Polarization Modulator

B Mode From Space
December 14, 2015

Akito Kusaka
Lawrence Berkeley National Laboratory

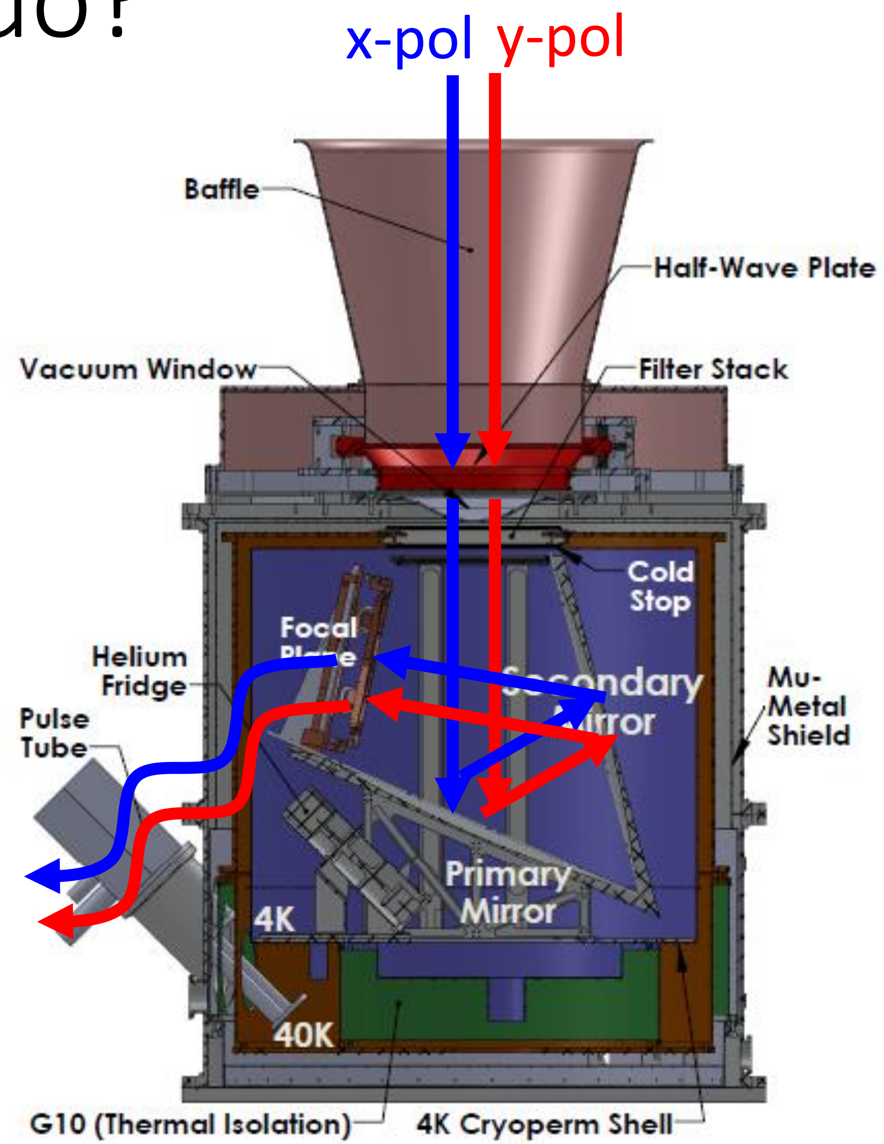
- What modulators do? (Why do we need it, or not?)
- Review of modulators for CMB polarization
- Requirements for next generation instruments?
- What modulators do not do? Systematics Residuals?

What modulators do?

- “Systematics Rejection”
- Those of statistical nature: correlated noise
  - Correlated: low frequency and/or among detectors
  - (Atmosphere)
  - Cryo temperatures: focal plane, mirrors, filters, baffles
  - Readout electronics: DAC, SQUID, ADC, amplifier, …
  - Cosmic ray hits
- Those of systematic nature: beam
  - Main beam systematics, T→P leakage
  - Readout and optical cross talk
  - Sidelobe response

