# MAIN BEAM AND SIDELOBE EFFECTS ON PLANCK OBSERVATIONS

C. BURIGANA[1], N. MANDOLESI[1], L. VALENZIANO[1],
F. VILLA[1], M. BERSANELLI[2] and D. MAINO[3]
[1]*Istituto TeSRE/CNR, Via Gobetti 101, I-40129 Bologna, Italy*
[2]*IFCTR/CNR, Via Bassini 15, I-20133 Milano, Italy*
[3]*SISSA - Intern. School for Advanced Studies, Via Beirut 2-4, I-34014 Trieste, Italy*

The extreme sensitivity of the Planck observations requires that all potential systematic effects are avoided or drastically reduced. Systematic errors can be expected from non-ideal optical performance, receiver instabilities, thermal effects, pointing accuracy. The impact of each effect on the measurements must be properly estimated, and it should be reduced by a careful instrument design and an adequate observational strategy, rather than relying on a-posteriori corrections of their combined effect in the data. We focus here on the effects introduced by beam distortions for the Planck optical design. We point out the main requirements on the primary mirror aperture to achieve the key cosmological goal of $10'$ resolution at the "clean" astrophysical window at 100 GHz.

## 1 Introduction

Future space missions dedicated to the imaging of the cosmic microwave background (CMB), like Planck and MAP, represent a powerful opportunity for cosmology and astrophysics. The nominal angular resolution and sensitivity of the Planck instruments, both at high frequencies (HFI) and low frequencies (LFI), allow to determine the angular power spectrum, $C_l$, of CMB primordial fluctuations up to multipoles, $l$, larger than $10^3$ (see Vittorio [1] and references therein), i.e. until secondary anisotropies do not largely overwhelm primordial signatures. On the other hand, experiences from the previous CMB experiments as well as a realistic analysis of Planck observational performances indicate that a stringent control of all the systematic effects is crucial to reach the mission objectives. Galactic and extragalactic foregrounds are important sources of astrophysical contaminations at a level that depend on the frequency and angular scale (see De Zotti *et al.* [2] and references therein), but, from the opposite point of view, their study represents an important co-product of the Planck mission. Two complementary approaches have been proposed by both LFI and HFI teams for reducing the impact of instrumental systematic effects on anisotropy measurements: the "hardware" approach, i.e. design mission strategy and instruments in order to minimize all the potential systematic effects, and the "software" approach, i.e. develop data analysis methods to further reduce residual effects in the data. We present here some results of the LFI team studies on the Planck telescope optical performances.

## 2 The effect of sidelobes and main beam distortions

Optical aberrations make the main (i.e. within few FWHM from the beam centre) beam response somewhat different from the reference case of a pure gaussian, centrally symmetric shape. The

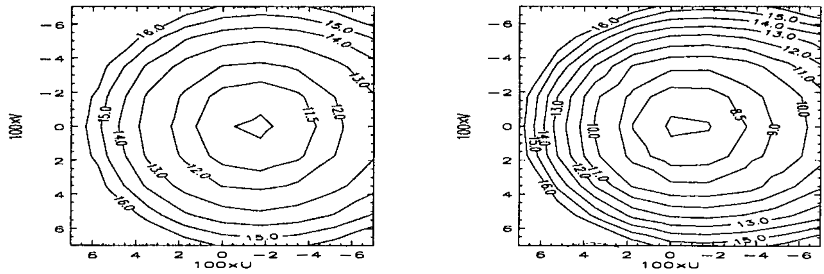


Figure 1: Contour plot of effective angular resolution (in arcmin) for the relevant sky field of view, U–V, in the case of a 1.3 m (left panel) and a 1.75 m (right panel) aperture gregorian telescope.

radiation pattern at large angles from the main beam (sidelobes) is dominated by diffraction effects on the structure edges, that make not negligible the response at large angles from the beam centre. Sidelobes introduce a contamination in sky temperature measured by the main beam due to the contribution of the sky signal entering the outer regions; this effect maybe significant owing to the Galactic emission, depending on the observed sky region, on the frequency and on the shielding efficiency. Further, the behaviour of the radiation pattern at intermediate angular scales from the beam centre has to be carefully considered. The present optical analysis for the "Phase A" Planck telescope is still preliminar but indicates a maximum ratio of about the 10% between the "outer" signal and the "inner" one, to be principally ascribed to the beam response immediately external to the main beam (K. Gorski and E. Hivon, private communication). Main beam distortions may introduce a degradation of the angular resolution and of the sensitivity per resolution element. These two last effects can be seen as orthogonal one each other in the space $\theta - \Delta T$ of angular scales and temperature anisotropy or, equivalently, in the space of $l - C_l$ (Burigana *et al.*[3], Mandolesi *et al.*[4]). For telescopes like that of Planck, the relative importance of main beam distortions and sidelobe effects is controlled by the edge taper (Sletten[5]): reducing its level reduces the sidelobe level and the main beam angular resolution. An edge taper of $-30$ dB relative to the centre for the central beam has been assumed for the present computations.

