CAPMAP

Control of Systematic Effects

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University of Chicago

Inflation Probe Systematics Workshop
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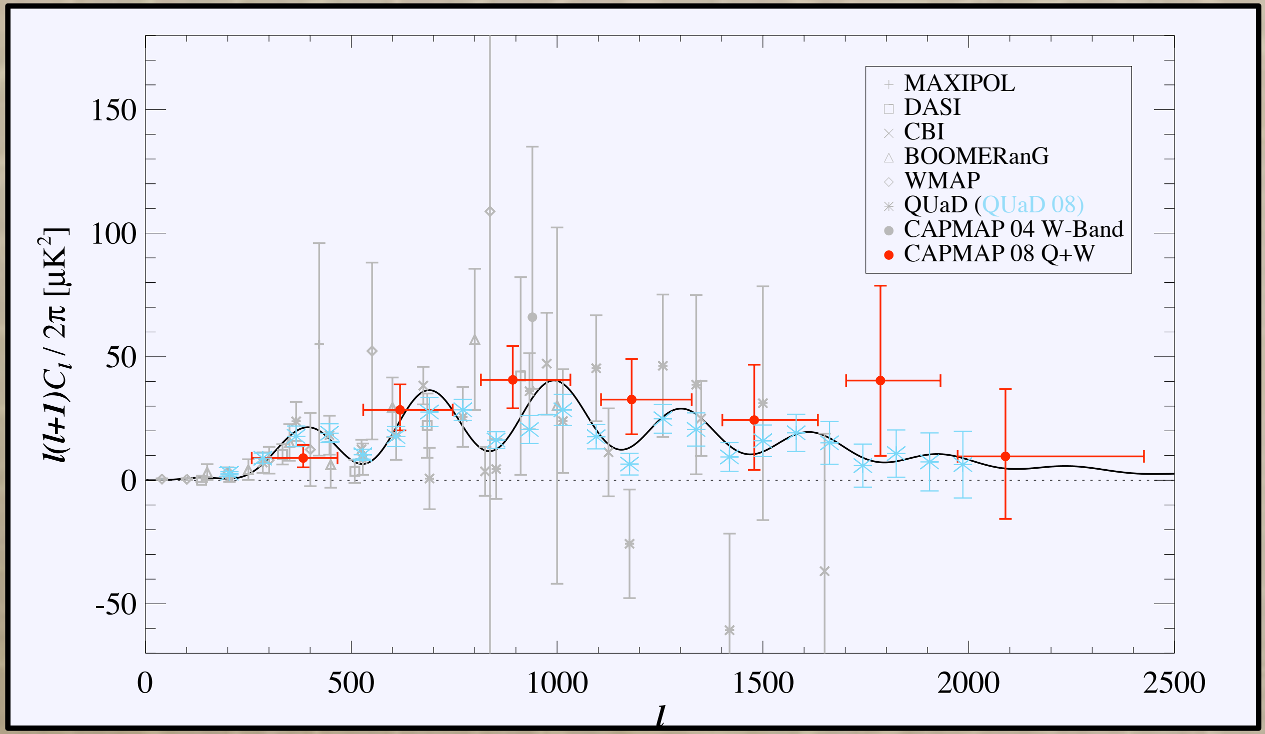
The CAPMAP Collaboration



- **U. Chicago:** Bruce Winstein, Colin Bischoff, Matt Hedman*, Dorothea Samtleben*, Kendrick Smith*, Keith Vanderlinde
- **Princeton:** **Suzanne Staggs**, Denis Barkats*, Phil Farese*, Lewis Hyatt, Jeff McMahon*, Glen Nixon
- **Miami:** Josh Gundersen
- **JPL:** Todd Gaier

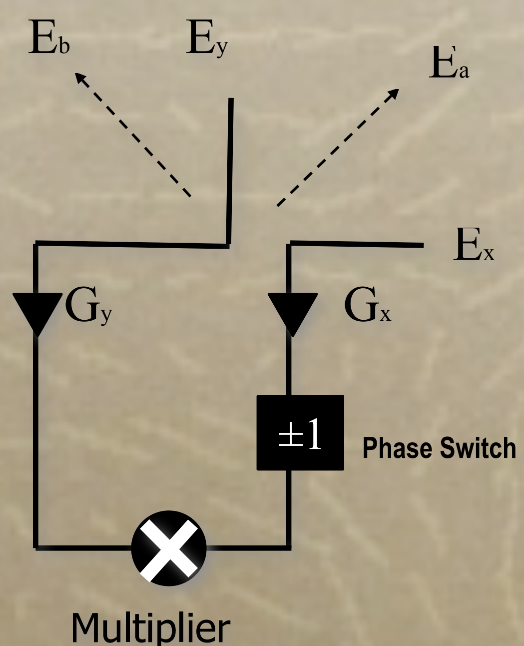
** new affiliation not listed*

Thanks for many figures, analyses, etc. from everyone!

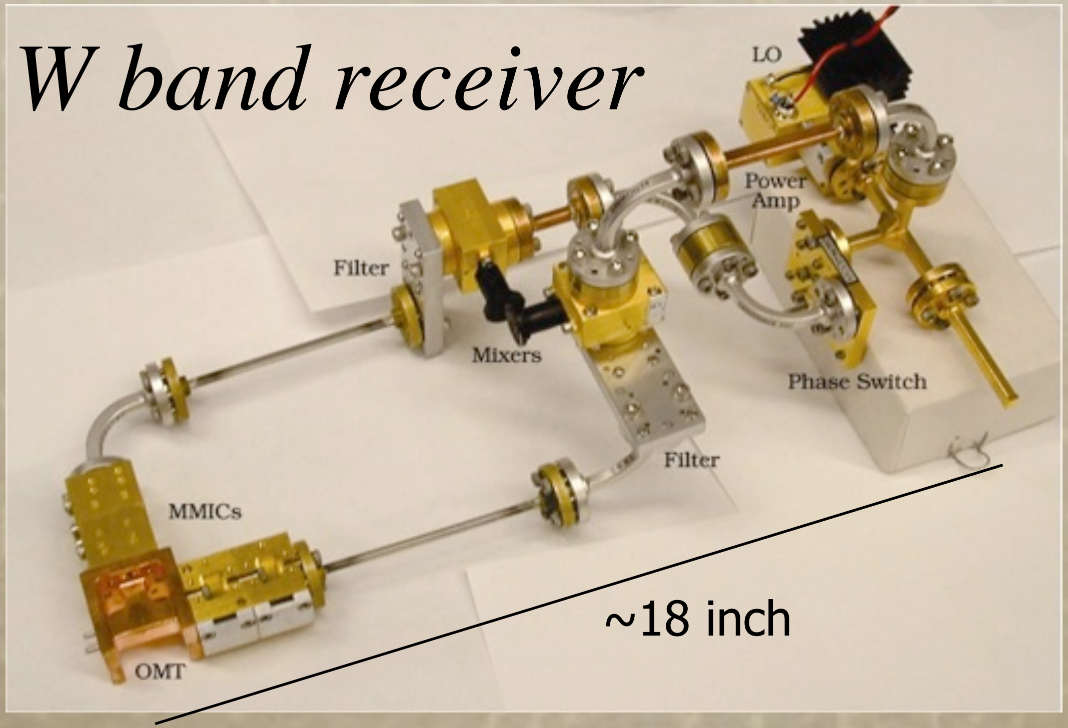
CAPMAP- summary table

Angular resolution	6.5 / 3.3	Arcminutes
Frequency Coverage	40 / 90	GHz
Sky Coverage	8	Square Degrees
Multipole Coverage	200 - 2500	-
Polarization Modulation?	wave guide phase-switch	-
Types of Detectors	correlation	-
Location	Ground	(Balloon/Ground/Space)
Instrument NEQ	400 / 375	$\mu K\ s^{1/2}$
Expected/Current limit on *r*	>1 (*4.8 uK^2 limit on BB*)	-
Status	Completed	(Funded/Proposed/ Future)

