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ESTIMATES OF PLANCK SENSITIVITY FOR THE DETECTION AND STUDY OF MOVING SOURCES

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SUMMARY – The final sensitivity of the PLANCK surveyour maps of temperature fluctuations of the cosmic microwave background and of several astrophysical components, of galactic and extragalactic nature, will take advantage from the whole set of receivers and the full observation time. On the contrary, for the detection and/or the study of moving sources, like comets or asteroids, we can take advantage only from the sensitivity of a limited number of receivers and/or for a limited time interval. Preliminary estimates of the PLANCK sensitivity to this scientific purpose are here provided by taking into account the current optical design of the PLANCK telescope and focal plane unit, the sensitivity and the particular way of PLANCK to observe the sky, the main astrophysical and cosmological source of confusion noise, and the possibility to use the previous observations of the MAP satellite. This work has been done in the framework of the PLANCK LFI activities.

1 Introduction: PLANCK performances

The PLANCK surveyour [1] will observe the sky at nine frequencies with different angular resolutions and sensitivities; we report in Table 1 the relevant parameters for the PLANCK Low Frequency Instrument (LFI) and High Frequency Instrument (HFI) (see columns 1, 4 and 5). The relative bandwidth of the LFI and HFI is respectively $\simeq 20\%$ and $\simeq 25\%$ (see column 2 of Table 1).

We will refer here to the nominal PLANCK sensitivity per resolution element (a squared pixel with side given equal to the Full Width at Half Maximum (FWHM) of the corresponding beam) in the measurement of microwave anisotropy in terms of antenna temperature and flux, as recently revised by the LFI Consortium (PLANCK Low Frequency Instrument, Instrument Science Verification Review, October 1999, LFI Design Report, private reference; see also the LFI proposal, Mandolesi et al. 1998) and as reported in the HFI proposal (Puget et al. 1998).

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[1] http://astro.estec.esa.nl/SA-general/Projects/Planck/

The normalized sensitivity per pixel in the sky (i.e., the sensitivity divided by the averaged sensitivity of the observed pixels in the sky) for a typical PLANCK beam improves with the module of the ecliptic latitude up to a ring of optimal sensitivity which contains a small unobserved sky region. The normalized sensitivity averaged over the ecliptic longitudes as function of the ecliptic colatitude is close to unit at the ecliptic colatitude $\theta_e \simeq 50^\circ$ and 130° and is quite well approximated by the law $\sqrt{\sin\theta_e/\sin 50^\circ}$ at least for ecliptic latitudes between about -70° and -70°, relevant for Solar System objects. Of course, the detailed behaviour of the sensitivity on θ_e depends on the choice of the scan angle α, the adopted scanning strategy and the beam position on the telescope field of view.

Since we are here interested on the study of objects with variable position (and possibly variable flux), their detection/observation and/or the estimate of their fluxes can not take easily advantage from the twice coverage of the sky in the planned period of observation (we assume here 14 months of observation) nor from the coadding of data from different feeds if they look at different sky positions at the same time. In this report we extend the previous estimates by Burigana (2000) of PLANCK LFI sensitivity for moving bodies and variable sources to the PLANCK HFI channels in the case of moving bodies; in fact, differently to the case of source variability (essentially radiosources), particularly relevant at lower frequencies, the HFI channels can play a crucial role for the study of the moving bodies of the Solar System, because of their frequency spectra, typically close to blackbodies or modified blackbodies at temperatures significantly higher than that of the CMB or dominated by dust emission components or by possible emission lines, particularly relevant at the highest PLANCK frequencies (see, e.g., Cremonese et al. 2000). We also refine here some considerations on the LFI sensitivities by taking into account the most recent computations of the LFI beam positions on the telescope field of view (M. Sandri & F. Villa, July 2001, PL-LFI-PST-TN-027, private reference).

In addition to the instrumental noise, the sky itself exibits a confusion noise given by the various galactic and extragalactic temperature fluctuations and from the cosmic microwave background (CMB) anisotropies, relevant at different angular scales $\theta \simeq 180^\circ/\ell$, where ℓ is the multipole of the harmonic expansion of the temperature fluctuation pattern. We report in Table 1 (column 7) the fluctuation level of the CMB anisotropy assuming a rms thermodynamic temperature fluctuation of about 95 μK as derived for a standard flat model approximately COBE/DMR normalized with cosmological parameters compatible with the present constraints on CMB fluctuations at moderate multipoles derived from recent balloon experiments; of course the accurate determination of the CMB confusion noise at small scales is the main PLANCK goal.

