Data Analysis of the Planck/LFI Ground-Test Campaign

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ABSTRACT

The ESA Planck mission is the third generation (after COBE and WMAP) space experiment dedicated to the measurement of the Cosmic Microwave Background (CMB) anisotropies. Planck will map the whole CMB sky using two instruments in the focal plane of a 1.5 m off-axis aplanatic telescope. The High Frequency Instrument (HFI) is an array of 52 bolometers in the frequency range 100-857 GHz, while the Low Frequency Instrument (LFI) is an array of 11 pseudo-correlation radiometric receivers which continuously compare the sky signal with the reference signal of a blackbody at $\sim$ 4.5 K.

The LFI has been tested and calibrated at different levels of integration, i.e. on the single units (feed-horns, OMTs, amplifiers, waveguides, etc.), on each integrated Radiometric Chain Assembly (RCA) and finally on the complete instrument, the Radiometric Array Assembly (RAA). In this paper we focus on some of the data analysis algorithms and methods that have been implemented to estimate the instrument performance and calibration parameters.

The paper concludes with the discussion of a custom-designed software package (LIFE) that allows to access the complex data structure produced by the instrument and to estimate the instrument performance and calibration parameters via a fully graphical interface.

Keywords: Planck, Low Frequency Instrument, LFI, data analysis, radiometer

1. THE PLANCK/LFI INSTRUMENT

1.1. The Planck Mission

Planck\textsuperscript{1} is a space mission of the European Space Agency (ESA) which will image the temperature and polarization anisotropies of the Cosmic Microwave Background (CMB) with an unprecedented combination of sensitivity, angular resolution and sky and frequency coverage. Following the breakthrough of the COBE/DMR\textsuperscript{2} discovery of CMB anisotropy, and the WMAP satellite launched in June 2001, Planck will be the third generation space mission dedicated to CMB observations.

The data gathered by these missions is revolutionizing modern cosmology by a precise determination of the fundamental cosmological parameters which govern our Universe, like the present expansion rate, the average density of the universe, the amount of dark matter, and the nature of the primordial fluctuations from which all structures in the universe arose. Planck will provide at the same time full sky surveys in a broad range of frequencies, with fundamental implications for a large area of problems in astrophysics.\textsuperscript{3}

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1.2. The Low Frequency Instrument (LFI)

Planck implements two instruments observing the sky through a common telescope: the High Frequency Instrument (HFI) and the Low Frequency Instrument (LFI). HFI is an array of 52 bolometers cooled at 0.1 K in the frequency range 100-857 GHz, while LFI is an array of 11 pseudo-correlation radiometric receivers centered at 30, 44 and 70 GHz and cooled at \( \sim 20 \) K by the Planck Sorption Cooler. Each receiver makes a differential measurement of the sky signal (\( \sim 2.7 \) K) by comparing it with the signal of a stable reference load (\( \sim 4.5 \) K) thermally connected to the HFI 4 K box.

To minimise power dissipation in the focal plane, the Radiometric Array Assembly (RAA) is split into two subassemblies: the Focal Plane Unit (FPU), kept at \( \sim 20 \) K, and the Back End Unit (BEU), mounted on top of the Planck Service Module at about 300 K. The FEU is connected to the BEU by means of waveguides (WGs), which carry the microwave signals and by means of the cryo harness that will carry the bias currents for the front-end active components. Both the WGs and the cryo harness are connected to three passive radiators that dissipate the heat coming from the BEU.

In the front-end part of the LFI feed horns the radiation is separated by an OrthoMode Transducer (OMT) into two perpendicular linearly polarised components that propagate independently through two parallel radiometers. In each radiometer, the sky signal and the signal from a stable reference load at \( \sim 4.5 \) K are coupled to cryogenic low-noise High Electron Mobility Transistor (HEMT) amplifiers via a 180° hybrid. One of the two signals then runs through a switch that applies a phase shift which oscillates between 0 and 180° at a frequency of 4096 Hz. A second phase switch will be present for symmetry on the second radiometer leg; this switch will not introduce any phase shift in the propagating signal. The signals are then recombined by a second 180° hybrid coupler, producing an output which is a sequence of signals alternating at twice the phase switch frequency.

