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Abstract

The main reason for the extension of the Planck mission beyond the lifetime of the 0.1-K dilution cooler is to obtain further data which will improve our understanding of systematic effects. In the present report, we justify the continuation of the current scanning strategy in order to obtain a sixth survey, allowing for better sensitivity and further "jackknife" (survey difference) tests. The fifth survey is already improving the estimates of the polarisation leakage for two of the LFI horns, and this improvement will continue with the sixth survey during the extension. In addition, we confirm the "deep rings" scanning strategy to improve mapping of the beams using radio sources, specifically Jupiter and the Crab Nebula. We propose to maintain the current spin rate: no other changes are foreseen, except the possibility to increase the sampling of some house-keeping data.

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LFI Project System Team

1 Introduction

Planck was launched on 14 May 2009 and started surveying the sky on 15 August 2009. The payload is composed of two instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI), designed to cover the peak of the Cosmic Microwave Background (CMB) spectrum and to characterize the spectra of the main galactic foregrounds. The instruments are cooled by three active subsystems: a Sorption cooler (SCS) cooling to 20 K, a Stirling cooler to 4 K and a Dilution cooler to 100 mK. Planck is operated by the Mission Operations Centre (MOC) at ESOC in Darmstadt, Germany, using the two ESA Ground Stations at New Norcia, Australia and Cebreros, Spain. The Planck Science Office (PSO) is located at ESAC, Villanueva de la Cañada, Spain and two operational teams for each of the two instruments (one for the instrument operations and one for the data processing) are located in Trieste, Italy for the LFI and in Paris, France for the HFI.
Since start of survey operations, Planck has been acquiring high-quality data continuously, and at the time this proposal is being submitted, it has already completed two full sky surveys. The original mission operations of 15 months has been extended by 12 additional months (ESA/SPC(2009)25) up to the end of the operational life of the HFI, so that operations are now approved until end November 2011, allowing the completion of more than 4 surveys of the entire sky with Planck's full payload complement. In this document we present a proposal to extend the operation of Planck's Low Frequency Instrument (LFI) beyond that date.

2 Science Case

2.1 The Planck Nominal Mission

The main objective of the Planck mission, as described in the 1996 Phase A report, is to measure temperature anisotropies in the CMB radiation with an accuracy set by fundamental astrophysical limits. To achieve this, Planck images the whole sky with an unprecedented combination of low noise ($\Delta T/T \sim 2 \times 10^{-6}$), high angular resolution (reaching 5') and wide frequency coverage (30–857 GHz). The detailed science case is described in "The Scientific Programme of Planck" (or "Bluebook", published in 2005). The actual performance of Planck is described in a special issue of Astronomy & Astrophysics[1] (currently in press to be published in September 2010, vol. 520).
From the start of operations, Planck's payload has performed extremely well. With no surveying interruptions so far, and with a cryogenic lifetime longer by a factor of two with respect to its original nominal requirement, it can truly be said that Planck already exceeds very significantly its design expectations.

[1] The papers referenced describe the performance of Planck as tested on the ground, but in fact its in-flight performance is in most critical respects identical to that measured on the ground.

2.2 2.2 Extension Concept and Expected Science Return

The basic observational concept for the Planck mission has been to survey the sky completely several times over. Increasing the number of times that the sky is surveyed gives significant scientific advantages, in terms of (a) increased data redundancy and consequent control of subtle systematic effects; (b) additional observations of calibrators; (c) improved sensitivity per sky pixel. Doubling the number of surveys originally planned (to a total of 4) was the basis for the already- approved 12-month extension of Planck, and a similar strategy has been very successfully applied by the Wilkinson Microwave Anisotropy Probe (WMAP) mission for 9 years. Similarly, increasing the currently-foreseen four surveys with two additional LFI surveys would add significantly to Planck's legacy value. Nonetheless, it is here asserted that the relatively short additional surveying time allowed by the Sorption cooler's lifetime would be even better used in a different manner.

During its approved mission, the strategy for Planck is to spread integration time as homogeneously as possible over the whole sky. During an LFI-only extension we propose to modify significantly this strategy in such a way as to concentrate the integration time of the LFI detectors into "deep annuli" across the sky. Satellite and orbital constraints allow the spin axis to be pointed continuously towards the same location on the sky for periods of up to 19 days (depending on the location of the satellite in its orbit around L2). It is proposed to observe a series of ~30 such "deep annuli" over 12 months, typically about 1.5 degrees wide, separated across the sky by 10-20 degrees and intersecting only near the ecliptic poles (see Fig. 1). Each annulus covers about 1.2% of the sky, so that after 12 months, about 30% of the sky will have been covered with very high sensitivity. A significant operational advantage of this strategy is that it does not depend critically on the lifetime (as would be true for all-sky surveys), but can be limited to whatever lifetime the sorption cooler will finally provide.

