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Abstract

We propose to extend the Planck mission in "LFI-only" mode until 13 August 2013, which will permit the completion of an 8th full-sky survey for all LFI detectors. This extension is made possible by the predicted lifetime of the 20K sorption cooler now in operation, which far exceeds previous projections. The additional observations will lead to a significant improvement in the control of systematic effects and calibration accuracy through a set of new powerful null tests probing the 6-months, 1-year, and 2-years time scales. The current status of the Planck data analysis indicates that such improvement may be very important for a full extraction of Planck cosmological science at low multipoles, especially for polarisation. We also note that the LFI may be the last instrument delivering full-sky temperature maps in its frequency range in a very long time, adding to its legacy value.

1 Introduction

The duration of the *Planck* survey, originally planned for 15 months, was first extended by an additional 12 months (ESA/SPC(2009)25), i.e., up to the end of the expected lifetime of the 0.1K dilution cooler serving the High Frequency Instrument (HFI). As the mission progressed it became clear that the lifetime of the 4K and 20K coolers would substantially exceed the duration of the dilution cooler, thus opening the possibility of an extension of the *Planck* mission using only the Low Frequency Instrument (LFI) detectors. In September 2010 the LFI Consortium, supported by the *Planck* Science Team, submitted a proposal to extend the operation of *Planck* in "LFI-only mode" for an additional year of observation, up to 31 January 2013, compatible with the duration of the 20K and 4K stages. This LFI-only extension was approved by ESA (ESA/SPC(2010)21). Based on the experience gained from analysis of in-flight data, the *Planck* Science Team proposed a scanning strategy for the LFI-only phase based on continuous scans and deep annuli for selected calibration sources (PL-LFI-PST-TN-099). The new baseline scanning strategy was approved by ESA on 25 October 2011.

Since the start of the nominal survey on 13 August 2009, the *Planck* satellite has been observing the sky continuously, producing high-quality data under very stable spacecraft and instrument conditions. The *Planck* results are expected to produce a major impact on cosmology and millimetre-wavelength astrophysics for many years to come. On 16 January 2012, precisely when expected, the 0.1K dilution cooler completed its operation. Since then, *Planck* has been operated in "LFI-only mode" with excellent performance and in perfect continuity with the full-mission mode. In this configuration LFI is operated in nominal conditions, using the 18-20K sorption cooler to cool the front-end amplifiers and the HFI 4K Stirling cooler to cool the LFI reference loads. The duration of the mission is currently approved until January 2013.

The natural lifetime of LFI is set by the lifetime of the 20K stage. In our 2010 proposal (ESA/SPC(2010)21) we aimed at a mission extension to January 2013, based on the best extrapolation of the in-flight performance of the 20K coolers available at the time. However, as will be detailed in Section 2 and Appendix A, the current assessment of the 20K stage lifetime is significantly longer, now estimated to be about 8 additional months beyond January 2013. Given this prediction, we believe there is a compelling scientific case, presented in Section 3, to plan an extension of the LFI-only mission to allow for the completion of an extra full-sky survey. The scanning strategy and operations foreseen for this extension will be discussed in Sections 4 and 5.

As for the previously approved "LFI-only" extension, our scientific case is based, first and foremost, on the opportunity to deeply understand and thus to remove systematic effects in the LFI data, as well as to improve calibration accuracy. In the present case, however, the experience gained in the analysis of the first 4 surveys (still on-going) allows us to be more specific in identifying the science benefits, the types of effects, and the analysis required. As in our previous proposal, while the extension will use only LFI detectors, we aim at a scientific outcome that will enhance the data quality of *Planck* as a whole.

2 Planck-LFI lifetime and extension duration

2.1 Instrument

The LFI instrument has been working flawlessly and uninterruptedly since the beginning of the Planck survey producing high quality data from all its 22 pseudo-correlation radiometers. The instrument is very stable and shows no measurable systematic degradation in noise properties over 3 years of cryogenic operation. The instrument front end is cooled to 20K by a sorption cooler and each radiometer uses a reference load cooled to 4K by the HFI Stirling cooler. Cooling of the instrument front-end to 20K is necessary for achieving its nominal sensitivity, while cooling the reference loads to 4K greatly reduces the impact of 1/f noise (Bersanelli et al. 2010).

2.2 Coolers

The *Planck* spacecraft is equipped with two units of 18-20K sorption coolers (Planck Collaboration 2011). The Flight Model 2 (FM2) was operated in the first part of the *Planck* mission, and since the switchover in August 2010 the cooling system has been relying on the FM1 unit. As of 15 April 2012, the FM1 sorption cooler has operated for 20 months, and it has dramatically outperformed FM2 in terms of in-flight behaviour and lifetime expectation.

The FM1 cooler has been exceptionally stable. Our estimates of the FM1 cooler lifetime, based on FM2 performance and on pre-launch ground tests, have been repeatedly surpassed by the observed in-flight behaviour of FM1. Furthermore, one of the main reasons for cooler ageing, i.e., the degradation of the compressor hydrides, can be mitigated by applying on board a process called "regeneration". This process consists of prolonged heating of the compressor beds to high temperatures by which the sorbent material recovers its efficiency to pump hydrogen to high pressure, and thus to provide cooling power. As discussed in detail in Appendix A, based on our present knowledge, our expectation for the FM1 unit end of life (EOL) is around August 2013. In addition, the FM2 cooler has another 4-6 weeks of residual lifetime after the switch-over was performed, which adds an important margin to the 20K stage EOL estimate.

Regarding the 4K cooler, there is no reason to expect degradation or malfunctions in the time scale of this proposed extension.

2.3 Duration of the proposed extension

Based on these projections, we propose to extend the *Planck* mission in "LFI-only" mode up to 13 August 2013, which will allow a full 8^{th} sky survey to be executed[1]. While the main scientific case, discussed next, is based on the completion of the 8th survey, were the system lifetime to exceed August 2013 by a few months, we propose that the LFI be not shut down but continue to its natural EOL.

[1] For a detailed definition of the start and end dates of each Planck survey, see Planck/PSO/2012-012 (and previous versions).

3 Scientific case

The central scientific argument for this extension is the improved control of systematic effects and calibration affecting large scale CMB science, particularly in polarisation. The polarisation power spectra at low multipoles include the imprint of cosmological reionization, possibly amplifying a non-zero gravitational wave component in the early Universe. Particularly for these fundamental issues, *Planck* is a unique instrument pushing the edge of our knowledge into new territory.

