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Foreground Separation Methods for Satellite and Balloon Experiments

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Abstract. A combined technique using the maximum-entropy method (MEM) and the mexican hat wavelet (MHW) to separate and reconstruct the physical components of the microwave sky is presented. We apply this method to simulated observations by the ESA Planck satellite in small patches of the sky. The reconstructed maps of the CMB and foregrounds are improved as compared to those obtained with MEM on its own. Moreover, more accurate point source catalogues are produced at each observing frequency. This technique may also be extended to deal with other multifrequency CMB experiments, including all-sky data.

1. Introduction

High-resolution CMB observations such as those from the Boomerang and MAXIMA balloon experiments or the future MAP and Planck satellites carry a wealth of information about the Universe. However, in addition to the cosmological signal, these data contain Galactic and extragalactic foreground emissions as well as instrumental noise. Therefore, performing a good separation of the CMB from the rest of the components of the microwave sky is critical in extracting all the valuable information encoded in the cosmological signal. Moreover, knowledge about the foregrounds will be extremely useful in studying different astrophysical phenomena.

A Fourier-MEM algorithm (Hobson et al. 1998) has proved to be very efficient in separating and reconstructing the CMB and foregrounds from multifrequency simulated data in the absence of point sources. This last contaminant is the most problematic one since each source has a unique frequency spectrum which is also very difficult to predict. In Hobson et al. (1999) the MEM technique was extended to deal with point sources. A different approach has been taken by Sanz et al. (2000). The previous authors have shown that the MHW is the optimal pseudo-filter to subtract point sources under reasonable conditions. This technique was applied to realistic simulations in Cayón et al. (2000) and Vielva et al. (2000a).

The aim of this work is to demonstrate that the MEM and MHW techniques are actually complementary. As will be shown below, a joint MEM and MHW analysis leads to better reconstructions of the foreground components as well as to more complete and accurate point source catalogues than those obtained with each technique independently.

2. Combined MEM and MHW analysis

In the extended MEM algorithm of Hobson et al., no attempt was made to directly remove point sources but instead they were introduced as an additional noise. This technique has been shown to efficiently reduce the point source contamination when performing a full reconstruction of the components of the microwave sky. Moreover, by comparing the input data with 'mock' data obtained from the reconstructions, point source catalogues can also be obtained at each frequency. However, some contamination coming from bright point sources still remains in the reconstructions, since these sources are not well characterised by noise.

In the MHW technique, the map to be analysed is transformed into wavelet space where the point sources are amplified with respect to the background. Therefore, detection of point sources is very efficiently performed in wavelet space at a certain optimal scale. Moreover, the amplitude of the point sources is accurately estimated. The MHW approach works very well for the brightest point sources. For fainter sources, however, this technique performs more poorly by either inaccurately estimating the flux or failing to detect the source altogether.

The strengths and weakness of the MEM and MHW approaches clearly indicate their complementary nature. In this work, we apply a MEM and MHW joint analysis to simulated data of the Planck satellite in small patches of the sky. First, the MHW is applied to each individual observing map in order to detect and subtract the brightest point sources. These processed data maps are then used as inputs for the MEM algorithm, producing more accurate reconstructions. These reconstructed components are then used to produce 'mock' data and subtracted from the inputs in order to generate data residuals maps at each observing frequency. Since the CMB and foregrounds have been (reasonably) well recovered, these residuals maps mostly contain point sources and instrumental noise. Finally, the MHW is applied to these maps to compile more accurate catalogues than those produced by each method independently.

3. Analysis of simulated observations

We have simulated multifrequency data of a $12.8^\circ \times 12.8^\circ$ patch of the sky that takes into account the characteristics of the Planck satellite, including the expected levels of instrumental noise. The data contain CMB, both thermal and kinetic Sunyaev-Zeldovich (SZ) effects from cluster of galaxies (from Diego et al. 2000), Galactic dust, free-free and synchrotron emission and extragalactic point sources (according to Toffolatti et al 1998). A description of these simulations is given in Vielva et al. (2000b).

Table 1. The rms in μK of the reconstruction residuals obtained with the joint MEM and MHW joint analysis. For comparison the rms of the input maps and the rms of the residuals when a previous subtraction of point sources is not performed are also given.

