BICEP1 analysis led by Barkats, Chiang, Yoon, Takahashi, Bierman

...what we’ve learned about BICEP1 systematics comes from their work.
Aperture fever: cured!?
(or, Why’d you use such a puny aperture?)

- Efficient to integrate / test / deploy
- Stability of (4K) telescope & beams
- Aperture filling calibrators
- Aperture filling waveplate (BICEP2)
- Superior sidelobe suppression
- Can observe Jupiter and Moon
Design Motivations

• Significant science can be done with degree-sized beams. ("Minimal Optics": Compact, obstruction-free aperture.)

• Need high sensitivity and exquisite control of systematics. (Control beam effects. Simplify, simplify…)

• Leverage proven technologies whenever possible. (PSBs, corrugated feeds, sorption coolers, filters, etc.)

• Focus on one major science goal: B-mode polarization at $l \sim 100$. (Gear strategy/methodology towards single goal.)
BICEP Receiver: Bolometric refractor minimizes complexity

Toroidal upward-looking liquid LN/LHe cryostat w/ 3-stage sorption fridge --> 250 mK

250-mm aperture (no mirrors)

2-lens cold refractor

FWHM 60' @ 100 GHz
FHWM 40' @ 150 GHz

17-deg field-of-view

4 K receiver insert

50 PSBs @ 100 GHz
48 PSBs @ 150 GHz
(Overdressed)
“Feed Garden”
4K INSERT

150 GHz
100 GHz

Instrument U

Instrument Q
Off to the South Pole...

Dark Sector Laboratory (BSPT) late 2005...
Early January 2006: a working instrument!
Where are we?

- 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
BICEP systematics characterization
Dirty Laundry List: All Systematics

Table 1. Potential Systematic Errors for BICEP.

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

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

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

\(^d\) Scan-synchronous, over \(\ell = 30 - 300\).
BICEP’s Observing Fields

Observations in a 48-hour cycle:

[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
9 hrs: E. CMB (upper half)
9 hrs: F. CMB (lower half)
10 minutes on GAL-cal region before & every segment...54% obs. effic.
2.8 deg/s AZ scans at each fixed elevation; EL = 55 - 60 deg
Repeat the 48-hr block at four different boresight angles.

GAL-cal

18-hr CMB scan

flash-cal & el-nod at every elevation
~1 K loading from the IR flash-cal arm swinging into the aperture, 
~100 mK IR pulse signal.

1° amplitude elevation nod gives strong common-mode signal for pair gain-matching.
Beam Systematic effects in real space

- differential beam offset (dipole IP effect)
- differential gain (monopole effect)
- differential FWHM (monopole effect)
- differential ellipticity (quadrupole effect)

Irreducible
Beam Shape Measurements

Beams mapped in highbay prior to deployment (41 m)
- Achieved sufficient precision to assure beam mismatch OK 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%)
Beam Characterization @ Pole

Carefully characterized the beams with thermal and Gunn oscillator sources on mast.

Extended scan tests with polarized eccosorb on the lip of ground shield to quantify far sidelobe rejection.

Extremely clean far sidelobes…
Beam Measurements

Beams mapped in highbay prior to deployment. (d=41 m)

Subsequently measured @ Pole using a mast (d=11 m)

Neither truly in the far field (2D_{aperture} / \lambda) for 150 GHz...
Highbay distance in the transition region for 100 GHz...

Highbay measurements indicated BICEP beam systematics well within spec for r ~ 0.1.

Differential pointing (dipole) dominates over other beam effects.
Pattern of A-B differential pointing offsets

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 removal to subdominant level for r=0.01
Beam shape effects

- 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 $r=0.1$. 

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$^a$ $\sigma = \text{FWHM}/\sqrt{8\ln(2)}$

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

$^c$ At 50$^\circ$ from the beam center, based on the measured upper limit of 26% (-7 dB) polarized response in the sidelobes.

$^d$ Scan-synchronous, over $\ell = 30 - 300$. 
Beam Systematics for $r=0.1$

“Real” Sims (ch. cuts, scans,. etc)

B-contamination from differential gain

B-contamination from differential pointing

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<th>Definition</th>
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<td>Relative gain mismatch</td>
<td>$(s_A - s_B) / \tilde{s}$</td>
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Errors in instrument characterization can lead to false polarization measurement when PSB pairs subtracted...
Transfer Function Measurements

Initial measurements in 2006 Feb using 100 GHz Gunn oscillator source, down to 0.1 Hz.

Follow-up measurements in 2006 Fall indicated significant roll-off below 0.1 Hz for some of the channels... If unaccounted for, results in large T-leakage into Q/U maps.

Comprehensive measurements using both 100/150 GHz Gunns down to 0.01 Hz in 2007 Feb.

Transfer functions well-characterized to within 1% for large majority of PSBs. Suspect channels cut from analysis.

