COre calibration and testing

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CMB: High precision and High accuracy

Low multipoles: Planck vs WMAP

~1% calibration discrepancy
Now completely solved!

Planck CMB Dipole calibration 0.2%
Extend to radio (e.g. VLA) and sub-mm (e.g. Herschel)

Planck dipole: high quality calibrator for COoRER

Planck Collaboration 2016
From Planck to COrE

Telescope: 1.5m;
Frequency coverage 30–850 GHz
Number of detectors ~ few 10’s
Cryogenically cooled to 0.1K
Detectors: rediometers, bolometers
Orbit: Sun-Earth L2

Telescope: ~1.2-1.5m;
Frequency coverage ~ 60–600 GHz
Number of detectors ~ few 1000’s
Cryogenically cooled to ~0.1K
Detectors: KIDs, TES, ...
Orbit: Sun-Earth L2

Replace few 10’s detectors with few 1000’s
→ Improve map sensitivity by a factor of 30: From 50 μK.arcmin to 1.5 μK.arcmin
Three orders of magnitude in power

Calibration challenge: ~ 100 times more channels, ~30 times deeper

→ Scan strategy optimized for polarization
→ Exploit where possible Planck heritage;
For COrE it is crucial to measure the re-ionization bump
At large scales foregrounds and systematics are most difficult
Planck: polarization systematics at large scales (after removal)

30 GHz

70 GHz

100 GHz

143 GHz

(D. Mennella’s talk tomorrow)
The ultimate data quality of COrE (as for Planck) is likely to be limited not by white noise, but by residual systematic effects.

- WMAP and Planck were (essentially) noise-limited
- For Planck, this would not be the case if sensitivity was a factor 5-10 better

In spite of major efforts, Planck ground calibration was a limiting factor

The main Planck residual systematics:

- **HFI**: ADC non-linearity, cosmic rays
- **LFI**: gain uncertainty, bandpass

could have been mitigated with deeper ground testing

CORE sensitivity is a factor of 30 better than Planck

A similar improvement in calibration accuracy is required
**COoRE Calibration**

*It is crucial to plan calibration in early phase of instrument/mission design*

In principle a detailed calibration plan requires a fully developed instrument and payload design, as well as scanning strategy.

**Ideal sequence:**

- Science objective
- Mission design (instrument, scan strategy, ...)
- Calibration plan
- Instrument development
- Calibration campaign

In practice, calibration plan and mission design will evolve together, with increasing levels of refinement.

**Real-life sequence:**

- Science objective
- Mission design (instrument, scan strategy, ...)
- Calibration plan

<table>
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<th>Instrument development</th>
<th>Calibration campaign</th>
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<td>Optimization</td>
<td>Tuning</td>
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</table>

*Significant impact on mission SCHEDULE and COST*
COrE Calibration

Classes of instrument parameters

1. **Photometric calibration**: Conversion of telemetry units to physical units (KCMB). Gain factors will be measured on the ground at several stages. The final calibration will be performed in-flight.

2. **Relative calibration**: stability of the gain, 1/f noise, noise spectra, zero-level stability. The redundancy of the scanning strategy will help on this.

3. **Thermal effects**: systematics induced by thermal fluctuations in the 0.1 K, 1.7 K, 4 K, 20 K, and 300 K stages; cooler induced microphonics. Thermal susceptibility of detector response. Verify that temperature sensors H/K provide sufficient monitoring of instrument thermal configuration and stability.

4. **Detector chain non-idealities**: detector (TES or KIDs) characterization, detector time-response; non-linearity of the detector response; nonlinearity of ADC converters; impact of cosmic rays; sensitivity to microphonics, temperature susceptibility, cross-talk.

5. **Spectral calibration**: filter characterization (module level), detailed bandpass measurements. These measurements will be done on the ground, as no sweeping sources is planned on the satellite. In-flight verification of the measured bandpasses will be possible through observation of diffuse and point sources with steep spectra.


7. **Polarization-specific calibration**: polarization efficiency and polarization angle of each detector; These will be measured both on-ground and in-flight.

8. **Noise characterization**: detailed measurements of the noise properties (noise power spectrum, 1/f noise, possible non-gaussianity) and their time evolution.

*(Discussion for tomorrow)*
“Calibration”:
Measurement of all the instrument/payload/SC parameters that are necessary to support in-flight operation and data analysis.

Global requirement:
The uncertainties in the measurements of all the instrument and payload parameters that have an effect on the data corresponds to a level of systematic effects that has negligible impact on the mission main science products.

Many of these parameters to be measured repeatedly at various stages of integration.

1) **Ground test levels** (*CDF study baseline*):
   - Detector, Module, Instrument (FPA), SM, AVM, RFQM, CQM, PFM

2) **In-flight** measurements using astronomical sources

Identify key parameters of instrument, P/L, S/C
Set clear requirements (value and accuracy) on each parameter

*Processing removal should be included only for very solid correction algorithm*

Correlation with other effects?
### RCA_SPR
#### RF Spectral Response
- Estimated data taking time: 3 hours
  (Note that this test requires warming-up of the facility - NOT included)

#### Sensitivity to thermal variations of the FEM
- Estimated data taking time: 4 hours

#### Sensitivity to thermal variations to temperature changes
- Both sky and load targets are at 4K, stable. The radiometer is working in normal switching mode. The radiometer is measured at RCA level, only, in cryogenic setup with the source coupled to the feedhorn aperture. The frequency of the input RF source is swept over the band of interest and the measured radiometer DC output is correlated with the input frequency to produce the RF frequency response. The test is done using the nominal operating mode and different data.