In the back-end of each radiometer (see bottom part of fig. 2) the RF signals are further amplified, filtered by a low-pass filter and then detected. After detection the sky and reference load signals are integrated, digitised and then differenced after multiplication of the reference load signal by a so-called gain modulation factor, \( r \), which has the function to make the sky-load difference as close as possible to zero.

This design has several advantages:

1. By doing a differential measurement with a fixed load, the impact of gain fluctuations in the front-end on the final measurement is reduced.

2. The use of phase-switches alternating the output with a frequency of 4096 Hz will reduce the impact of 1/f back-end noise.
The signal coming from the sky is split into two orthogonal polarization components and then amplified, compared and differenced with the signal coming from a stable reference load at $\sim 4.5$ K (top). Through a set of waveguides the sky/reference signal (alternating with a frequency of $1/4096$ Hz) is carried to the back-end module (bottom), where it is further amplified, digitized and compressed, and then sent to Earth.

3. Using an $r$ modulation factor lets to use a reference load with a temperature significantly different from the sky ($T_{\text{sky}} \sim 2.7$ K, $T_{\text{ref}} \sim 4.5$ K).

The testing of the LFI goes through a number of different phases: in each of them the instrument is tested in a different level of integration, e.g., Radiometric Chain Array (RCA) tests are done on a single feed horn (two radiometers, one per each polarization direction), while Radiometric Array Assembly (RAA) tests are done on the integrated instrument.

2. ANALYSIS OF SOME LFI RCA/RAA TESTS

2.1. Estimation of the linearity of LFI radiometers

Several noise properties (noise temperature, photometric calibration, input offset, linearity, isolation) can be obtained from a test in which either the sky or the reference load temperature is varied in steps and the corresponding output voltage is recorded by each diode.

In fig. 3 we show a schematic of the output from such a test; assuming linear response we have that the relationship between the output sky voltage and the input sky temperature is

$$V_{\text{sky}} = G \times T_{\text{sky}}^{\text{ant}} + V_{\text{sky}}^0,$$

where $G$, the slope, is the voltage-temperature calibration constant and $V_{\text{sky}}^0$ the voltage we would measure with a zero input temperature which also corresponds to $G \times T_N$.

We can therefore obtain the following parameters from this test:

1. Noise temperature. By setting $V_{\text{sky}}$ in (1) we can calculate the intercept with the $x$ axis which is $T_{\text{sky}}^{\text{ant}} = -V_{\text{sky}}^0/G \equiv -T_N$. Therefore we can calculate the noise temperature from a ramp of input sky temperature by fitting the data with a straight line and calculating the intercept with the $x$ axis.
2. Isolation. Assuming that the sky load temperature is varied and the reference load temperature is maintained constant, the isolation is defined as the relative change in the reference voltage output compared to the total voltage output,

\[ I = \frac{\Delta V_{\text{ref}}}{\Delta V_{\text{sky}} + \Delta V_{\text{ref}}} \].

(2)

The statistical uncertainty on the noise temperature calculated with this method can be calculated from the relative uncertainties in the slope \( G \) and in the intercept \( V_0^{\text{sky}} \) that we indicate with \( \sigma_r(G) \) and \( \sigma_r(V_0^{\text{sky}}) \) (these are calculated as a result of the linear fitting procedure\(^9\) FITEXY).

In particular the relative error in the noise temperature estimation correponds to

\[ \sigma_r(T_N) = \sigma_r(G) + \sigma_r(V_0^{\text{sky}}). \]

3. Photometric calibration constant. It is simply given by the slope of the straight line fitting the data and the statistical uncertainty is provided by the FITEXY procedure used to fit the data.\(^9\)

An analytical approximation is provided by the case in which the calibration constant is calculated from two temperature points, i.e.:

\[ G = \frac{T_{\text{high}} - T_{\text{low}}}{V_{\text{high}} - V_{\text{low}}}. \]

(3)

In this case the error will be given by:

\[ \sigma(G) = \sqrt{\frac{\sigma^2(T_{\text{high}}) + \sigma^2(T_{\text{low}})}{(V_{\text{high}} - V_{\text{low}})^2} + \frac{(T_{\text{high}} - T_{\text{low}})^2[\sigma^2(V_{\text{high}}) + \sigma^2(V_{\text{low}})]}{(V_{\text{high}} - V_{\text{low}})^4}}. \]

(4)

2.2. Estimation of the radiometer noise properties

2.2.1. Test objective and sequence

The determination of the receiver noise properties is one of the key tests in the LFI calibration plan. In practice the test consists in acquiring data in stable environmental conditions and calculate the noise spectrum from which the following quantities can be determined (see also fig. 4):

- white noise level, from which the following parameters can be calculated:
Figure 4. Typical power spectrum density showing the white noise limit, some isolated frequency peaks and the 1/f noise limit.

