On Planck simulations: towards “2-nd order” analyses

C. Burigana$^1$, D. Maino$^2$, N. Mandolesi$^1$, F. Villa$^1$, L. Valenziano$^1$, M. Bersanelli$^3$, L. Danese$^2$, L. Toffolatti$^{1,5}$ & F. Argüeso$^6$

$^1$Istituto TeSRE, CNR, Bologna, Italy; $^2$SISSA – International School for Advanced Studies, Trieste, Italy; $^3$IFC, CNR, Milano, Italy; $^4$Osservatorio Astronomico di Padova, Italy; $^5$Departamento de Física, Universidad de Oviedo, Spain; $^6$Departamento de Matemáticas, Universidad de Oviedo, Spain.

ABSTRACT – We simulate Planck observations by adopting a detailed model of the microwave sky including monopole, dipole, anisotropies of the cosmic microwave background (CMB) and galactic and extragalactic foregrounds. We estimate the impact of main beam optical aberrations on CMB anisotropy measurements in presence of extragalactic source fluctuations and we discuss the main implications for the Planck telescope design. By analysing the dipole pattern, we quantify the Planck performance in the determination of CMB spectral distortion parameters in presence of foreground contaminations.

KEYWORDS: Cosmic Microwave Background, Foregrounds – Simulations – Telescopes.

1. INTRODUCTION

The Planck satellite (Mandolesi et al. 1998a; Puget et al. 1998) will map CMB anisotropies over the entire sky at frequencies $\simeq 30 \div 857$ GHz with angular resolution of $\sim 30' \div 5'$ and sensitivities of $\sim 5 \div 15\mu$K per resolution element. It will lead to a determination of the primordial angular power spectrum $C_l$ up to multipoles $l \sim (1 \div 2) \times 10^4$ and of the fundamental cosmological parameters with unprecedented accuracy.

To reach the mission goals all instrumental and astrophysical systematic effects must be carefully controlled. We have simulated Planck observations by adopting a detailed model of the microwave sky – including CMB monopole, dipole and fluctuations together with galactic and extragalactic foregrounds (Section 2) – to study two different kinds of “2 – nd order” features in which astrophysical and/or instrumental effects are treated in combination.

The contamination from galactic diffuse emission and extragalactic source fluctuations, widely discussed in the literature (see, e.g., Lasenby 1997; Toffolatti et al. 1998; De Zotti & Toffolatti 1998), depends on the frequency and angular scale. A more refined analysis requires coupling the sky signal with realistic instrument response. At Low Frequency Instrument (LFI) channels, main beam distortions introduce, in the case of a pure CMB anisotropy sky, an added (non–white) noise of order of $\sim 2\div4\ \mu$K, depending on the level of optical distortions and beam width, and also on the $C_l$’s normalization and the cosmological model (Burigana et al. 1998; Mandolesi et al. 1998b). In the 30 GHz channel this effect can be $\sim 3$ times larger at low galactic latitudes, because of the Galaxy emission gradients (Burigana et al.
1998). In Section 3 we evaluate the impact on anisotropy measurements of main
beam distortions in presence of extragalactic source fluctuations and discuss the
main implications for the Planck telescope design.

The accurate knowledge of the microwave sky dipole pattern can be used to
derive detailed information on the local system velocity with respect to the CMB
frame (Fixsen et al. 1996) and to constrain possible CMB spectral distortions (see,
e.g., Burigana et al. 1995), that yield a dipole amplitude \( \Delta T_D \), sensitive to the
CMB spectrum derivative (Danese & De Zotti 1981). This method has the ad-
vantage of circumventing the problem of high accuracy absolute calibration needed
in traditional CMB spectrum experiments. In Section 4 we estimate the Planck
performance in the determination of CMB spectral distortion parameters from the
analysis of the dipole pattern in presence of foreground contaminations.

