Refractor for CMBpol

CMBpol Technology workshop
28 August 2008,

Photo: Steff Richter
BICEP optics

- Wide-field refractor:
  - Cold Optics: 2 lenses + filters
    - HDPE lenses (Darren Dowell)
    - Teflon AR coat (Chao-Lin Kuo)
  - 30cm -> 0.9°, 0.6° FWHMs
  - High throughput, 17° FOV
  - Instr-poll< 1%, Cross-pol< 0.01%
  - Flat, telecentric focal plane
  - Ready for lithographed arrays!
- -> BICEP2/Keck, Spider
- -> CMBpol?
Why did we choose a small refractor?

- High throughput in smallest possible package
- Efficient ($) to integrate / deploy
- Stability of 4K telescope & beams
- Ease of optical characterization (~100m range)
- Aperture filling calibrators
- Aperture filling waveplate (BICEP2/Keck)
- Superior sidelobe suppression
Why might CMBpol choose a small refractor?

- High throughput in smallest possible package (?)
- Efficient ($) to integrate / deploy
- Stability of 2K telescope & beams
- Ease of optical characterization (~100m range)
- Aperture filling calibrators (?)
- Aperture filling waveplate
- Superior sidelobe suppression
- Monochromatic optics – higher TRL
- Easier to shield ?
- Proven heritage: BICEP1, BICEP2, Keck, Spider…
BICEP1 refractor: lessons learned...
BICEP1 analysis led by Barkats, Chiang, Yoon, Takahashi, Bierman

...lessons learned from BICEP1 come from their work. See astro-ph/0808.1763

TEAM BICEP

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Evan Bierman

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Eric Hivon
Nicolas Ponthieu
Dark Sector Laboratory

November 2005...
Cryostat work...
Early January 2006: a working instrument!
March 2006 – March 2008: Observations to-date

CMB obs started March 4th 2006

24 months (17500 hours) since then:

<table>
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<tr>
<th>Activity</th>
<th>Hours</th>
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<td>Observing the sky</td>
<td>10900</td>
</tr>
<tr>
<td>Fridge cycling, Cryo ops</td>
<td>1640</td>
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<tr>
<td>Calibration, maintenance, upgrades</td>
<td>4950</td>
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Good CMB-field data, afterweather and other cuts = 5700 hours

Great observing efficiency!
Observed Fields

Observations in 48-hour cycles:

[day 1]
6 hrs: A. cycle fridge
9 hrs: B. CMB (lower half)
9 Hrs: C. CMB (upper half)

[day 2]
6 hrs: D. GAL-weak
9 hrs: E. CMB (upper half)
9 hrs: F. CMB (lower half)
Preliminary T/E/B Maps

- Data from first 2 years (2006 March through 2007 October).
- Temperature anisotropy measured with very high S/N
  - precise absolute calibration vs. WMAP on 2-day timescales.
  - faint striping due to ATM noise, removed by PSB differencing
- E/B maps (Weiner filtered, from Q/U maps used in analysis)
- Frequency jackknife maps of E/B are consistent with noise, as is the B signal map --> No evidence of foreground contamination.
- Q/U jackknife map-derived 1-deg² noise in line with expectation:
  100 GHz: 0.78 uK
  150 GHz: 0.62 uK
Where are we?
Preliminary analysis is maturing…

- black points: simulation based on 2-yr data used in current initial analysis
- TE and EE spectra are already sample-variance dominated
  - First high S/N pol measurements around $l \sim 100$
- Level of initial BB limits will depend strongly on cuts
  - these are likely to be conservative in first round
## Instrument Systematics

### B-contamination from
relative gain error

### B-contamination from
differential pointing

### Table 1. Potential Systematic Errors for BICEP.

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\(^a\) \(\bar{\sigma} = FWHM/\sqrt{8 \ln(2)}\).

\(^b\) A differential pointing which averages 1.3% has been repeatably characterized to 0.4% precision.

\(^c\) At 30\(^o\) from the beam center, based on the measured upper limit of 20\% (-7 dB) polarized response in the sidelobes.

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Beam shape effects

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- Upper limits on differential beam size and ellipticity easily meet specs for \( r=0.1 \) (and \( r=0.01 \))!

- Differential pointing was the surprise...measured to be significant even for \( r=0.1 \).
Beam Shape Measurements

Figure 6. The beam mapping setup on site consisted of sources mounted on top of fold-over masts. When using the mast on the MAPO building (200 m from the Dark Sector Laboratory), a flat mirror is mounted to direct the beams over the ground screen.