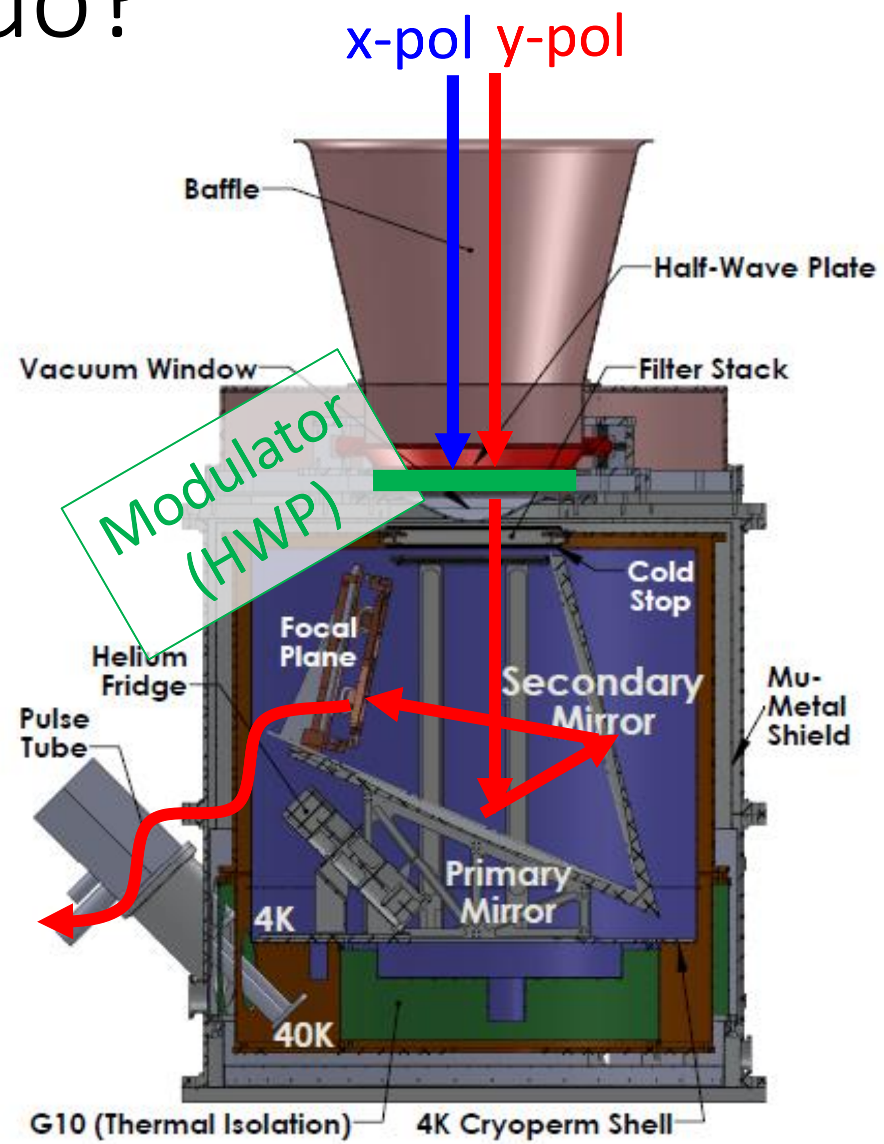
What modulators do?

- Without a modulator
  - Differencing of x vs. y
  - Explicitly or implicitly
- Differences in
  - Optical path
  - Detector
  - Readout electronics (noise, cross-talk)
- Leading to
  - Differential response to T
  - Residual noise (1/f noise)



What modulators do?

- Common path for x vs. y
  - Modulator: first element
  - Common path: optics, detector, readout
  - “Nulling” of systematics (stat. and syst.)
  - “Identical beams” (Eric Hivon’s talk)
- Asymmetric subtraction
  - Modulator can create differential response and differential noise.
- My view: a modulator does more good than bad!



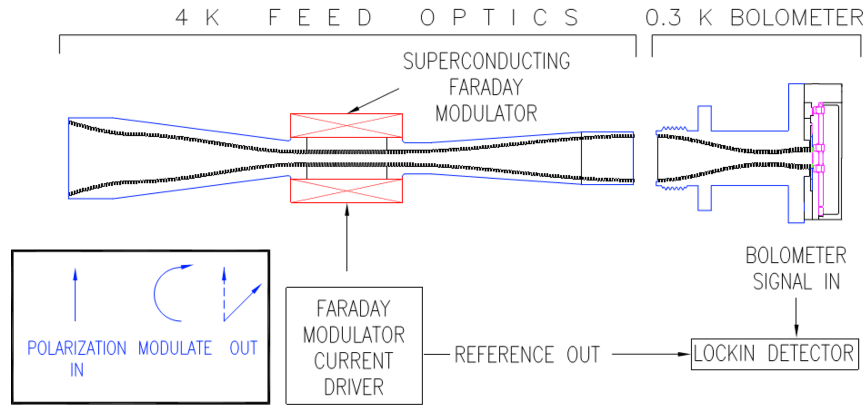
“Fast” Polarization Modulators for CMB

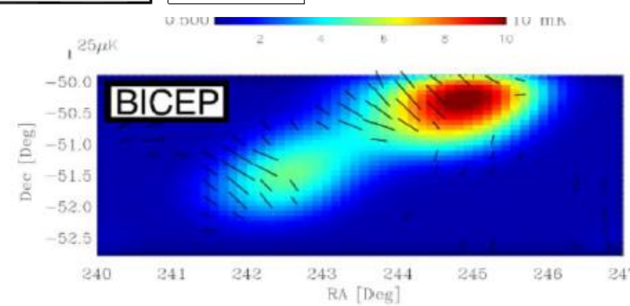
- Fast: $f_{\mathrm{mod}} > v_{\mathrm{scan}}/\theta_{\mathrm{beam}}$
- Modulation of each pixel
  - Phase switches: WMAP, CAPMAP, QUIET, DASI, CBI, …
  - Faraday Rotation Modulator: BICEP1
- Modulation of the entire focal plane
  - HWP: MAXIPOL, EBEX, ABS, POLARBEAR1, ACTPol, NIKA
  - Variable-delay Polarization Modulator: PIPER, CLASS
  - Fourier Transform Spectrometer: PIXIE

