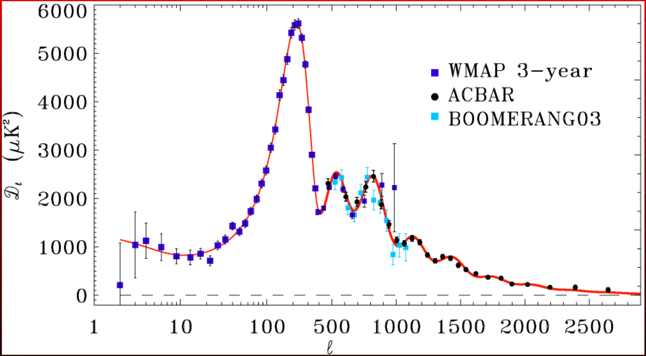
CMB Polarization Measurements with QUaD

Clem Pryke - University of Chicago

Aspen CMB Meeting

31 January 2008

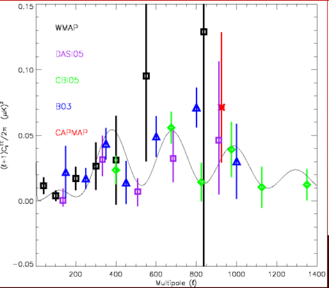
Current Total Intensity Results

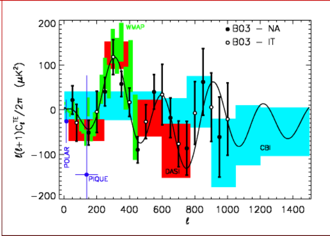


From Reichardt et al, astro-ph/0801.1491

Well defined peaks...

Pre QUaD Polarization Results

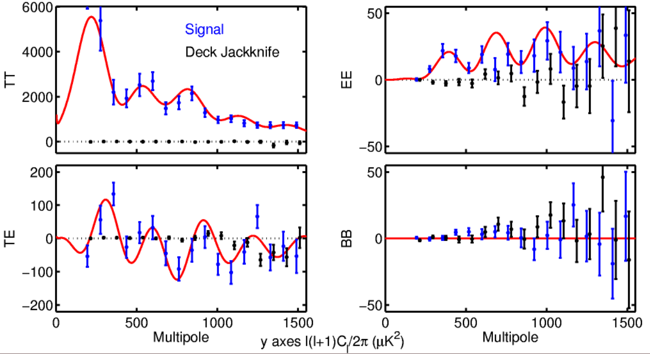




...EE peaks still very sketchy

Figures from Page et al, astro-ph/0603450 and Piacentini et al, astro-ph/0507507

Published First Season QUaD Results

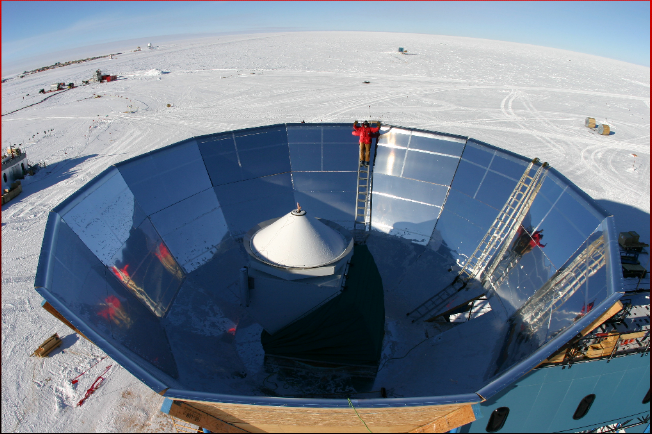


http://arxiv.org/abs/0705.2359 - ApJ v674, p22

Myths

- The map must be scanned at many angles - "cross linked"
  - Not true if you just want the power spectrum from a non full sky experiment
- A given map pixel must be measured at many polarization angles
  - Not true - 2 (well separated) angles is in principle sufficient, and a small range of specific angles will supress systematics just as well as a continuous distribution.
- The relative gains of the A/B detectors must be known with exquisite precision when doing direct pair difference to avoid T->Pol leakage
  - Not true so long as the gain errors are random
- A/B beam differences are a big problem
  - But only at angular scales comparable to those differences