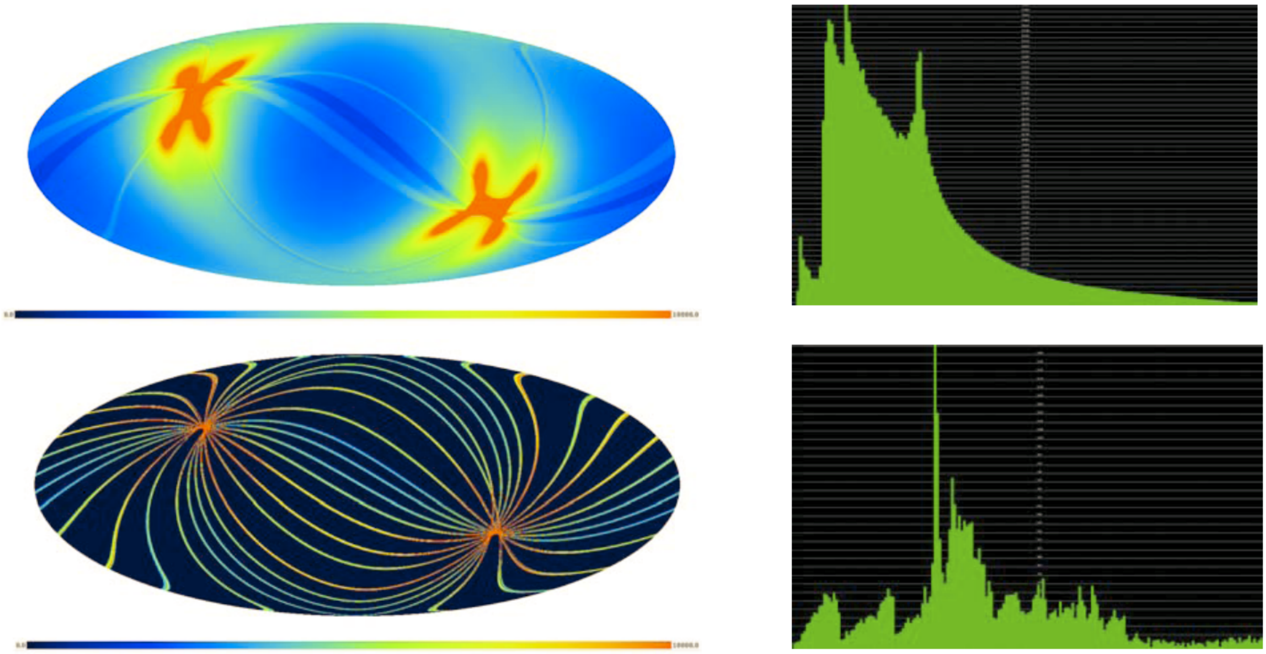
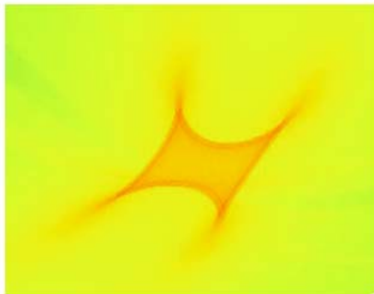


Figure 1: The left-hand images show maps of integration time for the approved survey (top), and (bottom) a typical set of deep annuli covering 6 months (or half of the requested extension). On the right are shown histograms of integration time for the approved survey (top), and for a single deep annulus (bottom). The median integration time for the approved survey and of the shortest annuli are 3500 secs/square degree, while for the longest annuli it is ~2.5 times larger.

The fundamental scientific advantages of such a strategy over a "standard" survey are:

- The noise level in the annuli will be very low. For the highest frequency LFI channel (70 GHz), the total integration time per sky pixel can be as high as 2.5 times (median) that achieved during the foreseen 4 surveys, and at 30 GHz the improvement factor is as high as 7. This implies that in these areas the current significant difference in noise level between the LFI's highest frequency (70 GHz) and the HFI's lowest frequency (100 GHz) can be removed or significantly reduced (that difference is currently a factor of 1.6 per LFI pixel).
- The deep annuli can be located at preferred locations on the sky, for example to cover key calibration sources such as planets. The standard surveying strategy of Planck also leads to regions where the integration time is very high (so-called "deep fields", see inset). However, the location of these fields is determined by the sky scanning strategy and cannot be optimised; in particular they are necessarily located near the ecliptic poles, where neither planets nor other key calibration sources are located.
- The geometry of the deep annuli selects specific angular scales which will be observed with high sensitivity. The deep fields obtained during standard surveying are compact and inhomogeneous (see inset), and therefore they do not provide high sensitivity to medium and large angular scales.



An important consideration for the effectiveness of the deep-annulus approach in some of the areas addressed above is the spatial overlap between different frequency channels. Although the design of the Planck focal plane is such that the lines of sight of detectors of differing frequency are separated on the sky, the 1.5 degree-wide deep annuli will overlap partially at the LFI frequencies. For specific targets such as regions important for component separation, the width of the annulus can be adjusted to increase the overlap – indeed the specific way in which each annulus is scanned will be individually planned according to the region being observed.

The specific characteristics of the deep annuli will allow for crucial improvements in several aspects of detector characterisation and calibration (more details are provided in Appendix):

- Planet mapping and optical beam measurements. Accurate knowledge of the optical angular responsivity is of key importance for the scientific analysis of both LFI and HFI data, and is in fact one of the major limitations to the extraction of cosmological information from the CMB. Even a very small error in the estimated FWHM of a beam, e.g. 0.1%, implies a significant ~1% error in the window function (and therefore on the reconstructed power spectrum) at multipoles ~1500 at 70GHz, and at multipoles ~2000 at 100GHz. In the current LFI measurements of the brightest planet (Jupiter), the agreement with the predicted nominal pattern is excellent in the central part of the beam, but at intermediate power levels (-15 to -20 dB) the data can accommodate deviations in the main optical parameters (mirror shape, alignment, FPU and horn location) at the several times 0.1% level. The improved sensitivity (factor of ~20) achievable on individually measured patterns in deep scanning of planets will lead to a corresponding reduction of the uncertainty in the beams measured, and will translate directly into significantly improved fits to models of the Planck optics. Measurements of the optical parameters using LFI beams are particularly important for HFI, in view of the time responsivity of HFI's bolometers, which is partly degenerate with the optical response. Finally, the improved knowledge of the beam shape will allow Planck to establish the most accurate absolute brightness of the major planets to date, and will provide the basis for the calibration of many future ground- and space-based experiments at similar wavelengths.

