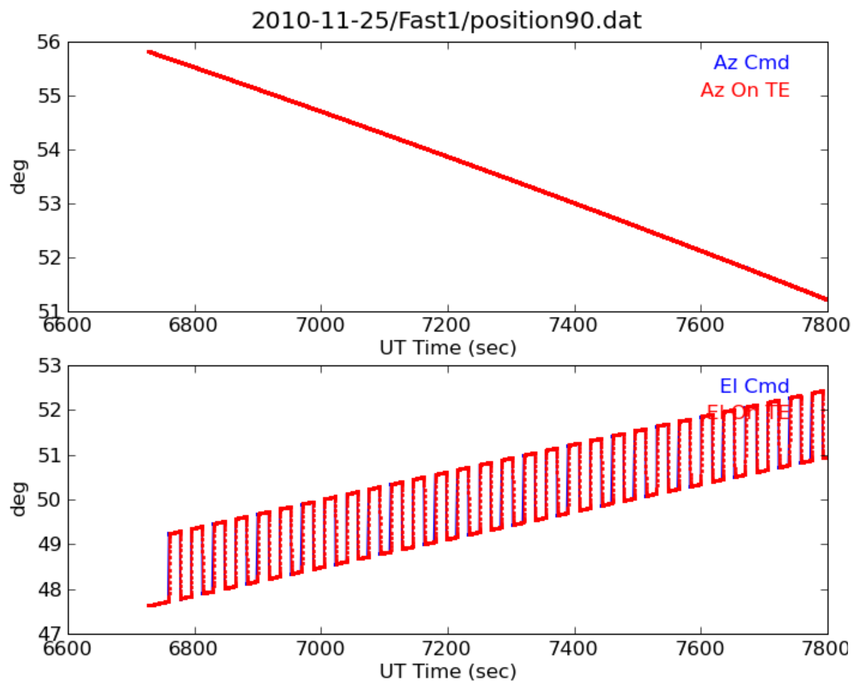
* Ignoring antenna drive shutdown due to apex oscillation

Fast Switching Measurement and Analysis

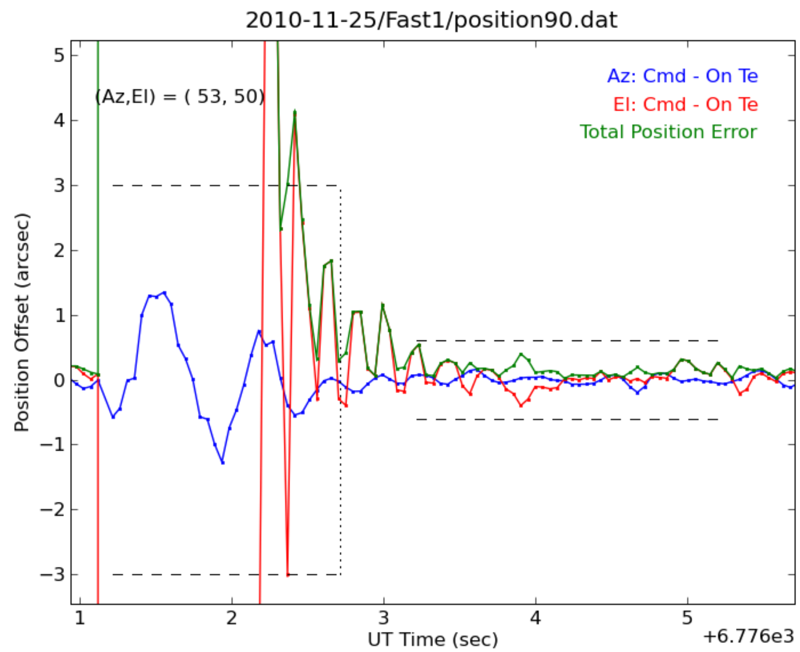
Production Antennas

- Fast switch between two positions separated by 1.5 degrees
- Integrate at each position for ≈ 15 seconds
- Measure at (A,E) positions defined as follows:
  - A = 0-360 deg in steps of 60 deg
  - E = 30-60 deg in steps of 15 deg
  - PA = 270 (pure A switch), 0 (pure E switch), and 45 or 135 (mixed A/E switch) deg for each (A,E) matrix position
  - 3240 individual FS measurements spanning 54 FS runs, each with 60 FS measurements
- Fast switch for ≈ 10 minutes per (A,E) and position angle