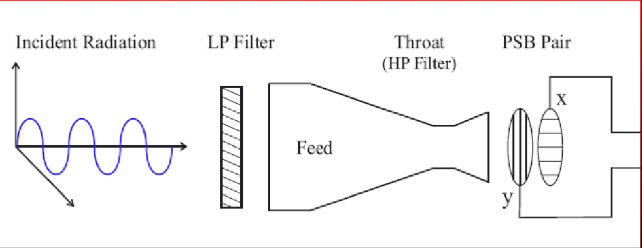
QUaD in Extended Shield Feb 2005



People in QUaD

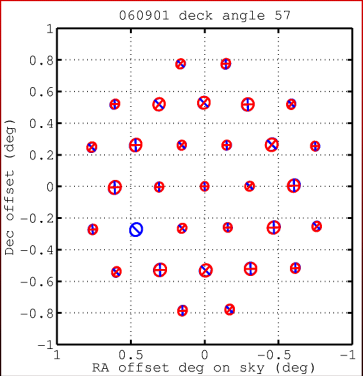
- Stanford: Sarah Church, Jamie Hinderks (NASA Goddard), Ben Rusholme (IPAC), Keith Thompson, Melanie Bowden (industry), Ed Wu
- Caltech: Andrew Lange, Jamie Bock, John Kovac, Ken Ganga (APC/CNRS)
- Chicago: Clem Pryke, Robert Friedman, John Carlstrom, Tom Culverhouse, Erik Leitch (JPL), Robert Schwarz (South Pole)
- Cardiff: Walter Gear, Simon Melhuish (Manchester), Lucio Piccirillo (Manchester), Peter Ade, Mike Zemcov (Caltech), Nutan Rajguru (UCL), Angiola Orlando (Caltech), Abi Turner, Sujata Gupta
- Edinburgh: Andy Taylor, Michael Brown (Cambridge), Patricia Castro (Lisbon), Yasin Memari
- Maynooth: Anthony Murphy, Creidhe O'Sullivan, Gary Cahill

Polarization Sensitive Bolometers



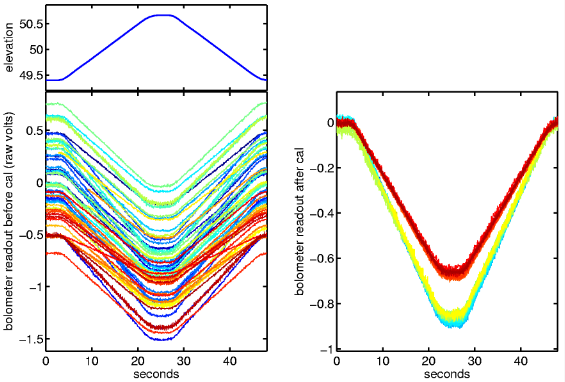
- Two orthogonal absorber grids read out independently
- Sum of X and Y measures total intensity
- Difference measures polarization
- 12 pairs @ 100GHz, 19 pairs @ 150GHz

Array Projected on Sky



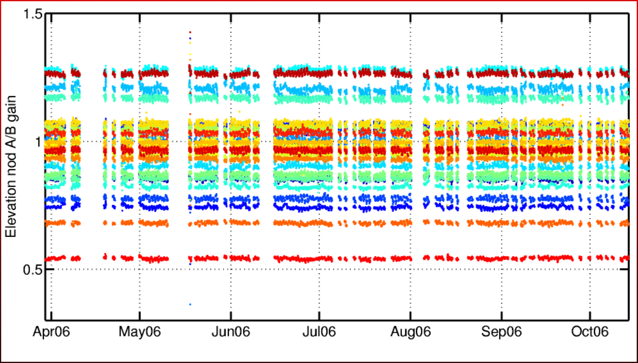
2 orientation "flavors", plus rotate whole telescope around line of sight by 60 deg

Relative Gain Cal



"Nod" the telescope in elevation to inject large signal from atmospheric gradient

Excellent A/B Gain Stability

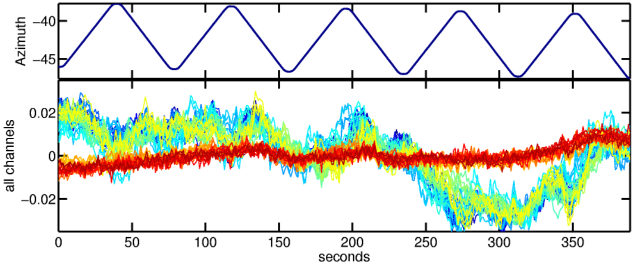


- Pair gain ratio is stable to <1% rms over full season!
  - and fluctuations average down...