- Polarisation calibration and mapping of the Crab Nebula. Polarization has become a strategic scientific objective for Planck and its success depends strongly on the understanding of instrumental systematic effects. The errors on the orientations of the linearly polarised detectors are currently one of the major contributors to CMB polarisation uncertainties. These errors can be constrained by mapping Taurus A (the Crab), at present the only brightly polarised source at mm-waves known to sufficient accuracy to be used as a calibrator. The key in this case is in being able to scan the Crab with a range of focal plane orientations. The proposed strategy of observing deep annuli provides the freedom to re-orient the scans of the Crab within the full range of satellite limitations, resulting in crucial additional leverage on the measurements. An important advantage also results for HFI: because in the deep annuli the LFI sensitivity will be close to that of HFI, and because the dominant polarization systematics are of different nature in the two instruments, a comparison of the independently-obtained polarization maps (particularly between LFI 70GHz and HFI 100GHz, where foreground signatures are similar) in those regions will yield a quantitative assessment of the residual systematic error on HFI polarization.
- Polarisation calibration and the shape of the bandpass. Currently, the residual uncertainty in the knowledge of the band-shapes leaves an error that is the dominant systematic effect in the LFI polarization analysis. The parameters needed to correct for this spurious effect with improved precision can be recovered by measuring bright, low-polarization sources with known frequency spectra, such as bright HII regions. Deep observations over M42 and other strong unpolarised sources (such as the Rosette Nebula, W3, …) will allow us to reduce the current residual effect by a factor of ~6, thus pushing the systematic effect below detector noise level. For example, current measurements of M42 lead to spurious power in Stokes U and Q of order 2%; correction using ground based models can reduce this level to below 0.5% - but this can only be done with confidence if the model parameters are verified in flight with deep measurements on multiple sources.
- Knowledge of gain stability and noise properties. As the experience of both WMAP and COBE-DMR have shown, the determination of an accurate signal gain model is essential for CMB data analysis, because the limiting factor in the reconstruction of the noise transfer function is in the uncertainty of the gain model rather than statistical errors. In particular, the separation of long-term drifts in the radiometer gain from intrinsic changes in instrument characteristics, such as system temperature or reflector emissivity, depends crucially on the capability to detect and precisely characterize the signal components over long observing times. The current LFI gain model is able to reconstruct temperature-induced gain variations to a level of 0.1 - 0.3%. With an extended LFI operation, an exquisite <0.05% will be possible, providing a corresponding improvement in the reconstruction of the power spectrum of the CMB and the extraction of cosmological information. It is also worth noting that long timescales will establish fundamental stability limits for the kinds of receivers that are likely to play a major role in future CMB polarisation experiments.

The LFI-only extension will also allow specific new ways to analyse the Planck data:

- Separating galactic and extragalactic foregrounds from the CMB remains one of the most significant challenges for Planck, particularly in polarisation where the foreground signals largely dominate. Using the broad frequency coverage of Planck is an important element in the component separation process, which in the approved mission is hampered by the lower sensitivity of the LFI with respect to the HFI channels. This difference will be removed in the deepest annuli, which in addition can be targeted to areas with specific characteristics that test the quality of the separation algorithms (for example regions containing the cleanest parts of the sky).
- Extragalactic radio sources (rather than dusty galaxies) are the dominant source of noise in fine-scale CMB observations at frequencies up to ~150 GHz. They are likely to dominate fine-scale polarization fluctuations to an even higher frequency, since reemission from dusty galaxies is probably very weakly polarized. With the LFI-only extension, the sample of radio galaxies detected

by Planck will be increased significantly in the deep annuli, putting on a firmer basis models of the radio source contamination, of great importance not only for Planck itself, but also for a number of current and future increasingly sensitive measurements of polarized fluctuations in the CMB. The increase in the detected radio source population is of course scientifically interesting per se, in particular as regards variability – which will benefit from a longer observational timescale, and polarization studies. Simulations have shown that the currently approved survey will yield only 10-12 polarization measurements of the brightest extragalactic sources; the LFI-only extension will significantly augment that number (to 40-50).

- The sparse but deep coverage of the sky during the LFI-only extension will be very substantially different in nature from that of the approved survey, and offers the possibility to make an independent and powerful test of the recovery of the angular power spectrum of the CMB. This is particularly true for the polarisation spectrum (see Fig. 2), which is noise rather than signal dominated. While the deep annuli will cover a smaller portion of the sky, the sensitivity implies that the errors in the recovery of the power spectrum in polarization will be no larger than those from the approved survey. On the other hand, the noise bias in the extended mission will be substantially less. Comparing the two results allows us to dig into subtle systematic effects and to enhance the confidence level in the cosmological results of Planck.

