The calibration of the Low Frequency Instrument

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The LFI calibration paper

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Planck 2013 results. V. LFI calibration

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(Affiliations can be found after the references)

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ABSTRACT

We discuss the methods employed to photometrically calibrate the data acquired by the Low Frequency Instrument on *Planck*. Our calibration is based on the Solar Dipole, caused by motion of the Solar System with respect to the CMB rest frame, which provides a signal of a few mK with the same spectrum as the CMB anisotrophies and is visible throughout the mission. In this data release we rely on the characterization of the Solar Dipole as measured by *WMAP*. We also present preliminary results on the study of the Orbital Dipole, caused by the motion of the *Planck* spacecraft, which agree with the *WMAP* value of the Solar System speed to 0.2 %.
We compute the calibration constant for each radiometer roughly once per hour, in order to keep track of changes in the detectors' gain. Since non-idealities in the optical response of the beams proved to be important, we implemented a fast convolution algorithm which considers the full beam response in estimating the signal generated by the dipole. Moreover, in order to further reduce the impact of residual systematics due to sidelobes, we estimated time variations in the calibration constant of the 30 GHz radiometers (the ones with the most important sidelobes) using the signal of an internal reference load at 4 K instead of the CMB dipole.
We estimated the accuracy of the LFI calibration following two strategies: (1) we have run a set of simulations to assess the impact of statistical errors and systematic effects in the instrument and in the calibration procedure, and (2) we have performed a number of internal consistency checks on the data. Errors in the calibration of this *Planck*/LFI data release are expected to be about 0.6 % at 44 and 70 GHz, and 0.8 % at 30 GHz.

Key words. cosmic microwave background – instrumentation: polarimeters – methods: data analysis

1. Introduction

This paper, one of a set associated with the 2013 release of data from the *Planck*[1] mission (Planck Collaboration I 2013), describes the techniques we employed to calibrate the voltages measured by the LFI radiometers into a set of thermodynamic temperatures (*photometric calibration*). We also discuss the quality of our calibration in terms of the required accuracy needed to achieve *Planck*'s final science goals. This paper is part of a larger set of articles (Planck Collaboration II 2013; Planck

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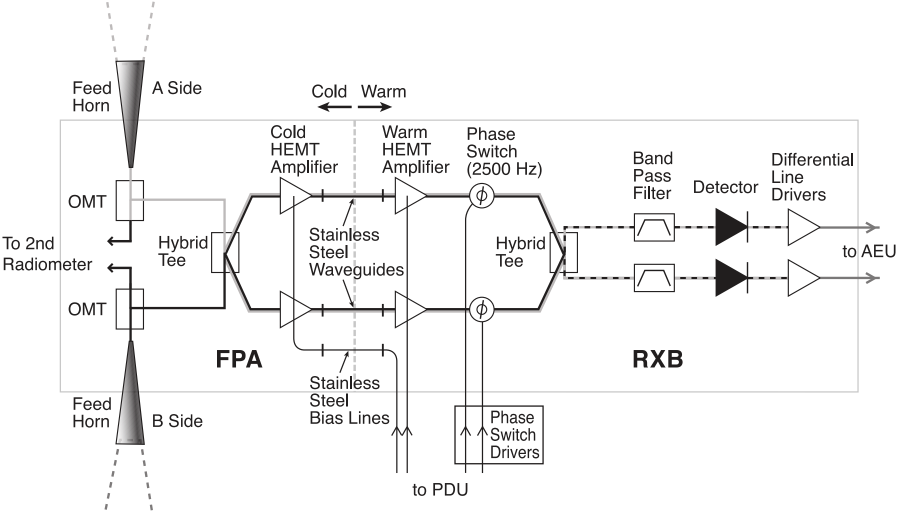
[1] *Planck* (`http://www.esa.int/Planck`) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states (in particular the lead countries France and Italy), with contributions from NASA (USA) and telescope reflectors provided by a collaboration between ESA and a scientific consortium led and funded by Denmark.