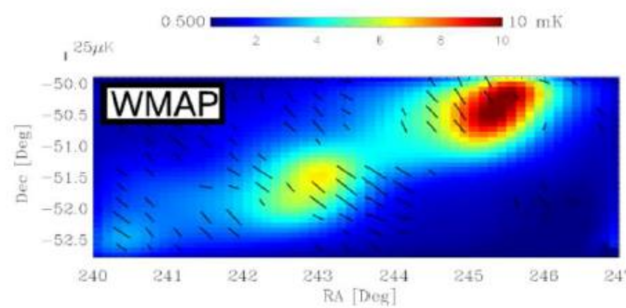
Contribution from B. Keating

BICEP
Faraday Rotation Modulator

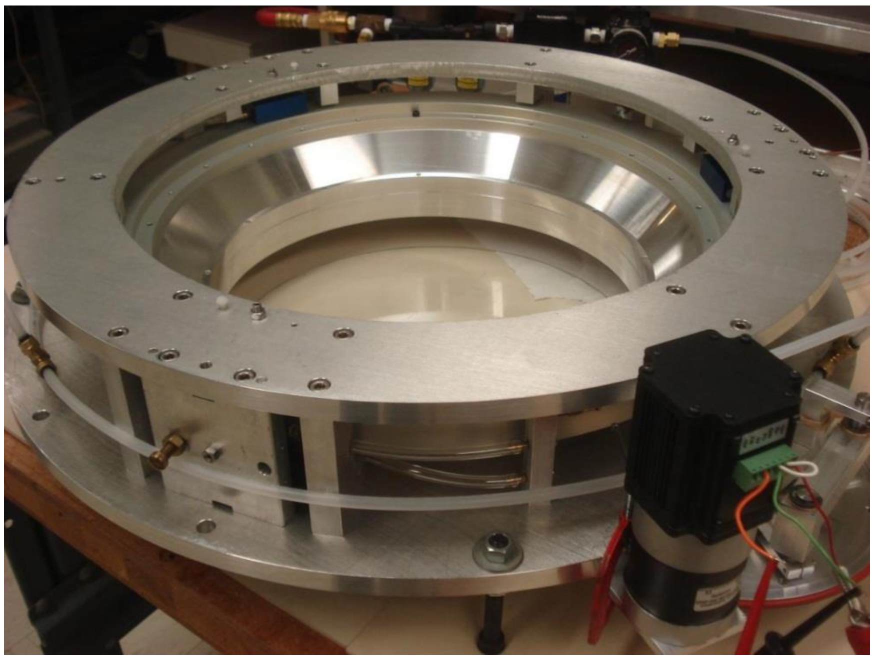
- Modulator at 4K
- No moving component.
- Individual pixel modulation
- Successfully demonstrated on BICEP1, @100 and 150GHz.

