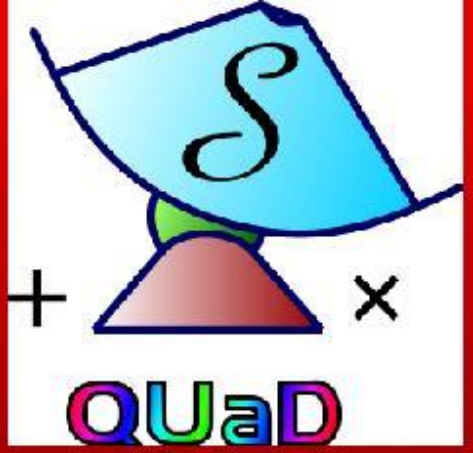


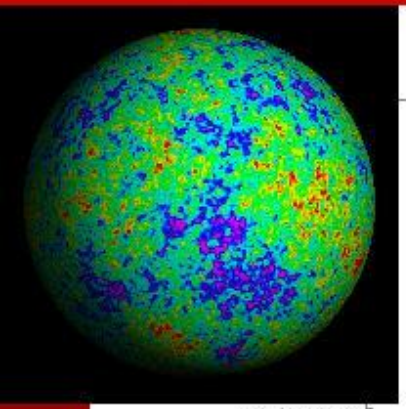
CMB Polarization Measurements with QUaD

Clem Pryke - University of Chicago

Cosmic Cartography

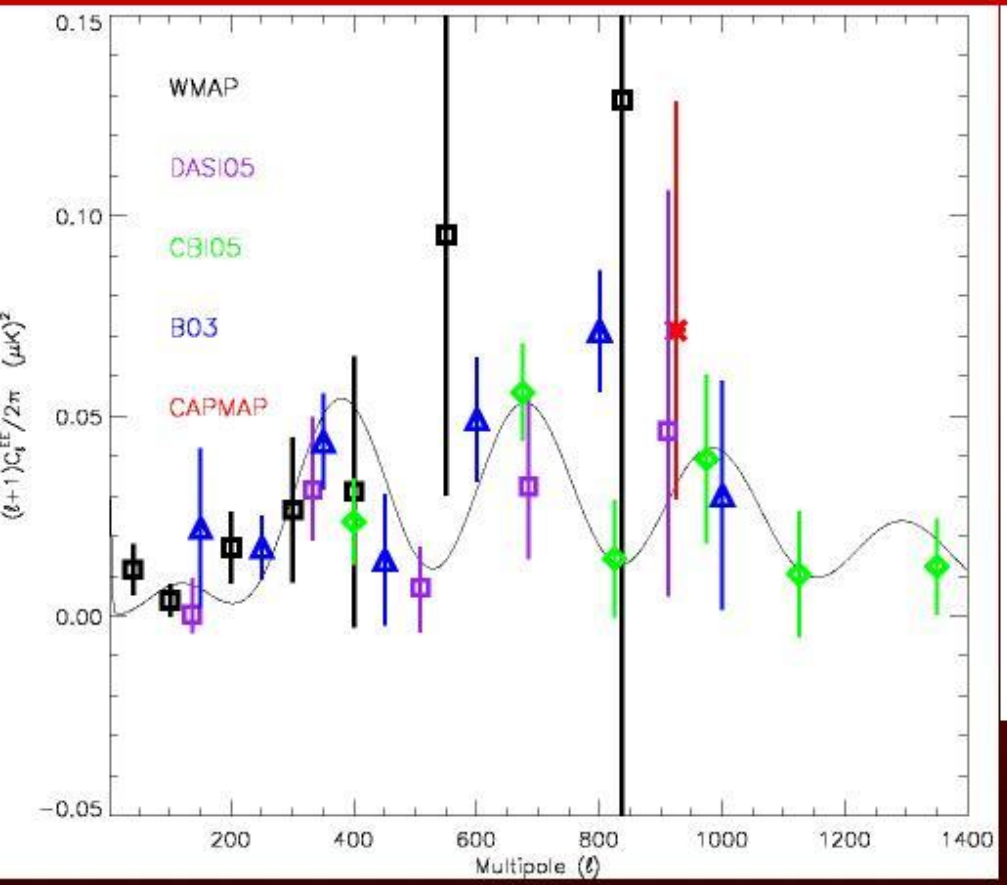
3 December 2007

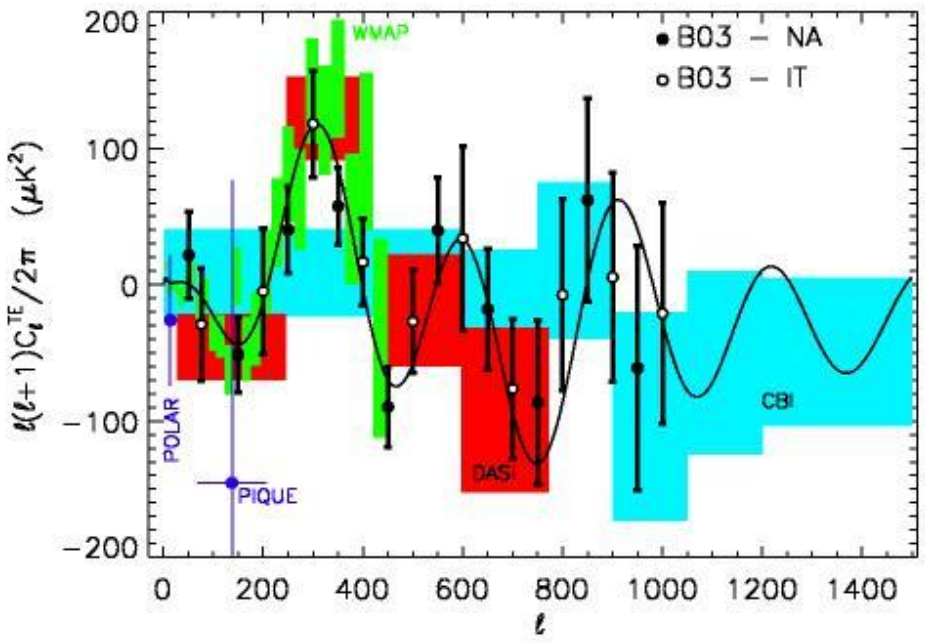
Current Total Intensity Results



From Kuo et al, astro-ph/0611198

Pre QUaD Polarization Results

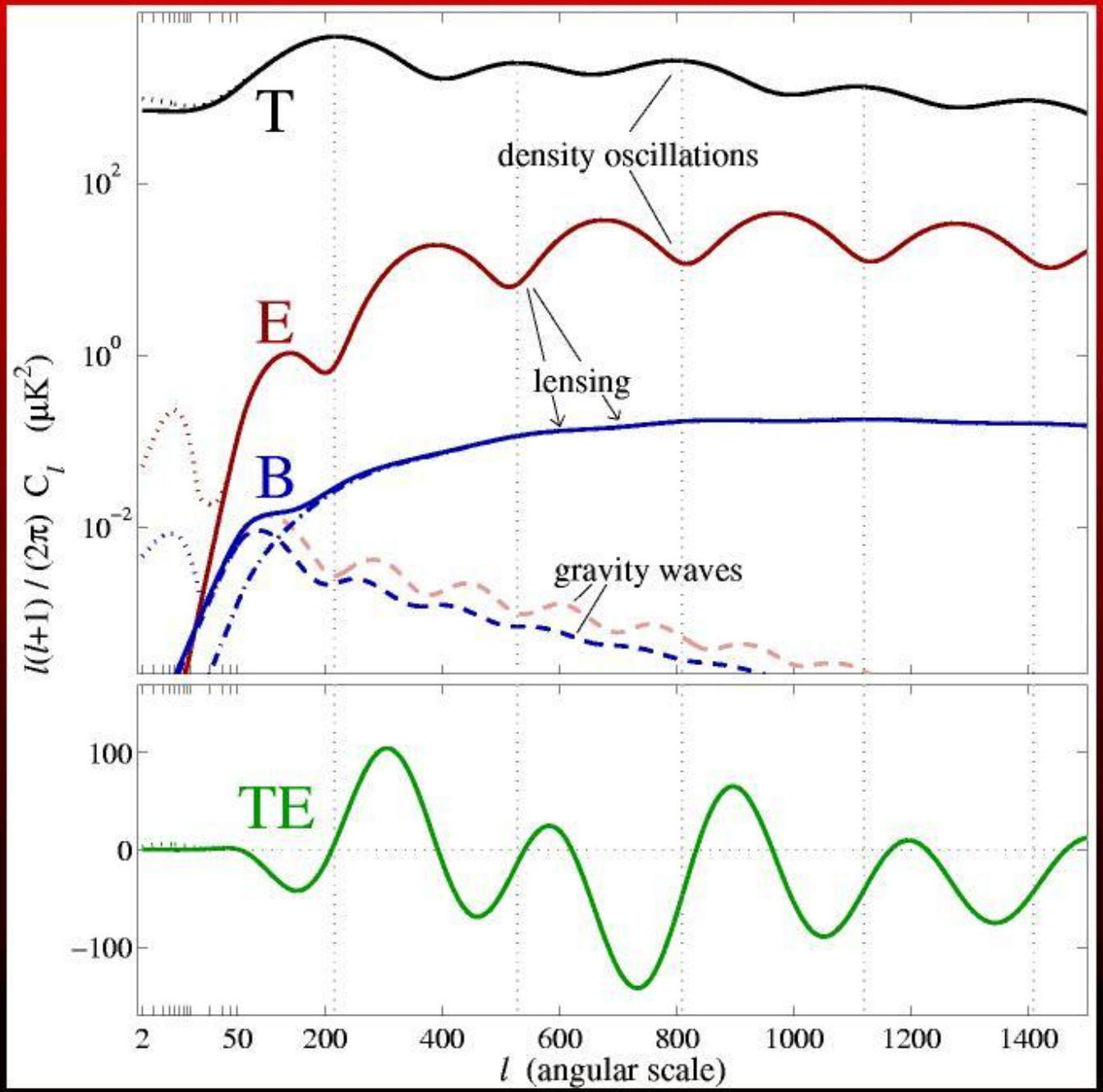




LCDM predictions from T looking good!...

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

Why Go Further?



Why Go Further?

- At $l>100$
  - Refine measurements of E and TE to further test paradigm
  - Try to detect lensing B to get info on neutrinos and dark energy

- At $l<100$
  - Refine measurements of E and TE to constrain re-ionization
  - Try to detect gravity wave B