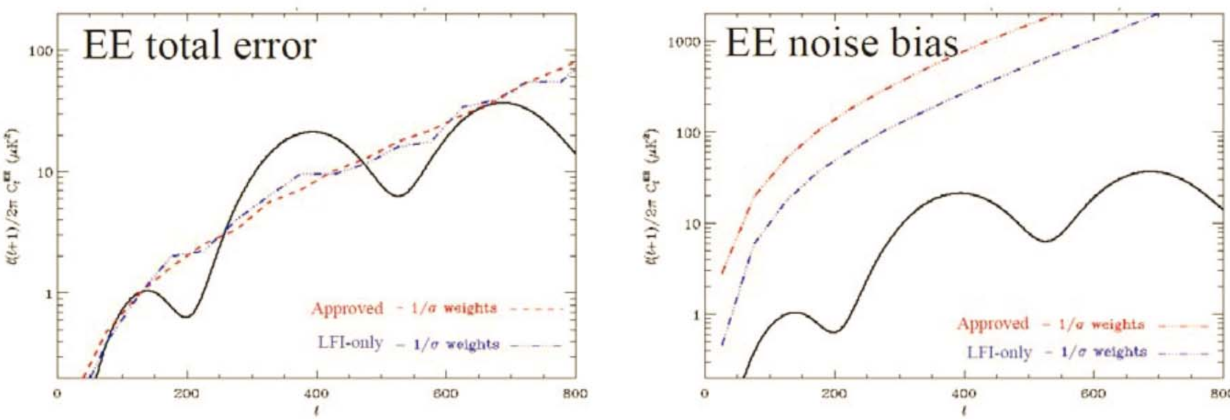


Figure 2: On the left are shown the errors (Δl ~ 50) on the recovery of the EE spectrum of the polarized CMB for both the approved survey (red) and the LFI-only extension (blue), compared to the canonical spectrum. On the right are estimates of the statistical bias in the recovery. These results are based on the actual planned scanning strategies and noise Monte Carlo runs. Using the LFI-only part of the survey, a similar level of sensitivity to the small scale CMB polarization modes can be reached as will be obtained in the approved survey, while attaining a lower overall noise bias level. The LFI-only survey thus provides an orthogonal measurement and opens the way to stringent cross tests.

Although we have here described a number of specific areas to be addressed during the LFI-only extension, which we already know will provide significant benefit to the mission, it is important to emphasize the fact that the use of a radically different observing strategy during the extension constitutes by itself a significant benefit in terms of experimental practice, which is certain to bring additional new ideas and data tests in due time.

2.3 Data products

In compliance with the approved Planck Science Management Plan, the current plan for data releases includes:

- An Early Release Compact Source Catalogue to be delivered to the community in January 2011
- A first set of data products (calibrated timelines, maps, components) based on the baseline mission (15 months of surveying), to be delivered to the community around December of 2012.
- A second set of data products (calibrated timelines, maps, components) based on the approved extended mission (baseline + 12 months of surveying with LFI and HFI), to be delivered to the community two years after end of extended operations (i.e. in the period between December of 2013 and February of 2014).

An LFI-only extension as proposed here would yield additional LFI-only products, namely:

- Calibrated timelines
- Maps per frequency including the deep annuli data
- Compact source catalogues within the deep annuli.

No new diffuse component products are foreseen, but of course all the new information acquired from the analysis of the deep annuli will be fed back into the Data Processing Centres (DPC) pipelines leading to the (second set of) maps and component products based on the full extended mission. These products will be delivered to ESA at the same time as the second set of survey products, i.e. in the period between December 2013 and February 2014.

2.4 Planck Science Team

The science case described in this proposal is fully supported by the Planck Science Team.

3 Spacecraft, Instruments and Ground Segment Status

3.1 Space Segment

At the Planck In-Orbit Performance Review held at ESOC on 9 June 2010 the performance of the spacecraft operations was reviewed. All sub-systems are operating on prime units with no loss of redundancy. Some of the redundant units have been switched on at one stage to support operations and all the ones used in flight are working properly. Only two cryo thermistors failed during the initial cool-down, but this has no impact on the mission as there are multiple thermistors on the Primary and Secondary reflectors. The operations of the LFI and HFI instruments are extremely smooth.

3.2 Consumables and degradation

Fuel: On 17 May 2010, 175.5 kg of fuel remained on-board and taking into account the foreseen manoeuvres the prediction is to have 140 kg remaining at the end of 2016.
Power: Planck is only using 66 % of the solar array. The decrease of the power generated in the past year is ~2.5 % due to degradation, so there are ~11 more years of operations before batteries are needed for peak demands.

Dilution cooler: Its life is limited by the depletion of the ^3He and ^4He stored on-board. The continuous in-flight characterization predicts that the ^3He gas will run out at the end of January 2012. Once the ^3He gas is exhausted, the HFI bolometers, which require the very low temperature provided by the Dilution cooler, will no longer be able to produce useable data.
Stirling 4 K cooler: Its operation is very stable since recovery from the only shutdown incident on 6 August 2009, and there is no indication of aging.
Sorption cooler: By a fortunate collusion of design and the favorable in-flight operating environment, the Sorption coolers[2] are expected with high probability to support the operation of the full payload (LFI + HFI) for as long as the Dilution cooler has working fluid, i.e. to the end of January 2012. However, the thermal environment required by the LFI radiometers may be maintained for a further period by applying on board the process of “regeneration” to the Sorption cooler, and continuing to operate the Stirling 4 K cooler. By regeneration, which consists of prolonged heating to high temperatures, the sorbent material recovers its efficiency to pump hydrogen to high pressure and provide cooling power.
Regeneration is an inherently low-risk operation which has been partly qualified on the ground, but there are still a number of uncertainties related to its effectiveness on the lifetime of the flight units. The best prediction which includes the knowledge gathered on the ground and in flight leads to an estimated additional lifetime after regeneration is carried out on both Sorption coolers of between 8 and 18 months (Sorption Cooler Tiger Team report issued in July 2010). This extension proposal is therefore based on an availability of 12 months, which is considered to be attainable with high probability.

