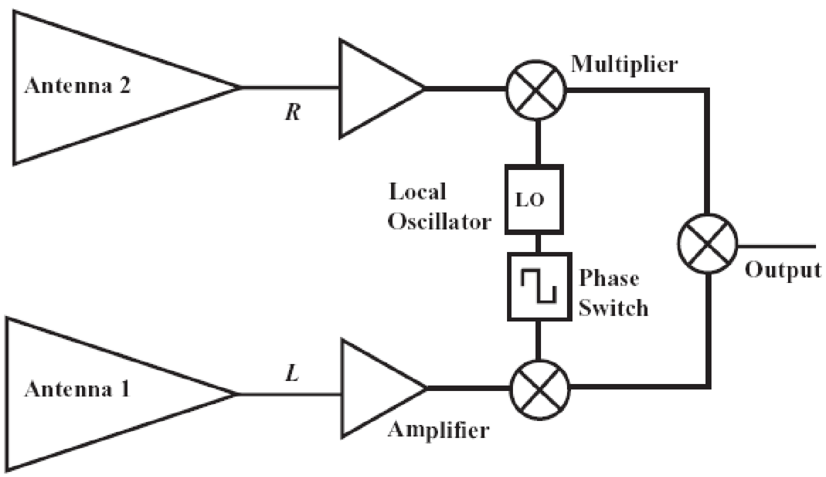
Multiplying Interferometers



L1 * L2 $\propto$ T + *i*V
R1 * R2 $\propto$ T - *i*V
L1 * R2 $\propto$ Q + *i*U
R1 * L2 $\propto$ Q - *i*U

Since each antenna can output both L and R polarization, all 4 Stokes parameters are *simultaneously measured* without noise penalty

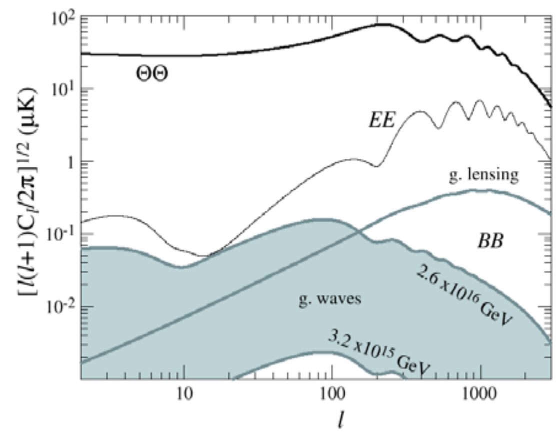
Correlate all possible baselines

Synthesize the equivalent aperture of the largest baseline

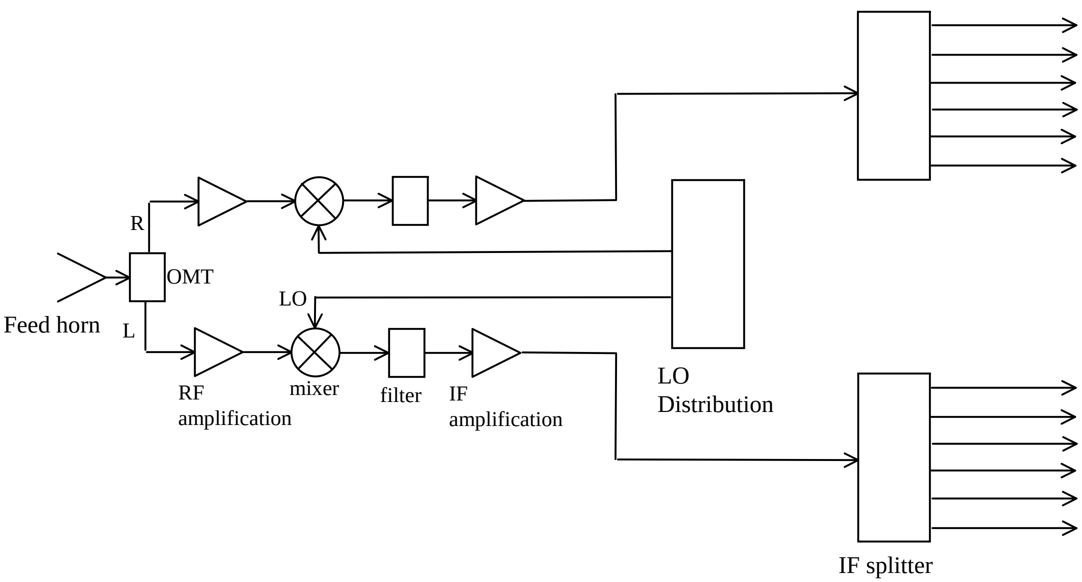
DASI interferometer
http://astro.uchicago.edu/cara/vtour/pole/darksector/cmbr/sunset.jpg