Scattering elements (washers) embedded into Zotefoam cover. Loading and square wave signal amplitude controlled across nominal ranges to look for measurement biases...
No dependence on optical loading (red/purple = low; blue/green = high), or non-linearity effects (red/blue = high; purple/green = low).
Transfer Function Measurements

Over the frequency range where they overlap, the 2006 and 2007 measurements are in good agreement for all but a couple PSBs.

Those channels with significant low-frequency roll-offs or inconsistent measurements were excluded from analysis:

2006: 11/98 channels total (3 100’s and 8 150’s)
2007: 6/98 channels total (2 100’s and 4 150’s)

Measured transfer functions are directly deconvolved from the timestreams instead of model fitting.

Errors derived from repeat measurements are well within 1%

--> Meets specification for r ~ 0.1
Relative Gains: pinned at low freq by el-nods

1° amplitude elevation nod gives strong common-mode signal for pair gain-matching.

~1 K loading from the IR flash-cal arm swinging into the aperture, 
~100 mK IR pulse signal.
Relgains measured to within 0.4% allows clean common-mode subtraction of the unpolarized sky fluctuations.
Dielectric Sheet Calibration

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

(Y. Takahashi)

Provides ~10% absolute calibration and ~1-deg polarization orientation
Quoted number is global errors per feed. Benchmark (r=0.1) for error on global orientation is ~ 1.0 degree.
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!
# Sidelobes

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Sidelobes
Thermal Stability

Actually, we have evidence for scan-synchronous \(~\text{nK}\) 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.
Sensitivity Projection

Derive measured $\text{NET}_{\text{CMB}}$ from WMAP cross-calibration

100 GHz: $480 \, \mu\text{K} \cdot \text{s}^{1/2}$ 150 GHz: $420 \, \mu\text{K} \cdot \text{s}^{1/2}$

Assuming 100 days and no hit from systematics or foregrounds…
(conservative 1st season)
Sensitivity Projection

Derive measured NET\textsubscript{CMB} from WMAP cross-calibration

100 GHz: 480 \( \mu \text{K} \cdot \text{s}^{1/2} \) 150 GHz: 420 \( \mu \text{K} \cdot \text{s}^{1/2} \)

Assuming 300 days and no hit from systematics or foregrounds…
(reasonable 2-3 seasons)
**Collected Data**

2006:
- March - October
- 362 complete blocks of 9-hour observations
- Equivalent to 181 operational days,
  - or > 2400 hours of actual data

2007:
- Mid-February - early November (actually never warmed-up)
- ~480 complete 9-hour blocks
- Equivalent to 240 operational days
  - or > 3100 hours of actual data
  - also added 2 pixels at 220 GHz pixels

Unprecedented observing efficiency from the South Pole!

Excluded channels:
- 2006 25 PSBs excluded
- 2007  12 PSBs excluded (mostly for transfer functions)
Preliminary T/E/B Maps

- Data from 2006 March through 2007 mid-May.
- Temperature anisotropy measured with very high S/N.
- BICEP-scanned WMAP W-band data with identical filtering gives effective absolute calibration to within ~10%. 
Preliminary E & B Maps

- E/B maps calculated from input Stokes Q/U maps using ‘anafast.’
- Wiener-filtered using the expected E-mode spectrum as the weight.
- No evidence for Foreground contamination in deep region
- Full analysis on-going: (less-aggressive filtering, proper noise treatment, etc.)
Galactic Foreground Polarization Results

- BICEP 150 GHz temperature map approximately tracks the FDS model.
- FDS model over-predicts dust intensity along some galactic regions.
- BICEP measures ~2% pol. fraction in bright galactic regions (T > 0.5 mK).
- Deep integrations at moderate galactic latitudes (red box) give dust polarization < 5%, consistent with WMAP all-sky estimates.
Conclusions

• BICEP has now run for 2.5 seasons, achieving excellent observing efficiency. On target for sensitivity projections.

• BICEP has demonstrated that sensitive measurements of the CMB polarization at $l = 50-100$ can be carried out with a small-aperture experiment using scan polarization modulation only, even from the ground. (This wasn’t obvious from the start—we’d have used > 6 FRMs if needed).

• Real data has revealed which systematics are most challenging:
  • Gain match / transfer functions: important, but can be well-measured in the field.
  • Differential pointing: poorly understood, but not dominant at $r=0.1$ and apparently stable to the level needed for $r=0.01$.
  • Thermal stability: achieving sub nK scan-synchronous stability on focal plane is a design goal for BICEP2. (Effects also appear to be cleanly removable in analysis).

• No killer systematic appears to stand between us and $r=0.01$.

• CMBpol lesson: use the simplest approach that works. (But no simpler!)
End
Faraday Rotation Modulators

- Used 3 @ 100 GHz
- 3 @ 150 GHz
- Season 1 only
- Only “fast” modulation