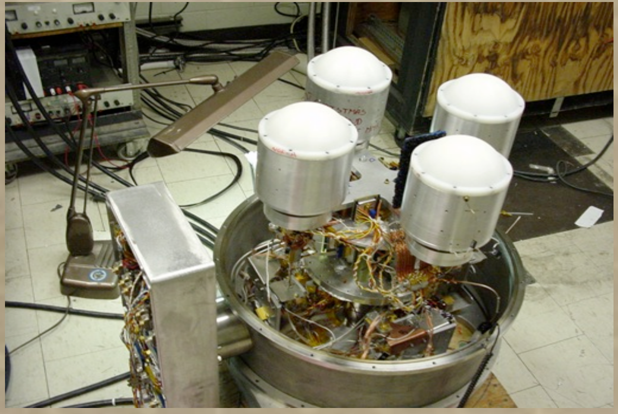
Correlation Polarimeters



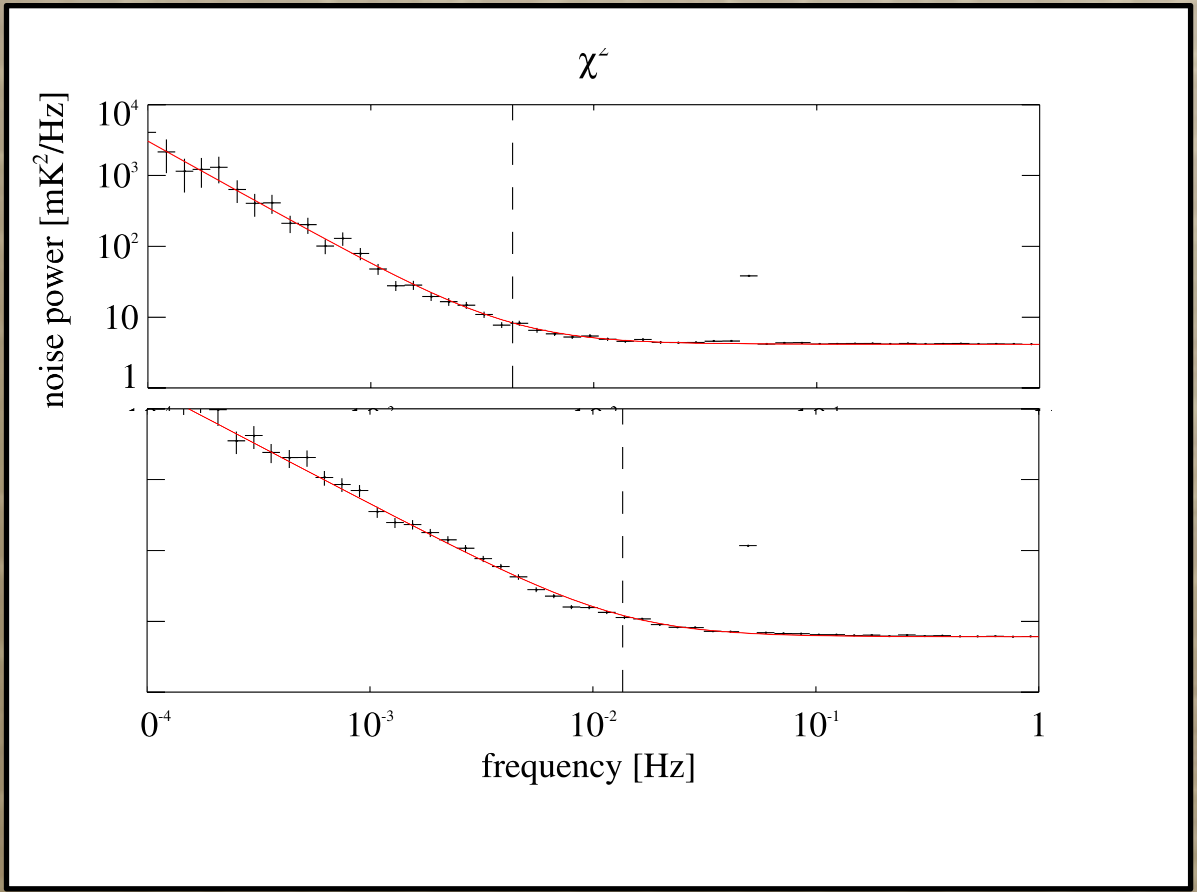
$$\text{Output} = \pm\, G_x G_y (E_a^2 - E_b^2) = \pm G_x G_y * U$$



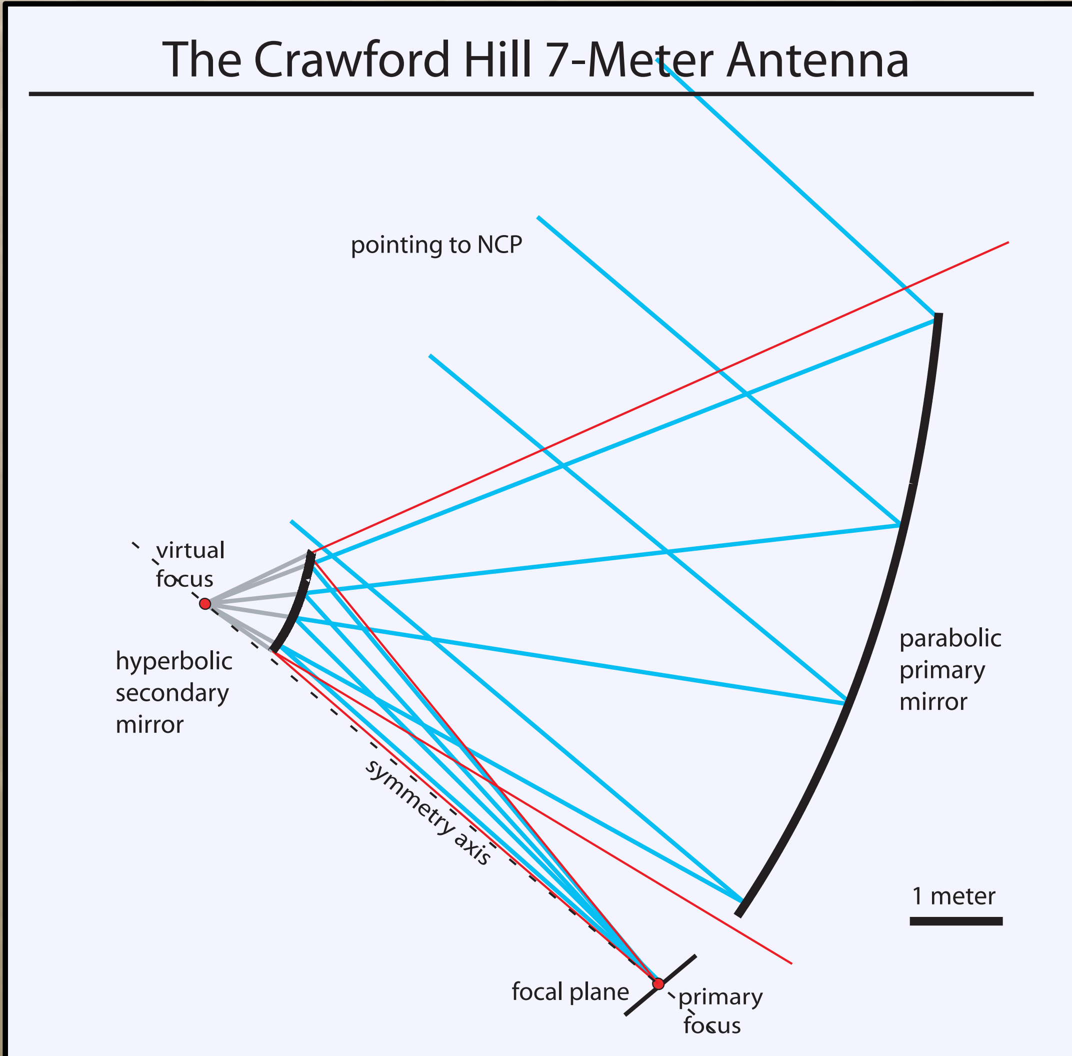
- Insensitive to relative gain drifts
- Instrument Polarization < -25 dB
- Phase switch mitigates 1/f noise



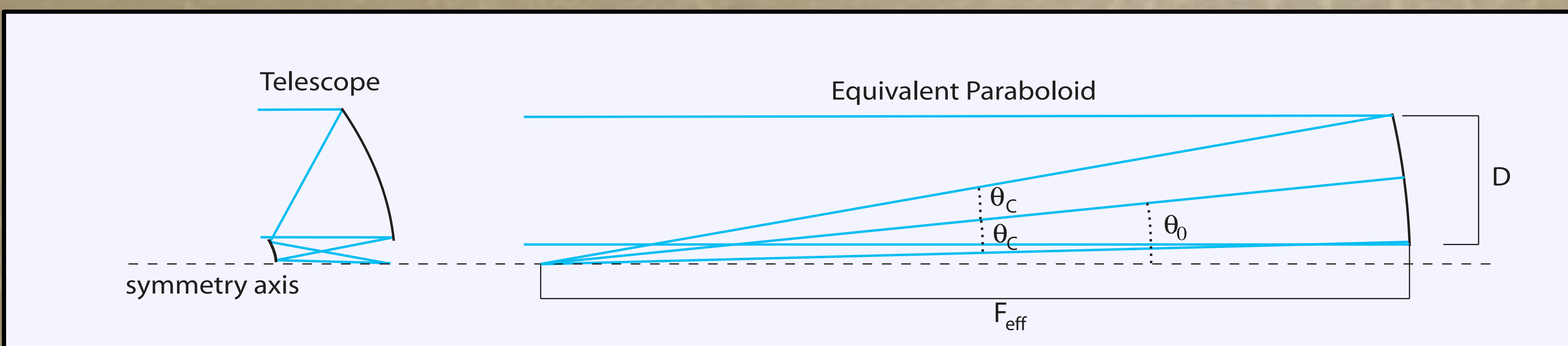
1/f Performance



- *typical knee-frequency: ~3 mHz*
- *worst channel: 15 mHz*
- *modeled noise as white in analysis*
- *1/f is a negligible effect*

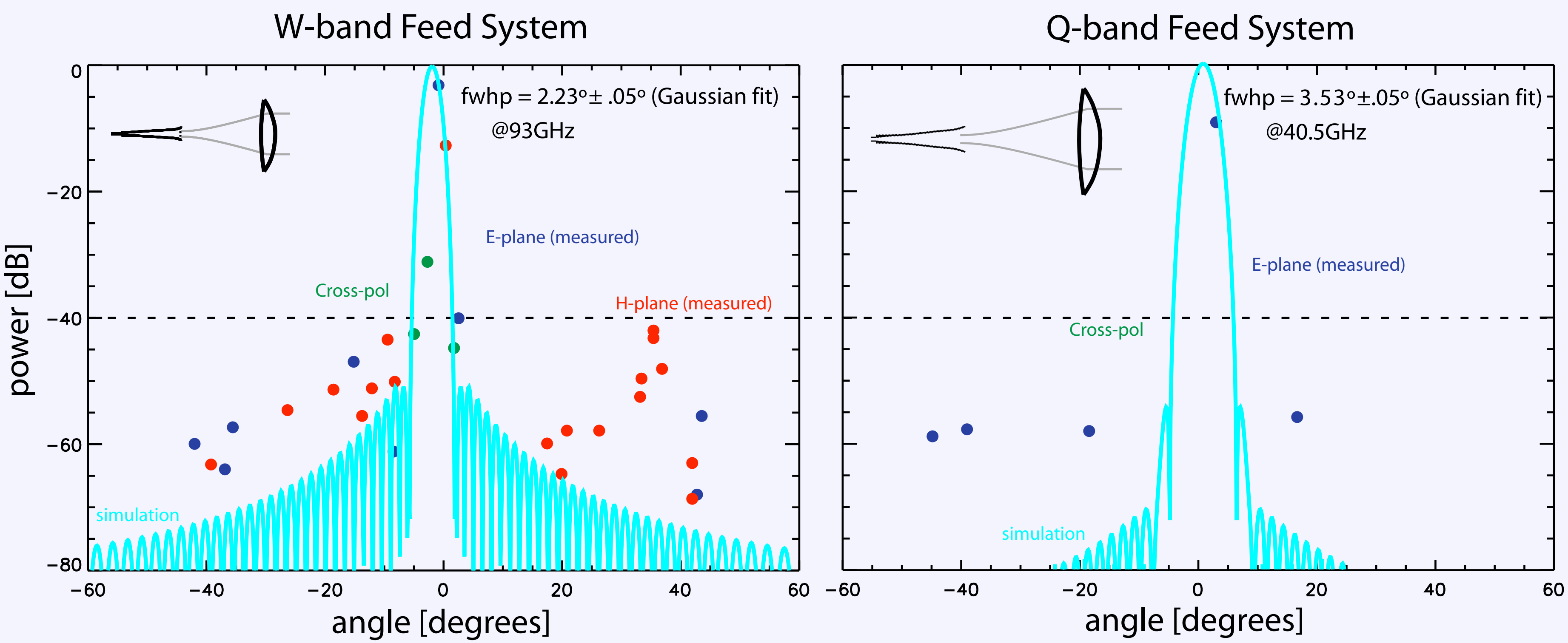


- *7 m in diameter*
- *full alt-az mount*
- *low cross-polarization (-58dB on focus)*
- *large focal plane (strehl ratio > .97 0.5 m from prime focus)*
- *orient each feed to minimize instrument polarization*
- *tight requirement on feed*