Interferometer compared to single dish measurements

- Single-dish receivers and interferometers have completely equivalent in sensitivity in ell-space, or map space, **if**
  - Total number of detectors and amplifiers are the same
  - Noise per detector and per amplifier are equal
  - Each single dish pixel measures *both* Q *and U* without noise penalty (true for amplifiers)
  - ***One exception***: an interferometer has a low-ell cut-off. Have to do "other things" to get low ells.



An interferometer measures *I*, *Q*, *U* and *V* simultaneously

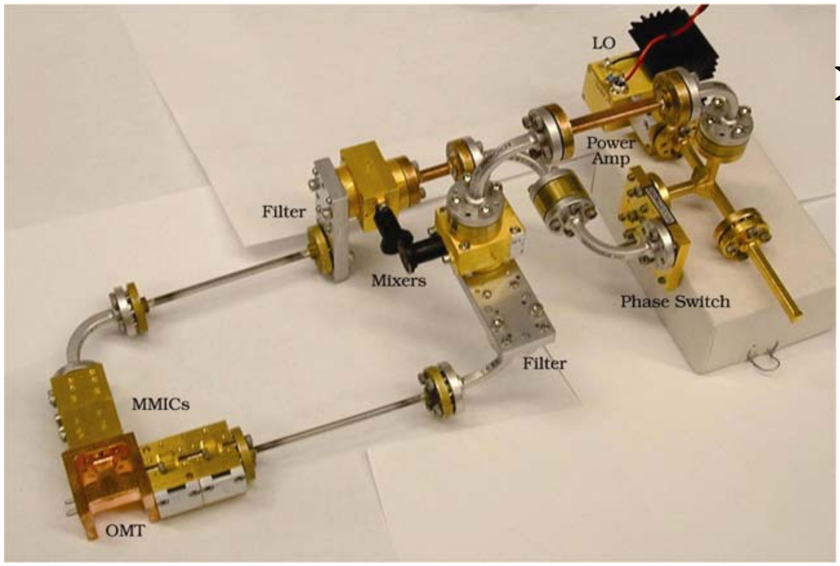


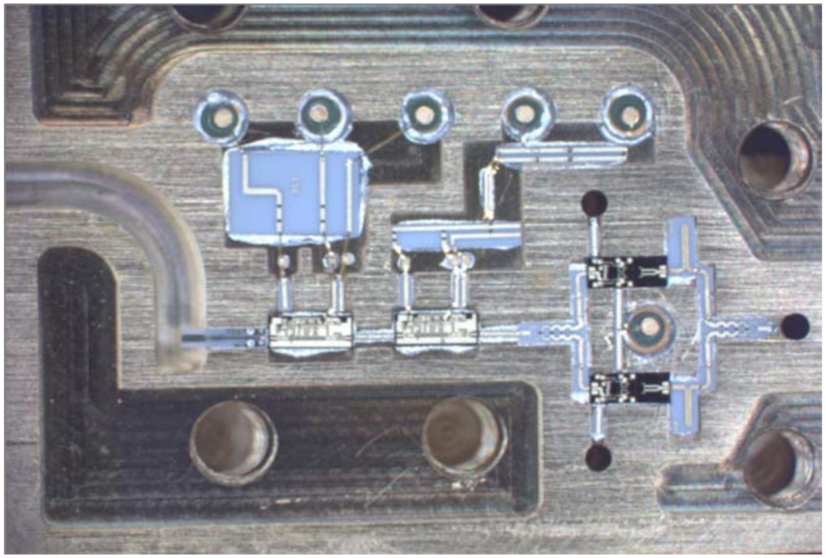
IF sub bands are digitized and cross-correlated with IF from second horn.

