Variable-Delay Polarization Modulator (VPM)

Measure linear and circular polarization
VPM Mitigates Cross-Polar Beam Mixing

Problem: Sky is bright in Q and U
Any other QU mixing (e.g. cross-pol) can then project bright [QU] foregrounds into false B-mode signal

Solution: Modulate Q↔V instead!
No celestial signal in V, so Q↔V mixing simply reduces amplitude of detected Q modulation.
Efficiency, not systematic error!
Polarization Modulator

- 36 μm diam wire
- 110 μm pitch
- 40 cm clear aperture

1.4 km of wire held to 5 μm tolerance
Cross-Polar Beam Systematics

Wave Plate: 
Q/U mixing 
plus 
Q/U modulation
Cross-Polar Beam Systematics

Wave Plate:
Q/U mixing
plus
Q/U modulation

Q
U

True Sky

X Position (Deg)
-1.0 -0.5 0.0 0.5
-10 10

X Position (Deg)
-1.0 -0.5 0.0 0.5 1.0
-10 10

After HWP Modulation
Cross-Polar Beam Systematics

Wave Plate: Q/U mixing plus Q/U modulation

True Sky

X Position (Deg)

-1.0 -0.5 0.0 0.5 1.0

-10 10

After HWP Modulation

Raw Signal (μK)

Error Signal (μK)

Detector Sample

-0.3 -0.2 -0.1 0.0 0.1 0.2 0.3

-32.5 -32.0 -31.5 -31.0 -30.5 -30.0 -29.5 -29.0

-10 10
Cross-Polar Beam Systematics

Wave Plate:
Q/U mixing
plus
Q/U modulation

True Sky

Q

U

X Position (Deg)

-1.0 -0.5 0.0 0.5 1.0

-10 10

-10 10

After HWP Modulation

Raw Signal ($\mu$K)

HWP

Detector Sample

Error Signal ($\mu$K)

0 50 100 150 200 250

0.1

-0.1

-0.2

-0.3
Cross-Polar Beam Systematics

Wave Plate: Q/U mixing plus Q/U modulation

true sky

Q

U

X Position (Deg)

-1.0 -0.5 0.0 0.5

Y Position (Deg)

-1.0 -0.5 0.0 0.5 1.0

-10 10

-10 10

After HWP Modulation

Raw Signal (μK)

Error Signal (μK)

Detector Sample
Cross-Polar Beam Systematics

Wave Plate:
Q/U mixing
plus
Q/U modulation

![Images of Q and U with contour lines and color scale]

-1.0 -0.5 0.0 0.5 1.0
X Position (Deg)

-10 0 10
Q/U mixing

After HWP Modulation
Cross-Polar Beam Systematics

Wave Plate: 
Q/U mixing  
plus 
Q/U modulation

![Images of Q and U polarization with X Position (Deg) and True Sky](image)

After HWP Modulation

![Graph showing Raw and Error Signal](image)
Cross-Polar Beam Systematics

Wave Plate:
Q/U mixing plus
Q/U modulation

True Sky

After HWP Modulation
Cross-Polar Beam Systematics

Wave Plate:
Q/U mixing
plus
Q/U modulation

Q

U

True Sky

Wave Plate Modulation

HWP

Raw Signal ($\mu$K)

Error Signal ($\mu$K)

Detector Sample
Cross-Polar Beam Systematics

Wave Plate: Q/U mixing plus Q/U modulation
Cross-Polar Beam Systematics

Wave Plate:
Q/U mixing
plus
Q/U modulation

After HWP Modulation

True Sky

X Position (Deg)

-1.0 -0.5 0.0 0.5
-1.0 -0.5 0.0 0.5 1.0

-10 10
-10 10

Raw Signal ($\mu$K)

Error Signal ($\mu$K)

Detector Sample

-0.3 -0.2 -0.1 0.0
0.1 0.2 0.3
Cross-Polar Beam Systematics

QPM:
Q/U mixing
but
Q/V modulation

After VPM Modulation

VPM

Raw Signal ($\mu$K)

Error Signal ($\mu$K)

Detector Sample
Cross-Polar Beam Systematics

VPM:
Q/U mixing
but
Q/V modulation

Q
U

True Sky

After VPM Modulation
Cross-Polar Beam Systematics

Q

U

True Sky

VPM:
Q/U mixing
but
Q/V modulation

Raw Signal (μK)

Error Signal (μK)

Detector Sample
Cross-Polar Beam Systematics

True Sky

After VPM Modulation
Cross-Polar Beam Systematics

VPM:
Q/U mixing
but
Q/V modulation

After VPM Modulation
Cross-Polar Beam Systematics

VPM:
Q/U mixing but
Q/V modulation

After VPM Modulation
Cross-Polar Beam Systematics

VPM:
Q/U mixing but
Q/V modulation

After VPM Modulation
Cross-Polar Beam Systematics

VPM:
Q/U mixing
but
Q/V modulation
Cross-Polar Beam Systematics

VPM:
Q/U mixing but
Q/V modulation

After VPM Modulation
Cross-Polar Beam Systematics

VPM:
Q/U mixing
but
Q/V modulation
Cross-Polar Beam Systematics

VPM:
Q/U mixing but
Q/V modulation

After VPM Modulation
VPM Advantages

Minimizes a whole range of systematic errors
• $Q \leftrightarrow V$ modulation distinct from $Q \leftrightarrow U$ ($E \leftrightarrow B$) mixing
• Take advantage of $V=0$ for sky

Decouples polarization from scan strategy
• Diagonal pixel covariance matrix
• No degradation at large angular separations/low $\ell$

Simple cryogenic implementation
• Small linear translation instead of large angular rotation
• Simple cooling path to grating and mirror
• Vary mirror sweep to vary $Q/V$ sampling
• Non-ideal effects are computable from first principles

Plus: Get full-sky map of Stokes $V$

Four orders-of-magnitude improvement!

Yow! Fun With Circular Polarization
VPM Stroke vs Efficiency

Full-sky maps in Q, U, and V
- Clean test for systematics
- Limit non-standard physics