- QUaD is aimed at $l>100$, sister experiment BICEP aimed at $l<100$

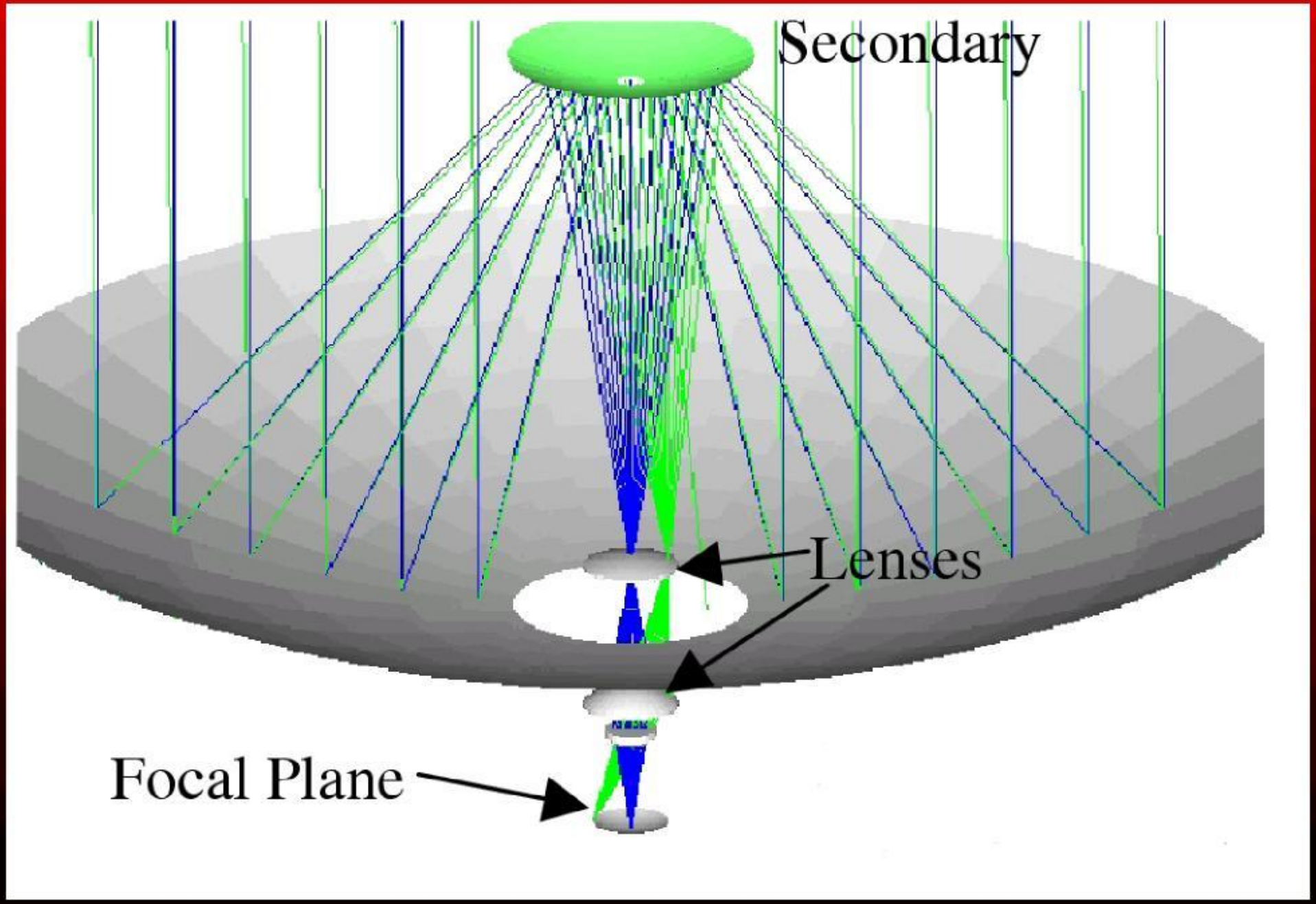
People in QUaD

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

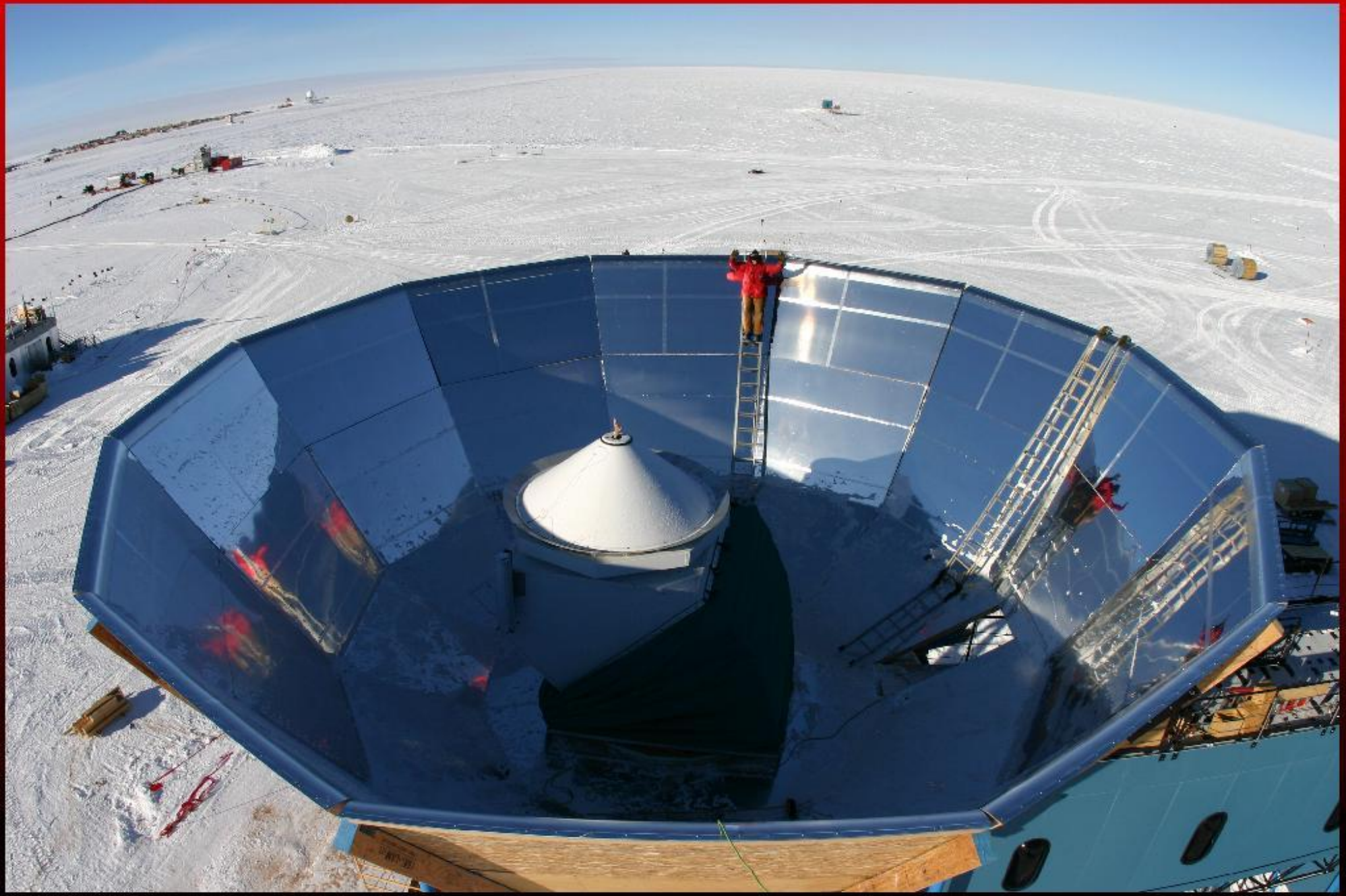
The QUaD Telescope

- 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.
- Ground shield extended

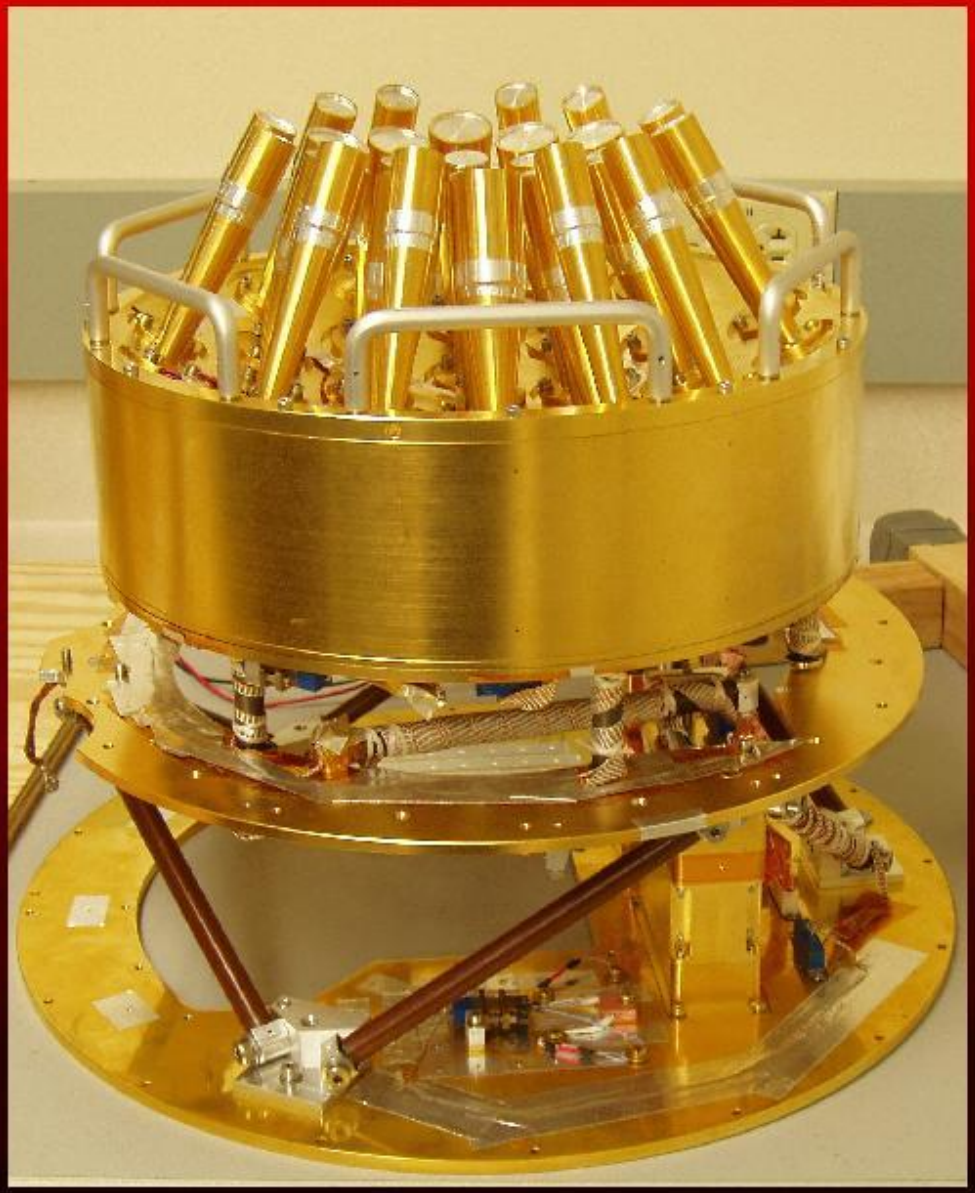
Optical Path



QUaD in Extended Shield Feb 2005

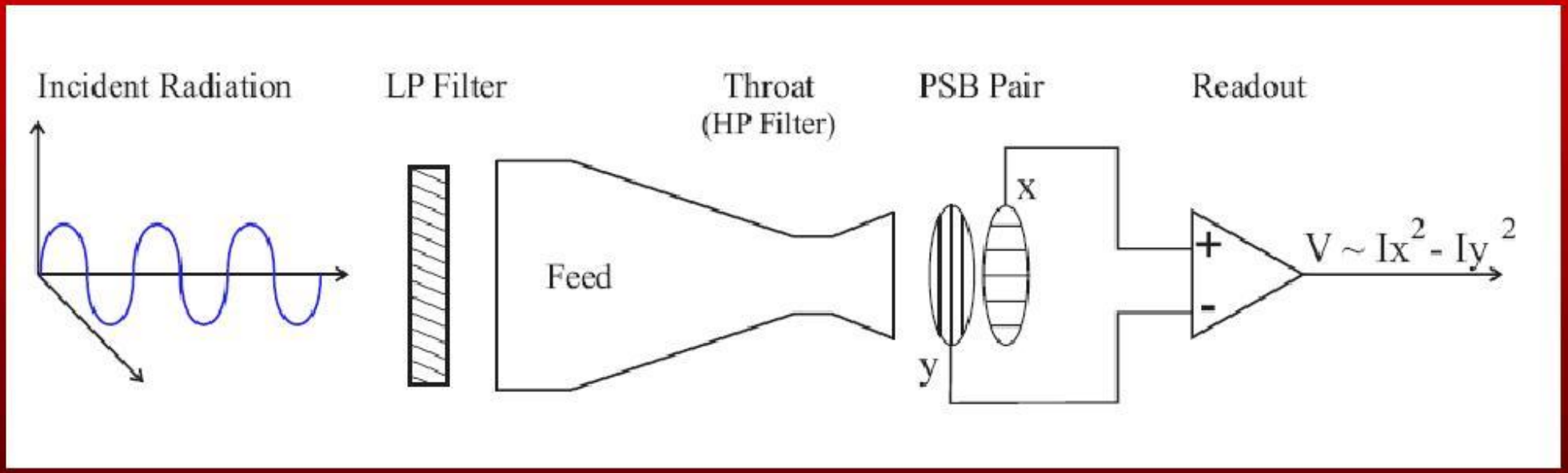


Receiver Focal Plane



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

Polarization Sensitive Bolometers

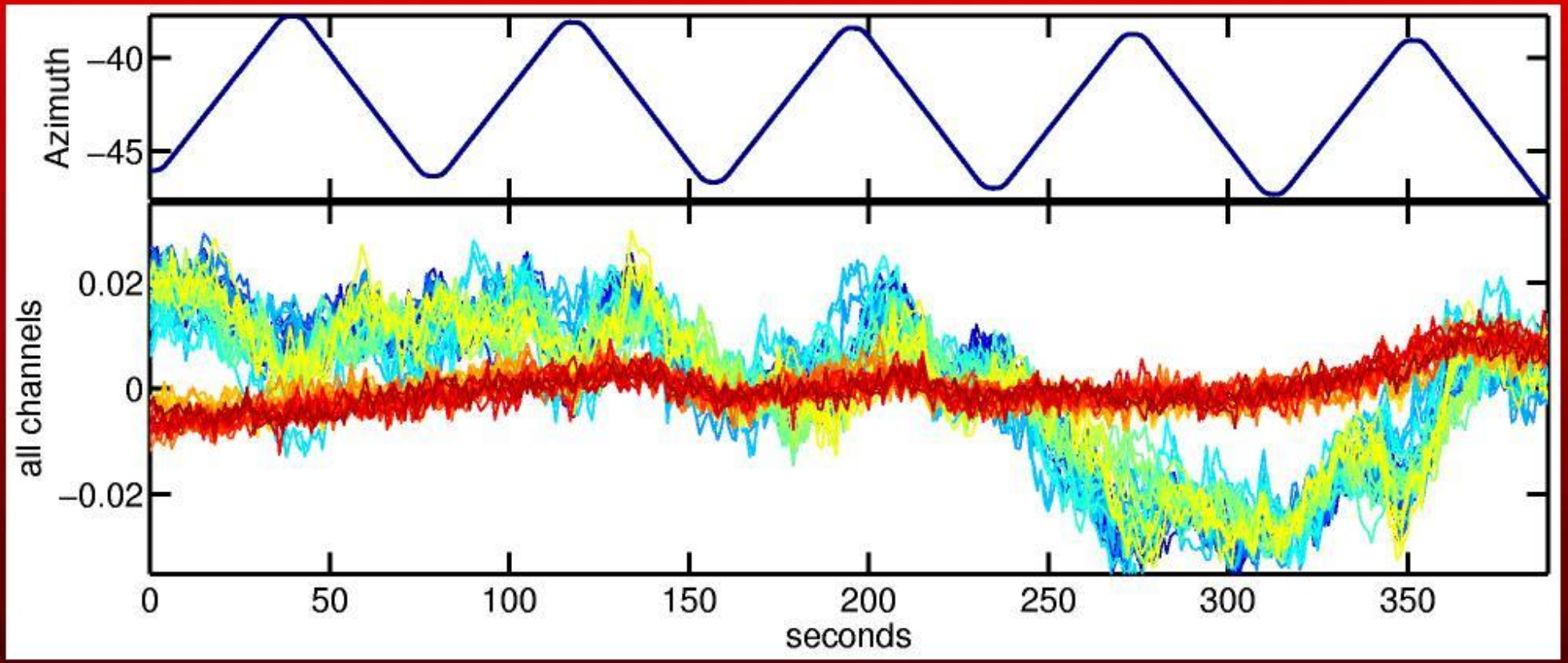


- Two orthogonal absorber grids
- Sum of X and Y measures total intensity
- Difference measures polarization

Why at the South Pole?