The current status of the LFI polarisation data at large angular scales (or low multipoles) is encouraging. The LFI has met the sensitivity requirements needed to constrain the optical depth to reionization. The LFI maps, particularly the 30 GHz channel, will provide the best data-set to remove low frequency foregrounds from the *Planck* cosmological channels (70-217 GHz). In our current analysis, however, both sensitivity and systematic effects compete with the cosmological signal. Suppressing systematic effects in the lowest frequency maps is essential, in particular, to fully exploit the the extreme sensitivity of the HFI channels, which may be ultimately limited by residual synchrotron polarization. For example, for the HFI 100 GHz channel the nominal white noise[2] per ~2° pixel will be ~1μK. To ensure synchrotron cleaning well below significance level, say < 10% of the nominal white noise, will require a rejection of additive systematics in the 30 GHz map to a level of ~3.5 μK over the entire sky. While it is possible that in-depth analysis of the present data will reduce systematic contamination below such stringent levels, any additional information acquired may turn out to be critical for a thorough exploitation of the Planck data.

A key point of this proposal is that the additional observation time will be sufficient for completing an 8th full-sky survey for all the LFI detectors. Recent (and on-going) analysis demonstrates the critical role of "null tests" between full-surveys in tracking systematic effects, especially at low multipoles. In general, the number of possible null tests increases quadratically with time. For this reason, the improvement in the precision of the observed maps is typically faster than that naively expected for white noise sensitivity, i.e., proportional to the square root of time.

This is clear in our current analysis of LFI data. For example, the precision in the correction for the bandpass mismatch effect has improved almost linearly with the number of surveys available. The experience of *WMAP* clearly confirms this trend. The precision in the determination of cosmological parameters extracted from *WMAP* data improved faster than the square root of time (Figure 1). 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. Interestingly, the optical depth parameter, τ, mainly deduced from low multipole polarisation, is the one showing the fastest improvement.

[2] Planck Blue Book, ESA-SCI(2005)1.

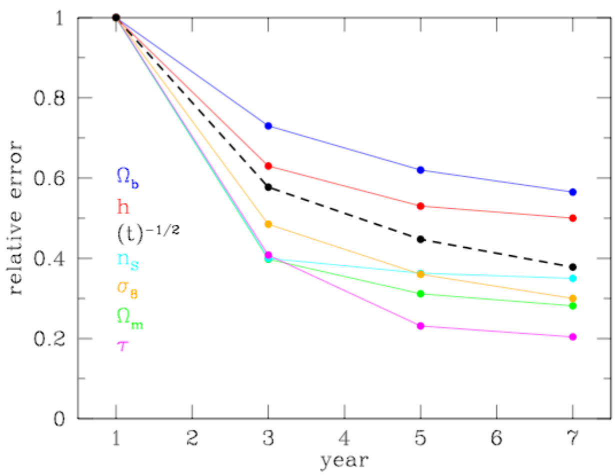


Figure 1 – Relative error in the basic six parameters of a standard cosmological model using four different data-sets based on 1, 3, 5 and 7 years of WMAP data. These are compared with the naïve expectation for improvement, $t^{-1/2}$.

The proposed extension, allowing for an eighth full sky survey, will nicely complete a full cycle of *Planck* observations and will maximize the number and kinds of large-scale null tests to be performed on the full data set (figure 2). The eighth survey will complete a 4-year cycle, increasing from 3 to 4 the number of independent odd-even-survey differences available. Furthermore, the 8th survey will match the number of surveys carried out with a cycloid phase ϕ_0 = 340° (first four surveys) with those with ϕ_0 = 250° (from the fifth on), thus allowing for additional self-consistency checks (see Section 4).

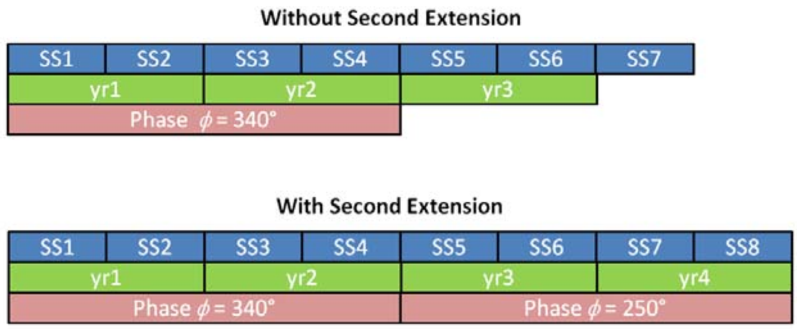


Figure 2 – Comparison of the redundancy cycles in the LFI data with and without the proposed extension. The increased redundancy directly translates into a new set of large-scale null tests, most powerful to fight systematic effects.

In the next two Sections we will show how, for LFI, large scale null tests offer by far the best opportunity to detect and quantify the effects that are currently limiting LFI polarisation sensitivity on large scales. These effects include far sidelobes (Section 3.1) and uncertainties in relative gain calibration (Section 3.2). Furthermore, survey-based power spectrum comparisons are the most powerful diagnostic tools for uncovering and characterizing systematics (Section 3.4). While it is impossible to precisely quantify the level of cleaning that will be ultimately possible to achieve at the μK level for each of these effects, it is clear that the additional survey will be very important for the full extraction of *Planck* low multipole polarisation science.

In addition, an 8th sky survey will lead to improved optical beam measurements, better polarisation calibration, and improved control on some polarisation-specific systematic effects. All these issues are discussed in Section 3.3.

3.1 Sidelobe effects

Straylight contamination from far sidelobes is an astrophysical systematic effect that may in principle impact both temperature and polarisation maps at low multipoles. For temperature anisotropy, sidelobe pickup, mainly from the Galactic plane and from the CMB dipole, directly enters the detector response. For polarisation, the effect would be in principle negligible if the M and S radiometers[3] had exactly the same angular patterns and bandpass response. In reality, differences in the M and S radiometer band shapes coupled to frequency dependent sidelobe level across the bandwidth, introduce a polarisation leakage possibly comparable to the very low (few μK) cosmological signal.

We have extensively simulated the effect of sidelobes in the LFI maps using "Level-S" software. We computed the full beam pattern for all LFI detectors with GRASP-9 (Sandri et al. 2010) and coupled them to a realistic simulation of the polarized Galactic emission ("FFP4 simulations"), CMB dipole, and orbital dipole. Far sidelobes are important at large angular scales, and are captured only by full (or nearly-full) sky maps. The *Planck* scanning strategy combined with the Earth's revolution around the Sun is such that the orientation of the satellite is reversed every six months. As a consequence, any sidelobe feature in the maps will be markedly different between odd and even surveys.