Then we report in column 8 of Table 1 the extragalactic source confusion noise as evaluated by Toffolatti et al. (1998) and revised by De Zotti et al. (1999a,b), by taking into account both radiosources and infrared sources. More precisely, in these estimates we compute the source confusion as $\sigma_{ex.sou.} = \sqrt{C_l}/(\mathrm{FWHM/rad})$ where the angular power spectrum C_l is the sum of the C_l of radiosource fluctuations and far-IR source fluctuations, as quoted by De Zotti et al. (1999b) for a conservative detection limit of 1 Jy (see their Table 6). These estimates may be pessimistic, on the other hand it would be probably difficult to to subtract sources in real time with high accuracy; we have also to take in mind that the source clustering, neglected here, may significantly increase the source confusion noise, at least for some cosmological models, particularly at the highest PLANCK frequencies (Magliocchetti et al. 2001).

The galactic fluctuation levels reported here in column 9 of Table 1 are only indicative and refer to moderate and high galactic latitudes, as large variations are present in the sky.

The relevant global sensitivity for point source detection/observation is typically assumed by the standard σ-clipping methods as the sum in quadrature of all the sources of confusion noise, multiplied by a proper constant (for example $n_c = 2$, 2.5, 3 or 5).

We report also in the last column of Table 1 the sensitivity of the MAP experiment[2] ($\sim 35\mu$K, in terms of thermodynamic temperature, on squared pixels with 0.3° side at each frequency channel, 22, 30, 40, 60 and 90 GHz), rescaled at the corresponding PLANCK beam size. In fact, we can argue that after the MAP mission, the sum of the CMB and foreground temperature fluctuation on each sky pixel will be known with the MAP accuracy.

The relationship between rms noises and temperature fluctuations in terms of antenna temperature and thermodynamic temperature is $\Delta\delta T_{ant} = \Delta\delta T_{therm} x^2 \exp x/(\exp x - 1)^2$, where $x = h\nu/k/T_0$, $T_0 = 2.725$ K being the CMB monopole thermodynamic temperature as estabhlished by Mather et al. 1999.

For a point source with flux F_ν observed with a beam response, J, normalized to the beam maximum response, the observed antenna temperature in given by

$$10^{-41}(c^2/2k)[(F_\nu/\mathrm{Jy})/(\nu/\mathrm{GHz})^2](J/\int_{4\pi} Jd\Omega)\,.$$

For a beam well approximated by a Gaussian shape $\int_{4\pi} Jd\Omega \simeq (\pi/4\ln2)(\mathrm{FWHM/rad})^2$. We are interested here to sources with weak or moderate flux, i.e. essentially detectable only when they fall within a pixel with a side $\simeq$ FWHM about the beam centre. In the relationship between the antenna temperature and the flux reported here we simplify the beam response as unit within a pixel with a side $\simeq$ FWHM about the beam centre and null otherwhere, i.e. $\int_{4\pi} Jd\Omega) \simeq (\mathrm{FWHM/rad})^2$ [it is clear that, in reality, a source may be in principle observable at angles larger than $\simeq$ FWHM/2 from the beam centre with the corresponding beam response; this is in particular the case of bright sources]. In this approximation, the relationship between the rms flux fluctuations and the rms antenna temperature fluctuations on a squared pixel with side $\Delta\theta$ ($\simeq$ FWHM) is $\Delta\delta B_\nu/\mathrm{Jy} \simeq 30.7[\Delta\delta T_{ant}/\mathrm{mK}][\nu/\mathrm{GHz}]^2[\Delta\theta/\mathrm{rad}]^2$. This approximation is used to translate the HFI sensitivities quoted by Puget et al. (1998) in terms of total flux to the antenna temperature sensitivities reported in Table 1.

In the following section we will derive the PLANCK sensitivity at the different channels relevant for the study of moving objects from the PLANCK time ordered data by appropriately rescaling the sensitivities of the final PLANCK maps. Since, at least at $\nu \lesssim 100$ GHz, it would be possible to exploit the microwave maps derived from MAP data and cleaned at the level of MAP sensitivity from the effect of source flux variations at the epoch of MAP observations and from the tracts of moving objects, it is clear that in the worst case scenario the 1σ sensitivity levels relevant for the following discussions after MAP will be the sum in quadrature of the appropriately rescaled PLANCK sensitivities and of the sensitivities of the MAP final maps; these will be also the sensitivities appropriate to the detection or study of moving objects before the production of PLANCK maps. On the other hand, after the PLANCK data analysis and the production of the PLANCK cleaned maps at all frequencies, we may be able to take advantage from the knowledge of the sky fluctuation in the positions of the considered moving objects with a sensitivity approximately equal to the final sensitivity of PLANCK maps multiplied by $\sqrt{2}$, i.e. about a factor 2 better than MAP final sensitivity in the common frequency range, because a moving objects do not assume the same sky position in the subsequent PLANCK sky coverages.