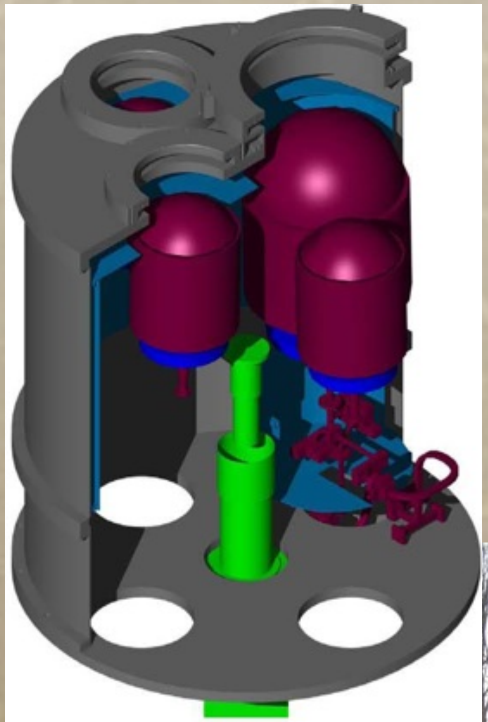
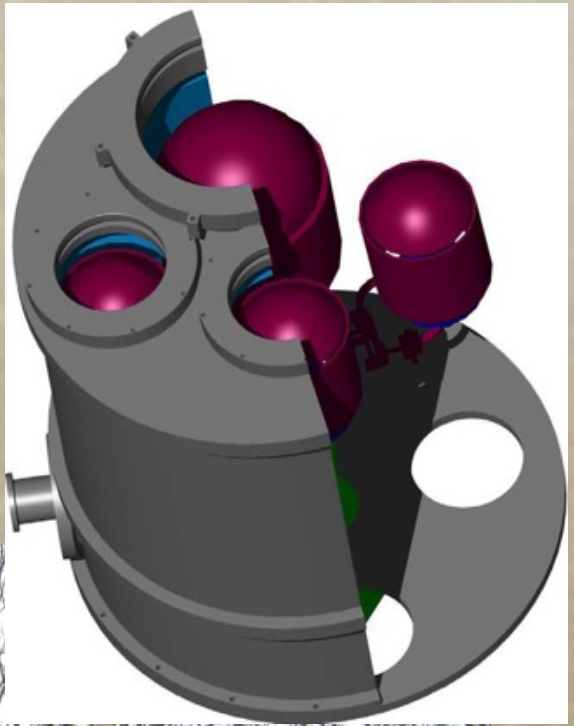


CAPMAP Feed System

Measurements and Simulations of the CAPMAP Feed Systems

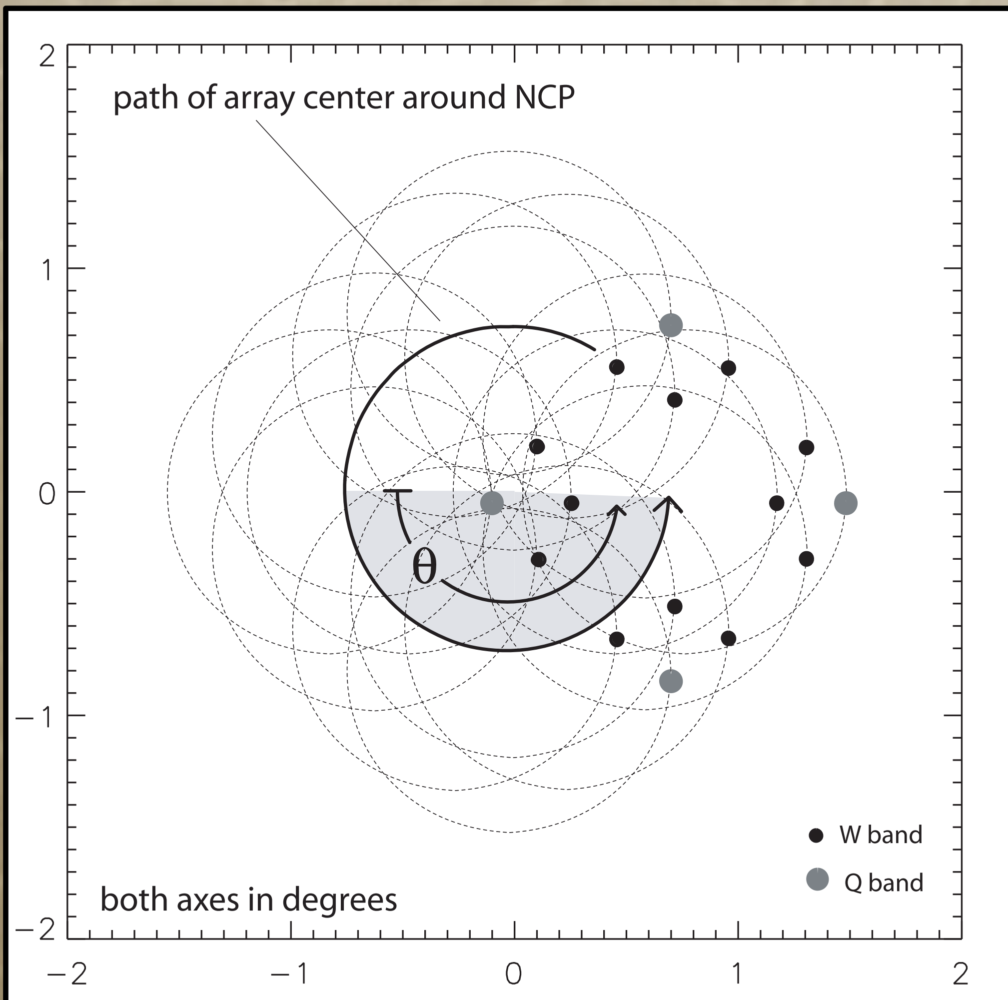


The CAPMAP Array


- 16 correlation polarimeters
- 12 @ W-band (84-100 GHz)
- 4 @ Q-band (35-45 GHz)

Scan Strategy

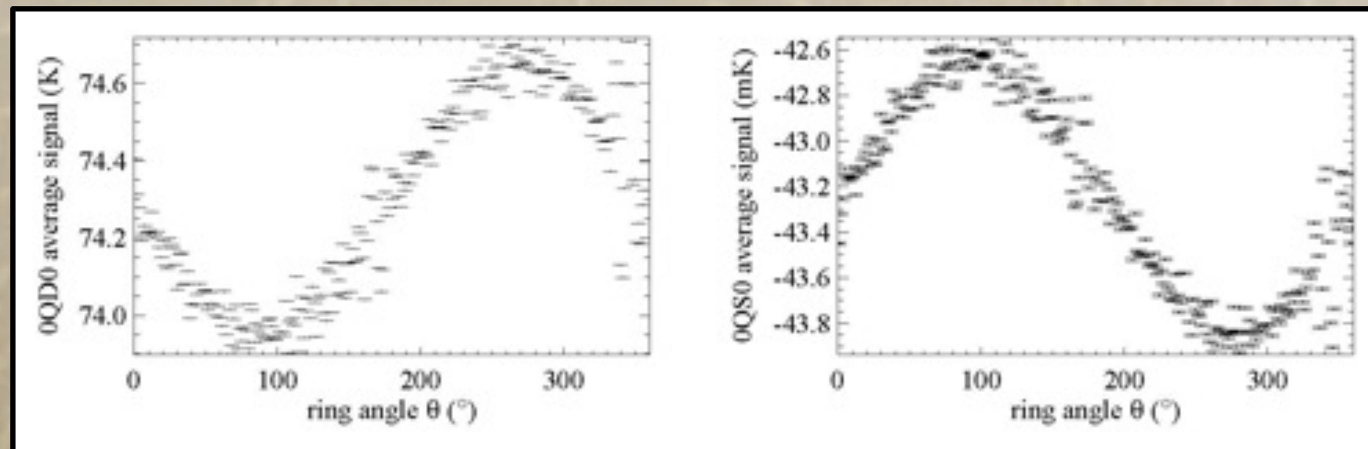


D. Fixsen

- *Ring / Drift scan*
- *uniform coverage*
- *excellent paralactic angle coverage*
- *allows measurement and removal of ground synchronus signals*
- *Cost: modulates the atmosphere*