Fast Switching Measurements

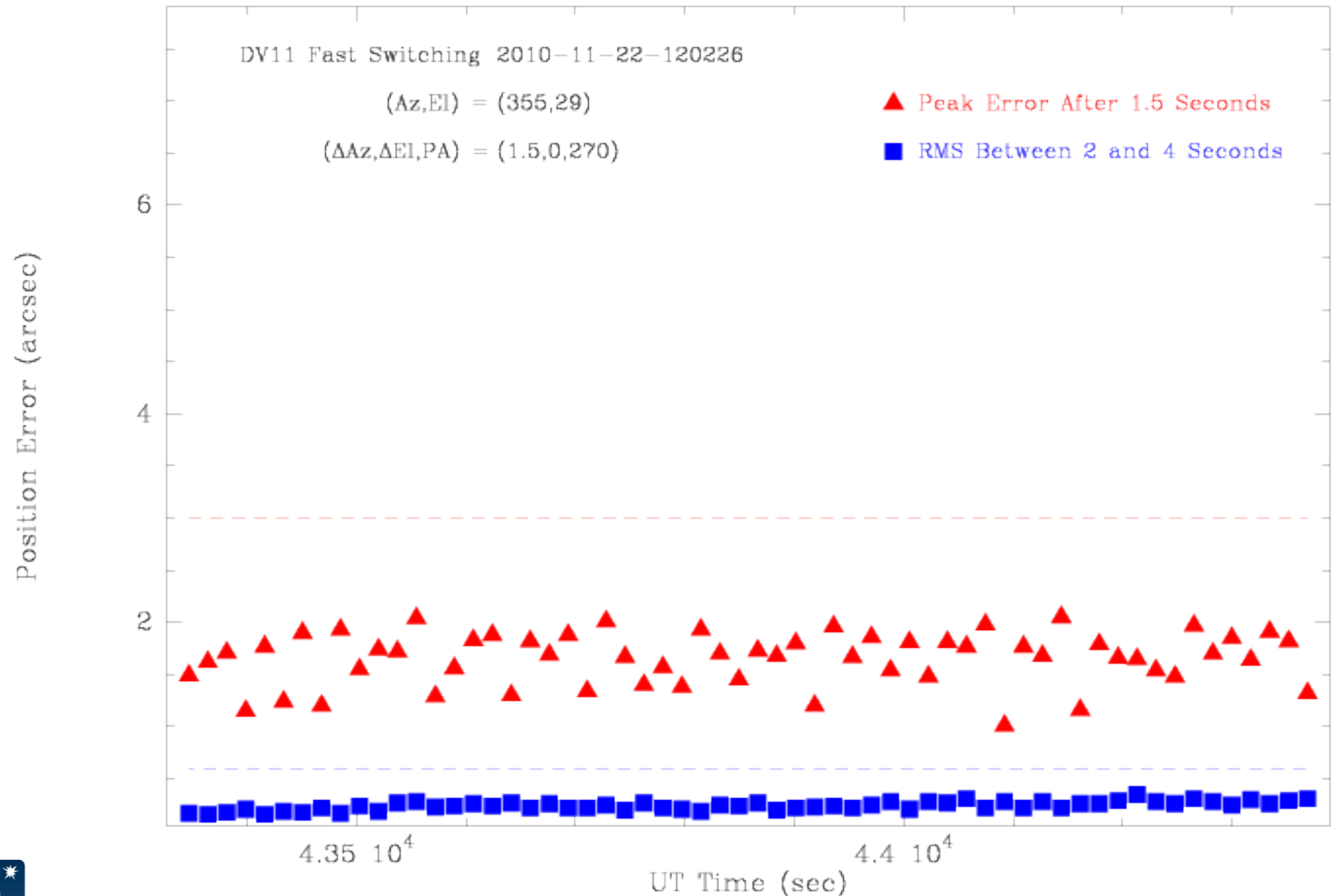


Production Antennas



Example FS Measurement Run

Production Antennas



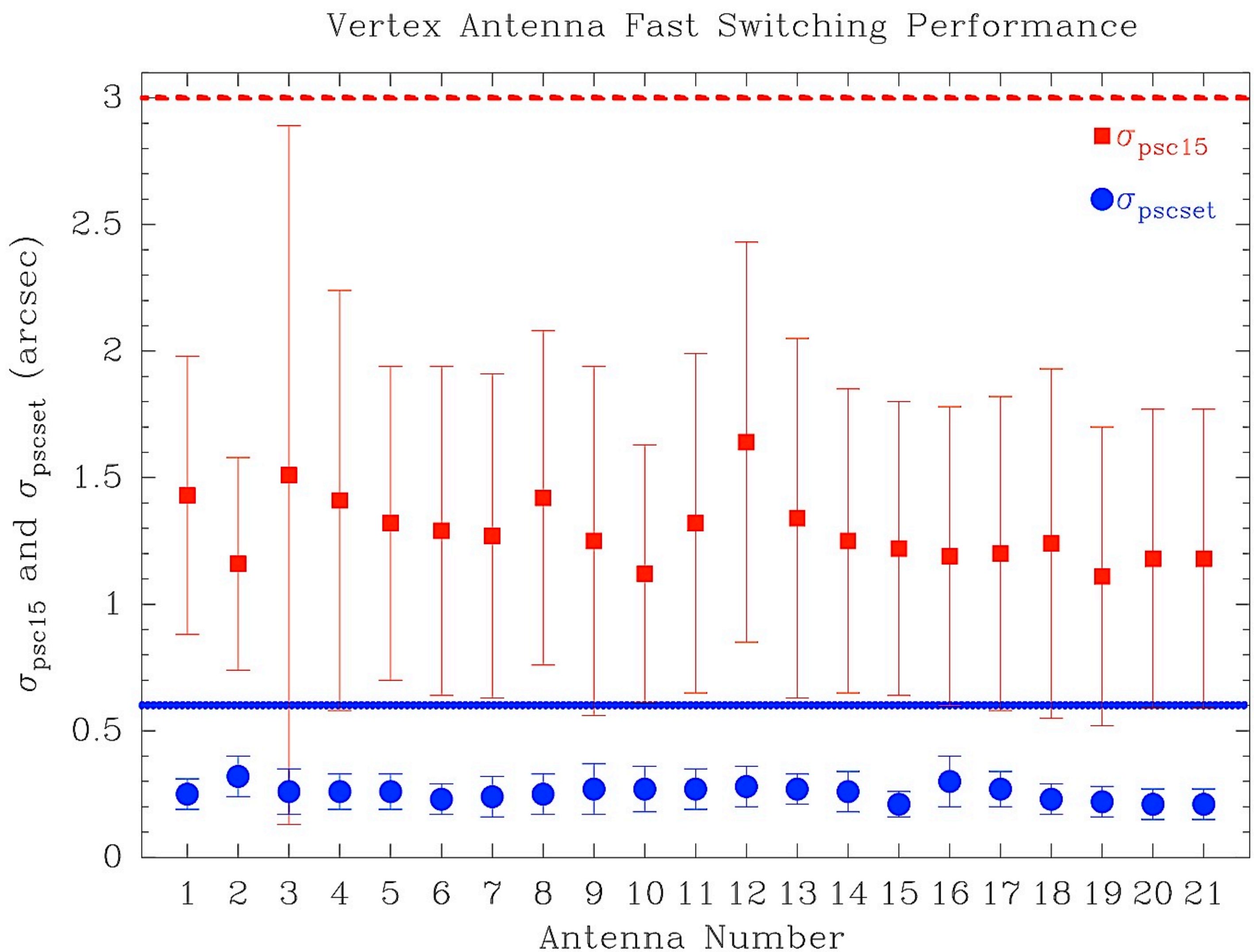
Fast Switching Performance

Antenna	Date[a]	N_{meas}	T_{amb} (C)	ΔT (C)	W_s (m/s)	σ_{psc15} (arcsec)	σ_{pscset} (arcsec)
DV01	2009/02/10	660	+13.6 – +17.0	0.2 – 1.5	1.0 – 3.4	1.43±0.55	0.25±0.06
DV02	2009/04/28	1320	+8.5 – +12.9	0.5 – 1.8	0.8 – 3.2	1.16±0.42	0.32±0.08
DV03	2009/09/10	5150	+3.4 – +22.1	0.1 – 2.3	0.6 – 5.6	1.51±1.38	0.26±0.09
DV04	2010/02/01	3420	+12.5 – +23.7	0.1 – 1.7	0.5 – 9.2	1.41±0.83	0.26±0.07
DV05	2009/11/03	4620	+6.8 – +21.1	0.1 – 2.0	1.1 – 7.6	1.32±0.62	0.26±0.07
DV06	2010/05/09	3240	+7.2 – +17.6	0.3 – 2.5	0.4 – 4.7	1.29±0.65	0.23±0.06
DV07	2010/04/22	3240	+9.6 – +18.4	0.1 – 2.0	1.2 – 7.0	1.27±0.64	0.24±0.08
DV08	2010/05/23	3240	+6.4 – +17.9	0.4 – 2.0	0.2 – 6.7	1.42±0.66	0.25±0.08
DV09	2010/08/02	3240	+5.8 – +14.3	0.2 – 2.1	0.6 – 4.2	1.25±0.69	0.27±0.10
DV10	2010/10/11	3240	+5.7 – +18.2	0.0 – 1.9	1.3 – 5.3	1.12±0.51	0.27±0.09
DV11	2010/11/29	3240	+9.4 – +21.3	0.2 – 1.9	1.7 – 6.0	1.32±0.67	0.27±0.08
DV12	2011/01/22	3240	+13.0 – +20.5	0.1 – 2.0	0.7 – 4.3	1.64±0.79	0.28±0.08
DV13	2011/03/16	3240	+12.1 – +21.5	0.2 – 3.2	1.1 – 6.2	1.34±0.71	0.27±0.06
DV14	2011/05/30	3780	+9.6 - +18.0	0.1 – 1.4	0.6 – 4.5	1.25 0.60	0.26 0.08
DV15	2011/07/27	3420	+6.1 - +11.7	0.1 – 2.5	1.3 – 8.2	1.22 0.58	0.21 0.05
DV16	2011/08/26	3420	+7.0 - +16.3	0.1 – 1.8	1.1 – 5.9	1.19 0.59	0.30 0.10
DV17	2011/10/10	3240	+14.6 - +22.0	0.6 – 1.7	0.6 – 5.0	1.20 0.62	0.27 0.07
DV18	2011/11/27	3240	+10.7 - +20.3	0.1 – 2.4	0.5 – 7.5	1.24 0.69	0.23 0.06
DV19	2011/12/22	3240	+11.9 - +23.6	0.6 – 2.3	1.3 – 6.0	1.11 0.59	0.22 0.06
DV20	2012/03/28	3240	+12.4 - +21.9	0.3 – 1.6	0.9 – 3.7	1.18 0.59	0.21 0.06
DV21	2012/05/10	3240	+14.1 - +19.8	0.1 – 1.6	1.3 – 6.9	1.14 0.52	0.23 0.06

