Detector Modeling and CMB Polarimetry Technology Development at GSFC

David T. Chuss, Edward J. Wollack, S. Harvey Moseley
NASA Goddard Space Flight Center

Stafford Withington, George Saklatvala
University of Cambridge

Introduction

- Planar detector modeling
  - Goal: To investigate the consequences of using planar bolometers in the limit in which pixel size is comparable to wavelength
  - We use the k-domain dyadic (Withington et al. 2003) to propagate the second-order statistical correlations of radiation through a model optical system
  - Model is general and preliminary, but it is unlikely more realistic bolometers will be better.
- CMB Polarization technology efforts
  - Modulators
  - Antenna-coupled detectors

Single-Mode

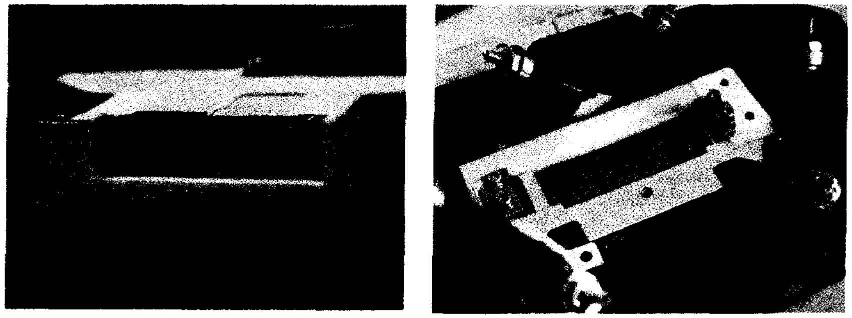
- Horn-coupled detectors
- Coherent across horn aperture
- Diffraction-limited resolution of optical system is dependent upon horn illumination of primary

Multi-Mode

- Geometric Limit
- Incoherent across imaging element
- Diffraction-limited resolution normally determined by size of the primary

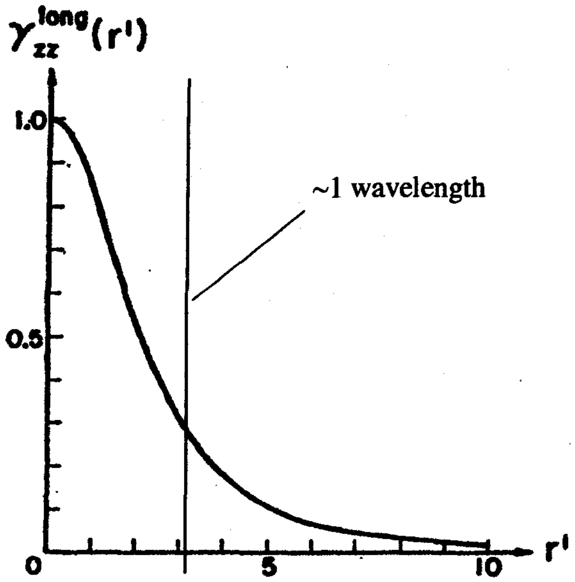
This work explores the intermediate case-Incoherent techniques in the limit where the Geometric limit is not strictly valid (few-mode Limit)

Bolometer Arrays

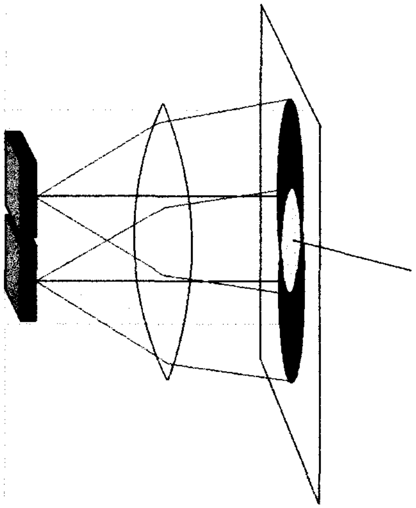


Selected Filled Focal Planes

Instrument	Array Size	Detector Type	λ(mm)	Pixel pitch (mm)	p/λ
HAWC/SOFIA	12×32	Semiconducting Bolometer	0.053	1.00	18.87
	12×32	Semiconducting Bolometer	0.088	1.00	11.36
	12×32	Semiconducting Bolometer	0.155	1.00	6.45
	12×32	Semiconducting Bolometer	0.215	1.00	4.65
SHARC II	12×32	Semiconducting Bolometer	0.350	1.00	2.86
	12×32	Semiconducting Bolometer	0.450	1.00	2.22
	12×32	Semiconducting Bolometer	0.850	1.00	1.18
SCUBA 2	64×64	TES	0.450	1.135	2.52
	32×32	TES	0.850	1.135	1.34
GBT	8×8	TES	3.00	3.00	1.00
GISMO	8×16	TES	2.00	2.00	1.00
ACT	32×32	TES	1.13	1.00	0.88
	32×32	TES	1.33	1.00	0.75
	32×32	TES	2.07	1.00	0.48