The instrument design of the Planck mission calls for multi-frequency focal plane arrays placed at the focus of an off-axis gregorian telescope, in order to achieve proper angular resolution, sensitivity, and spectral coverage. As a consequence, not all the feedhorns can be located very close to the centre of the focal plane, where optical distortions are minimum. This issue is crucial after the recent proposed baseline configuration of the Focal Plane Unit (FPU), a symmetric design with HFI in the central portion of the focal plane and LFI distributed as a ring around it, thus requiring a major effort to minimize the negative effect of beam distortions.

We have used a software, based on the calculations reported by Sletten[5], to compute the beam shapes for three gregorian telescopes with different aperture D: 1.3 m ("Phase A" mirror, see Bersanelli *et al.*[6]), 1.55 m, 1.75 m. A typical beam shape is reported in Villa *et al.*[7]. The contour plots of typical off-axis beams show that the curves of equal response roughly have elliptical shapes, with the centres of the different response level curves somewhat shifted one each other, coupled to localized distortions (spots) at response levels of about $-15$ dB respect to the centre (see Villa *et al.*[7] and Mandolesi *et al.*[4]). A decrease in the effective beam angular resolution is also evident in the off-axis beam shapes. These features increase with the distance from the optical axis and with the frequency.

In order to evaluate the main beam distortion impact on Planck observations, we have applied a modified version of the fully numerical method described in Burigana *et al.*[3]: a

Table 1: Beam properties at 100 GHz for telescopes of different aperture: $W_e$ (in arcmin) and values (in $\mu$K) of the thermodynamic temperature *rms* differences, $\sigma_{th}$, measured by "true" beams and corresponding gaussian beams. Results from pairs of beams located at the same U and | V | have been averaged. By averaging over all the feeds we have: $< W_e >= 13.1, 11.0, 9.7$ arcmin and $< \sigma_{th} >= 2.2, 2.1, 2.0\mu k$ respectively for the 1.3, 1.55, 1.75 m aperture telescopes.

| D → | 1.3m | | 1.55m | | 1.75m | | D → | 1.3m | | 1.55m | | 1.75m | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Feed | $W_e$ | $\sigma_{th}$ | $W_e$ | $\sigma_{th}$ | $W_e$ | $\sigma_{th}$ | Feed | $W_e$ | $\sigma_{th}$ | $W_e$ | $\sigma_{th}$ | $W_e$ | $\sigma_{th}$ |
| 1 | 12.00 | 2.10 | 10.00 | 1.70 | 8.90 | 2.60 | | | | | | | |
| 2 & 17 | 12.15 | 3.15 | 10.25 | 2.75 | 9.00 | 1.90 | 3 & 16 | 12.35 | 2.70 | 10.45 | 2.10 | 9.20 | 2.10 |
| 4 & 15 | 13.00 | 2.30 | 11.00 | 1.45 | 9.80 | 2.70 | 5 & 14 | 12.90 | 2.40 | 10.90 | 2.80 | 9.55 | 1.75 |
| 6 & 13 | 13.15 | 2.00 | 11.00 | 2.00 | 9.70 | 1.90 | 7 & 12 | 13.40 | 2.05 | 11.20 | 2.35 | 9.85 | 2.00 |
| 8 & 11 | 13.90 | 1.15 | 11.65 | 1.95 | 10.25 | 1.85 | 9 & 10 | 14.20 | 2.05 | 12.05 | 1.40 | 10.70 | 1.70 |

simulated CMB fluctuations sky (standard CDM, but our results are essentially independent of the assumed model) is convolved with the calculated beams truncated at 1° from the beam centre, as well as with a set of Gaussian beams of widths from 6′ to 17′. The FWHM of the Gaussian beam that gives the smallest sky temperature *rms* difference compared to a given distorted beam can be taken as the effective angular resolution, $W_e$, of that distorted beam (semi-analytical methods, based on effective window functions, give very similar results, see Mandolesi *et al.* [4]). In addition, this minimum value of *rms* quantifies the typical difference between signals measured by a distorted beam and the *corresponding* gaussian one, i.e. the added noise due to main beam distortions in absence of further reduction through data analysis.