Mode Removal

$$U_{atm} = \alpha T_{atm}\left(1 - e^{-\bar{\tau}/\sin el(\theta)}\right)$$

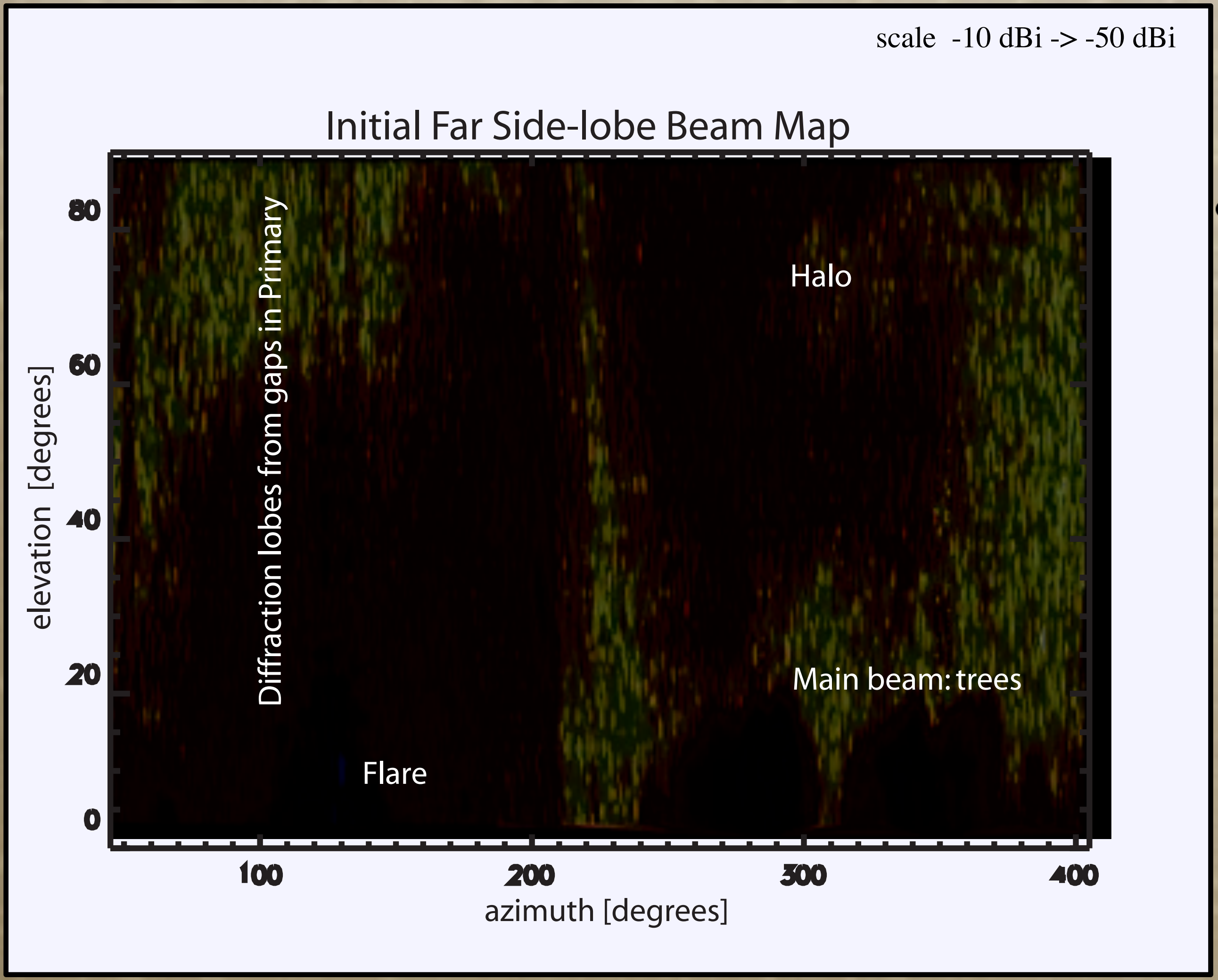


- *The atmospheric modulation (left) shows up in the polarization channels*
- *This must be removed by subtracting a 5-parameter model*

  $$\boxed{M(\theta) = A_1 + A_2 \sin\theta + A_3 \cos\theta + A_4 \sin 2\theta + A_5 \cos 2\theta}$$

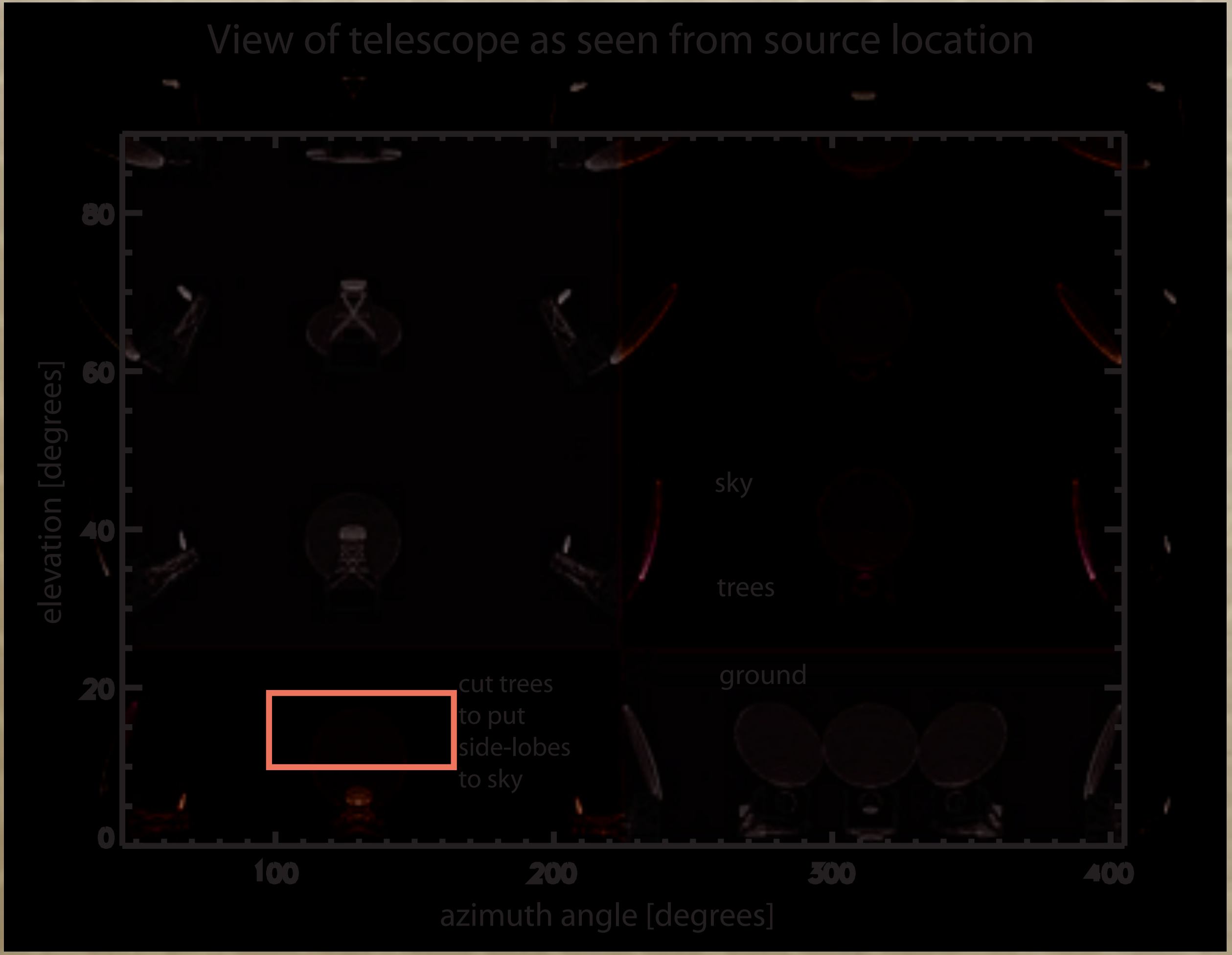
  fit to each 21-second ring cycle.
- *removal of 5 fourier modes reduces atmospheric contamination below 100nk*
- *expense of a 15% loss of sensitivity.*

Control of Ground Pickup



- *During the first season (2002)*
  - *variable ~500 uk / deg scan synchronus slopes*
  - *50 uK rms residuals*
  -

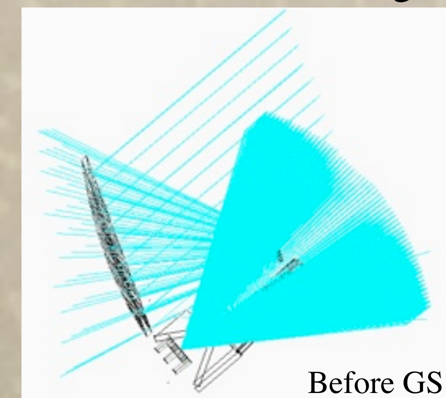
Where do the Sidelobes go?