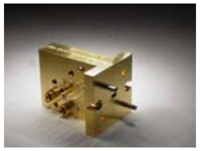
L1 * L2 $\propto$T + *i*V
R1 * R2 $\propto$T - *i*V
L1 * R2 $\propto$Q + *i*U
R1 * L2 $\propto$Q - *i*U

from which all 4 Stokes parameters can be recovered.

Heterodyne MMIC modules



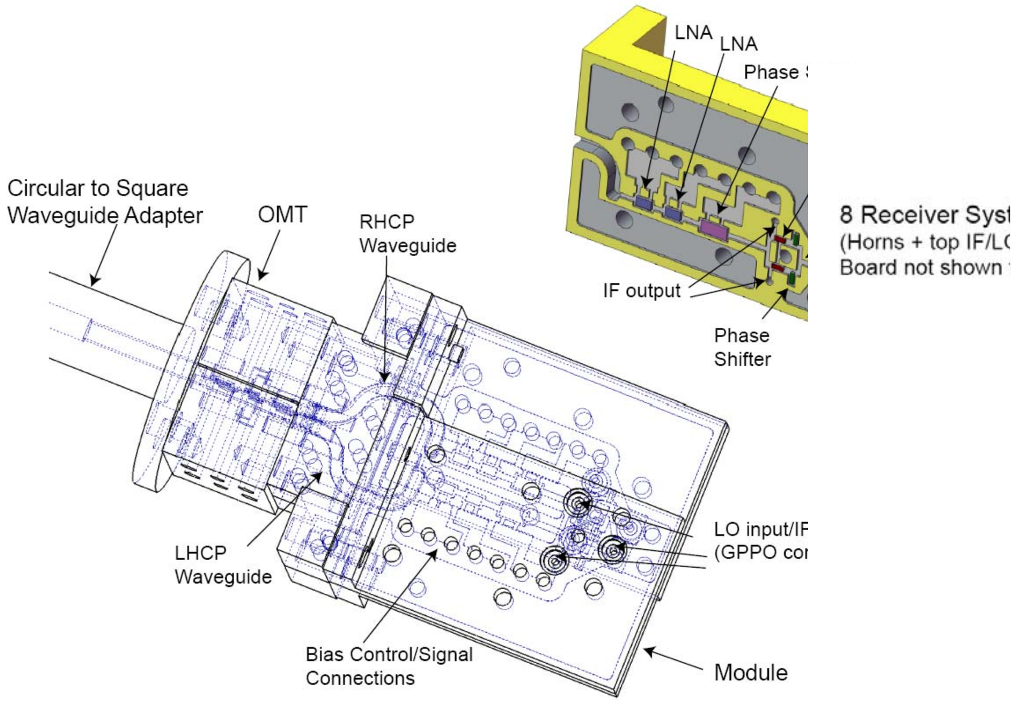


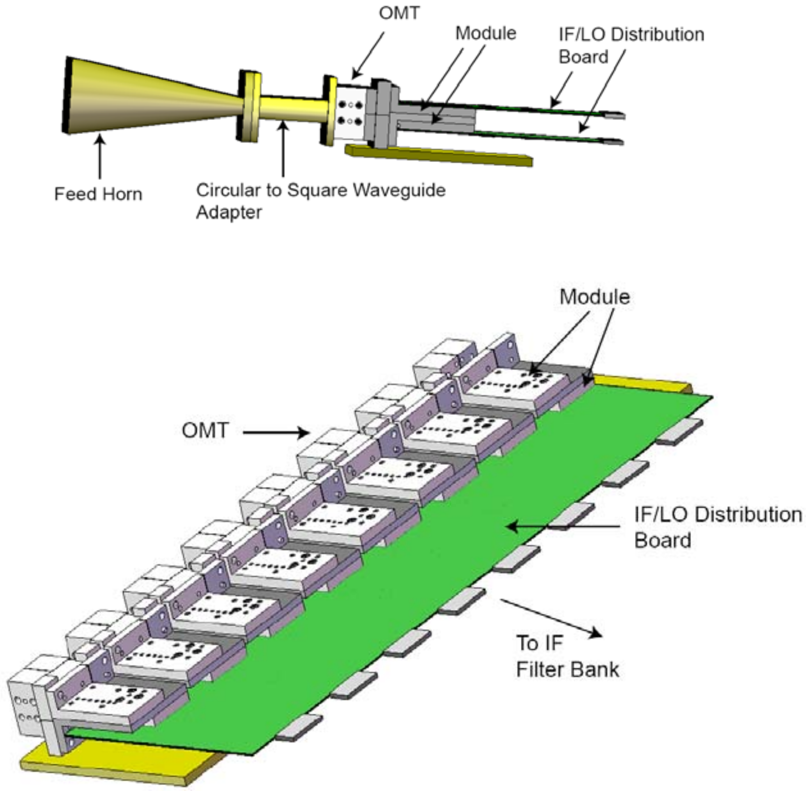


1.5 in

- Development of 90 GHz MMIC amplifier modules for a heterodyne spectrometer
- Only small modifications needed to make a module for an interferometer

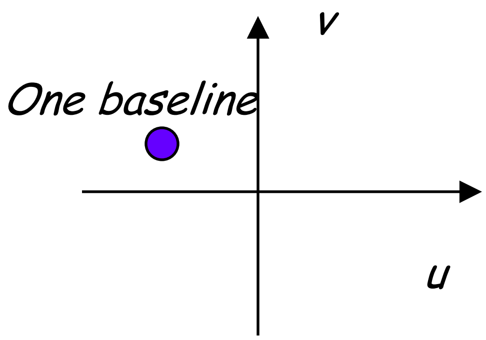
Prototype array for heterodyne modules

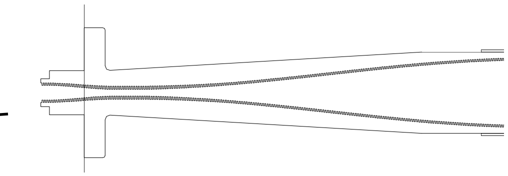