In Figure 3 we show results of our simulations at 30 GHz for odd surveys (left side) and even surveys (right side). Whereas in odd surveys the Galaxy is seen by the "feed sidelobe", in even surveys the Galaxy is seen by the "main spillover" (Sandri et al. 2010). The feed spillover points close to the main beam and, for this reason, the fingerprint on the sky is close to the Galactic plane. The main spillover points at about 85° from the main beam, so the fingerprint appears as a ring-shape. This is not the case for the CMB dipole contamination, as the effect (after destriping[4]) is the same in odd and even surveys. For the subdominant contribution by orbital dipole, the final effect is found to be opposite between odd and even surveys.

[3] Each LFI feed horn is connected to an OMT, which separates the sky signal into two orthogonal polarizations feeding a "Main" (M) and a "Side" (S) pseudo-correlation radiometer (Bersanelli et al 2010).

[4] The LFI time ordered data (TOD) are reprocessed through a destriping algorithm (Kurki-Suonio et al. 2009), This implies a change at some level in the resulting pattern with respect to maps produced with simple co-adding of the TODs. The effect from the CMB dipole in the purely co-added maps is nearly opposite in odd and even surveys (Burigana et al. 2006), while after destriping it becomes very similar in odd for even surveys. Optimized algorithms to remove straylight effects will be applied at TOD level, in order to avoid coupling with the destriping process.

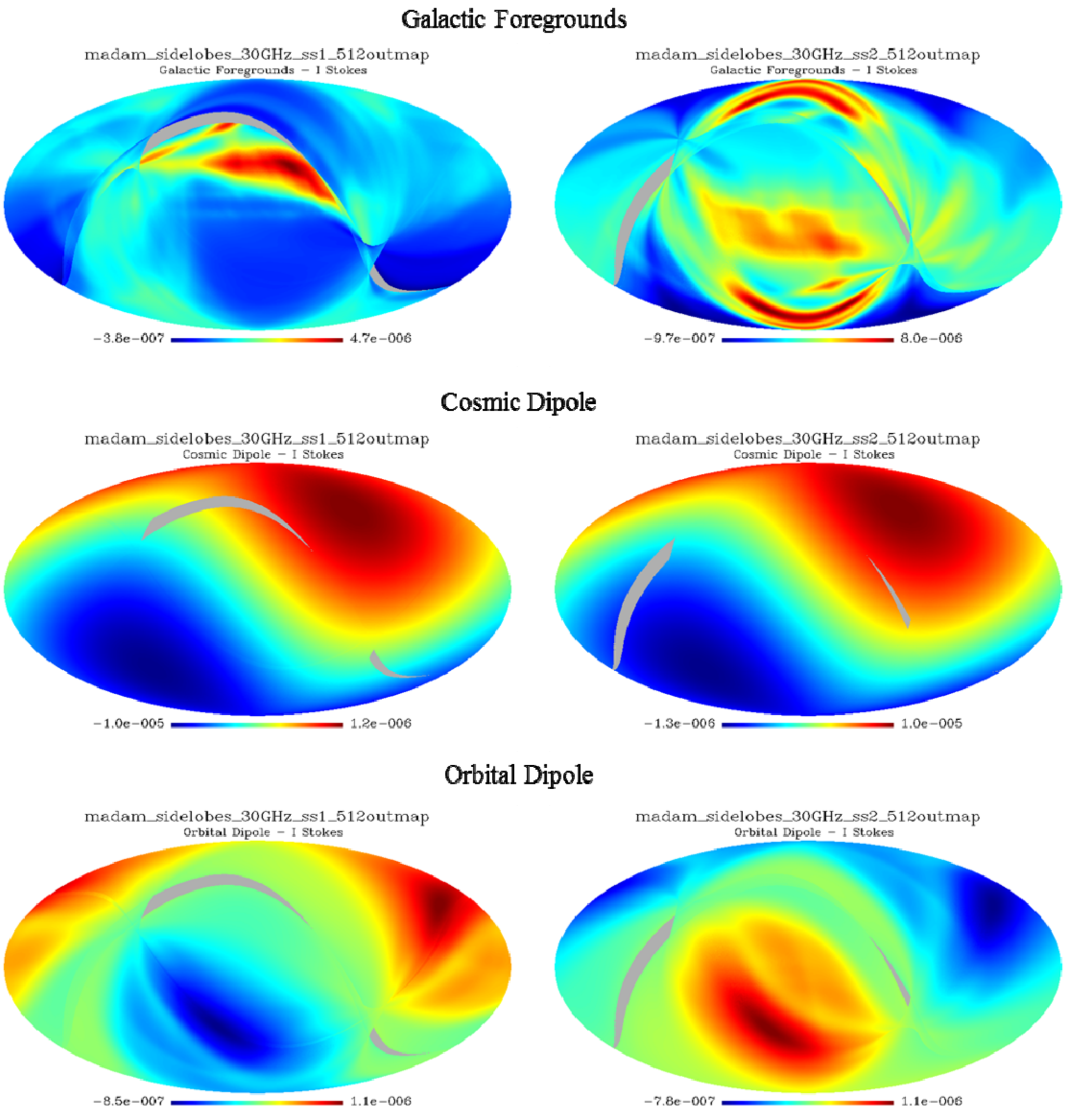


Figure 3 – Simulated sidelobe fingerprint in the LFI 30 GHz temperature maps due to Galactic foregrounds, CMB dipole, and orbital dipole after destriping (from F. Perrotta). Units are Kelvin. Note the different fingerprint of the Galaxy for the odd surveys (left side) and even surveys (right side).

At 30 GHz, the Galactic straylight in the temperature maps has a peak-to-peak value of a few μK, while for the CMB dipole it is roughly 10 μK. Survey-to-survey difference maps are essentially the only means to study such effects from in-flight data. Apart from the direct contribution, the spillover indirectly impacts calibration by slightly altering the measured gain values, and may lead to sub-optimal removal of 1/f noise in the destriping process.

