SPT collaboration

Chicago
Caristrom
Hu
Kravtsov
Meyer
Pryke
Aird
Leitch
Padin
Chang
Crawford
McMahon
Miknaitis
Keisler
Bleem
Crites
Vieira

Berkeley/LBNL
Holzapfel
Lee
White
Spieler
Benson
Reichardt
Lueker
Plagge
Shirokoff
Zahn

Illinois
Mohr

Cardiff
Filters
Ade

Boulder
Halverson

Davis
Knox

McGill
Dobbs
Holder
Shaw

SAO
Stark

Case
Ruhl
Staniszewski

MSFC
Joy
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular resolution</td>
<td>1.6, 1.0, 0.8</td>
<td>Arcminutes</td>
</tr>
<tr>
<td>Frequency Coverage</td>
<td>90, 150, 220</td>
<td>GHz</td>
</tr>
<tr>
<td>Sky Coverage</td>
<td>600</td>
<td>Square Degrees</td>
</tr>
<tr>
<td>Multipole Coverage</td>
<td>50-10000</td>
<td>-</td>
</tr>
<tr>
<td>Polarization Modulation?</td>
<td>HWP?</td>
<td>-</td>
</tr>
<tr>
<td>Types of Detectors</td>
<td>Bolometer, differencing</td>
<td>-</td>
</tr>
<tr>
<td>Location</td>
<td>Ground, South Pole</td>
<td>(Balloon/Ground/Space)</td>
</tr>
<tr>
<td>Instrument NEQ</td>
<td>14</td>
<td>$\mu$K s$^{1/2}$</td>
</tr>
<tr>
<td>Expected/Current limit on $r$</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>($\sigma(r) = 0.004$)</td>
<td>-</td>
</tr>
<tr>
<td>Status</td>
<td>Funded</td>
<td>(Funded/Proposed/Future)</td>
</tr>
</tbody>
</table>
Foregrounds

There is a really clean patch of sky accessible 24 hours a day from the South Pole!
SPT optics

Classical Gregorian with the secondary tilted to minimize aberrations.

FOV ~ λ(mm) x 0.7 deg

- Low background, low sidelobe optics
- Cooled secondary
- Accommodates 1000 elements
- Introduction of a wave plate is possible
Scan Strategy

- **Candidate scan-strategies** (which allow the removal of ground synchronous signals)
  - Lead-trail (Az only)
  - Elevation-drift scan

- **South Pole is a unique place on the earth**
  - Positives: cold, dry, stable
  - Features:
    - parallactic angle doesn’t changes with Earth’s rotation
    - position of sidelobes are fixed on sky relative to main beam
# Systematics

## Approach: Consider effects in map space

(Following HHZ)

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<th>Effect</th>
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<td>( E \rightarrow B )</td>
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<td>Polarization angle errors</td>
<td>( E \rightarrow B )</td>
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<tr>
<td>Pointing errors (on Q/U)</td>
<td>( E \rightarrow B )</td>
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<td>Main beam asymmetry (before differencing)</td>
<td>( dT \rightarrow B )</td>
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<td>Sidelobes</td>
<td>( dT \rightarrow B )</td>
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<td>Instrumental polarization</td>
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<td>Relative calibration errors</td>
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<td>Pointing errors before differencing</td>
<td>( T \rightarrow B )</td>
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<td>Gain drift before differencing</td>
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<td>Optics and spillover T variations</td>
<td>( dT_{\text{sp}} \rightarrow B )</td>
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<tr>
<td>Scan modulated cold stage variations</td>
<td>( dT_{\text{cs}} \rightarrow B )</td>
<td></td>
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<tr>
<td>Band shape errors, including modulator effects</td>
<td></td>
<td>( \text{foregrounds} \rightarrow B )</td>
</tr>
<tr>
<td>Others?</td>
<td></td>
<td>( ? )</td>
</tr>
</tbody>
</table>

**Effect in map space**

- Monopole dipole, quadrupole \( E \leftrightarrow B \)
- \( E \leftrightarrow B \) rotation
- "lensing like" deformation of map
- Quadrupole \( T \leftrightarrow E, B \)
- Higher order \( T \leftrightarrow E,B \)
- Coupling
- Monopole \( T \leftrightarrow E,B \)
- Dipole \( T \leftrightarrow E,B \)
- Monopole \( T \leftrightarrow E,B \), time varying
- Scan synchronous Noise
- Scan synchronous Noise
- Band Pass errors
Scan Strategy: ground pickup

The response of the telescope is given by:

\[ R(\hat{n}) = \int S B(\hat{n}) d\Omega \]

So scan synchronous signal is

\[ \frac{dR(\hat{n})}{d\hat{n}} = \int S \frac{dB(\hat{n})}{d\hat{n}} d\Omega \]

- Scan synchronous signals generated by side-lobes coupled to emitting structures matched to the scan strategy. The South Pole is nearly featureless.
- Current unpolarized observations limit pickup below 10 \( \mu \)K below 0.5\(^\circ\) scales (limited by 1/f)
Scan Strategy: sky pickup

