

An improved source-subtracted and destriped 408 MHz all-sky map

M. Remazeilles,^{★1} C. Dickinson,^{†1} A. J. Banday,^{2,3} M.-A. Bigot-Sazy,¹ T. Ghosh⁴

¹*Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics & Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, U.K.*

²*Université de Toulouse, UPS-OMP, IRAP, F-31028 Toulouse cedex 4, France*

³*CNRS, IRAP, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France*

⁴*Institut d'Astrophysique Spatiale, CNRS (UMR8617) Université Paris-Sud 11, Bâtiment 121, Orsay, France*

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ABSTRACT

The all-sky 408 MHz map of Haslam et al. is one the most important total-power radio surveys. It has been widely used to study diffuse synchrotron radiation from our Galaxy and as a template to remove foregrounds in cosmic microwave background data. However, there are a number of issues associated with it that must be dealt with, including large-scale striations and contamination from extragalactic radio sources.

We have re-evaluated and re-processed the rawest data available to produce a new and improved 408 MHz all-sky map. We first quantify the positional accuracy (≈ 7 arcmin) and effective beam (56.0 ± 1.0 arcmin) of the four individual surveys from which it was assembled. Large-scale striations associated with $1/f$ noise in the scan direction are reduced to a level $\ll 1$ K using a Fourier-based filtering technique. The most important improvement results from the removal of extragalactic sources. We have used an iterative combination of two techniques – two-dimensional Gaussian fitting and minimum curvature spline surface inpainting – to remove the brightest sources ($\gtrsim 2$ Jy), which provides a significant improvement over previous versions of the map. We quantify the impact with power spectra and a template fitting analysis of foregrounds to the *WMAP* data.

The new map is publicly available and is recommended as the template of choice for large-scale diffuse Galactic synchrotron emission. We also provide a higher resolution map with small-scale fluctuations added, assuming a power-law angular power spectrum down to the pixel scale (1.7 arcmin). This should prove useful in simulations used for studying the feasibility of detecting HI fluctuations from the Epoch of Reionization.

Key words: methods: data analysis – radio continuum: general – techniques: image processing – diffuse radiation – cosmic microwave background

1 INTRODUCTION

The total-power radio sky has been surveyed at a number of frequencies using single-dish radio telescopes. A compilation of large-area radio maps from 10 MHz to 94 GHz was produced by de Oliveira-Costa et al. (2008), who used them to produce a Global Sky Model (GSM) of diffuse Galactic radio emission. These maps can be used to study the diffuse Galactic synchrotron radiation from the interstellar medium (Beuermann et al. 1985; Reich & Reich 1988; Koo et al. 1992; Davies et al. 1996; Platania et al. 1998, 2003; Bennett et al. 2003a; Finkbeiner 2004; Jaffe et al. 2011; Strong et al. 2011;

Orlando & Strong 2013; Mertsch & Sarkar 2013), as well as Galactic sources such as supernova remnants (Sushch & Hnatyk 2014; Xiao & Zhu 2014) and HII regions (Wendker et al. 1991; Foster & Routledge 2001; Xu et al. 2013). Perhaps more importantly, radio maps have been used extensively as a synchrotron template for removing foreground emission in cosmic microwave background (CMB) data (Netterfield et al. 1997; Bennett et al. 1992, 2003b; Kogut et al. 1996; Banday et al. 2003; Bennett et al. 2003a, 2013). More recently, they have been used in simulations for HI intensity mapping experiments, both at moderate redshifts (Ansari et al. 2012; Battye et al. 2013; Wolz et al. 2014) and at high redshift from the Epoch of Reionization (Jelić et al. 2008; Parsons et al. 2012; Moore et al. 2013; Shaw et al. 2014).

The most famous and widely used radio map, is the

[★] E-mail: mathieu.remazeilles@manchester.ac.uk

[†] E-mail: clive.dickinson@manchester.ac.uk

Table 1. Summary of the different versions of the 408 MHz Haslam map.

Map version map	Location	Characteristics	Coordinates	Post-processing
Bonn ECP	MPIfR Survey Sampler website ⁴	1080×540 pixel grid	Celestial B1950	None
LAMBDA ECP map	NCSA Digital Image Library	1024×512 pixel grid	Galactic	None
Unfiltered LAMBDA map (HAS82)	LAMBDA website ²	HEALPix $N_{\text{side}} = 512$	Galactic	None
LAMBDA dsds map (HAS03)	LAMBDA website ²	HEALPix $N_{\text{side}} = 512$	Galactic	Destriping/desourcing
Davies et al. (1996) map	R. A. Watson (priv. comm.)	1080×540 pixel grid	Celestial B1950	Destriping
Platania et al. (2003) map	VizieR hosted by CDS ¹	HEALPix $N_{\text{side}} = 512$	Galactic	Destriping/desourcing
Finkbeiner map	D. Finkbeiner (priv. comm.)	HEALPix $N_{\text{side}} = 256$	Galactic	Destriping/desourcing
This work (HAS14)	LAMBDA website ²	HEALPix $N_{\text{side}} = 512$	Galactic	Destriping/desourcing

408 MHz all-sky map of Haslam et al. (1981, 1982), hereafter the Haslam map, which has accrued over 1000 citations to date. The data were taken in the 1960s and 1970s as part of four separate surveys using three of the worlds largest single-dish telescopes. However, only a processed combined map produced by Haslam et al. (1982) is readily available. Remarkably, it is still widely used (Macellari et al. 2011; Planck Collaboration et al. 2011; Guzmán et al. 2011; Ghosh et al. 2012; Peel et al. 2012; Lu et al. 2012; Iacobelli et al. 2013; Planck Collaboration et al. 2013) over 30 years since the full-sky version was first released. Although total-power radio surveys have been made more recently at 1.4 GHz (Reich & Reich 1986; Reich et al. 2001) and 2.3 GHz (Jonas et al. 1998), and new data at higher frequencies are forthcoming (King et al. 2014; Hoyland et al. 2012; Tello et al. 2013), the Haslam map is likely to remain a widely used template of synchrotron emission.

However, the sky at frequencies of ~ 100 –1400 MHz is still poorly understood, and the fidelity of the synchrotron template is rather poor compared to modern CMB data. Despite the application of various post-processing techniques, the current Haslam map still suffers from strong source residuals and other artefacts including significant striations caused by $1/f$ noise in the scan direction. Several attempts have been made to correct for these effects, as described in Davies et al. (1996); Platania et al. (2003); Bennett et al. (2003a).

The most widely used version of the Haslam map is the destriped and source-subtracted version produced by the WMAP team (Bennett et al. 2003a) using data from the NCSA ADIL and made available through NASA’s Legacy Archive for Microwave Background Analysis (LAMBDA) website²; specifically, the map contained in the file `lambda_haslam408_dsds.fits`, available from the LAMBDA website³, which hereafter we refer to as the HAS03 map. However, closer inspection of this map reveals significant residuals from the source removal process, which add significant small-scale power at high Galactic latitudes. Furthermore, additional artefacts have been introduced due to multiple regridding steps during post-processing (see Section 2.2).

In this paper, we produce a new clean 408 MHz radio map with fewer artefacts and reduced systematics. In particular, the strong source residuals have been minimised and

additional pixelization artefacts have been negated by reprocessing the Equidistant Cylindrical Projection (ECP) raw map downloaded from the Max Planck Institute for Radioastronomy Survey Sampler website⁴. We use a multi-stage source processing based on both two-dimensional Gaussian fitting and minimum curvature spline surface inpainting. We also determine the effective beam of the 408 MHz sky map and estimate the positional accuracy of the data. The goal is that the new 408 MHz template will be used both for accurate synchrotron modelling and as a robust template for component separation.

The paper is organised as follows. In Section 2, we describe the current version of the Haslam map and its associated problems. In Section 3 we perform a new characterisation and processing of the raw map, including an estimation of the beam in Section 3.1 and positional offsets in Section 3.2. We then discuss the destriping of the map in Section 3.3, and in Section 3.4 we present our two desourcing approaches and the corresponding results of source removal on both simulations and data. We discuss the scientific exploitation of our product in Section 4, and conclude in Section 5, where we describe a website dedicated to the release of the new Haslam map.

2 DATA DESCRIPTION

2.1 The raw data

The 408 MHz all-sky map of Haslam et al. (1982) is an atlas combining data from four different partial surveys of the sky, using the Jodrell Bank Mk-I 76-m, the Effelsberg 100-m, the Parkes 64-m, and the Jodrell Bank Mk-IA 76-m telescopes at four different epochs between 1965 and 1978 (Haslam et al. 1970, 1974, 1981). The surveys were made by scanning the telescopes in elevation, which, through the rotation of the earth, allowed the zero levels to be set in a consistent manner. The other advantage is that contamination from the sky and ground will be similar for a given declination, allowing their removal. The angular resolution of each survey ranges from 37 arcmin to 51 arcmin, with the full-sky map smoothed to a common resolution, stated to be 51 arcmin (0.85°). Positional accuracies are claimed to be accurate to ≈ 1 arcmin. We believe this to be an underestimate given the discussions in the aforementioned papers and the likely pointing accuracy of telescope control systems in those years. The overall calibration, including zero levels, was achieved by

² <http://lambda.gsfc.nasa.gov>.

³ http://lambda.gsfc.nasa.gov/product/foreground/fg_haslam_get.cfm.

⁴ <http://www3.mpifr-bonn.mpg.de/survey.html>.

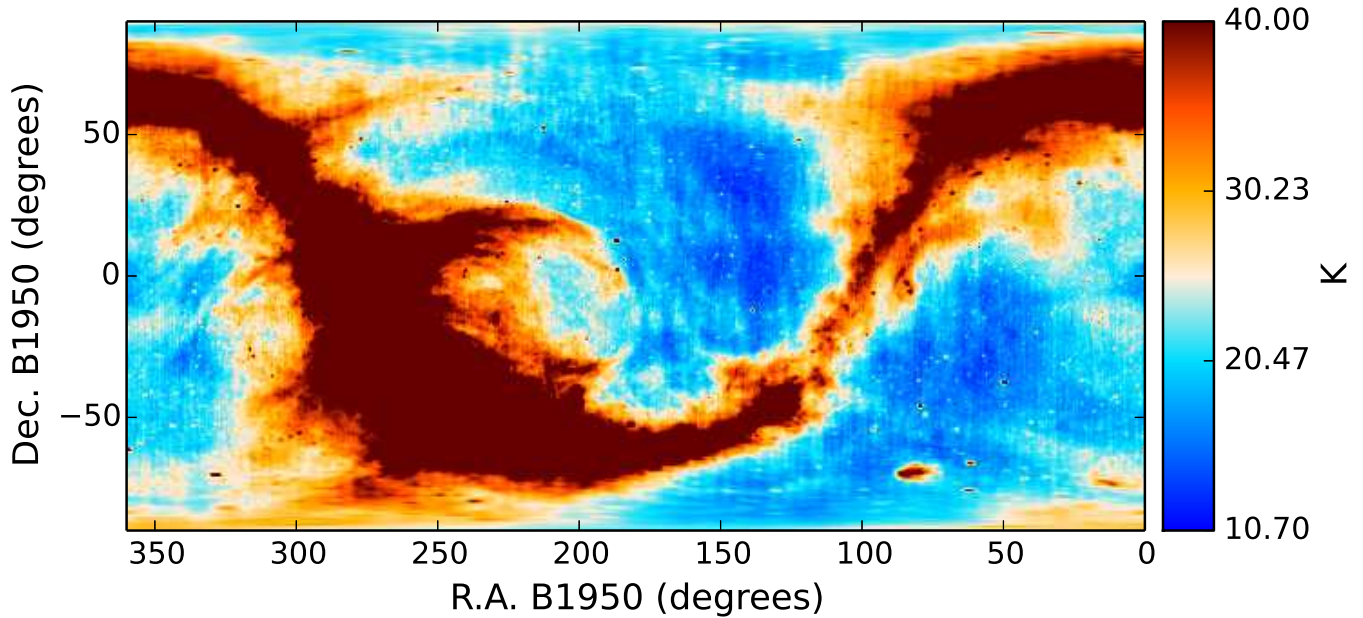


Figure 1. Mapping of the raw Haslam map at 408 MHz from the Bonn Survey Sampler website (1080×540 pixel ECP map in B1950 Celestial coordinates). The map covers the entire sky with RA = 0° on the far right-hand side, increasing to the left, and the celestial poles at the top (Dec. = $+90^\circ$) and bottom (Dec. = -90°). Vertical striations as well as numerous extragalactic radio sources can be seen to contaminate the diffuse Galactic synchrotron emission.

comparison with a previous 404 MHz survey (Pauliny-Toth & Shakeshaft 1962). The absolute calibration is thought to be accurate to better than 10 % and the overall zero level to ± 3 K.