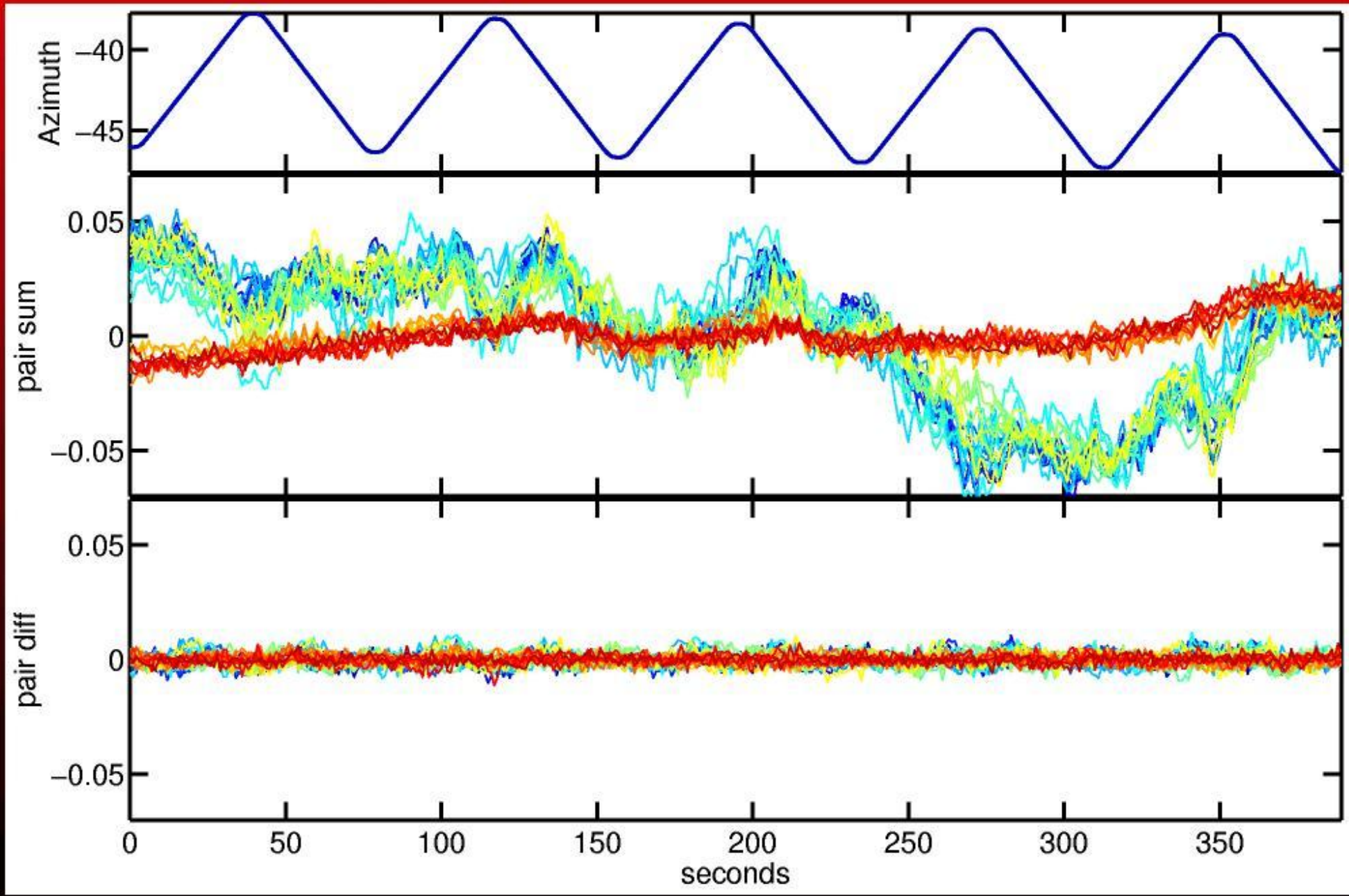
- Very cold, and high altitude - Very low atmospheric moisture.
- Atmosphere extremely stable (no daily sunrise/set)
- No Sun for 6 months of the year:
  - Work on instrument in summer.
  - Observe in winter.
- Fields remain at constant elevation angle
  - and superb low foreground sky available at high el!
- Existing infrastructure and logistics.

A raw scan set

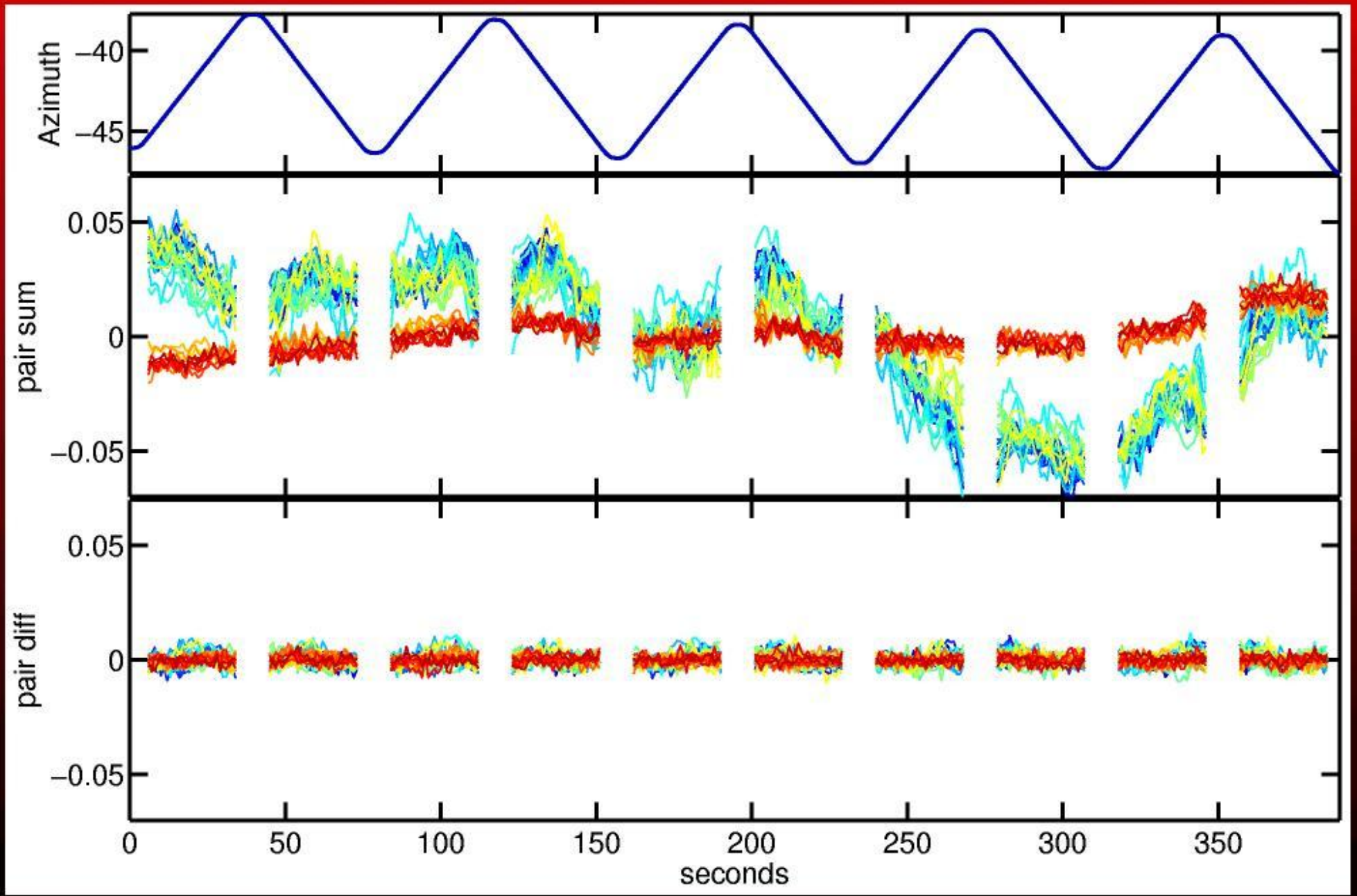


(Well actually deconvolved, low-passed, deglitched, downsampled, relative gain calibrated)

