Separation of foregrounds from cosmic microwave background observations with the MAP satellite

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ABSTRACT
Simulated observations of a $10^\circ \times 10^\circ$ field by the Microwave Anisotropy Probe (MAP) are analysed in order to separate cosmic microwave background (CMB) emission from foreground contaminants and instrumental noise and thereby determine how accurately the CMB emission can be recovered. The simulations include emission from the CMB, the kinetic and thermal Sunyaev-Zel’dovich (SZ) effects from galaxy clusters, as well as Galactic dust, free-free and synchrotron. We find that, even in the presence of these contaminating foregrounds, the CMB map is reconstructed with an rms accuracy of about 20 $\mu$K per 12.6 arcmin pixel, which represents a substantial improvement as compared to the individual temperature sensitivities of the raw data channels. We also find, for the single $10^\circ \times 10^\circ$ field, that the CMB power spectrum is accurately recovered for $\ell \lesssim 600$.

Key words: methods: data analysis – techniques: image processing – cosmic microwave background.

1 INTRODUCTION
The NASA MAP satellite is due to be launched in 2000 and aims to make high-resolution, low-noise maps of the whole sky at several observing frequencies. The main goal of the mission is to use this multi-frequency data to produce an all-sky map of fluctuations in the cosmic microwave background (CMB). As with any CMB experiment, however, MAP is also sensitive to emission from several foreground components. The main contaminants are expected to be Galactic dust, free-free and synchrotron emission, the kinetic and thermal Sunyaev-Zel’dovich (SZ) effect from galaxy clusters, as well as Galactic dust, free-free and synchrotron. We find that, even in the presence of these contaminating foregrounds, the CMB map is reconstructed with an rms accuracy of about 20 $\mu$K per 12.6 arcmin pixel, which represents a substantial improvement as compared to the individual temperature sensitivities of the raw data channels. We also find, for the single $10^\circ \times 10^\circ$ field, that the CMB power spectrum is accurately recovered for $\ell \lesssim 600$.

Aside from extra-galactic point sources, the other physical components mentioned above have reasonably well defined spectral characteristics, and we may use this information, together with multi-frequency observations, to distinguish between the various foregrounds. In this paper, we perform a separation of the different components, in order to determine the accuracy to which the MAP satellite can recover the CMB emission in the presence of contaminating foreground emission. The separation is carried out using the Fourier space maximum-entropy method (MEM) developed by Hobson et al. (1998) (hereafter HJLB98), which in the absence of non-Gaussian signals reduces to linear Wiener filtering (Bouchet, Gispert & Puget 1996; Tegmark & Efstathiou 1996).

2 SIMULATED MAP OBSERVATIONS
The simulated input components used here are identical to those described in HJLB98, so that a direct comparison between the MAP and Planck Surveyor results can be made. These simulations were performed by Gispert & Bouchet (1997) and consist of a $10^\circ \times 10^\circ$ field for each of the six foreground components described above. The realisations of the input components used are shown in Figure 9. Each component is plotted at 50 GHz and, for illustration purposes, has been convolved with a Gaussian beam of FWHM equal to 12.6 arcmin, which is the highest resolution of the current design for the MAP satellite. For convenience, the mean of each map is set to zero, in order to highlight the relative level of fluctuations due to each component.