Beam Overlap



Space-Domain Dyadic

$$\boxed{\bar{\bar{E}}(\bar{r}_1,\bar{r}_2) = \left\langle \bar{E}(\bar{r}_2)\bar{E}^*(\bar{r}_1)\right\rangle}$$

K-domain Dyadic

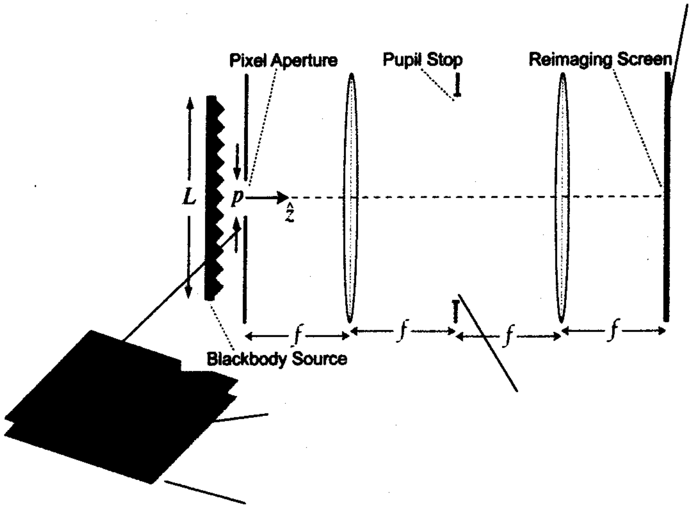
$$\overline{\overline{A}}(\overline{k}'_t, \overline{k}_t) = \frac{1}{(2\pi)^2} \int \int \overline{\overline{E}}(\overline{r}_1, \overline{r}_2) e^{-j\overline{k}_t \cdot \overline{r}_{t2}} e^{j\overline{k}'_t \cdot \overline{r}_{t1}} e^{-jk_z z_2} e^{jk'_z z_1} d^2\overline{r}_{t1} d^2\overline{r}_{t2}$$

$$\overline{\overline{E}}(\overline{r}_1, \overline{r}_2) = \frac{1}{(2\pi)^2} \int \int \overline{\overline{A}}(\overline{k}'_t, \overline{k}_t) e^{j\overline{k}_t \cdot \overline{r}_{t2}} e^{-j\overline{k}'_t \cdot \overline{r}_{t1}} e^{jk_z z_2} e^{-jk'_z z_1} d^2\overline{k}_t d^2\overline{k}'_t$$

