Systematics in QUaD

Clem Pryke

Inflation Probe Systematics Workshop

28 July 2008

QUaD Collaboration

- Stanford: Sarah Church (PI), Jamie Hinderks (NASA Goddard), Ben Rusholme (IPAC), Keith Thompson, Melanie Bowden (industry), Ed Wu
  - Focal plane design, receiver integration, readout electronics, analysis
- Caltech/JPL: Andrew Lange (co-PI), Jamie Bock, John Kovac, Ken Ganga (APC/CNRS)
  - Detectors, calibration sources & methods
- Chicago: Clem Pryke (co-PI), Robert Friedman, John Carlstrom, Tom Culverhouse, Erik Leitch (JPL), Robert Schwarz (South Pole)
  - Mount, foam cone, DAQ, observations, analysis
- Cardiff: Walter Gear (PI), Simon Melhuish (Manchester), Lucio Piccirillo (Manchester), Peter Ade, Mike Zemcov (Caltech), Nutan Rajguru (UCL), Angiola Orlando (Caltech), Abi Turner, Sujata Gupta
  - Cryostat, mirrors, fridge, cal source, analysis
- Edinburgh: Andy Taylor, Michael Brown (Cambridge), Patricia Castro (Lisbon), Yasin Memari
  - Analysis
- Maynooth: Anthony Murphy, Creidhe O'Sullivan, Gary Cahill
  - Optics design

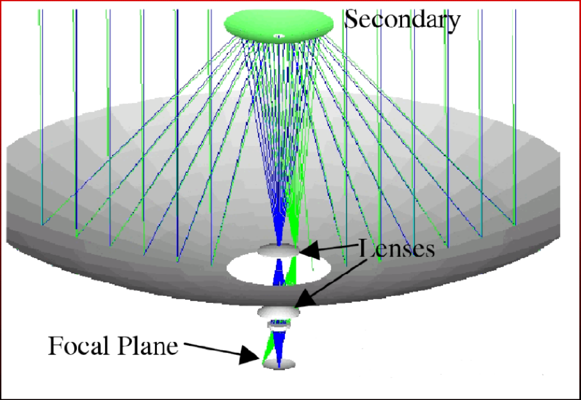
Experiment Summary

- Angular resolution: 5.5/3.5 arcmin @ 100/150GHz
- Sky Coverage: 30/60 square deg with/without field difference
- Multipole coverage: 200-2000+
- Polarization Modulation: rotate whole telescope about line of sight
- Type of Detectors: PSB pairs
- Location: South Pole (ground)
- NEQ: 510/450 uk/sqrt(s) per pair at 100/150GHz
  - 9/18 good pairs so divide by sqrt(4.5)/sqrt(9) to get intrument NEQ
- Status: ran three seasons, decomissioned fall 2007
  - Results out: Instrument paper Hinderks et al arxiv:0805.1990, Results paper Pryke et al arxiv:0805.1944

The QUaD Telescope

- 2.6 meter Cassegrain radio telescope attached to front of DASI mount (3rd axis preserved)
- 31 pixel polarization sensitive bolometer camera (PSBs), no internal pol modulator (waveplate)
- Secondary supported on foam cone - aperture blockage small and uniform
- DASI tower, equipment room, drive system, DAQ system re-used.
- Large, fixed, reflective ground shield

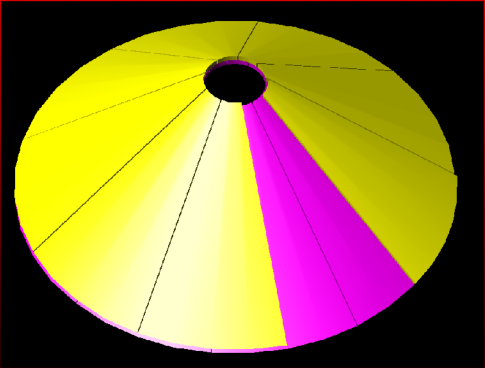
Optical Path



Lenses in the cryostat (cold)

Optical design by Maynooth (Ireland)

