Tackling systematics and Foregrounds in future CMB Space Missions

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53rd Rencontres de Moriond
What is left to know?

At what energy scale?

- Reionisation
- Neutrino Mass
- Several other cosmological parameters
- Dark Matter
- Dark Energy
- Big Bang Expansion
- 13.7 billion years
- 1st Stars about 400 million yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Afterglow Light Pattern 380,000 yrs.
- Inflation
- Quantum Fluctuations
How do we want to achieve it?

Better CMB Polarisation measurement

Primordial B-modes

Also see Jens’ talk
4th Generation Mission Proposals/Concepts

**ESA**
- COrE -> 2010
- PRISM -> 2013
- COrE+ -> 2015
- CORE -> 2017

**NASA**
- EPIC/CMBpol -> 2009
- PIXIE -> 2017
  - Spectroscopic study over several decades of frequency
- CMB Probe/PICO -> 2020

**ISRO**
- CMBBharat
  - Announcement of opportunity out. Due mid-April

**JAXA**
- LiteBIRD -> 2008
  - Has not yet been selected. Currently undergoing a Phase A study
GSLV MkIII
Advantages of Space

Availability of full electromagnetic spectrum

Superior raw sensitivity

Full sky available
Scanning Strategy

- Constraints such as
  - Sun-shielding
  - Full-sky scanning
  - Passive polarisation modulation

- The second Earth-Sun Lagrange point (L2) is an ideal location.
Well, that’s good news, right?

Not so fast
Foregrounds

- Synchrotron, thermal dust, free-free ....
- Need several frequency bands to estimate the foreground components

Matthieu’s Talk
### Systematics

<table>
<thead>
<tr>
<th>Name</th>
<th>Origin</th>
<th>Description</th>
<th>Major mode of Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandpass Mismatch</td>
<td>Spectral Filters</td>
<td>Edges and shape of the spectral filters vary from detector to detector.</td>
<td>I -&gt; P</td>
</tr>
<tr>
<td>Beam Mismatch and Asymmetry</td>
<td>Optical beams</td>
<td>Beam shape differs from an ideal Gaussian form.</td>
<td>I -&gt; P</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E -&gt; B</td>
</tr>
<tr>
<td>Pointing Uncertainty</td>
<td>Attitude control, pointing</td>
<td>Detector pointing at location different from that given by reconstructed</td>
<td>I -&gt; P</td>
</tr>
<tr>
<td></td>
<td>reconstruction</td>
<td>pointing data.</td>
<td>E -&gt; B</td>
</tr>
<tr>
<td>Polarisation Misalignment</td>
<td>Detectors</td>
<td>Uncertainty in polarisation calibration. Polarisation axis misaligned</td>
<td>E -&gt; B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with measured direction.</td>
<td></td>
</tr>
<tr>
<td>Gain mismatch and stability</td>
<td>Detectors and Calibration</td>
<td>Gain calibration mismatch between detectors. These could also be variable</td>
<td>I -&gt; P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>over time</td>
<td></td>
</tr>
</tbody>
</table>
**Planck LFI Systematics**

Fig. 26: Angular power spectra of the various systematic effects at 70 GHz, compared to the CMB temperature and polarization spectra and to the instrumental noise from half-ring (HR) difference maps. The CMB TT and EE spectra are best fits to the Planck cosmological parameters (see figures 9 and 10 in Planck Collaboration I 2016) filtered by the LFI window functions. The example CMB B-mode spectrum is based on Planck-derived cosmological parameters and assumes a tensor-to-scalar ratio $r = 0.1$, a tensor spectral index $n_T = 0$, and no beam-filtering. The thick dark-grey line represents the total contribution. The dotted dark-green line is the contribution from far the sidelobes that has been removed from the data and is therefore not considered in the total.
BANDPASS MISMATCH SYSTEMATICS
Bandpass Mismatch

Calibrated on the CMB dipole

Equal among detectors

Mismatch among detectors

Will leak signal from intensity to polarisation
**Bandpass Leakage Projection**

CMB + Thermal Dust

*Thuong’s poster*

140 GHz
Spin period = 120s
Precession period = 4 days
Precession angle = 30
Opening angle = 65
Modelling the Leakage

\[ X_{[i_a-i_b]}(p) \simeq [Q(p) \cos(2\psi_{it}) + U(p) \sin(2\psi_{it})] + \sum_{c \neq CMB} \Delta \gamma_i c I_c(p) + \text{noise} \]

\[ X = PS + T \Delta \gamma + n \]

A simple regression problem
Correction algorithm

\[ \hat{S} = [P^T C_n^{-1} F_T P]^{-1} P^T C_n^{-1} F_T X \]

\[ \hat{\gamma} = [T^T C_n^{-1} F_P T]^{-1} T^T C_n^{-1} F_P X \]

\[ \hat{S} = [P^T C_n^{-1} P]^{-1} P^T C_n^{-1} (X - T \hat{\gamma}) \]

Construct your template \( T \) from available high S/N foreground intensity maps.

Similar to SRoll. See Luca’s talk
Bandpass Leakage Correction - Map Projection
Bandpass Leakage Correction - Spectra
Before we move on ......
Correction algorithm

\[
\hat{S} = [P^T C_n^{-1} F_T P]^{-1} P^T C_n^{-1} F_T X
\]
\[
\Delta \gamma = [T^T C_n^{-1} F_P T]^{-1} T^T C_n^{-1} F_P X
\]
\[
\hat{S} = [P^T C_n^{-1} P]^{-1} P^T C_n^{-1} (X - T \Delta \hat{\gamma})
\]

Pointing mismatch

\[
T = \begin{bmatrix}
\nabla_{\parallel} I(t) \\
\nabla_{\perp} I(t)
\end{bmatrix}
\]

Other effects

\[
T = \begin{cases}
< \text{model it appropriately} >
\end{cases}
\]

Ex: Elliptical Beams
BEAM SYSTEMATICS
Real Space Scanning

Break down an inherently 2D problem into a 1D problem
Scales a $N \log(N)$ instead of $N^2$
Real Space Scanning - TOD
Results - Smooth Maps

Map smoothed in harmonic space

T map, 2 det: Smoothed in real space

Q map, 2 det: Smoothed in real space
Beam Systematics

Elliptical/Irregular beams
Due to optical aberrations + other effects

Integrates sky differently at each pass.

Generates signal mismatch
Intensity -> Polarisation leakage
Grasp Beams

I

Q

U

V

I logarithmic

High

Boresight

Low

x / deg

y / deg

10^{-6} 10^{-4} 10^{-2} 10^{0}

x / deg

y / deg

x / deg

y / deg

x / deg

y / deg

x / deg

y / deg
Beam Systematics Correction
Beam Systematics Correction
Outlook

- We’ll be in a noise dominated regime with main contributions from foreground emissions and systematic effects.

- Develop techniques to optimise mission.
  - Not only to achieve desired sensitivity for the mission.
  - Also, so that ground and space observations complement each other.
  - Use available tools to set tolerances on mission parameters.

- Foreground cleaning and systematics correction algorithms.
  - Commander 2, SRoll..........(the regression method I described)
  - Joint foreground removal, systematics correction map-making pipeline. Very ambitious
Thank You