Several electronic versions of the Haslam map are in existence, as listed in Table 1. As far as we are aware⁵, the rawest available data are provided in the form of an Equidistant Cylindrical Projection (ECP) map, which can be downloaded from the Bonn Survey Sampler website⁴ of the Max Planck Institute for Radioastronomy. The ECP map is a 1080×540 pixel grid⁶ in Celestial coordinates at Epoch B1950, with a pixel size of $0.^\circ33$. We believe this is the original map created by Haslam et al. (1982) because the minimum/maximum intensity scale is the same, and the pixel size is identical. No additional interpolation has been applied, as verified by the fact that the rotation matrix used in the Bonn survey sampler script is diagonal. However, we note that this version has been corrected for the zero level mismatch between the Jodrell Bank telescope survey and the Effelsberg telescope survey, as described in Reich & Reich (1988). Other versions include destriped and desourced versions by Davies et al. (1996) and Platanina et al. (2003), as well as an unpublished version from D. Finkbeiner (priv. comm.). A HEALPix interpolation, at $N_{\text{side}} = 512$, of the ECP grid is available on the LAMBDA website under the name of “Haslam 408 MHz map with no filtering”, which

hereafter we refer to as the HAS82 map. According to the documentation header, the beam full width at half maximum (FWHM) of the map is 51 arcmin. The scanning technique used to make the original observations is well suited to mapping extended emission, but does not provide a precise representation of point sources, as explained succinctly in Reich & Reich (1988). Because of additional smoothing from scanning and pointing errors, and the repixelization of the ECP grid to a HEALPix map, we expect that the effective beam FWHM of the HEALPix projection map will be slightly larger than the original 51 arcmin resolution.

However, an additional version of the raw data is available from the NCSA (National Center for Supercomputing Applications) Image Library. This is a 1024×512 pixel grid in Galactic coordinates that assumes that the data corresponds to the Celestial Epoch B1975. This is the version that has been post-processed and interpolated by the WMAP team (Bennett et al. 2003a) and provided as the destriped and desourced Haslam map released on the LAMBDA website (HAS03). This version of the 408 MHz sky map has been widely used in recent years, particularly as a synchrotron foreground template, and will be discussed further in Section 2.2.

In this paper, we start from the 1080×540 ECP map of the Bonn survey sampler (see Fig. 1), hereafter referred to as the “raw map”, which we believe this to be the least manipulated data available. It is mainly dominated by diffuse Galactic synchrotron emission on large angular scales coming from the Galactic plane and large radio loops and spurs at high Galactic latitudes. However, it is clearly contaminated by strong extragalactic radio sources on the beam scale, and exhibits strong baseline striping, due to correlated low-frequency $1/f$ instrumental noise, with a typical amplitude of ± 1 K (Davies et al. 1996).

⁵ The original raw data are thought to be available on tape and attempts are being made to retrieve these data via Glyn Haslam’s family members.

⁶ When downloading this map, it is possible to create a 1081×541 pixel map due to the way the script creates the pixel grid. In this case, the additional pixels are simply a repetition of some pixels and should be removed.

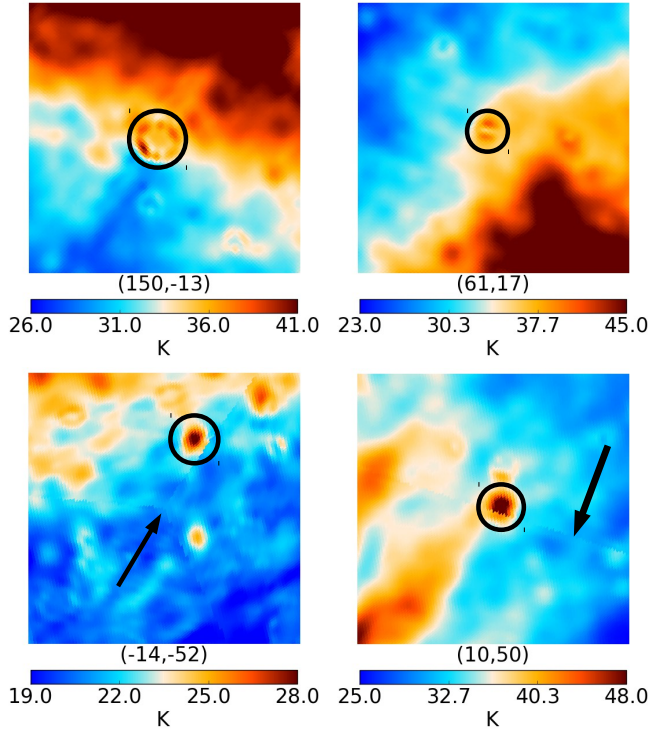


Figure 2. Four $12.5^\circ \times 12.5^\circ$ gnomonic projections of the LAMBDA post-processed (HAS03) version of the 408 MHz Haslam map. All the gnomonic projections shown in the present work have Galactic latitude increasing upward and longitude to the left. Artefacts are evident, including source residuals (indicated by circles in the *top left* and *top right* panels), unsubtracted sources (indicated by circles in the *bottom left* and *bottom right*), and line features due to remapping to a *quadcube* pixelization (indicated by arrows in the *bottom left* and *bottom right*).

2.2 The LAMBDA post-processed Haslam map (HAS03)

The WMAP post-processing consists of three steps: cubic interpolation of the 1024×512 NCSA map from Galactic coordinates to Celestial B1975 coordinates, destripping of the map in the Fourier domain, and interpolation over the location of the strong sources in the spatial domain (“inpainting”) for source removal. The destripped and desourced map was then converted to a *HEALPix* grid in Galactic coordinates with $N_{\text{side}} = 512$. Since it was assumed for the first step that the mean epoch of observations was B1975, it implies that the original 408 MHz data must have been precessed from the B1950 epoch to B1975 in the image extracted from the NCSA Digital Image library.

In the second step, the two-dimensional Fourier transform of the 1024×512 map was computed in order to remove in the Fourier domain the low-frequency pattern that is responsible for the vertical stripes in the spatial domain in Celestial coordinates. In order to avoid that the sources affect the Fourier transform, a basic source subtraction was applied on the data before destripping by median filtering the source pixels. In the third step, the destripped map was reprojected onto a Quadrilateralized Sky Cube (*quadcube*), i.e. the edges of a cube are projected onto a sphere so that the sky is divided into six equal area faces (White & Stemwedel 1992).

The strong radio sources were then isolated using iterative median filtering: pixels exceeding the local background by more than 2σ were replaced by the local median, and the process repeated iteratively. An inpainting technique was then applied, using a locally weighted polynomial regression (LOESS) method to interpolate through the locations of the sources.

However, Fig. 2 indicates that the HAS03 version still shows significant artefacts. These include source residuals from imperfect desourcing, baseline offsets, and artefacts due to a remapping of the raw data to the *quadcube* projection. In the top panels of the figure, we have drawn circles to indicate spurious small-scale residual patterns arising from the imperfect source processing. Moreover, some of the strongest radio sources have not been filtered at all in the HAS03 map, as shown in the bottom panels of the figure. In the bottom left panel, an arrow has been drawn to highlight a cube vertex due to the *quadcube* projection of the raw data utilised in the post-processing.

These numerous deficiencies in the HAS03 version of the Haslam map have motivated the present work: a new reprocessed version of the Haslam map is needed to better characterize the synchrotron foreground in the CMB/radio observations.

3 REPROCESSING THE HASLAM MAP

The residual artefacts in the HAS03 version of the Haslam map may introduce an excess of power at small angular scales in the computation of the angular power spectrum of the Galactic synchrotron at 408 MHz. Moreover, these artefacts may be wrongly interpreted as a synchrotron signal by component separation algorithms, such as template fitting methods (Davies et al. 2006) and Bayesian parametric fitting methods (Eriksen et al. 2008). In the context of multi-frequency CMB data analysis, such residuals could influence the final estimation of some cosmological parameters. In this section, we perform a reprocessing of the Haslam map to reduce, as far as possible, those artefacts.

We begin by quantifying the beam of the 408 MHz Haslam map. The beam FWHM of the Haslam map is claimed to be 51 arcmin in the original survey, and according to the documentation header of the unfiltered HAS03 map. However, the transformations/interpolations between different pixelisation schemes and the applied filtering processes could modify the effective beam. In fact, the HAS03 map specifies a resolution of $\sim 1^\circ$.

In addition, the exact epoch of the data survey is not well defined since the overall Haslam map is an atlas obtained from four different partial sky surveys with data taken at different epochs. The imperfect knowledge of the epoch of the survey may generate positional (pointing) offsets in the Haslam map that we quantify by examining the position on the map of known point-like radio sources.

3.1 Estimation of the effective beam of the *HEALPix* interpolation of the Haslam map

After interpolating the ECP grid to a *HEALPix* map in Celestial B1950 coordinates, we first perform independent estimations of the effective local beam in the sky regions cor-

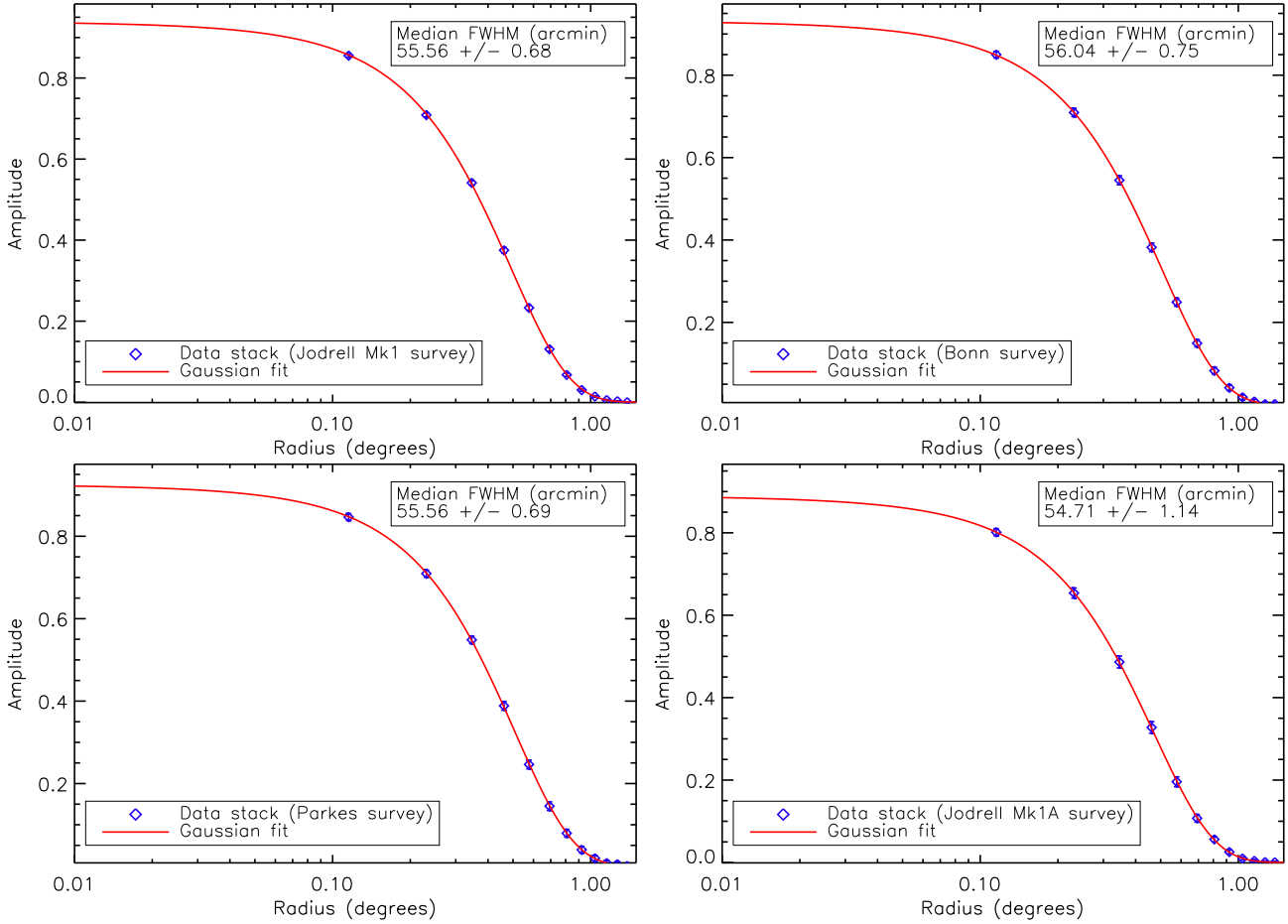


Figure 3. Estimation of the effective beam for the four independent surveys – Jodrell Mk-I, Bonn, Parkes south, and Jodrell Mk-IA – that comprise the Haslam map.

responding to each of the four original surveys. Specifically, we consider the 75 strongest radio sources in each of the Jodrell Mk-I Galactic Anticentre survey, the Bonn survey, the Parkes South survey, and the Jodrell Mk-IA North Polar survey. These point-like sources are isolated using a median filtering with a 1° radius on the **HEALPix** sphere. We compute the profiles of the 75 sources of the survey, in a 1.5° aperture by averaging the amplitudes of the pixels in successive rings of one pixel width, and then perform a Gaussian fit for each source profile (with four parameters including the maximum value of the Gaussian function, the central value, the sigma value, and the background offset). We renormalise the 75 source profiles and stack them by using both the median average and the median absolute deviation to reject outliers in the determination of the mean profile: those deviating at more than 3σ are rejected. We then perform a Gaussian fit of the stack profile, which provides the FWHM of the median stack. For completeness, we also provide the FWHM computed from the median average of the FWHM of each independent profile. We have tested the robustness of our beam estimation on a Planck Sky Model⁷ (PSM, Delabrouille et al. (2013)) simulation of a radio source map with an in-

put Gaussian beam of 51 arcmin, for which we recovered $\text{FWHM} = 51.09 \pm 0.25$ arcmin.