- sensitivity, i.e. the white noise limit;
- noise effective bandwidth. The effective bandwidth of the RCA can be calculated from the amplitude spectrum using the white noise limit of the total power or differenced noise spectrum using the relationship linking the r.m.s. receiver sensitivity to the bandwidth and integration time:

\[ \Delta T_{\text{r.m.s.}} = K \frac{T_{\text{signal}} + T_{\text{noise}}}{\sqrt{\beta \tau}}, \]  

where \( K \) is a constant which depends on the operating mode of the radiometer.
- noise temperature (requires estimation of effective bandwidth and photometric calibration);

- 1/f noise knee frequency, i.e. the frequency where the 1/f noise has the same power as the white noise.
- 1/f noise slope, i.e. the \( \alpha \) factor in the 1/f\(^\alpha\) profile of the noise.
- gain modulation factor,\(^1\) approximately equal to

\[ r \simeq \frac{T_{\text{ant}}}{T_{\text{ref}}} + T_{N} \]

In order to resolve knee frequencies of the order of \( \sim 10 \text{ mHz} \) the acquisition time must be of the order of 1 hour in stable conditions. To resolve the white noise level, instead, a fast acquisition is necessary (as in the RCA tests where the full sampling rate is 4096 Hz, high enough to see the white noise level also in the total power data streams). Where fast sampling is not available (as in the default configuration of the RAA tests) the white noise plateau can be resolved by analysing differenced data streams, in which the major part of the 1/f noise is removed. In the following paragraphs we discuss the details of the algorithms used to calculate noise spectra.

2.2.2. Receiver output

The signal at the four RCA outputs is a sequence of sky – reference samples alternating at the phase switch frequency, i.e. 4096 Hz (see fig. 5).

The output from each diode can be separated into two independent data streams of sky and reference samples that can be expressed (assuming gain matching better than 1 dB and noise temperature matching better than 10%) in the following form:
\[ s(t_j) \approx aG_1(t_j)k\beta[T_{\text{ant\ sky}} + T_{N_1}(t_j)] \]
\[ l(t_k) \approx aG_1(t_k)k\beta[T_{\text{ant\ ref}} + T_{N_1}(t_k)] \]

where \( s \) and \( l \) indicate the sky and reference load samples, respectively, \( a \) is the diode constant, \( k \) the Boltzmann constant, \( \beta \) is the RCA effective bandwidth, \( G_{1,2}(t_j) \) represent the gain of the two radiometer arms at time \( t_j \), \( T_{N_{1,2}} \) represents the noise temperature of the two radiometer arms at time \( t_j \) and \( t_k = t_j + \delta t \) where \( \delta t \) represents the time interval between two subsequent RCA samples.

The differenced output for each diode can therefore be written as:

\[ d_{\text{diode1}} = s(t_j) - r_{\text{diode1}} \times l(t_k) \]
\[ d_{\text{diode2}} = l(t_j) - r_{\text{diode2}} \times s(t_k) \]

The differenced radiometer output is, therefore,

\[ d_{\text{rad}} = \frac{1}{2} \left( \frac{d_{\text{diode1}}}{\langle G_1 \rangle} - \frac{d_{\text{diode2}}}{\langle G_2 \rangle} \right) \]

The gain modulation factor, \( r \), that appears in eq. (7) is calculated from the data\(^{10} \) and is approximately equal to:

\[ r \approx \frac{T_{\text{ant\ ref}} + T_N}{T_{\text{ant\ ref}} + T_N} \]