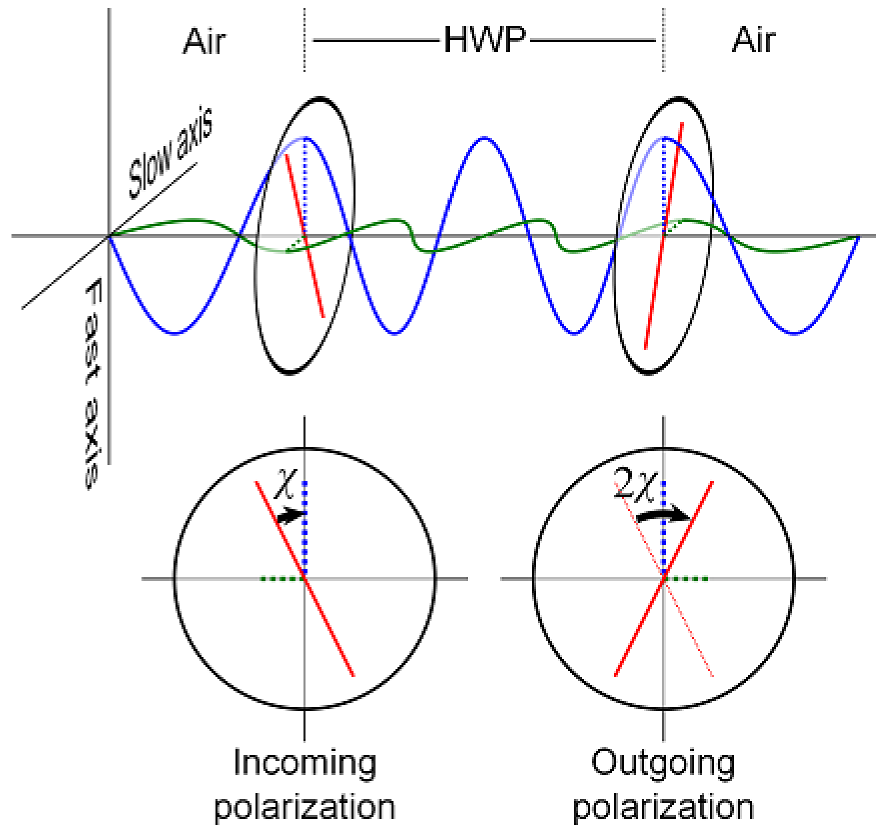






ABS: Continuously rotating warm half-wave plate

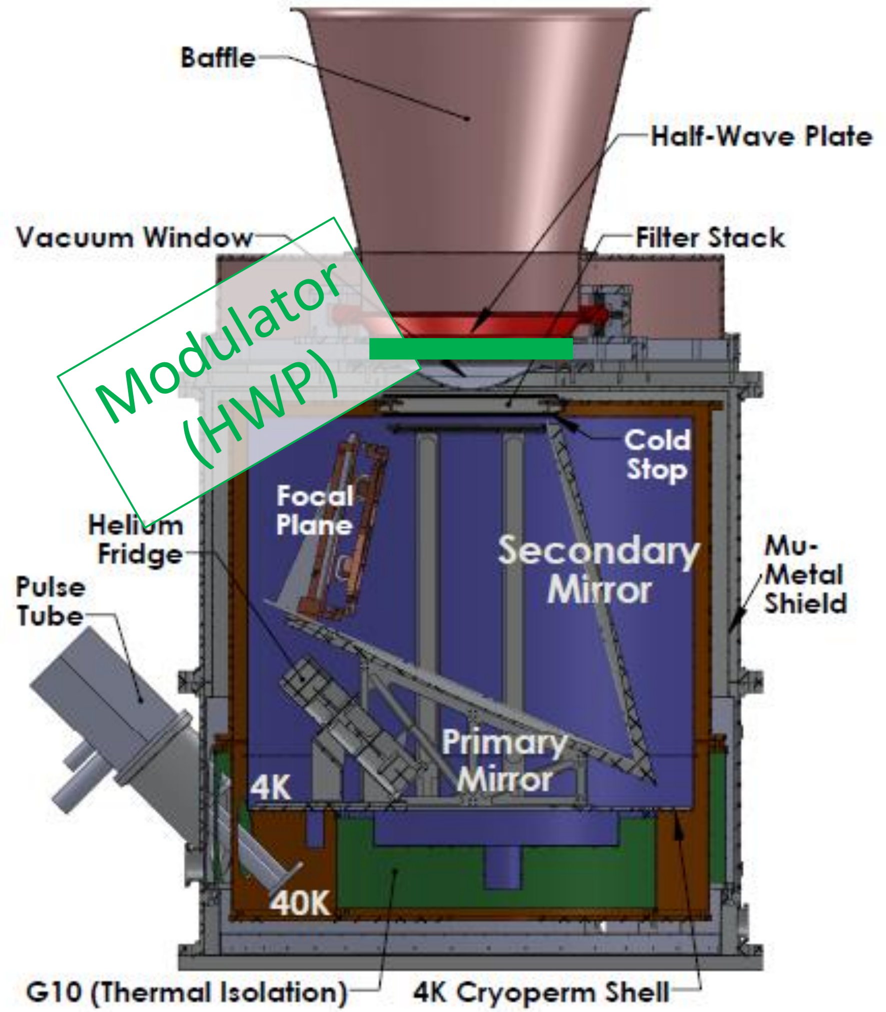




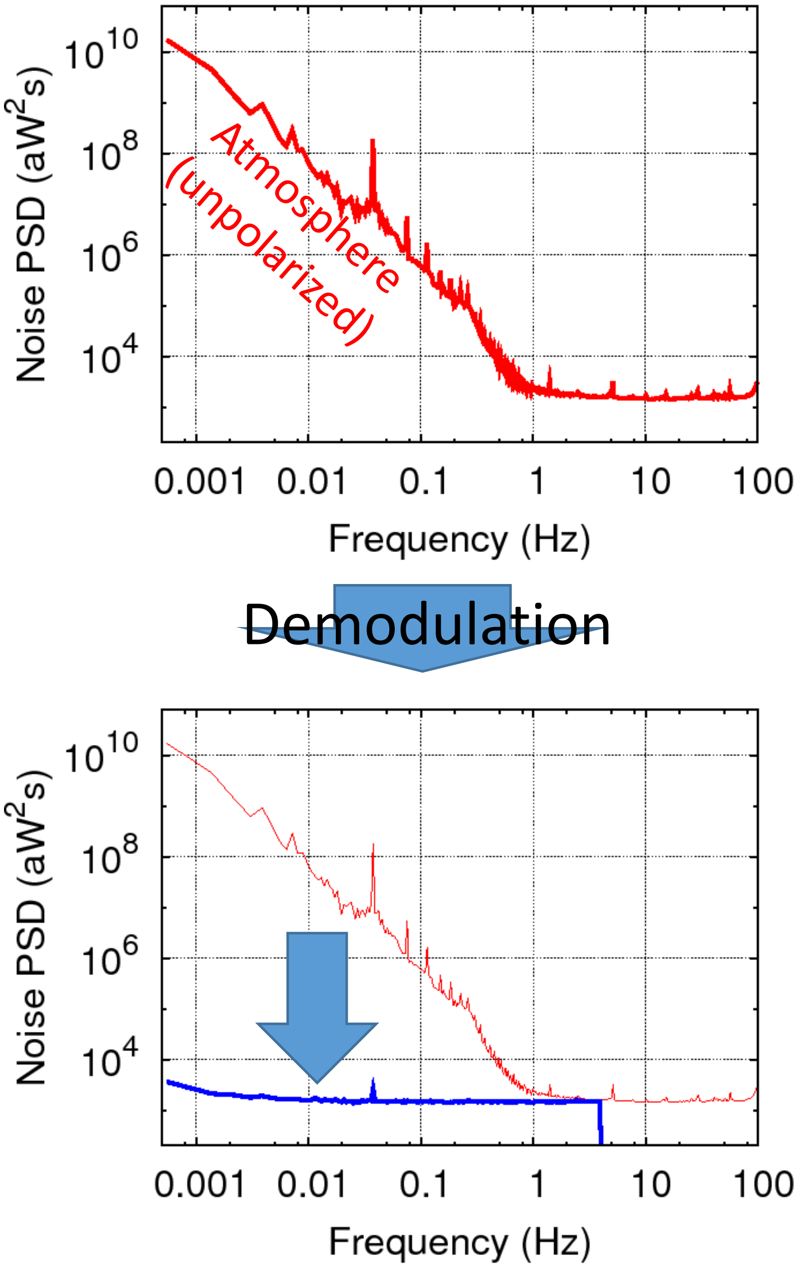
A-cut sapphire (D=330 mm)
f~2.5 Hz rotation
→ f~10 Hz modulation
Air-bearing → Stable rotation