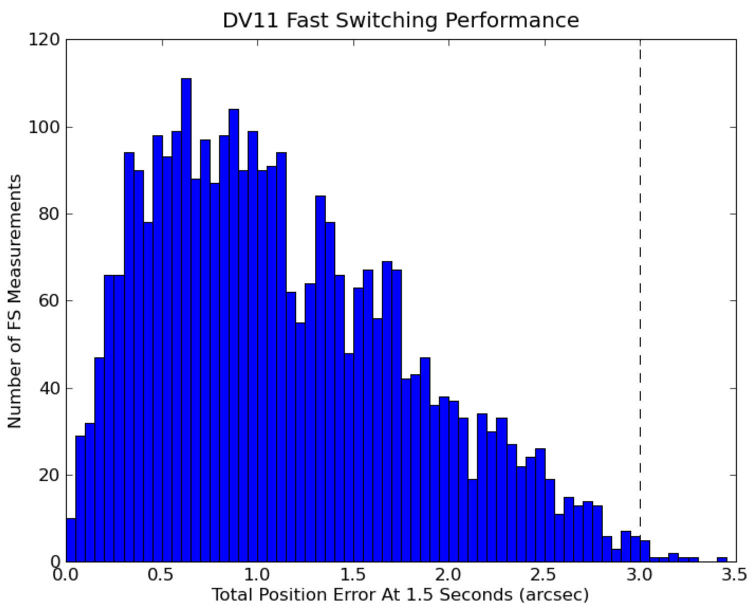
[a] Date of final report

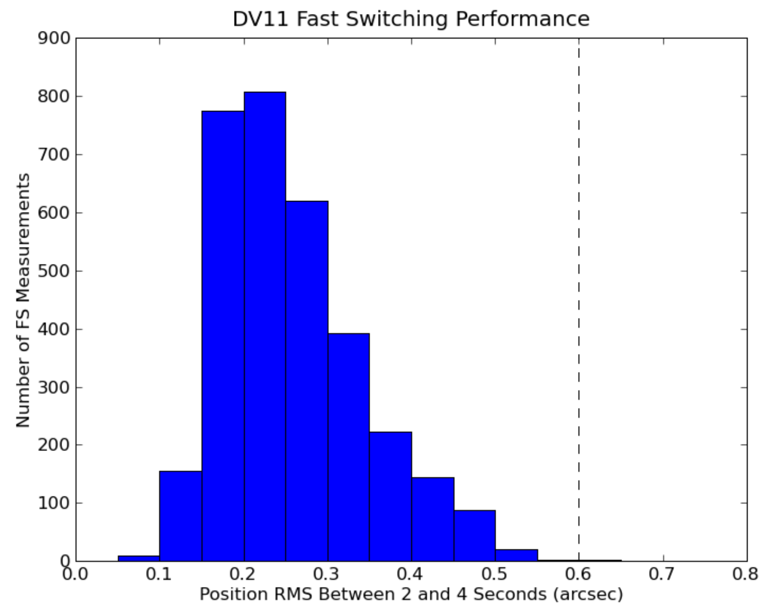
Fast Switching Performance

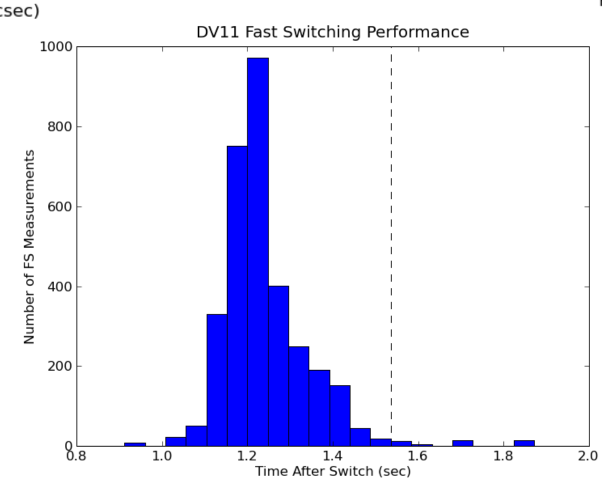
Production Antennas



Sample DV Fast Switching Performance

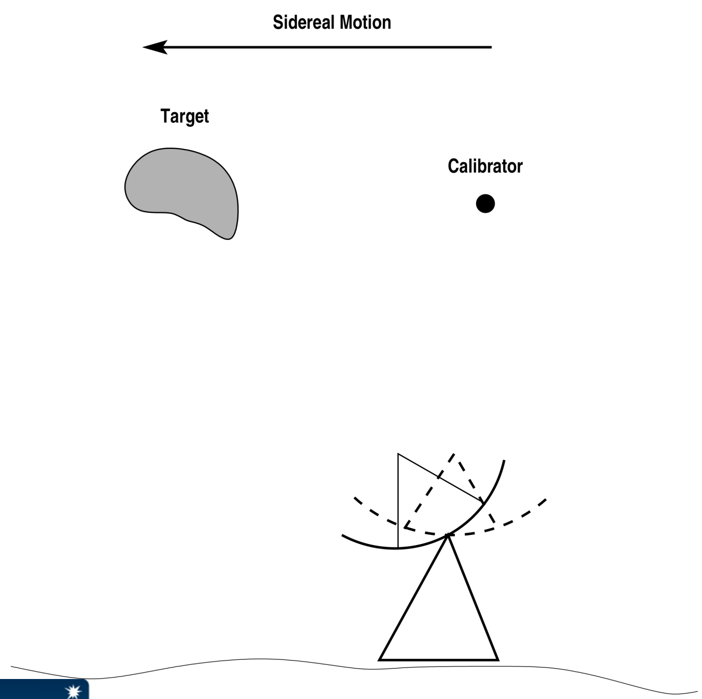


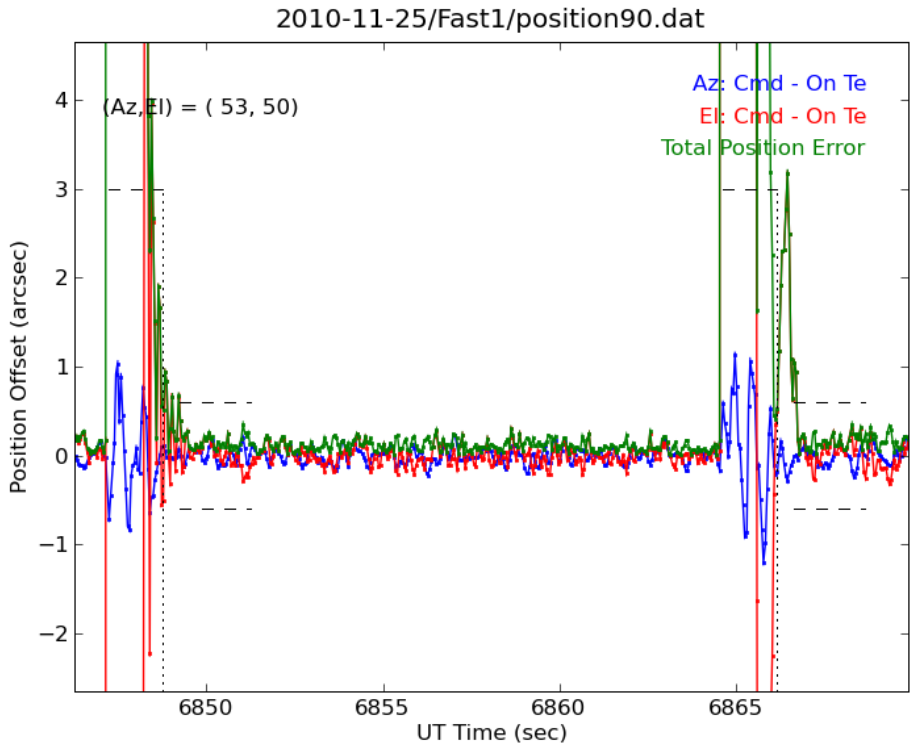




Differential Sidereal Motion and FS

- During the time that it takes to move from one position to another 1.5 degrees away the Earth has rotated a bit.
- In certain regions of the sky this differential sidereal motion can add a bit of distance to a nominal 1.5 degree fast switch.