1

Part I

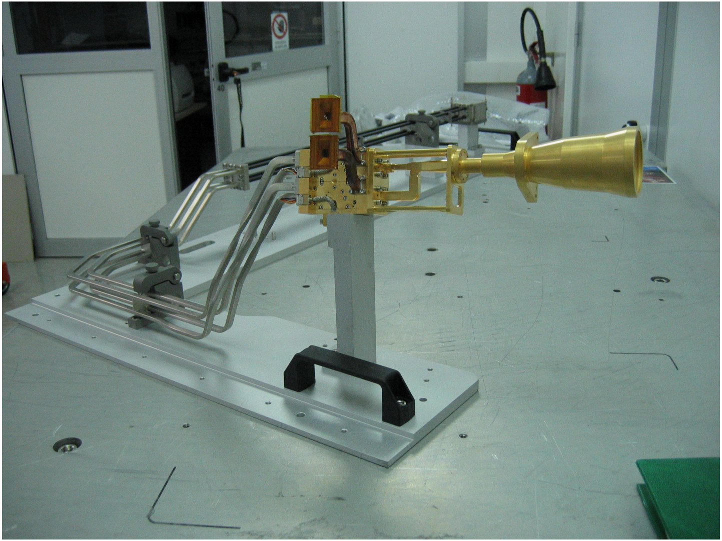
Introduction

WMAP's radiometer



(Jarosik et al., ApJS 145:413-416, 2003.)

Radiometric Chain Assembly



Radiometer equation

$$
\begin{aligned}
V_{\mathrm{sky}} &= G\big(T_{\mathrm{sky}} + T_{\mathrm{noise}}\big), \\
V_{\mathrm{ref}} &= G\big(T_{\mathrm{ref}} + T_{\mathrm{noise}}\big).
\end{aligned}
$$

Radiometer equation

$$\begin{aligned} V_{\rm sky} &= G\left(T_{\rm sky} + T_{\rm noise}\right), \\ V_{\rm ref} &= G\left(T_{\rm ref} + T_{\rm noise}\right). \end{aligned}$$

$T_{\rm sky} \approx 2.7\,\mathrm{K}$,

Radiometer equation

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$$V_{\mathrm{diff}} = V_{\mathrm{sky}} - r\,V_{\mathrm{ref}},$$

with $r = \langle V_{\mathrm{ref}} \rangle \,/\, \langle V_{\mathrm{sky}} \rangle$.

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What gets into the map is derived from V_{diff}.

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What gets into the map is derived from V_{diff}.
To build temperature maps, we need $G^{-1} \equiv K$.

Part II

Calibration of CMB experiments

Calibration sources

CMB experiments are usually calibrated using:

1. Internal calibrators (e.g., *Boomerang*);
2. Astronomical sources (*ACBAR*, *QUIET*);
3. The CMB dipole (*Maxima*, *WMAP*, *Planck*).

Calibration sources

Internal calibrators (cryogenic blackbodies) are complex to implement and use.

Calibration sources

It's difficult to find suitable calibration sources:

- Unpolarized;
- Not too bright nor too dim;
- No source is visible at any time;
- Mismatch between their spectra and the CMB's;
- TauA, CenA, RW38, Jupiter. . . : calibration accuracy limited to a few %.

The CMB dipole

WMAP and *Planck* use the CMB dipole as their calibration source:

- Visible everywhere;
- Brighter than the Galaxy and the CMB anisotropies (but not too bright to trigger non-linearities);
- Same spectrum as the CMB;
- Characterized accurately ($\sim 0.25\%$).