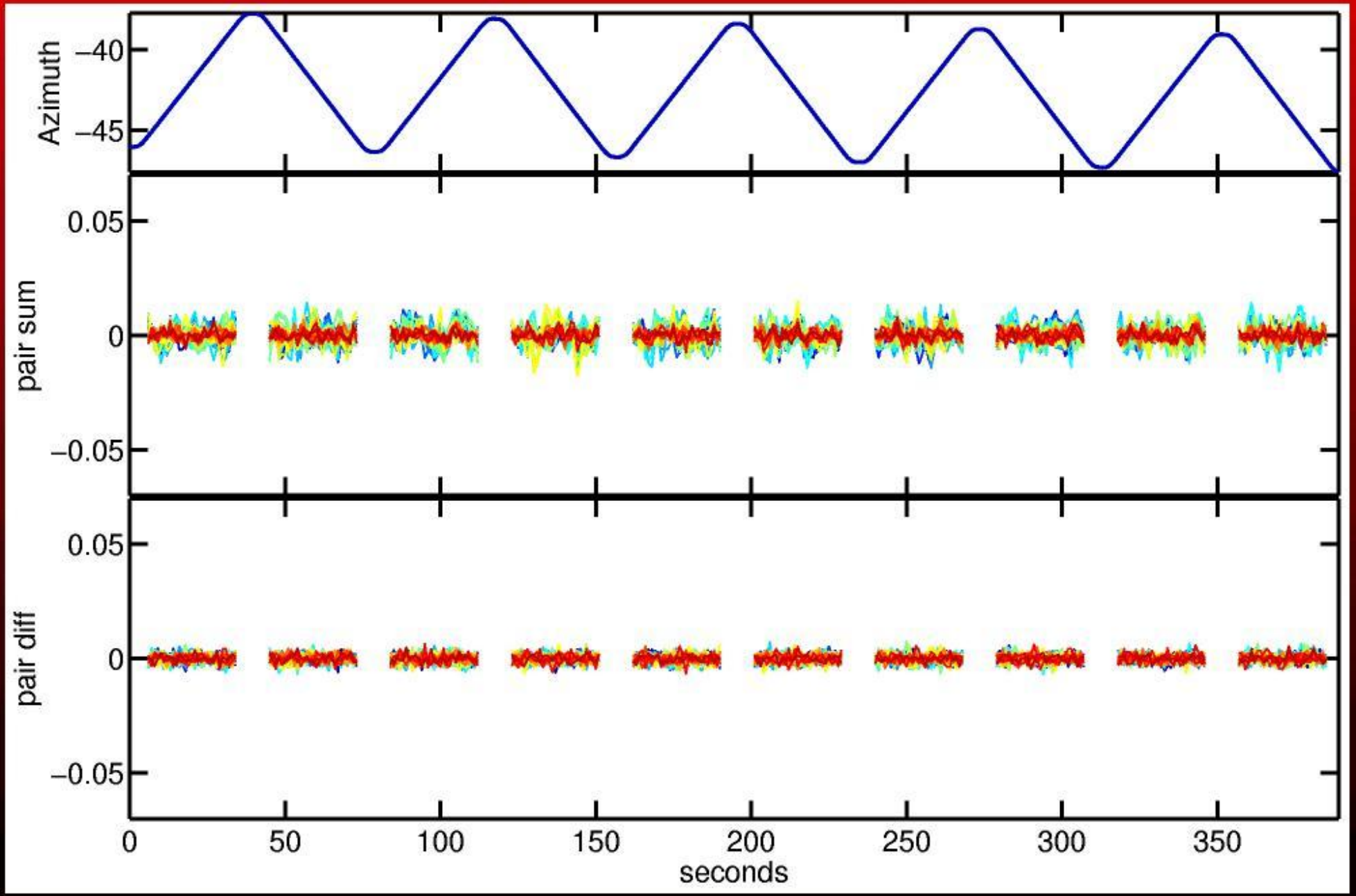
...pair sum/difference

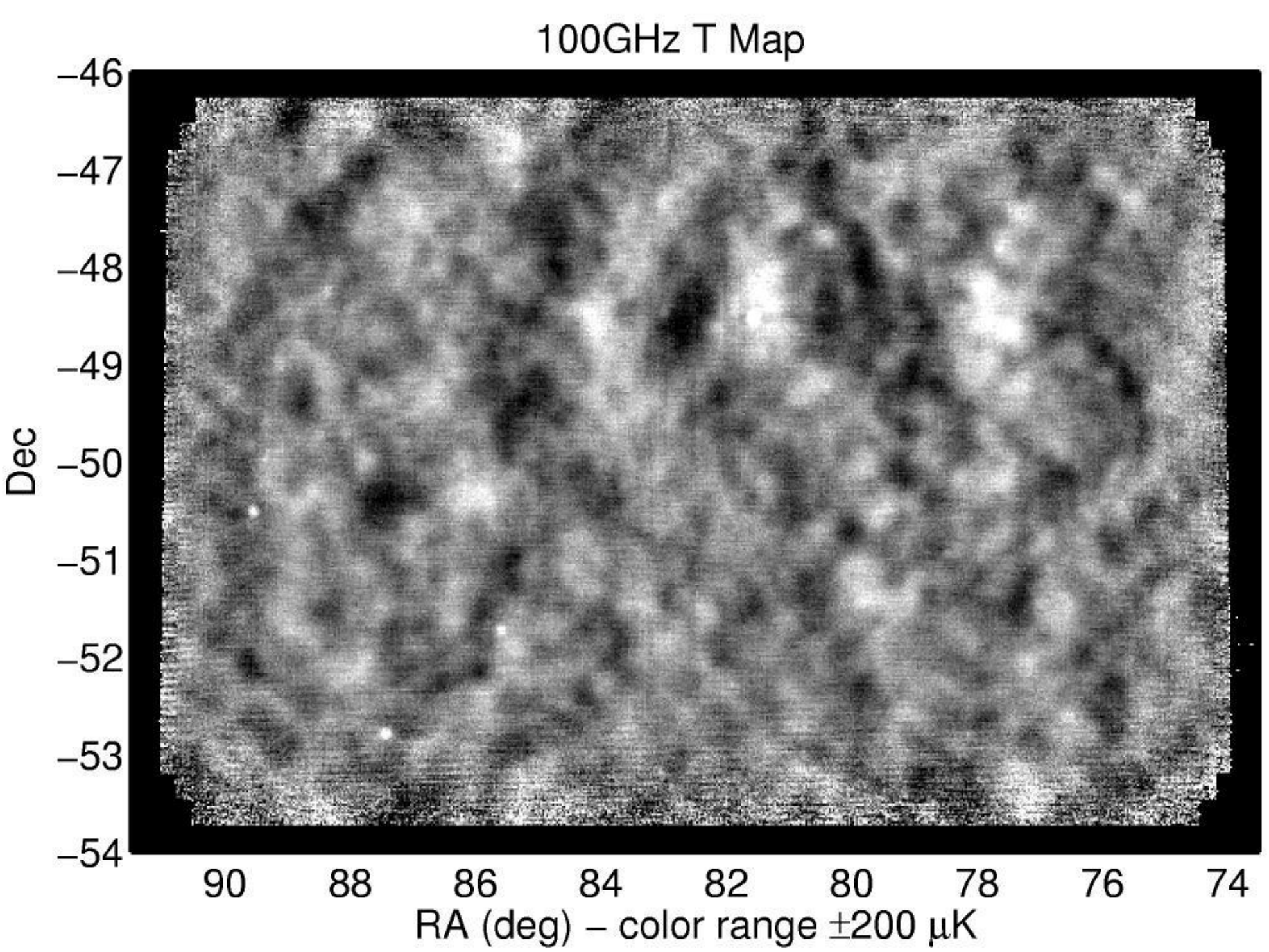


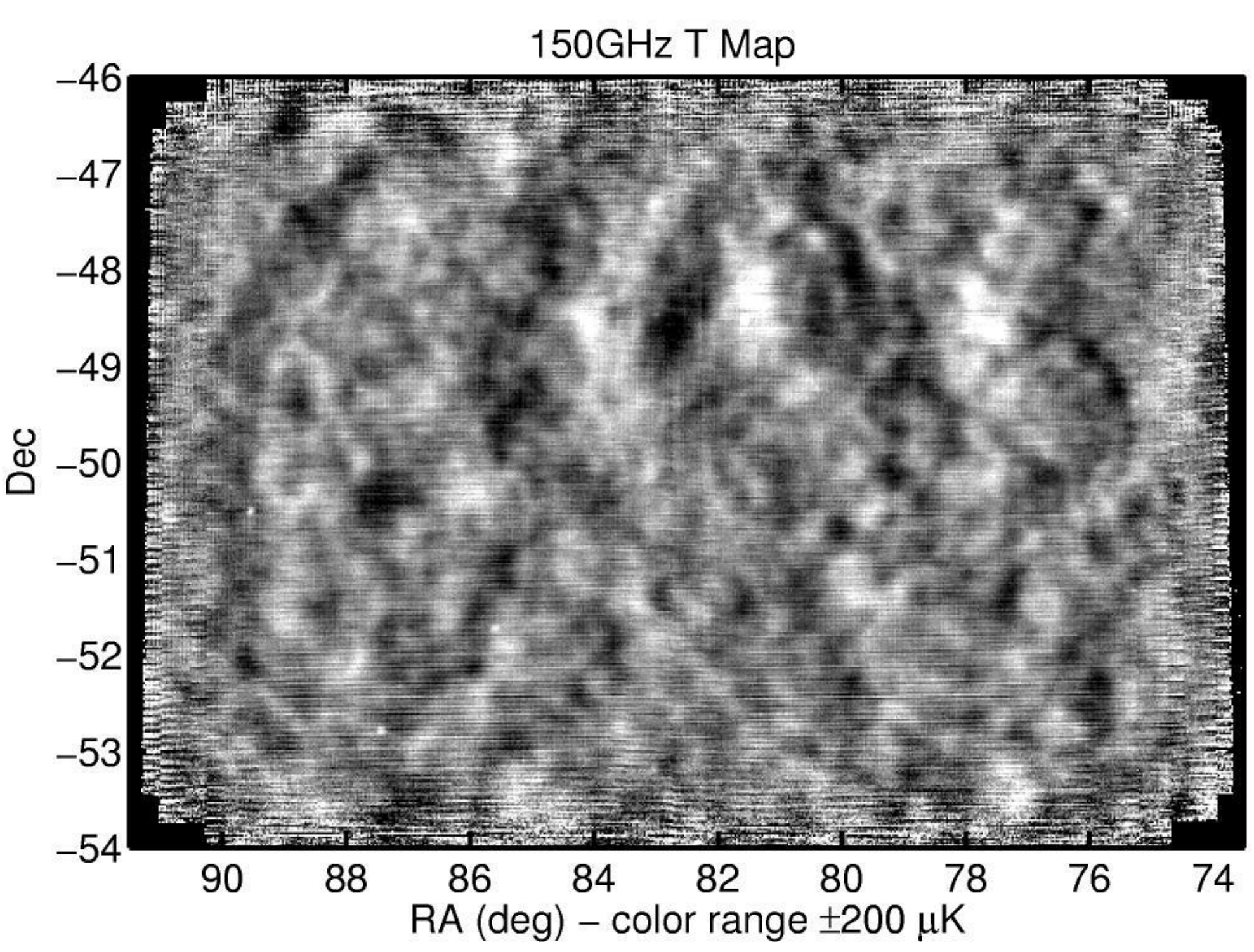
...cut to "half-scans"...



...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
−46
−47
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−49
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−54
Dec
90
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86
84
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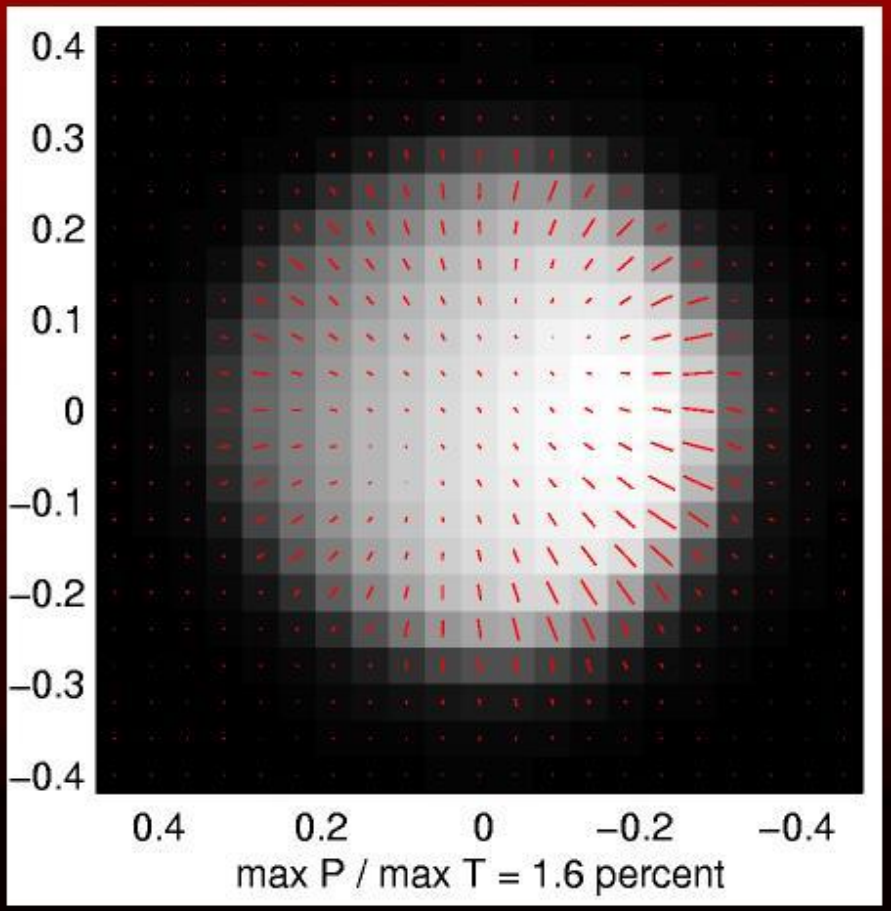
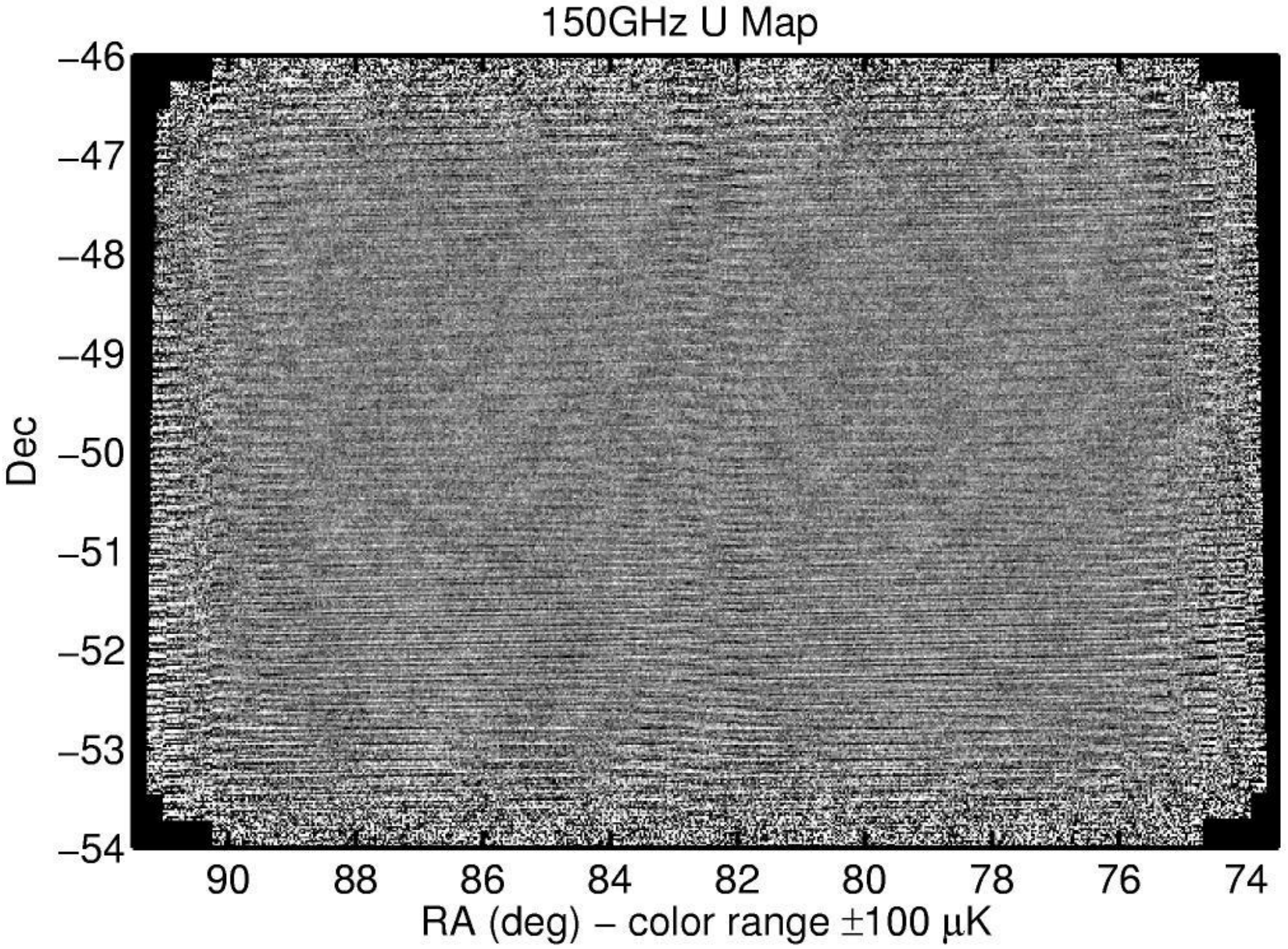
80
78
76
74
RA (deg) – color range ±200 μK