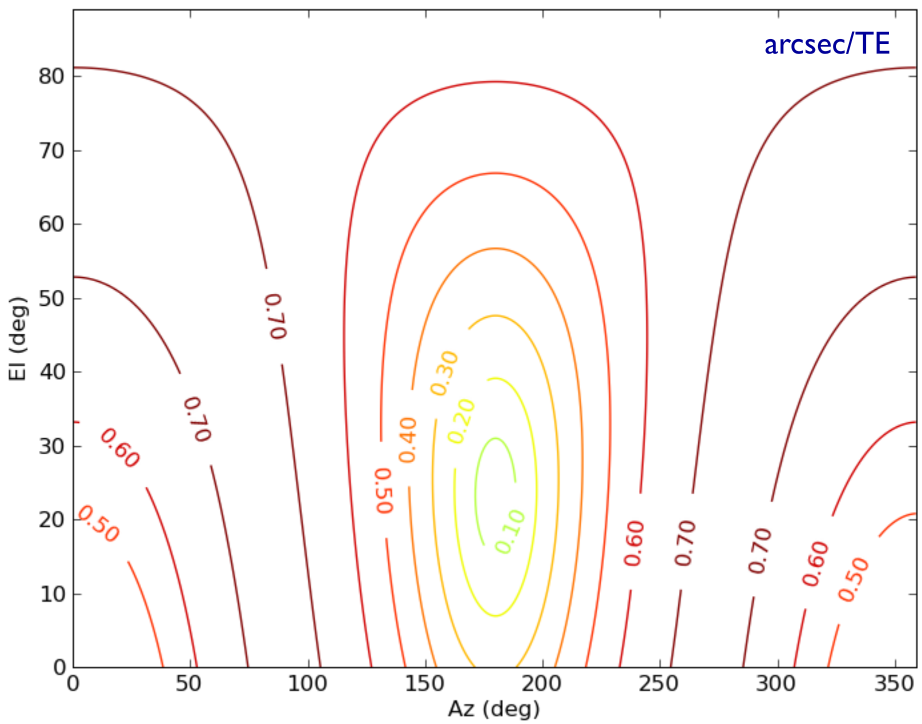


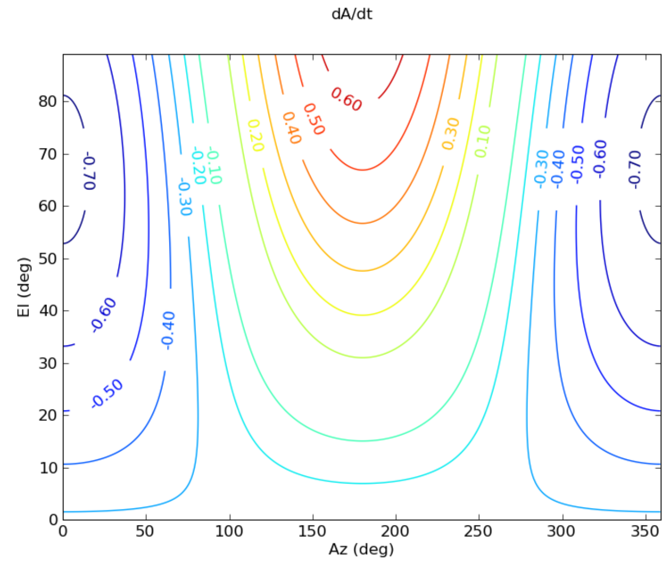
Differential Sidereal Calculation

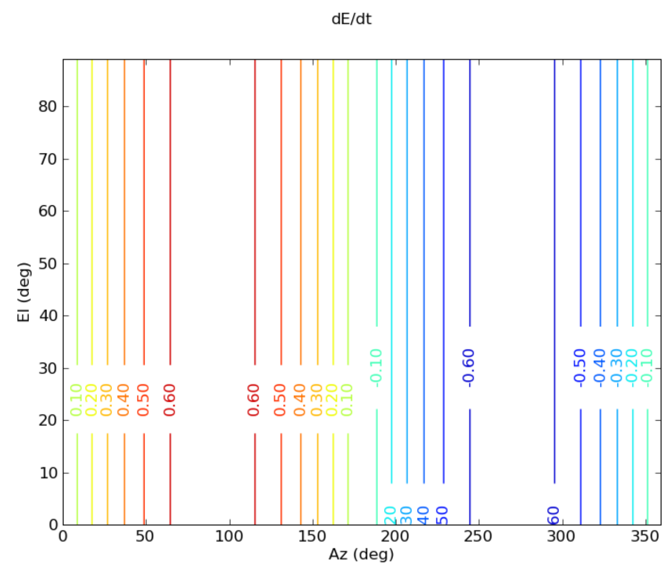
$$\frac{dA}{dt} = \frac{d\tau}{dt}\left[\frac{\sin\phi\cos E - \cos\phi\sin E\cos A}{\cos E}\right]$$

$$\frac{dE}{dt} = \frac{d\tau}{dt}\cos\phi\sin A$$

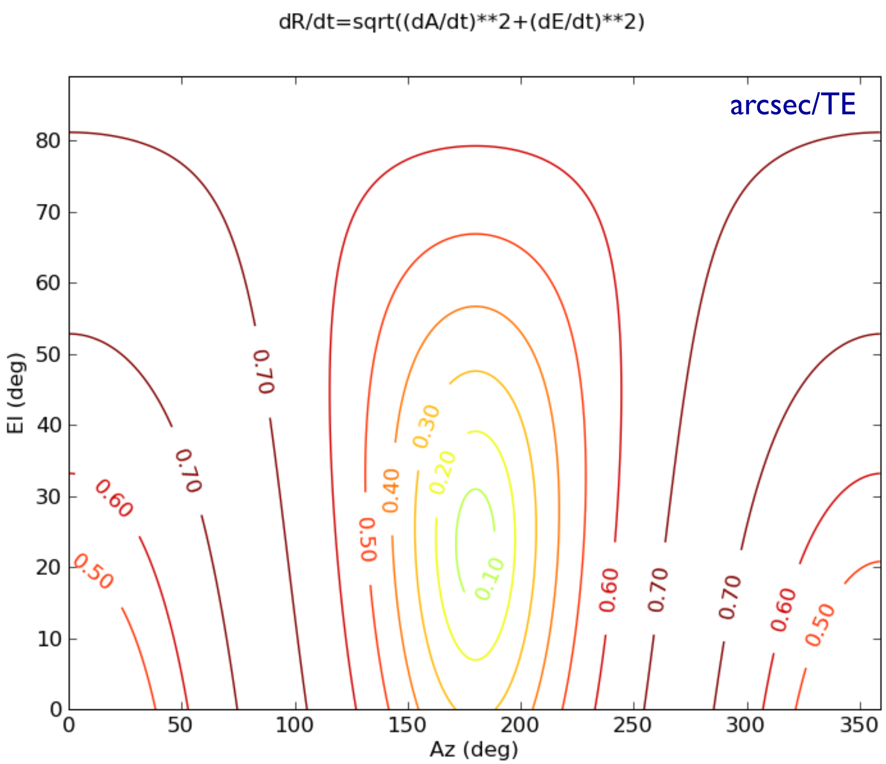
dR/dt=sqrt((dA/dt)**2+(dE/dt)**2)