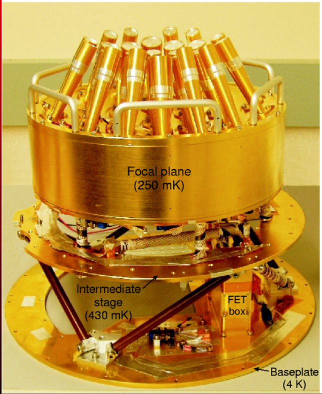
Secondary Support Foam Cone



Zotefoam only manufactured in 6x3' flat sheets - adhesive causes 1-2% scattering

Foam cone designed/built at Chicago

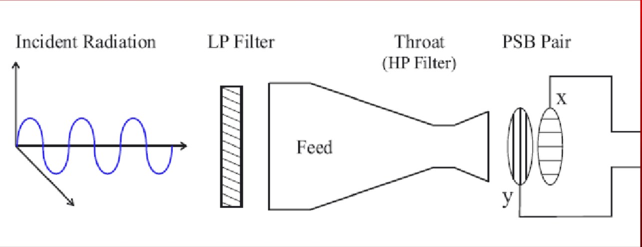
Receiver Focal Plane



12 feeds @ 100GHz (6 arcmin), 19 @150GHz (4 arcmin)

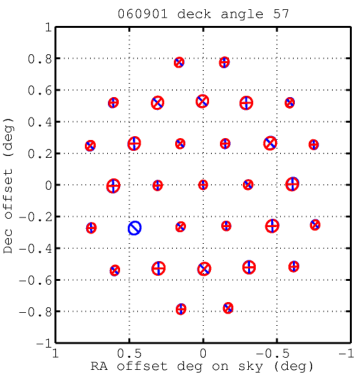
Focal plane designed/built at Stanford

Polarization Sensitive Bolometers



- Two orthogonal absorber grids measure linear polarizations
  - Sum measures total intensity
  - Difference measures polarization
- Timestreams read out and recorded to disk separately
  - Scaled and sum/diff'ed in offline analysis

Array Projected on Sky

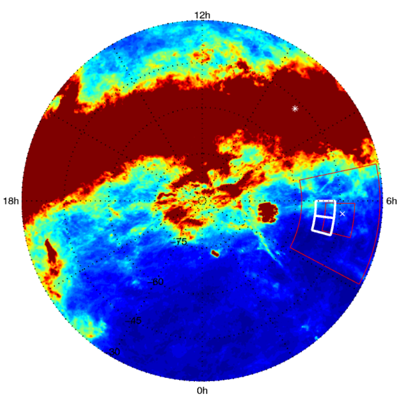


2 orientation "flavors", plus rotate whole telescope around line of sight by 60 deg

QUaD Observing Strategy

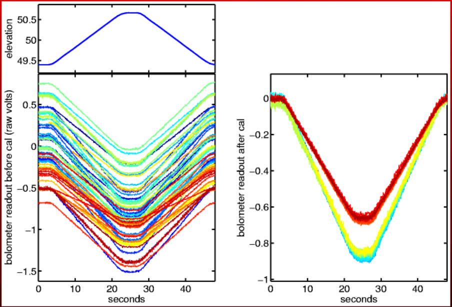
- Telescope scans 7.5 deg in azimuth as modulation on top of sky track (at Pole sky rotates around zenith)
- Scan 5 times out and back - then step in el by 0.02 deg and repeat.
  - Build simple raster map - no cross linking!
  - Scan at 0.25 deg/sec putting ell range 200 to 2000 at 0.1 to 1Hz in timestream.
- One run per day starting always at same LST
  - (Start as observing field clears lab building)
- Cal, 8 hours CMB, cal, rotate telescope, cal, 8 hours CMB, cal (and 5 hour fridge cycle)

Location of QUaD Field



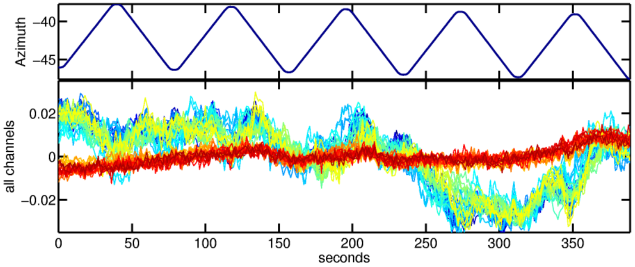
FDS dust prediction @ 150GHz around SCP, linear color scale 0 to 100uK (heavily saturated), QUaD field in white, Boomerang03 in red