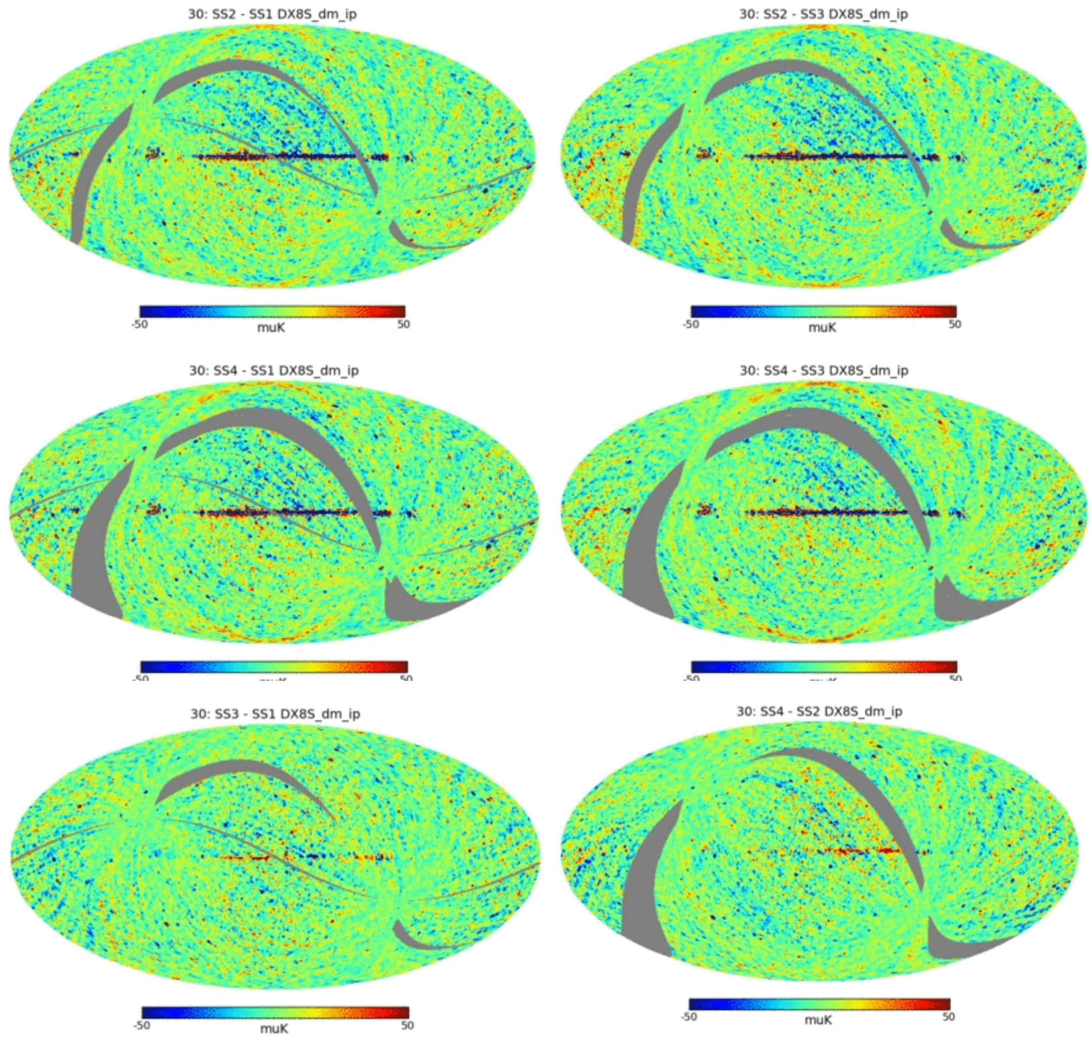


Figure 4 – Survey-survey null-tests from 30 GHz LFI data for the first four Sky Surveys (SS). The top and middle rows show differences between even and odd surveys (SS2–SS1, SS2–SS3, SS4– SS1, SS4–SS3), while the bottom row shows odd–odd and even-even differences (SS3–SS1, SS4–SS2). The ring-shaped features and the asymmetric lobes near the Galactic plane are clearly visible in the first two rows, while they disappear in the bottom row.

For polarisation, while the levels are as low as ~1 μK, they must be compared to a cosmological signal of just a few μK. Therefore, more sophisticated simulations are needed to evaluate the impact on polarisation maps. We are currently carrying out detailed calculations taking into account the coupling between the large variation of the far sidelobe patterns within the radiometers' bandwidth (e.g. from 27 to 33 GHz for Ka band) and different band shapes of the main and side arms. Preliminary results indicate that sidelobes may induce a significant contamination in the Q and U maps at 30 GHz. Subdominant effects, possibly not negligible, are expected also at 44 and 70 GHz.

In order to remove the straylight contamination, accurate simulations are not sufficient: it is necessary to measure the sidelobes in the data with good precision. Only by combining survey-to-survey difference maps of GRASP-9 simulations with measured sidelobe amplitudes can this effect be properly treated.

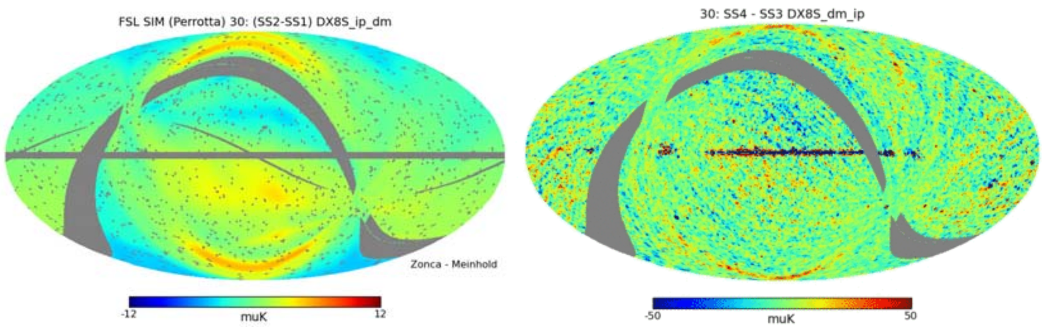


Figure 5 – Sidelobes signature in the difference map between an even ad an odd survey. Left: simulation based on Grasp full beam model. Right: measured difference map (SS4-SS1). It is from the combination of simulations and data at full survey level that the sidelobe effect can be quantified and removed.

Recently, we have observed evidence of sidelobe contamination in the 30 GHz LFI flight data. In Figure 4 we show a set of survey-survey null tests, in which the bulk of the signal is naturally removed while features that are asymmetric for odd and even surveys are highlighted. The ring-shaped feature and the asymmetric lobes near the Galactic plane are clearly visible in all the odd-even difference maps, while they disappear in the even-even and odd-odd differences. Figure 5 shows a comparison between the simulated and measured difference maps. Note that while the overall shape of the signature is clearly recognizable, the amplitude of the measured map is scaled up by a factor ~4.

The best strategy to correct for this effect is currently under investigation. In any case it is clear that we will be limited by signal-to-noise and an optimal sidelobe removal process will necessarily require maximizing the redundancy of even and odd full-sky maps.

The addition of an 8th survey would provide a crucial advantage for three reasons:

1) It will increase from 3 to 4 the number of independent 1-year cycles, and from 12 to 16 the number of null tests for even-odd surveys
2) It will increase the signal to noise ratio in the overall map difference by ~15%
3) The eighth survey will be an even survey, in which the Galaxy straylight contamination is at its maximum level

These benefits may well turn out to be decisive for removing the subtle effects of sidelobes from the LFI data, particularly in polarisation. It should be noted that while straylight effects are greater at 30 GHz, i.e. away from the *Planck* cosmological channels 70 to 217 GHz, their impact will propagate through the component separation process. Furthermore, a precise characterization of far sidelobes at 30 GHz will place constraints on the *Planck* telescope and therefore support analysis of far sidelobes at the highest HFI frequencies (545 and 857 GHz).