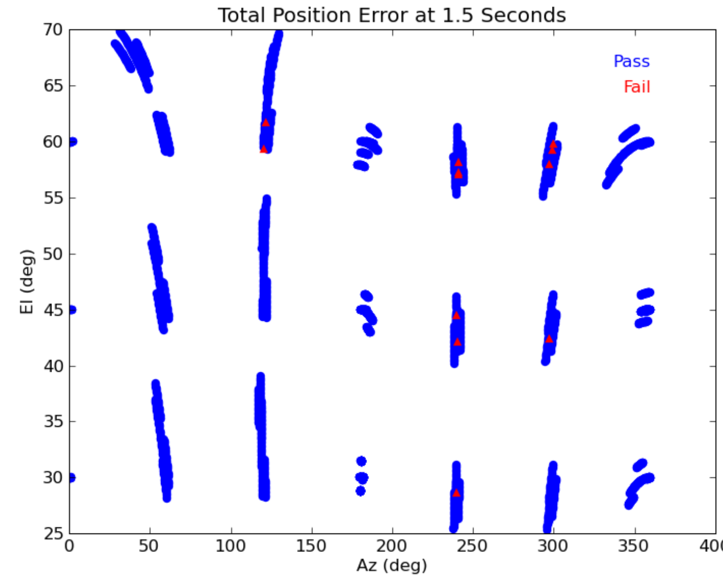


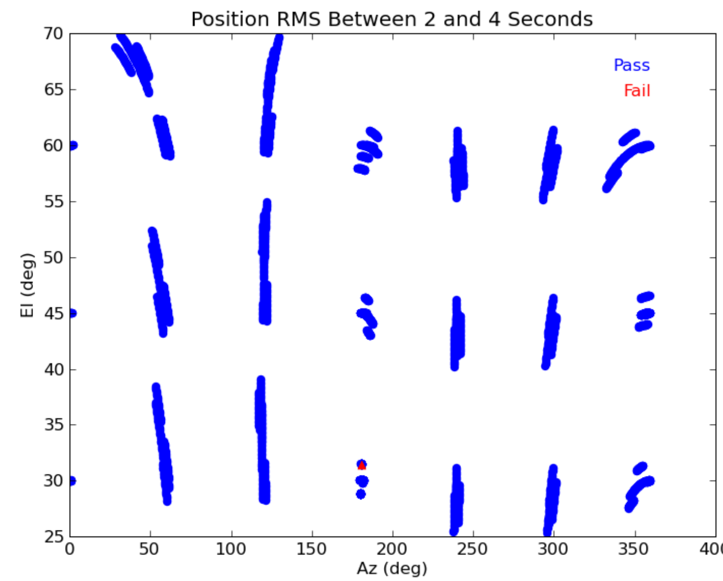




Differential Sidereal Affect on FS Measurements

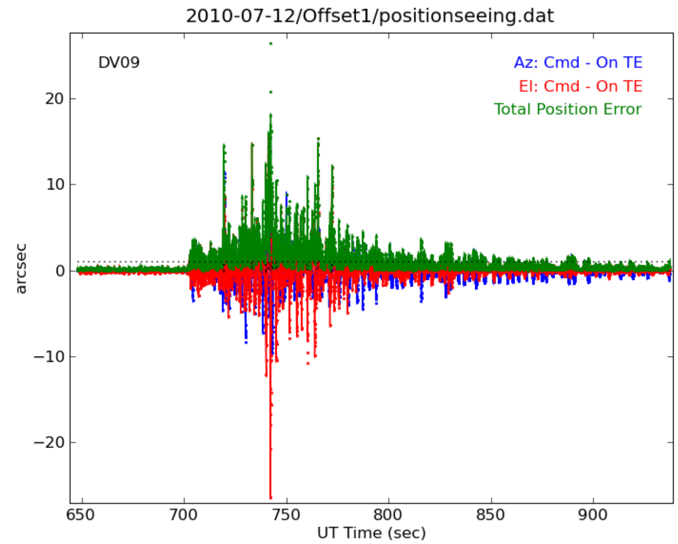


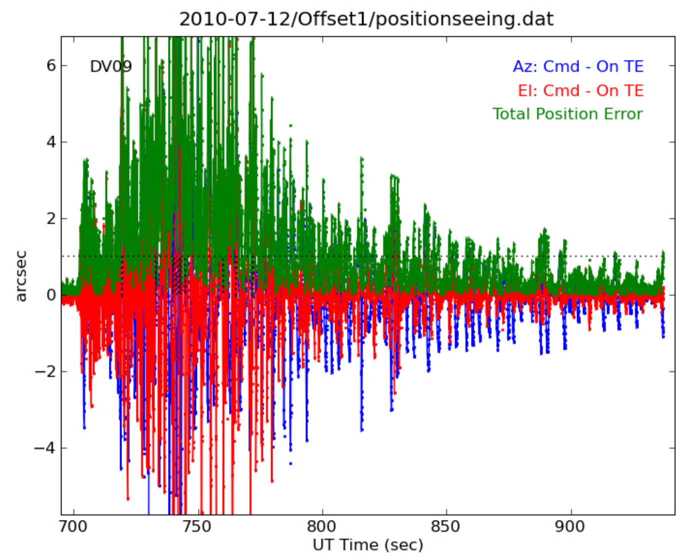




A Multi-Million Dollar Earthquake Detector

- On the evening of July 12 2010 a magnitude 6.2 earthquake jolted a remote area approximately 80 km ENE of Calama (latitude = −22.26, longitude = −68.20; 0.86 degrees of distance on the earth's surface).
- When the earthquake started DV09 was making a PSC measurement as part of a regular seeing observation.
- Operator noted: "The star did figure-eights on the screen for about 3 minutes".
- Using information from the USGS listing for this earthquake at http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2010yqad.php:
  - ✓ The PSC diagram shown indicates that the quake began at the ALMA site at UT 701 seconds, which is 00:11:41 UT.
  - ✓ The USGS lists the start time of the quake as 20:11:18 local time, which is 00:11:18 UT.
  - ✓ The USGS web site has an online propagation time calculator which allows one to calculate the propagation time from the epicenter to the ALMA site.
  - ✓ The estimated propagation time is about 18 seconds, which is tantalizingly close to the 23 second difference between the USGS quake time of 00:11:18 UT and the measured start time of 00:11:41.
  - ✓ Propagation time from the epicenter to the ALMA site is the explanation for the difference in measured start times.
- The quake shook the antenna pretty hard for about 100 seconds, then slowly damped until well after the end of the PSC measurements.
- The PSC measurements ended around UT 938 seconds, or 00:15:38 UT, while the antenna was still being shaken (see lower panel).
- The antenna reacted to the earthquake for more than 4 minutes.
- We note this event due to the fact that two all-sky pointing runs were made just before the earthquake, while offset pointing measurements 001751 and 004516 were made immediately after this event.
- None of these measurements show any ill effects due to the earthquake.