Fig. 3 shows the effective beam profile (blue dots) and Gaussian fit (red line) for each of the four surveys in separate panels. In each case, the beam is well approximated by a Gaussian profile up to 1° radius. Moreover, the beam FWHM is stable across the four surveys, with the inverse variance weighted average of the four beams, $\sum_{i=1}^4 (b_i/\sigma_i^2) / \sum_{i=1}^4 (1/\sigma_i^2)$, yielding $\text{FWHM} = 55.59$ arcmin while the mean value of the four beams, $(1/4) \sum_{i=1}^4 b_i$, and the standard error on the mean, $(1/4) \sqrt{\sum_{i=1}^4 \sigma_i^2}$, give $\text{FWHM} = 55.47 \pm 0.42$ arcmin.

We then repeat the analysis on the full sky 408 MHz map, and determine $\text{FWHM} = 56.02 \pm 0.56$ arcmin, which is consistent with the average value obtained from the four partial surveys. We conclude that the effective beam FWHM of the 408 MHz Haslam map is 56.0 ± 0.6 arcmin, which is larger than the typically quoted value.

3.2 Pointing offsets

We now investigate the positional accuracy of the Haslam map. Pointing errors are expected at a level of a few arcmin, due to positional inaccuracies of the telescopes. Fur-

⁷ <http://www.apc.univ-paris7.fr/~delabrou/PSM/psm.html>

thermore, the reprojection and assumed epoch of the individual surveys can generate additional positional errors. We quantify the positional accuracy of the data by examining the locations of the strongest radio sources in the 408 MHz raw map.

For this purpose we isolate the 22 strongest sources in the Haslam map (i.e., a subset of those used in Section 3.1), at latitude $|b| > 20^\circ$ outside the Galactic plane, by implementing a median filter on the sphere. Here, the medians are calculated over a 1.5° radius disc. We identify these sources in the NASA Extragalactic Database (NED)⁸ to obtain their true R.A./Dec. positions in the B1950 Celestial coordinate system, which are known to $\ll 1$ arcmin accuracy. The name of each radio source and its location on the sky are listed in Table 2. We then perform a two-dimensional (2D) Gaussian fitting of each source profile in the 408 MHz raw map to determine their positions (R.A., Dec.) in B1950 coordinates. The 2D Gaussian fitting of the data is performed over 3° radius discs centred on the NED locations of the sources on the sky. The pointing offsets of the sources are computed by measuring the angular distance on the sphere between their measured and expected coordinates.

The pointing offsets measured are listed in the fourth column of Table 2. The average value of the offsets is 7.4 ± 3.2 arcmin, which is comparable to the pixelization size, but is not a significant fraction of the beamwidth. Nevertheless, it is considerably larger than the quoted positional error (≈ 1 arcmin) of the original data. Furthermore, any desourcing of known sources based on their true coordinates could be affected by such offsets (Section 3.4).

To investigate these offsets further, we plot them on the sky in Fig. 4, multiplied by a factor of 100 to make them visible. They appear to be mostly random, yet there are specific directions which are peculiar to the area of the sky considered. It is interesting to note that the different areas correspond to the four distinct surveys at 408 MHz: for example, in the area of the sky corresponding to the Parkes south survey (R.A. $\in [00^h, 24^h]$, Dec. $\in [-90^\circ, -5^\circ]$), all the offsets are pointing toward the south pole direction. With access to the data from the individual surveys, this could be investigated further and possibly corrected for. However, for now we consider that they are small enough to be acceptable given the beam width. We have verified that a simple error in precessing the maps from their original epochs to B1950 can not be responsible for the large-scale patterns observed.

3.3 Destriping

The reduction of the striping in the Haslam map can be performed by implementing a destriping algorithm. We apply the WMAP approach (code provided by Janet Weiland, priv. comm.) that we adapted to the size of the ECP grid (1080×540), which is different from the size of NCSA grid (1024×512) processed by the WMAP team. We also improved the destriping by removing a slightly wider range of wavelengths in Fourier space⁹. The improvement is shown

⁸ <http://ned.ipac.caltech.edu/>

⁹ Note that a simple source subtraction by median filtering is performed prior to destriping to avoid strong source pixels affect the Fourier transform.

Table 2. Source name (first column), Right Ascension in degrees (second column), Declination in degrees (third column), and pointing offsets in arcmin (fourth column) of the 22 strongest radio sources of the raw 408 MHz map.

Source	B1950 R.A. (deg.)	B1950 Dec. (deg.)	$\Delta\theta$ (arcmin)
M87	187.1	12.7	3.6
NGC1316	50.2	-37.4	8.8
ESO 252-G A018	79.6	-45.8	7.7
PKS 0540-693	85.1	-69.3	8.0
PKS 2356-61	359.1	-61.2	9.4
ESO 075-G 041	328.2	-69.9	7.7
Hydra A	138.9	-11.9	10.8
3C273	186.6	2.3	2.3
3C295	212.4	52.4	4.2
PKS 1932-46	293.1	-46.5	12.5
PKS 1814-63	273.7	-63.8	5.3
NGC4261	184.2	6.1	2.8
3C033	16.6	13.1	8.5
NGC7018	316.1	-25.6	12.6
ESO 362- G 021	80.3	-36.5	7.7
IC 4296	203.4	-33.7	1.3
3C433	320.4	24.8	9.9
3C048	23.7	32.9	9.8
PKS 0410-75	62.5	-75.2	7.6
3C196	122.5	48.4	7.4
3C444	332.9	-17.3	11.0
3C098	59.0	10.3	4.7

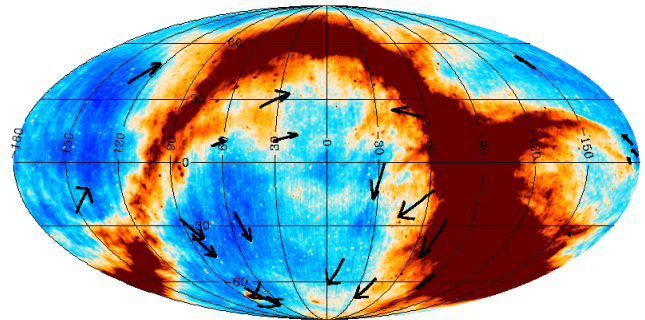


Figure 4. Pointing offsets, multiplied by a factor of 100, of the 22 strongest radio sources from Table 2 on the raw map. The head of the arrows corresponds to the effective position of the source on the map. R.A. = 0° is in the centre of the map and increases to the left.

in Fig. 5: the HAS03 map (left panel) clearly shows residual stripes near the north celestial pole where our newly processed map (right panel) does not. The Galactic plane is masked such that the destriping is applied to 98% of the sky (bottom panel of Fig. 6). In the Galactic plane, the diffuse background level is so large compared to the level of striations that destriping is not required. In the top panel of Fig. 6, the raw ECP map is represented before destriping: the striations are clearly visible near the south pole. The middle panel presents the destriped ECP map, in which we can see, particularly near the south pole, that the striations have been reduced. The bottom panel of the figure shows the difference between the raw and destriped ECP maps,

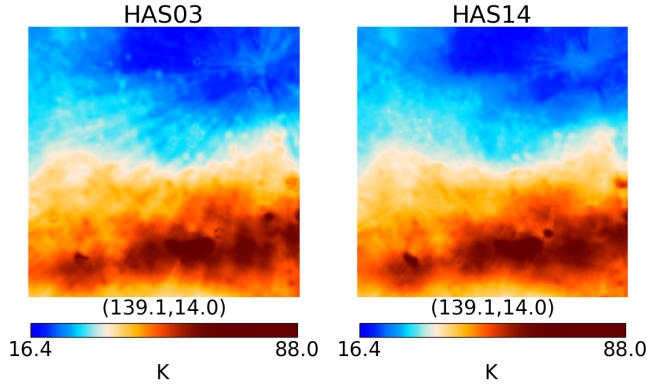


Figure 5. Improvement in destriping shown in a $33^\circ \times 33^\circ$ gnomonic projection of the 408 MHz map centred at $(l, b) = (139^\circ, 14^\circ)$, near the north celestial pole. *Left* panel: the HAS03 destriped map. *Right* panel: our newly destriped map (HAS14).

exhibiting the level of striations that have been removed from the raw Haslam map.

In order to quantify the amount of residual striations in the destriped map, we inspect a low-background $2^\circ \times 2^\circ$ region of the sky, centred at $(\text{R.A.}, \text{Dec.}) = (0^\circ, -40^\circ)$ in Celestial coordinates. We make a horizontal cut of the region, i.e. a band $\{\text{R.A.} \in [-0.5^\circ, 0.5^\circ], \text{Dec.} = -40^\circ\}$, that is orthogonal to the striations. In Fig. 7, we plot the resulting profile of the pixel amplitude in that band for both the raw map (solid black) and the destriped map (solid red), from which we have removed the background zero level to highlight the fluctuations due to the striations. The r.m.s. of the striping fluctuations in this region of the sky is found to be $\sigma_{\text{raw}} = 0.35 \text{ K}$ for the raw ECP map and $\sigma_{\text{destr}} = 0.10 \text{ K}$ for the destriped ECP map. The destriping algorithm reduces the amplitude of the striations in the Haslam map by more than 70%. Nevertheless, residual striations can still be seen at a low-level, in regions devoid of strong Galactic emission.

3.4 Desourcing

The destriped ECP map (middle panel of Fig. 6) is clearly contaminated by strong extragalactic radio sources. In this section we remove these from the destriped 408 MHz map by implementing two different desourcing algorithms.

We detect the sources by implementing a median filter on the map. The median average value at each pixel is determined from those pixels within a 1.5° radius disc. An alternative would be to use the coordinate information from a source catalogue. However, we have seen in Section 3.2 that the ECP Haslam map suffers from positional offsets, typically ~ 7 arcmin, hence it is better to process sources at their effective location rather than at their true location on the sky. The radio sources are subsequently identified simply by subtracting the median filtered map from the input Haslam map.