3.2 Calibration

The LFI is calibrated by using the CMB and orbital dipoles as calibration sources and by tracking radiometer gain changes with four different methods. Relative calibration methods are based on dipole fitting, total power level, principal component using house-keeping data, and the white noise level. Up to the previous version of the Planck data ("DX8"), the baseline LFI relative calibration has been obtained by fitting the observed modulation with (properly corrected) CMB dipole amplitude of each channel (Zacchei et al. 2010). We have intensively used survey-survey null tests to verify the self consistency of the calibration. While for temperature maps the baseline methods gave very good results, as we advanced in polarisation analysis we found evidence of significant residuals in LFI Q and U maps, particularly at 30 GHz. Such residuals were quite visible also in survey-survey null tests utilizing *WMAP* data (corrected for the frequency shift) as a diagnostic tool.

Our analysis led to the conclusion that the dipole-based relative calibration was affected by foreground residuals in the main beams and by sidelobe pickup. This was demonstrated by the clear improvement in self-consistency achieved with relative calibration based on total power level, which is immune from sky signal as it uses the 4K reference loads as the input load. In Figure 6 we show how calibration based on the reference load drastically reduces the deviation between *WMAP* and LFI full-sky maps. Some residual deviations are still present, and it is again through a series of survey-to-survey null tests that such low-level deviations are now being investigated. The analysis is still on-going, but we believe that this breakthrough will have an impact on the low-ell science of Planck.

Survey-to-survey null tests are essential to identify and quantify such small but crucial effects. The addition of the 8th survey will allow production of 7 additional survey-survey null tests for each detector and for each calibration scheme. While it is too early to state whether or not the present calibration accuracy is sufficient to fully extract polarisation science for the final *Planck* results, there is no doubt that with the 8th survey the calibration of the final Planck results in 2014-15 will improve on the current process.

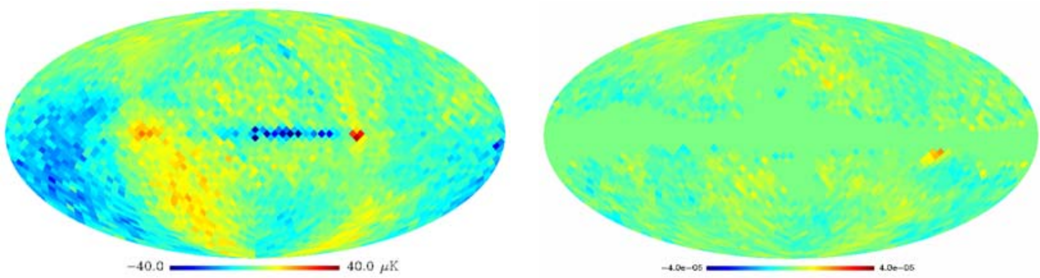
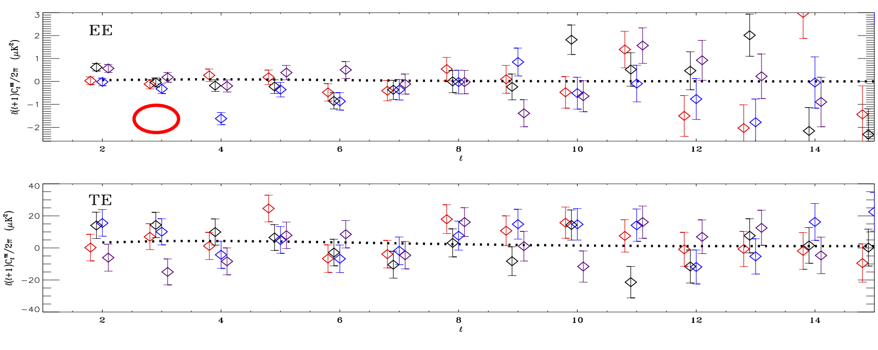


Figure 6 – Full-sky null tests comparing LFI Ka band and extrapolated WMAP K band in Q polarisation, using two different relative calibration methods. Left: dipole fitting; Right: total power level. Color scale is ±40μK in both maps.

3.3 Polarisation at low multipoles: power spectra

A very important set of diagnostic tools is provided by comparing angular power spectra at low resolution for different data sets. Power spectra need to be estimated through optimal methods, since correlations in the noise cannot be neglected.



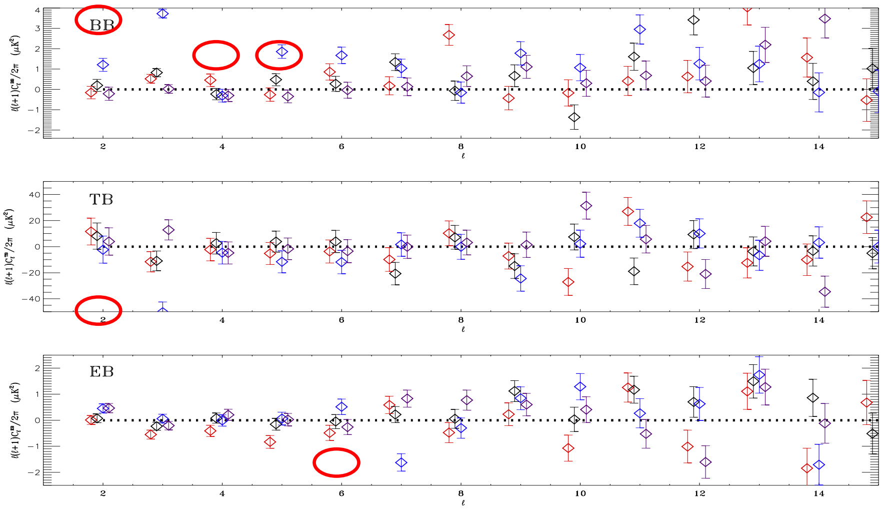


Figure 7 – Polarization angular power spectra at 70 GHz for each of the first four surveys. LFI 70GHz data are foreground-cleaned with WMAP 7 K band as synchrotron template and the HFI DX8 353 GHz channel as dust template. Red: Survey1; Black: Survey 2; Blue: Survey 3; Purple: Survey 4. Most of the outlying points in the lowest multipoles (below ~10) are from Survey 3 (circled in red).