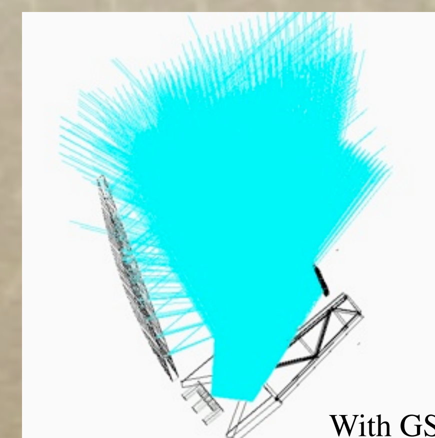
Control of Ground Pickup

Improvements to reduce SSS

Ground Screen Design



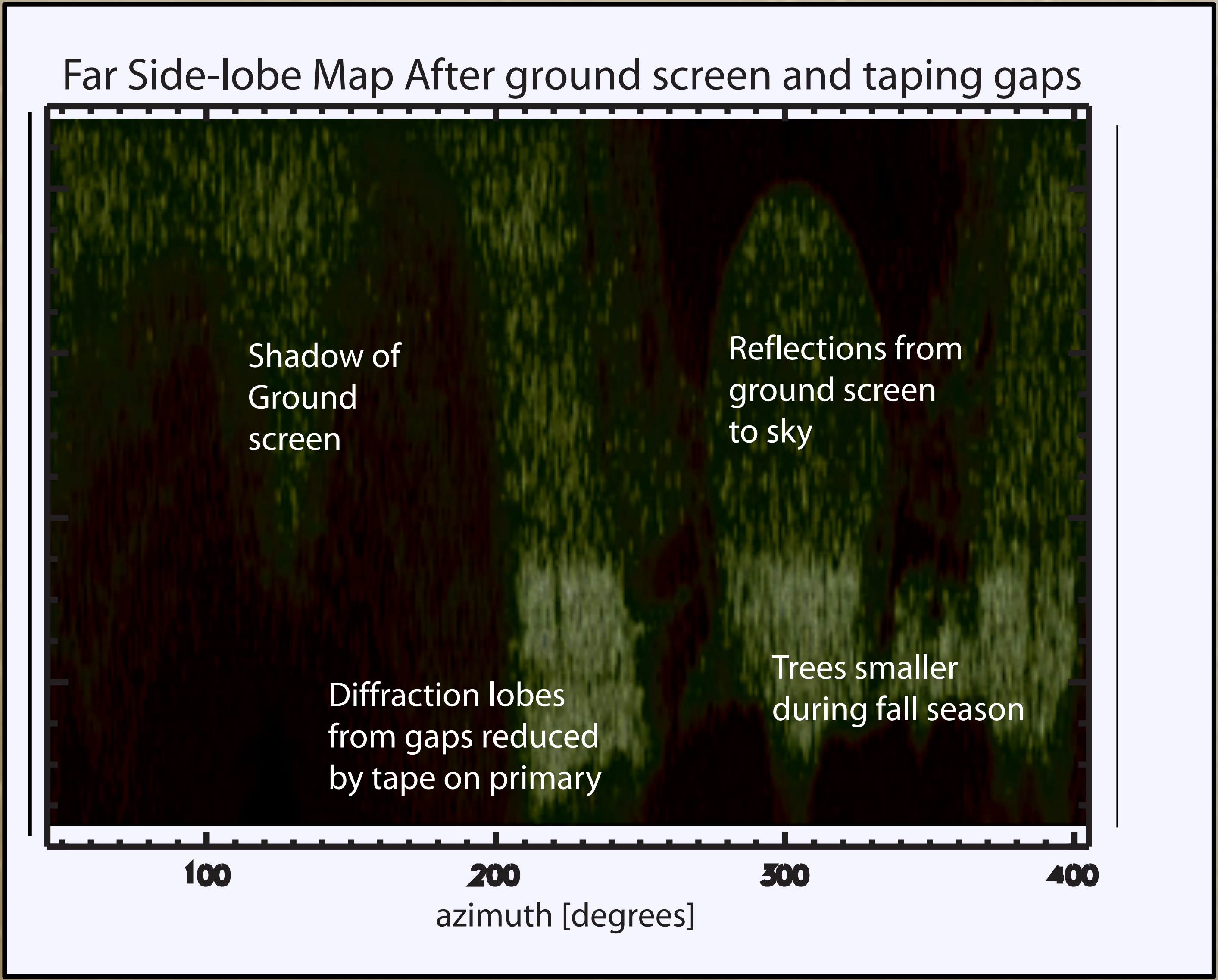
Before GS



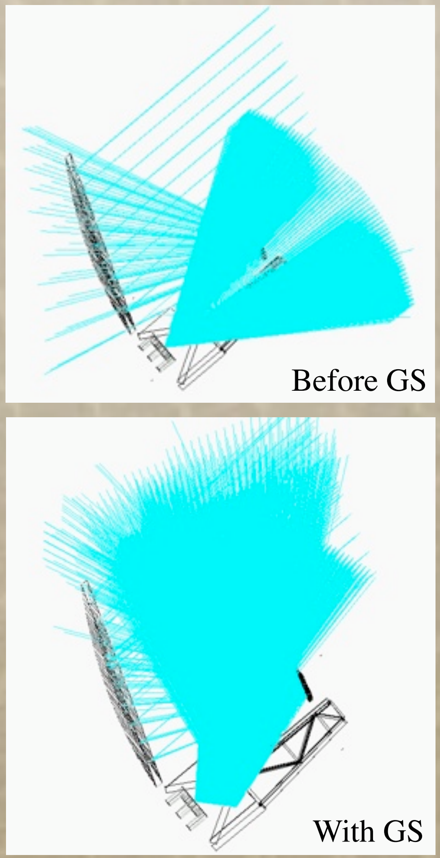
With GS

- Slopes < 50 uK / deg
- most channels show scan synchronous residuals consistent with 0

Control of Ground Pickup

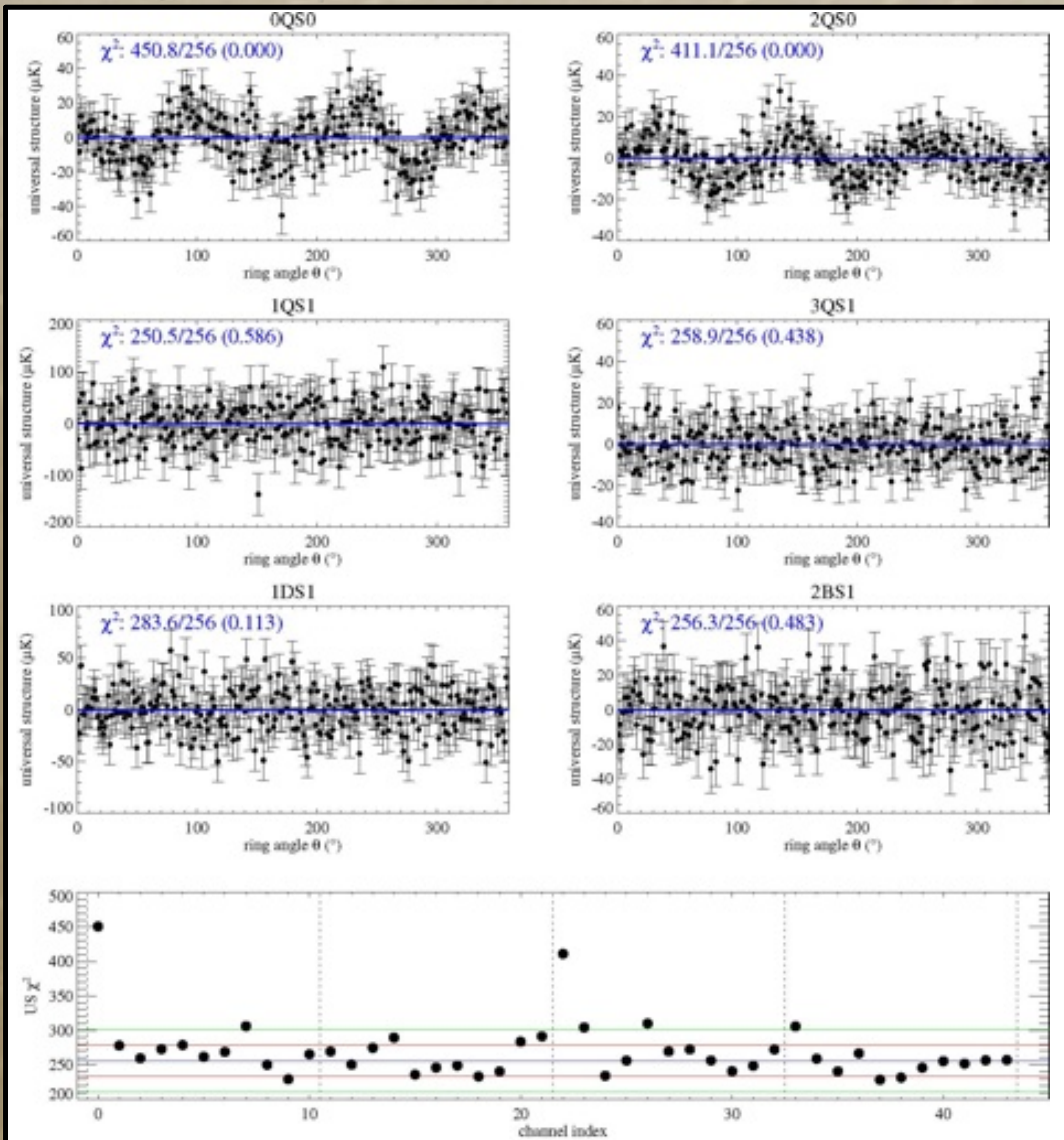


Ground Screen Design



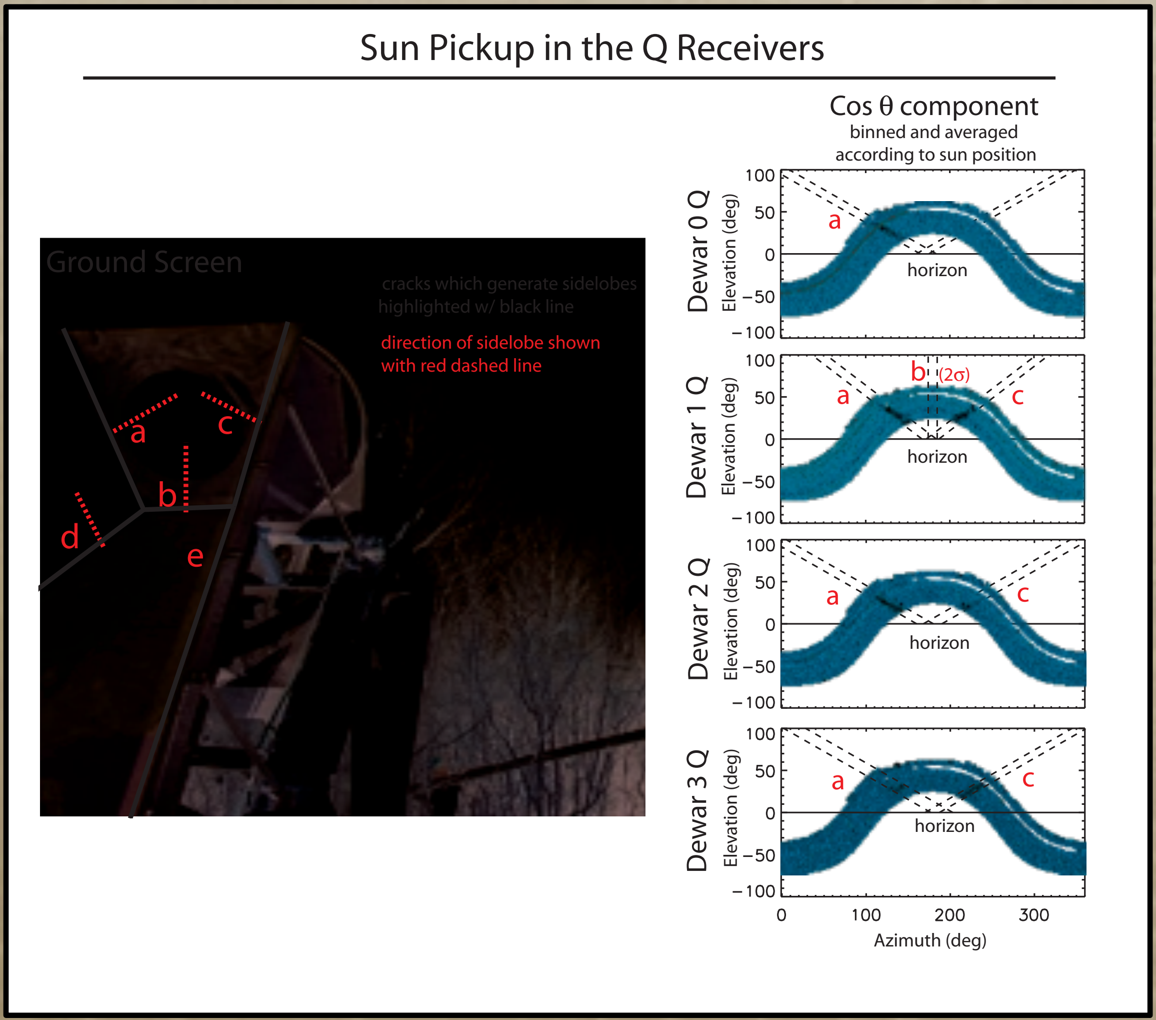
- Slopes < 50 uK / deg
- most channels show scan synchronous residuals consistent with 0