No need for pair differencing

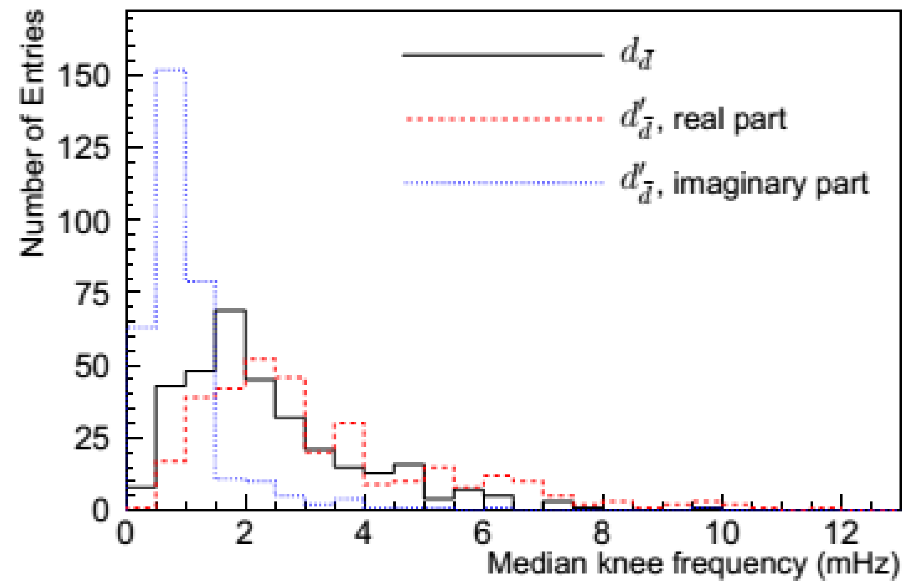
ABS: Continuously rotating warm half-wave plate

- Optics and HWP
  - Cryogenic cross Dragone
  - HWP near aperture, beam waist
  - HWP: first optical element
- LiteBIRD design resembles ABS