Stokes Parameters

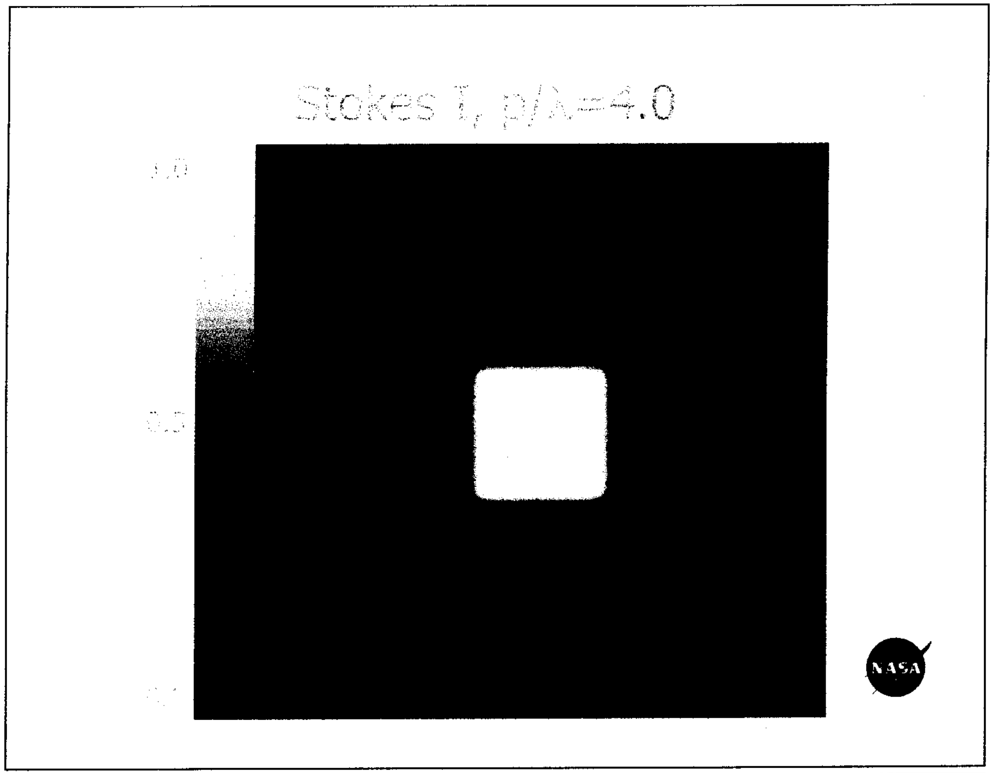
$$\begin{aligned} I &= E_{xx}(\bar{r}, \bar{r}) + E_{yy}(\bar{r}, \bar{r}) \\ Q &= E_{xx}(\bar{r}, \bar{r}) + E_{yy}(\bar{r}, \bar{r}) \\ U &= \Re E_{xy}(\bar{r}, \bar{r}) \\ V &= \Im E_{xy}(\bar{r}, \bar{r}). \end{aligned}$$