#### Variations of the BEM
- Estimated data taking time: 3 hours
- Characteristics of the BEM are monitored while perturbing by controlled amounts the physical temperatures of the BEM. The RCA gain and noise temperatures are measured according to RCA, TNG, the output voltage and offset variations are recorded from the output signal. The measurements are performed at a minimum of 3 temperatures (nominal 30K, higher and lower) to determine the first order dependence.
  - For a subset of RCAs, hysteresis effects will be checked by repeating the test with the opposite sign of the temperature change.

#### Variations of the V-grooves
- Estimated data taking time: 4 hours
- Both sky and load targets are at 4K, stable. The radiometer is working in normal switching mode. The radiometer output voltage level is monitored while perturbing by controlled amounts the physical temperatures of the three V-grooved interfaces. To determine the first order dependence, the measurements are performed at a minimum of 3 temperatures (nominal 30K, 100K, 500K) and higher and lower values by about 10-20%.

#### Variations of Reference load temperature
- Estimated data taking time: 2 hours
- The RCA output is monitored (signal level and of spectral noise) while the 4K reference load is varied by TBD E (or perturbed with a controlled sine wave) to test sensitivity. Normal RCA operations and fully differentiated data are used for this test.
<table>
<thead>
<tr>
<th>Objective of test/measurement</th>
<th>Requirements</th>
<th>On-ground (at what stage)</th>
<th>In-flight</th>
<th>Instrument model verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical coupling at FPA</td>
<td>FWHM (Edge taper): 30dB Losses &lt; 0.1dB Reflections: VSWR &gt; 40dB Cross-polarization: &lt;30dB</td>
<td>- Single detector - Module - Instrument</td>
<td>N/A</td>
<td>Compare to GRASP simulations Feeds/lenses prototypes</td>
</tr>
<tr>
<td>Main beam determination</td>
<td>FWHM per freq (value spread) Ellipticity &lt; 1.1</td>
<td>- Single detector - Module RFQM (With telescope)</td>
<td>Direct measurements of main beam exploiting signals from ALL external planets Strong polarization sources: polarized beams</td>
<td>Compare to GRASP simulations Beam variation in-band</td>
</tr>
<tr>
<td>Both total intensity and polarization</td>
<td></td>
<td>RFQM (With telescope)</td>
<td>Intermediate sidelobes down to -35 dB to -40 dB with Jupiter will be possible in-flight</td>
<td>Trade off edge taper with angular resolution</td>
</tr>
<tr>
<td>Sidelobe determination</td>
<td>Rejection needed for: Galaxy, Sun, Earth, Moon 20dB lower than Planck</td>
<td>RFQM (With telescope)</td>
<td></td>
<td>Compare to GRASP simulations Beam variation in-band</td>
</tr>
<tr>
<td>- near side-lobes, - far side-lobes</td>
<td></td>
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<td></td>
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<tr>
<td>Both total intensity and polarization</td>
<td></td>
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<tr>
<td>Internal straylight</td>
<td>Limit background on detectors from - FPA environment - P/L environment - Baffle</td>
<td>- Single detector - Module - Instrument - CQM - PFM (at CSL)</td>
<td>May be able to test during cooldown</td>
<td>Thermal model Emissivity Baffle</td>
</tr>
<tr>
<td>Filter characterization</td>
<td>- Band definition (from comp sep) - Bandwidth (sensitivity) - Consider CO lines (and other molecules)</td>
<td>- Unit/Module level - CQM (cryo conditions)</td>
<td>N/A</td>
<td>Filter models Filters prototypes</td>
</tr>
</tbody>
</table>
Planck RFQM & Optical Calibration

Main beam

Sidelobes

LFI 30 GHz
- Predicted
- Measured

HFI 100 GHz
- Predicted
- Measured

<1% between in-flight data and GRASP (<0.3% in the 70 GHz)

(Maffei, Sandri talks tomorrow)
Planck thermal calibration and thermal model

COrE temperature requirements expected to be similar to Planck led to stable conditions

Planck: thermal model crucial to optimize lifetime & extended mission
Figure 6.3-1 shows a schematic representation of the RAA test facility showing the position of the LFI inside the cryo-chamber. The approximate size of the cryo-chamber is given as well as the additional equipment needed to achieve a stable RAA temperature of 20K and a vacuum of TBD atm. As shown in the schematic diagram, the RAA waveguides and DAF are integrated in the flight configuration with the
LFI FM cryo testing
Milano, Thales-I,
August 2006

Waveguides
Back-end unit
Front-end unit
Blackbody calibrator
integrating sphere blackbody sources

Planck/HFI PFM

polarizer optical system

HFI FM cryo testing

2K Saturne plate
System level campaign

- System level test is normally conceived as a functionality test
- In the case of COre (as for Planck) is critical for calibration and performance verification

6.5.2 System-level Cryofacility and MGSE

The cryo facility will support the instrument in its nominal cryogenic conditions. Cryo-testing of the PPLM will be carried out with the CSL cryo-facility with requirements given in RD25. In particular, the cryo-facility will include an intermediate cooling stage at liquid Nitrogen temperature and it will incorporate a 20K shroud surrounding the entire PPLM during cryogenic tests and a target that can be cooled down to 4K in front of the Planck FPU.

Figure 6.3.1/1 – Thermal and cryogenic test configuration of the Planck PPLM. Left: support and test adapters (THA: Transport Handling Adapter; PHA: Planck Hosting Adapter). Right: a schematic of the system level test cryo chamber (From RD 25).

CSL facility, chamber and (possibly) shroud could be re-used for COre
Fine tuning of facility needed
New shrouds to be developed (Helium/Nitrogen?)
Conclusions

- Calibration must be planned starting in the very early stages of instrument/mission design & development
- It will be one of the main drivers of COrE schedule and cost
- Planck experience (ground and in-flight) showed the criticality of calibration down to the science exploitation
- A great deal of experience gained in Planck calibration process will be inherited by COrE