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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−52
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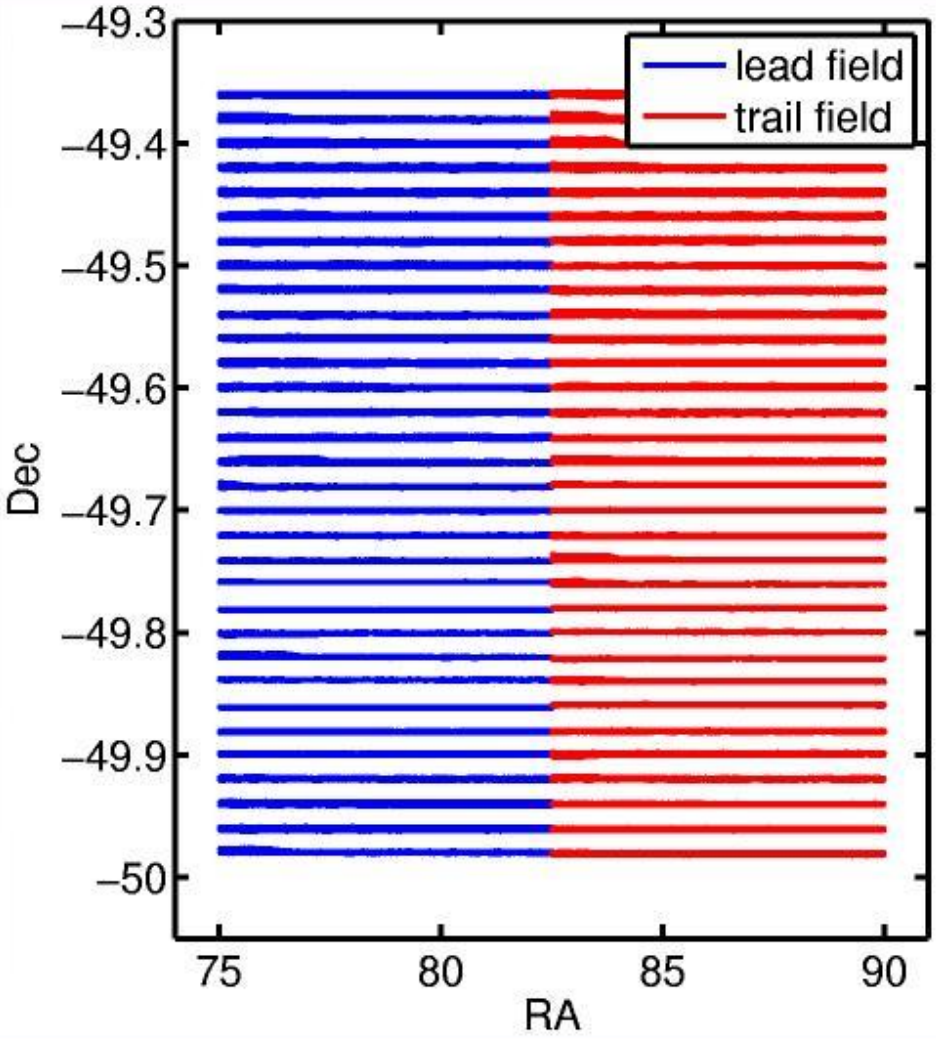
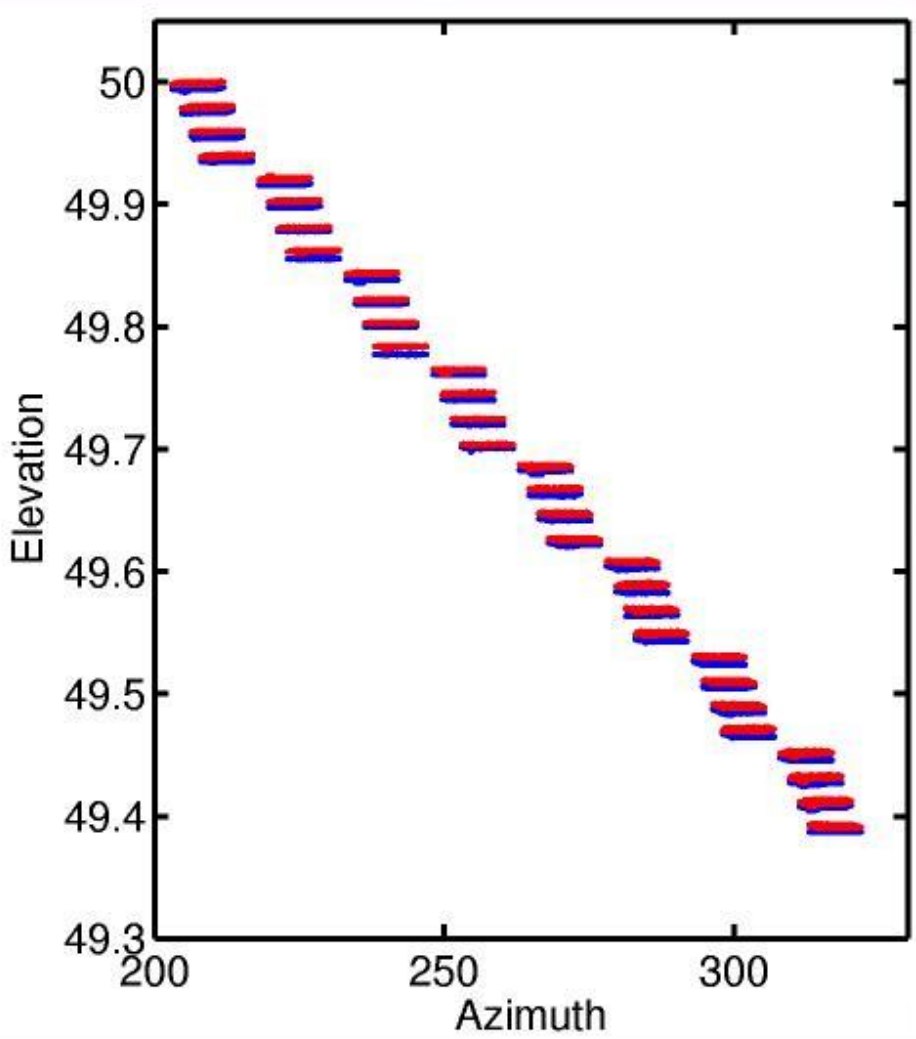
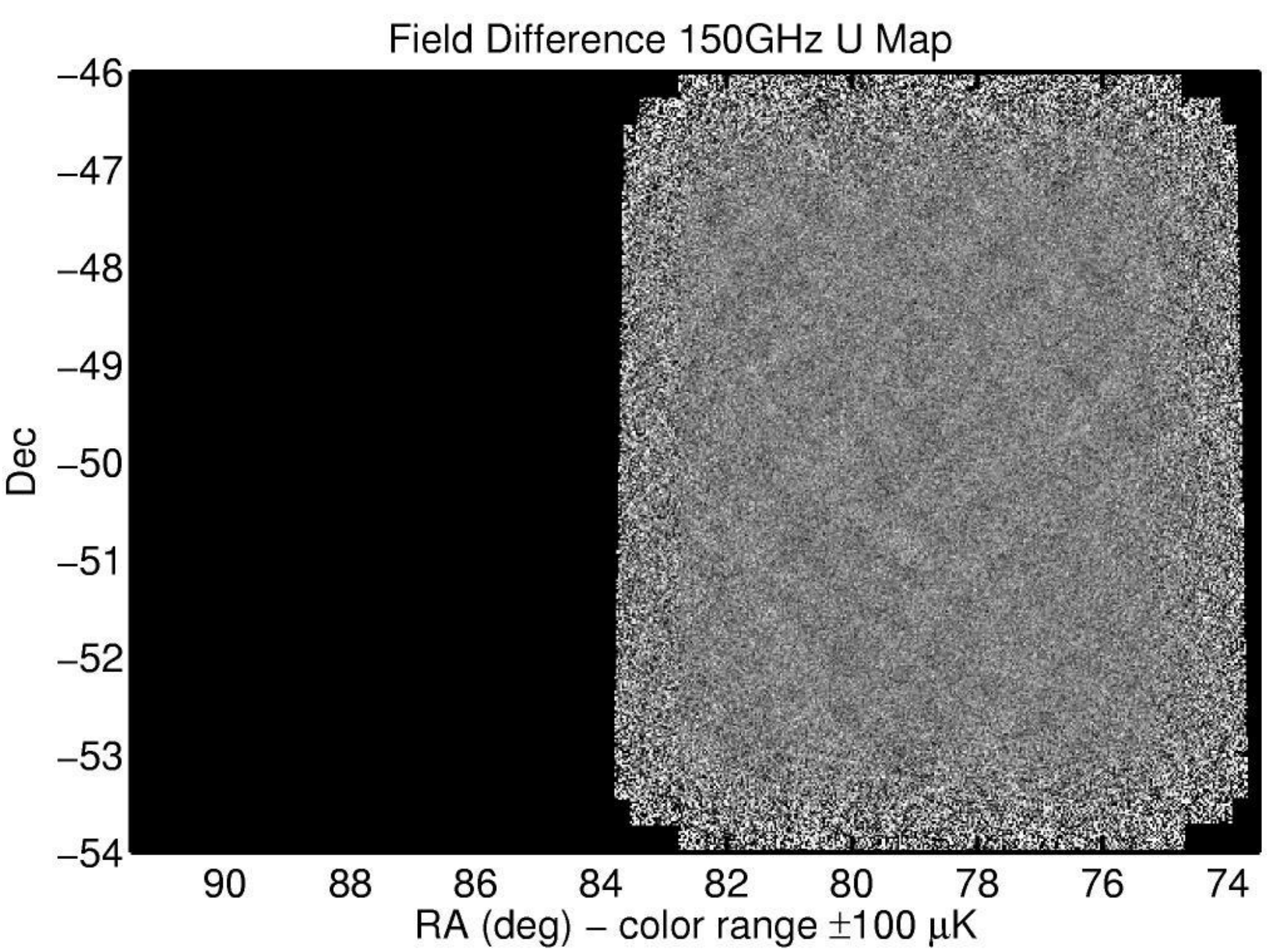
Dec
90
88
86
84
82
80
78
76
74
RA (deg) – color range ±100 μK

Lead/Trail Mapping





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


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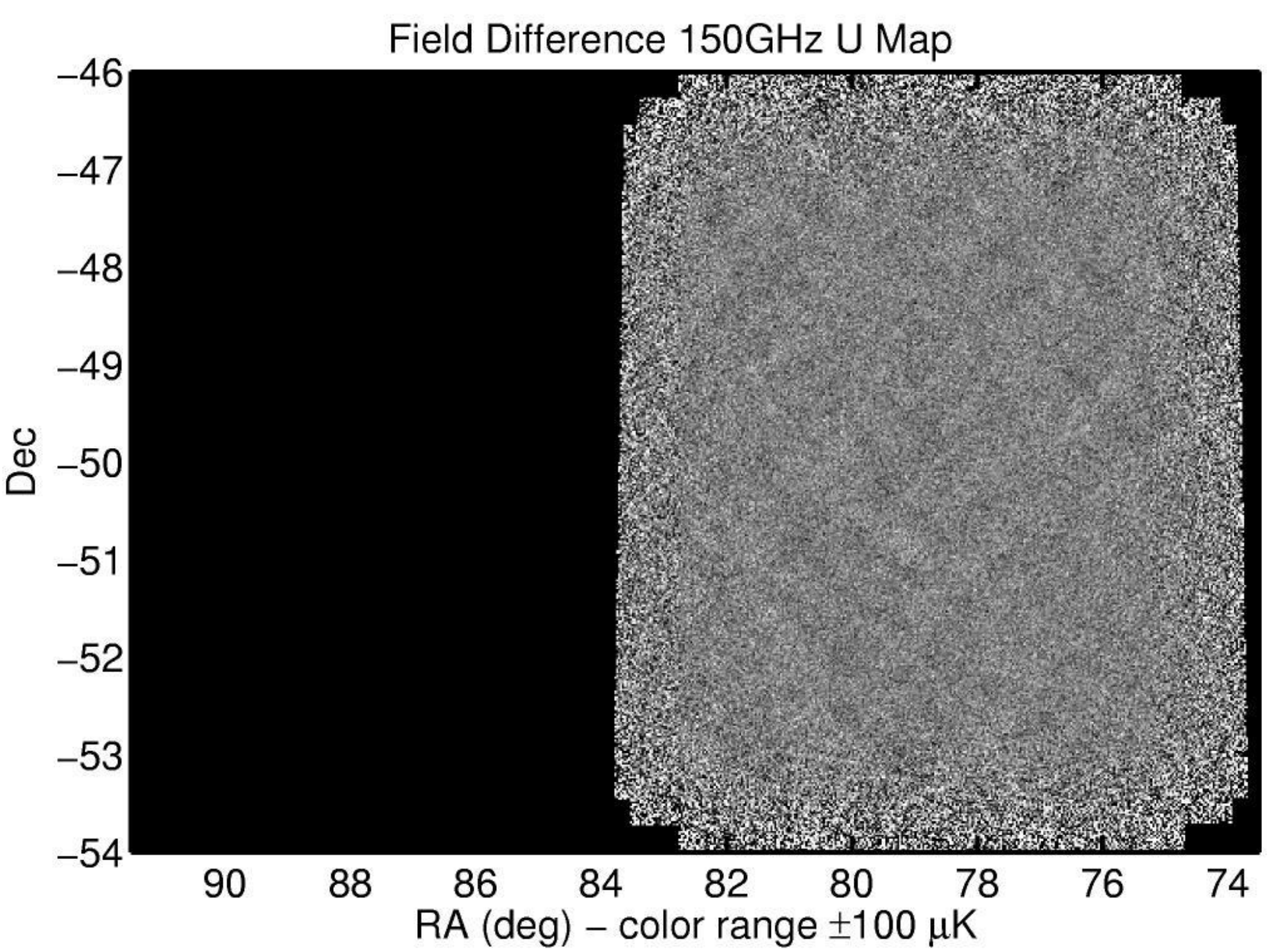
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) – color range ±100 μK