Origin of the dipole

Doppler effect caused by:

1. The motion of the Solar System relative to the CMB rest frame ($v_\odot = 369.0 \pm 0.9\,\mathrm{Km\,s^{-1}}$)
2. The motion of the spacecraft relative to the Sun ($v_\mathrm{Planck} \approx 30\,\mathrm{Km\,s^{-1}}$)

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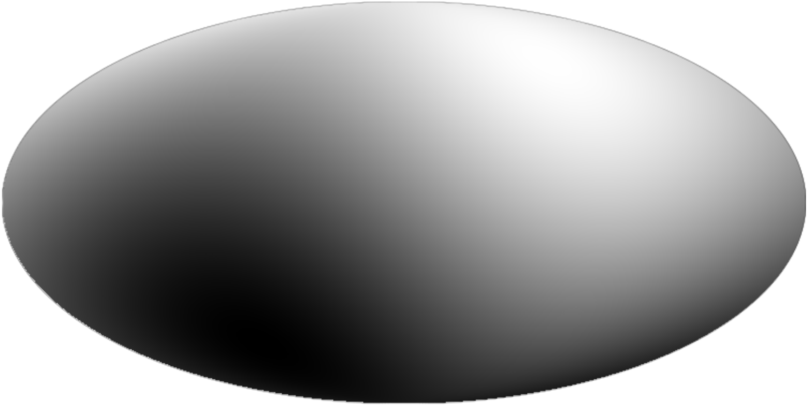
$$
\begin{aligned}
\boldsymbol{\beta} &= \frac{1}{c}\left(\mathbf{v}_\odot + \mathbf{v}_\mathrm{Planck}\right).\\
T_\mathrm{dipole}(\hat{\mathbf{x}}) &= T_\mathrm{CMB}\left(\frac{1}{\gamma(1 - \hat{\mathbf{x}}\cdot\boldsymbol{\beta})} - 1\right)\boldsymbol{\beta}\cdot\hat{\mathbf{x}}
\end{aligned}
$$

The dipole as a calibrator



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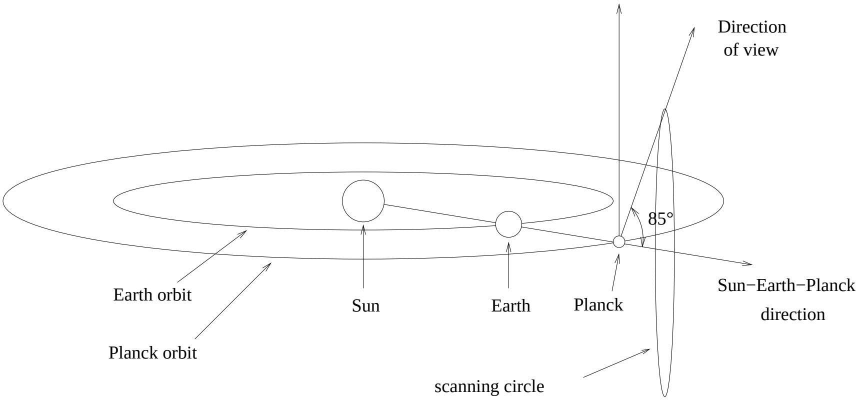


The dipole as a calibrator

To track gain changes, we recalibrate the instrument for every pointing period, i.e., once per hour (because we can!).

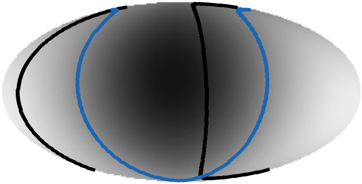
The dipole as a calibrator

The calibration code used in *LFI* models the observation of the dipole $T_{\mathrm{dipole}}(\hat{\mathbf{x}})$ to produce a timestream of temperatures $T_{\mathrm{dipole}}(t)$.

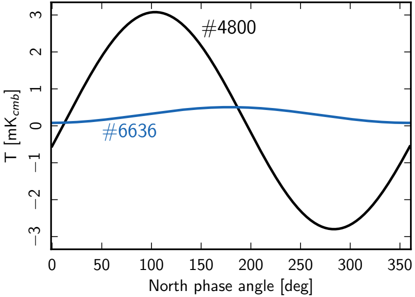
The dipole as a calibrator

$T_{\mathrm{dipole}}(t)$ has the form

$$T_{0,i} + \Delta T_i \sin\left(2\pi\nu_{\mathrm{spin}} t + \varphi_i\right).$$



The amplitude ΔT_i depends on the orientation of the spacecraft with respect to the dipole axis.