2. GENERATION OF A SIMULATED MICROWAVE SKY

- **Modelling the CMB pattern** – The CMB monopole and dipole, for black-
body or distorted CMB spectra, have been generated by using the Lorentz invari-
ance of photon distribution functions, \( \eta \), in the phase space (Compton–Getting
effect): \( \eta_{\text{obs}}(\nu_{\text{obs}}, \vec{n}) = \eta_{\text{CMB}}(\nu_{\text{CMB}}) \), where \( \nu_{\text{obs}} \)
is the observation frequency, \( \nu_{\text{CMB}} = \nu_{\text{obs}}(1 + \vec{\beta} \times \vec{n})/\sqrt{1 + \beta^2} \)
is the corresponding frequency in the CMB
rest frame, \( \vec{n} \) is the unit vector of the photon propagation direction and \( \vec{\beta} = \vec{v}/c \)
the observer velocity. For gaussian models, the CMB anisotropies at \( l \geq 2 \) can be
simulated by following the standard spherical harmonic expansion (see, e.g., Bur-
igana et al. 1998) or by using FFT techniques which take advantage of equatorial
pixelisations (Muciaccia et al. 1997).

- **Modelling the Galaxy emission** – The Haslam map at 408 MHz (Haslam
et al. 1982) is the only full-sky map currently available albeit large sky areas are
sampled at 1420 MHz (Reich & Reich 1986) and at 2300 MHz (Jonas et al. 1998).
To clean these maps from free-free emission we use a 2.7 GHz compilation of \( \sim 7000 \)
HII sources (C. Witebsky et al. 1978, private communication) at resolution of \( \sim 1^\circ \).
We use a spectral index \( \beta_{\text{ff}} = 2.1 \) from 2.7 to 1 GHz and \( \beta_{\text{ff}} = 0 \) below 1 GHz.
We then combine the synchrotron maps producing a spectral index map between
408-2300 MHz with a resolution of \( \sim 2^\circ \div 3^\circ \) \( (< \beta_{\text{sync}} > \sim 2.8) \). This spectral
index map is used to scale the synchrotron component down to \( \sim 10 \) GHz. In fact,
for typical (local) values of the galactic magnetic field \( (\sim 2.5 \mu G) \), the knee in the
electron energy spectrum in cosmic rays \( (\sim 15 \text{ Gev}) \) corresponds to \( \sim 10 \) GHz (Pla-
tania et al. 1998). From the synchrotron map obtained at 10 GHz and the DMR
31.5 GHz map we derive a high frequency spectral index map for scaling the syn-
chrotron component up to Planck frequencies. These maps have a poor resolution
and the synchrotron structure needs to be extrapolated to Planck angular scales.
An estimate of the synchrotron angular power spectrum and of its spectral index,
\( \gamma (C_l \propto l^{-\gamma}) \), has been provided by Lasenby (1997); we used \( \gamma = 3 \) for the angular
structure extrapolation (Burigana et al. 1998). Schlegel et al. (1998) provided a
map of dust emission at 100µm merging the DIRBE and IRAS results to produce a map with IRAS resolution (≃ 7′) but with DIRBE calibration quality. They also provided a map of dust temperature, $T_d$, by adopting a modified blackbody emissivity law, $I_\nu \propto B_\nu(T_d)\nu^\alpha$, with $\alpha = 2$. This can be used to scale the dust emission map to Planck frequencies using the dust temperature map as input for the $B_\nu(T_d)$ function. Unfortunately the dust temperature map has a resolution of $≃ 1^\circ$; again, we use an angular power spectrum $C_l \propto l^{-3}$ to scale the dust skies to the Planck proper resolution. Merging maps at different frequencies with different instrumental features and potential systematics may introduce some internal inconsistencies. More data on diffuse galactic emission, particularly at low frequency, would be extremely important.