2 PLANCK sensitivity for moving sources

The PLANCK sensitivity relevant for the study of moving sources has to be appropriately rescaled with respect to that reported in Table 1 to include several factors of sensitivity

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[2] http://map.gsfc.nasa.gov/html/

Table 1: Instrumental performances and confusion noise estimates for Planck LFI.

$\nu_{\rm eff}$ (GHz)	Band (GHz)	$N_{rad;bol}$ (unpol;pol)	FWHM (arcmin)	$\sigma_{\rm noise}$ (μK)	$\sigma_{\rm noise}$ (mJy)	$\sigma_{\rm CMB}$ (mJy)	$\sigma_{\rm ex.sou.}$ (mJy)	$\sigma_{\rm Gal}$ (mJy)	$\sigma_{\rm noise,MAP}$ (mJy)
30	27.0÷33.0	4	33.6	5.1	13.4	245	60	100	48
44	39.6÷48.4	6	22.9	7.8	20.5	238	45	45	69
70	63.0÷77.0	12	14.4	10.6	28.0	221	30	15	102
100	90.0÷110.0	32	10.0	12.8	33.2	192	20	7	127
100	87.5÷112.5	4 ; 0	10.7	2.9	8.7	192	20	7	127
143	125.1÷160.9	3 ; 9	8.0	3.4	11.5	149	15	6	–
217	189.9÷244.1	4 ; 8	5.5	3.1	11.5	82.6	8÷15	5	–
353	308.9÷397.1	6 ; 0	5.0	2.4	19.4	19.1	20÷35	18	–
545	476.9÷613.1	0 ; 8	5.0	2.0	38	1.5	45÷80	62	–
857	749.9÷964.1	6 ; 0	5.0	0.9	43	0.016	100÷180	120	–

degradation.

A first sensitivity degradation factor, $\sim \sqrt{2}$, derives by considering only a single sky coverage and provides a lower limit to the sensitivity relevant here (we neglect in the present estimates the small increase of this degradation factor with respect to the value $\sqrt{2}$ introduced by the limited sky regions possibly observed three times duration the mission). This estimates of the Planck best sensitivity to moving bodies refer to the case in which, in a given transit of a body on the Planck telescope field of view, it is possible to properly use and average the informations from all the receivers at a given frequency channel. Of course, a realistic situation may be less favourable, because of the motion of the considered object.

The LFI beams at different frequencies are located on the Planck telescope field of view in a ring with a radius of about 4° around the telescope line of sight. The HFI beams are more centrally located; on the other hand, they may be also at few degrees from the telescope line of sight. On the Planck telescope field of view, two coordinates U,V are typically used to identify the beam positions. The direction in the sky of the coordinate V is parallel to scan circle of the Planck telescope line of sight generated by the spacecraft rotation around its spin axis. The direction in the sky of the coordinate U, orthogonal to V, is, at least for simple scanning strategies (i.e., with the spacecraft spin axis always parallel to the antisolar direction), parallel to the spin axis shift direction during the mission.

Given the spread of the Planck LFI beams on the telescope field of view, another degradation factor, $\sqrt{N_{ric,sky}}$, has to be taken into account; here $N_{ric,sky}$ is the number of radiometers per channel pointing at the same sky position at the same time and ranges from 2 to 16 (M. Sandri & F. Villa, July 2001, PL-LFI-PST-TN-027, private reference). In column 3 of Table 1 we report the number of LFI radiometers (all intrinsically sensitive to polarization) and of the unpolarized and polarized HFI bolometers. In the case of the LFI channels the total temperature measurement is given by adding the signals from the two radiometers coupled to a given feed horn (or beam); therefore, $N_{ric,sky} = N_{rad}/2 = N_{feed}$. On the other hand, in all the cases except for one feed at 44 GHz, a pair of LFI feeds look simultaneously the same scan circle in the sky, being located in the focal plane unit to follow the sky scan direction as the spacecraft spins (each the LFI beam, except one at 44 GHz, is symmetrically located to another LFI beam with respect to the axis V=0, i.e. they have the same U). This factor, $\sqrt{N_{ric,sky}}$, taken into account in Table 2 at 44 GHz, provides then a pessimistic value for our sensitivity estimates; a factor more adequate for the majority of the cases, and taken into account in Table 2 at 30, 70 and 100 GHz, is $\sqrt{N_{ric,sky}/2}$.

