



PowellSnakes II: a fast Bayesian approach to discrete object detection in multi-frequency astronomical data sets

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ABSTRACT

PowellSnakes (PwS) is a Bayesian algorithm for detecting compact objects embedded in a diffuse background, and was selected and successfully employed by the *Planck* consortium in the production of its first public deliverable: the Early Release Compact Source Catalogue (ERCSC). We present the critical foundations and main directions of further development of PwS, which extend it in terms of formal correctness and the optimal use of all the available information in a consistent unified framework, where no distinction is made between point sources (unresolved objects), Sunyaev–Zel’dovich (SZ) clusters, single- or multi-channel detection. An emphasis is placed on the necessity of a multi-frequency, multi-model detection algorithm in order to achieve optimality.

Key words: methods: data analysis – cosmology: observations.

1 INTRODUCTION

The detection and characterization of discrete objects is a common problem in many areas of astrophysics and cosmology. Indeed, every data reduction process must resort to some form of compact object detection, since either the objects themselves are the goal of the study or they act as contaminants and therefore must be removed. In such analyses, the key step usually involves the separation of a localized object signal from a diffuse background, defined as all contributions to the image aside from the objects of interest.

A well-established method to address this issue is to assume that most of the pixels are part of the background exclusively¹, the background is smoothly varying, i.e. has a characteristic length scale much larger than that of the objects of interest and the objects are bright compared with the background. A successful example of an object detection algorithm based on these assumptions is SExtractor (Bertin & Arnouts 1996). Its first step is to estimate the image background. The algorithm builds up an intensity histogram iteratively and clips it around its median. The resulting mesh (resembling a ‘swiss-cheese’) is then bilinearly interpolated to fill in the holes. After this background has been subtracted, the detection and characterization of the objects is performed either by looking for sets of connected pixels above a given threshold or by boosting the image maxima with the help of an ‘on-the-fly’ convolution using a pre-defined kernel or the beam point spread function (PSF). Despite their general acceptance, such methods run into difficul-

ties when the characteristic extent of the fluctuations of the diffuse background matches the size and the amplitudes of the objects of interest. Moreover, problems also arise when dealing with low or very low signal-to-noise ratio (SNR) data, when the rms level of the background is comparable to, or even somewhat larger than, the amplitude of the localized objects of interest. A good example of this situation is the detection of the Sunyaev–Zel’dovich (Sunyaev & Zeldovich 1972) (SZ) effect in galaxy clusters, which have characteristic scales similar to that of the primordial CMB emission, and at the same time are very faint and extended. In such cases, traditional methods fail to provide a statistically supported prediction about the uncertainties on the parameter estimates.

The standard approach for dealing with such difficulties is to employ linear filtering, which is an extremely well-developed field, very firmly rooted in the principles of the orthodox school of statistics and signal processing (Van Trees 2001). These methods usually start by applying a linear filter $\psi(x)$ to the original image $d(x)$, and instead analyse the resulting filtered field. The filter is most often constructed by assuming a given (possibly parametrized) spatial template, $\tau(x)$, for the objects of interest. Depending on the application, this profile may contain parameters (to be estimated) and already include the beam spreading effects. The common design goals for the filter follow the traditional, orthodox figures of merit: unbiasedness and efficiency. The optimal solution under these constraints is well known to be the matched filter (MF; North 1943). One may consider the filtering process as optimally boosting (in a linear sense) the signal from discrete objects, while simultaneously suppressing the emission from the background. The filtering methodology has yet another major advantage of being extremely fast and very simple to implement using ‘off-the-shelf’ routines

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¹This is possible only if the fields are not very densely packed with objects.

(such as Fast Fourier Transforms (FFTs)). The uncertainties in the parameter estimates are usually obtained from simulations. In practice, however, implementations of the filtering codes must be supported by ancillary steps in order to cope with the artefacts introduced as a consequence of the statistical description of the detection process being incomplete (Melin, Bartlett & Delabrouille 2006; López-Caniego et al. 2007).

A natural evolution of the MF, the matched multi-filter (MMF), follows exactly the same underlying principles and extends them to multi-channel data sets (Herranz et al. 2002a; Herranz & Sanz 2008; Lanz et al. 2010, 2011). The simultaneous multi-frequency analysis of a set of images has the immediate advantage of exploiting the objects' distinctive spectral signature, if any. Two further advantages of this technique are: (i) it boosts the signal from the objects of interest simply by adding more data; and (ii) it improves the elimination of the background components by taking advantage of their correlation between channels. Once again, the thermal SZ effect embedded in primordial CMB emission provides a very good example. Owing to the well-defined and unique frequency dependence of the SZ effect, it is possible to design a filter that combines multi-frequency maps to make possible the extraction of deep catalogues even if the SZ component is sub-dominant in all the channels (Planck Collaboration et al. 2011b).

Further development of traditional filtering techniques includes the ‘scale-adaptive filter’ (SAF; Sanz, Herranz & Martínez-González 2001; Herranz et al. 2002b), in which the physical scale of the objects of interest is added as an extra degree of freedom and an additional condition for optimality is added in the derivation of the filter. Schäfer & Bartelmann (2007) generalized the SAF to the spherical topologies and added multi-channel support.