Fast Switching Performance Summary

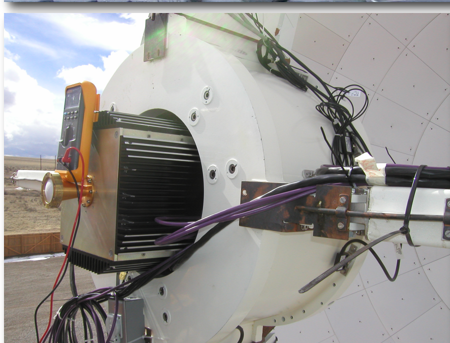
- All Vertex antennas meet both parts of the fast switching specification

Reflector Surface Accuracy

Techniques and Systems Used:

- Near-Field Radiometric Holography
- Accelerometer System
- Radiometric Efficiency Measurements
- Temperature Sensor System

Near-Field Radiometric Holography System



- Transmitter:
  - Photonically-generated signal
  - 50m high tower located 310m from antenna
- Receiver:
  - 79/104 GHz dual-receiver system
- 10 μm spec; 5 μm goal
- Gildas data analysis (Lucas)

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Surface Setting

Prototype Antennas

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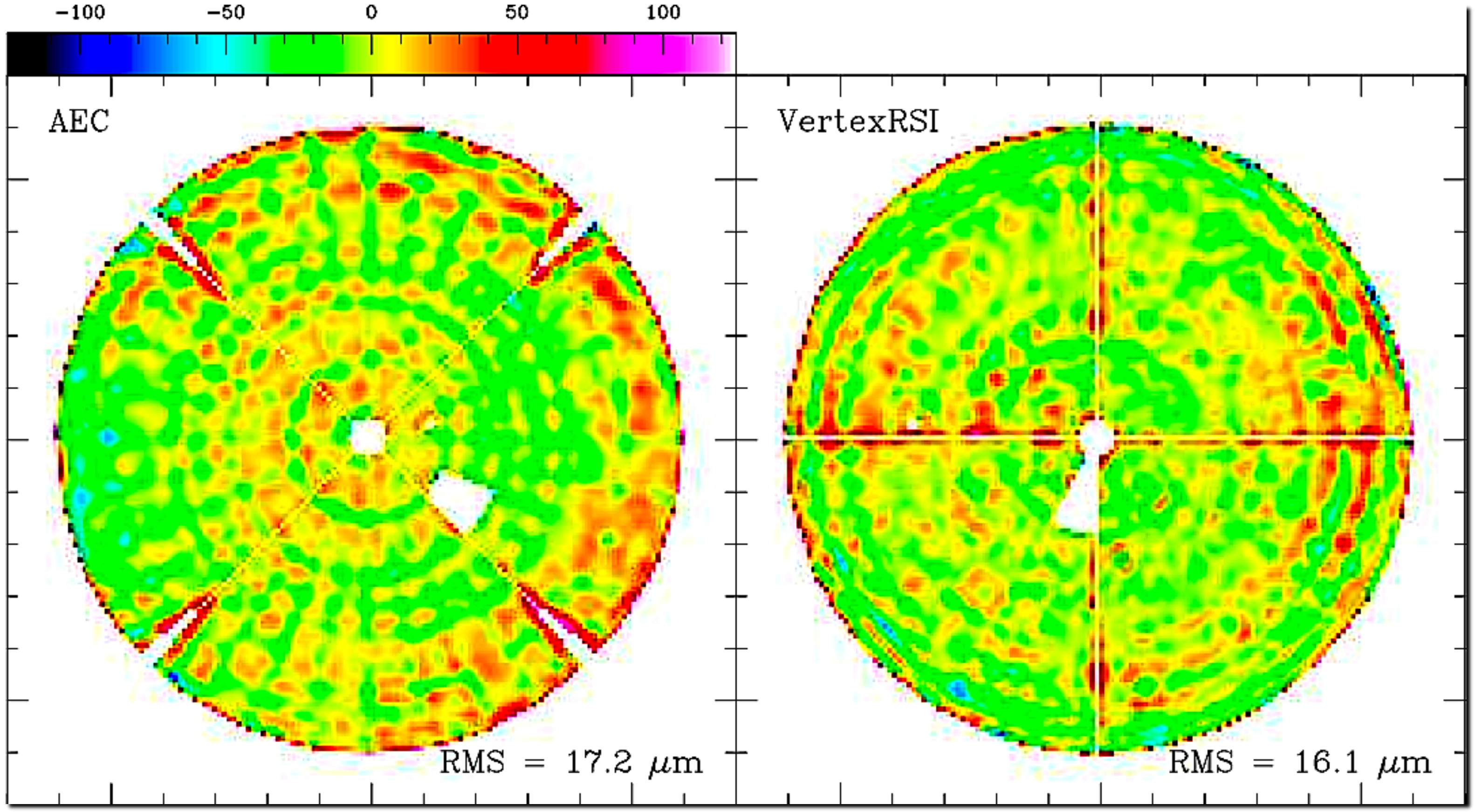
Near-Field Radiometric Holography Results

Prototype Antennas



Reflector Surface Accuracy Performance Summary

Prototype Antennas

Technique/System	***AEC***	***VertexRSI***
Holography	17±5 μm	16±5 μm
Accelerometers	ΔRMS < 8 μm	ΔRMS < 7 μm
Radiometric	< 40 μm	< 40 μm
Temperature Sensors	…	ΔRMS ≤ 3 μm