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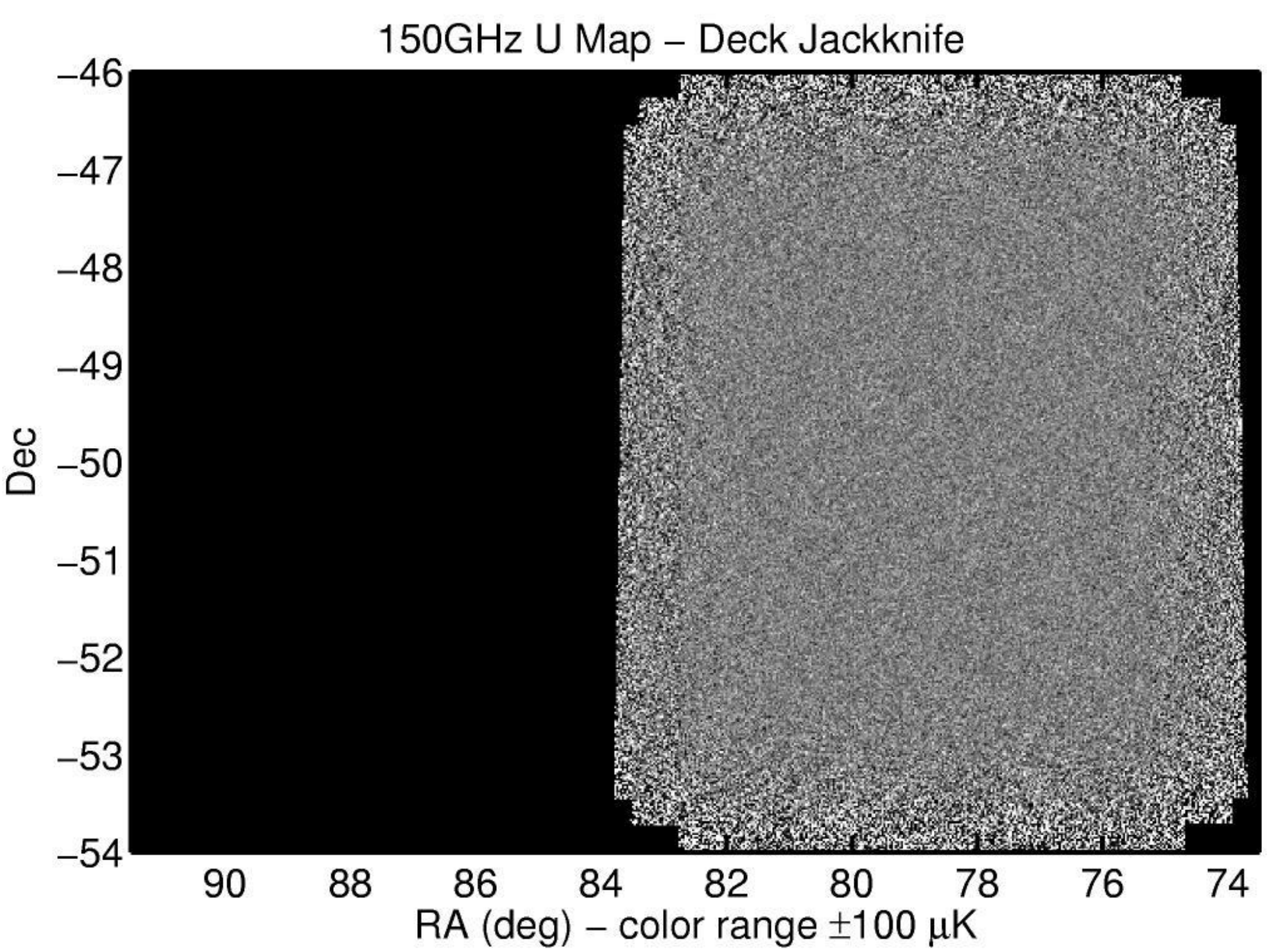
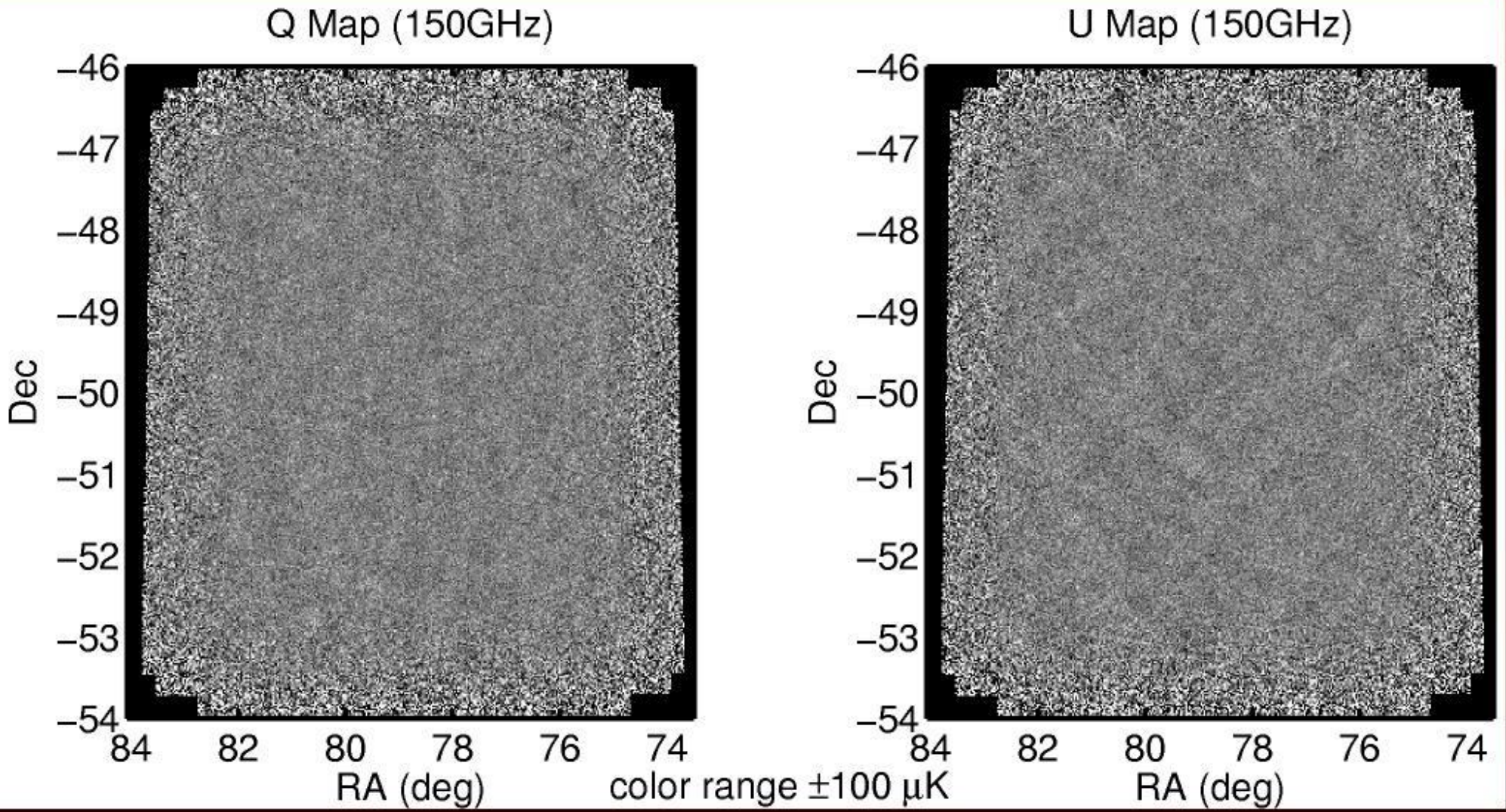
−52
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) – color range ±100 μK

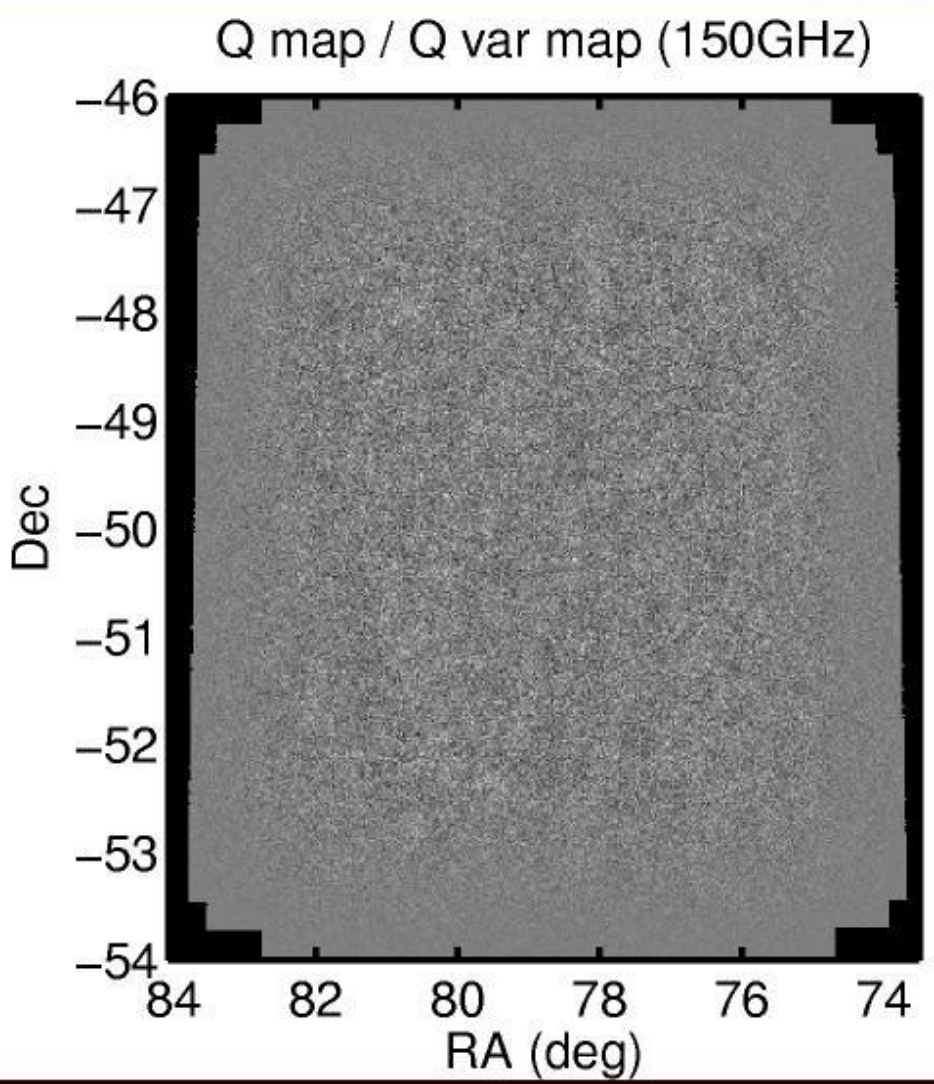

150GHz U Map – Deck Jackknife
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
90
88
86
84
82
80
78
76
74
RA (deg) – color range ±100 μK

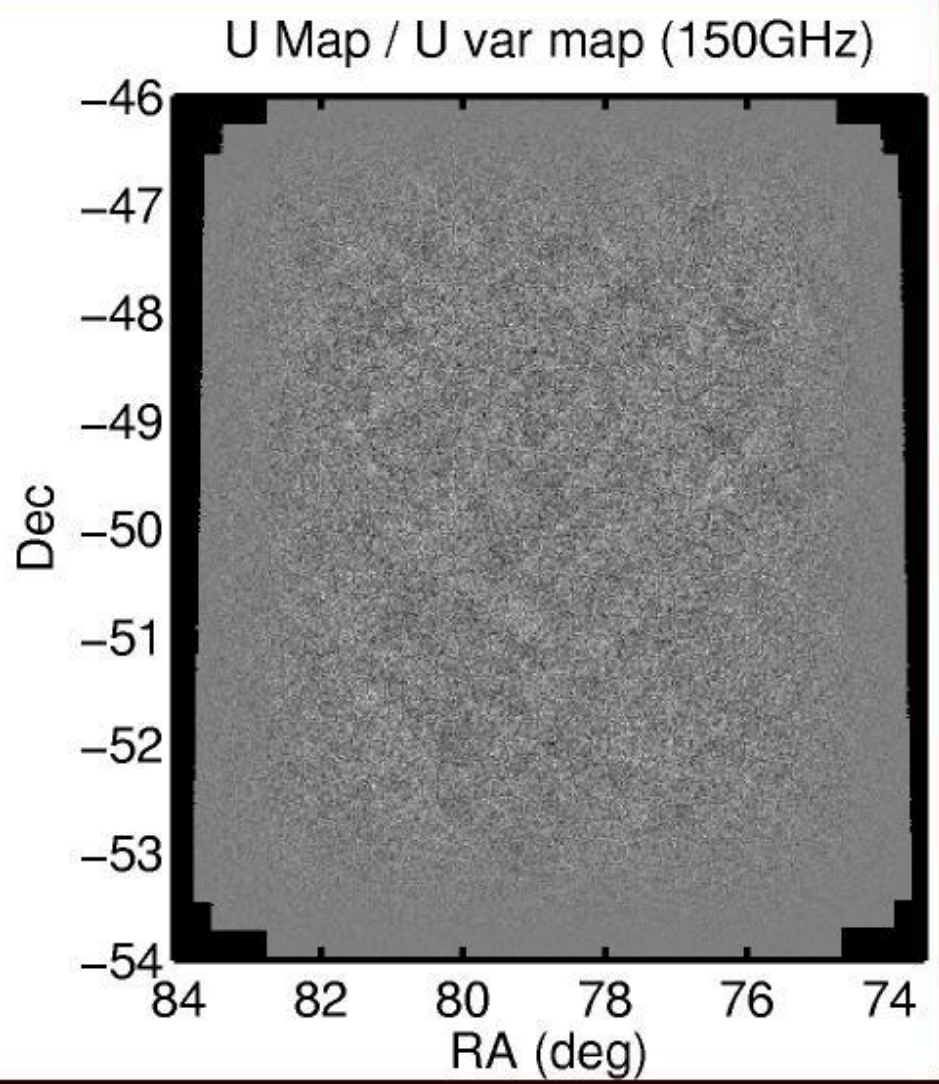
Take the Q/U maps...