The primary CMB fluctuations are a realisation of COBE-normalised standard CDM with critical density and $\Omega_0 = 0.3$, $\Omega_{\Lambda} = 0.7$, $\Omega_b = 0.044$, $\Omega_c = 0.24$, $\Omega_\gamma = 0.0045$, $\Omega_\nu = 0.0005$, $\Omega_\nu_0 = 0.0006$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$. IRAS 100-$\mu$m maps are used as spatial templates for the
Figure 1. The $10^5 \times 10^5$ realisations of the six input components used to make simulated MAP observations: (a) primary CMBR fluctuations; (b) kinetic SZ effect; (c) thermal SZ effect; (d) Galactic dust; (e) Galactic free-free; (f) Galactic synchrotron emission. Each component is plotted at 50 GHz and has been convolved with a Gaussian beam of FWHM equal to 12.6 arcmin, the maximum angular resolution proposed for the MAP satellite. The map units are equivalent thermodynamic temperature in $\mu$K.
Table 1. Proposed observational parameters for the MAP satellite. Angular
resolution is quoted as FWHM for a Gaussian beam. Sensitivities are quoted
to the convolution with beams of different sizes. Furthermore, it is
ices following a $C_\ell \propto \ell^{-3}$ power law on angular scales below 0.85
degrees. The kinetic and thermal SZ effects are generated using a
Press-Schechter formalism, as discussed in Bouchet et al. (1997)
and a King model for the cluster profiles. The MAP satellite is not
designed to be sensitive to either of the SZ effects but they are in-
cluded here for completeness.

Using the realisations for each physical component and the
design specifications summarised in Table 2, it is straightforward
to perform all-sky maps of the foreground components as well as
the CMB. This should be contrasted with the

![Figure 2](image-url)

Figure 2. The rms thermodynamic temperature fluctuations at the MAP
satellite observing frequencies due to each physical component, after con-
volution with the appropriate beam and using a sampling rate of FWHM/2.4.
The rms noise per pixel at each frequency channel is also plotted.

3 THE COMPONENT SEPARATION

The component separation is performed using the Fourier space
MEM algorithm developed by HJLB98, and the reader is referred to
that paper for details of the method. In the absence of non-Gaussian
signals the method reduces to linear Wiener filtering. In this Sec-
tion, we apply the MEM algorithm to the simulated MAP data dis-
cussed in Section 2. Since the dominant contributions to the MAP
data are the CMB and the pixel noise, which are both Gaussian,
the results of the MEM algorithm should be very similar to those
obtained using a Wiener filter approach (Bouchet, Gispert & Puget
1996; Tegmark & Efstathiou 1996). Our primary aim is simply to
determine the accuracy to which the CMB emission can be recov-
ered from MAP observations after such a component separation has
been performed.

As discussed in HJLB98 there are several layers of informa-
tion that we can use in the analysis of the data. For the CMB and SZ
emissions this is not true. However, as discussed in Jones et al.
(1998b) it is possible to use the data itself to constrain the spec-
tral dependence of any Galactic emission that is significant in the
data. If it is not a significant component then the uncertainty in the
spectral index will only affect the reconstruction of that Galactic
component and not the reconstruction of any of the other compo-
nents. Therefore, in this letter, we assume perfect knowledge of the
frequency spectra of each component.

Our other prior knowledge concerns the spatial distribution,
or power spectrum of the various emission components. We are
never entirely ignorant of the shape of the power spectra for the
foregrounds in the data. In HJLB98 two levels of power spectrum
information were used. The first assumed no information on the
power spectra of any component and the second assumed perfect
knowledge of the power spectra and cross-correlation information.
In this letter we will assume a more conservative approach than the
latter but also remembering that we have some prior information
on the components. We choose to use the best guess theoretical
power spectrum for each component. This is a white noise power
spectra for the two SZ effects, standard CDM for the CMB and
an $\ell^{-3}$ power spectra for the Galactic components. In any case, as
noted in HJLB98, the MEM algorithm is an iterative process and

| Central frequency (GHz): | 22 | 30 | 40 | 60 | 90 |
|--------------------------|----|----|----|----|----|
| Fractional bandwidth ($\Delta \nu/\nu$): | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Transmission: | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Angular resolution (arcmin): | 56 | 41 | 28 | 21 | 12.6 |
| $\Delta T$ sensitivity ($\mu$K) (17' pixel): | 26 | 32 | 27 | 35 | 35 |
Figure 3. The $10^\circ \times 10^\circ$ maps observed at each of the five MAP frequencies listed in Table 2. At each frequency we assume a Gaussian beam with the appropriate FWHM and a sampling rate of FWHM/2.4. Isotropic noise with the relevant rms has been added to each map. The map units are equivalent thermodynamic temperature in $\mu$K.
3.1 The reconstructed CMB map