3.3 Ground Segment

The overall performance of the Ground Segment is very good, with a timely flow of activities of all its components (MOC, LFI, HFI and PSO) following the agreed interfaces and timing. With a data return so far of 100 %, there have been no gaps in the data products generated by LFI and HFI.

4 Changes to Operations Concept and Management

4.1 Space Segment

During the LFI-only extension, the Planck satellite will remain in full operation with the only exception of the HFI, whose operation will be reduced to support the 4K cooler only. The revised scanning strategy does not require any new capabilities from the satellite. The decreased data transmission needs will be used to reduce the contact periods with the satellite.

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[2] There are two units flying on board Planck: the first one was used until 11 August 2010 and the second one will provide for operations until the ^3He for the dilution cooler is exhausted.

4.2 Ground Segment

As long as Planck is operated together with Herschel the current operational concept and setup at MOC will be continued: it is working well and exploits the synergies between the two missions. Whilst the HFI Instruments Operations Team will be reduced to the minimum required to support the monitoring of the 4 K Stirling cooler, the LFI Operations Team will continue with the same level of support, including the monitoring of the Sorption cooler operations. Since the Planck LFI-only extension will take place in parallel to the currently funded “Nominal Post-Operational phase” the scientific staff in the PSO will support both in parallel and the operational staff will be kept for the length of the LFI-only extension phase.
The ground station passes will be reduced from 3 to 2 hours since the amount of telemetry to be downloaded will decrease with only one instrument in use.

5 MEOR Review

In June 2010 the Mission Extended Operation Review (MEOR) examined the status and future outlook for the spacecraft, instruments and ground segment performance. No significant technical limitations were found to a one-year extended operation of Planck.

6 National Funding Status

The two nationally funded Instrument Operations Teams/Data Processing Centres need to be operational for 12 additional months to cover an LFI-only phase extension. The two main agencies involved (CNES and ASI) have confirmed that they will support the LFI-only extension phase operations with an adequate level of resources. NASA has also confirmed continued support to the operation of the sorption coolers.

7 Financial Request

The cost to ESA of a Planck mission extension arises mainly from two elements, which need to be funded for one extra year of operations: (a) the Planck Science Office (the ESA entity charged with scientific operations aspects of the Planck mission), and (b) the Mission Operations Centre. The cost to ESA of extending Planck operations for a period of 12 months to perform the LFI-only phase described above is 3.39 M€ at 2010 e.c.

8 Conclusions

The one-year LFI-only phase extension as described in this proposal will provide better characterization, calibration, and systematic effect determination for both LFI and HFI. It will also improve confidence in the foreground separation process of the Planck surveys, and in the statistical characterization of the recovered CMB. All of these will combine to yield considerably improved products for the astronomical community, and to increase confidence in Planck's cosmological results. Not least, the extension will enhance significantly the legacy value of Planck towards future experiments. No new functionalities are required to support the extension, and the costs benefit strongly from the continued parallel operations of Herschel.

Appendix A - Improved calibration and control of systematic effects

The proposed plan for the "LFI-only" extension of the Planck mission is largely driven by the opportunity to measure specific targets that will improve the understanding of LFI systematic effects relevant for optimal exploitation of the Planck data. In this Appendix we describe in some more detail the specific improvements in LFI calibration and control of systematics that will be achieved through the proposed plan.

1. Improvements in beam determination

Detailed measurements of the main beam of the LFI channels will be gathered with deep observations of external planets, in particular of Jupiter. Such observations will improve our knowledge of the LFI beams by a factor proportional to the square root of the observation time, or to the number of points measured in the xy-plane. These dedicated scans will be carried out with reduced cross-scan de-pointing (< 0.5 arcmin, instead of the 2 arcmin of the nominal scanning strategy) thus optimizing the coverage of the xy-plane in terms of uniformity.

A significant reduction of the uncertainty in the beam contours below about –15 dB of the peak (where the beams deviate considerably from a Gaussian shape) will translate directly into improved polynomial fits with the models of the beams based on the RFFM Planck Telescope (Sandri et al. 2010). This in turn will lead to an enhanced understanding of the actual optical surface of the Planck telescope, as operating in flight, and of the alignment of the Planck focal plane unit (FPU) after launch and in-flight cool-down. The accurate control of optical and alignment parameters is of great importance for the scientific analyses of both LFI and HFI data (Tauber et al. 2010). Even a very small error in the FWHM, say of 0.1%, would imply a significant ~1% error in the window function, and therefore on the power spectrum, at multipoles ~1500 at 70GHz, and at multipoles ~2000 at 100GHz. Furthermore, in-flight measurements of the HFI beams are partly degenerated with the measurement of the bolometer time constant (Lamarre et al. 2010), which produces an apparent elongation of the beam in the direction of the scan. Thanks to the enhanced reconstruction of the Planck telescope from the LFI deep annuli, it will be possible to better separate these two effects.