Once the sources are detected, we process only those with a magnitude larger than a certain threshold with respect to the local background. In the following, we consider three different thresholds: 6 K, 3 K, and 1.5 K over the background. In terms of flux density, these correspond to 9 Jy,

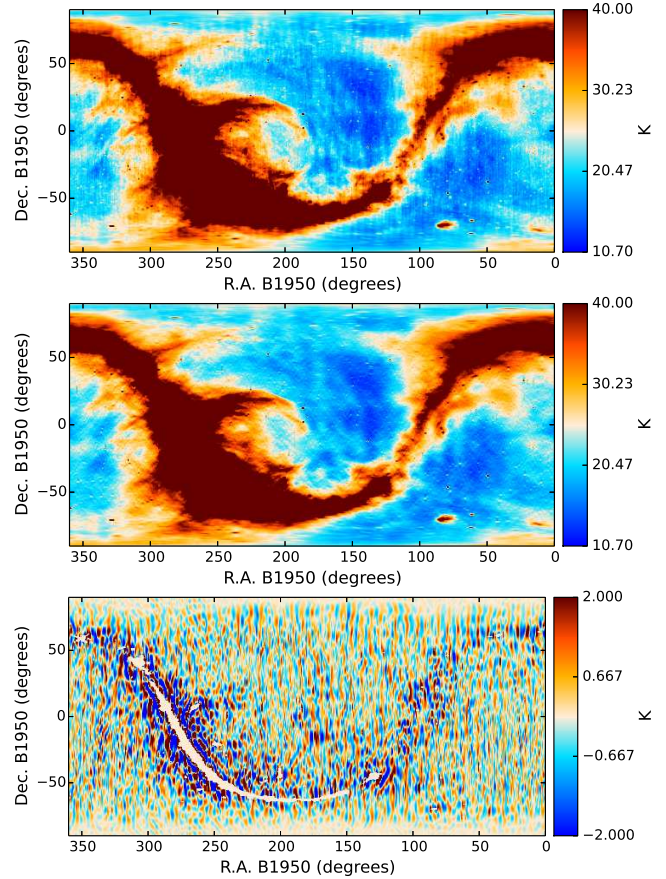


Figure 6. Destriping of the 408 MHz sky map: raw Haslam map (*top panel*), destriped Haslam map (*middle panel*), and the difference map (*bottom panel*).

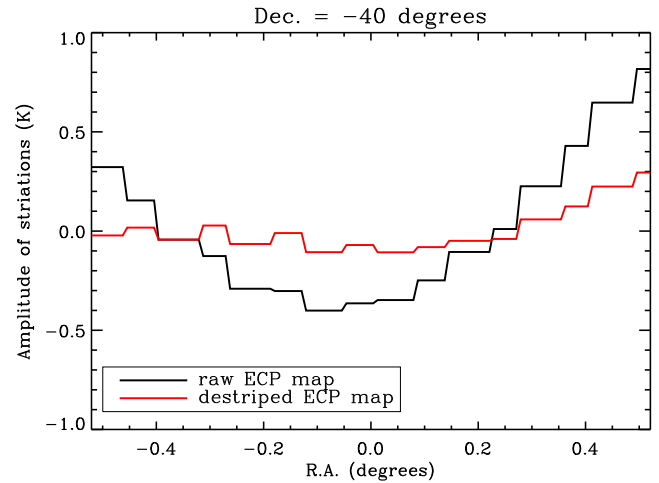


Figure 7. Amplitude of the striations in the band $\{\text{R.A.} \in [-0.5^\circ, 0.5^\circ], \text{Dec.} = -40^\circ\}$ of both the raw map (solid black) and the destriped map (solid red).

5 Jy, and 2 Jy at 408 MHz and 56 arcmin resolution. Our approach for desourcing the Haslam map then combines two methods, either Gaussian fitting (Section 3.4.1) or minimum curvature inpainting (Section 3.4.2), depending both on the source considered and on the local diffuse background surrounding the source.

3.4.1 Two-dimensional Gaussian fitting

In order to remove a given source from the diffuse 408 MHz map, we fit a 2D Gaussian profile at the location of the source, and then subtract the resulting fit from the data. There are then nine parameters to fit, corresponding to the background plane geometry (A_0, A_1, A_2), the amplitude of the Gaussian profile (A_3), the centre coordinates (A_4, A_5), the orientation angle (A_6), and the Gaussian FWHM in both dimensions (A_7, A_8). It is necessary to fit for the background profile surrounding the source but only the Gaussian part of the fit is then subtracted from the data.

The expression for the nine-parameter fitting function is given by the equations 1 and 2:

$$F(X, Y; \{A_i\}) = A_0 + A_1X + A_2Y + A_3 \exp \left[-\frac{1}{2} \left(\frac{\tilde{X}}{A_7} \right)^2 - \frac{1}{2} \left(\frac{\tilde{Y}}{A_8} \right)^2 \right], \quad (1)$$

where

$$\begin{aligned} \tilde{X} &= \cos \left(A_6 \frac{\pi}{180} \right) (X - A_4) - \sin \left(A_6 \frac{\pi}{180} \right) (Y - A_5) \\ \tilde{Y} &= \sin \left(A_6 \frac{\pi}{180} \right) (X - A_4) + \cos \left(A_6 \frac{\pi}{180} \right) (Y - A_5). \end{aligned} \quad (2)$$

The data are fitted within a disc of 1.5° radius centred on the location of a given detected source, and the Gaussian part of the fit is then subtracted from the data within a disc of 5° radius. The goodness-of-fit is measured as:

$$\chi^2 = \sum_{k=1}^N \frac{(Z_k - F(X_k, Y_k; \{A_i\}))^2}{\sigma^2}, \quad (3)$$

where Z_k is the data point at the location (X_k, Y_k) , $F(X_k, Y_k; \{A_i\})$ is the fit at the same location, σ is the noise r.m.s. value (here we set $\sigma = 800$ mK), N is the number of data points that are fitted. The number of degrees of freedom is $N_{\text{dof}} = N - 9$, although the data points are not completely independent (the absolute value of χ^2 is unimportant for this application).

3.4.2 Minimum curvature spline surface inpainting

As an alternative to Gaussian fitting, we also implement an inpainting technique, based on the interpolation of a set of points with a minimum curvature spline surface.

The interpolating function $F(X, Y)$ minimises the Lagrangian

$$\begin{aligned} \mathcal{L}(F, \lambda) &= \sum_{i=1}^N \|Z_i - F(X_i, Y_i)\|^2 \\ &+ \lambda \iint \left[\left(\frac{\partial^2 F}{\partial X^2} \right)^2 + \left(\frac{\partial^2 F}{\partial Y^2} \right)^2 + 2 \left(\frac{\partial^2 F}{\partial X \partial Y} \right)^2 \right] dX dY, \end{aligned} \quad (4)$$

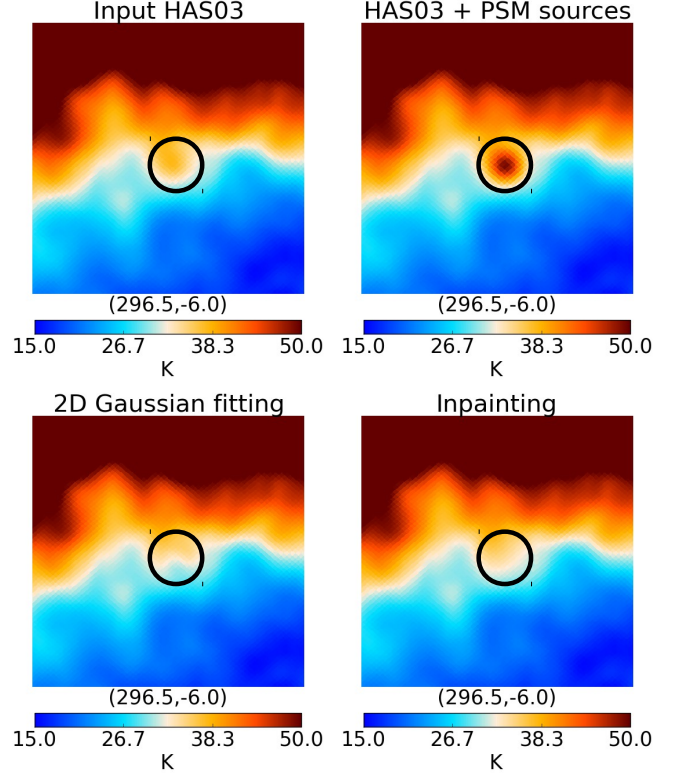


Figure 8. Desourcing of PSM simulations: an $8^\circ \times 8^\circ$ gnomonic projection centred on $(l, b) = (296.5^\circ, -6.0^\circ)$. *Top left:* input map (HAS03). *Top right:* total map (input HAS03 map + PSM source map). *Bottom left:* 2D Gaussian fitting. *Bottom right:* inpainting.

where Z_i is the data value at the interpolation point pixel (X_i, Y_i) . The integral expression under the Lagrange multiplier λ is the “bending energy” that constrains the interpolated surface to be as smooth as possible. In the case of three interpolation points, the interpolating function is a plane surface. In the case of more than three interpolation points, the solution for the interpolating function is given by the Thin Plate Spline (Frank 1982):

$$F(X, Y) = \sum A_i d_i^2 \log d_i + a + bX + cY, \quad (5)$$

where

$$d_i^2 = (X - X_i)^2 + (Y - Y_i)^2 \quad (6)$$

is the distance to the interpolation point.

A mask with 1.5° radius discs centred on the locations of the sources is constructed, then inpainting is performed on the masked pixels.

3.4.3 Results on PSM simulations

We first validate both methods, inpainting and 2D Gaussian fitting, on simulations. The input diffuse 408 MHz map is the HAS03 map. The radio sources are simulated using the PSM software to generate a map containing strong sources with a flux larger than 10 Jy. Both methods are then tested on the coaddition of the HAS03 and the PSM source map. For the inpainting, the source mask is constructed by blanking the pixels of the total map where the amplitude of the PSM

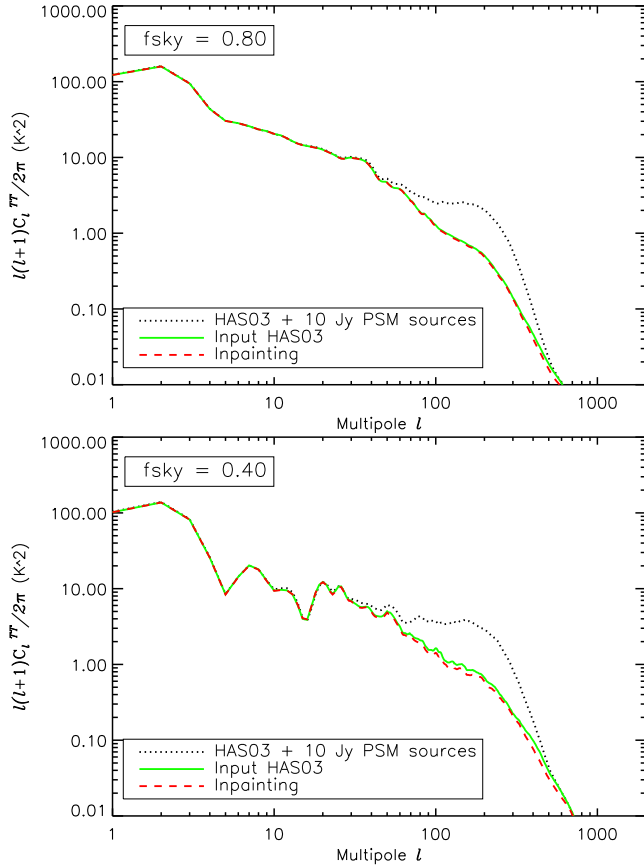


Figure 9. Angular power spectrum of the PSM simulation (*top*: $f_{sky} = 0.80$, *bottom*: $f_{sky} = 0.40$): input map (solid green), total map (dotted black), inpainted map (dashed red).

source map is larger than 0.8 K. For the Gaussian fitting, the fit is performed on the total map within 1.5° radius discs and the subtraction applied within 5° radius discs. The results are shown in Fig. 8 and Fig. 9.

The top left panel of Fig. 8 shows the input diffuse map, i.e. the HAS03 map. This input map exhibits spurious small scale patterns, as indicated by the circle, because of the imperfect desourcing achieved in the HAS03 version of the 408 MHz data. The top right panel presents the total map, where we have added the simulated PSM sources to the input map. In the bottom right panel we then show the result of inpainting on this map, while in the bottom left panel the result of the Gaussian fit and subtraction process can be seen. In both cases, the recovered map is similar to the input diffuse map: the spurious small scale structures within the drawn circle have been restored whereas the PSM source has been removed.

We also compute the angular power spectrum of the different maps using the `PolSpice` pseudo- C_ℓ code (Chon et al. 2004). We produce two different Galactic masks ($f_{sky} = 0.80$ and $f_{sky} = 0.40$) based on two successive intensity thresholds of the input map. In the top panel of Fig. 9 we plot the angular power spectra for 80% sky coverage of the input map (solid green), the total map with the PSM sources added (dotted black), and the inpainted map (dashed red). The power spectrum of the total map shows an excess of power on small scales due to the presence of the PSM sources

whereas the power spectrum of the inpainted map successfully matches the input power spectrum by removing the source contamination at small scales. In the bottom panel of the figure, we also validate the inpainting result at high Galactic latitude by computing the power spectrum on 40% of the sky, after masking the Galactic plane, so that the Galactic signal is not dominating the power spectrum on scales of $\sim 1^\circ$.