The reconstruction of the CMB component is shown in Figure 4. The greyscale in this figure was chosen to coincide with that of Fig. 3 in order to enable a more straightforward comparison with the true map. At least by eye the CMB has been reproduced quite accurately. The reconstructions of the other physical components are significantly worse and are not plotted. In fact, the only other components for which the reconstruction differs significantly from zero are the free-free and synchrotron Galactic components. This is expected as the other three components are well below the noise (see Figure 3) in all frequency channels. The free-free and synchrotron reconstructions appear smoothed to a larger degree than the CMB reconstruction which is also expected because the two Galactic components only appear above the noise in the lowest resolution (22 GHz) channel. Further tests on the thermal SZ effect show that only clusters with an integrated decrement of $> 250 \mu K$ (at 22 GHz) will be observable with the MAP satellite and even then the reconstructed decrement is severely underestimated. This is because the frequency dependence of the thermal SZ at frequencies below 100 GHz closely follows that of the CMB and it is very difficult to extract the information on the SZ effect from the data.

In order to obtain a quantitative description of the accuracy of the reconstructions, we calculate the rms of the residuals. For any particular physical component, this is given by

$$\epsilon_{\text{rms}} = \left[ \frac{1}{N} \sum_{i=1}^{N} (T_{i}^\text{rec} - T_{i}^\text{true})^2 \right]^{1/2} \tag{1}$$

where $T_{i}^\text{rec}$ and $T_{i}^\text{true}$ are respectively the reconstructed and true temperatures in the $i$th pixel and $N$ is the total number of pixels in the map. The value of $\epsilon_{\text{rms}}$ for the CMB reconstruction is 22 $\mu K$ per 12.6$'$/pixel. We note that this is very close to the desired 20 $\mu K$ accuracy generally quoted for the MAP satellite. This error should be contrasted with the result obtained by using the 90 GHz data channel as the CMB map. In this case, the error on the map is 46 $\mu K$ (of which 45 $\mu K$ is due to instrumental noise and 1 $\mu K$ is due to the presence of the unsubtracted foregrounds), so some form of component separation is clearly desirable.

As mentioned above, the other physical components were only poorly reconstructed. Indeed no recovery of the dust or either SZ effect was possible at all, and only a low-resolution reconstructions of the other two components were obtained. The rms errors on the free-free and synchrotron reconstructions were 0.6 $\mu K$ and 0.07 $\mu K$ respectively. By comparing these rms errors with the peak amplitudes in each map, which are 1.0 $\mu K$ and 0.1 $\mu K$ respectively, we see that the reconstructions are not very accurate.

As a further test of the quality of the CMB reconstruction, we plot the amplitudes of the reconstructed pixel temperatures against those of the true map. The temperature range of the true input map is divided into 100 bins. Three contours are then plotted which correspond to the 68, 95 and 99 per cent points of the distribution of corresponding reconstructed temperatures in each bin. Clearly, a perfect reconstruction would be represented by a single diagonal contour of unit gradient with width equal to the bin size. Figure 5 shows this comparison for the CMB reconstruction from the MAP data. The gradient of the best fit line is 1.03 and the 68 per cent contours lie approximately 25 $\mu K$ on either side of the true value. This agrees with the value for the $\epsilon_{\text{rms}}$ quoted above. Figure 6 shows the same comparison for the case in which the highest frequency data channel used as the CMB reconstruction at 12.6$'$ resolution. We see that in this case the 68 per cent contour is much wider, corresponding to about 45 $\mu K$ errors, in agreement with the $\epsilon_{\text{rms}}$ value quoted above.