QUaD Observing Strategy

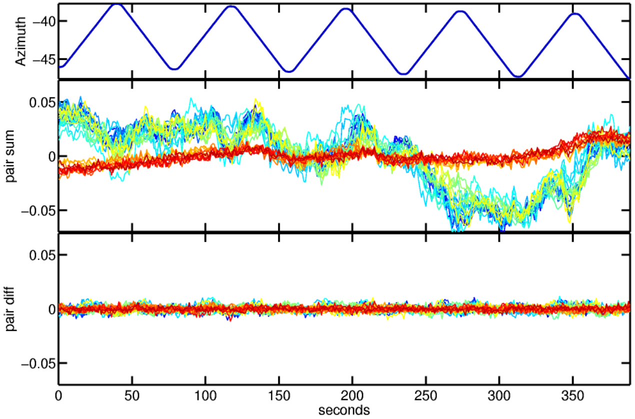
- Whole telescope 7.5 deg azimuth scan as modulation on top of sky track (at Pole sky rotates around zenith)
- Scan 5 times out and back - then step in el by 0.02 deg and repeat.
  - Build simple raster map - no cross linking!
- Scan at 0.25 deg/sec putting ell range 200 to 2000 at 0.1 to 1Hz in timestream.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

A raw scan set



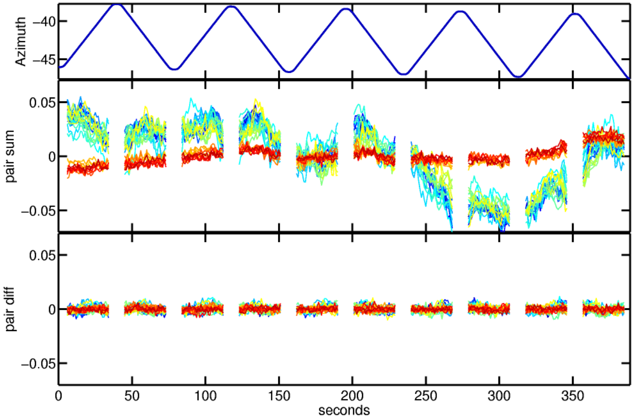
(Well actually deconvolved, low-passed, deglitched, downsampled, relative gain calibrated)

...pair sum/difference...

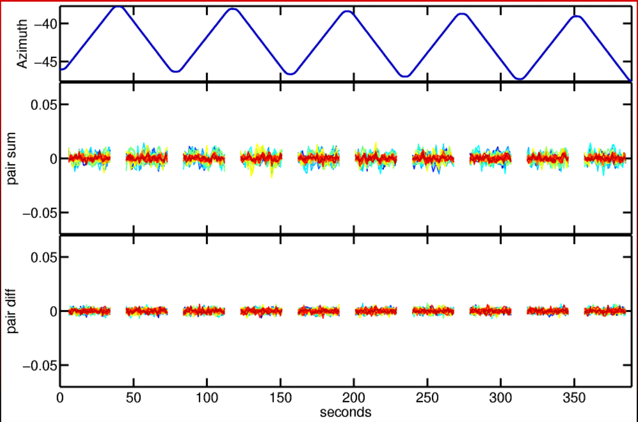


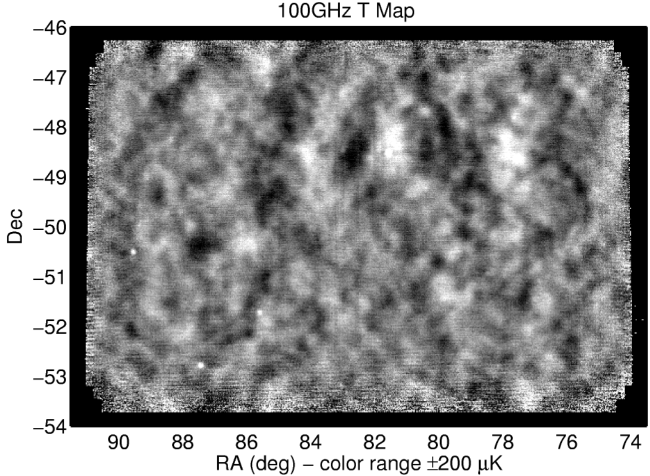
0.05 on y-axis approx 10mK

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



...remove 3rd order polynomials...