Withington et al. 2003 Bolometer Modeling Method

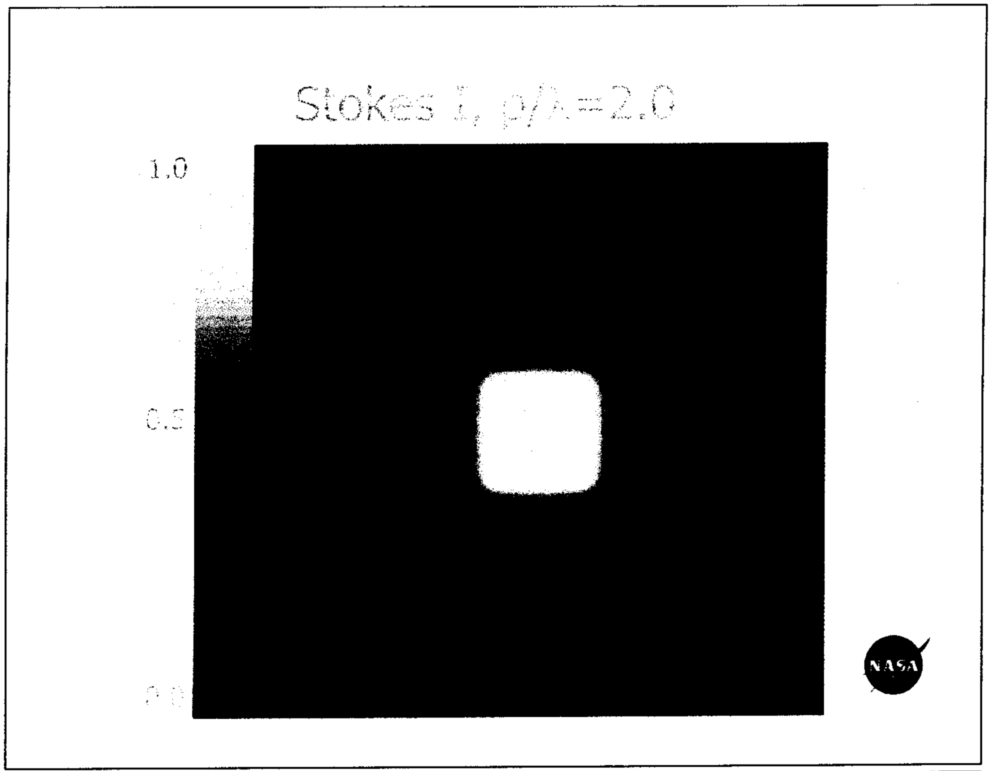


Technique

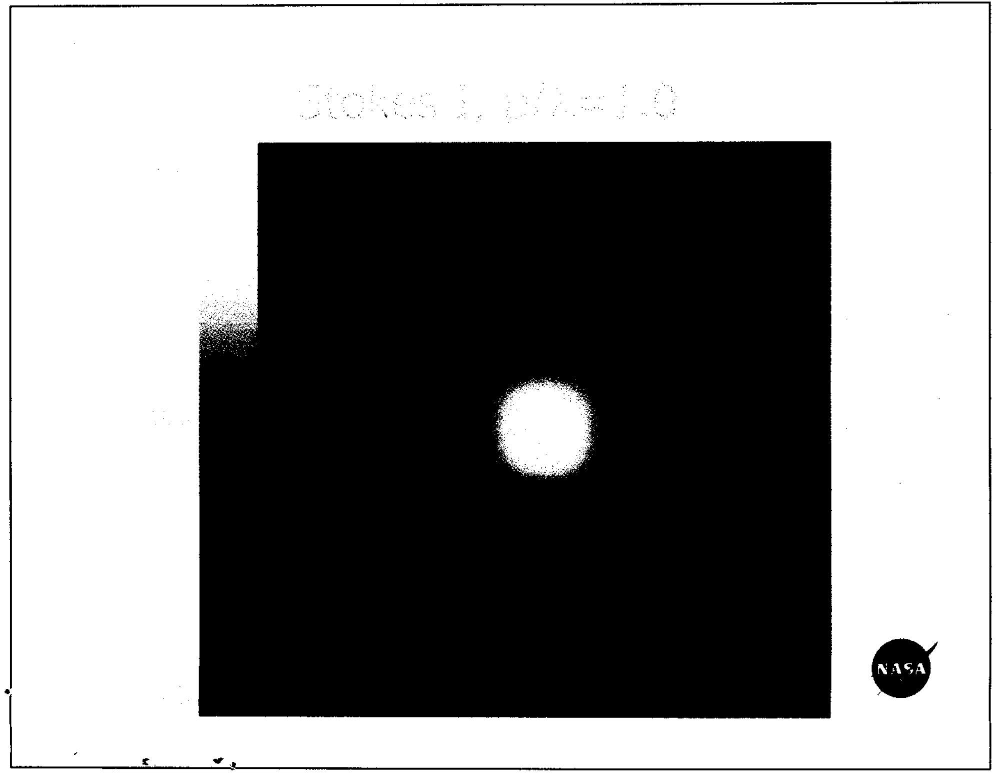
- Develop space domain correlation dyadic for blackbody radiation using plane wave expansion
- Transform to k-domain and scatter through aperture(pixel)
- Limit number of modes (pupil)
- Reconstruct the 2-D space domain correlation dyadic
- Construct the real Stokes parameters from the complex space domain correlation dyadic