Why consider an interferometer for CMB polarization measurements? Systematics control is one argument

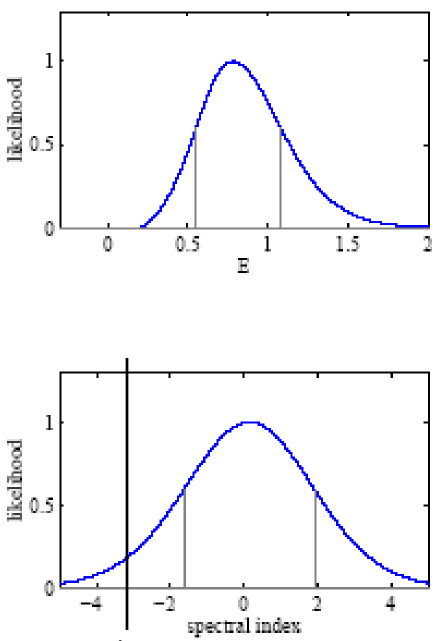
- Key for the next generation of experiments
- Interferometers have some advantages
  - Measurement is made in Fourier space; modeling the noise properties of the experiment is much more straightforward
  - I Q and U are measured simultaneously on same baseline
  - Large angular scales allow the use of corrugated feedhorns with very low spillover without the need for a telescope.
  - High resolution beams are synthesized – beam measurement errors reduced