100GHz T Map
Dec
−46
−47
−48
−49
−50
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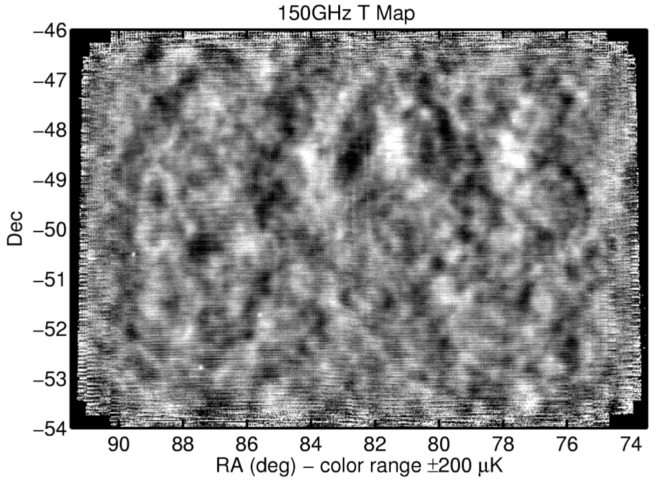
74
RA (deg) − color range ±200 μK



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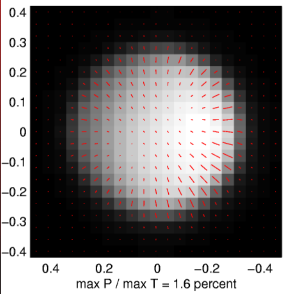
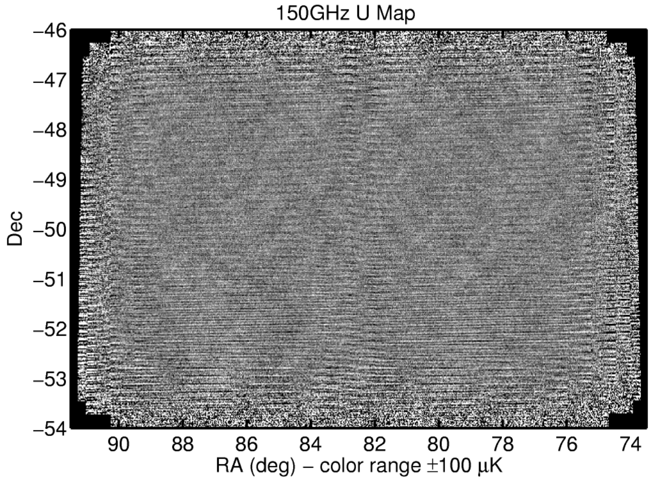
RA (deg) − color range ±200 μK

Constructing Polarization Maps

- To go from pair diff timestream to pol map need to know orientation of bolometer pairs as projected on sky
  - Confirmed very close to design values using external source.
- Complete pipeline confirmed by mapping Moon
  - (has weak radial polarization pattern due to scattering as radiation exits lunar surface)




150GHz U Map
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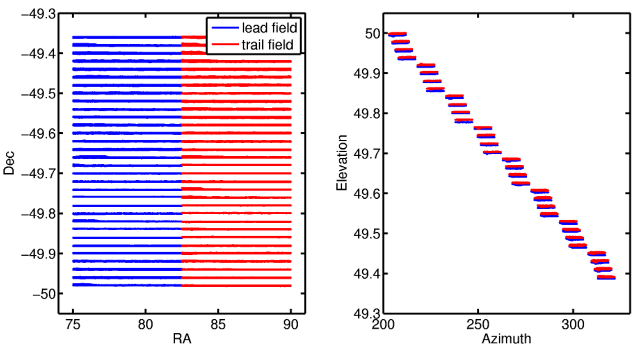
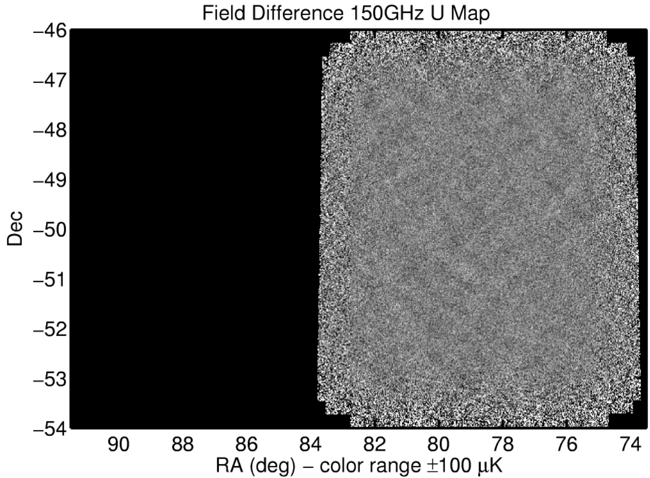
74
RA (deg) − color range ±100 μK