Stability achieved



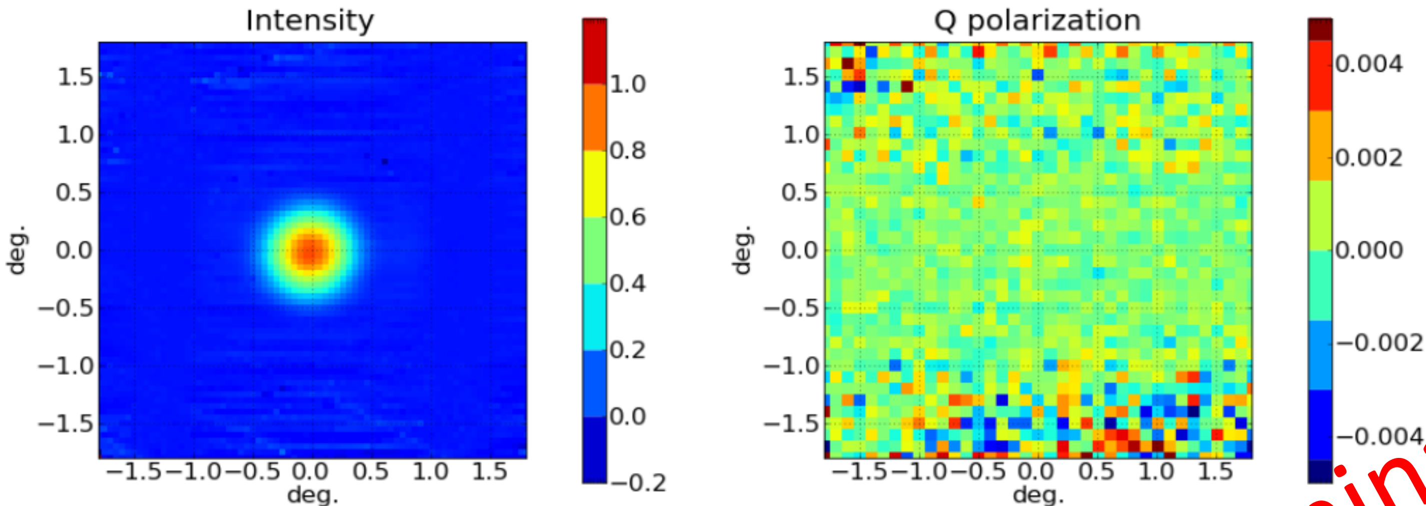


Knee frequency is typically 1-2mHz

ABS collaboration,
Kusaka, Essinger-Hileman, et. al. (2014)

Systematics

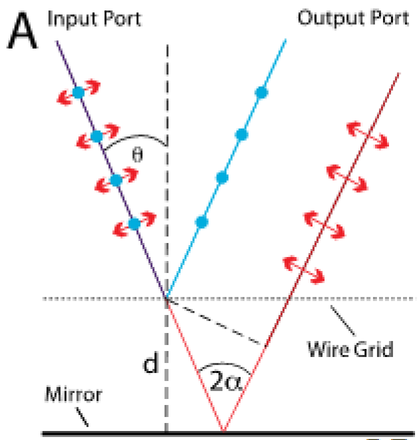
ABS collaboration,
Essinger-Hileman, Kusaka, et. al. in prep.



Preliminary

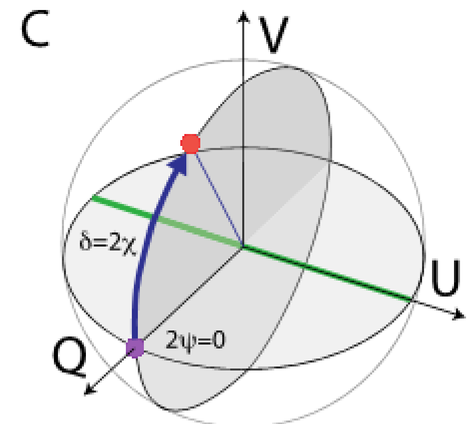
- Scalar leakage: ~0.01%.
- Unpolarized source (Jupiter) observed
  - No signature in the polarization map → limit on leakage
  - Higher order leakages <~ 0.06%.

Variable-Delay Polarization Modulator (VPM): Principles of Operation



B

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\delta & 0 & -\sin\delta \\ 0 & 0 & 1 & 0 \\ 0 & \sin\delta & 0 & \cos\delta \end{bmatrix}$$



D.T. Chuss, et. al., "Phase-Controlled Polarization Modulators," Proc. Of SPIE, Vol. 8452, (2012)

Variable phase delay is introduced between orthogonal linear polarizations by moving mirror relative to stationary polarizing wire grid.

Modulates between Q and V (linear and circular) polarizations.

Time spent on Q vs. V can be tuned by changing endpoints of mirror throw.

Contribution from T. Essinger-Hileman, E. Switzer, D. Chuss, J. Eimer

VPMs: Upcoming Suborbital Technology Demonstration

PIPER

Balloon, 200, 270, 350, 600 GHz

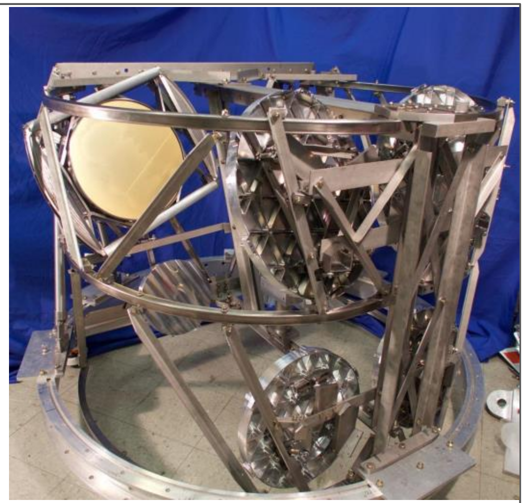
Cryogenic, 1.5K

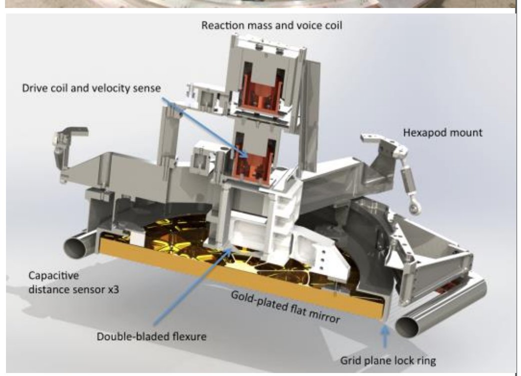
Voice-coil drive, 3 Hz operation

39 cm grid diam, 117 µm spacing, 40 µm diameter

Dual VPMs with grids rotated 45° simultaneous Q/U,

Mirror throw tuned for each band, 1 mm throw maximum.