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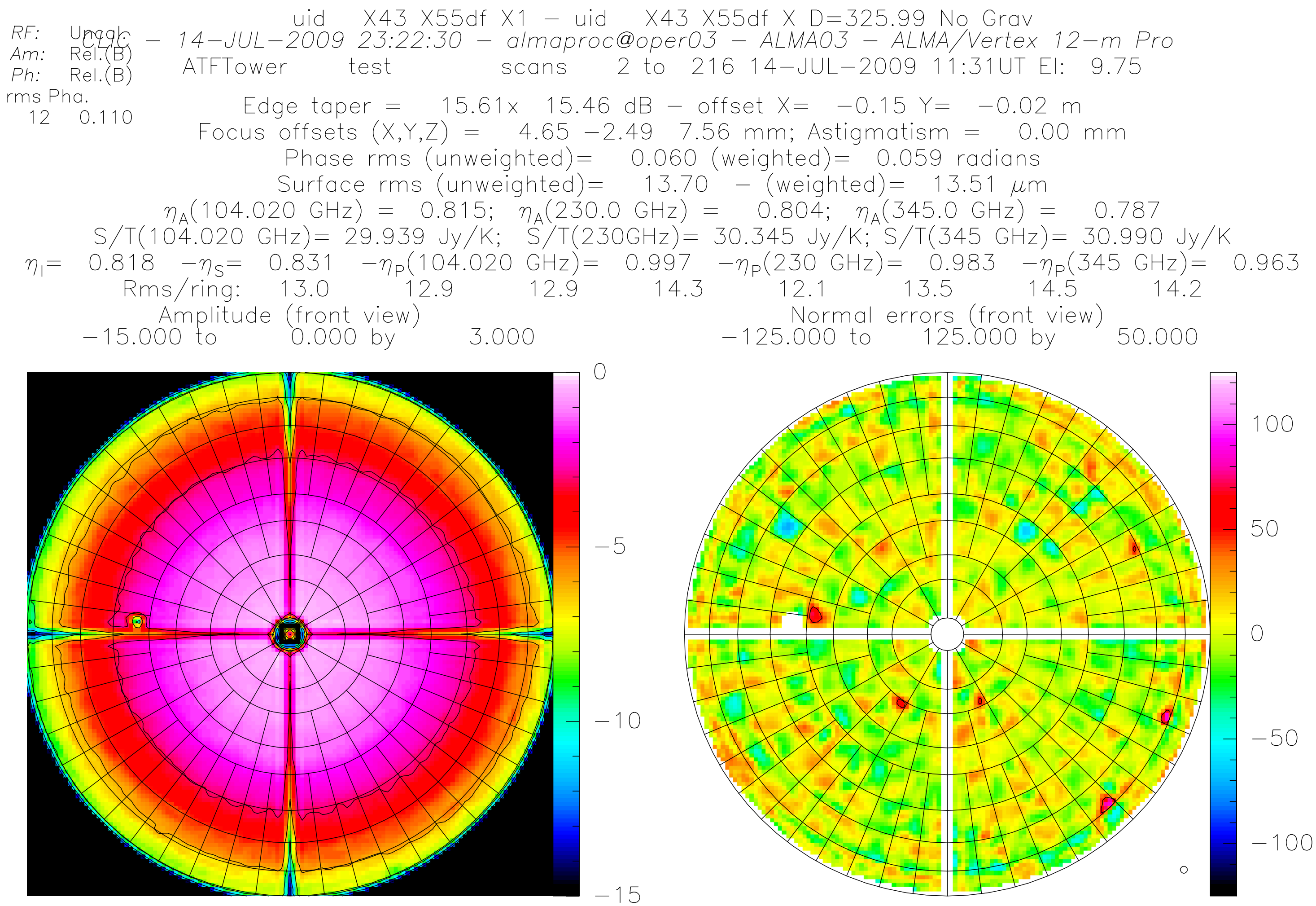
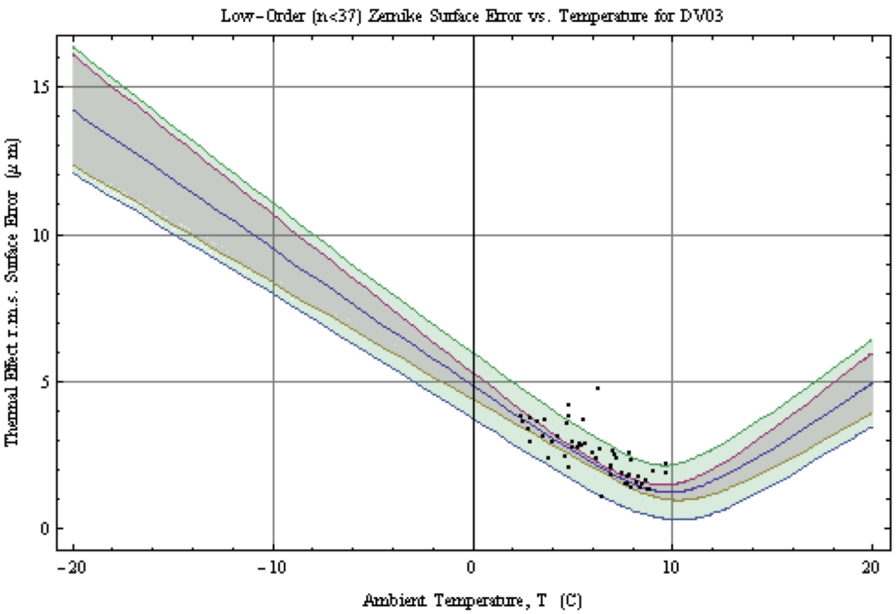
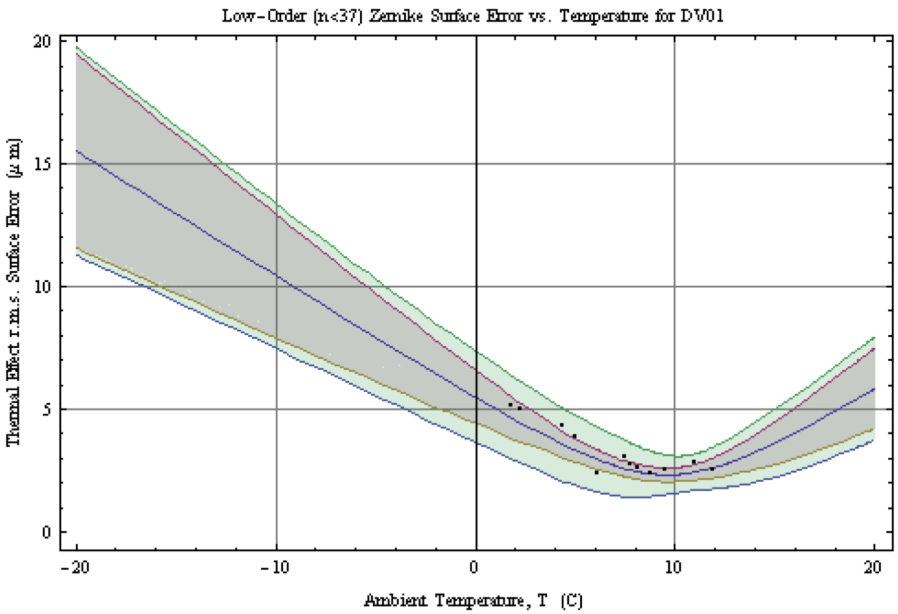
Near-Field Radiometric Holography Results