Lead/Trail Mapping



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


Field Difference 150GHz U Map
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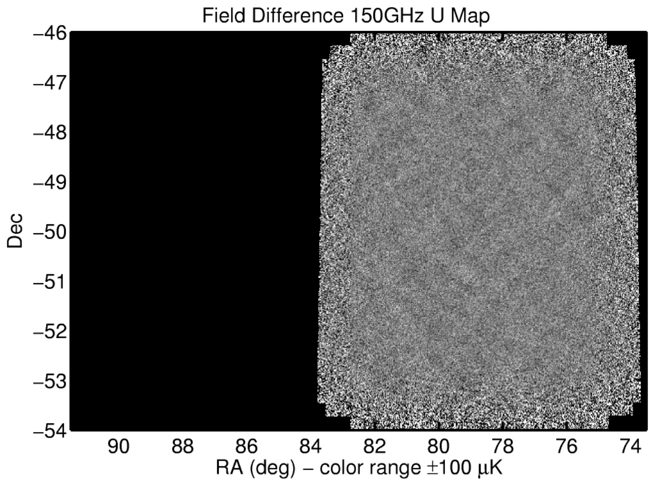
RA (deg) − color range ±100 μK

Map Based Jackknifes

- To confirm data is uncontaminated (after field diff) split into approx equal subsets which should contain identical sky signal but different false signal:
  - "Deck jack" - different azimuth range (different ground) with los rotation of 60 degrees.
  - "Scan jack" - forward versus backwards scans
  - "Season jack" - first/second halves of run
  - "Focal plane jack" - bolo pair orientation groups
  - ("Frequency jack" - 100 and 150GHz)

- Make maps using each half of data
  - Subtract the maps and proceed with power spectrum analysis as usual.


Field Difference 150GHz U Map
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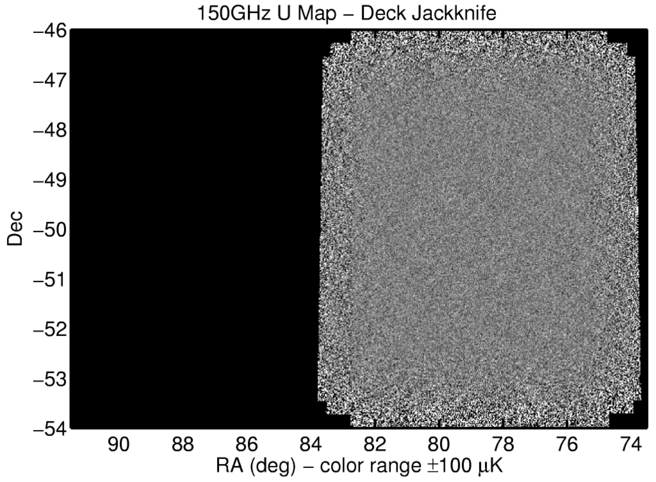
RA (deg) − color range ±100 μK


150GHz U Map − Deck Jackknife
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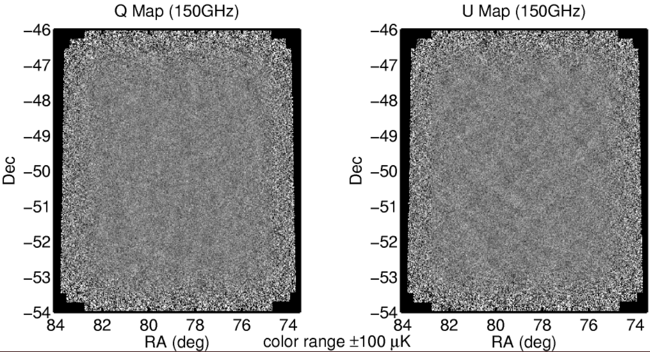
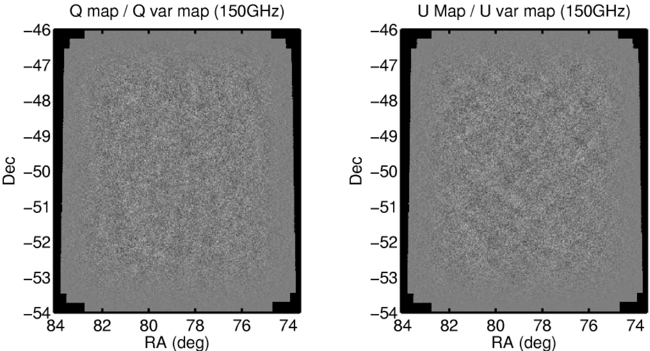
RA (deg) − color range ±100 μK