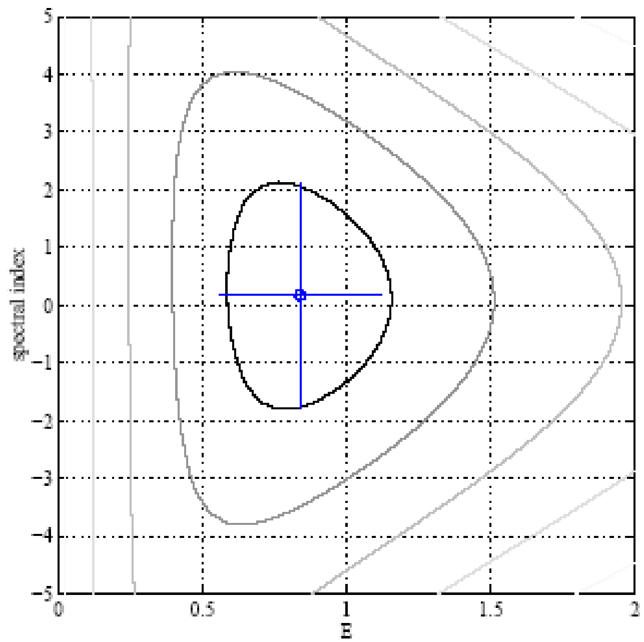


Why an interferometer? Foregrounds?

- Split IF into sub-bands to reduce chromatic aberration
- Retains additional spectral information each frequency band
- Useful for confirming that signal is CMB



Synchrotron



Spectral information helped to validate the DASI detection of polarization
Kovac et al. 2002

Systematics in an Interferometer

Systematic	Effect in: Bolometer	Effect in: Coherent Int.	Mitigation in Coherent Interferometer
Crosspolar beam	E to B	E to B	Corrugated feed horns have very low crosspolar response
Polarization angle errors	E to B	no leakage	Because each pixel images the entire primary beam, errors in polarization angle change u-v point the location but do not rotate E into B
Pointing errors (on Q/U)	E to B	N/A	Not present (Q, U from same feed)
Main beam asymmetry (before differencing)	ΔT to B	ΔT to B	Corrugated feed horns have highly symmetric beams
Sidelobes	ΔT to B	ΔT to B	Corrugated feed horns have very low sidelobes. Large scale structure in sidelobes is attenuated further by coherence length effects in the interferometric process.
Instrumental polarization (optics)	ΔT to B	ΔT to B	Corrugated feedhorns have very small effect. Measure.
Instrumental polarization (receiver)	ΔT to B	ΔT to B	Measure pre-launch.
Relative calibration errors	ΔT to B	no leakage	Feed to feed gives calibration error on amplitude of E and B. Calibrate.
Pointing errors before differencing	T to B	N/A	Absent. No differencing
Gain drift before differencing	T to B	N/A	Absent. No differencing
Optics and spillover T variations	$\delta T_{\rm opt}$ to B	$\delta T_{\rm opt}$ to B	Corrugated feeds have extremely low spillover. Attenuated by coherence length effects in interferometric process
Scan modulated cold stage variations	$\delta T_{\rm CS}$ to B	N/A	No effect in an interferometer
Band shape errors, including modulator effects	Foregrounds to B	Foregrounds to B	Band shape can be flattened in data analysis (sub bands)
Primary Beam Uncertainty	Tilts power spectrum by affecting window function at large ℓ	Fourier space measurement with identical window functions at all ℓ. Just affects overall calibration of spectrum	