For the HFI channels at 143 and 217 GHz the sensitivity on temperature fluctuation measurements quoted in Puget et al. (1998) is obtained by combining both unpolarized and polarized detectors; at 545 GHz only polarized detectors operate, whereas at 100, 353 and 857 GHz only unpolarized detectors are planned. The HFI Focal Plane Unit arrangement is more complex than that of LFI and will be re-defined in few months (B. Maffei, private communication at the PLANCK Systematic Effect Working Group meeting, ESTEC, June 2001). To translate the sky map temperature sensitivity of Table 1 to the simple estimates of the upper limits on sensitivity for moving bodies sources studies quoted in Table 2 we consider here that, typically, analogously to the case of the LFI, the HFI feeds at each frequency are alligned in two or three groups, the feeds of each group looking at the same scan circle in the sky, being located with the same, or very similar value, of U. In the case of the PLANCK HFI, we have then to include a degradation factor, different from $\sqrt{N_{ric,sky}}$ or $\sqrt{N_{ric,sky}/2}$ which is appropriate to the LFI, of about $\sqrt{2} \div \sqrt{3}$. In the sensitivity estimates reported in Table 2, we conservatively use the value $\sqrt{3}$.

A last degradation factor $\sim \sqrt{\mathrm{FWHM}/\Delta\theta_s}$, where $\Delta\theta_s$ is the spin axis shift between two consecutive hours (2.5 arcmin), takes into account the possibility that a moving object falls out of the beam after a given spin axis repointing. Of course, this factor has to be applied to LFI as well as to HFI.

Taking into account all these sensitivity degradation factors, the nominal PLANCK sensitivities can be resumed in the ranges reported in columns 2 and 3 of Table 2; we provide these sensitivities in terms of antenna temperature and flux.

In practice, we have to take in mind that the interesting moving objects are generally located close to the ecliptic plane, where the PLANCK sensitivity is $\simeq$ 15% worst than the averaged sensitivity. Therefore, the values reported in columns 2 and 3 of Table 2 have to be typically multiplied by $\simeq 1.15$. By taking this factor into account, we report also in Table 2 the sum in quadrature of the PLANCK sensitivity to moving objects as quoted in column 3 and of the astrophysical and cosmological confusion noise sources of Table 1 (column 4), the sum in quadrature of the PLANCK sensitivity to moving objects as quoted in column 3 and of the sensitivity of MAP final maps (column 5) and, finally, the sum in quadrature of the PLANCK sensitivity to moving objects as quoted in column 3 and of the PLANCK sensitivity appropriate to half mission (column 6).

3 Conclusion

By properly scaling the sensitivities of the final PLANCK maps at different frequencies, we have obtained simple estimates of the PLANCK sensitivities relevant for the detection and the study of moving objects. We have also taken into account the main astrophysical and cosmological sources of confusion noise as well as the future informations from the MAP satellite and from PLANCK itself.

The 1σ sensitivity ranges from few tens to few hundreds of mJy, according to the considered frequency channel and case.

Table 2: Instrumental noise estimates for moving sources. The second and third columns refer the PLANCK sensitivity for moving sources derived in section 2 and have to be multiplied by 1.15 for objects close to the ecliptic plane. In the case of low ecliptic latitude objects, we report also the 1σ overall confusion noise including CMB and astrophysical fluctuations neglecting at all the future informations from space missions (column 4), by considering the informations provided by the MAP survey (column 5), and, finally, the sensitivity appropriate to a PLANCK single sky coverage (see also the text). Of course these numbers are indicative because of the large variations of the Galaxy intensity in the sky and the uncertainty of extragalactic source fluctuations at $\nu \gtrsim 143$ GHz (intermediate values are here adopted).

$\nu_{\rm eff}$/GHz	$\sigma_{\rm noise}/\mu$K	$\sigma_{\rm noise}$/mJy	$\sigma_{\rm overall}$/mJy	$\sigma_{\rm afterMAP}$/mJy	$\sigma_{\rm afterPLANCK}$/mJy
30	7÷26	19÷70	272÷283	53÷94	29÷83
44	11÷76	29÷153	249÷303	77÷189	44÷178
70	15÷62	40÷165	228÷293	112÷215	61÷194
100	18÷102	47÷266	201÷362	138÷331	72÷309
100	4.1÷14.7	9.5÷34	193÷197	127÷133	16÷41
143	4.8÷14.9	16.3÷51	151÷161	151÷161	25÷61
217	4.4÷11.3	16.3÷42	86÷97	86÷97	25÷51
353	3.4÷8.3	27.4÷67	49÷86	49÷86	42÷82
545	2.8÷6.9	53.7÷132	108÷175	108÷175	82÷161
857	1.3÷3.1	60.8÷149	197÷252	197÷252	93÷182

From the point of view of the sensitivity, the most favourite channels result to be the HFI channels at 217 and 353 GHz in the worst case in which the astrophysical and cosmological sources of confusion noise are taken into account without considering the informations on them provided by MAP and PLANCK. By taking advantage from the knowledge of microwave sky fluctuations from MAP and PLANCK, the whole PLANCK frequency range show much more interesting sensitivity. Of course, they have to be compared with the typical spectral shapes of the considered celestial bodies to properly define the PLANCK scientific capabilities in the study of the Solar System bodies.

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