In temperature, the survey-by-survey spectral analysis of LFI data shows excellent self-consistency. However, in the polarisation power spectra, the same analysis has highlighted a slight increase of scatter in the third survey compared to surveys 1, 2 and 4 (Figure 7). This behaviour has been confirmed by the cosmological parameters analysis where τ (the optical depth) has been sampled using a Monte Carlo Markov Chain (MCMC) method. This effect is currently under study, and it is very likely correlated with the increase of thermal fluctuations in the 20K stage after the sorption cooler switchover at the end of the second survey (Mennella et al. 2011). The analysis of this effect has triggered a series of further tests on the noise properties of the LFI 70GHz channel before and after the SCS transition, based on survey-by-survey null tests. After correction, the level of fluctuations then came back close to the original value for surveys 4 and 5.

This example demonstrates two aspects. First, it shows the key importance of survey analysis from an angular power spectrum point of view. Second, it is clear that achieving an 8^{th} survey would compensate for the poorer data quality of Survey 3, whose proper treatment is currently under investigation. The experience gained in the analysis so far gives us compelling evidence that to deepen our understanding of the data, it is essential to produce power spectra for each survey independently, as well as to perform null tests between any pair of surveys. This allows us to monitor the time evolution of the instrumental characteristics and performance.

3.4 Deep scan over calibrating sources

In our previous LFI-only extension proposal, we identified four main instrument-related aspects that would benefit from the "LFI-only" phase: Optical beam measurements; polarisation calibration; polarisation systematics removal (bandpass mismatch); determination of noise properties. All these issues remain valid points, and are discussed in this Section.

Beam determination with Jupiter

Uncertainties in the beam knowledge is a potential limiting factor for *Planck*'s scientific return. A 0.1% error in FWHM would imply a significant ~1% error in the window function, and therefore on the power spectrum, at multipoles ~1500 at 70 GHz, and at multipoles ~2000 at 100 GHz. Using the "nominally scanned" Jupiter observations we have been able to derive the main beam parameters (pointing direction, FWHM and ellipticity) from an elliptical Gaussian fit (Zacchei et al. 2010) and to reconstruct beam shapes down to –25 dB at 70 GHz and down to –20 dB at 30 GHz and 44 GHz. Jupiter measurements are also used to compare the beam maps with GRASP-9 simulated beams. During 2012, in the first 12 months of the LFI-only extension, we will be acquiring two sets of deep scans of Jupiter that will lead to an improved quality in main beam recovery.

In the first half of 2013, during the proposed 2nd extension, Jupiter will be observable by *Planck* in one period around 16-17 February 2013, and Saturn on 31 January – 1 February 2013 and 24-25 July 2013. Adding deep Jupiter scans by LFI will provide very useful data to discriminate among various telescope models. As *Planck* will be in the "LFI-only" mode, since the HFI is not active, all the available time during Jupiter visibility can be devoted to deep scans by LFI detectors, thus increasing the sensitivity. The definition of the details of the scan strategy does not present any difficulty and will be set in due time.

Remarkably, the possibility of performing several deep scans separated in time by about half a year is useful to verify either the stability or possible subtle variations in the optical system, an issue that is also of importance for HFI. In the study of the scanning strategy for the previous "LFI-only" extension, we already defined criteria for the best implementation of such a test.

Finally, these measurements will also provide valuable data for planetary scientists, given *Planck*'s accurate absolute calibration. Accumulating further scans will increase the available data base and monitoring duration.

Mapping of the Crab Nebula

The Crab Nebula is the brightest polarised source at LFI frequencies, and hence it represents an ideal choice as a polarisation calibrator. Deep-ring scans of the Crab Nebula during the 2nd extension will reduce the uncertainty in polarisation orientation of the worst-measured feed horns by a factor of two, bringing the error for all horns below 0.5°, i.e., comparable to *WMAP*, whose scanning strategy is much more advantageous than *Planck*'s from this viewpoint. The improved accuracy will also enable us to use the Crab as a check for the "*a*-factor" estimates of polarisation leakage; see (ESA/SPC(2010)21). Detailed calculations of the improvement coming from deep scans of the Crab in 2012 have already been presented in our previous study. Adding a further deep scan will improve the sensitivity of these analyses by a moderate amount (about 7%) in sensitivity, and more importantly will serve as a repeatability check.

Finally, for both Jupiter and Crab Nebula deep annuli, the deep scans will cut through various regions of low foregrounds, where the improved sensitivity will produce locally exquisite and very clean detection of the CMB polarisation, albeit along narrow stripes.

Polarisation calibration: bandpass effect

Receiver bandpass mismatch is currently the most important source of polarisation systematic effects in the LFI maps where significant foregrounds are present. The principal effect is simply an effective frequency offset between the two polarisations, characterised by the so-called "*a*-factor", defined as $a = (\nu_S - \nu_M)/(2\nu_0)$, where ν_0 is the receiver mean centre frequency and ν_S, ν_M represent centre frequencies of the main and side receiver arms. For an ideal receiver, the *a*-factor would of course be zero, and a non-zero *a*-factor specifies the amount of leakage of temperature to polarisation, known as the "spurious signal", $S = aL = a(\beta - \beta_{CMB})T_{Foreground}$, where β and β_{CMB} are spectral indices of the foreground and CMB (Leahy et al. 2010).

The spurious signal can be solved by observing pixels crossed by scans at several angles and applying suitable improved correction schemes. Current analyses based on the first four surveys have determined the *a*-factors with statistical errors of typically 0.2%, whereas requirements for optimal polarisation recovery indicate that an accuracy of 0.1% should be attained. Our current best results are from a Maximum Likelihood technique based on fitting the Tarantula nebula in the Large Magellanic Cloud, which lies in the multiply-scanned South Ecliptic pole region. We have calculated that the smooth scanning strategy applied during the "LFI-only" phase will reach the 0.1% requirements for all the horns and will also improve the *IQUSS* solutions[5] across the sky, allowing for improved separation of systematics and signal. Applying this procedure for one additional survey will provide a very welcome margin in meeting this requirement and may even allow a check for possible time variations in the *a*-factor.

3.5 Legacy

Planck is the third generation CMB satellite, following the phenomenal success of *COBE* and *WMAP*. Although there has been much discussion of future CMB missions, it seems clear at this point that these plans are more than a decade away. *WMAP* data have been extensively used for all sorts of studies, including Galactic and extragalactic foregrounds as well as cosmology. This is reflected in the huge citation rates for *WMAP* papers.

At the end of survey 6, *Planck* LFI became approximately a factor of 2 deeper than *WMAP* (specifically making the conservative comparison of 70GHz LFI with 90GHz *WMAP*). *Planck* is working now, and LFI continues to integrate down into new territory with data of excellent quality.

In the coming several years a number of sub-orbital experiments, either from balloons or from the ground, will produce maps with sensitivity surpassing that of *Planck* in limited sky regions. However, the *Planck* all-sky maps will remain the most sensitive until the next generation CMB satellite. The LFI frequencies are important for synchrotron, free-free and anomalous dust foregrounds. The 70 GHz channel is the most foreground-free of all *Planck* channels for both total intensity and polarisation and hence has intrinsic value for cosmology, particularly at low multipoles, as well as for component separation.

