Beam Systematics, Lensing, and Current & Future Experiments

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Overview

- Imperfect beams lead to spurious power spectra
  - $TT$, $EE$, $BB$, $TE$, $TB$, $EB$
- How does this affect reconstruction of the lensing power spectra?
  - It will affect the extraction of lensing parameters from data
  - How does the scan strategy affect reconstruction?
- How does this affect the different estimators for current/future experiments?
- References:
  - Shimon, Keating, Ponthieu, & Hivon PRD 77 083003
  - Miller, Shimon, & Keating PRD 79 063008
  - Miller, Shimon, & Keating PRD 79 103002
How do systematics affect this estimator?

For the polarization data, EB estimator has the lowest noise
Systematic Beam Effects in Real Space

differential FWHM
(monopole effect)

differential pointing
(dipole effect)

differential ellipticity
(quadrupole effect)

Irreducible

differential gain
(monopole effect)
Systematic Beam Effects in Real Space

Now we will investigate how these systematic effects will affect the EB estimator.
Reducible Beam Systematic Differential Pointing

Reducible: Optimizing scan strategy will reduce systematic
Reducible Beam Systematic: Differential Pointing

\[ T_2 - T_1 \Rightarrow \text{Diff. Pointing} \]

Reducible: Optimizing scan strategy will reduce systematic
B-mode Polarization
Differential Pointing

\[ \ell(\ell+1)C_\ell^{BB}/2\pi(\mu K^2) \]

- Grav. Waves
- Systematic
- Lensing

\[ \rho = 0.01 \sigma \]

\( r = 0.01 \)
Irreducible Beam Systematic Differential Ellipticity

\[ T_1 - T_2 = \text{Diff. Ellipticity} \]

Irreducible: Optimizing scan strategy will NOT reduce systematic
Irreducible Beam Systematic
Differential Ellipticity

Irreducible: Optimizing scan strategy will NOT reduce systematic
B-mode Polarization
Differential Ellipticity

\[ \ell (\ell + 1)C^{BB}_\ell / 2\pi (\mu K^2) \]

- Grav. Waves
- Lensing
- Systematic

- \( r = 0.01 \)
- \( e = 0.01 \)
Imperfect Beams: Ellipticity

\[ \varepsilon = \frac{\sigma_x - \sigma_y}{\sigma_x + \sigma_y} \]
Imperfect Beams: A Theorist Builds a Bolometer
Imperfect Beams: A Theorist Builds a Bolometer
Imperfect Beams: A Theorist Builds a Bolometer

SCAN

Attack angle

\( \alpha \)
Imperfect Beams: A Theorist Builds a Bolometer
Scan Strategy Functions

Nearly ideal scanning

\[ f_1 = \frac{1}{2} |\langle \exp(2i\alpha) \rangle|^2 \]  "Quadrupole"

\[ f_2 = \frac{1}{2} \left( |\langle \exp(i\alpha) \rangle|^2 + |\langle \exp(3i\alpha) \rangle|^2 \right) \]  "Dipole"/"Octupole"

\( \alpha \): attack angle – angle between polarization sensitive direction of bolometer and a constant vector on the sky
# Systematic Parameters

<table>
<thead>
<tr>
<th>effect</th>
<th>parameter</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>gain</td>
<td>$g$</td>
<td>$g_1 - g_2$</td>
</tr>
<tr>
<td>monopole</td>
<td>$\mu$</td>
<td>$\frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2}$</td>
</tr>
<tr>
<td>dipole</td>
<td>$\rho$</td>
<td>$\rho_1 - \rho_2$</td>
</tr>
<tr>
<td>quadrupole</td>
<td>$e$</td>
<td>$\frac{\sigma_x - \sigma_y}{\sigma_x + \sigma_y}$</td>
</tr>
<tr>
<td>rotation</td>
<td>$\varepsilon$</td>
<td>$\frac{1}{2}(\varepsilon_1 + \varepsilon_2)$</td>
</tr>
</tbody>
</table>
For the polarization data, EB estimator has the lowest noise.
## Systematic Power Spectra: E/B