Take the Q/U maps...



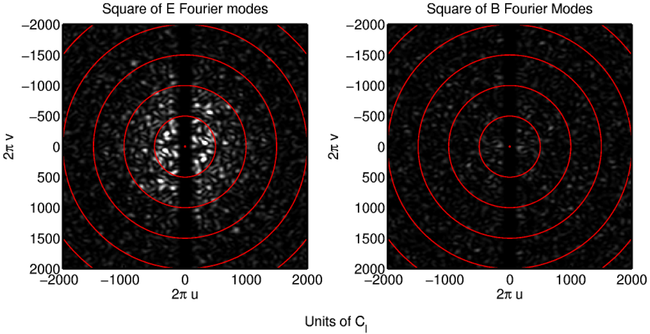
How to make CMB power spectra step by step with pictures...

...appodize...



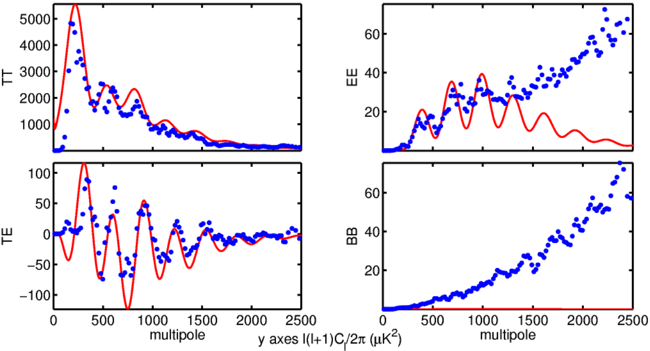
Divide signal map by variance map

...FT, go from Q/U to E/B and square...



$$\chi = \arctan 2(v,u) - \pi/2$$
$$E = +Q\cos 2\chi + U\sin 2\chi$$
$$B = -Q\sin 2\chi + U\cos 2\chi$$

...mean in annuli is raw power spectrum.



Now need to correct for noise and filtering/beam...

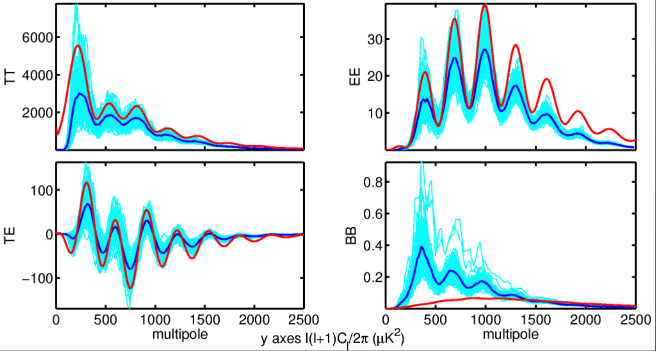
Simulations

- Analyze timestream noise and generate random timestream realizations
  - Make noise only sim maps and spectra using standard code
    - Subtract mean of noise only sims from real spectra

- Generate LCDM sky realizations (Healpix), convolve with beam and re-sample timestream
  - Make signal only sim maps and spectra using standard code (including polynomial half-scan filtering)
    - Compare mean of sig sims to input spectra to determine the filter/beam "suppression factor" and divide this out of real spectra