- Modelling the extragalactic source fluctuations – The simulated maps of point sources have been created by an all–sky Poisson distribution of the known populations of extragalactic sources in the $10^{-5} \leq S(\nu) \leq 10$ Jy flux range exploiting the number counts of Toffolatti et al. (1998) and neglecting the effect of clustering of sources. The number counts have been calculated by adopting the Danese et al. (1987) evolution model of radio selected sources and an average spectral index $\alpha = 0$ for compact sources up to $\approx 10^3$ GHz and a break to $\alpha = 0.7$ at higher frequencies (see Impey & Neugebauer 1988; De Zotti & Toffolatti 1998), and by the model C of Franceschini et al. (1994) updated as in Burigana et al. (1997), to account for the isotropic sub-mm component estimated by Puget et al. (1996) and Fixsen et al. (1996). At bright fluxes, far–IR selected sources should dominate the number counts at High Frequency Instrument (HFI) channels for $\nu \gtrsim 300$ GHz, whereas radio selected sources should dominate at lower frequencies (Toffolatti et al. 1998). Moreover, the angular power spectra calculated by Toffolatti et al. (1998) allows us to simulated gaussian extragalactic source fluctuation skies, by using the method adopted for generating CMB gaussian fluctuations.

At 353 GHz we also exploited, for comparison, the number counts of model “E” of Guiderdoni et al. (1998) which better accounts for the far–IR extragalactic background recently detected by the COBE–DIRBE team (Hauser et al. 1998), although it overestimates the level of the isotropic sub-mm component as derived by Fixsen et al. (1998). Model “E” of Guiderdoni et al. (1998) is found to produce a Poisson confusion noise higher by a factor $\sim 1.5$ with respect to the prediction of Toffolatti et al. (1998) at the same frequency (De Zotti & Toffolatti 1998).

- Modelling the observed signal – We produce full sky maps, $T_{\text{sky}}$, by adding the antenna temperatures from CMB (with or without spectral distortions), Galaxy emission and extragalactic source fluctuations. The white noise depends on instrumental performances and on the observed signal and changes in the sky according to the Planck scanning strategy. Planck will perform differential measurements and not absolute temperature observations; we then represent the final observation in a given $i$-th pixel in the form $T_i = R_i(T_{\text{sky},i} + N_i - T_{x,i})$, where $N_i$ is the noise (the $1/f$ noise can be reduced at levels smaller than the white noise by efficient cooling and with destriping algorithms), $T_{x,i}$ is a reference temperature subtracted in the
differential data and $R_i$ is a constant which accounts for the calibration. Of course, the uncertainty on $R_i$ and the pixel to pixel variation of $T^r_{x,i}$ have to be much smaller than the Planck nominal sensitivity. Then, we generate the “observed” map assuming a constant value, $T^r_x$, of $T^r_{x,i} \forall i$. We note that possible constant small off-sets in $T^r_x$ could be in principle accepted, not compromising an accurate knowledge of the anisotropy pattern. A possible isotropic astrophysical foreground relevant at Planck frequencies not covered by other experiments (from $\simeq 1$cm to $\simeq 1$mm) may be very difficult to subtract at a high level of accuracy, being orders of magnitudes smaller than the CMB monopole. To be conservative, we can mimic this effect by analyzing the “observed” map by assuming $T^r_x$ to be somewhat different from that adopted in the map generation; this can also mimic our uncertainty in estimating the foreground level at higher frequencies. We arbitrarily generate the “observed” map with $R_i = R = 1 \forall i$; again, by analyzing it with a different value of $R$, we can estimate the impact of a systematic error in the absolute calibration (for example, without using the dipole itself, the calibration with the planets achieves an accuracy of few percent; we will assume a relative error of 5% in the absolute calibration for numerical estimates).