In Figure A1 we illustrate the sensitivity of LFI to some of the key parameters of the Planck telescope and FPU alignment. The black contours show the main beam reconstruction for a single-pass measurement of Jupiter during the first sky survey. While in the central part of the beam the agreement with the predicted nominal pattern is excellent, at intermediate power levels (-15 to -20 dB) the data can accommodate deviations in the main optical parameters (mirrors shape, alignment of the optical system, FPU and horn location) at the 0.1% level. Deviations at this level, while small, would introduce non-negligible systematic effects in the analysis of the power spectrum reconstruction. By carrying out the proposed deep scan over Jupiter we will largely improve the sensitivity (up to factor of ~20 for single beam), leading to proportionally improved constraints to Planck optical parameters. Furthermore, by scanning Jupiter in steps much smaller than the 2 arcmin of the nominal surveys, we will optimize the accuracy of the beams' contours and improve the signal/noise ratio through a suitable pixel-average over the scan.

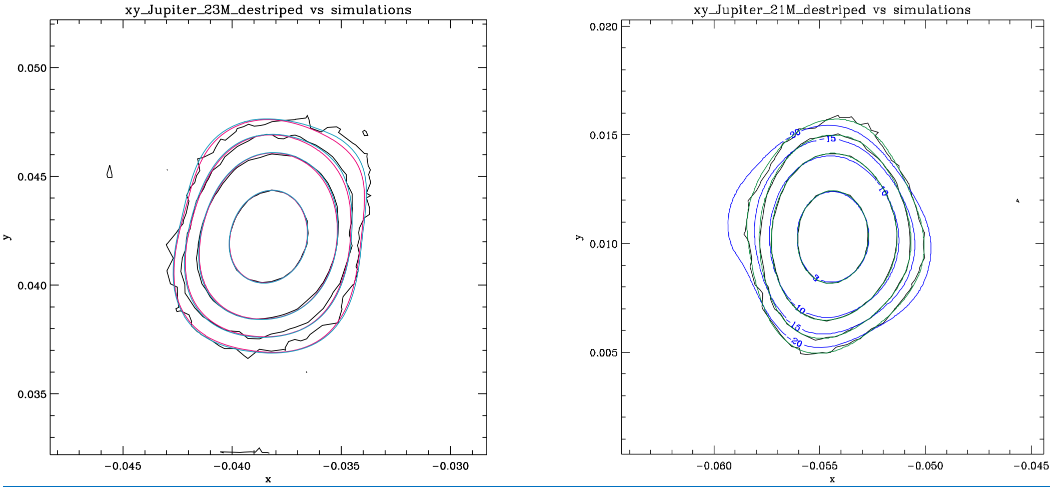

Figure A1: Sensitivity of LFI measurements to Planck telescope parameters. The black contour lines are the beams as measured in-flight (-3, -10, -15, -20 dB levels) for two 70 GHz radiometers (left: LFI23M; right: LFI21M). Superimposed to the measured contours, simulated beams are shown assuming slight deviations from the ideal optical design. In the left panel, the two simulated sets of contours (magenta and cyan) represent <0.1% deviations from ideal mirror shape in terms of curvature radius and conic constant. In the right panel, the two simulated sets of contours (blue and green) represent the effect of a shift of the focal plane unit of 3.5 mm (Reference: PL-LFI-PST-TN-095 issue 1.0).

In addition to being useful for Planck, these measurements will also provide valuable data for planetary scientists, given Planck's accurate absolute calibration. This in turn means that Planck measurements of the planets will provide the basis for the calibration of many future ground- and space-based experiments at similar wavelengths.

2. *Polarization calibration and band-pass effect*

Polarization has become a strategic scientific objective for Planck and its success highly depends on the understanding of instrumental systematic effects. All the LFI channels are sensitive to linear polarization. High-performance orthomode transducers, connected to the LFI feed horns, separate the incoming sky signal into two orthogonal polarizations which are fed into pairs of independent pseudo-correlation radiometers (Bersanelli et al. 2010). Differences in the effective band shape of the paired radiometers, if not precisely known, introduce a leakage of the total intensity of foreground emission into the polarization term. The size of the effect depends on the mismatch in band-shape and on the spectral index of the foreground components in a given sky pixel (Leahy et al. 2010). Pre-launch characterization of the LFI band-passes and detailed model analysis allow us to take this effect into account (Zonca et al. 2009). However, the residual uncertainty in the knowledge of the band-shapes leaves an error that is currently the dominant systematic effect in the LFI polarization analysis.

Extensive study by the LFI team during the first year survey has shown that by measuring strong, low-polarization sources with known frequency spectra, such as bright HII regions, we can recover the parameters needed to correct for this spurious effect with improved precision. Extending the LFI survey to deep annular observations containing suitable sources will yield a much increased accuracy in the ability to correct for this effect, leading to cleaner polarization maps.

As an example, Figure A2 shows the potential for the correction of bandpass effects using observations of the Orion Nebula (M42). The effectiveness of the correction at current level is verified with observations of the Crab Nebula. The residual spurious signal (~0.5% in the U map of the Crab, panel at lower right) is above the noise level of LFI. With the proposed mission extension, deep observations of M42 and of other strong unpolarised sources (such as the Rosette Nebula, W3, or other bright HII regions), will allow us to reduce the residual effect by a factor of ~6, thus pushing any systematic deviations below detector noise level. When combined with HFI data, this improvement will directly translate into a cleaner separation of polarized foregrounds, which is crucial for Planck polarization science, in particular for the search of primordial B-modes.