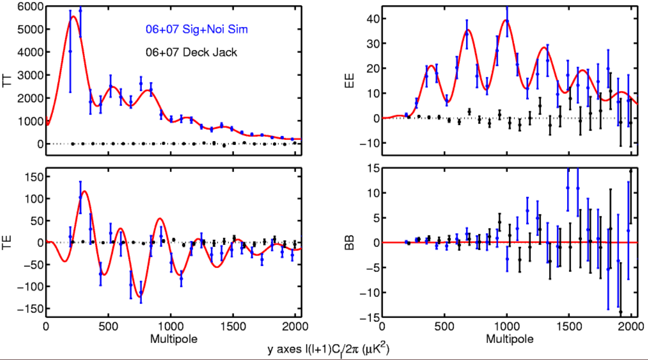
- Add noise and signal sim maps and make spectra
  - Apply above two corrections to the these
    - Scatter gives bandpower uncertainty (Warning - error bars only correct if cosmology assumed in sims is close to reality...)

Signal only sims



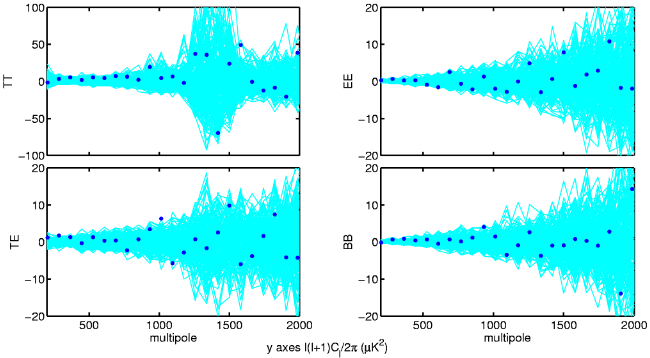
In:out ratio is filter/beam "suppression factor"
(Fluctuation is the sample variance)
(Note E to B leakage)

2006+7 Season Upcoming Results



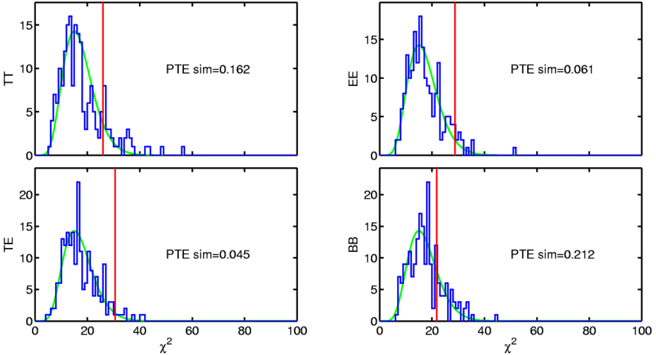
Note - deck jack is real but signal spectra replaced by LCDM sim realization!

Compare real jack spectra to sims...



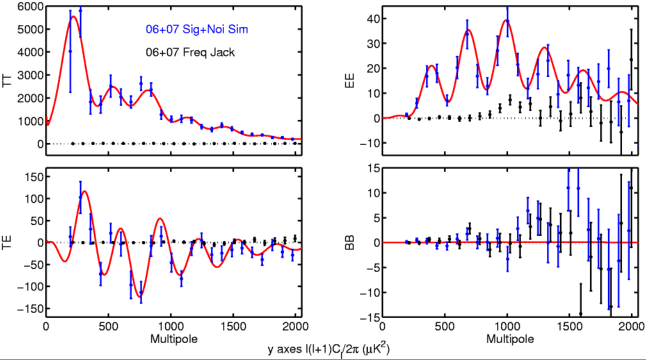
Real spectra should just look like a sim realization
(this is 2006+7 deck jack)

Chi squared is the final arbiter



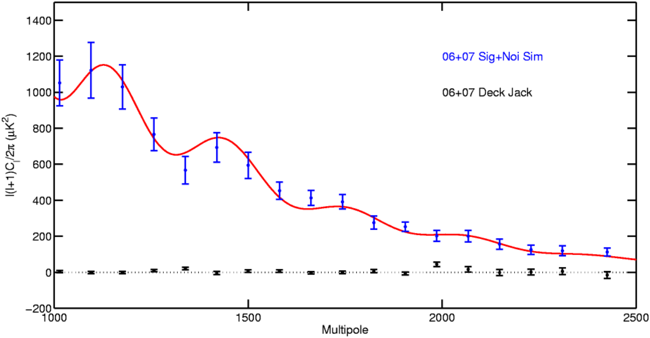
(this is 2006+7 deck jack)

Frequency Jackknife



Frequency jackknife tests for foreground contamination
(each freq abs cal against B03)

High Ell TT Rocks



High ell TT spectrum potentially best to date...