A very popular member of the filter family is the wavelets group, in particular the Mexican-hat (MexHat) wavelet family. Indeed, the MexHat wavelet of the order of 1 is the MF or the SAF solution under particular assumptions about the statistical properties of the background and the objects profile (Sanz et al. 2001). Since such conditions hold very well in modern cosmological data sets, such as those obtained from *Wilkinson Microwave Anisotropy Probe* (WMAP) (Bennett et al. 2003) or *Planck*, and the simplicity of the function allows easy and robust engineering, the MexHat wavelet family has been the favourite detection tool of many authors (González-Nuevo et al. 2006; López-Caniego et al. 2006). Nonetheless, obtaining good characterization of the catalogues with the MexHat filter is extremely dependent on the value of the acceptance/rejection threshold. The only way to ensure optimal performance is to run the code on realistic simulations and then assess the code's yield against the simulation's input catalogue, but a large number of runs are needed to fine-tune the threshold value. Exactly the same procedure must be followed to determine the uncertainties on the parameter estimates. This may not seem a severe limitation, since immense computing resources are now cheaply available. Given the increased level of accuracy and complexity of current cosmological data sets, however, simulations must be rather sophisticated to provide a realistic test bed, and so even the enormous computational resources available are not sufficient to cope with the massive throughput demanded. For example, a single realistic *Planck* simulation (FFP) takes about one full week to run on a very large cluster and to have reasonable estimates of the parameter uncertainties and detection thresholds, at least several hundred independent simulations are needed.

To overcome these limitations of linear filtering methods, Hobson & McLachlan (2003) introduced a detection algorithm based on a Bayesian approach. As with the filtering techniques, the method assumed a parametrized form for the objects of inter-

est, but the optimal values of these parameters, and their associated uncertainties, were obtained in a single step by evaluating their full posterior distribution. Another major advantage of this method is the consistent inclusion of physical priors on the parameters defining the objects and on the number of objects present, which improve the detection efficiency. Although this approach represented a further step in the direction of bringing a more solid statistical foundation to the object detection/characterization problem, its implementation was conducted using a Monte Carlo Markov chain (MCMC) algorithm to sample from a very complex posterior distribution with variable dimensionality (dependent on the number of objects). This technique therefore proved extremely computationally intensive. Despite the considerable progress that has recently been made towards increasing the efficiency of sampling-based Bayesian object detection methods (Feroz & Hobson 2008), such algorithms are still substantially slower than simple linear filtering methods. In a recent work, Argüeso et al. (2011) suggested a semi-analytical hybrid Bayesian *maximum a posteriori* (MAP) scheme to overcome the complexity and the massive resources required for the Hobson & McLachlan method. However, the method still relies on the MF to find the sources' positions, and this procedure is not integrated within a fully Bayesian approach for calculating the evidence. Meanwhile, Carvalho et al. (2009) and Feroz, Hobson & Bridges (2009) have moved one step further towards the theoretically optimal Bayesian solution by exploring the use of evidence ratio methods, which are the optimal decision-making tools (see section 2.2), rather than simply adopting the MAP solution.

Our proposal here is to blend detection strategies, i.e. multi-channel filtering, Bayesian posterior sampling and evidence ratio evaluation, into a rigorous, hybrid, multi-model scheme (as opposed to traditional binary models). This novel methodology is simultaneously general, formally and statistically firmly grounded, and overcomes the computation inefficiencies of the pure sampling methodologies.

The structure of this paper is as follows. In Section 2, we give an overview of Laplace–Bayes probability theory and its close relationship with decision theory (DT) as a consistent inference and decision-making device. Our data model and the different constituents of the Bayesian framework, namely the likelihood and priors, are discussed in Section 3, and in Section 4 we bring together these elements and recommend an implementation strategy based on the exploration of the properties and symmetries of the posterior manifold. We also identify problems that may arise and suggest effective ways of tackling them using the Bayesian formalism. Finally we present our conclusions and directions for future work in Section 6.

2 BAYESIAN INFERENCE

2.1 Basic tools

The Bayesian system of inference is the only one that provides a consistent extension of deductive logic($\{0 = \text{false}, 1 = \text{true}\}$) to a broader class of ‘degrees-of-belief’ by mapping them into the real interval $[0, 1]$ (Jaynes 2003, ch. 1,2). Combining the multiplication rule together with the associativity and commutativity properties of the logical product, one may write the equation which will give us the posterior probability of a set of parameters (Θ) taking into account the data (d) and the underlining hypothesis (H). This equation is also known as Bayes theorem

$$\Pr(\Theta | d, H) = \frac{\Pr(d | \Theta, H) \Pr(\Theta | H)}{\Pr(d | H)}, \quad (1)$$

where, for brevity, we denote $\Pr(\Theta | \mathbf{d}, H) \equiv P(\Theta)$ as the posterior probability distribution of the parameters, $\Pr(\mathbf{d} | \Theta, H) \equiv \mathcal{L}(\Theta)$ as the likelihood, $\Pr(\Theta | H) \equiv \pi(\Theta)$ as the prior and $\Pr(\mathbf{d} | H) \equiv \mathcal{Z}$ as the Bayesian evidence. The (unnormalized) posterior distribution is the complete inference of the parameter values Θ , and thus plays the central role in Bayesian parameter estimation.