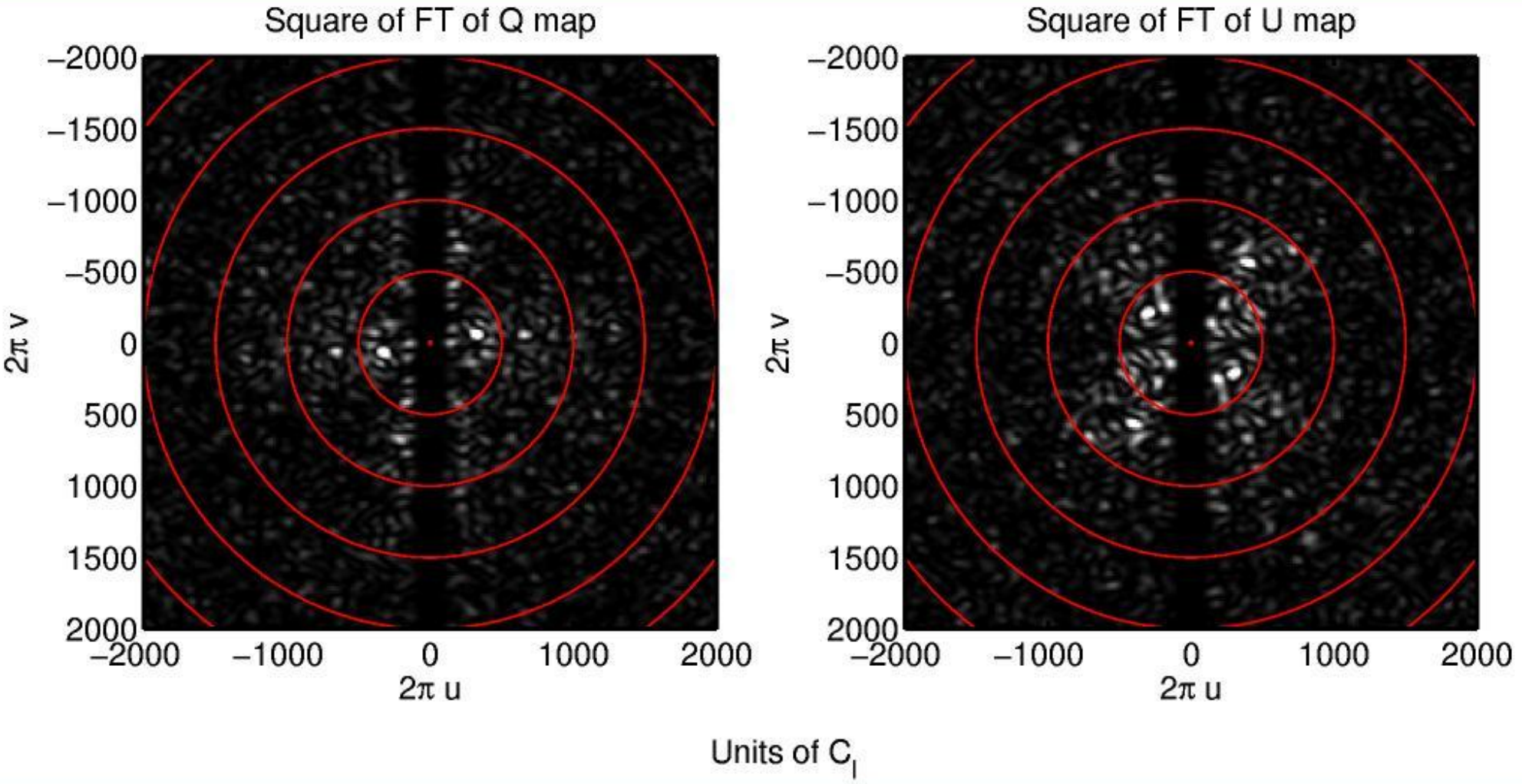
How to make CMB power spectra step by step with pictures...

...appodize...


Q map / Q var map (150GHz)
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
84
82
80
78
76
74
RA (deg)

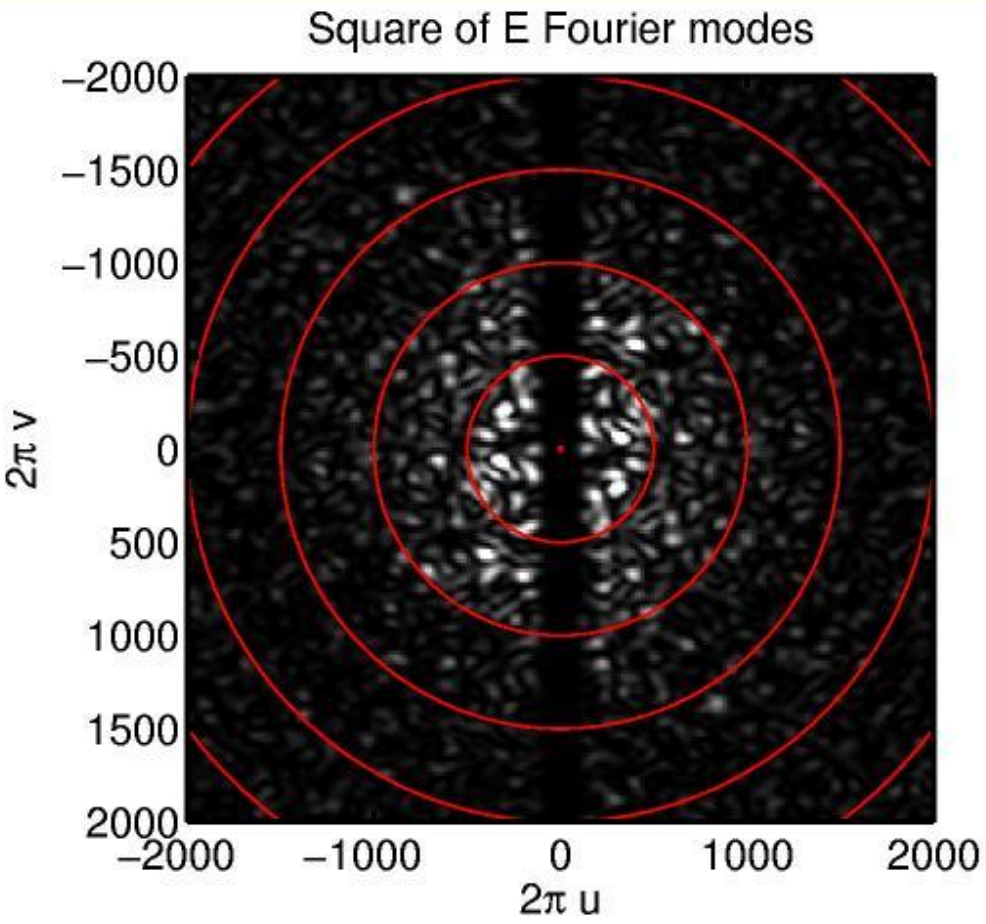

U Map / U var map (150GHz)
−46
−47
−48
−49
−50
−51
−52
−53
−54
Dec
84
82
80
78
76
74
RA (deg)

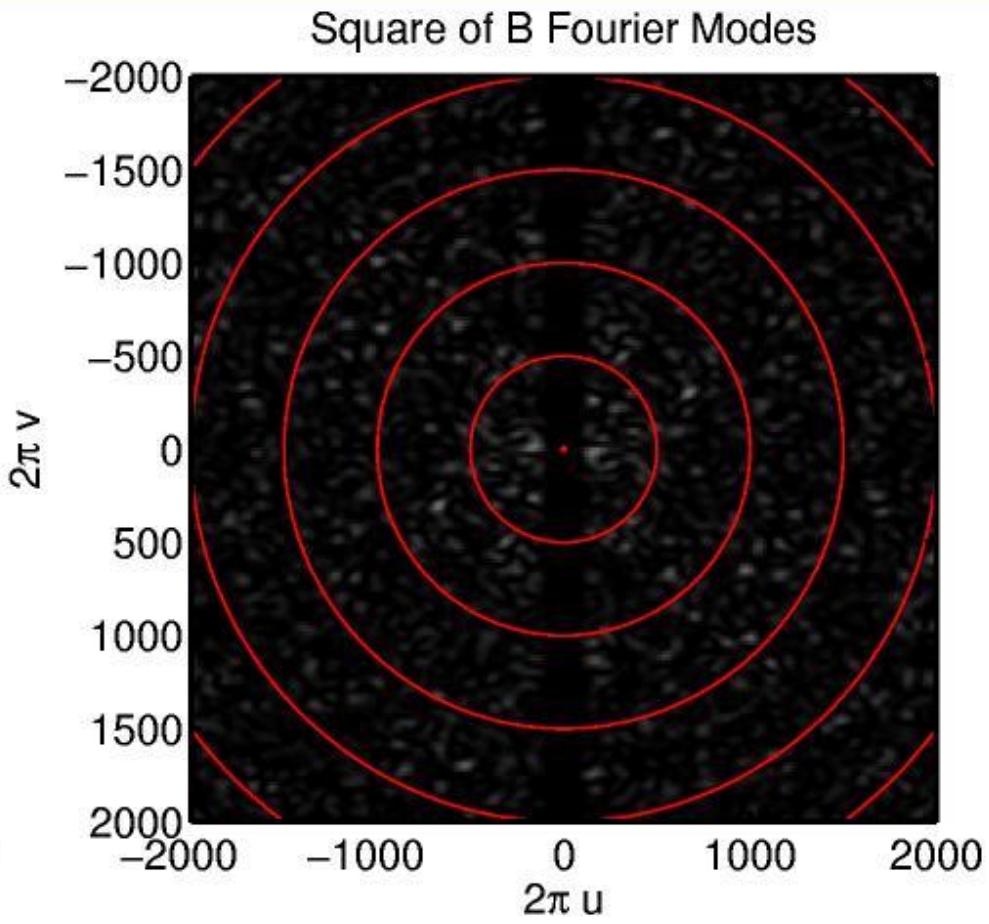
...Fourier transform and square...



(Dark stripe along y-axis is due to half-scan polynomial filtering)

...go from Q/U to E/B...