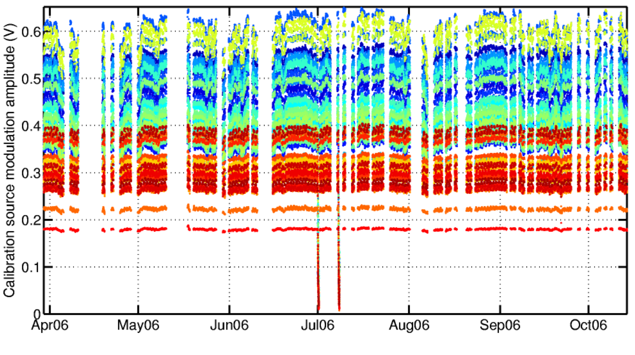
Lessons from QUaD

- A ground based CMB polarimeter can have excellent stability
  - Direct pair difference worked
  - Half wave plate modulation was not required
- An extremely simple analysis has proven to be adequate
- By far the biggest problems have been good old fashioned sidelobe pickup, and detector weirdness
- (Caveat: obviously the above are shown to be true only for the specific configuration and sensitivity of QUaD)

Conclusions

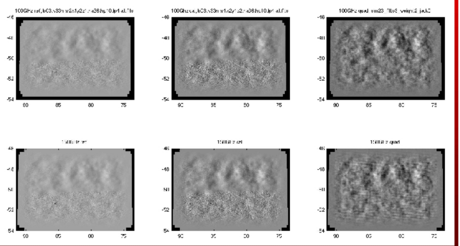
- First season results published
  - http://arxiv.org/abs/0705.2359
- Third and final season has now ended
- A long war on systematic contamination (jackknife failure) has basically been won
- The polarization signal cancels under frequency jackknife
  - Foreground contamination is negligible
- Expect a paper on astro-ph soon!

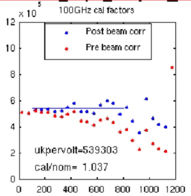
Good Absolute Gain Stability

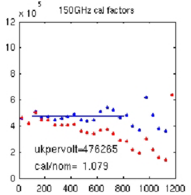


- Cal source injects signal through hole in secondary
- As opacity up, loading up and gain suppressed
  - Correction applied

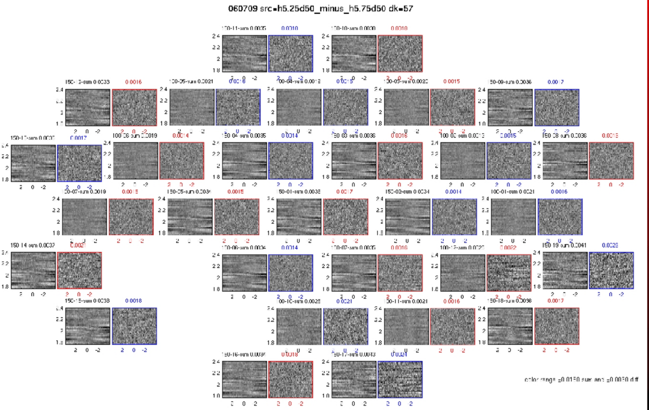
Absolute Cal versus B03





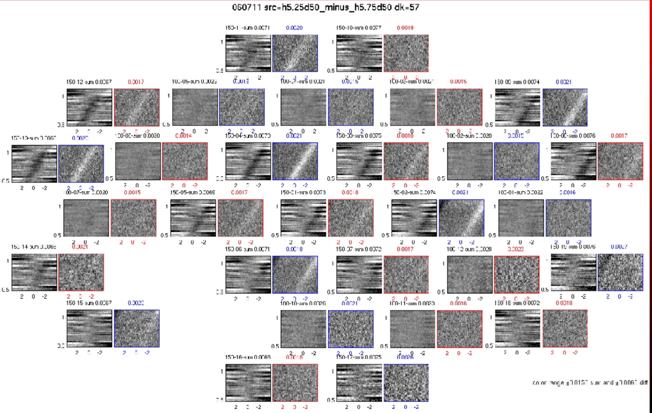


Individual pair sum/diff maps good day



8h data block field differenced

Individual pair sum/diff maps moon day



Sims can reproduce -> Tom Culverhouse

Real/sim Noise Power Spectra