Relative Gain Cal



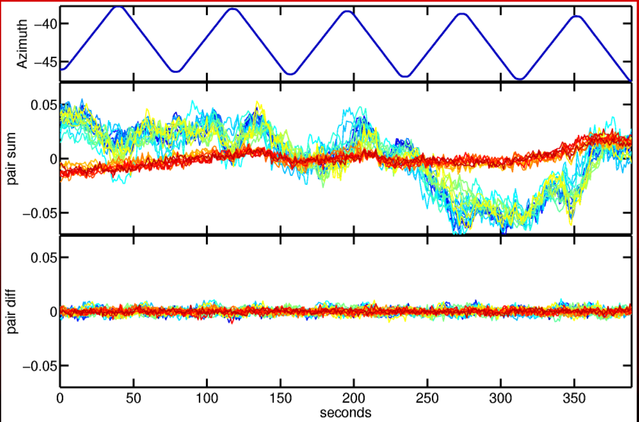
- Before can take pair diff. need to adjust relative gain
  - "Nod" the telescope in elevation to inject large signal from atmospheric gradient
    - Assume atmosphere unpolarized

A raw scan set



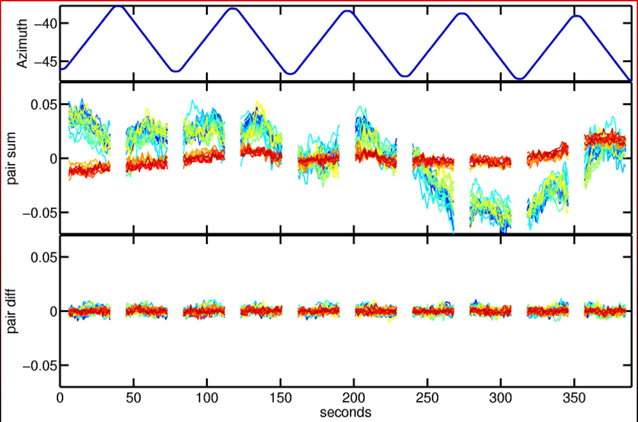
(Well actually deconvolved, low-passed, deglitched, downsampled, relative gain calibrated)

...pair sum/difference...