The normalized posterior distribution may be easily obtained by integrating over all possible values of the parameters and equating the resulting expression to unity, and from this argument one can easily see that the evidence is given by

$$\mathcal{Z} \equiv \Pr(\mathbf{d} | H) = \int \mathcal{L}(\Theta) \pi(\Theta) d^K \Theta, \quad (2)$$

where K is the dimensionality of the parameter space. Inspecting this expression, one immediately recognizes that the evidence is the expectation of the likelihood over the prior, and hence is central to Bayesian model selection between different hypothesis H_i . We note that the evidence evaluation requires the prior to be properly normalized.

2.2 Decision theory

Probability theory defines only a state of knowledge: the posterior probabilities. There is nothing in probability theory *per se* that determines how to make decisions based on these probabilities. Indeed, a range of actions are always possible, even when using the same state of knowledge, because the cost of making a wrong decision usually changes according to the kind of problem under analysis. For example, in the case of object detection, one often considers each type of error, i.e. an undetected object or a spurious detection, as equally bad. For a moment, however, suppose we instead wished to determine whether or not a certain person was immune to a certain pathogen. Failing to detect a previously acquired immunity would only cost the price of an extra vaccine, but failing to determine that someone was not immune could seriously put her/his life at risk. Thus, even with the same degree of knowledge, the cost of choosing incorrectly is not the same in every case. To deal with such difficulties, one must apply decision theory, which we now summarize briefly.

To apply DT, one must first define the *loss/cost function* $L(\mathbf{D}, \mathbf{E})$ for the problem at hand, where \mathbf{D} is the set of possible decisions and \mathbf{E} is the set of true values of the entities one is attempting to infer. In general, these entities can be either continuous parameters or discrete hypotheses, and so DT can be applied equally well to both parameter estimation and model selection. The loss function simply maps the ‘mistakes’ in our estimations/selections, \mathbf{D} , into positive real values $L(\mathbf{D}, \mathbf{E})$, thereby defining the penalty one incurs when making wrong judgments. The Bayesian approach to DT is simply to minimize, with respect to \mathbf{D} , the expected loss

$$\langle L(\mathbf{D}, \mathbf{E}) \rangle = \iint L(\mathbf{D}, \mathbf{E}) \Pr(\mathbf{D}, \mathbf{E}) d\mathbf{D} d\mathbf{E}. \quad (3)$$

2.2.1 Parameter estimation

In the estimation of a set of continuous parameters,² the ‘decisions’ \mathbf{D} are the parameter estimates $\hat{\Theta}$ and the ‘entities’ \mathbf{E} are the true

² In astronomical object detection, the majority of the interesting parameters (amplitude, position, geometry, etc.) are continuous and real valued. Moreover, discrete parameters can always be handled within the same framework by resorting to delta Dirac functions.

values Θ^* of the parameters. Typically, the loss function is taken to be a function of the difference, or error, $\epsilon \equiv \hat{\Theta} - \Theta^*$.

Some popular choices of loss functions are: (i) the square error ϵ^2 ; (ii) the absolute error $|\epsilon|$ and (iii) the uniform cost inside error bar, i.e. unity if $|\epsilon| > \Delta$ and zero if $|\epsilon| < \Delta$, where Δ is some pre-defined small quantity. In each case, one can easily find the optimal estimator by minimizing the expected loss (3) with respect to $\hat{\Theta}$. The solutions are, respectively: (i) the posterior mean; (ii) the posterior median and (iii) the posterior mode.³

The most popular choice of loss function among the astronomical community is the square error ϵ^2 . When detecting astronomical objects, however, the requirements are usually not those of the square error function, which puts an extreme emphasis on values very far from the true ones. This extreme sensitivity to the outliers makes the posterior mean estimator less robust than, for example, the posterior median, which is much more resilient to outliers. An even better choice would be not to penalize the estimates at all if they fall within a small neighbourhood Δ around the true parameter values and prescribe a constant penalty otherwise. This is precisely the ‘uniform cost inside error bar’ loss function described above. This loss criterion closely matches what we would intuitively expect when assessing the quality of a detection algorithm. For example, if the estimated value of a source flux lies outside the allowed range it does not matter how far it lies from the true value, since it will always be counted as a spurious detection (Planck Collaboration et al. 2011a).

2.2.2 Interval estimation

In addition to an estimate $\hat{\Theta}$, one typically summarizes the inference implied by the full posterior distribution by quoting either joint or marginalized confidence intervals (or, more precisely, Bayesian credible intervals). One could, in principle, obtain an optimal interval by employing an appropriate loss function, but a simpler approach is now widely accepted, namely the high probability density (HPD) interval. The HPD interval containing the fraction $(1 - \alpha)$ of the total probability is defined such that: $\Pr(\Theta \in \text{HPD} | \mathbf{d}, H) = 1 - \alpha$ and, if $\Theta_1 \in \text{HPD}$ and $\Theta_2 \notin \text{HPD}$, then $\Pr(\Theta_1 | \mathbf{d}, H) \geq \Pr(\Theta_2 | \mathbf{d}, H)$.

The characterization of the HPD interval may be easily obtained by sampling from the posterior distribution. When the posterior distribution is known to be Gaussian or close to it, which is a very common case, the $\pm \text{rms}$ interval is usually quoted instead.