3.4.4 Results on data: multi-stage approach

Some of the radio sources at 408 MHz are faint or extended. In this case the Gaussian fitting may fail because the number of fitted data points becomes insufficient to compensate for the low signal-to-noise ratio. Some other sources, especially at low Galactic latitudes, are surrounded by a strong background signal, with a varying and complex geometry. In this case also, the 2D Gaussian fitting approach may fail because the removal of the source would require a much larger number of parameters to be fitted. We therefore need to perform a multi-stage approach on the data, where some of the sources are fitted with a 2D Gaussian profile and then subtracted from the Haslam map whereas other sources are inpainted.

In the first stage, we perform a two-dimensional Gaussian fitting of all the sources detected above 6 K over the background. This threshold typically corresponds to sources with a flux density larger than 9 Jy at 408 MHz for a 56 arcmin beam. We quantify the goodness-of-fit by using the χ^2 (Eq. 3) measuring the deviation of the Gaussian fit from the source profile. The median value of the goodness-of-fit is $\chi_m^2 = 6775.6$ for the 6 K-threshold. We visually validated on the map the performance of the source removal for that particular case where the goodness-of-fit reaches the limit $\chi^2 = \chi_m^2$. We therefore choose as a conservative upper limit criterion of the goodness-of-fit the median value χ_m^2 in order to guarantee the exclusion of the imperfect Gaussian fits: if the χ^2 of the fit is smaller than the median value χ_m^2 of all the fits then we subtract the fit from the data. Otherwise, if $\chi^2 > \chi_m^2$ then we process the source by inpainting instead of fitting as a second stage.

Figure 10 shows the location of the sources detected in the Haslam map when processed using three different detection thresholds, applied successively. We can see that there are more inpainted sources near the Galactic plane (or regions of high background), whereas the Gaussian fitting works better at higher Galactic latitude, as expected.

A total number of 369 sources are detected at the 6 K (~ 9 Jy) detection threshold with 202 extragalactic in origin. Since most of the well-known Galactic sources are very bright, they should be present in the list. We inspected each of the detected sources by hand and compared it to sources in the NED⁸ and SIMBAD¹⁰ online databases. If a bright Galactic source was matched, we did not subtract it from the map. At this threshold, 167 were found to be Galactic.

After the first step at the threshold of 6 K, fainter radio sources are still found to contaminate the diffuse 408 MHz map. We therefore need to use a deeper detection threshold for the desourcing. However, instead of desourcing the raw

¹⁰ <http://simbad.u-strasbg.fr/simbad/>

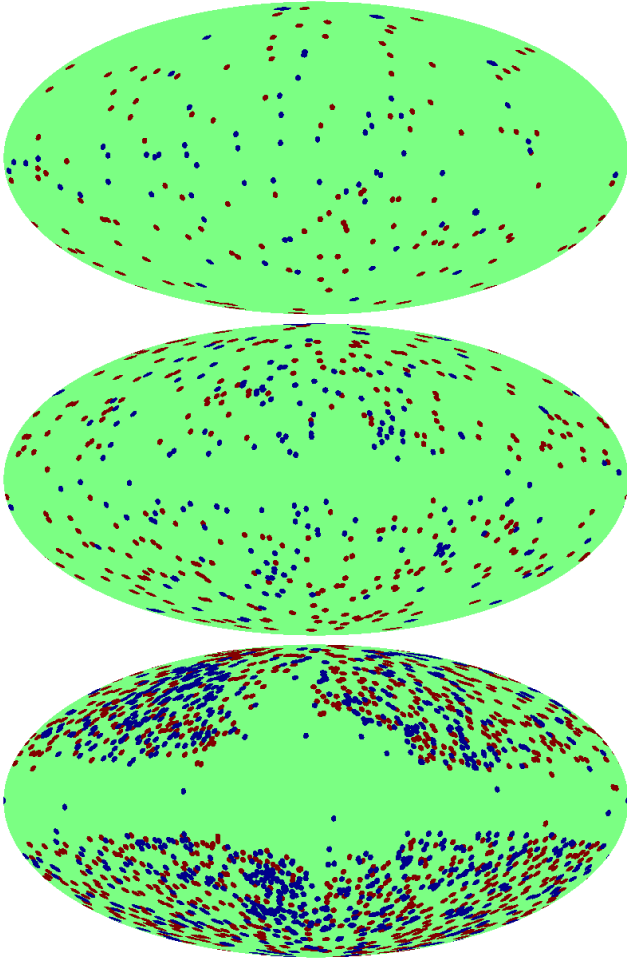


Figure 10. Location of the extragalactic sources that have been fitted (red) or inpainted (blue). *Top:* set of sources processed at the first threshold (> 6 K over the background). *Middle:* further set of sources subsequently processed at the second threshold (> 3 K over the background). *Bottom:* additional set of sources finally processed at the third threshold (1.5 K over the background). Note that we have attempted to retain the brightest Galactic sources in the map, hence their clear absence from the figure.

Haslam map at a deeper threshold, we repeat the processing directly on the 6 K-processed map. Specifically, we search for the sources in the 6 K-processed map that are 3 K (~ 5 Jy) over the background, and we perform either Gaussian fitting or inpainting on the 6 K-processed map. For the 3 K threshold, $\chi^2_m = 2773.7$, and a total of 924 sources are detected, with 462 corresponding to Galactic sources, so that only the remaining 462 are then subtracted (middle panel of Fig. 10). We then repeat the multi-stage processing again on the 3 K-processed map and locate 1613 more sources that are 1.5 K (~ 2 Jy) over the background (2870 point-like sources are detected at this threshold but 1257 were found to be Galactic in origin). The use of successive detection thresholds for desourcing is motivated by the necessity to avoid overlapping sources in the processing. We stop the desourcing at the threshold of 1.5 K since this is approaching the level of residual artefacts (striations) and noise in the map. This is then the final processed map.

The new filtered 408 MHz sky map (HAS14) is presented for different patches of the sky and compared to the HAS03 version in Figs. 11, 12 and 13. The first column panels of Figs. 11, 12 and 13 show the source contaminated ECP raw map, where circles are used to highlight the sources. The HAS03 map is shown in the second column, which clearly shows many artefacts, including edges due to the `quadcube` projection, residual source artefacts, and unsubtracted sources. The third column shows the new (HAS14) map using the combination of inpainting and Gaussian fitting. We can see a clear improvement by comparison to the HAS03 version. The `quadcube` artefacts are no longer present and there are no strong residual source artefacts.

We can make an estimate of the depth (in terms of flux density) to which we have removed sources from the Haslam map at high Galactic latitudes where the background confusion is minimised. We do this using the source flux catalogue of Kuehr et al. (1981), which lists all the radio sources detected with a flux density larger than ~ 1 Jy at 5 GHz. We select a low-background area of the sky in the new Haslam map, R.A. $\in [07^h, 18^h]$ and Dec. $\in [30^\circ, 90^\circ]$. In this area, the catalogue lists 2 radio sources having a flux density S larger than 20 Jy at 408 MHz, 3 sources with $S > 10$ Jy, 11 sources with $S > 5$ Jy, 18 sources with $S > 3$ Jy, 46 sources $S > 2$ Jy, and a total of 62 sources with $S > 1$ Jy. We have identified in this area of the sky the sources that have been removed in the new Haslam map and we have computed the completeness of our processing: 100% of the radio sources having a flux density $S > 5$ Jy at 408 MHz have been removed, 89% of the sources with $S > 3$ Jy, 83% of the sources with $S > 2$ Jy, and 68% of the sources with $S > 1$ Jy.

Using the completeness we also give an estimate of the confusion noise in the new Haslam map. We use the 408 MHz source count (i.e., the cumulative distribution of the number of sources, dN/dS , brighter than a given flux density) of Condon (1984) to fit a power law $N(S) = \alpha S^{-\gamma}$ in the range 2 Jy–10 Jy, where $S_{\text{lim}} = 2$ Jy is roughly the completeness limit ($\geq 80\%$ over this flux density range). We find $\alpha \sim 67$ and $\gamma \sim -2.8$. We then apply the formula for the confusion noise in the Gaussian beam approximation (Condon 1974)

$$\sigma_c = \frac{\alpha}{3 - \gamma} \frac{\pi \theta_b^2}{4 \ln 2} (S_{\text{lim}})^{3-\gamma}, \quad (7)$$

where $\theta_b \sim 56$ arcmin is the beam FWHM and S_{lim} is the upper limit of flux density. Based on completeness, the upper limit of flux density is $S_{\text{lim}} = 2$ Jy, and we find that the confusion noise is $\sigma_c \sim 0.1$ K in the new Haslam map.

4 DISCUSSION

4.1 Angular power spectrum

We compute the angular power spectrum of the Haslam map, both before and after desourcing, using the `PolSpice` code on 80% and 40% of the sky defined using intensity thresholds in the HAS03 map. Rather than providing an accurate measure of the synchrotron power spectrum, our aim is to highlight, by doing a side-by-side comparison of the different versions of the Haslam map, how the imperfect desourcing generates a spurious excess of power at small scales in the angular power spectrum of the synchrotron template. In the top panels of Fig. 14 we plot the power spectrum of

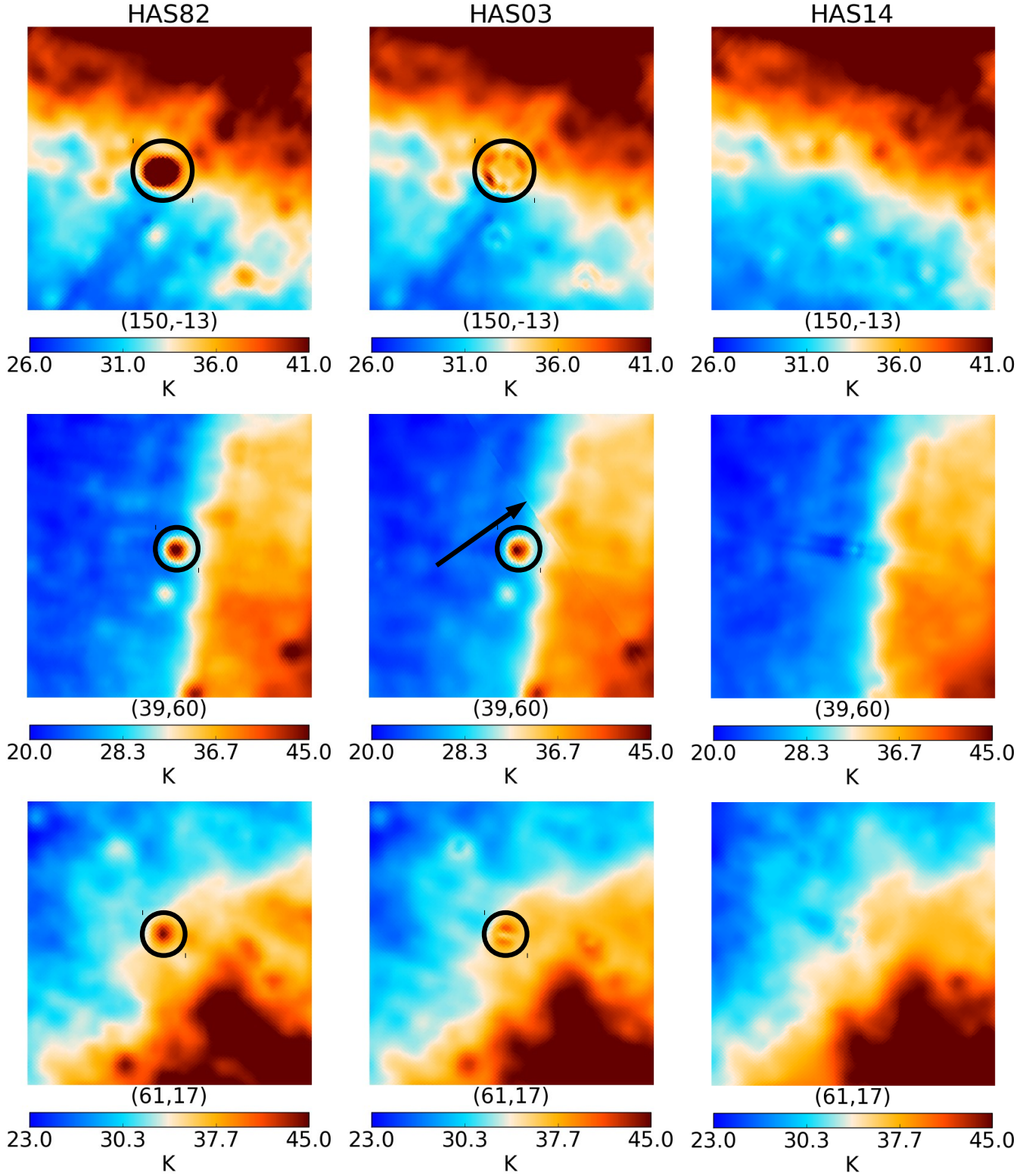


Figure 11. Three $12.5^\circ \times 12.5^\circ$ gnomonic projections (*first row to third row*) of the raw Haslam map (*left column*), of the HAS03 post-processed version (*middle column*), and of our reprocessed 408 MHz sky map (HAS14) (*right column*). Note that the HAS03 post-processing is based on the NCSA map whereas that described here utilises the ECP map.