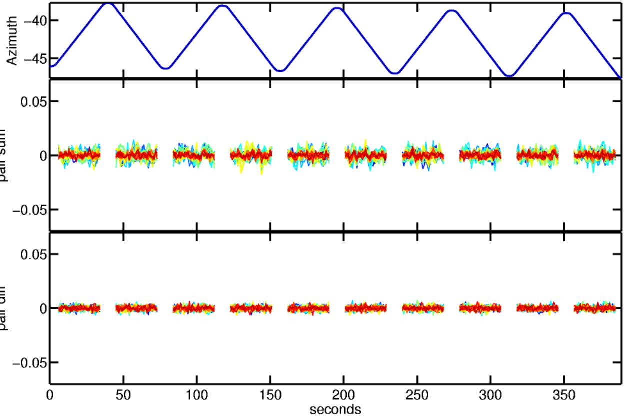


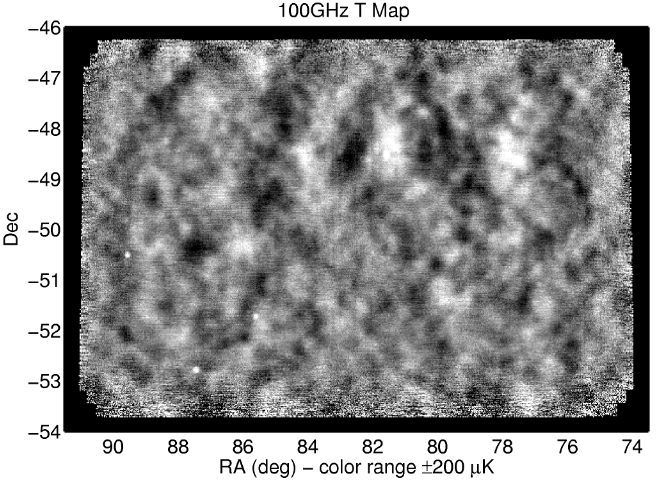
0.05 on y-axis approx 10mK

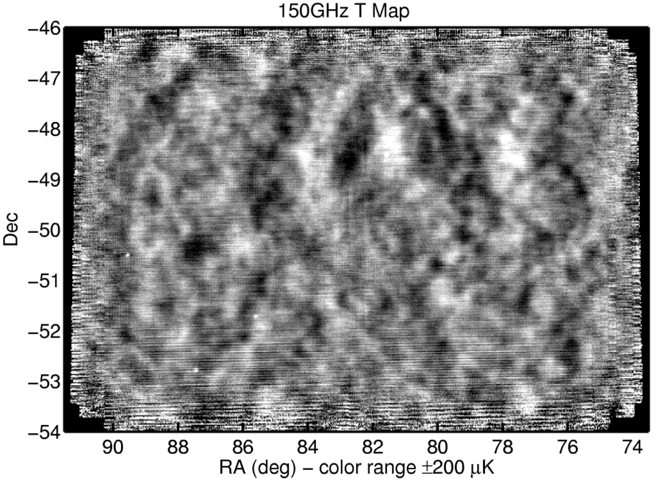
...cut to "half-scans"...

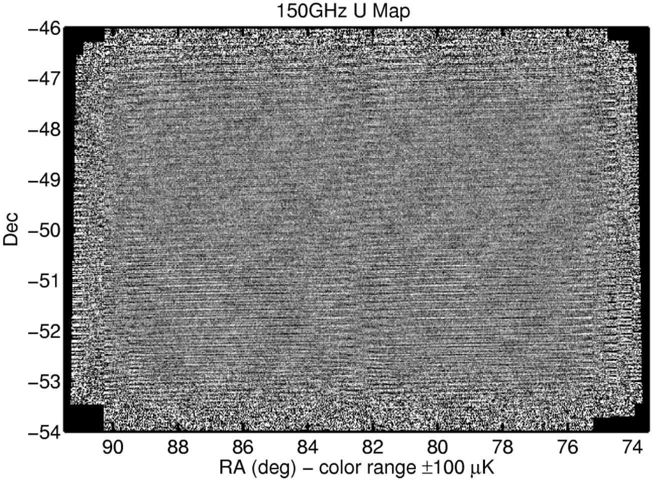


...remove 3rd order polynomials...

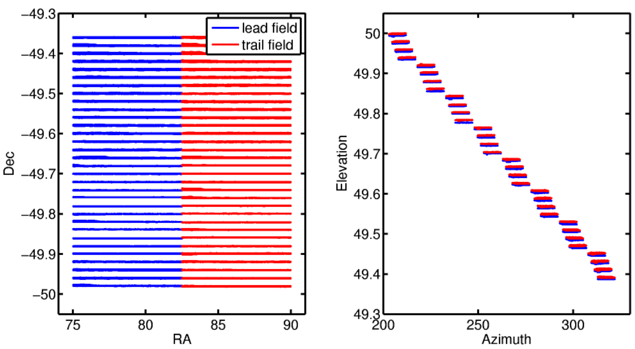



100GHz T Map
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) – color range ±200 μK

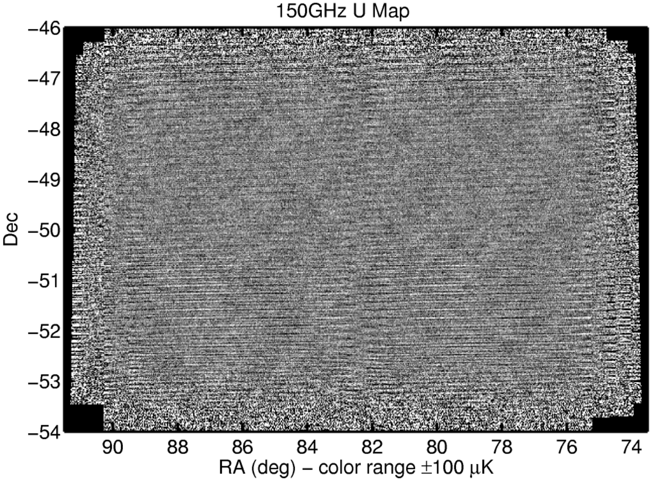

150GHz T Map
Dec
−46
−47
−48
−49
−50
−51
−52
−53
−54
90
88
86
84
82
80
78
76
74
RA (deg) – color range ±200 μK