2.2.3 Model selection and catalogue making

In model selection, the DT ‘entities’ \mathbf{E} are the hypotheses under consideration and the ‘decisions’ \mathbf{D} are the chosen hypotheses, such that $L(D_i, H_j) \equiv L_{ij}$ is the loss associated with the decision $D_i \equiv \text{choose } H_i$, when H_j is true. Thus, inserting this form for the loss matrix into the right-hand side of equation (3) and performing the integration using the delta Dirac functions to represent discrete values as infinite densities, the average loss reads

$$\langle L(\mathbf{D}, \mathbf{H}) \rangle = \sum_{ij} L_{ij} \Pr(D_i, H_j). \quad (4)$$

³ The posterior mean is the Bayesian optimal estimator under a very broad class of reasonable loss functions. When the posterior distribution is Gaussian all three common estimators match, and the posterior mode is often the simplest to compute. Nonetheless, if the parameter space is, in practice, discrete (e.g. pixelization), the posterior mean might provide a hyper-resolution estimate (sub-pixel accuracy).

If, for example, one is interested in distinguishing between a null hypothesis H_0 and a given alternative hypothesis H_1 from amongst a wider collection, then typically the loss function has the form

$$L_{ij} = \begin{cases} 0 & \text{if } i = j \text{ (no penalty if correct)} \\ \text{positive value} & \text{if } i = 1, j \neq i \text{ (false positive)} \\ \text{positive value} & \text{if } j = 1, i \neq j \text{ (false negative)} \\ 0 & \text{otherwise (alternative selection error).} \end{cases} \quad (5)$$

Minimizing (4) is not a difficult task (Van Trees 2001), but the general case above leads to long and cumbersome expressions that we shall not explore now. This particular loss arrangement makes it possible to restate the problem as the ratio of the posterior probability of a hypothesis, against its complement (Jaynes 2003, ch. 3),

$$\ln \left[\frac{\Pr(H_j | \mathbf{d})}{\Pr(\widetilde{H}_j | \mathbf{d})} \right]_{\widetilde{H}_j}^{\widetilde{H}_j} \gtrless \xi, \quad (6)$$

where choosing \widetilde{H}_j means leaving the putative detection out of the targeted catalogue and $\xi \equiv \ln \frac{L_{\text{spurious}}}{L_{\text{miss}}}$ is the \ln ratio of the losses when accepting a false positive (spurious) and when missing a source (see Section 4.5). If the same loss matrix template applies equally well to any source population, then by iterating through all object hypotheses, using the above formula, we can ‘classify’ them, i.e. assign each individual source to a catalogue. In the case an object appears in more than one catalogue, choose the one where the left-hand side of (6) is larger.

Much simpler and enlightening, but still capable of a very broad and interesting range of practical applications, is the binary case consisting of just two hypotheses H_0 and H_1 . In this case, the decision criterion that minimizes the expected loss is

$$\ln \left[\frac{\Pr(H_1 | \mathbf{d})}{\Pr(H_0 | \mathbf{d})} \right]_{H_0}^{H_1} \gtrless \xi \quad (7)$$

where $\xi \equiv \ln \frac{L_{10}}{L_{01}}$. The ‘posterior odds’ ratio

$$\frac{\Pr(H_1 | \mathbf{d})}{\Pr(H_0 | \mathbf{d})} = \frac{\mathcal{Z}_1}{\mathcal{Z}_0} \frac{\Pr(H_1)}{\Pr(H_0)} \quad (8)$$

gives the posterior probabilities of the models given the data and is a very commonly used quantity in the Bayesian model selection. Indeed, Jaynes asserts that the best way to decide between two models is by computing the posterior odds and compare it against a threshold. Using DT we have recovered this result and, at the same time, given it a precise statistical meaning and also defined a threshold for decision making based on the loss criterion.

Unfortunately, in astronomy it is often not possible to assign meaningful values to the loss. In particular, in object detection and catalogue making, astronomers like instead to measure the quality of a catalogue in terms of the expected/maximum contamination (false positive rate) and the expected/minimum completeness (true positive rate). There is, of course, a connection between this approach and DT, but quantifying it is not trivial. Nonetheless, there is a very simple and powerful way to define the acceptance/rejection threshold in the Bayesian catalogue making, based on the probabilities of the different errors that might occur (i.e. spurious or missed detections), but we shall postpone its discussion until Section 4.

Before moving on, it is worth mentioning that, if one ignores the (often crucially important; (Riley, Hobson & Bence 2006, ch. 30, p. 1132)) factor $\Pr(H_1)/\Pr(H_0)$ in (8), the remaining evidence ratio $\mathcal{Z}_1/\mathcal{Z}_0$ depends only on the data and can thus be viewed as an orthodox statistic. As such, the properties of its sampling distribution can be investigated using standard frequentist tools, such as the

‘power’ (true positive rate) $\Pr(D_1 | H_1)$ and the ‘type I error rate’ (false positive rate) $\Pr(D_1 | H_0)$ (Jenkins & Peacock 2011). Such analyses overlook, however, that the evidence ratio is the optimal decision rule. The only degree of freedom remaining is the choice of a threshold, which determines whether it is preferable to have fewer (more) detections at the cost of good (poor) rejection; there is no way of decreasing both error rates simultaneously because the evidence ratio is already the most discriminating statistic. The claim by Jenkins & Peacock (2011) that the evidence ratio test is not ‘powerful’ results from them fixing the threshold in an arbitrary way; it is this threshold that controls the balance between different error rates, and not the statistic itself. A better way of measuring the quality of a binary classifier based on some statistic is to allow the threshold to vary and plot the resulting true positive rate against the false positive rate. This produces the receiver operating characteristic (ROC) curve of the classifier. A common measure of classifier quality is the Area Under the ROC-Curve (the AUC statistic), which obviously does not rely on choosing a single threshold. One may show that the AUC is equal to the probability that the classifier will rank a randomly chosen data set generated from H_1 higher than a randomly chosen data set generated from H_0 .