2.2.3. Amplitude and power spectrum – basic definitions

We follow here a classical approach to the discrete Fourier Transform.\(^{11} \) Let us consider a time ordered signal \( x(t) \) sampled at equal times \( \delta t \), so that \( x(t) \rightarrow \bar{x} = x_j(t_j) \), where \( t_j = t_0 + j \times \delta t, \quad j = 1, \ldots, N \). The discrete Fourier transform of \( \bar{x} \) is given by:

\[ X_k = \sum_{j=0}^{N-1} x_j e^{i2\pi j k/N}, \quad k = 0, \ldots, N - 1. \]

The amplitude spectrum of \( \bar{x} \) is defined in the frequency range

\[ f_k = \frac{k}{N\delta t} = \frac{k}{2f_c} \frac{k}{N}, \quad k = 0, 1, \ldots, \frac{N}{2}, \quad f_c \]
and can be written as:

\[ A(0) = \frac{1}{N} |X_0| \]
\[ A(f_k) = \frac{1}{N} [ |X_k| + |X_{N-k}| ] \quad k = 1, 2, \ldots, \left( \frac{N}{2} - 1 \right) \quad (11) \]
\[ A(f_c) = A(f_{N/2}) = \frac{1}{N} |X_{N/2}| \]

The power spectrum of \( \vec{x} \), instead, is defined as follows:

\[ P(0) = \frac{1}{N^2} |X_0|^2 \]
\[ P(f_k) = \frac{1}{N^2} [ |X_k|^2 + |X_{N-k}|^2 ] \quad k = 1, 2, \ldots, \left( \frac{N}{2} - 1 \right) \quad (12) \]
\[ P(f_c) = A(f_{N/2}) = \frac{1}{N^2} |X_{N/2}|^2 \]

The amplitude and power spectral densities (\( A_{SD} \) and \( P_{SD} \), respectively) are defined in terms of the sampling frequency \( f_s = 1/\delta t \) so that \( A_{SD} = A/\sqrt{f_s} \), \( P_{SD} = P/\sqrt{f_s} \).

2.2.4. Welch windowing function and frequency rebinning

The amplitude and power spectra calculated according to the equations discussed in the previous section have two main limitations, i.e.:

1. the power spectra are calculated using a square windowing function in the frequency domain, which cause a significant leakage of the signal between various frequencies;
2. the uncertainty in the spectrum estimate at each frequency does not reduce using longer acquisition times. In fact by acquiring longer one gets a finer resolution between the zero and the Nyquist frequencies but there is no gain in the statistical accuracy of the estimate.

The first limitation can be mitigated by using a smoother window function to reduce the frequency leakage; in other words the discrete Fourier transform is calculated by adding weights to the coefficients \( x_j \) that are maximum at the centre of the data stream and zero at the borders. In practice:

\[ \tilde{X}_k = \sum_{j=0}^{N-1} w_j x_j e^{i2\pi j k/N} \quad k = 0, \ldots, N - 1 \quad (13) \]

where \( w_j \) represent the weights. In this case the amplitude and power spectra can be written as:

- Amplitude spectrum

\[ \tilde{A}(0) = \frac{1}{W_{ss}} |\tilde{X}_0| \]
\[ \tilde{A}(f_k) = \frac{1}{W_{ss}} [ |\tilde{X}_k| + |\tilde{X}_{N-k}| ] \quad , k = 1, 2, \ldots, \left( \frac{N}{2} - 1 \right) \quad (14) \]
\[ \tilde{A}(f_c) = \tilde{A}(f_{N/2}) = \frac{1}{W_{ss}} |\tilde{X}_{N/2}| \]
• Power spectrum

\[
\tilde{P}(0) = \frac{1}{W_{ss}} |\tilde{X}_0|^2 \\
\tilde{P}(f_k) = \frac{1}{W_{ss}} \left[ |\tilde{X}_k|^2 + |\tilde{X}_{N-k}|^2 \right] \quad k = 1, 2, \ldots, \left( \frac{N}{2} - 1 \right) \\
\tilde{P}(f_c) = A(f_{N/2}) = \frac{1}{W_{ss}} |\tilde{X}_{N/2}|^2
\]

where \( W_{ss} = \sum_{j=0}^{N-1} w_j^2 \). In practical FFT applications a widely used window function is the so-called Welch window function, that is defined as:

\[
w_j = 1 - \left( 1 - \frac{j - N/2}{N/2} \right)^2.
\]

In order to address the second limitation, i.e. to increase the spectrum estimation accuracy, we applied data segmentation to the input data streams. The idea is simply to divide the input data into \( K \) segments of \( 2M \) points each, calculate the FFT of each segment and then average the \( K \) spectra to obtain a spectrum estimate at \( M + 1 \) frequency values from 0 to \( f_c \) (see fig. 6).