Figure 7. Beams for each PSB pair are normalized and differenced to produce this composite differential beam map. The overplotted lines show the fitted centroid offsets magnified by a factor of 100.

Beams were mapped in highbay prior to deployment (41 m)
- Achieved sufficient precision to assure beam effects not dominant for r=0.1

Subsequently measured on site using a mast (200 m) and moon.
- Differential pointing is only measurable effect
- Repeatable/stable to current measurement error (0.4%)
Evidence for similar pattern of A-B beam offsets in QUAD and BICEP beams.
- c.f. Clem’s talk
- effect is smaller in BICEP
- Follow-up lab measurements to understand origin of effect are ongoing…
- Stable to current measurement error (0.4%), which in principle allows
to subdominant level for $r=0.01$
Quoted benchmark is (I believe) for random errors per feed. Benchmark \((r=0.1)\) for error on global orientation is \(\sim 1.0\) degree.

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Measuring Polarization orientation: the Yukical

Polarization response angle is characterized using POLAR-style (O’Dell 2002) dielectric sheet calibrator.

(Y. Takahashi)

Provides polarization orientation to ~ 0.7 deg accuracy
# Sidelobes

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Sidelobe characterization

- Extremely clean optical design:
  - Unobstructed aperture
  - Black forebaffle
  - Reflective groundshield

- Sidelobes mapped on-site using amplified sources on 30’ mast

- Ground pickup reduced $>10^3$ compared to QUAD…
  …no ground subtraction needed in analysis so far!
Actually, we have evidence for scan-synchronous ~nK level thermal fluctuations in our thermistor maps, but only at certain scan rates and orientations.

These appear significant to polarization maps only for the largest scales ($l < 50$) but understanding which data and which detector pairs are affected has been a major focus in making cuts.

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BICEP2/Keck refractors: if it ain’t broke…
BICEP2 & Keck

Exploit BICEP refractor methodology to aggressively push down to $r=0.01$ using antenna-coupled TES and SQUIDTmuxarrays.

BICEP2 (2009 - 2011):

- Upgrade BICEP1LHe receiver
- 512 detectors @ 150 GHz

Keck (2010 - 2012):

- Pulse-tube receivers
- Up to 6 such monochromatic receivers on the existing DASI mount (3 X 288 detectors at 100 GHz, 2 X 512 @ 150 GHz, 1 X 512 @ 220 GHz)
BICEP2/Keck Refractors: new features

- 2fλ antenna-coupled feeds increase edge illumination from
  - BICEP1: -22 dB edge taper
  - BICEP2: -12.4 dB edge taper, so…
- Lens design reoptimized using ZEMAX (RandolAikin)
  - BICEP2: < 1e-5 calculated diff. ellipticity; VERY symmetric illumination
- Aperture stop refined (tapered HR10)

- AR coats still expanded PTFE, but optimized for monochromatic

- 4” Zotefoam window unlaminated, reducing scattering
  - BICEP1: 1.5% transmission loss at 150 GHz (0.5% onto forebaffle)
  - BICEP2: 0.3% transmission loss at 150 GHz
DETERMINING LENS CURVATURE:

OPTIMIZING W.R.T. ABERRATION:
+ SHARP FOCUS IN ARRAY
- ASYMMETRIC ILLUMINATION OF APERTURE

OPTIMIZING W.R.T. TELECENTRICITY:
- ABERRATION IN THE FP
+ SYMMETRIC ILLUMINATION OF APERTURE
Cryostat work…

BICEP2: optimized lens design, monochromatic AR coat, HR10 aperture stop
Refractor Readiness…

• BICEP has demonstrated that a wide field refractor can make sensitive measurements of the CMB polarization at \( l = 50-100 \) using no polarization modulation, even from the ground.

• Optical systematics have been characterized to level needed for \( r=0.01 \)

  \( \Rightarrow TRL \ 5 \ ? \ 4.99 \ ? \)

• Differential pointing still poorly understood. Stable, and “not likely to be a serious concern” (Hinshaw/systematics), nonetheless

  • need lab measurements to trace origin of effect (AR coats?)

  • need better optics code

• Need verification that optics systematics remain under control with more aggressive detector coupling (BICEP2 will address, \( \sim 6 \) months)

• CMPpol: alternatives for high-throughput, compact systems?

  1.5m crossed design?