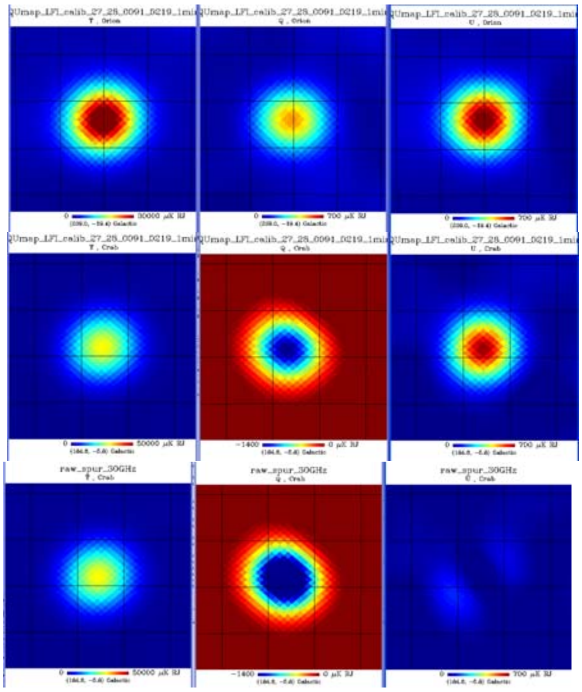

Figure A2 – Illustration of the band-pass effect on polarization and correction method. The top thee panels (left to right) show maps in the I, Q and U Stokes parameters of the Orion Nebula (M42) from LFI at 30 GHz data obtained during the first survey (note the widely different color scales). Most of the ~2% power in the Q and U polarization maps is a residual due to the spurious band-pass effect. Then, using a model of the foreground emission, we calculate a map of the spurious (Q,U) leakage projected in the sky, and subtract it from the raw (Q,U) maps. We can verify the effectiveness of the correction process on a strong polarized source such as the Crab. The second and third rows show, respectively, the raw and corrected maps for the Crab. The residual spurious signal in the U map of the Crab is ~0.5% (panel at lower right).

Furthermore, the dominant systematic effect in HFI polarization analysis (calibration of polarization angle) is totally independent of the LFI-dominant band-pass effect. Because in the deeply observed annuli the LFI sensitivity will be closer to that of HFI, a comparison of the polarization maps from the two instruments (particularly between LFI 70GHz and HFI 100GHz, where foreground signatures are similar) in those regions will yield a quantitative assessment of the residual systematic error on polarization, of great interest for Planck polarization analysis.

3. *Calibration and gain model*

Calibration accuracy is an essential element for a proper reconstruction of the angular power spectrum and consequent extraction of cosmological parameters, as well as for other cosmological and astrophysical science (Mandolesi et al. 2010). Furthermore, relative calibration between coupled radiometers is crucial for polarization analysis (Leahy et al. 2010). The LFI strategy for in-flight calibration (Mennella et al. 2010, Villa et al. 2010) is based on a combination of absolute calibration, which uses the signal from the Galactic and orbital dipoles; and relative calibration, which can be measured from the radiometer total power signal, routinely sent to the ground.

After the first year of observation, the LFI absolute calibration accuracy is ~0.3-0.7% (depending on channel), and it is limited by residual non-dipole components and instrumental drifts. Much progress is already being made since the beginning of the mission. Because the limiting factor comes from gain model uncertainties and systematics rather than statistical errors, the improvement achieved with additional observations has been roughly linear with time, rather than proportional to its square root (see below). We expect that the calibration accuracy will improve significantly in the second year, approaching the goal of 0.1-0.2% at the end of the nominal mission. The proposed extension will further improve the absolute calibration accuracy, especially because it will lead to an increased ability to separate long-term drifts in the radiometer gain from intrinsic changes in instrument characteristics, such as system temperature or reflector emissivity.

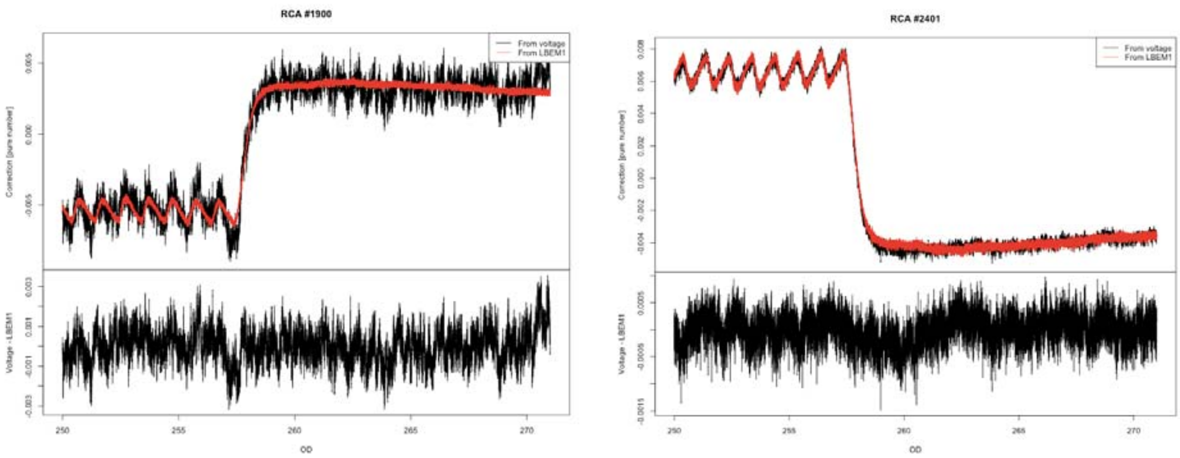

Figure A3 – Preliminary results on LFI relative calibration in a period of 22 days of flight data. The top panels display a comparison between the total power ΔV/V of reference load channels (black) and a preliminary gain model using flight temperature sensor data (red). The step near OD 257 corresponds to the time when the Transponder was switched on all the time. Left: a typical 70 GHz channel (RCA19-00); right: typical 30 or 44 GHz channel (RCA24-01). The lower panels show the residuals, which are ~0.3% at 70 GHz and ~0.1% at 30 and 44 GHz.