3 BAYESIAN OBJECT DETECTION

3.1 Data model

The specification of the PowellSnakes (PwS) statistical model for a single-frequency observation of localized objects embedded in a background is given in Carvalho et al. (2009). This can be straightforwardly extended to accommodate multi-frequency observations. At each observing frequency ν , PwS treats the observed data $d_\nu(\mathbf{x})$, where \mathbf{x} is the position vector in pixel space, as the superposition of a ‘generalized’ noise background $n'_\nu(\mathbf{x}) = b_\nu(\mathbf{x}) + n_\nu(\mathbf{x})$, consisting of background sky emission [$b_\nu(\mathbf{x})$] and instrumental noise [$n_\nu(\mathbf{x})$], plus a characteristic signal [$s_\nu(\mathbf{x})$] coming from the sources. For ease of notation, we will collect the fields at different frequencies into vectors. Moreover, the signal and background components in each frequency channel are assumed to have been smoothed with a known beam, which may differ between channels. The resulting model for the data vector $\mathbf{d}(\mathbf{x})$ reads

$$\mathbf{d}(\mathbf{x}) = \sum_{j=1}^{N_s} s_j(\mathbf{x}; \Theta_j) + \mathbf{b}(\mathbf{x}) + \mathbf{n}(\mathbf{x}), \quad (9)$$

where N_s is the number of sources, $s_j(\mathbf{x}; \Theta_j)$ is the signal vector due to the j th source, which depends on the parameter vector Θ_j characterizing the object, $\mathbf{b}(\mathbf{x})$ is the signal vector due to the diffuse astronomical backgrounds and $\mathbf{n}(\mathbf{x})$ is the instrumental noise vector. The astronomical backgrounds denoted by $\mathbf{b}(\mathbf{x})$ are expected to exhibit strong correlations between different frequency channels, whereas the instrumental noise $\mathbf{n}(\mathbf{x})$ is expected to be uncorrelated between frequency channels, and also between pixels in the case of simple white noise.⁴

We write the signal vector due to the j th source in (9) as

$$s_j(\mathbf{x}; \Theta_j) = A_j f(\phi_j) \tau(\mathbf{x} - X_j; \mathbf{a}_j), \quad (10)$$

⁴ The condition of the instrumental noise being white is not necessary. The general case of correlated noise between pixels does not complicate the mathematical development, but can increase computational expense. In any case, the assumption of white noise applies extremely well to *Planck* data on the small scales of interest used for the identification of localized objects.

where the vector $\tau(\mathbf{x} - \mathbf{X}_j; \mathbf{a}_j)$ denotes the convolved spatial template at each frequency of a source centred at the position \mathbf{X}_j and characterized by the shape parameter vector \mathbf{a}_j , the vector \mathbf{f} contains the emission coefficients at each frequency, which depend on the emission law parameter vector $\boldsymbol{\phi}_j$ of the source (see below), and A_j is an overall amplitude for the source at some chosen reference frequency. Thus, the parameters to be determined for the j th source are its overall amplitude, position, shape parameters and emission law parameters, which we denote collectively by $\boldsymbol{\Theta}_j = \{A_j, \mathbf{X}_j, \mathbf{a}_j, \boldsymbol{\phi}_j\}$. The totality of these parameters, for all the sources present, plus the number of sources N_s , is concatenated into the single parameter vector $\boldsymbol{\Theta}$. For convenience, we denote the signal vector generated by all the sources by

$$\mathbf{s}(\mathbf{x}; \boldsymbol{\Theta}) \equiv \sum_{j=1}^{N_s} \mathbf{s}_j(\mathbf{x}; \boldsymbol{\Theta}_j). \quad (11)$$

The nature of the emission law parameter vector $\boldsymbol{\phi}$ depends on the class of object under consideration. PwS analyses the data assuming that all the objects belong to a single class, and repeats the analysis for each class of interest. The assignment of individual sources to a particular class is then performed via a model selection step (see Section 4.5). The number and specification of classes can be arbitrary, including, for example, SZ clusters, point sources, Galactic objects, etc. Previous multi-frequency versions of PwS have been limited to the case where all objects share the same, fixed emission law. SZ clusters fall exactly in this category as, ignoring the relativistic corrections, they all follow exactly the same spectral signature (Birkinshaw 1999), which does not depend on any parameters. For extragalactic point sources, however, the emission law is phenomenological and can vary between sources. Consequently, PwSII has been extended to accommodate such cases. For example, two important families of extragalactic point sources in *Planck* data are as follows.