Plans for future CMB missions are concentrating on B-mode polarization detection, and typically employ polarimeter designs which have no (or poor) capability in total intensity. So LFI may well be the last space mission in its frequency range producing full sky temperature maps in a very long time, adding to its legacy value. It is likely that future CMB experiments will be limited by foregrounds rather than by instrumental noise. The LFI maps will have better sensitivity and angular resolution than those of *WMAP*, and they will provide the deepest and most accurate templates of the synchrotron component of foregrounds for the foreseeable future. Exploiting the full observing power of LFI will ensure a long lasting heritage in cosmology and millimeter astrophysics to be used by future generations of experiments.

4 Scanning strategy

Initially, the first LFI-only extension proposal assumed an observational strategy based on "deep annuli", i.e., a scanning plan allowing for long integrations of a few, selected, narrow, annular regions of the sky. The motivation for this choice was that, at the time of submission of the proposal, the 20K cooler lifetime was highly uncertain, raising the possibility that less than a full extra survey could be acquired. The deep annuli concept was seen as a beneficial strategy for a limited and uncertain extension. Following the submission of

[5] We refer to IQUSS to indicate an effective analysis approach, which solves for two spurious maps in addition to the usual I, Q and U maps.

the proposal, in 2011, the scanning strategy was revised to insure increased power in understanding systematics at low multipole power spectra (l < 100), both in temperature and polarisation. At that time, the well established expectation to complete a sixth sky survey was a major driver for reconsidering the scanning strategy, as it would allow us to perform null tests to improve diagnostics of systematic effects and calibration.

As discussed in Section 3, the on-going data analysis of the first four surveys shows that such a choice was extremely appropriate, particularly in providing stronger control of polarisation systematics al low multipoles.

The first four *Planck* surveys were carried out with the spin axis executing a 6-month period cycloid motion around the anti-Sun direction with a fixed phase (ϕ_0 = 340°). This choice allowed us to perform powerful null-tests tests between surveys 1–4 (sharing the same cycloid phase), and between surveys 1&3 and 2&4 (with identical patterns in the sky). Starting with Survey 5 and up to now, however, in order to improve our ability to remove high-frequency baselines and pin down spurious polarisation from bandpass mismatch, we shifted the cycloid phase to ϕ_0 = 250°. This shift proved successful for removing those effects. By maintaining the same phase ϕ_0 = 250° in Survey 8 , we will match the number of surveys with the two phase angles, four in each case, thus optimizing the possibility to perform null tests.

In conclusion, we request no change in the scanning strategy.

5 Operations and management

5.1 Instrument and SCS operation

Given the present behaviour of FM1, it is safe to assume that FM1 will support LFI uninterruptedly until and beyond September 2012 when *Planck* will observe both Jupiter and the Crab (deep scans) – a priority target for LFI.

As recommended by LFI Core Team (Bologna, March 15-16, 2012), operations will continue with FM1 through September with no interruption. SCS regeneration activity will be performed afterwards, at the end of the FM1 lifetime (Section 2.1). The exact timing and operation plan for regeneration will be decided by September 2012, based on the evolution of the in-flight behavior of FM1.

The LFI and SCS Instrument Operation Team (IOT) will continue to support instrument operations until the end of *Planck* lifetime.

Discussion is currently on-going about the possibility of far sidelobe test at end-of-life (Section 5) while a warm extension (i.e., after Sorption Cooler end-of-life) is not considered.

5.2 Risk assessment.

20K cooler Regeneration. While ground tests are encouraging, regeneration has never been carried out in flight and its success is not guaranteed. In the unlikely case that in-flight regeneration is not successful, there will still be good value in acquiring data up to the EOL of FM1 and then switching to FM2 to exploit the 4-6 weeks of lifetime. From the operations point of view no additional requirements are presented by this scenario.

4K cooler. The 4K cooler has worked continuously with very stable performance. There is no reason to expect changes.

LFI Instrument. The LFI has been working with stable performance in terms of white noise and other HK observables, except for moderate changes due to major system transitions (transponder ON, sorption cooler switch-over). There is no reason to expect changes.

5.3 Space Segment

During the extended survey the spacecraft will remain in full operation; no changes in scanning strategy are planned.

The decreased data transmission needs (related to the HFI reduced operations) were already used to reduce the contact periods with the satellite from three to two hours. Taking advantage of the experience gained in the first part of the "LFI-only" extension, this reduction can be further optimized, substantially reducing the number of connections. The most favourable situation now seems to be three connections per week on Monday, Wednesday and Friday, eventually limiting to contingency operations the connections during the rest of the week and during the week-ends. In this regard, it should be noted that from the beginning of *Planck* nominal operation until the present, the number of contingency events occurring has been limited to just a few.

If and when the communication periods are no longer provided on a daily basis, the spacecraft on board memory stores will need to be re-sized in accordance with the end of HFI operations and to allow up to 118 hours of storage space to the LFI. No additional special operations are foreseen with respect to previous surveys. The LFI instrument has been conceived to deal with this kind of situation, and the on-board parameters of the monitoring and autonomous functions can be easily modified to deal with three days of data without a connection to the ground. So far, this operation has not even been required because of the large memory allocation on the spacecraft.

In case a sidelobe measurement is attempted at the end of *Planck* operations, a dedicated analysis will be performed.

5.4 Ground Segment

As long as *Planck* is operated together with *Herschel*, the current operational concept and setup at the MOC will be continued. After completion of the *Herschel* mission, MOC support will be optimized and reduced to the minimum.

ESA support

Ways should be investigated to reduce *Planck* costs of operation as feasible. The ground station passes were already reduced to 2 hours since the amount of telemetry to be downloaded decreased with only one instrument in use and will be probably go through a further optimization with a reduced number of weekly connections (three times per week). Another possibility being considered is to stop the leased communications lines between ESOC and LFI DPC in Trieste and use public internet instead.

LFI Operation

The LFI Operations Team will continue with constant manpower until 2015 (supported by ASI with a new contract), including the monitoring of the sorption cooler operations. No changes to operations, working practices, procedures, etc. are expected. LFI will continue producing DQR and WHR as during the nominal mission but no longer on a daily basis due to the reduced frequency of ground contacts.

HFI 4K cooler operation

The HFI 4K Stirling cooler will be operated with the minimum level of support through an agreement between the HFI and LFI Teams. The necessary additional support will be provided by LFI.

The HFI consortium can continue to support the 4K cooler operations as long as it can minimize the resources needed (hardware, software items and personnel), namely:
HFI will operate with the existing hardware (which have some redundancy) and software items and operational procedures; HFI cannot afford to replace and integrate new computers or software programs.