Relative calibration is measured from the relative variation of the total power signal from the reference loads (Bersanelli et al. 2010). Gain variations can be verified through the LFI gain model, constructed from in-flight housekeeping information and measured transfer functions of relevant instrument components (mainly the feeds, OMTs, front-end and back-end modules of the radiometers). Our current LFI gain model is able to reconstruct temperature-induced gain variations to a level of 0.1-0.3% (see Figure A3). With the extended LFI survey, we expect to reach an exquisite <0.05%, providing an unprecedented calibration precision. This would represent a result of great relevance for several science issues relating to LFI data, for the Planck internal cross-calibration, and for future CMB experiments as well.

4. Null tests and redundancy

As both WMAP and COBE-DMR has shown, deep understanding of the behaviour of instrument gain and noise properties is essential for optimal data analysis, and can be significantly improved with extended observations. Null tests (or "jackknives") on the noise component provide an essential tool for the data analysis, which impacts the precision in the determination of cosmological parameters and any other science exploitation. In general, the number of possible null tests increases quadratically with time. This leads to an improvement in the precision of the observed maps that is typically faster than that naively expected for white noise sensitivity, i.e., proportional to the square root of time. The experience of WMAP, whose survey has been extended to nine years, clearly shows this fact. The WMAP team has so far published results based on 1, 3, 5 and 7 years of data. In Fig. A4 we plot the uncertainties in six basic cosmological parameters as a function of the number of years of observation amassed in the WMAP surveys. As Fig. A4 shows, the uncertainty in four of the cosmological parameters has dropped faster than the square root of time that might be naively expected. The WMAP papers (e.g., Jarosik et al. 2010; Weiland et al. 2010) make it clear that the dominant contribution to the decrease in uncertainty in these parameters is the enhanced understanding of systematic errors and foregrounds which becomes possible as more data were acquired.

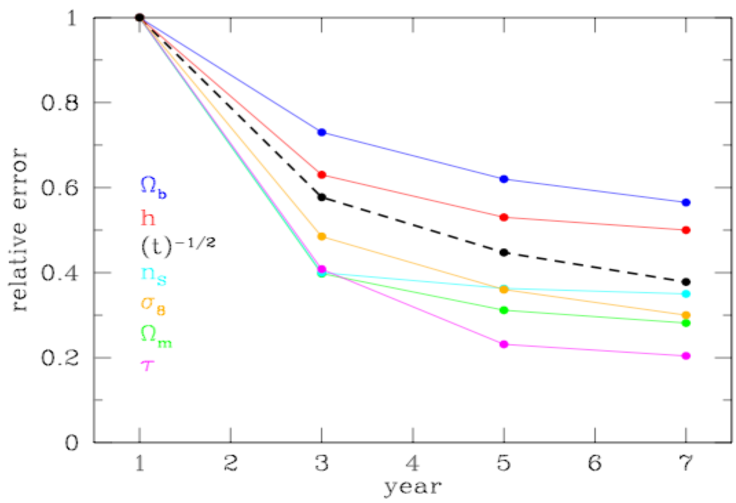

Figure A4 – Relative error or uncertainty in the basic six parameters of a standard cosmological model using four different data-sets based on 1, 3, 5 and 7 years of WMAP data (solid lines). These are compared with the naïve expectation for improvement, $t^{-1/2}$. For two parameters, Ω and h, WMAP quickly becomes cosmic variance limited, so the improvement with additional time is slight (we note that Planck's ability to measure the fourth acoustic peak at good precision gets around this problem).

The proposed "LFI-only" phase for Planck will not be, as in the case of WMAP, a simple increase in the number of surveys. The deep scan strategy means that it will not be straightforward to use the extension data to produce null tests involving the sky signal. However, it will be possible to perform crucial jackknife tests on noise properties, gain stability, environmental effects, and any time-dependent instrument or spacecraft parameter. Furthermore, the high sensitivity achieved in the observed annuli will enhance the visibility of subtle systematic effects, otherwise embedded in the white noise (especially for polarisation), thus allowing a detailed study beneficial to the overall survey. An additional advantage of the deep-annuli strategy is to allow an improved precision in the subtraction of the sky signal, beneficial for a detailed noise characterisation. We therefore expect that extending the LFI observing time from 2 to 3 years, will lead to a rate of improvement similar or better than that shown in Figure A4.

5. *Spin-synchronous effects and 1/f noise*

The nominal 1-rpm spin rate of Planck was defined as a compromise between the HFI need for a slow spin rate (to cope with bolometer time constants and data-rate) and the LFI need for a fast spin rate (to minimise the effects of $1/f$ noise). Although this is not a central argument in our proposal, we mention here that in the "LFI-only" phase it would be possible in principle to increase the Planck spin rate, e.g. by a factor of 1.5–2, to optimise the system to the needs of LFI. The additional data rate resulting from the higher satellite spin could be accommodated in the bandwidth no longer required by HFI. In addition to a moderate reduction of the impact of $1/f$ noise, this configuration would provide an interesting opportunity to search for spin-synchronous effects by performing null tests between surveys carried out at different spin rates. The implementation of this possibility will depend on feasibility and opportunity.

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