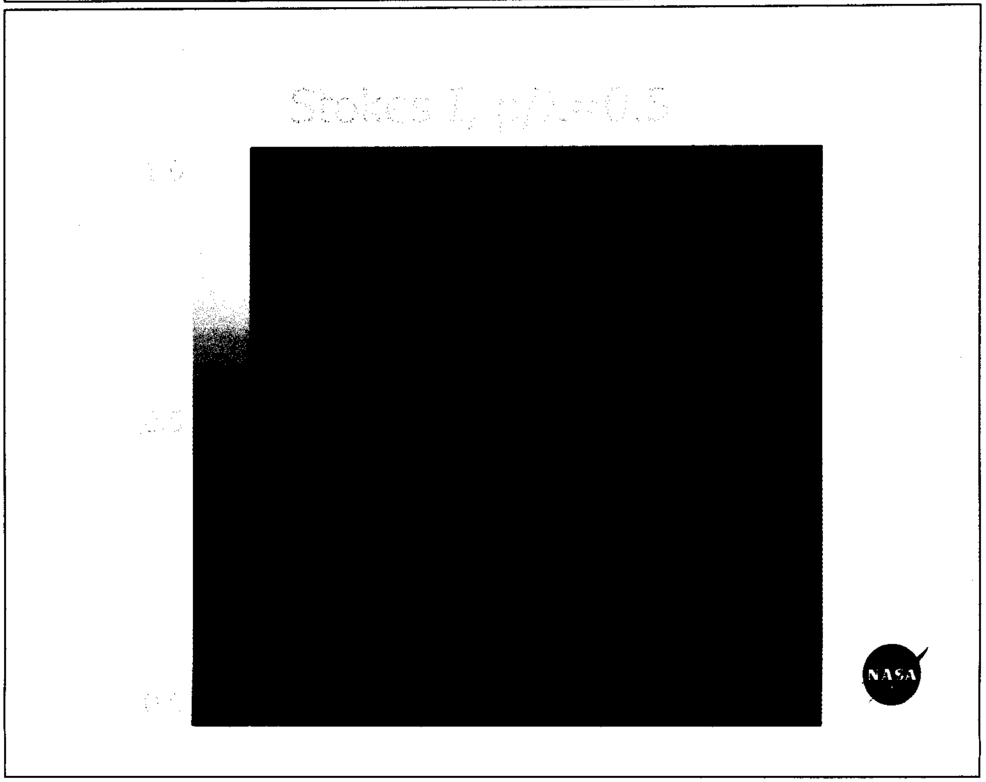
Stokes I, p/λ=4.0



Stokes I, p/λ=2.0

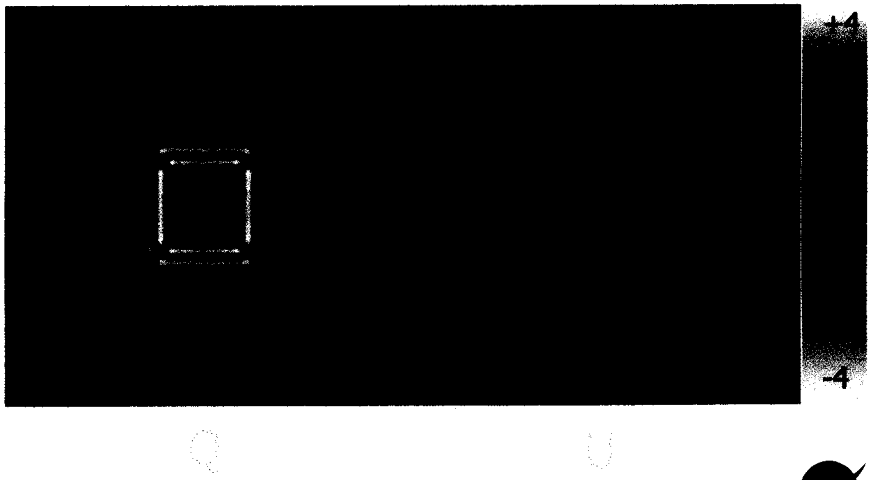


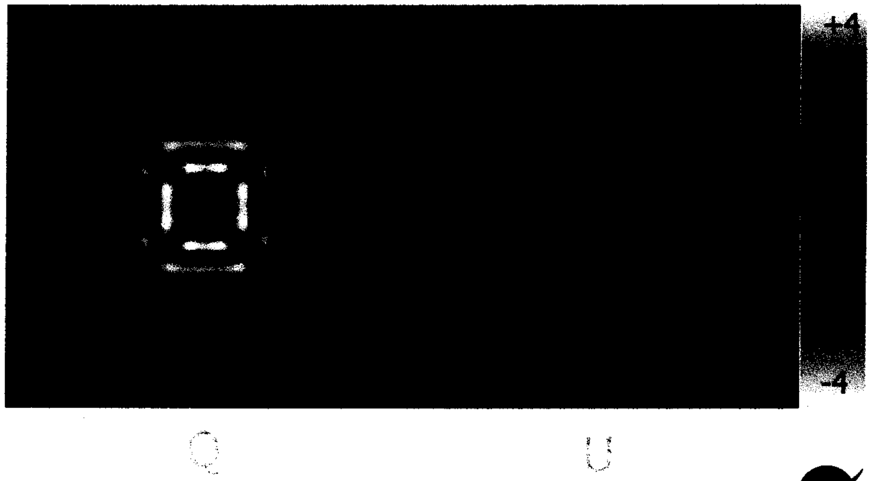
Stokes I, p/λ=1.0

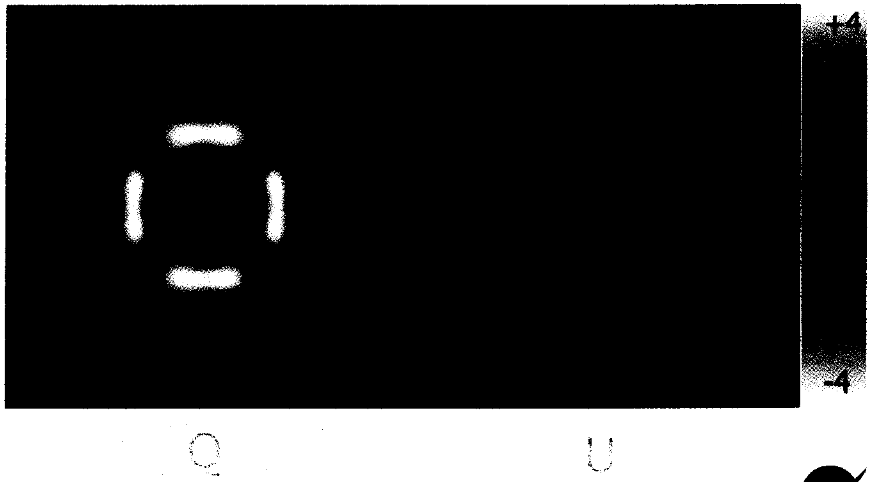


Stokes I, p/λ=0.5

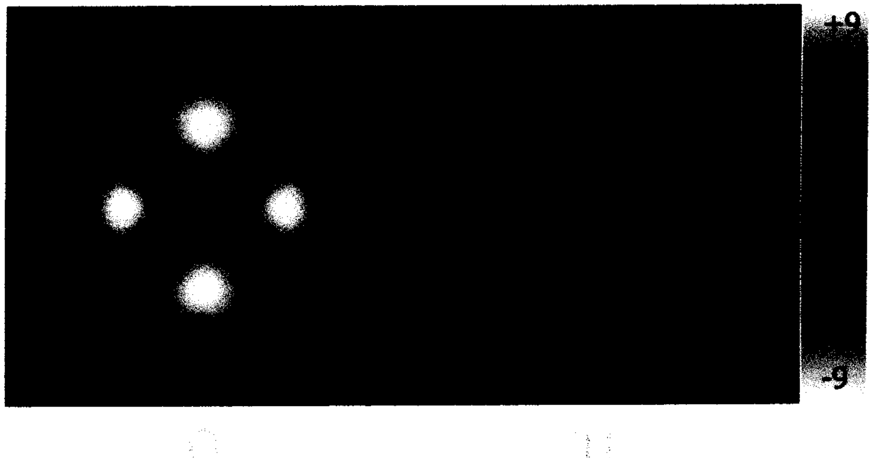

Stokes I, p/λ=0.25


P/λ=4

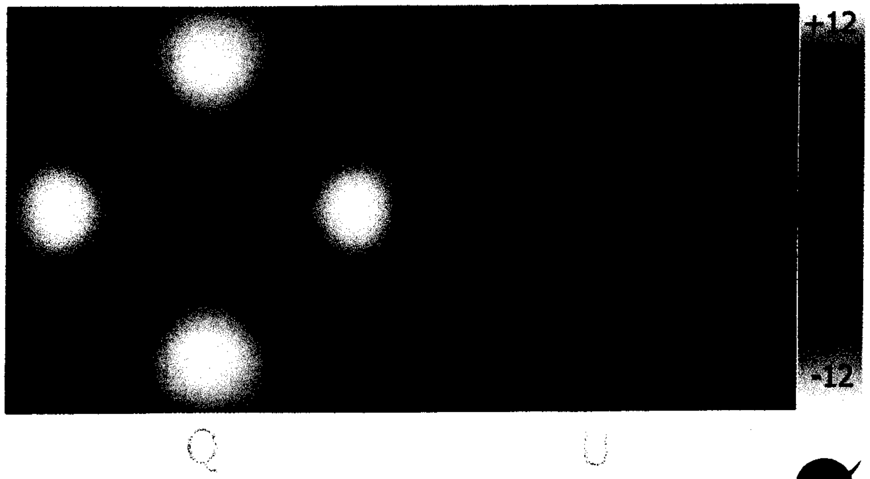

P/λ=2


P/λ=1

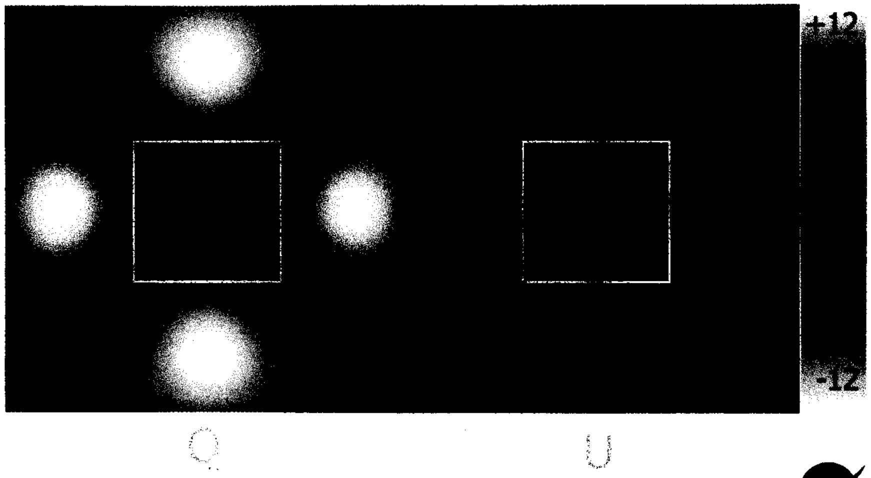
P/λ=0.5