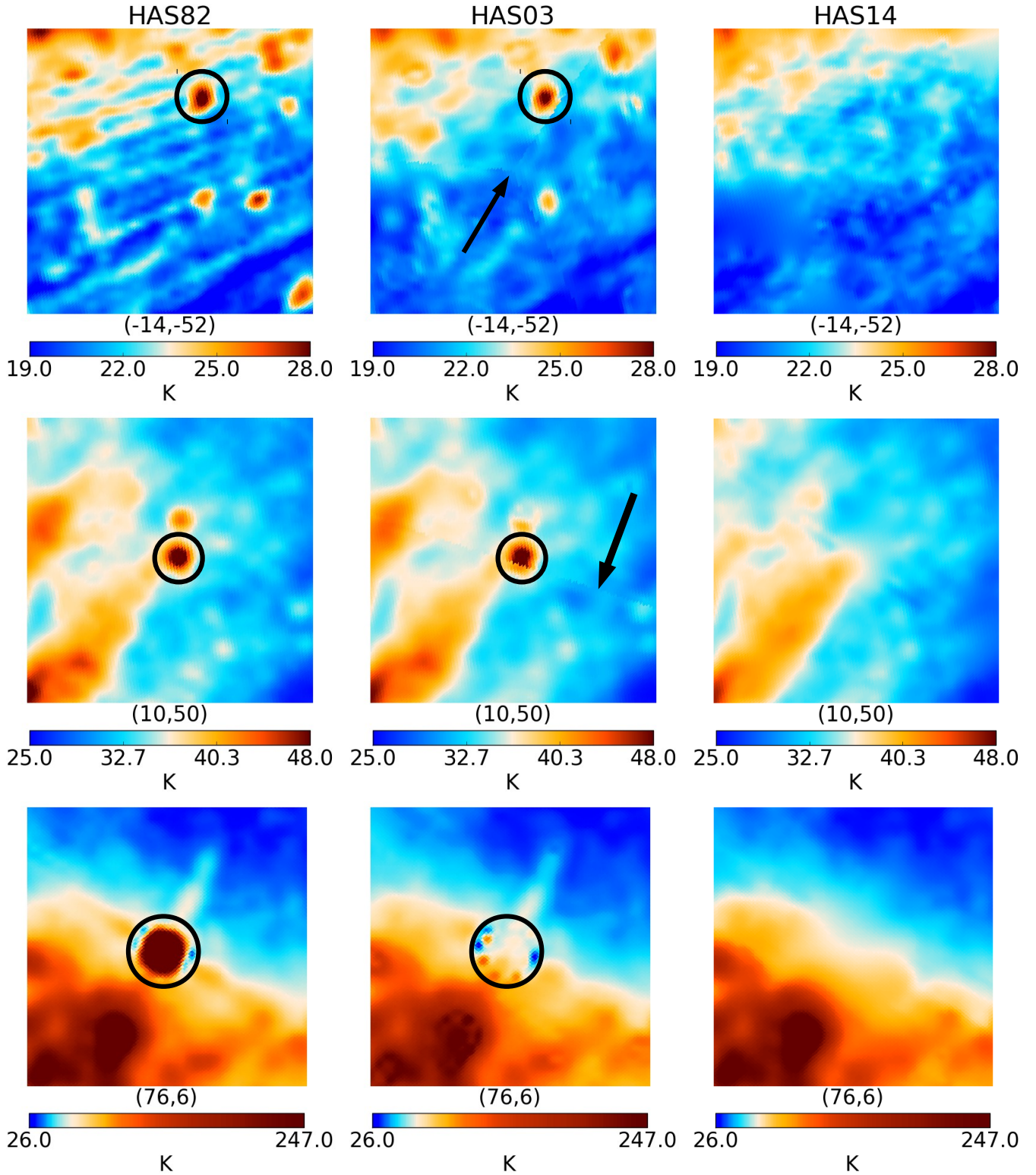


Figure 12. Three more $12.5^\circ \times 12.5^\circ$ gnomonic projections (*first row to third row*) of the raw Haslam map (*left column*), the HAS03 post-processed version (*middle column*), and of our reprocessed 408 MHz sky map (HAS14) (*right column*).

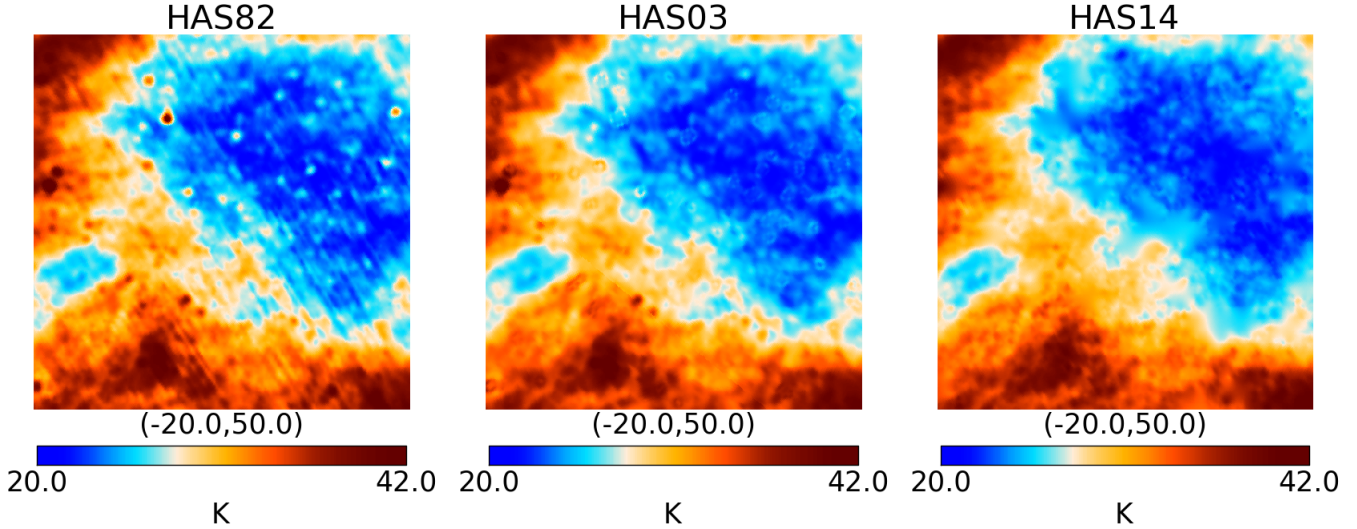


Figure 13. A $43^\circ \times 43^\circ$ gnomonic projection of the 408 MHz map centred at high latitude $(l, b) = (340^\circ, +50^\circ)$ for the raw (*left*), HAS03 (*middle*) and HAS14 (*right*) versions of the map. Both striations and numerous extragalactic radio sources are evident across the raw map. The HAS03 version also contains artefacts, including source residuals, unremoved sources, and line features due to remapping to a *quadcube* pixelization. In our map, the striations and source residuals have been minimised.

the raw Haslam map, i.e. the unfiltered LAMBDA version (dotted black), the power spectrum of the HAS03 destriped desourced map (dashed blue), and the power spectrum of our newly reprocessed HAS14 map (solid red). The excess of power at $\ell \sim 200$ (beam scale) in the raw Haslam map (dotted black line) is due to contamination by extragalactic radio sources. At the smallest scales ($\ell > 500$), where the beam suppresses the power, there are additional features in the power spectrum, which could be due to beam side-lobes and/or artefacts from the various repixelization procedures that have been applied to the data. The power spectrum should be, to first approximation, corrected for by a Gaussian beam window function with FWHM = 56 arcmin. However, at $\ell > 500$, the true window function is not well-modelled due to the repixelization effects. The excess of small-scale power due to the source contamination in the raw Haslam map (dotted black) is clearly suppressed in both versions of the filtered data. However, the angular power spectrum of the HAS03 map still shows an excess of power on scales smaller than the 56 arcmin beam scale, i.e. for $\ell > 200$. This excess power is due to numerous residual source artefacts in the HAS03 map that we have mentioned earlier in this paper (e.g., top left panel in Fig. 2). Conversely, the angular power spectrum of the newly reprocessed HAS14 map (solid red line) in the top panels of Fig. 14 shows less power at $\ell > 200$.

4.2 Small-scale fluctuations

A high-resolution template of synchrotron emission would be particularly useful for preparing for upcoming 21 cm experiments, e.g. SKA and HI intensity mapping experiments, in particular to allow the study of foreground cleaning techniques for such projects (see e.g. Wolz et al. 2014; Shaw et al. 2014). However, the 408 MHz sky map is limited in resolution to a beam FWHM of 56 arcmin, thus cannot, by itself, be directly used as a template of Galactic synchrotron emis-

sion for high-resolution sky simulations. Moreover, there are still no full-sky astronomical data sets corresponding to synchrotron emission on degree scales or smaller. It is therefore useful to add small-scale fluctuations to the Haslam map in order to produce a high-resolution template of synchrotron for simulation studies. Our newly processed Haslam map with such fluctuations added is available for these purposes. This high-resolution template is produced at $N_{\text{side}} = 2048$ ¹¹ beaming smoothing effects removed (i.e. a FWHM of zero arcmin).

To achieve this, we follow the approach used in Delabrouille et al. (2013). We first simulate a Gaussian random field G_{ss} having the following power spectrum:

$$C_\ell = \ell^\gamma [1 - \exp(-\ell^2 \sigma_{\text{temp}}^2)], \quad (8)$$

where $\sigma_{\text{temp}} = 56$ arcmin is the original beam resolution of the Haslam map that we have estimated in Section 3.1. The index γ is obtained by fitting a power-law to the power spectrum of the original Haslam map between $\ell = 30$ and $\ell = 90$. We find a best-fitting value of $\gamma = -2.703$, similar to values estimated by other analyses on similar angular scales ($\ell \lesssim 100$; La Porta et al. 2008). However, we note that recent higher resolution observations suggest that the spectrum is flatter on smaller angular scales ($\ell \gtrsim 1000$; Bernardi et al. 2009). The Gaussian field G_{ss} is whitened to have zero mean and unit variance, then multiplied by the template map I_{temp} as follows:

$$I_{ss} = \alpha G_{ss} I_{\text{temp}}^\beta. \quad (9)$$

The small-scale fluctuations I_{ss} are then added to the original template I_{temp} :

$$I'_{\text{temp}} = I_{\text{temp}} + I_{ss}. \quad (10)$$

¹¹ Higher N_{side} maps with small-scales added are available on request from the authors.