Component	CMB	kSZ	tSZ	Dust	ff	syn
input rms	112.3	0.69	5.37	55.8	0.66	0.32
error (with MHW)	7.68	0.70	4.64	2.68	0.22	0.11
error (no MHW)	8.62	0.70	4.66	3.39	0.24	0.12

Following the combined method outlined in the previous section we have separated and reconstruct each of the contributions considered. In Table 1 we give the rms reconstruction errors for each of the components that MEM has directly attempted to recover. We find that the reconstructions of the main components are very accurate and mostly free of point source contamination. In particular the CMB has been very faithfully reproduced with an accuracy of ~6.8 per cent as compared to the rms of the input map. The recovered dust map is also very good. Indeed, none of the numerous infrared point sources that contaminate the high frequency channels is present in the reconstruction. The main features of the free-free and synchrotron emissions are also recovered. Most of the bright clusters have also been reproduced in the thermal SZ reconstructed map whereas only a few point sources have been misidentified as clusters. Finally, as expected, only a few clusters, all of them with a large thermal SZ, have been detected in the reconstructed kinetic SZ map.

Regarding the compilation of point source catalogues, the combined method also performs better than each of the methods on its own. Table 2 gives the number of detected point sources, minimum flux achieved and the mean percentage error for the amplitude estimation for the catalogues obtained using MHW alone (MHWc), MEM alone (MEMc) and the joint technique (M&M). We find that the recovered M&Mc has improved regarding both completeness and accuracy. In particular, the number of detected point sources is similar to (at the low and intermediate frequencies) or larger (at high frequencies) than those recovered in the most complete of the catalogues obtained with the individual techniques at each frequency. In addition, those point sources present in all of the three catalogues are best estimated, in average, in the M&Mc. In fact, when only MEM is used, the brightest point sources remain, contaminating the reconstructed maps of the physical components since they are not well characterised by an additional noise. This leads to a bias in the estimation of their amplitude, which is underestimated. This problem is solved when using the combined technique.

4. Discussion and conclusions

We have presented a powerful MEM and MHW joint analysis to separate and reconstruct the physical components of the microwave sky as well as to compile point source catalogue from multifrequency observations of the CMB. We have applied this technique to simulated data of the Planck satellite in small patches of the sky. We have showed that the combined analysis produces more complete

Table 2. The point source catalogues MHWc, MEMc and M&Mc. For each Planck observing frequency, we list the number of detected sources, the flux limit of the catalogue and the mean percentage error for the amplitude estimation.

	MHWc			MEMc			M&Mc		
Freq. (GHz)	No. detect.	Flux (Jy)	E_{abs} (%)	No. detect.	Flux (Jy)	E_{abs} (%)	No. detect.	Flux (Jy)	E_{abs} (%)
30	4	0.46	12.1	21	0.10	12.1	19	0.10	12.3
44	3	0.58	6.7	11	0.24	8.6	11	0.24	8.4
70	5	0.28	21.0	19	0.12	10.5	18	0.15	8.1
100 (L)	3	0.59	6.8	16	0.13	15.6	14	0.13	10.0
100 (H)	7	0.27	7.7	33	0.08	13.4	33	0.07	12.9
143	4	0.40	13.6	1	0.10	14.2	8	0.06	24.2
217	5	0.25	9.9	1	0.10	23.4	8	0.06	19.0
353	10	0.07	34.6	6	0.24	41.4	9	0.24	8.2
545	29	0.26	20.4	13	0.23	39.4	41	0.24	14.4
857	86	0.58	10.4	107	0.41	17.6	150	0.31	13.8

and accurate catalogues than each of the techniques independently and it also improves the reconstructions of the diffuse components achieved by MEM on its own.

Finally, we point out that this technique may be applied to any other multifrequency CMB experiment and in particular to those covering a significant proportion of the sky. Indeed, the MEM technique has recently been extended to analyse all-sky maps at full Planck resolution by working in spherical harmonic space and allows high-resolution maps of each foreground to be accurately recovered even at low Galactic latitude (Stolyarov et al., in preparation). Additionally, the MHW has been implemented on the sphere (Martínez-González et al., in preparation) and work is in progress to implement the point source subtraction algorithm using all sky maps.

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