<table>
<thead>
<tr>
<th>effect</th>
<th>parameter</th>
<th>$\Delta C_l^E$</th>
<th>$\Delta C_l^B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>gain</td>
<td>$g$</td>
<td>$g^2 f_1 \ast C_l^T$</td>
<td>$g^2 f_1 \ast C_l^T$</td>
</tr>
<tr>
<td>monopole</td>
<td>$\mu$</td>
<td>$4\mu^2 (l\sigma)^4 f_1 \ast C_l^T$</td>
<td>$4\mu^2 (l\sigma)^4 f_1 \ast C_l^T$</td>
</tr>
<tr>
<td>pointing</td>
<td>$\rho$</td>
<td>$c_\theta^2 C_l^T J_2^2 (l\rho)$</td>
<td>$s_\theta^2 C_l^T J_2^2 (l\rho)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ J_1^2 (l\rho) C_l^T \ast f_2$</td>
<td>$- J_1^2 (l\rho) C_l^T \ast f_2$</td>
</tr>
<tr>
<td>quadrupole</td>
<td>$e$</td>
<td>$I_1^2 (z) c_\psi^2 C_l^T$</td>
<td>$I_1^2 (z) s_\psi^2 C_l^T$</td>
</tr>
<tr>
<td>rotation</td>
<td>$\varepsilon$</td>
<td>$4\varepsilon^2 C_l^B$</td>
<td>$4\varepsilon^2 C_l^E$</td>
</tr>
</tbody>
</table>

$$z = \ell^2 \sigma^2 e$$

For ellipticity:  

- $c_\psi = \cos(2\psi)$
- $s_\psi = \sin(2\psi)$
- $I(z) = \text{modified Bessel function}$
### Systematic Power Spectra: EB

<table>
<thead>
<tr>
<th>effect</th>
<th>parameter</th>
<th>( \Delta C^E_B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>gain</td>
<td>( g )</td>
<td>0</td>
</tr>
<tr>
<td>monopole</td>
<td>( \mu )</td>
<td>0</td>
</tr>
<tr>
<td>pointing</td>
<td>( \rho )</td>
<td>( s_\theta c_\theta J^2_2(l \rho) C^T )</td>
</tr>
<tr>
<td>quadrupole</td>
<td>( e )</td>
<td>( I^2_1(z) s_\psi c_\psi C^T )</td>
</tr>
<tr>
<td>rotation</td>
<td>( \varepsilon )</td>
<td>( 2\varepsilon C^E )</td>
</tr>
</tbody>
</table>

\[
z = \ell^2 \sigma^2 e
\]

For ellipticity:
- \( c_\psi = \cos(2\psi) \)
- \( s_\psi = \sin(2\psi) \)
- \( l(z) = \) modified Bessel function
Effect of Scan Strategy on Systematics

- Differential gain and beamwidth couple to the "quadrupole" of the scan strategy.
- Differential pointing couples to the "dipole" and "octupole" of the scan strategy.
- If we remove the "dipole", "quadrupole", and "octupole" from the scan strategy, then we remove the effects of differential gain, beamwidth, and pointing.
- Differential ellipticity and rotation are irreducible, therefore the scan strategy has no effect on systematics.
- If we are given a scan strategy, we can construct the f functions.
## Experiments

<table>
<thead>
<tr>
<th></th>
<th>$f_{\text{sky}}$</th>
<th>$\nu$ (GHz)</th>
<th>$\theta_b$</th>
<th>$\Delta_T(\mu K)$</th>
<th>$\Delta_E(\mu K)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Reference Experiment</td>
<td>0.03</td>
<td>90</td>
<td>6.7'</td>
<td>1.13</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
<td>4'</td>
<td>1.70</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>220</td>
<td>2.7'</td>
<td>8.0</td>
<td>11.3</td>
</tr>
<tr>
<td>CMBPol</td>
<td>0.65</td>
<td>150</td>
<td>5'</td>
<td>0.22</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Lensing Reconstruction
Current Experiment

Noise on estimators

\( \ell (\ell + 1) C_\ell / 2\pi \)

\( l \)

\( 10 \) \( 100 \) \( 1000 \)
Lensing Reconstruction With Systematics
Current Experiment

Ellipticity

$\ell(\ell+1)C_{\ell}^{aa}/2\pi$

e = 0.0, 0.01, 0.02, 0.05, 0.10, 0.20
Lensing Reconstruction: Rotation

$\epsilon = 0.0, 0.01, 0.02, 0.05, 0.10, 0.20$ radian
Lensing Reconstruction: Pointing

\[ \rho = 0.01 \sigma, 0.10 \sigma \]
We care about this part of the power spectrum for lensing parameters.
Lensing Reconstruction: Pointing

Rotation

$\epsilon = 0.0, 0.01, 0.02, 0.05, 0.10, 0.20$ radian

$\ell(l+1)C_{\ell}a/a/2\pi$

$\ell$

$e = 0.0, 0.01, 0.02, 0.05, 0.10, 0.20$ radian
Lensing Reconstruction: Pointing

\[ \rho = 0.01 \sigma, 0.10 \sigma \]
Conclusions

- Beam systematics will lead to spurious polarization and power spectra.
- This will affect the reconstruction of the lensing potential.
- Future experiments will be very susceptible to the effect of beam systematics.
- We need to put a lot of work into limiting beam systematics for future experiments.
- For non-polar sites, we can get very good coverage with just sky rotation.