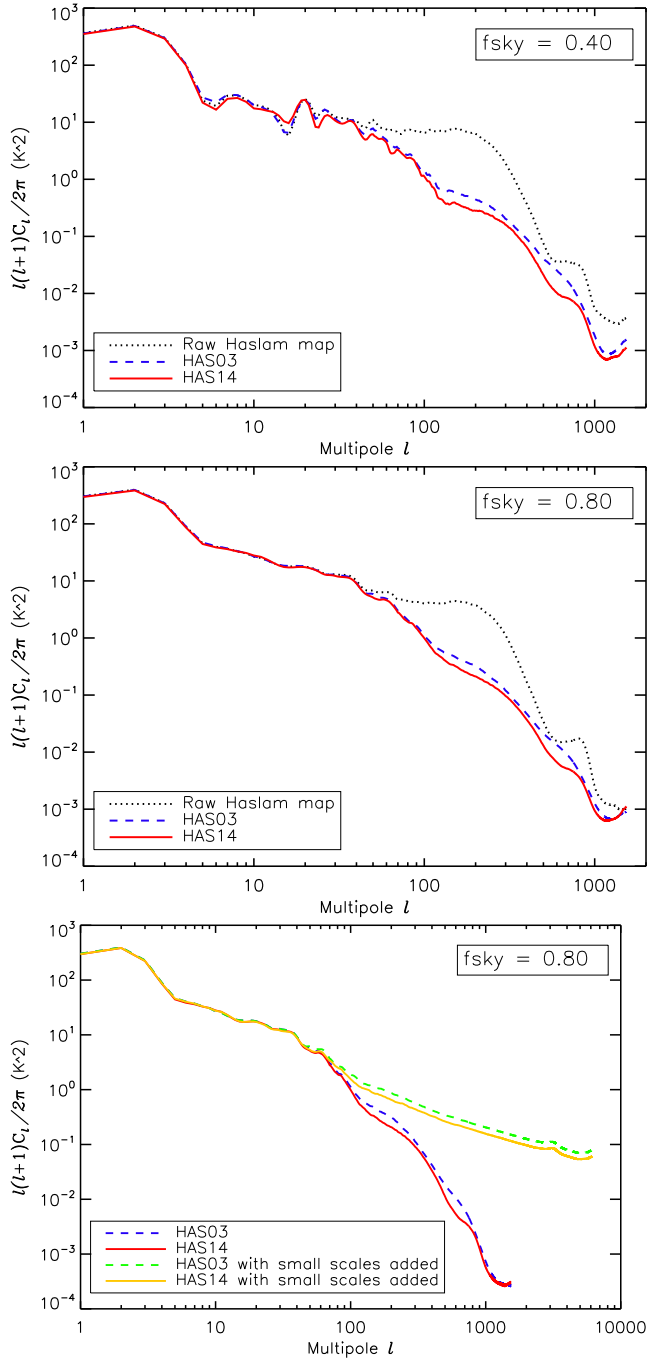


Figure 14. Angular power spectrum of 408 MHz sky map computed on both the HAS03 map (dashed blue line) and HAS14 map (solid red line) for different fractions of the sky: $f_{sky} = 0.4$ (top panel) and $f_{sky} = 0.8$ (middle panel). The power spectrum of the raw Haslam map is overplotted (dotted black line). Bottom panel: the power spectrum on 80% of the sky of the Haslam map with the small-scale fluctuations added.

The parameters α and β in the small-scale map I_{ss} have been determined such that the new template map with the small-scales added, I'_{temp} , conserves the same statistics (mean, variance, and skewness) as the original template map, I_{temp} . The best fit is found for $\alpha = 0.0599$ and $\beta = 0.782$. We constrained these two parameters in order to

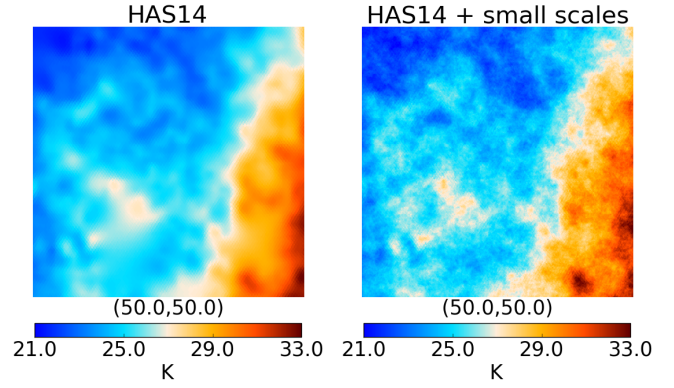


Figure 15. A $12.5^\circ \times 12.5^\circ$ gnomonic projection centred at $(l, b) = (50^\circ, 50^\circ)$ showing the addition of small-scale fluctuations to the newly processed Haslam map. Left panel: the map at its native beam resolution. Right panel: the map with small-scale structure added.

match the statistical moments of the final map I_{temp} with the ones of the input map I_{temp} , after subtracting the small-scale fluctuation map by its mean and dividing by the standard deviation. This is slightly different from the approach used in Delabrouille et al. (2013) where the parameters α and β were fixed for each template at a given value in the simulation.

The addition of small scales to the Haslam map is illustrated in Fig. 15. The small-scale fluctuations can be seen and are superposed onto the large-scale structure defined by the Haslam map. The angular power spectrum of the Haslam map with the small scales added is computed on 80% of the sky, and plotted in the bottom panel of Fig. 14. We generate small scales both in the HAS03 map and in our newly processed HAS14 map. It is obvious from the bottom panel of the figure that the excess power in the HAS03 map due to residual source artefacts generates extra spurious power in the high-resolution template after the addition of small scales (dashed green line). Any spurious power is reduced when we generate small scales from our newly reprocessed Haslam map, where the desourcing is much cleaner (solid yellow line).

Although we believe the HAS14 is more reliable due to the reduction in small-scale artefacts, we cannot be entirely sure that this is the correct power spectrum on these scales since our fitting procedure removes small-scale power. Furthermore, the power spectrum may depart from a simple power-law at high ℓ -values. High-resolution observations of the diffuse synchrotron sky are needed to measure arcmin scales accurately (e.g., Bernardi et al. 2009).

4.3 Applications of the Haslam map

The Haslam 408 MHz map still remains as one of the few total-power full-sky surveys made at radio frequencies. This map has been used numerous times for studying a wide range of phenomena. A recent example of this is the analysis of the power spectrum of diffuse synchrotron emission by Mertsch & Sarkar (2013). They found that an ensemble of shell supernova remnants could explain the shape of the power spectrum at $\ell \sim 200$. Given that the residual source artefacts

Table 3. Template fit coefficients between the K-, Ka-, and Q-bands of *WMAP* data and the 408 MHz data, used as a proxy for Galactic emission due to synchrotron radiation, in units of $\mu\text{K K}_{408\text{ MHz}}^{-1}$. The last column lists the template fit coefficients between the 408 MHz data and the K-Ka difference map. The mean of the synchrotron coefficient is computed from all sky regions.

Region	Map	K	Ka	Q	K-Ka
1	HAS03	4.4 ± 0.9	0.4 ± 0.9	-0.1 ± 0.9	2.4 ± 0.1
	HAS14	3.4 ± 1.3	-0.5 ± 1.3	-0.6 ± 1.3	2.3 ± 0.1
2	HAS03	6.9 ± 0.7	3.4 ± 0.8	2.1 ± 0.8	3.8 ± 0.0
	HAS14	8.7 ± 0.9	4.2 ± 1.0	2.9 ± 1.0	3.7 ± 0.0
3	HAS03	5.4 ± 0.4	1.6 ± 0.4	0.8 ± 0.4	3.0 ± 0.0
	HAS14	5.6 ± 0.5	2.0 ± 0.5	1.1 ± 0.5	2.9 ± 0.0
4	HAS03	6.1 ± 1.3	5.3 ± 1.9	3.0 ± 1.8	4.0 ± 0.2
	HAS14	7.2 ± 1.7	2.2 ± 2.2	1.1 ± 2.2	3.9 ± 0.2
5	HAS03	4.1 ± 1.9	4.5 ± 2.1	4.8 ± 2.6	3.1 ± 0.6
	HAS14	9.4 ± 2.9	6.8 ± 3.0	7.5 ± 3.2	3.4 ± 0.7
6	HAS03	3.9 ± 0.9	1.3 ± 1.0	1.0 ± 1.0	3.3 ± 0.1
	HAS14	5.6 ± 1.2	1.7 ± 1.3	0.9 ± 1.3	3.6 ± 0.1
7	HAS03	4.9 ± 0.9	0.7 ± 1.1	0.0 ± 1.0	3.2 ± 0.1
	HAS14	5.1 ± 1.1	0.9 ± 1.3	0.2 ± 1.3	3.2 ± 0.1
8	HAS03	5.6 ± 0.5	2.4 ± 0.6	1.1 ± 0.6	4.5 ± 0.0
	HAS14	6.4 ± 0.6	2.2 ± 0.6	0.9 ± 0.6	4.4 ± 0.0
9	HAS03	7.8 ± 0.9	3.1 ± 0.9	2.3 ± 1.0	2.2 ± 0.1
	HAS14	8.2 ± 1.1	3.5 ± 1.1	2.2 ± 1.2	1.7 ± 0.1
10	HAS03	3.8 ± 1.0	3.7 ± 1.4	3.0 ± 1.4	4.1 ± 0.1
	HAS14	5.8 ± 1.3	3.3 ± 1.7	3.1 ± 1.7	4.0 ± 0.1
11	HAS03	2.8 ± 0.7	0.2 ± 0.8	-0.4 ± 0.8	2.2 ± 0.0
	HAS14	4.7 ± 1.0	1.2 ± 1.1	0.4 ± 1.1	2.4 ± 0.0
12	HAS03	1.6 ± 0.9	0.2 ± 1.4	0.5 ± 1.3	4.4 ± 0.1
	HAS14	4.9 ± 1.5	0.3 ± 1.7	0.3 ± 1.7	4.1 ± 0.1
13	HAS03	5.5 ± 0.9	1.8 ± 1.2	0.6 ± 1.2	3.4 ± 0.1
	HAS14	6.1 ± 1.2	-0.6 ± 1.4	-1.3 ± 1.4	3.3 ± 0.1
14	HAS03	4.8 ± 1.2	-1.4 ± 1.3	-0.7 ± 1.3	-0.8 ± 0.1
	HAS14	1.0 ± 1.4	-1.2 ± 1.5	-0.2 ± 1.5	-1.0 ± 0.1
15	HAS03	8.8 ± 0.8	2.0 ± 0.9	1.6 ± 0.9	5.4 ± 0.1
	HAS14	21.1 ± 0.9	8.2 ± 0.9	5.6 ± 0.9	6.7 ± 0.1
16	HAS03	3.5 ± 0.5	0.9 ± 0.6	-0.1 ± 0.6	3.9 ± 0.0
	HAS14	4.2 ± 0.6	1.0 ± 0.6	-0.0 ± 0.6	3.8 ± 0.1
17	HAS03	3.0 ± 0.8	2.3 ± 1.0	1.5 ± 1.0	5.9 ± 0.1
	HAS14	4.0 ± 1.0	2.5 ± 1.2	1.5 ± 1.1	5.9 ± 0.1
18	HAS03	6.0 ± 1.1	2.1 ± 1.5	1.1 ± 1.4	5.0 ± 0.1
	HAS14	7.2 ± 1.3	3.8 ± 1.7	3.0 ± 1.7	4.8 ± 0.1
19	HAS03	2.6 ± 1.2	-1.2 ± 1.9	-2.9 ± 2.0	3.3 ± 0.2
	HAS14	1.8 ± 1.8	-3.7 ± 2.6	-4.4 ± 2.7	3.2 ± 0.2
20	HAS03	4.9 ± 1.9	1.3 ± 1.6	2.3 ± 1.8	-0.3 ± 0.2
	HAS14	-0.5 ± 2.5	-1.2 ± 2.2	0.1 ± 2.2	-1.6 ± 0.2
21	HAS03	5.1 ± 1.1	1.8 ± 1.2	0.9 ± 1.2	4.4 ± 0.0
	HAS14	3.2 ± 1.4	0.5 ± 1.5	-0.7 ± 1.5	4.5 ± 0.0
22	HAS03	4.3 ± 1.1	2.5 ± 1.4	2.4 ± 1.5	4.0 ± 0.2
	HAS14	5.3 ± 1.4	3.3 ± 1.7	3.9 ± 1.8	3.5 ± 0.2
23	HAS03	3.0 ± 1.2	2.2 ± 1.4	2.0 ± 1.4	5.0 ± 0.1
	HAS14	2.0 ± 1.5	0.3 ± 1.7	0.2 ± 1.7	4.8 ± 0.1
24	HAS03	3.1 ± 0.9	1.1 ± 1.2	0.2 ± 1.2	1.3 ± 0.1
	HAS14	5.0 ± 1.3	3.3 ± 1.6	2.0 ± 1.6	1.1 ± 0.1
25	HAS03	3.5 ± 1.2	-1.1 ± 1.7	0.2 ± 1.7	1.5 ± 0.2
	HAS14	3.7 ± 1.8	-3.5 ± 2.4	-1.8 ± 2.5	1.3 ± 0.3
26	HAS03	3.1 ± 1.4	-0.1 ± 2.1	0.1 ± 2.3	3.8 ± 0.3
	HAS14	4.0 ± 2.0	-1.3 ± 2.7	-0.7 ± 2.8	3.5 ± 0.4
27	HAS03	3.8 ± 1.4	1.7 ± 1.9	0.5 ± 1.9	3.5 ± 0.3
	HAS14	3.7 ± 1.8	2.7 ± 2.4	1.6 ± 2.4	1.6 ± 0.3
28	HAS03	-0.5 ± 1.6	-0.6 ± 1.6	1.1 ± 2.0	3.3 ± 0.5
	HAS14	-1.4 ± 2.5	1.1 ± 2.4	0.7 ± 2.8	1.2 ± 0.5
29	HAS03	0.9 ± 1.2	-1.4 ± 1.8	2.4 ± 2.0	2.6 ± 0.5
	HAS14	-1.5 ± 2.8	-2.1 ± 3.2	1.2 ± 3.4	2.5 ± 0.5
30	HAS03	6.5 ± 1.7	6.1 ± 2.1	4.6 ± 2.3	4.3 ± 0.3
	HAS14	7.1 ± 2.3	4.3 ± 2.5	3.2 ± 2.7	4.2 ± 0.3
31	HAS03	1.4 ± 1.1	1.4 ± 1.4	1.0 ± 1.4	1.4 ± 0.2
	HAS14	4.1 ± 1.4	5.0 ± 1.8	4.3 ± 1.7	0.8 ± 0.2
32	HAS03	5.2 ± 0.6	2.4 ± 0.6	1.2 ± 0.6	4.3 ± 0.0
	HAS14	5.1 ± 0.8	2.5 ± 0.8	1.5 ± 0.8	4.2 ± 0.0
33	HAS03	4.4 ± 1.0	2.8 ± 1.2	2.8 ± 1.2	4.4 ± 0.1
	HAS14	5.6 ± 1.4	3.8 ± 1.5	4.2 ± 1.5	4.2 ± 0.1
Mean	HAS03	4.3 ± 0.3	1.6 ± 0.3	1.2 ± 0.3	3.3 ± 0.3
	HAS14	5.0 ± 0.7	1.7 ± 0.5	1.3 ± 0.4	3.1 ± 0.3