Scan Synchronus Signals



- residuals reduced to immeasurable levels for all but 2 channels with various optical improvements.
- To be conservative, we project out this mode from all channels.
- scan syncrhonus slopes below ~20 μK/ deg

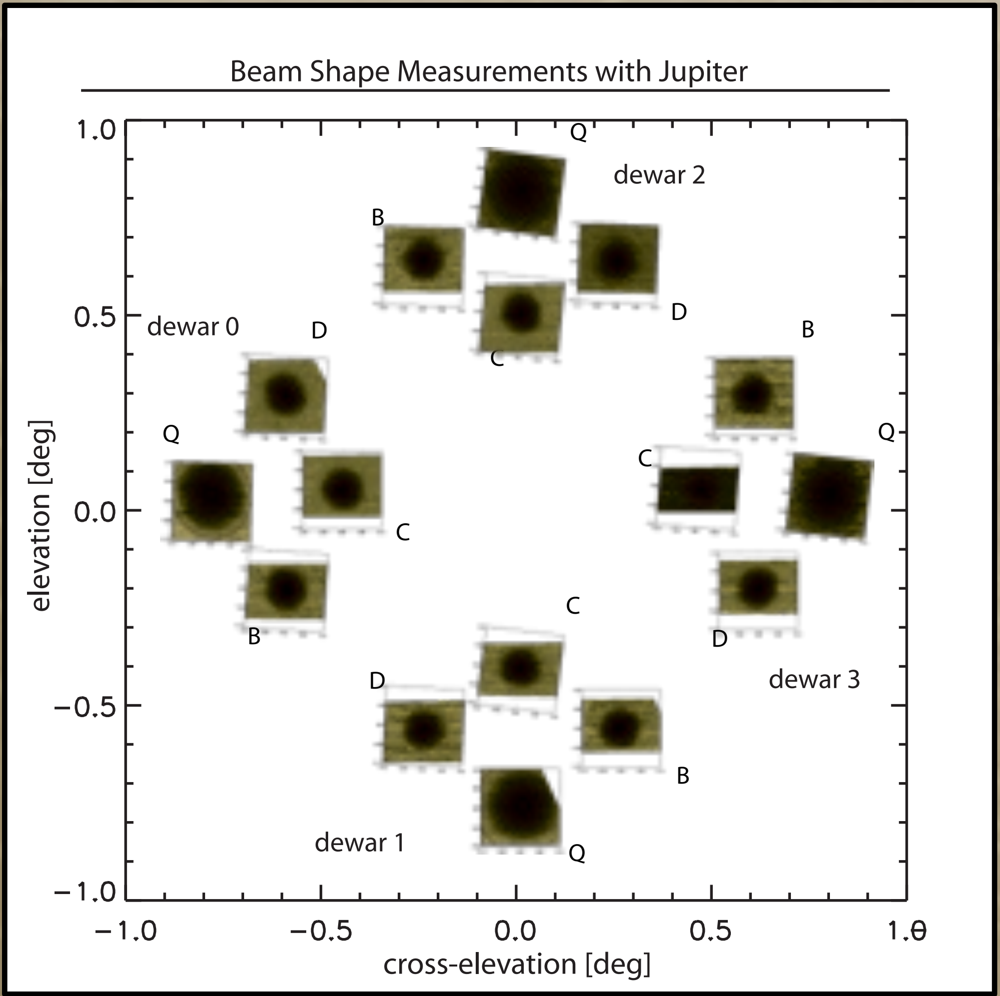
Sun Pickup



- *Ground screen caused sun pickup in 40 GHz channels*
  - *cut 8% of 40Ghz data*
  - *caused by diffraction from panel gaps*
- *No evidence for effect in 90 GHz*
  - *illumination of panel gaps down by 20-30dB*
  - *estimate from beam map gives 50 uK effect DC, falls off rapidly with ring mode*
  - *Day night null passes*

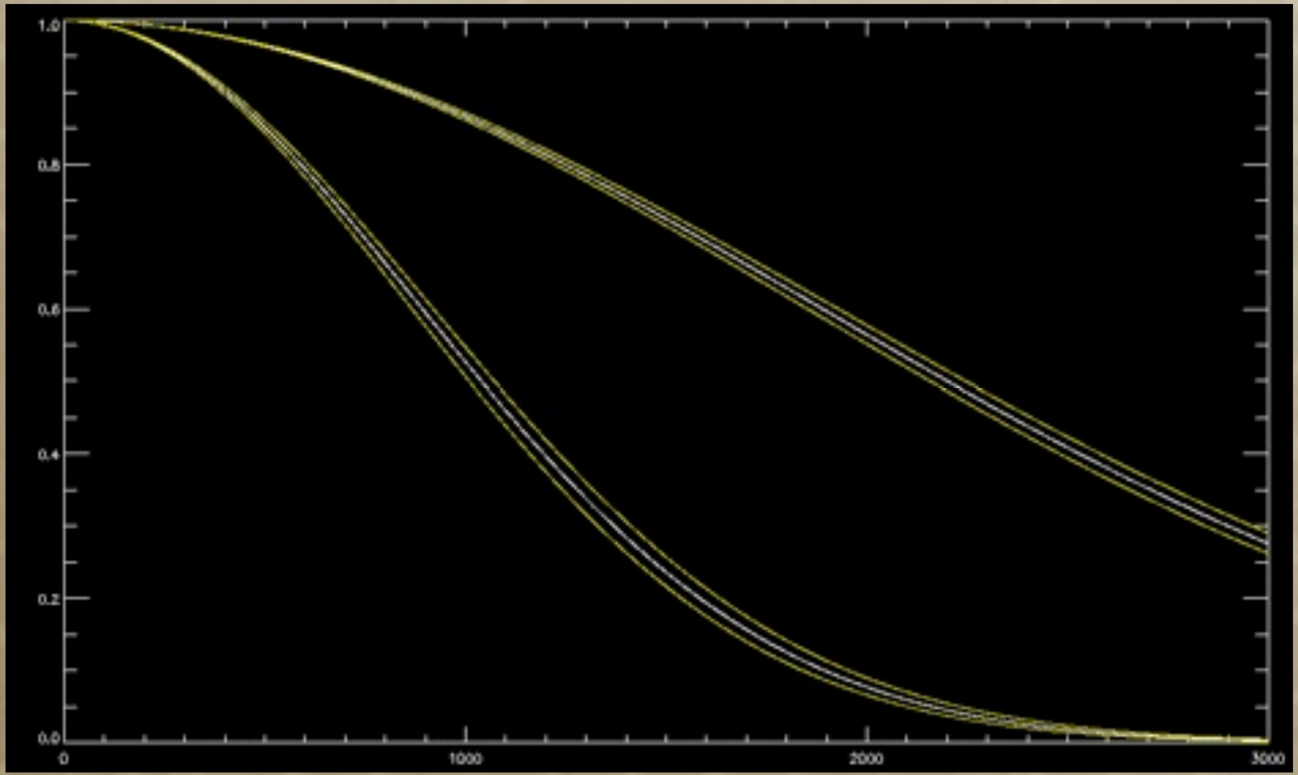
Beam Shapes

(+ relative pointing)



- *Measured with Jupiter*
  - *mean beam size: sqrt(ab)*
    - *3.3' (6.5') @ 90 (40) GHz*
    - *<1% errors in measured beam sizes*
    - *spread in beam size of different radiometers: 2% (3%) rms @ 90 (40) GHz*
  - *elongation:* (b-a)/(b+a)
    - *less than 8%*
- *Small systematic effects from:*
  - *treating all 90 (40) GHz beams as same*
  - *neglecting elongation*