(i) Radio sources are the dominant family of point sources for all *Planck* channels up to and including 217 GHz. Based on the work of Waldram et al. (2007) and Planck Collaboration et al. (2011c), we assume an emission law for such objects of the form

$$\ln f_\nu = \alpha \ln \left(\frac{\nu}{\nu_0} \right) + \beta \left[\ln \left(\frac{\nu}{\nu_0} \right) \right]^2, \quad (12)$$

where $\boldsymbol{\phi} = \{\alpha, \beta\}$ are spectral parameters that can vary between sources, and ν_0 is the reference frequency (note that $f_\nu = 1$ at $\nu = \nu_0$). Setting $\beta = 0$ recovers the commonly assumed power-law spectral behaviour with spectral index α . The more general form (12) accommodates most of the common types of radio-source spectra, namely: flat, steep and inverted.

(ii) Dusty galaxies dominate the *Planck* highest frequency channels, starting at 217 GHz up to 857 GHz. Their spectral behaviour may be represented to very good accuracy using the well-known greybody model

$$\ln f_\nu = \beta \ln \left(\frac{\nu}{\nu_0} \right) + \ln \left[\frac{B_\nu(T)}{B_{\nu_0}(T)} \right], \quad (13)$$

where the spectral parameters $\boldsymbol{\phi} = \{\beta, T\}$ are the dust emissivity and temperature, respectively, $B_\nu(T)$ is the Planck law of blackbody radiation and ν_0 is once again the reference frequency (Serjeant & Harrison 2005). We have again normalized (13) such that $f_\nu = 1$ at $\nu = \nu_0$.

(iii) New/unexpected sources can be easily accommodated inside the current framework by allowing the emission coefficient f_{ν_i} at each frequency to be a free parameter $\mathbf{f} = [f_{\nu_1}, \dots, f_{\nu_n}]^t$. Such a

spectral energy distribution (SED) model is certainly more generally applicable because it contains the other two models. This ‘generic’ model may be used with great advantage to prevent data artefacts being mistaken for a genuine source, although it may be disfavoured by the evidence because of its larger number of parameters (see Section 4.5).

3.2 Likelihood

The form of the likelihood is determined by the statistical properties of the generalized noise (background sky emission plus instrumental noise) in each frequency channel. As in PwS, we will perform our analysis in sufficiently small patches of sky such that it is not unreasonable to assume statistical homogeneity. In this case, it is more convenient to work in Fourier space, since there are no correlations between the Fourier modes of the generalized noise, which leads to considerable savings in computation and storage. Moreover, we will assume that both the background emission and instrumental noise are Gaussian random fields. This is a very accurate assumption for instrumental noise and the primordial CMB, but more questionable for Galactic emission.

We are, in fact, interested only in the likelihood ratio between the hypothesis H_s that objects (of a given source type s) are present and the null hypothesis H_0 that there are no such objects. The latter corresponds to setting the sources signal $\mathbf{s}(\mathbf{x}; \boldsymbol{\Theta})$ to zero. Under our combined assumptions, the log-likelihood ratio has the form

$$\ln \left[\frac{\mathcal{L}_{H_s}(\boldsymbol{\Theta})}{\mathcal{L}_{H_0}(\boldsymbol{\Theta})} \right] = \sum_{\eta} \tilde{\mathbf{d}}^t(\eta) \mathcal{N}^{-1}(\eta) \tilde{\mathbf{s}}(\eta; \boldsymbol{\Theta}) - \frac{1}{2} \sum_{\eta} \tilde{\mathbf{s}}^t(\eta; \boldsymbol{\Theta}) \mathcal{N}^{-1}(\eta) \tilde{\mathbf{s}}(\eta; \boldsymbol{\Theta}), \quad (14)$$

where the tilde denotes a Fourier transform, the usual mode wavenumber $\mathbf{k} = 2\pi\eta$, and the matrix $\mathcal{N}(\eta)$ contains the generalized noise cross-power spectra.

From (10) and (11), the Fourier transform of the signal due to all the sources may be written as

$$\tilde{\mathbf{s}}(\eta; \boldsymbol{\Theta}) = \tilde{\mathbf{B}}(\eta) \sum_{j=1}^{N_s} A_j \mathbf{f}(\boldsymbol{\phi}_j) \tilde{\tau}(-\eta; \mathbf{a}_j) e^{i2\pi\eta \cdot \mathbf{X}_j}, \quad (15)$$

where the vector $\tilde{\mathbf{B}}(\eta)$ contains the Fourier transform of the beam at each frequency and $\tilde{\tau}(\eta; \mathbf{a})$ is the Fourier transform of the template for an unconvolved object at the origin, characterized by the shape parameters \mathbf{a} .