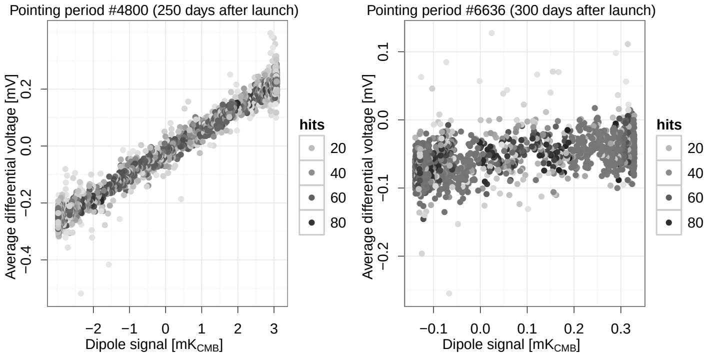
The dipole as a calibrator

Fit $T_{\mathrm{dipole}}(t)$ with V_{diff} to find the calibration constant $K \equiv G^{-1}$, in K/V:

$$\delta V_{\mathrm{diff}} = G \delta T_{\mathrm{dipole}}$$

(if the noise temperature T_{noise} is kept constant.)

The dipole as a calibrator



The dipole as a calibrator

Once we have the set of K_i,

$$T_{\mathrm{diff}}(t) = K_i \, V_{\mathrm{diff}}(t)$$

is the calibrated timestream of the i-th pointing period.

Part III

Complications

Observing the dipole

Not straightforward to use:

- The Galaxy and the CMB are small but not negligible;
- *LFI* beams are not pencil-like;
- You must scan the sky wisely in order to make use of it.

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4. Set $V_{\mathrm{diff}} \leftarrow V_{\mathrm{diff}} - V_{\mathrm{dirt}}$
5. Repeat from 2 until convergence

Observing the dipole

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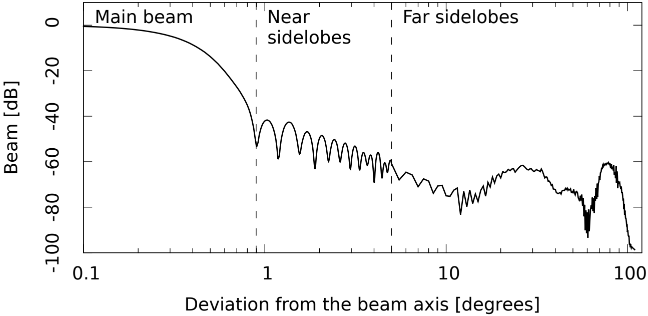
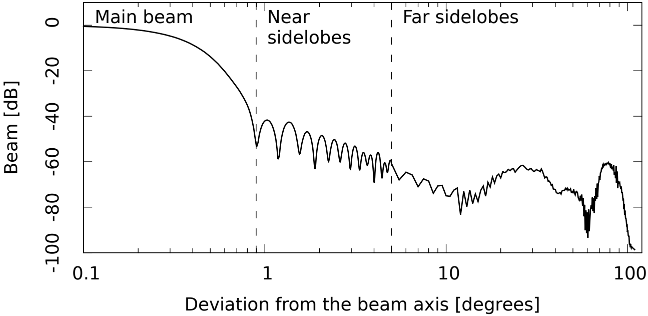
LFI beams


Main beam
Near
sidelobes
Far sidelobes
Beam [dB]
0
-20
-40
-60
-80
-100
0.1
1
10
100
Deviation from the beam axis [degrees]

LFI beams



Two problems:

- The main beam is not pencil-like;
- Sidelobes are asymmetric.