Production Antennas

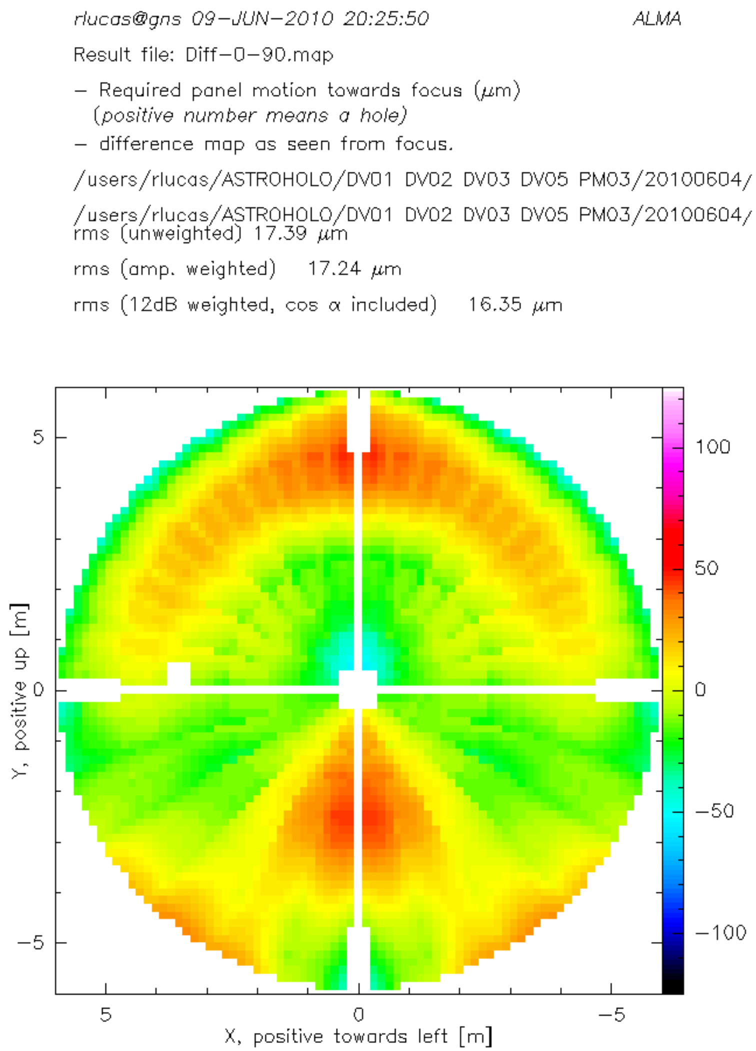


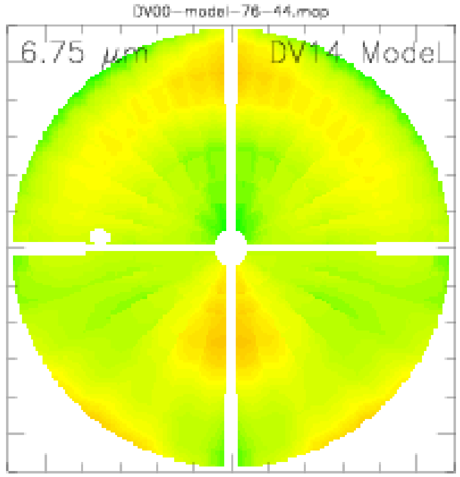
ALMA Vertex Production Antenna Measured Temperature Dependence

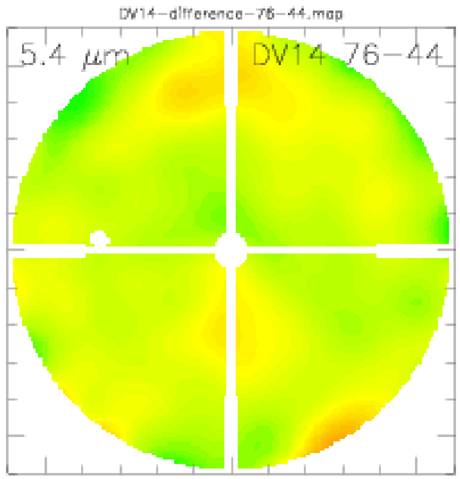


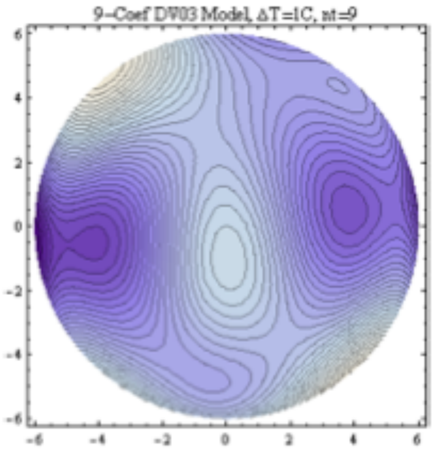


Gravitational and Thermal Deformation

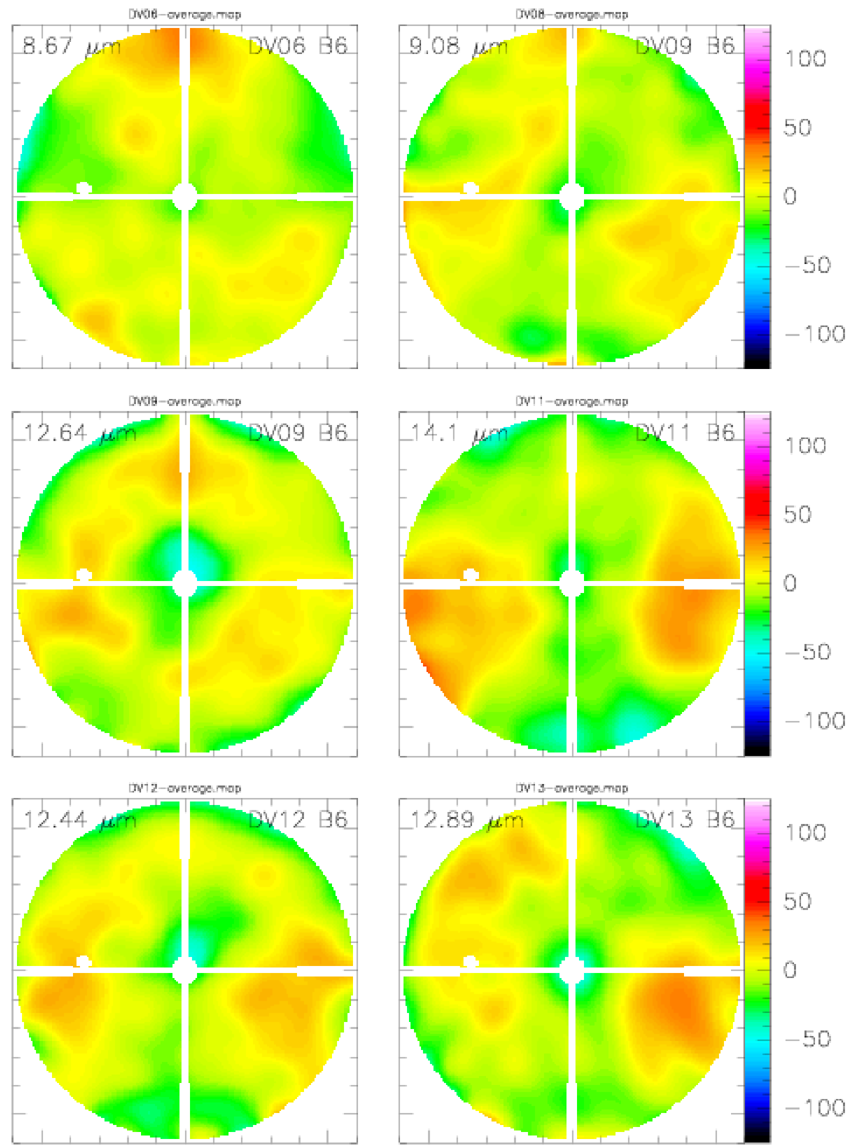








ALMA Vertex Production Antenna Astronomical Holography



Publications

- Mangum, J. G., Baars, J. W. M., Greve, A., Lucas, R., Snel, R., Wallace, P. T., & Holdaway, M. 2006, PASP, 118, 1257: ***Evaluation of the ALMA Prototype Antennas***.
- Baars, J. W. M., Lucas, R., Mangum, J. G., & Lopez-Perez, J. 2007, IEEE Antennas and Propagation Magazine, 49, 24: ***Near-Field Radio Holography of the Large Reflector Antennas***.
- Snel, R. C., Mangum, J. G., & Baars, J. W. M. 2007, IEEE Antennas and Propagation Magazine, 49, 84: ***Study of the Dynamics of Large Reflector Antennas with Accelerometers***.
- Greve, A. & Mangum, J. G. 2008, IEEE Antennas and Propagation Magazine, 50, 66: ***Mechanical Measurements of the ALMA Prototype Antennas: Path Lengths, Thermal Behaviour, and Azimuth Bearing***.

NRAO

Summary

- The ALMA prototype and production antennas meet or surpass all performance metrics:
  - Positioning (pointing, fast switching, OTF, etc.)
  - Surface Accuracy
  - Path Length Stability
- Large (12m) efficient antennas can be built allowing precision radiometry up to 1 THz
- Many aspects of the ALMA antenna performance (i.e. stability with time, transport, environment, etc.) still need to be studied
- The effort expended in developing high-performance antennas always results in observatory efficiency and longevity