150GHz U Map
Dec
−46
−47
−48
−49
−50
−51
−52
−53
−54
90
88
86
84
82
80
78
76
74
RA (deg) − color range ±100 μK

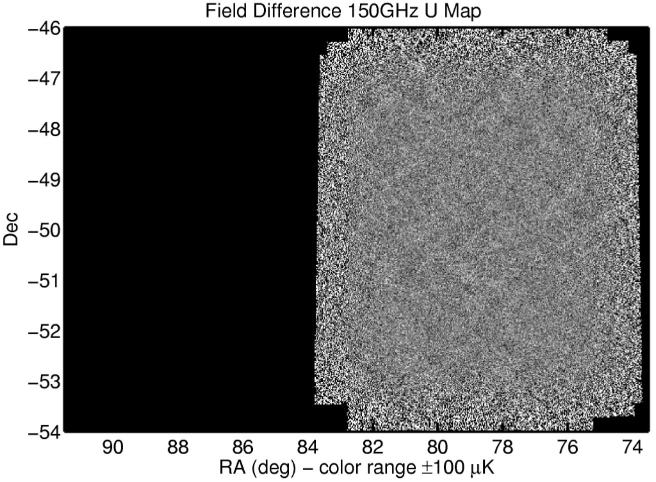
Field Difference to Remove Ground



- Scan two sub-fields separated by 0.5hr in RA
  - Sky signal different - ground signal same

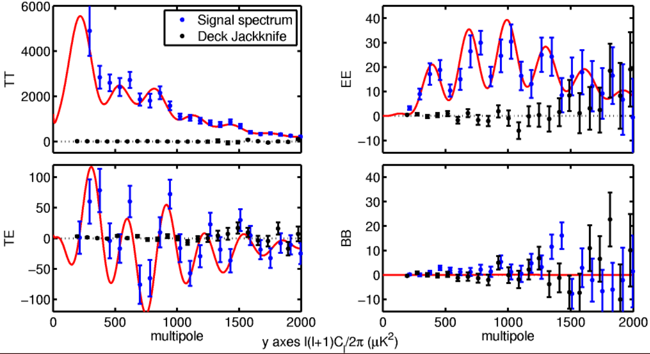


150GHz U Map
Dec
−46
−47
−48
−49
−50
−51
−52
−53
−54
90
88
86
84
82
80
78
76
74
RA (deg) − color range ±100 μK



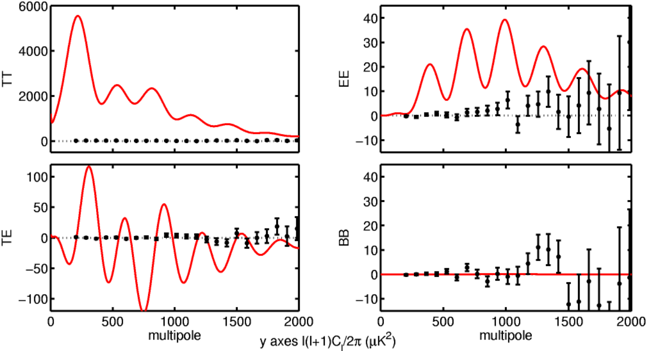
Field Difference 150GHz U Map
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) − color range ±100 μK

150GHz Spectra (as published)



- Signal to noise high! (except BB)
  - No obvious jackknife cancellation failure...