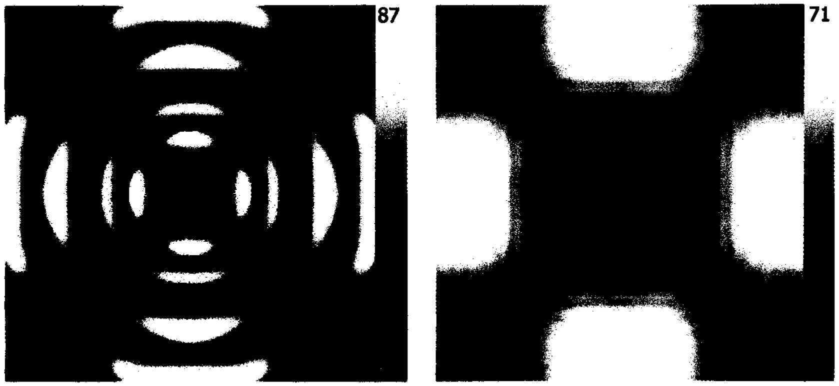
P/λ=0.25



P/λ=0.25



Polarization



0.01	0.08	0.01
0.08	1.00	0.08
0.01	0.08	0.01

$p/\lambda = 4.00$

0.02	0.13	0.02
0.13	1.00	0.13
0.02	0.13	0.02

$p/\lambda = 2.00$

0.07	0.25	0.07
0.25	1.00	0.25
0.07	0.25	0.07

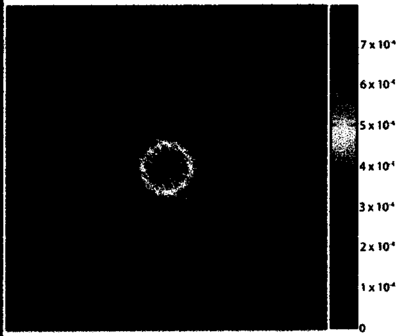
$p/\lambda = 1.00$

0.02	0.04	0.07	0.04	0.02
0.04	0.24	0.45	0.24	0.04
0.07	0.45	1.00	0.45	0.07
0.04	0.24	0.45	0.24	0.04
0.02	0.04	0.07	0.04	0.02

$p/\lambda = 0.50$

0.01	0.02	0.04	0.06	0.06	0.06	0.04	0.02	0.01
0.02	0.05	0.10	0.15	0.18	0.15	0.10	0.05	0.02
0.04	0.10	0.22	0.38	0.46	0.38	0.22	0.10	0.04
0.06	0.15	0.38	0.67	0.82	0.67	0.38	0.15	0.06
0.06	0.18	0.46	0.82	1.00	0.82	0.46	0.18	0.06
0.06	0.15	0.38	0.67	0.82	0.67	0.38	0.15	0.06
0.04	0.10	0.22	0.38	0.46	0.38	0.22	0.10	0.04
0.02	0.05	0.10	0.15	0.18	0.15	0.10	0.05	0.02
0.01	0.02	0.04	0.06	0.06	0.06	0.04	0.02	0.01