An improved version of this concept consists in partially overlapping the bins as shown in fig. 7. This results in an increased computational load (twice as many FFTs are computed) with a corresponding reduction in the power spectrum variance. The total variance reduction (considering that the segments are not independent) is of the order of \( 9K/11 \).

The price paid for the accuracy increase is in a reduction in frequency resolution. In particular the lowest resolved frequency is equal to \( K f_{\text{lowest}} \), where \( f_{\text{lowest}} = N/(2\delta t) \) is the lowest detectable frequency in the case without rebinning.

2.2.5. Calculation of Knee Frequency

The radiometric data streams will typically show a frequency spectrum characterised by a white noise limit at high frequencies, a series of frequency peaks caused by periodic fluctuations in the measured signal (either induced or spurious) and a \( 1/f^\alpha \) low frequency tail, the so-called \( 1/f \) noise limit (see fig. 4).
The knee frequency, $f_k$, is defined as the frequency at which the $1/f$ tail disappears under the white noise plateau. From a computational point of view, $f_k$ is generally calculated by fitting the low frequency end of the power spectrum with a power law (which yields the slope $\alpha$) and then find the frequency at which the fitted power law reaches the value of the white noise limit. Only one user inputs is required to perform the calculation: $N_{\text{first}}$, i.e. the number of points to use to interpolate the low frequency end of the power spectrum with a power law.

2.3. Removal of BEM fluctuations

During the RAA tests an unwanted fluctuation in the BEU temperature was detected (see fig. 8). This fluctuations appears to couple both with the sky load and with the thermal tent inside the cryo-chamber, which implies that the measurements performed using these data will be affected by this coupling.

Although in the Flight Model tests we do not expect to have similar fluctuations, we have nevertheless developed a software procedure to remove this effect by correlating the scientific with the housekeeping data has been setup. By considering a "stationary" interval in the test (i.e. where the sky load and the reference load are both kept at a fixed temperature), we derived a transfer function of the BEU temperature to the radiometer output, and then used this transfer
function to remove the effect of this fluctuation on the data used in the analysis. In fig. 9 we show, as an example, the radiometric output (LFI28 channel A) before and after the cleaning procedure.

3. THE LIFE SOFTWARE SUITE

In order to have a common tool to perform the analysis for the scheduled tests, a team made by people involved in the RCA/RAA tests has developed a software tool named LIFE (LFI Integrated perFormance Evaluator). See fig. 10

Currently LIFE is composed by two packages: RaNA (Radiometer aNALyser) and LAMA (LFI Array Measurements Analyser), to analyze the RCA and RAA tests respectively. They will be eventually completed with a tool to analyze the flight data and a software to measure the sorption cooler performances.

RaNA and LAMA are designed in a modular way. We wrote a number of analysis modules using the IDL language to estimate the radiometer linearity, noise temperature, noise properties and so on (see fig. 10). They were designed in order to be used both by RaNA and LAMA without any modification in the code. The trick is to let the analysis modules access the data only through an Input module, which is substantially different in RaNA and LAMA but provides the same data access interface.

Both RaNA and LAMA provide a “Report module” (REP) which records any calculation done by the other modules and generates a LaTeX report when asked by the user. The REP module is able to insert data plots (in Postscript format) in the final report. These reports are regularly circulated among the LFI scientific community, as their standard format makes any calculation performed with LIFE easily reproducible by the other people in the team.

4. CONCLUSIONS

Despite its complexity, the LFI RCA/RAA data analysis pipeline has showed to be an efficient way to test the performance of the radiometers. The experience gained in the RCA/RAA QM tests will be extremely useful during the FM tests (which, at the time of writing, are already started, at least for the RCAs).
The use of a dedicated software tool (LIFE) developed by the same people actively involved in the tests proved to be an extremely productive way of working. The analysis modules were continuously upgraded to answer the most important needs, even while doing the tests in the laboratory. The development of LIFE still continues, foreseeing its use in the RAA FM tests to be done in the next months and further on during system level tests and during flight operations.

REFERENCES


