MuSE: The Multimoded Survey Experiment

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B-mode Odds
Next five years...

- 80%: B-mode power will be found at $r > 0.01$
  - 50%: Foreground
  - 10%: Instrumental systematics
  - 20%: Primordial gravitational wave
- 10%: None gets to $r \sim 0.01$ sensitivity
- 10%: No detection of B-mode power

Full coverage of frequency
Unique instruments
Better sensitivity
MuSE
(Multimoded Survey Experiment)
Kusaka et. al. (2012)
## Multimoded Survey Experiment (MuSE)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multimode coverage</td>
<td>25 – 250 ℓ</td>
<td></td>
<td>1.4m primary 1.1deg tophat</td>
</tr>
<tr>
<td>Frequency</td>
<td>44 / 95 / 145 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>225 / 275 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0.23 / 0.27 / 0.25</td>
<td>Fractional</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.22 / 0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw NEQ</td>
<td>4.5 μK_{CMB}√s</td>
<td></td>
<td>95+145GHz</td>
</tr>
<tr>
<td>Foreground cleaned NEQ</td>
<td>8.0 μK_{CMB}√s</td>
<td></td>
<td>Linear combination</td>
</tr>
<tr>
<td># of pixels</td>
<td>50</td>
<td></td>
<td>8000 modes</td>
</tr>
<tr>
<td>Location</td>
<td>Ground</td>
<td></td>
<td>e.g., Atacama</td>
</tr>
</tbody>
</table>
What are single-mode detectors

Detector array

Telescope

Sky

Diffraction limited sampling of focal plane
What are multimoded detectors

Conditions
1. Physically large
2. E&M signal does not propagate through a single “line”
Why do I care about the modes?

- Advancement of the detector technology
  - Detector reached the “photon noise limit”
  - Physics limits the information per mode.
- The only way to improve the sensitivity: to increase the number of channels (crossed out)
- To increase the number of “modes”: more photons!
  - Increasing the number of channels is only one way.
- Multi-moded detector is the other way!
Why Multimoded Instrument?

- No/minimal multiplexing
  - What we need is sensitivity.
  - 100 multimoded bolometers is equivalent to 8000 single-mode bolometers.

- Focal plane packing efficiency
  - Our design is in “Filled Array” category in this context.
  - Many single modal design are similar to “Feedhorn Coupled” category.
  - Gain of ~x2 in mapping speed (see Griffin, Bock, Gear 2002)
Why Multimoded Instrument?

- Larger focal plane
  - Aberration does not reduce antenna gain since each pixel is big.

- High primary aperture illumination eff.
  - No need for edge tapering, since it is not diffraction limited.
  - Lyot stop → well controlled illumination.

- Less need for computational resources.
  - Think about analyzing data from 100 channels, as opposed to those from 8000.
Multimoded Detector Array for CMB Polarimetry: not yet done. Why?
Disadvantages of multimoded instrument

- Worse angular resolution
  - There are situations where one does not need good resolution.
    - Low I B-mode, high frequency in satellite
  - MuSE concept provides a low-cost option.

- Optics systematics, beam control
  - Probably the most compelling reason why single-mode instrument dominates the field.
  - We provide a solution for multimoded system.
Why is it difficult?

- Multimoded polarization: Difficult intermediate regime

Single-mode polarization

Multimode polarization

Multimode intensity
20th International Symposium on Space Terahertz Technology, Charlottesville, 20-22 April 2009

Ideal Grid Generates Cross Polarization

B. Lazareff Member IEEE, S. Mahieu, and D. Geoffroy

Abstract—The ALMA Band 7 cartridge dual-polarization cold optics has been designed to meet a number of specifications, among which the level of cross polarization (initially \(<-20\text{dB}, \text{now} < -23\text{dB})\). The initial design was based on the assumption that the coupling diagram from each of the two horns would be free from cross polarization (Xpol) just beyond the polarization diplexing grid, with the only contribution to Xpol coming from the final refocusing mirror.