$p/\lambda = 0.25$



$$\beta(\Delta x, \Delta y) = \int \rho(x, y, \Delta x, \Delta y)dx\,dy$$

$$\Gamma = \int [I(x', y')]^2 dx'\,dy'$$

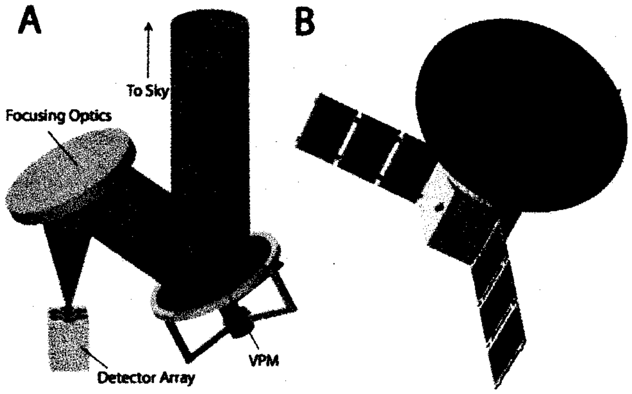
$$\rho(x, y, \Delta x, \Delta y) = \frac{1}{\Gamma} I(x, y) I(x + \Delta x, y + \Delta y)$$

Summary

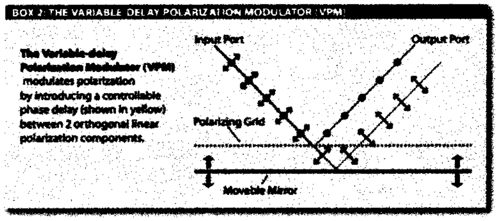
- Pixel size limits the resolution in the focal plane. This should be accounted for in optical design. Alternatively, this reduces the effective number of independent detectors.
- Polarization and scattering are intrinsically related, and both are more severe at low p/lambda.
- Future work: Quantification of the pixel cross-coupling- calculate a theoretical covariance matrix to predict performance of future detector arrays.

GSFC CMBPol Detector Effort

Harvey Moseley, Ed Wollack, Dave Chuss,
Gary Hinshaw, Al Kogut, Chuck Bennett (JHU)

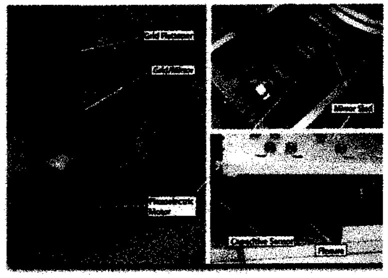


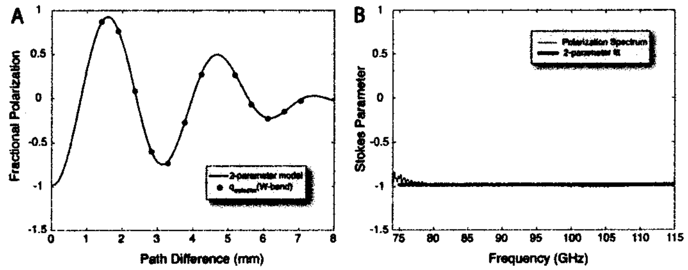
Modulators



BOX 2: THE VARIABLE DELAY POLARIZATION MODULATOR (VPM)

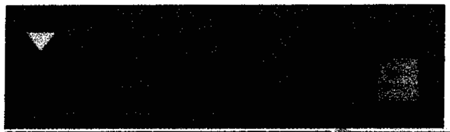
The Variable-delay Polarization Modulator (VPM) modulates polarization by introducing a controllable phase delay (shown in yellow) between 2 orthogonal linear polarization components.

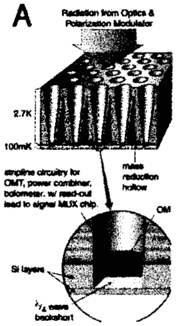


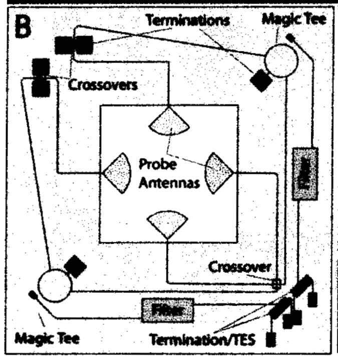


Laboratory Tests at 90 GHz

Detectors




A
Radiation from Optics & Polarization Modulator
2.7K
100mK
stripline circuitry for OMT, power combiner, bolometer. w/ read-out lead to signal MUX chip.
mass reduction hollow
OM
Si layers
$\lambda/4$ wave backshort


B
Terminations
Magic Tee
Crossovers
Probe Antennas
Crossover
Filter
Magic Tee
Termination/TES