3. BEAM DISTORTIONS AND EXTRAGALACTIC SOURCE FLUCTUATIONS

Bright sources, for example above a $5\sigma$ clipping threshold, contaminate a relatively small number of pixels and can be clearly identified by carrying out multi-frequency observations. On the other hand, source fluctuations could in principle contaminate Planck observations in a way difficult to predict in presence of optical aberrations. We analyze here this effect for the 30 GHz channel, the most critical of the LFI for this effect. The main beam shape has been computed following the method described in Mandolesi et al. (1998b) for two extreme Planck telescope apertures: 1.3m and 1.75m. In the present symmetric configuration for the Planck focal plane unit, the two 30 GHz beams present specular shapes: we can then study only one beam. We convolve a CMB anisotropy map with the simulated beam and with a set of symmetric gaussian beams with $25' \leq FWHM \leq 40'$; by comparing these simulated observations for a suitable number of telescope positions in the sky, we find the FWHM of that gaussian beam which gives measurements most similar to those obtained by our beam. For the 1.3m and 1.75m telescope we find an “equivalent” FWHM of $38'.8$ and $28'.7$ respectively. We can then convolve our extragalactic source fluctuation sky with the simulated beam and with the symmetric gaussian beam with the “equivalent” FWHM. The $rms$ of the differences of the temperatures “measured” in these two cases provides an estimate of the noise added by optical distortions. For the 1.3m and 1.75m telescopes we have a $rms$ value of $\sim 1.5\mu K$ and of $\sim 0.8\mu K$ respectively. This effect is significantly smaller than the average final sensitivity and the analogous effect in presence of CMB anisotropy only and of Galaxy emission at low galactic latitudes. On the other hand it is not negligible compared to the sensitivity at high ecliptic latitudes, where the Planck integration time is much larger than the average. Increasing the primary mirror size
respect to the Phase A study (1.3m aperture), necessary to achieve the key goal of 10' resolution at the “cosmological” channel at 100 GHz, helps also in reducing this kind of contamination (the present baseline allows to significantly increase the primary mirror aperture). Also, further improvements in the optical design, like that suggested by our preliminary study on aplanatic configurations, can hopefully reduce this effect. We stress the relevance of suppressing this effect by optimizing the optical design, being difficult and time consuming, if not impossible, to reduce it in the data analysis only, in presence of many other kinds of systematic effects.

4. CONSTRAINTS ON THE CMB SPECTRUM FROM THE DIPOLE PATTERN

We fit our simulated maps by modelling only the CMB monopole and dipole contributions to $T_{\text{sky}}$ and the local system velocity (we assume $T_0$ and $\beta$ within the 95% CL FIRAS limits, $aT_0^4$ being the present radiation energy density). We subtract the Galaxy emission, by using a model more rough than that adopted for generating it, in order to test the impact of a non-accurate Galaxy subtraction on the recovering of the CMB distortion parameters. We use the 408 MHz map (Haslam et al. 1982) as a synchrotron template and scale it to 10 GHz with a spectral index $\beta_{\text{sync}} = 2.8$; the dust emission ($\propto B_\nu(T_d)\nu^{2}$) is scaled from the 100 $\mu$m map (Schlegel et al. 1998) with a dust temperature $T_d = 20$K; $\beta_{\text{sync}}$ and $T_d$ are taken constant over the sky. No extrapolation at small angular scales has been performed. The difference between models with $\beta_{\text{sync}} = 2.65$ and 2.95 and $T_d = 15$ K and 25 K respectively for extrapolating synchrotron emission in the $\sim 1 \div 10$ GHz range and dust emission from 240$\mu$m provides an estimate of the uncertainty of this Galaxy subtraction model. Conservatively, we did not subtract the contributions to small scales anisotropies from primordial fluctuations and extragalactic sources, which give an additional uncertainty in this calculation. On the contrary, we simply include in the quoted error in each pixel the variances of the input maps of CMB anisotropies and extragalactic source fluctuations, each being a scientific output of the Planck mission.

We have separately exploited three Planck channels (30, 100 and 353 GHz), for a planckian spectrum and three kinds of “standard” distorted spectra: the Bose–Einstein distortion, the comptonization distortion, described respectively by the chemical potential $\mu$ and the comptonization parameter $u$, related to the fractional energy injected in the radiation field, and the free–free distortion, described by a parameter, $y_B$, related to the plasma thermal history at redshifts less than $\approx 10^4$.