The HFI DPC will transfer to the LFI team the same data as during the mission to this point. Should problems arise on the HFI side, we might need to limit the transfer to the house-keeping data only (this will require some modification of the software which will be a substantial effort and will require us to reopen the discussion of HFI commitments).

In case of a failure of the 4K cooler, the HFI team will investigate the problem, but if the problem cannot be solved within our resource constraints a decision will have to be made on whether or not to end the extended mission.

LFI Consortium Partners

- ASI – The program will be covered by a new ASI contract up to 2015.
- NASA – The US team will support the cooler operations if the extension is granted.
- UK – has been given a grant extension, so post-launch support will cover up to April 2015 assuming extension to the 8th survey is approved.
- SPAIN – REBA support is confirmed by IAC (Tenerife) for the extension period
- GERMANY – The German LFI team will be supported up to the end of 2014

6 Conclusions

The proposed extension of the *Planck* mission in "LFI-only" mode until August 2013, while requiring only a moderate increase of observing time, has the potential to enhance significantly *Planck*'s scientific output. The current analysis on the first four surveys shows that polarisation science at low multipoles is limited by systematic effects and foreground residuals. For LFI, the most powerful tools for fighting the dominant effects, such as sidelobes and calibration residuals, is the use of long-term null tests. The addition of an 8^{th} survey will allow us to produce a number of null tests on time scales of 6-month (single survey), 1-year (odd-even-survey), and 2-years (spin phase angle), which will be very powerful in quantifying and removing those effects. The improved rejection of systematic errors will transfer into more precise cosmological results, both directly and through the use of 30 GHz map as synchrotron template in *Planck* component separation The extension will also provide better characterization of beams and polarisation calibration, beneficial for both LFI and HFI. Not least, the extension will enhance significantly the legacy value of *Planck* for future experiments.

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Appendix A - Planck Coolers Lifetime

A.1 The 20K Sorption Coolers

The ultimate lifetime of the sorption cooler is determined by permeation of hydrogen gas into the gas-gap heat switches and by degradation of compressor hydrides. The lifetime of the compressor hydride can in principle be extended indefinitely by the regeneration process. For permeation, the lifetime limit is reached when the amount of gas permeated into the gas-gap produces a pressure that prevents the heat switch from thermally isolating the compressor element.

The temperature of the compressor element during operation determines the rate at which gas permeates into the gap volume. This temperature, in turn, is dependent on the cycle-time for the cooler. Short cycle times will keep the compressor element temperature lower, leading to lower permeation into the gas-gap. On the other hand, short cycle times will age the hydride of the cooler at a faster rate. Thus the ultimate lifetime of the cooler depends on the chosen cycle-time strategy. Thanks to the excellent performance of FM1, for the first 18 months is has been possible to keep the cycle-time quite long (>700 seconds), while maintaining the compressor element temperatures low (< 440 K). During this period, the temperatures have remained relatively constant, leading to uniform permeation rates.

As of 15 April 2012, our projection of the end-of-life for the hydride without any regeneration is 1 January 2013, once again surpassing (by about three months) our previous "optimistic" projection. Given the continual over-performance of FM1 relative to predictions, it cannot be ruled out that a further increase of the expected hydride life might occur. In any case, we conservatively assume that the hydride EOL will be reached in January 2013. Then, to increase the FM1 lifetime, regeneration will be performed. This is expected to extend the FM1 lifetime by an additional ~8 months, with EOL in August 2013. Recent experiments at JPL indicate that regeneration is effective at pressures similar to the estimated in-flight values of FM1.

The predicted lifetime associated with the gap permeation is somewhat more uncertain. Our calculations must take into account the fact that regeneration may introduce excess hydrogen gas into the gas-gap into the gas-gap, due to the high temperatures reached during the process. The precision of the predicted lifetime will improve as we accumulate more operation time. The main uncertainty in this effect is the pressure at which regeneration occurs. It is known that residual liquid was formed in the FM2 after switchover, which means that a pressure anywhere from 2.3 to 25 Bar will be present during the regeneration of FM1. The exact amount will depend on the loss of hydride capacity from operations. This value will become known when the cooler is shut off, close to when regeneration will take place. For a pressure of 15 Bars the EOL would be July 1st, while if the pressure is around 2.3 Bar, EOL will be reached on 15 August 2013.

In addition, the FM2 cooler unit still has an estimated residual lifetime of 4-6 weeks. If needed, when the EOL of FM1 is reached, we will switch the system back to FM2 and run the LFI for the remaining life of FM2. This provides an important margin to the lifetime of the 20K stage.

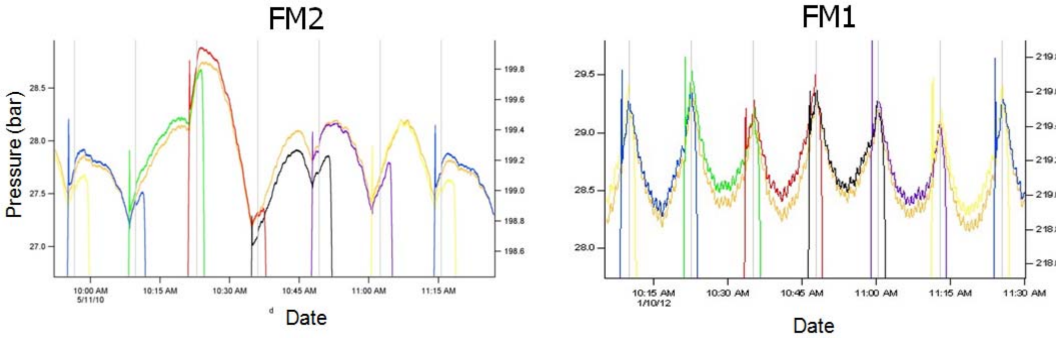

Figure A1. Comparison of pressure profiles of the FM2 cooler (left) and FM1 (right) at similar age. The regular profile cycle of FM1 indicates the superior performance of the cooler unit currently in operation, whose lifetime has been repeatedly surpassing our most optimistic predictions.

A.2 The 4K Cooler

The HFI 4K Stirling cooler is used to cool the LFI reference loads, which in turn are used to minimize the input imbalance and thus suppress the effect of 1/f noise in LFI data. The 4K cooler has been operating flawlessly and has been very stable since the beginning of the *Planck* survey. In particular, the micro-vibration cancelling system did not require any readjustment; the temperature stability insured by the 4K PID is within the HFI specifications, which are more stringent than those of the LFI. At present, there is no reason to expect noticeable degradation or malfunctions of the 4K cooler in the time scale of this proposed extension.