Substituting (15) into (14) and rearranging, one obtains the final form for the likelihood ratio, which we will use throughout, namely

$$\begin{aligned} \ln \left[\frac{\mathcal{L}_{H_s}(\boldsymbol{\Theta})}{\mathcal{L}_{H_0}(\boldsymbol{\Theta})} \right] &= \sum_j^{N_s} \left\{ A_j \mathcal{F}^{-1} [\mathcal{P}_j(\eta) \tilde{\tau}(-\eta; \mathbf{a}_j)]_{X_j} \right. \\ &\quad \left. - \frac{1}{2} A_j^2 \sum_{\eta} \mathcal{Q}_{jj}(\eta) |\tilde{\tau}(\eta; \mathbf{a}_j)|^2 \right\} \\ &\quad - \sum_{i>j}^{N_s} \left\{ A_i A_j \mathcal{F}^{-1} [\mathcal{Q}_{ij}(\eta) \tilde{\tau}(\eta; \mathbf{a}_i) \tilde{\tau}(-\eta; \mathbf{a}_j)]_{X_i - X_j} \right\}, \end{aligned} \quad (16)$$

where $\mathcal{F}^{-1}[\dots]_x$ denotes the inverse Fourier transform of the quantity in brackets, evaluated at the point x , and we have

defined the quantities $\mathcal{P}_j(\boldsymbol{\eta}) \equiv \tilde{\mathbf{d}}^t(\boldsymbol{\eta})\mathcal{N}^{-1}(\boldsymbol{\eta})\boldsymbol{\psi}(\boldsymbol{\eta})$ and $\mathcal{Q}_{ij}(\boldsymbol{\eta}) \equiv \tilde{\boldsymbol{\psi}}_i^t(\boldsymbol{\eta})\mathcal{N}^{-1}(\boldsymbol{\eta})\boldsymbol{\psi}_j(\boldsymbol{\eta})$, in which the vector $\boldsymbol{\psi}_i(\boldsymbol{\eta})$ has the components $(\boldsymbol{\psi}_i)_v = \tilde{B}_v(\boldsymbol{\eta})(f_i)_v$, with v labelling frequency channels.

We have written the likelihood ratio in this way since it combines multi-channel data into a single equivalent channel. Moreover, it highlights the importance of the final ‘cross-term’ on the right-hand side of (16). Let us assume for a moment that this cross-term is negligible. In this case, the parameters of each source enter the likelihood independently. This parameter independence allows us to perform our analysis one source at a time and forms the basis of the ‘single source model’ discussed in Section 4.1, which greatly simplifies the source detection problem. The physical meaning of the neglected cross-term is most easily understood by considering the simple, but important, example of point sources, for which $\tau(\mathbf{x}, \mathbf{a}) = \delta(\mathbf{x})$. In this case, the cross-term in (16) becomes

$$\sum_{i>j} A_i A_j \mathcal{F}^{-1}[\mathcal{Q}_{ij}(\boldsymbol{\eta})]_{X_i - X_j}. \quad (17)$$

A sufficient condition for this expression being small is that all the sources are sufficiently well-separated that $\mathcal{F}^{-1}[\mathcal{Q}_{ij}(\boldsymbol{\eta})]_x$ is close to zero for such distances. For simple, uncorrelated backgrounds, $\mathcal{Q}_{ij}(\boldsymbol{\eta})$ contains just linear combinations of the instrument beams in each frequency channel. Thus, the condition that (17) is small is just a generalization of the common assumption in astronomy that objects are well separated, or that object blending effects are negligible.⁵ When detecting point sources, and assuming the blending is not severe, an efficient implementation of the full deblending term is possible, but this will be addressed in a forthcoming publication.

It is worth noting that maximizing the likelihood ratio (16), in the absence of the cross-term (17), with respect to the source amplitudes A_j , gives

$$\hat{A}_j = \frac{\mathcal{F}^{-1} [\mathcal{P}_j(\boldsymbol{\eta}) \tilde{\tau}(-\boldsymbol{\eta}; \hat{\mathbf{a}}_k)]_{\hat{X}_j}}{\sum_{\eta} \mathcal{Q}_{jj}(\boldsymbol{\eta}) |\tilde{\tau}(\boldsymbol{\eta}; \hat{\mathbf{a}}_j)|^2}, \quad (18)$$

which recovers the expression for the MMF (Herranz et al. 2002a). Thus, we see that the filtered field is merely the projection of the likelihood manifold on to the sub-space of position parameters X_j . This identification further allows one straightforwardly to estimate the uncertainties on all the MMF parameter estimates simultaneously by calculating and inverting the Hessian matrix of the likelihood at its peak(s). This should be contrasted with traditional approaches to MMF in which the uncertainty on the estimated source flux is calculated assuming the values of all other parameters are fixed (Melin et al. 2006).

Moreover, substituting the maximum-likelihood (ML) estimate (18) into expression (16) for the likelihood ratio, one obtains for the j th object

$$\max \left[\ln \left(\frac{\mathcal{L}_{H_s}}{\mathcal{L}_{H_0}} \right) \right] = \frac{1}{2} \sum_{\eta} \mathcal{Q}_{jj}(\boldsymbol{\eta}) |\tilde{\tau}(\boldsymbol{\eta}; \hat{\mathbf{a}}_j)|^2 \hat{A}_j^2 = \frac{1}{2} \widehat{\text{SNR}}_j^2 \quad (19)$$

where $\widehat{\text{SNR}}_j$ is the SNR (at the peak) of the j th source, and the rms σ of the noise satisfies

$$\frac{1}{\sigma^2} = \sum_{\eta} \mathcal{Q}_{jj}(\boldsymbol{\eta}) |\tilde{\tau}(\boldsymbol{\eta}; \hat{\mathbf{a}}_j)|^2. \quad (20)$$

⁵ When the background is uncorrelated, this condition is immediately fulfilled if each pixel contains signal coming from one and only one source. However, this is not the case when there are strong correlations in the background as in the case of *Planck*.