Frequency Difference Spectra

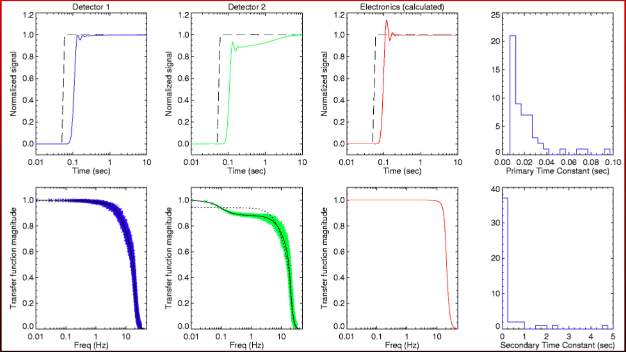


Tests if pattern identical at each freq.
(both freq. abs. cal'ed against same B03 150GHz map)

Calibration/Systematics Discussion

- Timeconst measure/deconv.
- Relative/absolute gain stability (and 1/f)
- Polarization angle/efficiency measurement
- Beam mismatch - centroid offsets
- Far sidelobes inc. 100 deg ringlobe

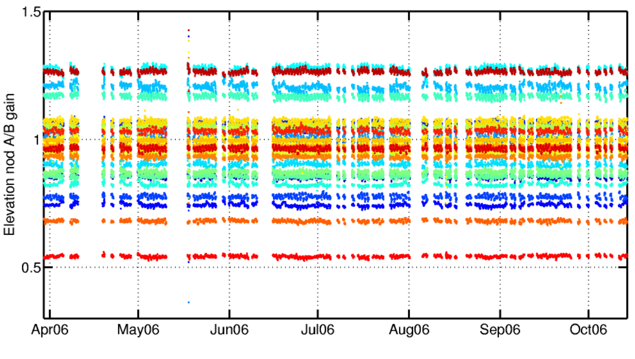
Detector Time Constants



- Some dets have order 10% additive second timeconstant of few seconds
  - (Very similar detectors to Planck!)
- Can "perfectly" correct temporal response (deconvolve it)

Gunn sources from Kovac, analysis Pryke/Hinderks

Excellent Relative Gain Stability



- Pair gain ratio is stable to <1% rms over full season!

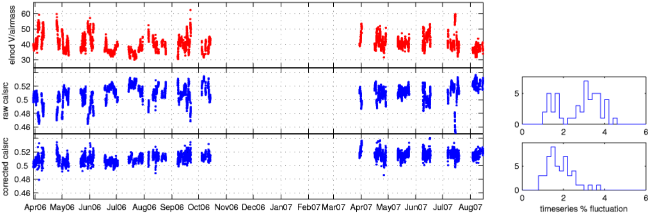
Comments on Relative Gains

- Instrumental polarization completely degenerate with relative gain
  - Therefore a non-issue for a pair diff experiment

- We measure rel gains every 30 minutes
  - Fluctuating errors average down (T sometimes leaks to +Q, sometimes to -Q)

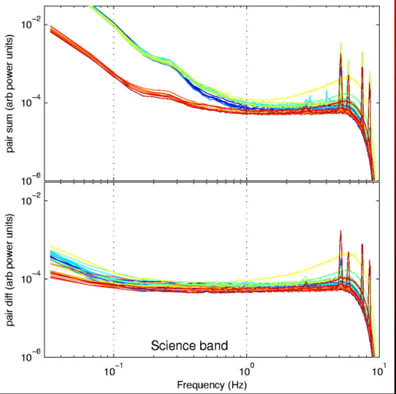
- Even systematic errors average down due to observing at different angles
  - In a sim with zero intrinsic EE/BB and fore/aft gain flat at 1.03 EE/BB power 1e-4 of TT power

Absolute Gain Stability



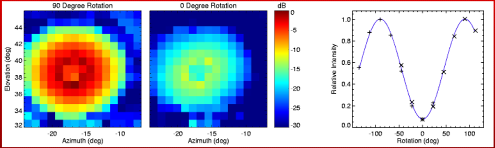
- Gain measured every 30 mins using calibration source
  - Raw values fluctuate by 3% rms over 2 seasons
  - After correction for loading gain supression 2%
- Focal plane had active temperature control - highly recommended

Sum/Diff Timestream Noise Spectra

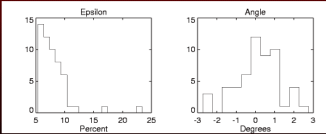


Pair diff has minimal 1/f noise

Measuring Polarization Efficiency/Angle



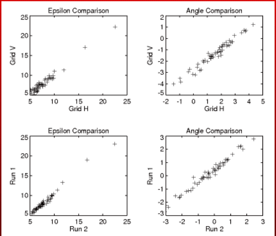
- Use polarized source to measure (near field) co- and cross-polar beams of each detector
  - Do this at many telescope rotations
    - Find polarization efficiency and angle