3.2 The reconstructed CMB power spectrum

Since the component separation is performed in the Fourier domain, it is straightforward to compute the reconstructed power spectrum of the CMB component. As noted in HJLB98 it is also straightforward to calculate the errors on the reconstructed power spectrum using the inverse Hessian. Figure 7 shows the power spec-
4 DISCUSSION AND CONCLUSIONS

In this paper, we have analysed simulated MAP observations in a $10^\circ \times 10^\circ$ field, in order to separate the CMB emission from various foreground contaminants and determine how accurately the CMB emission can be recovered. The algorithm used to perform the component separation is the Fourier space maximum-entropy method discussed by Hobson et al. (1998), which reduces to a Wiener filter in the absence of non-Gaussian signals. The simulated observations include contributions from primary CMB, kinetic and thermal SZ effects, and Galactic dust, free-free and synchrotron emission. Assuming knowledge of both the one-dimensional ensemble average power spectrum for each component and its frequency behaviour, we find that the CMB emission can be reconstructed with an rms accuracy of 22μK per 12.6 arcmin pixel. We note that this represents a substantial improvement as compared to the individual temperature sensitivities of the raw data channels, and thus indicates that some form of component separation is desirable for MAP observations. We also find that the power spectrum of the reconstructed CMB map lies close to the true power spectrum for $\ell < 1000$. In contrast to our analysis of simulated Planck Surveyor observations (Hobson et al. 1998), we find that it is not possible to recover the emission from Galactic dust or the kinetic/thermal Sunyaev-Zel’dovich effects, although low-resolution reconstructions of the Galactic free-free and synchrotron emission were obtained.

We have also repeated the component separation using a straightforward Wiener filter algorithm, and find that, as expected, the reconstructions are very similar to those presented above and the rms error on the reconstructed CMB map is almost identical. Moreover, both techniques take the same computational time as they are based upon similar calculations in Fourier space. As mentioned above, the similarity of the results is due to the fact that the dominant contributions to the MAP data are the CMB and instrumental noise, which are both Gaussian. Thus, although several non-Gaussian foregrounds were included in the simulated observations, the angular resolution and frequency coverage of the MAP satellite preclude the presence of significant non-Gaussian effects in the data (although this is certainly not the case for the Planck Surveyor satellite). If, however, the input CMB component in the MAP simulations is replaced by a realisation of CMB fluctuations due to cosmic strings, there still exists a significant non-Gaussian signal in the data. In this case we find that the rms error on the CMB reconstruction is consistently 2μK lower for the MEM algorithm as compared to the Wiener filter.

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REFERENCES

Bouchet F.R., Gispert R., Puget J.L., 1996, in Dwek E., ed., Proc. AIP Conf. 348, The mm/sub-mm foregrounds and future CMB space missions. AIP Press, New York, p. 255
Gispert R., Bouchet F.R., 1997, in Bouchet F.R., Gispert R., Guideroni B., Tran Thanh Van J., eds, Proc. 16th Moriond Astrophysics Meeting, Microwave Anisotropies. Editions Frontière, Gif-sur-Yvette, p. 503
Haslam C. G. T et al., 1982, A&AS, 47, 1
Hobson M.P., Jones A.W., Lasenby, A.N., Bouchet, F.R., 1998a, MNRAS, in press
Hobson M.P., Barreiro R.B., Toffalati L., Lasenby A.N., Sanz J.L., Jones A.W., Bouchet F.R., 1998b, MNRAS, submitted
Jones A. W., Hancock S., Lasenby A. N., Davies R. D., Gutiérrez C. M., Rocha G., Watson R. A., Rebolo R., 1998a, MNRAS, 294, 582
Jones A. W., Hobson, M.P., Mukherjee, P., Lasenby A.N., 1998b, to appear in Proc. of 'The CMB and the Planck Mission', Santander
Maisinger K., Hobson M.P., Lasenby A.N., 1997, MNRAS, 290, 313
Tegmark M., Efstathiou G., 1996, MNRAS, 281, 1297
Toffolatti L., Argüeso Gómez F., De Zotti G., Mazzèi P., Francheschini A., Danese L., Burigana C., 1998, MNRAS, 297, 117

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