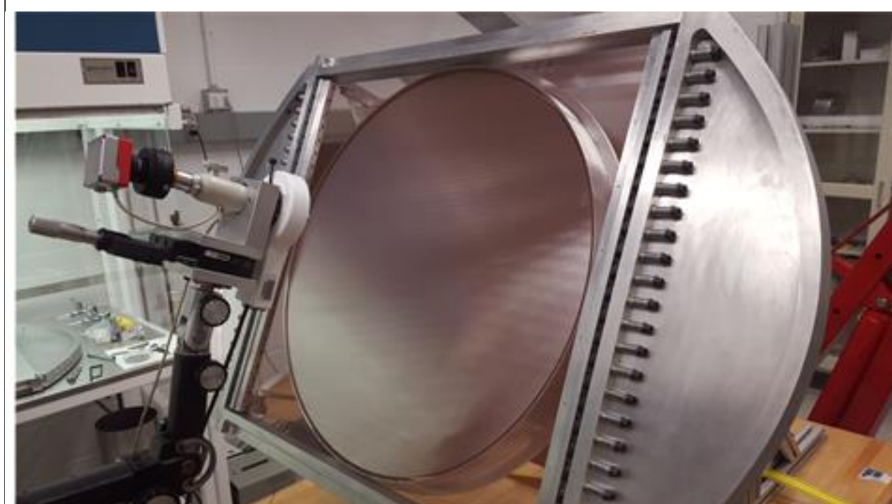




CLASS

- Ground-based
- Atacama Desert, Chile

- Four frequencies: 40, 90, 150, 220 GHz
- Dual-frequency operation at 150/220 GHz
- 60 cm mirror, ambient-temperature
- Voice-coil drive, 10 Hz operation



Contribution from T. Essinger-Hileman, E. Switzer, D. Chuss, J. Eimer

Considerations for a Space Mission

1. Small linear motions can be accomplished using simple frictionless bearings.

2. The VPM does not require dielectrics, which are subject to damage via deep dielectric charging in the space environment.

3. Cross-polarization is mapped into (null) V-channel and does not mix Q↔U (E↔B).

4. Polarization basis is fixed to spacecraft, so Q, U basis is fixed across all frequencies and detectors.

Polarizer is broadband- multiple frequencies can be accommodated by

1. Setting frequency bands to match the VPM efficiency (in “switching mode”)

2. Continuously stroking the VPM (FTS mode)

3. Changing the modulation band ↔ changing the mirror stroke.

Residual systematics (variable emission) can be greatly reduced in a space environment, ideally: T(VPM)=T(CMB)

Contribution from T. Essinger-Hileman, E. Switzer, D. Chuss, J. Eimer

Modulator for next generation

- Simultaneous modulation of multiple frequency
- Simultaneous modulation of multiple pixels
  - Possible downside: correlated systematics
  - Large aperture required
- Low levels of systematics
  - High modulation efficiency
  - Low spurious modulated signal
    - In particular those that are time variable
- Possible technologies:
  - Achromatic HWP (sapphire, metamaterial, metal meash)
  - Reflective HWP
  - VPM, TRP
  - 30-60 cm aperture size available now

Do we need fast modulator for LiteBIRD?

- LiteBIRD $f_{\mathrm{scan}} \sim 1.6\ \mathrm{mHz}$
  - What is the “TRL” of achieving $f_{\mathrm{knee}} \sim 1\ \mathrm{mHz}$?
  - Examples from the past:
    - ABS: ~1-2 mHz w/ fast HWP
    - QUIET: 5-10 mHz w/ fast phase switching
    - POLARBEAR1: 2-10 mHz w/ fast HWP (~2 mHz after PCA)
    - EBEX: ?? mHz w/ fast HWP
    - Planck, BICEP, SPT, PB1 (w/o HWP), ACTPol: ??
- Beam systematics mitigation
  - Detector and optics have intrinsic differential response