Initial measurements showed levels of Xpol significantly worse than expected. This led (after some time) to the realization that an ideal grid can generate cross polarization, which can be brought down to a negligible level by a proper orientation of the grid.

The design has been modified accordingly, and the measurements indeed have shown a significant improvement, that allowed a tighter specification to be instated.

The beam from each horn is refocused by an offset elliptical mirror (respectively M1 and M1R), with a deviation angle of 40°; that relatively large angle is not optimized for low Xpol.

In the next step, a wire grid recombines the two beams, respectively in transmission and reflection. With the chosen grid parameters (25µm diameter, 100µm pitch), the unwanted couplings, intrinsic to the grid, should be below 1%. Furthermore, the Xpol rejection of the grid combines with the intrinsic polarization purity of the scalar horns (even degraded by the first offset elliptical mirror), so that we expected the polarization purity just after beam recombination to be better than \(-30\text{dB}\).

Accordingly, a driving consideration in the design of the Band 7 tertiary optics has been to minimize the Xpol induced by the final offset elliptical mirror (M2). This requires "slow" beams and a small angle of reflection. We designed for a 1/6 beam width (at the central frequency) \(w=13\text{mm}\), an equivalent demagnification and Xpol at the grid of 1/6.
Detector developed at NASA GSFC

- Developed for PIXIE satellite proposal (Kogut et. al. 2011)
- Polarization selective absorbing strings
- Can be configured for narrow-band application
  - 87 modes/detector @145GHz
- Cryogenically testing at Princeton

Kogut et al.
### Detector: per-pixel parameters

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>44</th>
<th>95</th>
<th>145</th>
<th>225</th>
<th>275</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (GHz)</td>
<td>10</td>
<td>26</td>
<td>36</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Optical loading (pW)</td>
<td>9</td>
<td>82</td>
<td>370</td>
<td>1800</td>
<td>3800</td>
</tr>
<tr>
<td>NEP (fW/√Hz)</td>
<td>0.09</td>
<td>0.29</td>
<td>0.70</td>
<td>1.8</td>
<td>2.9</td>
</tr>
<tr>
<td>NEQ (μK_CMB√s)</td>
<td>79</td>
<td>24</td>
<td>24</td>
<td>36</td>
<td>63</td>
</tr>
<tr>
<td># modes / pol.</td>
<td>8</td>
<td>37</td>
<td>87</td>
<td>210</td>
<td>310</td>
</tr>
<tr>
<td>NEQ per mode (μK_CMB√s)</td>
<td>220</td>
<td>150</td>
<td>230</td>
<td>520</td>
<td>1100</td>
</tr>
</tbody>
</table>

\[ T_{\text{bath}} = 300 \text{mK}, \ A\Omega = 3.7 \text{cm}^2\text{sr}, \ \text{PWV} \sim 1\text{mm (e.g., Atacama)} \]

- Benefit from PIXIE R&D
  - Wide-band sensitive, loading~PIXIE (minimum modification)
- Photon noise limited (on the ground)
- HB&T effect ignored, but minor (Zmuidzinas 2003)
Array configuration

50 pixels distributed to 5 bands.
Raw NEQ (95+145): 4.5μK_{CMB}/√s, FG cleaned NEQ: 8.0μK_{CMB}/√s
Two years of operation, 50% efficiency.
Variance from lensing B-mode included.
Two sigma error on $r$ of 0.009, after foreground reduction.
(sensitivity assumes nominal FG spectrum, to give a FoM.)
Summary

- Requirements for next generation
  - Sensitivity, Frequency, Systematics
- MuSE: Highly multi-moded architecture
  - 100 bolometer experiment equivalent to 8000 single-moded bolometers.
  - Optics design has well controlled systematics
  - With two years of operation, it would achieve two $\sigma$ error on $r$ of 0.009 with foreground reduced.