The response of the telescope is given by:

$$R(\hat{n}) = \int SB(\hat{n})d\Omega$$

So scan synchronous signal is:

$$\frac{dR(\hat{n})}{d\hat{n}} = \int S \frac{dB(\hat{n})}{d\hat{n}}d\Omega$$

**Plan:** Measure far side-lobes then improve the optics to eliminate any large lobes

**How hard is that? (depends on angular scale)**

- for 600 sq degrees @ 1K, -55dBi gives ~ 40 nK undifferenced
- requires ~100 mW of source power to measure in a few hours
- once we have a side-lobe measurement we can refine the requirement
SPT beams

- I→P leakage
  - monopole term dominated by A-B gain mismatch
  - ~-20dB

From beam simulations
- dipole ~ -20dB peak
- quadrupole ~ -20dB peak

- cross-polar E→B leakages from optics below -35dB
  - ⇒ dominated by uncertainty in detector angle
Effects Mixing I and (Q,U)

Calculation for the particular case of the South Pole Telescope (1 arc minute beam)

- Convenient to think of all effects mixing $I \rightarrow Q/U$ as ‘leakage beams’ connecting $T$ on the sky to measured $Q/U$

- This formalism handles instrument specific effects on a unified footing

Two sources of suppression geometric / optical design
- smaller beams better geometric suppression
- dipole suppressed by parallactic angle rotation

quadrupe is not!
Effects Mixing I and (Q,U)

Calculation for the particular case of the South Pole Telescope (1 arc minute beam)

- Convenient to think of all effects mixing I->Q/U as ‘leakage beams’ connecting T on the sky to measured Q/U
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Two sources of suppression geometric / optical design
- smaller beams better geometric suppression
- dipole suppressed by parallactic angle rotation
  quadruple is not!
I->Q/U mixing can be cleaned

Removing Temperature to Polarization Leakage from Maps

Simulation done using MASTER technique.

- Plan of attack:
  project measured T map (convolved with leakage beam) from the measured Q and U maps

- Calculation done for monopole only (should apply to higher order terms)

-15dB monopole leakage is very pessimistic

- Requires high fidelity map of T preferably with the same instrument

- This technique can surely be extended to dipole, quadrupole + higher order leakages.
Detector Angle Calibration

Calibration Requirement

Approaches to Detector Angle Calibration

- **Moon**
  CAPMAP achieved $\pm 2^\circ$ accuracy
  statistical errors much better, limited by model
  improved model could yield sub degree accuracy
  saturation is an issue: (Add high $G$ detectors)

- **Astronomical sources**
  Cen A w/ ATCA @ 90 GHz?

- **Terrestrial Sources (Towers)**
  high signal to noise
  requires refocusing, not on sky
  great for relative calibration

- **Use the EB spectrum!** +rel cal from tower

---

Errors in the detector angles mix $E$ and $B$ in the
same way as $Q$ and $U$ are mixed

$$
\begin{bmatrix}
E_m \\
B_m
\end{bmatrix} =
\begin{bmatrix}
\cos 2\theta_c & -\sin 2\theta_c \\
\sin 2\theta_c & \cos 2\theta_c
\end{bmatrix}
\begin{bmatrix}
E \\
B
\end{bmatrix}
$$

$E$ is about 100 times larger than $B$ (in thermal units)

$\Rightarrow$ need to control to $1 / 1000 \Rightarrow 0.5^\circ$ cal. requirement
Detector Angle Calibration

Using the EB spectrum to calibrate detector angle

from theory: \( \langle EB \rangle = 0 \) 
(assuming no foregrounds)

paralactic angle errors cause mixing and a non-zero \( \langle EB \rangle \)

\[ \langle EB \rangle_m = \langle EE \rangle \cos(\theta_e) \sin(\theta_e) \]

Note: the EB spectrum is more sensitive to this effect than BB since the mixing is first order

\[ \langle BB \rangle_m = \langle BB \rangle \cos^2(\theta_e) + \langle EE \rangle \sin^2(\theta_e) \]

Idea from Kendrick Smith

* Lensing increases the variance of \( \langle EB \rangle \) but does not change the mean.
Conclusion

Systematics Summary:

- Ground Pickup is already small + scan strategy will moderate this effect
- Measure far side-lobes and eliminate any possible sensitivity to the galaxy
- Small beam suppresses I->P dipole and quadrupole
- E->B mixing from cross-polarization is small
- Can use measurements of T to check for (or clean) I->P leakages
- EB provides a check on detector angles

Outlook:

- SPTpol will do a great job with Lensing
- SPTpol will measure r to 0.01 (provided we can control ground pickup + 1/f)
B-mode Projection

Simulation inputs:
1000 bolometer pairs
3 years / 50% efficiency

Simulation includes:
1/f noise
point sources
foregrounds + cleaning
E/B separation
projection of monopole
removal of DC on each scan

\[ \sigma(r) = 0.004 \]