The elegant 4π convolver

The best solution would be to convolve the dipole with the beam. Unfortunately this takes a long time!

Michele Maris (OATS) found a clever way to quickly compute the convolution using the high symmetry of the Dipole.

(This is an improvement over *WMAP* and *HFI*, which assume a pencil beam!)

Observing the dipole

Not straightforward to use:

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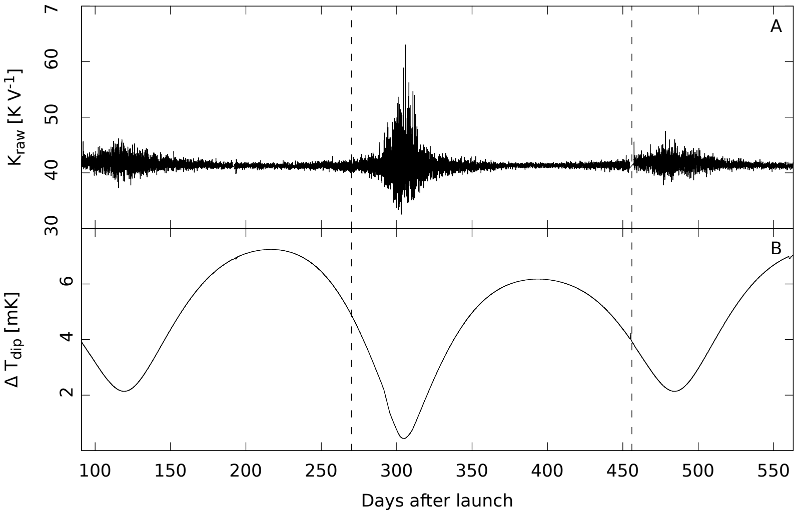
Dipole maxima and minima



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Assuming T_{ref} constant, a variation in G triggers a change in V_{ref} is due to a change in G. Therefore:

$$\frac{\delta G}{G} = \frac{\delta V_{\mathrm{ref}}}{V_{\mathrm{ref}}} = -\frac{\delta K}{K}.$$

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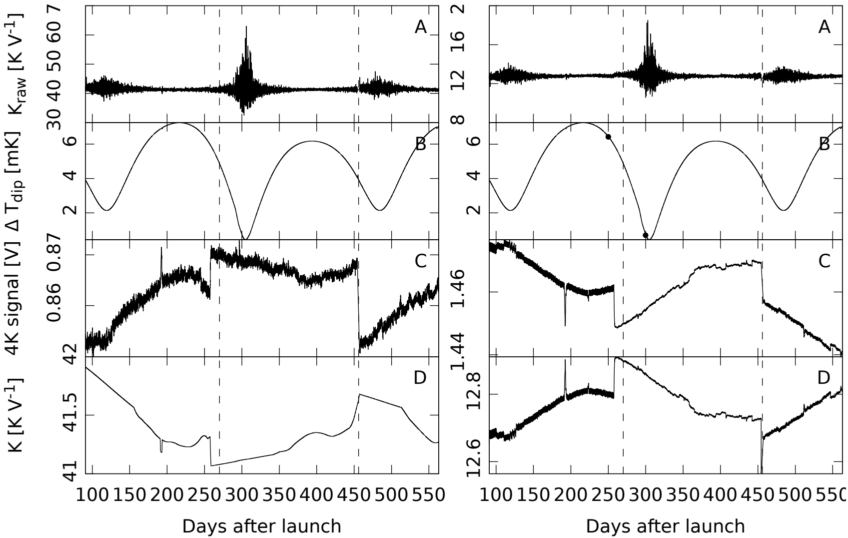
$$

(This is something that *WMAP* couldn't do.)

Dipole maxima and minima



Part IV

Conclusions

Further work

- Convolution across the bandwidth
- Galaxy pickup through sidelobes
- Further improvements to the methods
- Sidelobes and stellar aberration

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See you in 2014!