## 3 Optical performance versus primary mirror aperture

Figure 1 shows our results as contour plots of effective angular resolution over the relevant sky field of view (the U–V plane, the U (V) direction corresponding to the $x$ ($y$) direction on the FPU – see the figure in Villa *et al.* [7]) for the smallest and largest primary mirrors considered here. Note the symmetry of this effect in the V direction and the large asymmetry in the U direction which strictly reflects the intrinsic asymmetry of the adopted gregorian configuration; the locations of the feedhorns in the focal plane have been designed to take this effect into account (see Villa *et al.* [7] and Mandolesi *et al.* [4]). Table 1 summarize our results for all the 100 GHz beams.

We are able also to quantify one of the most important effects of distorted beams: even observations at the same position on the sky taken by different feeds at a given frequency *cannot be simply averaged together*, being each beam differently distorted, possibly with a different orientation. Figure 2 shows the distributions histogram of differences between the signal measured by the all the 17 LFI 100 GHz feeds (solid lines) at 100 different positions choosen along a typical scan circle on the sky and for two subsets of feeds with quite similar (differences $\lesssim 0.2'$, dotted lines) or quite different ($\sim 2'$, dashed lines) $W_e$. Unfortunately, this dispersion of the sky temperature measurements cannot be significantly reduced by increasing the telescope aperture. It can be reduced only with a different FPU configuration which allows a location of all the 100 GHz feeds closer to the centre or, hopefully, in the data analysis; nevertheless, all previous experience with CMB data shows that the more and larger are the systematic effects that must be scrubbed from the data in analysis, the more uncertain is the result.

As shown by the evaluations in Figure 1 and Table 1, a larger telescope allows to reach the nominal 10′ resolution; this is due both to the better resolution of the best LFI feed and to the partial reduction of the (absolute) angular resolution degradation between the best and the worst LFI feed in the LFI ring region; in addition, at least a partial reduction of the added noise is obtained. This is due to the better optical performance as well as to the well known geometrical property that larger aperture telescopes lead to beam locations closer to the optical

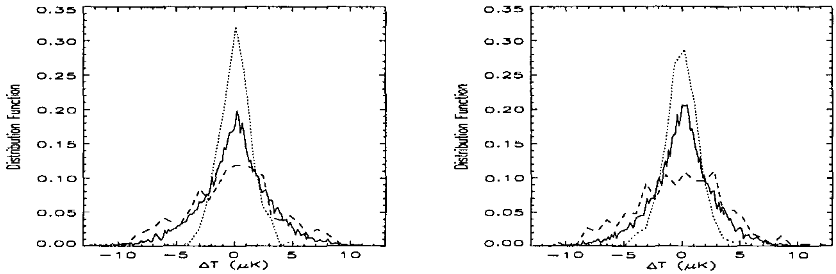


Figure 2: Distribution functions of differences between the signal measured by the LFI 100 GHz feeds and for two subsets of them (see text). [Telescope aperture of 1.3 m (left panel) and of 1.75 m (right panel)].

axis direction, so automatically releasing the issue of the distortions. For example, in the case of 1.3 m aperture telescope the mean 100 GHz beam points at an angle of 3.3° from the optical axis; this angle becames about 2.8° or 2.5° respectively for an aperture of 1.55 m or of 1.75 m.

## 4 Conclusions

Our results show that the "Phase A" optical design of Planck suffers from large off-axis beam distortions that seriously degrade the beam effective angular resolution and compromise Planck science as well as enormously complicate the data analysis. The "Phase A" telescope and the present FPU arrangement yields a $\sim$ 30 percent degradation of the LFI effective angular resolution, and is therefore not acceptable.

Our analysis shows that these deficiencies can be reduced by enlarging the primary mirror (hopefully up to 1.75 m aperture), using an edge taper of about $-(30\div35)$ dB and optimizing the shapes of the primary and secondary. Such a telescope would have little thermal and structural impact on the mission design. Moreover, possible elimination of the need for a large radiation shield may result in net mass savings to ESA compared to the "Phase A" design. It would be more prudent and advantageous to build a larger telescope for Planck that minimizes the beam distortions (particularly for what concerns the impact on the angular resolution) and/or to locate the LFI feeds at 100 GHz closer to the centre (so minimizing the dispersion of the sky temperature measurements too) than to try the reduction of these distortion effects during the data analysis only.

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