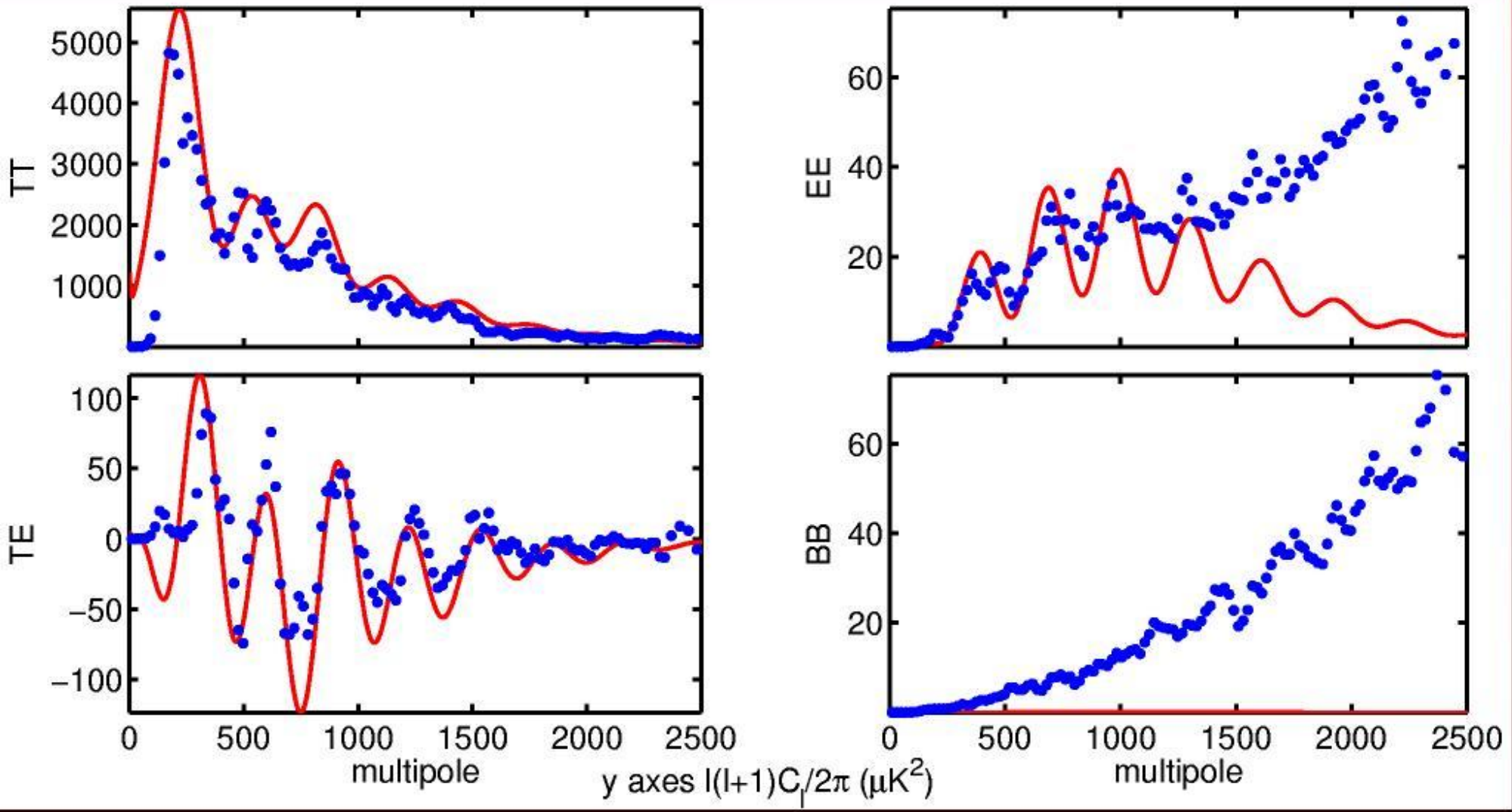




Units of C_l

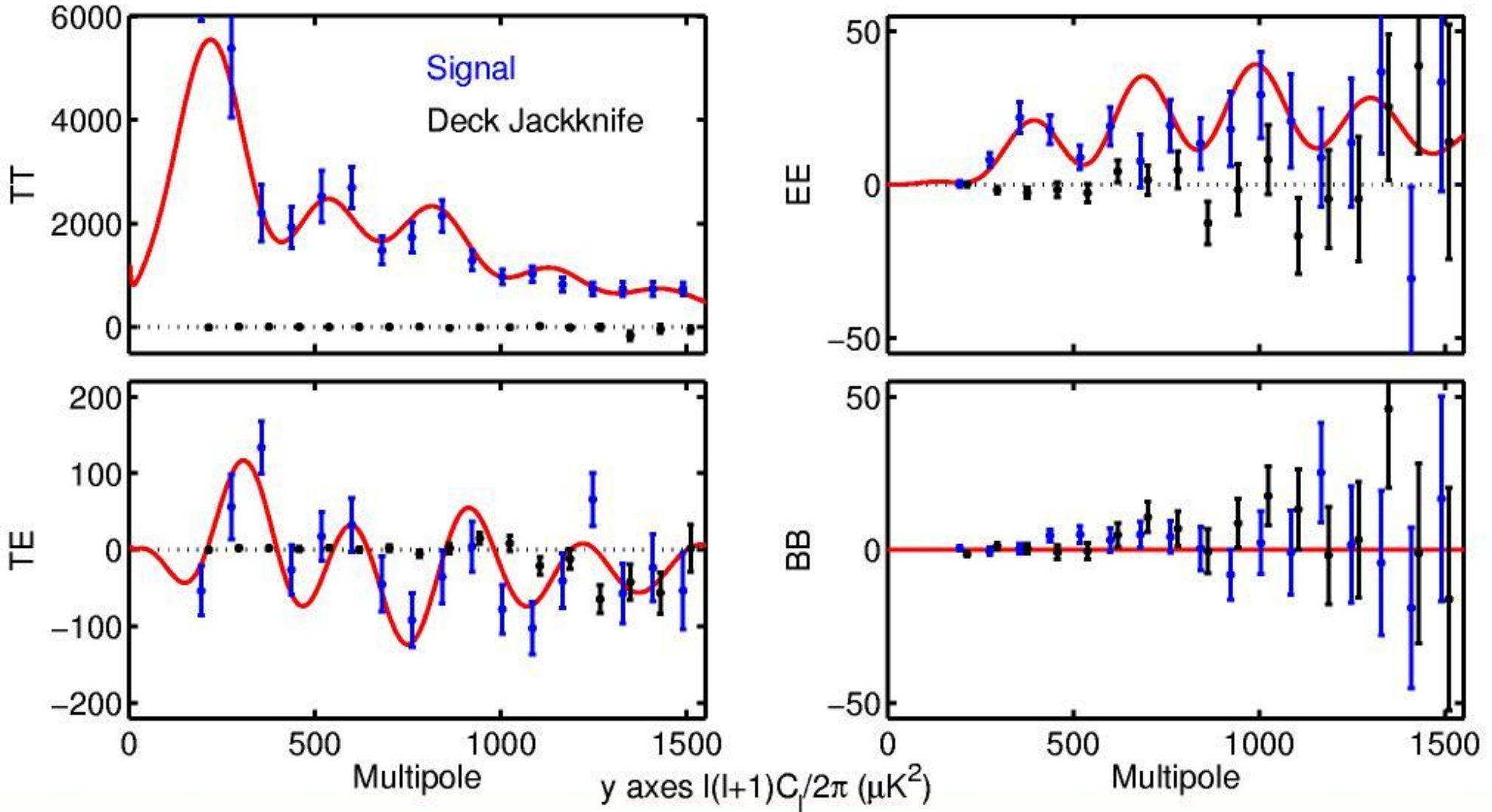
$$\chi = \arctan 2(v,u) - \pi/2$$
$$E = +Q\cos 2\chi + U\sin 2\chi$$
$$B = -Q\sin 2\chi + U\cos 2\chi$$

...mean in annuli is raw power spectrum.



Need to correct for noise and filtering/beam...

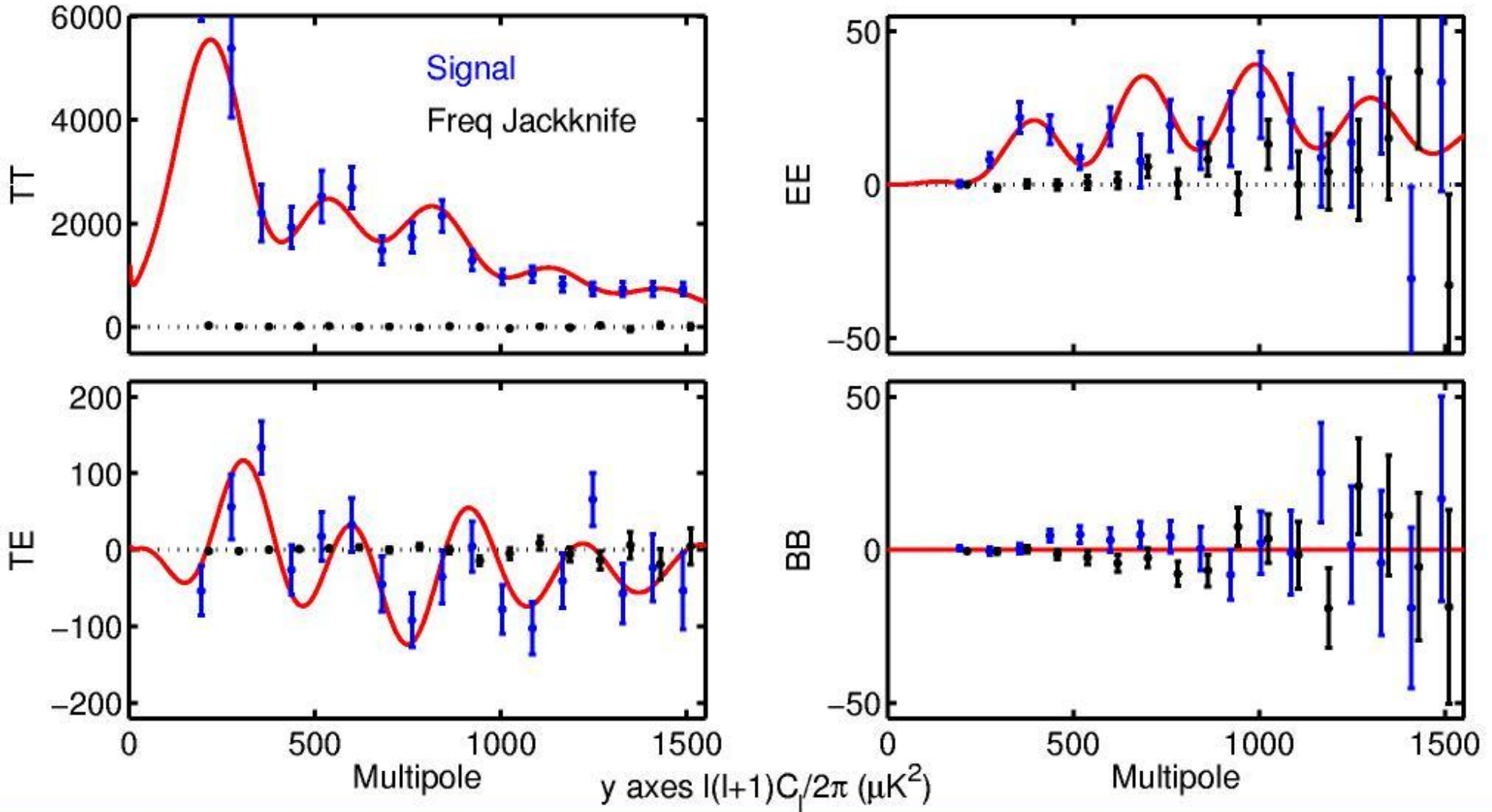
2005 Season Signal/Deck Jackknife



Deck jackknife tests for residual ground contamination

http://arxiv.org/abs/0705.2359

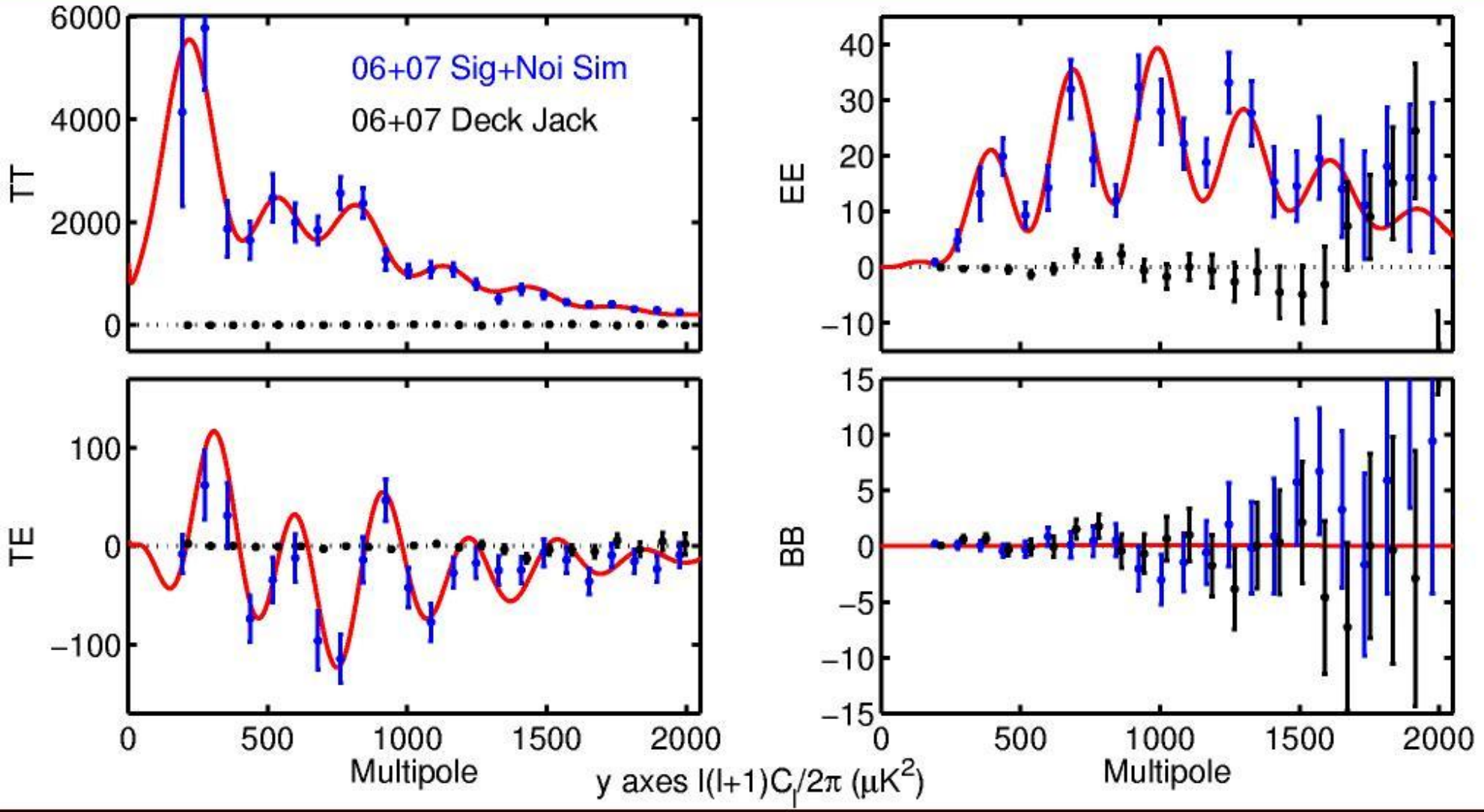
2005 Season Signal/Freq Jackknife



Frequency jackknife tests for foreground contamination

http://arxiv.org/abs/0705.2359

2006+7 Season Upcoming Results



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

Summary of QUaD

- First season results published
  - http://arxiv.org/abs/0705.2359
- Third and final season just ended
- Still fighting with contaminants
  - Ground pickup massively reduced by field difference technique
    - But does any remain?...
  - Moon pickup being exhaustively investigated...
  - Noise modelling is tricky...
- However, for TT,TE,EE residual contamination is already very small compared to sample variance
- Trying to get season 2+3 result out very soon!