By fitting the dipole pattern in absence of foreground contaminations, we recover exactly the input distortion parameters at each channel with very small statistical uncertainties ($\sim$ few $\times 10^{-3}$ $\div$ few $\times 10^{-8}$ at 95% CL). Similarly, gaussian extragalactic source fluctuations insignificantly affect the input parameter recovering. On the contrary, Poisson extragalactic source fluctuations, Galaxy emission and CMB anisotropies at $l \geq 2$ degrade our capability of recovering the input distortion parameters (we have verified that an intrinsic CMB dipole with $C_1 \sim C_2$ does not affect our conclusions). For example, by adopting an input planckian spectrum and
working at 100 GHz we obtain $\mu \sim 2.2 \times 10^{-5}$, $u \sim 2.6 \times 10^{-6}$ and $y_B \sim -1.6 \times 10^{-5}$ with statistical uncertainties in the range few $\times 10^{-8}$ ÷ few $\times 10^{-7}$. In general, working at low (high) frequencies is more advantageous for recovering $\mu$ and $y_B$ ($u$) distortions, as we have found from the channels at 30 and 353 GHz. By fitting the same observed maps by assuming a calibration constant $R = 0.95$, we find absolute differences between the input distortion parameters and the recovered ones in the range $\sim 3 \times 10^{-6} \div 3 \times 10^{-5}$, quite close to those previously obtained. Finally, we consider also the presence of a possible ignored foreground (we assume for the present estimates a value lower than the CMB monopole by a factor $\sim 5 \times 10^{-5}$ at 30 and 100 GHz and $\sim 10^{-4}$ at 353 GHz, with no calibration error): we find absolute differences between input and recovered distortion parameters in the range $\sim 4 \times 10^{-6} \div 10^{-5}$, again with very small statistical uncertainties. Then, the most important source of uncertainty derives from astrophysical contaminations. Similar degradations and uncertainties are obtained also for distorted spectra.

Even in presence of all the uncertainties discussed above, these preliminary results are promising, indicating that Planck could improve the present constraints on distortion parameters by a factor $\gtrsim 5$ [i.e. with errors $\Delta \mu \sim \Delta u \sim \Delta y_B \gtrsim (1 \div 2) \times 10^{-5}$] or detect possible spectral distortions with a similar level of uncertainty.

ACKNOWLEDGMENTS

We gratefully acknowledge stimulating and helpful discussions with G. De Zotti, P. Platania and G.F. Smoot. We wish to thank B. Guiderdoni for kindly providing us the number counts of their model “E”. LT and FAG acknowledge partial financial support from the Spanish Dirección General de Enseñanza Superior (DGES), projects PB95–0041 and PB95–1132–C02–02.

REFERENCES

Burigana, C., De Zotti, G., Danese, L. 1995, A&A 303, 323
Burigana, C., et al. 1997, MNRAS 287, L17
Burigana, C., et al. 1998, A&ASS 130, 551
Danese, L., De Zotti, G. 1981, A&A 94, L33
Danese, L., et al. 1987, ApJ 318, L15
De Zotti, G., Toffolatti, L. 1998, this Conference
Fixsen, D.J., et al. 1996, ApJ 473, 576
Fixsen, D.J., et al. 1998, ApJ, in press [astro-ph/9803021]
Franceschini, A., et al. 1994, ApJ 427, 130
Guiderdoni, B., et al. 1998, MNRAS 295, 877
Haslam, C.G.T., et al. 1982, A&ASS 47, 155
Hauser, M.G., et al. 1998, ApJ, in press [astro-ph/9806167]
Impey, C.D., Neugebauer, G. 1988, AJ 95, 347
Jonas, J.L., Bart, E.E., Nicolson, D. 1998, MNRAS, 297, 977
Lasenby, A.N. 1997, in proc. of XVth Moriond Astroph. Meeting, pg. 453 [astro-ph/9611214]
Mandòlesi, N., et al. 1998a, Planck LFI, A Proposal Submitted to the ESA.
Mandòlesi, N., et al. 1998b, A&A, submitted
Muciaccia, P.F., Natoli, P., Vittorio, N. 1997, ApJ 488, L63
Platania, P., et al. 1998, ApJ 505, 473
Puget, J.-L., et al. 1996, A&A 308, 5
Puget, J.-L., et al. 1998, HFI for the Planck Mission, A Proposal Submitted to the ESA.
Reich, P., Reich, W. 1986, A&ASS 63, 205
Schlegel, D.J., Finkbeiner, D.P., Davis, M. 1998, ApJ 500, 525
Toffolatti, L., et al. 1998, MNRAS 297, 117