- Epsilon 0.05 to 0.10 and angles scatter by 1 deg rms around nominal

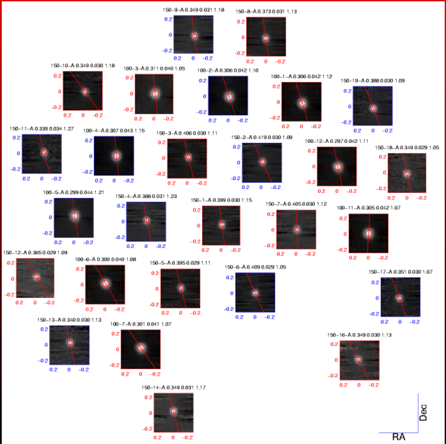
Source measurements by Kovac et al, analysis by Hinderks

Accuracy of Polarization Efficiency/Angle

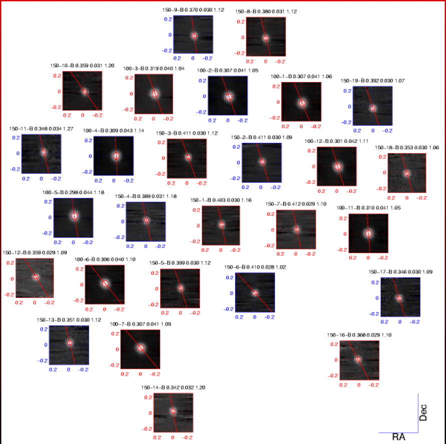


- Estimated by repeatability between measurements with source horiz/vert and with different source appertures.
- Random error in efficiency averages down over array
  - Systematic error leads to incorrect pol map cal
    - Estimated sys uncertainty 0.02
- Random error on angle averages down across array
  - Systematic error leads to E->B mixing
    - Estimated sys uncertainty 2 deg
    - But in sim 5 deg bias has no effect for QUaD's sensitivity level!

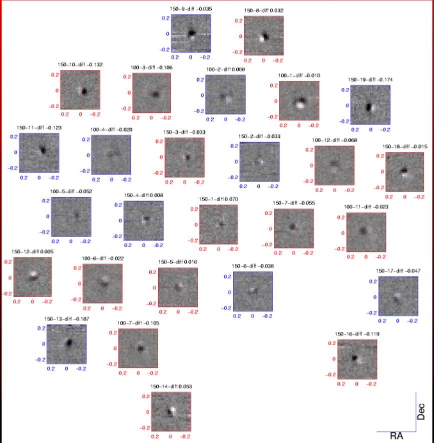
"A" Bolometer Beams



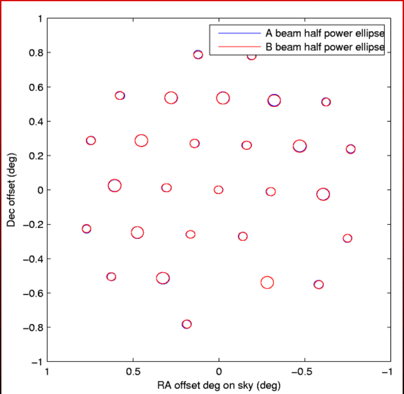
"B" Bolometer Beams



Pair Difference Beams

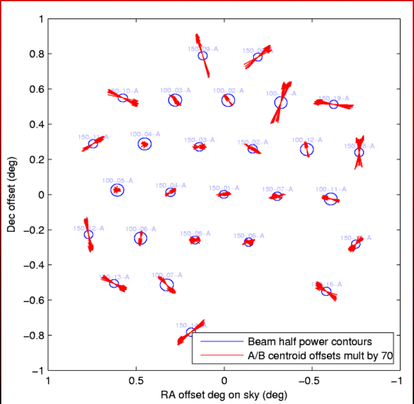


A & B Beam Half Power Ellipses



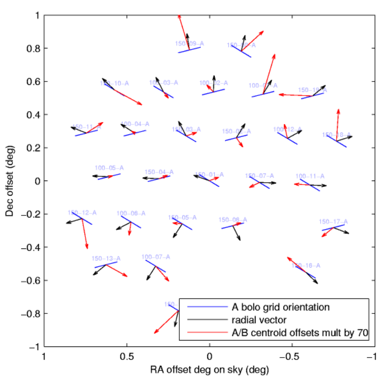
Centroid offset order 0.1 arcmin which is few percent of FWHM