Beam Size Variation

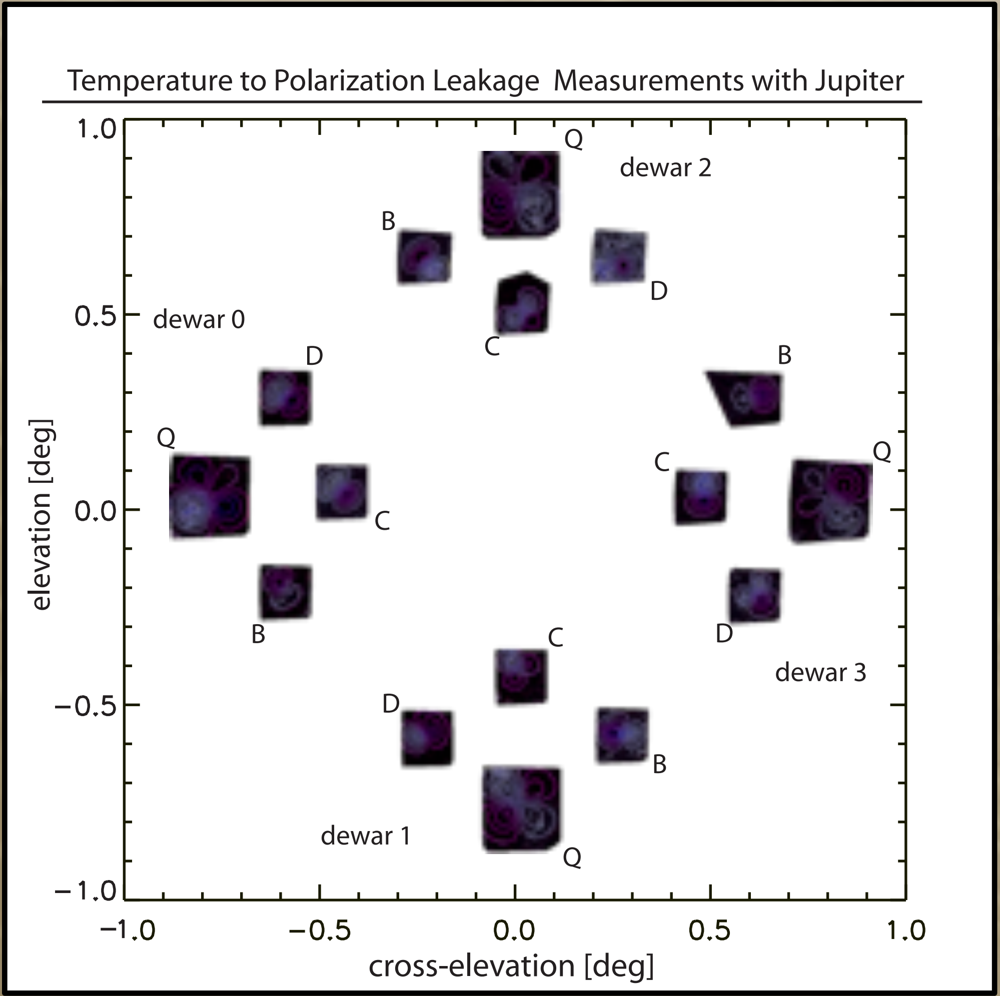


Different beam sizes give different window functions

Treating all beams as the same adds extra varaince to a power spectrum measurement

This simple calculation is in rough agreement with the simulations that we used to quantify this effect

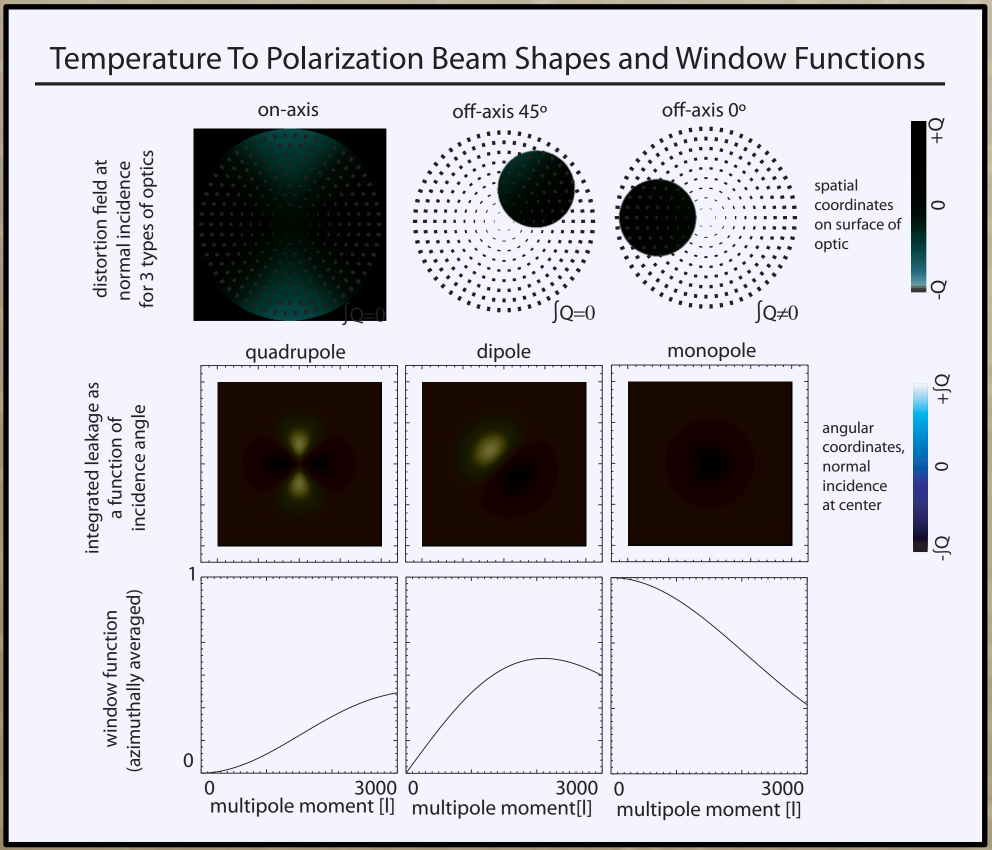
I->P Leakage

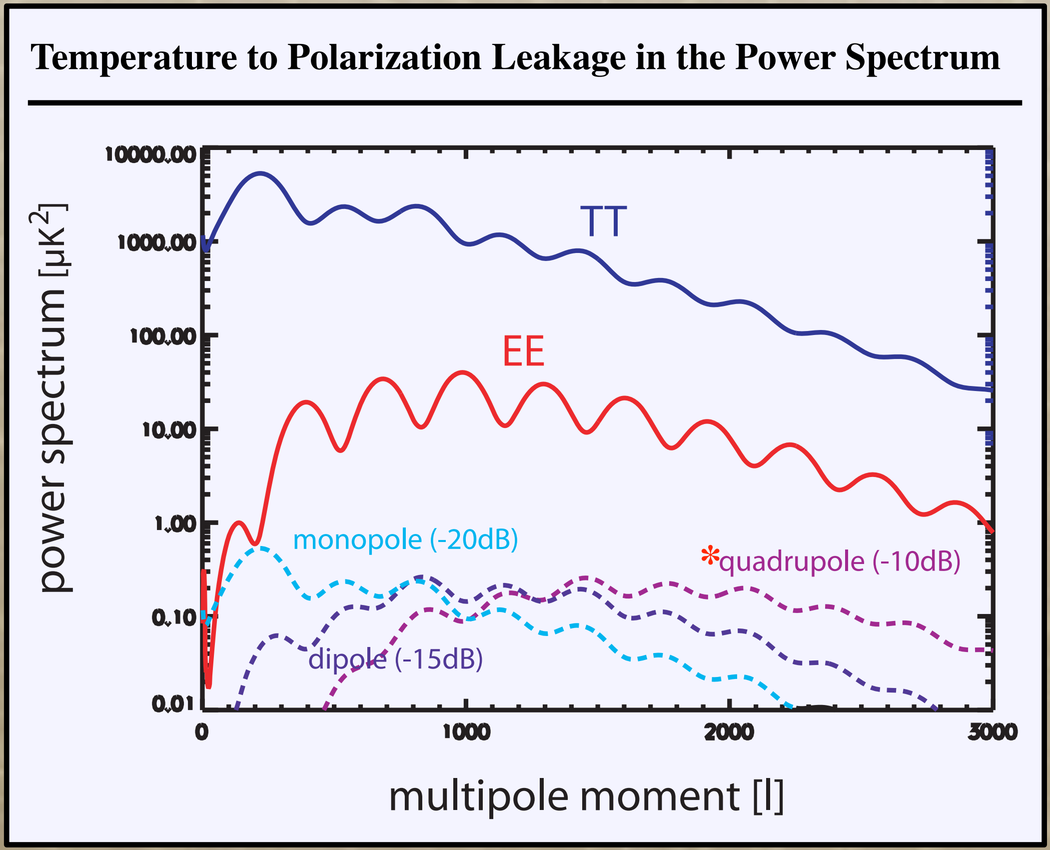


Color scales vary from beam to beam
(these were made by an inexperienced grad student: me)

- *Measured with Jupiter*
  - *fit to monopole, dipole, quadrapolar beam model*
  - *typical fit parameters*
    - *-23 dB monopole*
    - *-20 dB dipole*
    - *-22 dB quadrapole*
  - *also measued monopole with atmosphere: ~0.5% agreement*
- *Negligible systematic*
  - *these couplings are small*
  - *further surpressed by scan strategy and averaging across receivers*

I->P Leakage

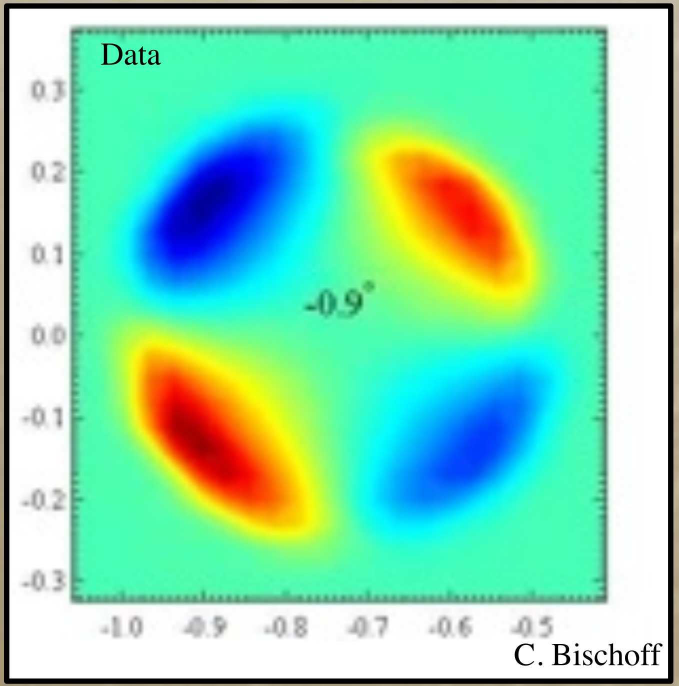


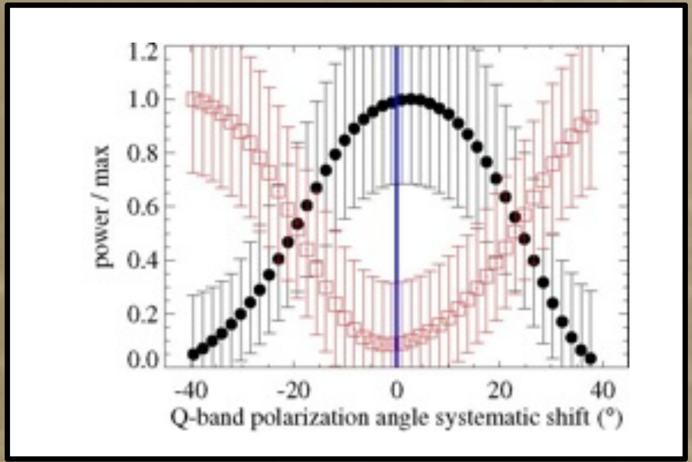


*actual quadrupole is off the bottom of the plot

These are worst case estimates, averaging across detectors and scan-strategy further supresses these effects