The old showstopper…

- Multiplying interferometers require
  $N(N-1)/2$ times a prefactor O(10–100)
  correlations to recover all possible information

- Power, mass, size were all impossible for space

Low Power Correlator Development (Ruf)

Current Technology

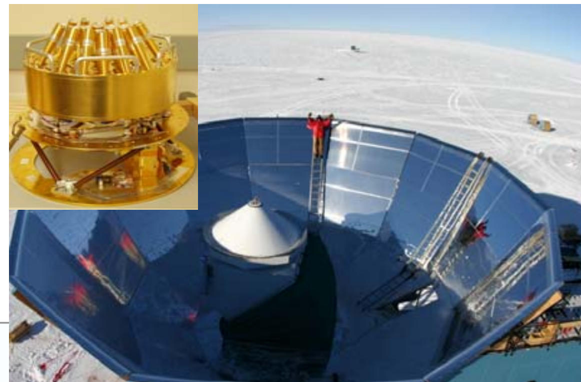
ASIC 25 channel complex correlator
Real time DSP @ 2960 GigaInstructions/sec
Input bandwidth: 11 Gigabytes/sec
DC Power required: 1500 mW
(U-Idaho/CAMBR manufactured)

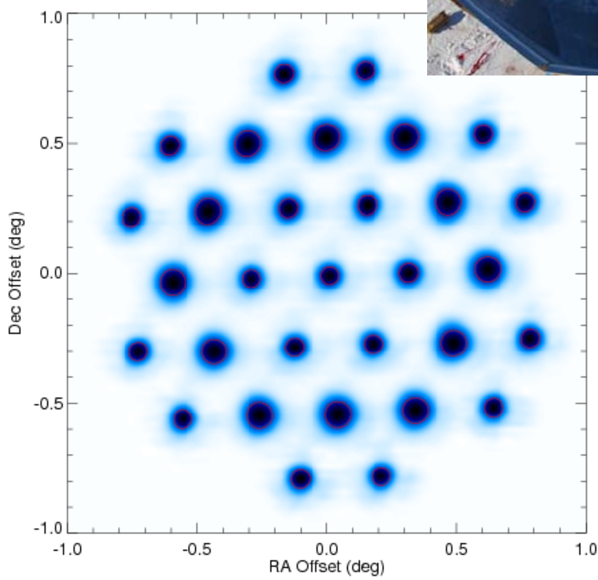
- Development in progress for GEOSTAR
  - 90nm CMOS process ASICS
  - 196 channels, all correlations
  - 1.4 MHz clock speed = 400 MHz bandwidth
  - 1.7 W
- For a CMB interferometer

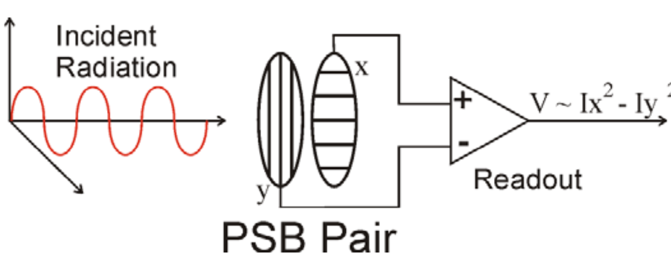
$$\underbrace{P = 98 \left(\frac{N_{\rm el}}{196}\right)^2 \left(\frac{\Delta\nu}{19.8\,\mathrm{GHz}}\right)}_{\text{Correlator}} + \underbrace{40 \left(\frac{N_{\rm el}}{196}\right) \left(\frac{\Delta\nu}{19.8\,\mathrm{GHz}}\right)}_{\text{Digitizer}} \mathrm{W}.$$

Correlator power is no longer a showstopper. Development of ASICs is proceeding rapidly (Moore's law rate), driven by wireless communications.