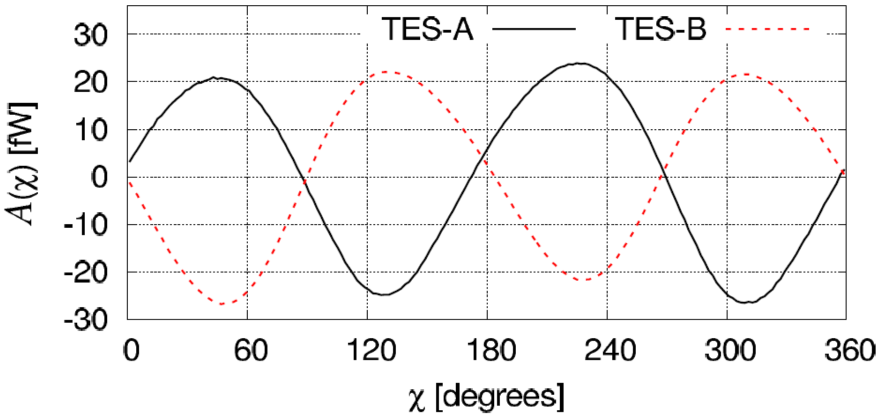
Systematics from HWP

- Optically expected systematics
  - Monopole leakage ~0.01%
  - Higher order terms is even smaller
  - Small and stable
- Non-uniformity (to be specified)
  - Emissivity
    - 2.725 K would be great.
  - Axis misalignment
  - Anti-reflection coating
  - Constant polarization signal (+ non-linearity.)
- Temperature stability
  - How to maintain the constant temperature?
- Scattering

Constant "polarization" signal

- "2f" is dominant
  - Differential emissivity
  - ~200mK for ABS
- "4f" is ~1/100: ~2mK
  - Depends on optics.
  - Depends on T_{HWP}
  - ABS configuration minimizes the "4f"
  - Possible sources
    - Multiple reflection
    - Non-uniformity
    - Scattering
    - Baffle polarization
- Harmless, *in principle*

ABS example
(Kusaka, Essinger-Hileman, et. al. 2014)



Constant "polarization" signal

- Constant signal + detector non-linearity

$$Q(t) = g(t)Q_0$$

O(10^{-3}~10^{-4}) [K^{-1}] (?)

Satoru Takakura

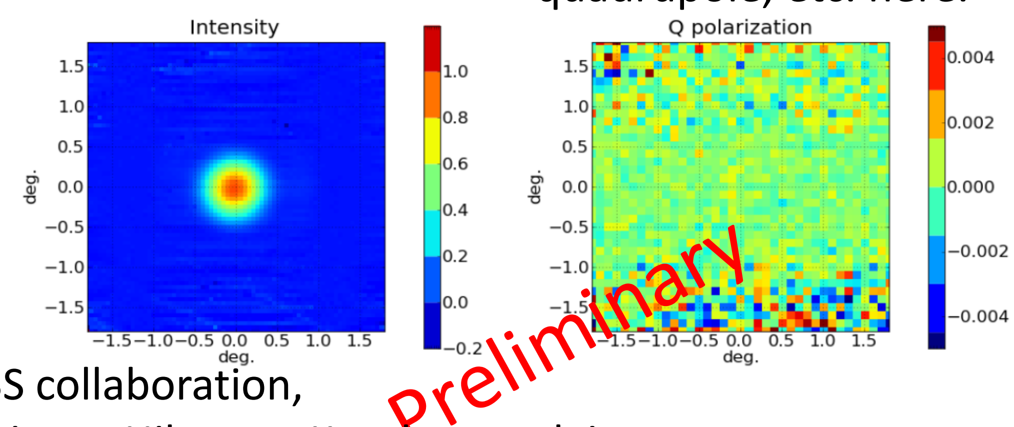
$$g(t) = 1 + aT_{FP} + bT_{sky}$$

  - Leakage: bQ_0 ~0.001% (but less stable)
- "Constant" signal variation due to T_{HWP} change
  - Upper limit: $Q_0 \cdot \Delta T_{HWP}/T_{HWP}$
  - This naïve analysis would imply $\Delta T_{HWP} \leq 1\text{mK}$, but
    - Emissive component should reduce as $T_{HWP} \rightarrow T_{CMB}$
    - Non-emissive component scales better than $\Delta T_{HWP}/T_{HWP}$
- Analysis to be made for each implementation

Non-uniformity, beam walking

- Advantage of fast modulation: effective beam
- "Beam walking" effect can be expressed as higher order T→P leakage
  - Origin highly dependent on optical configuration.
  - HWP at Aperture: non-uniform transmission.

It would show up as dipole, quadrupole, etc. here.



ABS collaboration,
Essinger-Hileman, Kusaka, et. al. in prep.

And more…

ABS collaboration, Simon et. al. (2014)

- Time constant:
  - Variable polarization angle

Satoru Takakura, and others…

- Clocking and encoding:
  - Excess noise leaking from constant polarization

QUIET collaboration, Bischoff et. al. (2013)

- Localized non-linearity:
  - ADC non-linearity → non-stationary noise and leakage
- Polarization angle vs. frequency of AHWP

→ Shaul's talk

We should to compile the "knowledge of the field"

Summary

- Polarization modulators help to reject “systematics”
  - Those of statistical nature: e. g., 1/f noise
  - Those of systematic nature: e.g., beam systematics
- Fast polarization modulation already demonstrated.
- Modulators for next generation instruments
  - Multi-frequency modulation
  - Multi-pixel modulation
  - Low levels of systematics
- Possible systematic sources
  - We need to create a complete list.