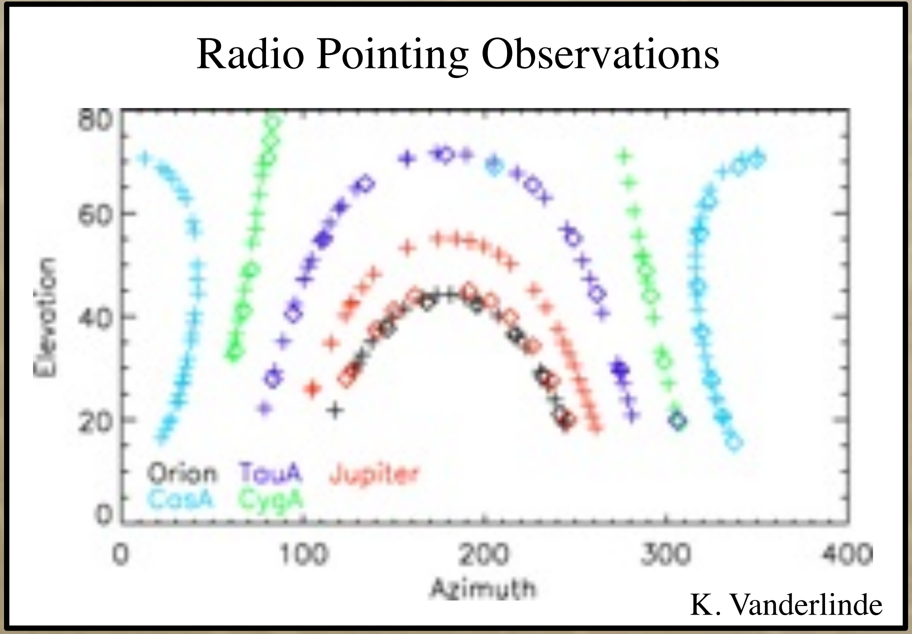
Detector Angles





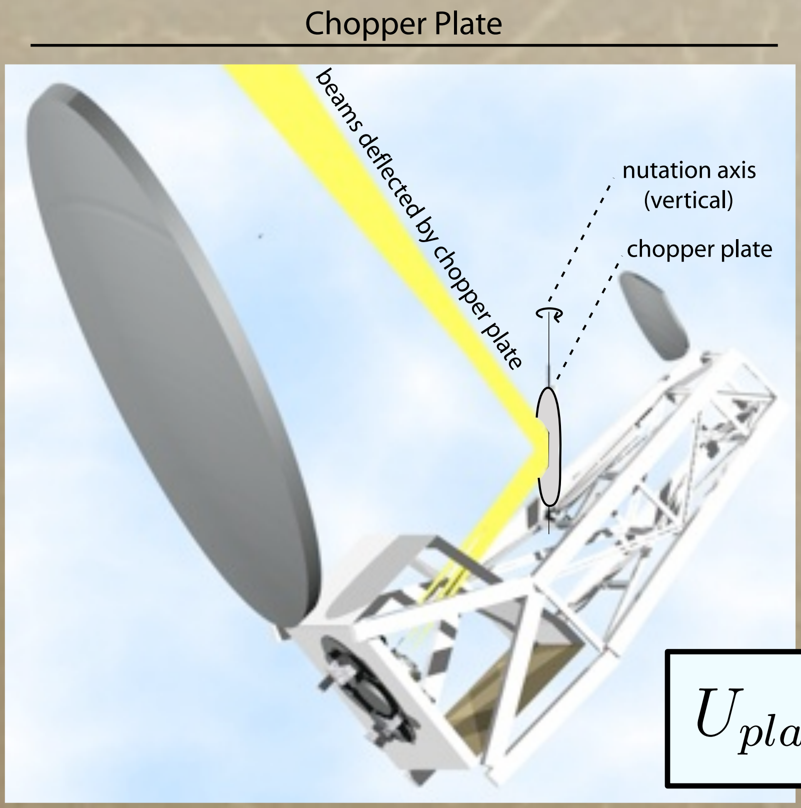
- *Measured with moon*
  - *Fit included: moon temperature, moon index of refraction, + removal of offsets*
  - *uncertainty varied by radiometer from 1º-2.5º at 1-sigma*
  - *Residuals dominated by systematics: detector non-linearity?, variation of the index of refraction of the moon?, etc.*
- *Small systematic effect for EE*
  - *rotates between E and B*

Absolute Pointing



- Observed 5 sources across the sky with a single radiometer
  - run 1 - Dec. 2003, 150 sources
  - run 2- Nov. 2004, 50 sources
- Fit to a 10-parameter pointing model (Meeks 1968)
  - fits to either run yield consistent parameters, implies stability
  - residuals to combined fit:
    - 29” rms in elevation,
    - 18” rms in Az
- negligible systematic effect (will quantify later in the talk)

Gain Calibration

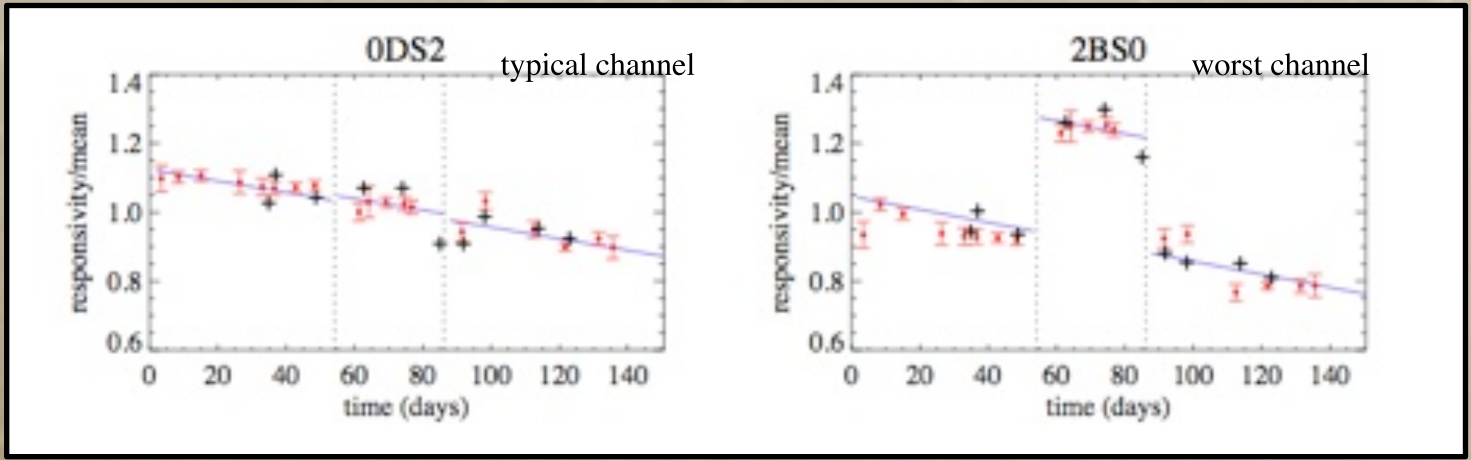


~12 % Absolute gain uncertainty dominated by;

1) uncertainty in plate conductivity
2) uncertainty in T_plate - T_sky
3) Ruze correction for dish

$$U_{plate} = \alpha \tan\beta \sqrt{16\pi\rho\epsilon_0 f}\,(T_{plate} - T_{sky}).$$

Gain Drifts (here are our warts)



- *Thermal drifts lead to a linear variation in gain with time*
  - *difficult to correct due to phase-lags of the house keeping thermometers relative to the relevant amplifiers*
  - *sensitivity did not change with time*
- *Uncertainty in this gain correction is our dominant systematic*
  - *simulations show that this effect is no more than 10-20% of our statistical errors*
  - *(the central limit theorem comes to the rescue)*

Systematics Summary

- Fully simulated the effects of largest systematics
  - responsivity, beam-size, pointing, detector angles
- 1-band simulations for smaller effects
  - I->P leakage, 1/f
- back of envelope calculations for very small effects
  - elongation, unmeasured sidelobes
- Ran a suite of 72 null tests to check data purity
  - cumulitave probability to exceed for all 72 null tests: 30%
  - distribution of individual null tests consistant with the expected distribution

Q+W SYSTEMATIC EFFECTS

Band	Responsivity	Beams	Pointing	Angles	Total
1	0.6	0.2	0.3	0.2	0.7 (0.15σ)
2	1.4	0.5	0.7	0.3	1.7 (0.18σ)
3	1.8	1.2	1.3	0.9	2.7 (0.21σ)
4	2.5	1.7	1.9	2.0	4.1 (0.27σ)
5	4.8	3.4	3.9	3.7	8.0 (0.37σ)
6	6.6	4.0	4.5	4.8	10.1 (0.29σ)
7	5.3	3.1	3.7	3.0	7.8 (0.29σ)

Wrap-up

- *Things we did well*
  - *modulation*
    - *sky rotation*
    - *scanning the telescope*
    - *RF modulation*
  - *drift scan (for removing ground)*
  - *clean optics (I->P, ground pickup)*
- *Things we could have imporved*
  - *absolute calibration*
  - *long term gain drifts*
  - *diffraction from ground shield*
- *Things to address for more sensitive measurements*
  - *Treat beam sizes individually, ellipticity, sidelobes*
  - *Better measurement of detetor angles*