add power on small-scales ($\ell \gtrsim 100$), this analysis should be re-evaluated in light of the new data.

It has also been used extensively as a template for synchrotron emission in CMB studies at microwave wavelengths. Although we do not expect a significant change in any CMB results obtained using the new template (since the synchrotron is relatively weak at frequencies $\gtrsim 30$ GHz and the brightest areas are typically masked), it may have some implications for the inferred properties of the synchrotron emission at these frequencies.

We have performed an analysis following the standard template fit approach from Davies et al. (2006). In particular, each of the 5 *WMAP* frequency maps is fitted simultaneously with a constant offset and three external templates, namely the 408 MHz survey, the Dickinson et al. (2003) (DDD) H α survey, and the Finkbeiner et al. (1999) (FDS8) 94 GHz map, corresponding respectively to tracers of the synchrotron, free-free and dust emission. The *WMAP* data and the external templates are smoothed to a common Gaussian full-width half-maximum (FWHM) beam resolution of 1° and reprojected onto a HEALPix map with a pixel resolution of $N_{\text{side}} = 128$. We then analyse the set of 33 sky regions defined in Ghosh et al. (2012). We use full pixel-pixel noise covariance matrix for each region, taking into account 1° beam smoothing applied to the *WMAP* data. It contains contributions from the correlated CMB emission and the uncorrelated instrumental noise.

We compare results derived using either the HAS03 map or the HAS14 map as the synchrotron template, while keeping fixed the free-free and dust templates. Any significant difference between the HAS03 and HAS14 templates at 1° resolution is evident in the cross-correlation coefficients.

Table 3 presents the 408 MHz correlated (or synchrotron) coefficients at K-, Ka- and Q-bands, expressed in antenna temperature units, derived using the HAS03 and HAS14 templates. The synchrotron coefficients for most of the regions are consistent at the $1\text{-}2\sigma$ level, with the exception of region 15. This region lies close to the Galactic plane where the Cygnus Loop, a large supernova remnant from our Galaxy located at $(l, b) = (74.0^\circ, -8.6^\circ)$, has been subtracted in the HAS03 template while it has been deliberately kept in our HAS14 template because it is an extended Galactic radio source. That is the reason why a discrepancy between HAS03 and HAS14 synchrotron coefficients is observed in region 15.

We do not find any significant difference on the mean synchrotron coefficient, derived from all sky regions, with respect to use of different 408 MHz templates. Note that the uncertainties on the synchrotron coefficients are large due to the presence of a dominant CMB cosmic variance term.

The synchrotron coefficients for a given sky region include a contribution from the random chance correlation between the CMB and the 408 MHz template. This term can either be positive, negative, or zero, but is constant in units of thermodynamic temperature. For the mean of the 33 sky regions, the CMB chance correlation term averages out, without introducing any bias on the mean synchrotron coefficient. To convert the coefficients into a synchrotron spectral index (β_s), we assume a simple single power-law model of the synchrotron emission that applies from 408 MHz to the *WMAP* frequencies. However, such conversion is not triv-

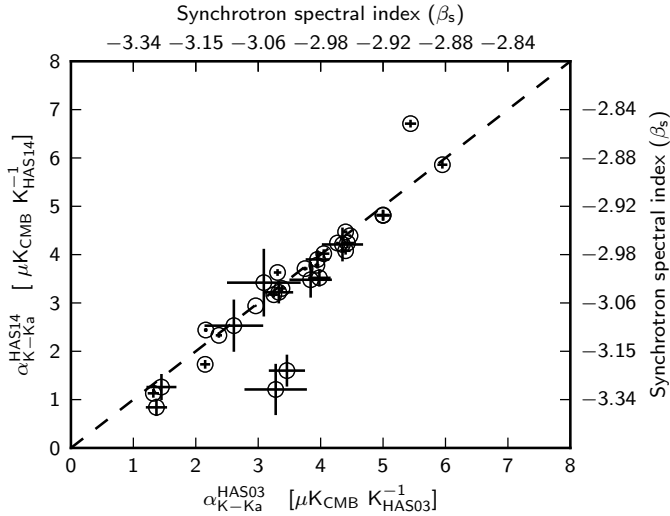


Figure 16. The correlation plot between the synchrotron coefficients derived using the K–Ka map, in thermodynamic units, with the two 408 MHz templates (HAS03 and HAS14). Here the uncertainties on each synchrotron coefficient comes from the uncorrelated instrumental noise present in K- and Ka- bands. A given coefficient is written as $\alpha_{K-Ka}^{\text{template}}$, where template refers to the specific synchrotron template used.

ial due to the large correlated error bars introduced by the CMB emission and the presence of the CMB chance correlation term. Here we present an approach to circumvent these problems and derive β_s for each of the sky regions.

We remove the CMB emission directly at the map level by taking the difference between the K- and Ka- bands in thermodynamic units. We choose to work with the K–Ka map as it has the highest signal-to-noise ratio in terms of the synchrotron emission. We apply the template-fit analysis on this K–Ka map in a similar fashion as discussed before. We add quadratically the instrumental noise coming from the K- and Ka- bands and include it in the noise covariance matrix. In this way, we remove the contribution of the correlated CMB uncertainty as well as the CMB chance-correlation term. The correlation plot between the synchrotron coefficients using K–Ka map with the use of HAS03 and HAS14 templates is shown in Fig. 16. The error bars on the plot come from the instrumental noise contribution of the K- and Ka- bands. Most of the sky regions return consistent fit coefficients (or β_s values) using the two Haslam templates, except sky regions 9, 27, and 28, in which the HAS03 template still shows a large area of either unrecovered or imperfectly removed extra-galactic radio sources. In general, the use of HAS14 template on average returns slightly lower synchrotron coefficients for the K–Ka map as compared to the HAS03 template. In terms of the template-fit analysis, both the Haslam templates provides similar synchrotron spectral indices at 1° resolution. Reassuringly, the change of the 408 MHz template does not significantly affect the dust or free-free coefficients.

4.4 Calibration and fidelity of the Haslam map

The calibration of the Haslam map is not very well understood. Furthermore, the map is often used without any knowledge of some of the issues related to calibration, such as the zero-level, overall temperature scale, and full-beam to main-beam calibration. Here we briefly describe our current understanding of these issues.

The 408 MHz Haslam et al. (1982) map has a quoted zero-level uncertainty of ± 3 K. This is a significant uncertainty given that high latitude areas have typical brightness temperatures of tens of K (the minimum temperature is 11.4 K). The definition of the zero-level in this case includes the contribution of the CMB ($T_{\text{CMB}} = 2.73$ K). A recent analysis by Wehus et al. (2014) have re-estimated the zero-level in conjunction with a foreground model fitted to WMAP/Planck and Reich et al. (2001) 1420 MHz maps, and determined a map monopole of 8.9 ± 1.3 K, which would include CMB and any other isotropic component (Galactic or extragalactic). However, this result is somewhat dependent on the foreground model and the data being fitted. We therefore leave the zero-level untouched, with a minimum temperature on the map of 11.4 K.

The absolute calibration uncertainty is often quoted as $\pm 10\%$, based on the scatter of correlation slopes between the 408 MHz data and the absolutely calibrated survey of Pauliny-Toth & Shakeshaft (1962). However, careful reading of the individual surveys suggests that the overall calibration scale is better than this ($\sim 5\%$). The major calibration uncertainty comes from the fact that the brightness temperature scale is not constant as a function of angular scale. This occurs because there is significant power outside the main beam (in the sidelobes), which means that there is more sensitivity to large angular scale emission (full beam calibration) while point-like sources are only sensitive to the main beam (main beam calibration); see Jonas et al. (1998) for a clear description and example of this effect. For some telescopes this can be as much as a $\sim 50\%$ correction (Reich & Reich 1986) with more typical values of $\sim 30\%$ (Jonas et al. 1998). Very carefully designed and under-illuminated telescopes can reduce this to $\sim 10\%$ (Holler et al. 2013). For the Haslam et al. (1982) data these information do not seem to be readily available. Haslam et al. (1974) discuss a full-beam to main-beam factor of 1.05 up to a radius of 5° . However, this is unlikely to be the case (it is too small). Since the calibration is based on the comparison of a large area survey (Pauliny-Toth & Shakeshaft 1962) the calibration is expected to be on the “full-beam” scale, where this is somewhat arbitrarily defined. This is the (approximately) correct scale for studying diffuse synchrotron emission. For studying point sources such as external galaxies, the brightness is likely to be under-estimated.

5 CONCLUSIONS

The 408 MHz all-sky map of Haslam et al. (1982) is one of the most important radio surveys to-date. We have re-evaluated and quantified its properties in detail. The positional accuracy is found to be good to ≈ 7 arcmin. The effective beamwidth FWHM is estimated to be 56.0 ± 1.0 arcmin on average, significantly larger than the claimed value of

51 arcmin. This is presumably due to the processing and gridding of the data into a pixelised sky map.

We have re-processed the rawest data available to produce an improved version of the Haslam map (HAS14). We have reduced the effect of scanning artefacts, visible as striations in Declination, using a Fourier-based filtering technique. The amplitude of the striations have been reduced by a factor of ≈ 5 .

The most important improvement over the widely-used HAS03 version is in the removal of extragalactic sources. This map contains obvious artefacts around bright sources, which add small-scale power to the map. We used a combination of Gaussian fitting and inpainting techniques to remove the brightest (> 2 Jy) from the map. The results are visually appealing and we estimate that we have removed the majority of sources above 2 Jy at high Galactic latitudes.

We have made our new and improved Haslam HAS14 map publicly available¹². This new map will be useful for detailed studies of the Galactic synchrotron radiation, CMB component separation and HI intensity mapping experiments. A limitation of the Haslam map is the relatively low angular resolution ($\sim 1^\circ$) which is not good enough for high resolution CMB and intensity mapping experiments. For simulation work, we have also produced a map at higher resolution, by artificially adding small-scale fluctuations. We assume a power-law for the angular power spectrum for the synchrotron emission and extrapolate this to the pixel scale, in this case $\text{HEALPix } N_{\text{side}} = 2048$ (≈ 1.7 arcmin).

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¹² The new Haslam maps can be downloaded from http://lambda.gsfc.nasa.gov/product/foreground/2014_haslam_408_info.cfm or alternatively, http://www.jb.man.ac.uk/research/cosmos/haslam_map/. A bit mask of the removed extra-galactic sources is also released.

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