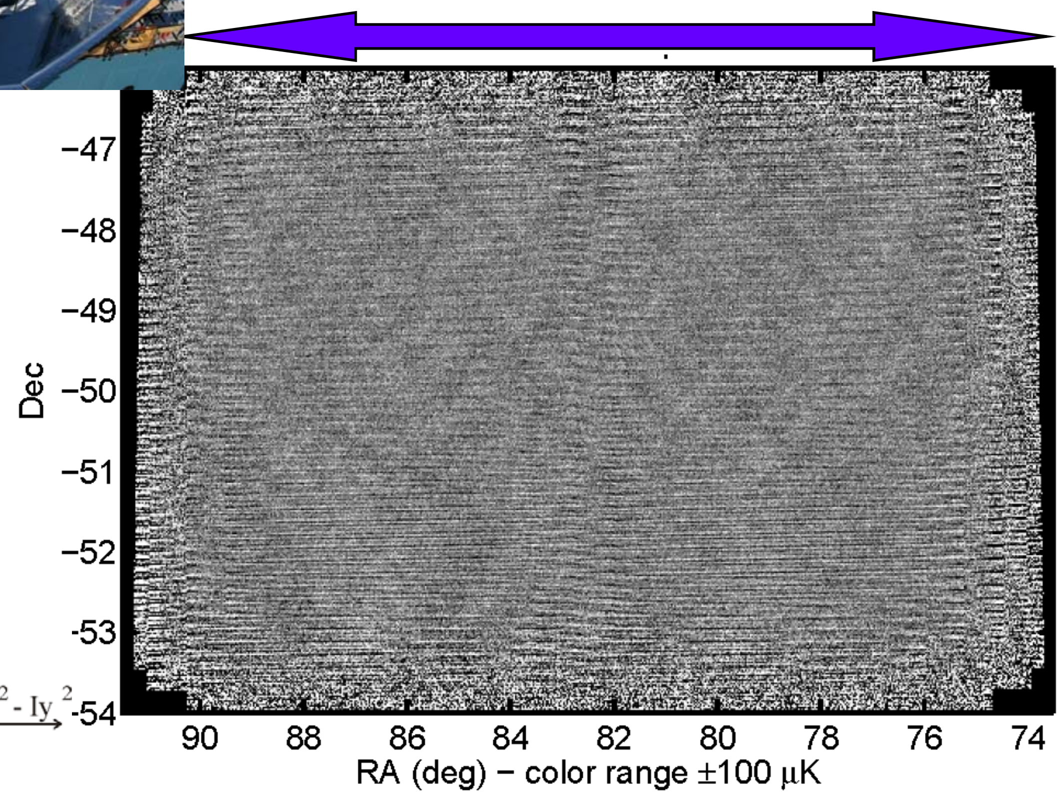
Compare to QUaD's method of measuring the CMB power spectrum







Scan backwards and forwards in azimuth

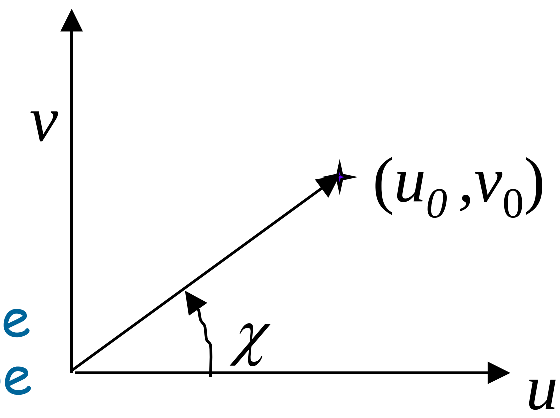


Half the QUaD detectors map Q, half U

- Recover *E* and *B* modes from Fourier plane

$$E = Q\cos 2\chi + U\sin 2\chi$$

$$B = -Q\sin 2\chi + U\cos 2\chi$$



- Trench removes 1/f noise from atmosphere and detectors and ground pickup (telescope sidelobes)