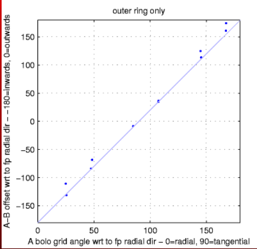
Exaggerated Centroid Offset Vectors



Sets of arrows from different runs - offsets are repeatable

Centroid Offsets Obey Simple Model





- Radial/tangential pairs offset radially
- 45 deg pairs offset tangentially
  - Cause remains mysterious...

Far Sidelobes

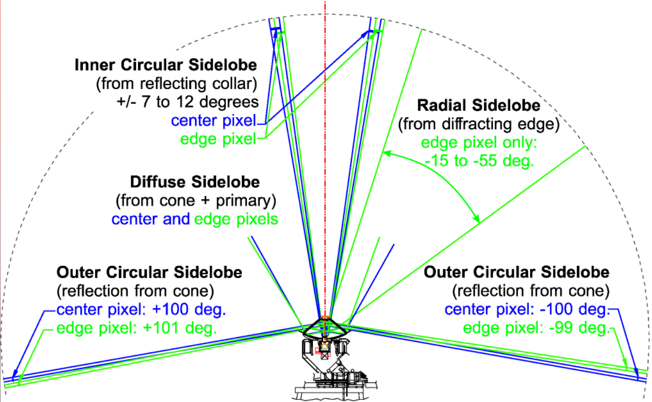
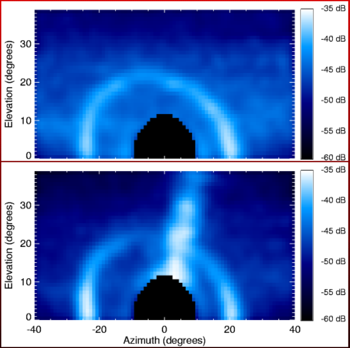


Figure from Hinderks et al arxiv:0805.1990

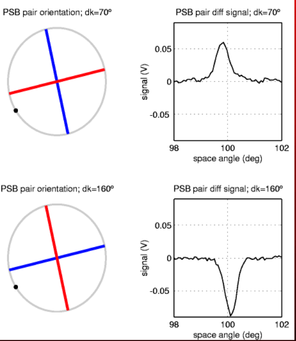
"Inner" Sidelobes for Center/Edge Pixels

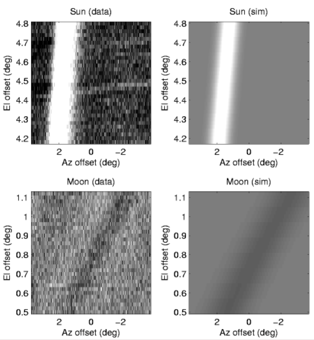


- Near field measurements using Gunn source
  - Ring due to scattering from collar baffle around cryostat window
  - Radial due to truncation of the beam inside the cryostat

Source measurements by Kovac et al, analysis by Zemcov

100 degree Ringlobe Due to Foam Cone





- Caused by reflection from adhesive in cone
  - Probed in detail using Sun as source, and in lab measurements
  - Detailed model reproduces contamaination in CMB data

Modelling by Culverhouse

Conclusions wrt Future Space Mission

- After three years neck deep in QUaD data some comments…
- We showed that even on the ground gain stability (1/f) and relative gain cal. can be excellent:
  - I believe with careful design this can remain true for space mission
  - I believe rapid pol. modulation would do more harm than good
- Calibration of polarization efficiency and angle was a weak point…
  - OK for us but will be a big challenge for next generation
- Far sidelobes were a major cause of pain for us
  - Should be (completely?) avoidable in space mission
- Beam shape effects were not a problem for us. However for the future:
  - Calcs of these effects should NOT ignore averaging down across array and scan pattern
  - With knowledge of (stable) beam shapes can correct for much of the contamination
    - I believe in the end this last will be necessary to reach r=0.01