Thus, one sees that in the traditional approach to catalogue making, in which one compares the maximum SNR of the putative detections to some threshold, one is really performing a generalized likelihood ratio test.

3.3 Priors

If the data model provides a good description of the observed data and the SNR is high, then the likelihood will be very strongly peaked around the true parameter values and the prior will have little or no influence on the posterior distribution. At the faint end of the source population, when we are getting close to the instrument sensitivity limit, however, priors will inevitably play an important role. Moreover, since for most cases in astronomy the faint tail overwhelmingly dominates the population, the selection of the priors becomes important and has to be addressed very carefully.

PwSII separates the tasks of source detection (deciding whether a certain signal is due to a source) and source estimation (determining the parameters of the source). This separation has the advantage of allowing the use of different sets of priors at each stage. Typically, we first perform the source detection step using ‘informative’ priors, which encompass all the available information, since they provide the optimal selection criterion and the optimal estimators. After the set of detections has been decided, PwS proceeds to the estimation pass, in which ‘non-informative’ priors may be used instead.

Non-informative priors are constructed such that the MAP estimator of any quantity should depend exclusively on the data.⁶ One way of expressing this condition is that, when changing the data, the likelihood shape remains unchanged and only its location in the parameter space changes (Box & Tiao 1992). Thus, the idea is to find an appropriate re-parametrization of the likelihood that transforms the parameters into location parameters, for which the ignorance prior is locally uniform (locally, in this sense, means the parameter range where the mass of the likelihood is concentrated). One then performs the inverse parametrization transformation on the uniform prior to obtain the appropriate prior in the original parametrization. Finding such a transformation can, however, be very difficult for a general multi-dimensional prior.

Nonetheless, in a large majority of applications, the parameters may be assumed independent, so that the prior factorizes

$$\pi(\theta_1, \theta_2, \dots, \theta_n) = \pi_1(\theta_1)\pi_2(\theta_2) \cdots \pi_n(\theta_n). \quad (21)$$

For one-dimensional distributions, Jeffreys devised a general way to derive the non-informative prior on a parameter based on invariance properties of the likelihood under a change of variable. The Jeffreys rule for constructing ignorance priors for the one-dimensional case reads

$$\pi(\theta) \propto \mathcal{J}^{1/2}(\theta), \quad (22)$$

where

$$\mathcal{J}(\theta) \equiv - \left\langle \frac{\partial^2 \ln \mathcal{L}(\theta)}{\partial \theta^2} \right\rangle \quad (23)$$

is the Fisher information. We will adopt this approach and now consider the prior on each parameter of interest.

⁶ These priors usually need not be properly normalized, since one wishes only to locate the maximum of the posterior distribution and the normalization does not depend on any parameters.

3.3.1 Prior on positions

It is obvious that the distribution of sources is not uniform across the sky. The Galactic regions (Milky Way and Magellanic Clouds) have a much higher density of detectable sources than the rest of the sky. Moreover, assuming extragalactic sources to be uniformly distributed across the sky (no clustering) is not sufficient to ensure that the distribution of detectable sources is uniform, since the background/noise is itself inhomogeneous over the sky.

Nonetheless, PwS divides the sky into small patches and, in each such region, the assumptions of background homogeneity and a uniform source distribution are reasonable. Moreover, if the sky patches used are sufficiently small, our locally uniform model can easily cope with clustering when the gradient of the density of sources is small across the patch boundaries. The correctly normalized positions prior for the complete ensemble of sources in a patch is simply

$$\Pr(X^{N_s} | N_s, N_{\text{pix}}) = \frac{1}{N_{\text{pix}}^{N_s}}, \quad (24)$$

where N_{pix} is the number of pixels in each patch and N_s is the number of sources in that patch.⁷

3.3.2 Prior on the number of sources

Following the same rationale of local uniformity, i.e. no clustering, the probability of finding N_s objects (above a given flux limit) in a sky patch follows a Poisson distribution

$$\pi(N_s) = \Pr(N_s | \lambda) = e^{-\lambda} \frac{\lambda^{N_s}}{N_s!}, \quad (25)$$

where λ is the expected number of such objects in that region. Moreover, λ should be proportional to the region size $\lambda = \Lambda_s N_{\text{pix}} \Delta_p$, where Λ_s is the number of sources per pixel and Δ_p is the pixel area. Note that Λ_s may change across the sky as we are only enforcing the uniformity locally within each patch.

3.3.3 Prior on flux

A good flux estimator should be unbiased, but this goal is often problematic. The optimal estimators in the sense of DT, i.e. those that minimize the expected loss/cost, are most often biased and they combine the data with external information from ancillary data sets. PwSII thus includes two different sets of flux priors with distinct goals.

(i) *Non-informative*. Our data model depends linearly on the source fluxes A_j and is a particular case of the general linear model (Box & Tiao 1992). Considering only a single source for simplicity (the solution for multiple sources is a mere repetition of this simpler case.), one may show that the likelihood can be written in a form that makes it clear that the flux is in fact a location parameter:

$$\mathcal{L}_{H_s}(A_j) \propto \exp \left[-\frac{\sum_i Q_{ji}(\eta) |\tilde{\tau}(\eta; \hat{a}_i)|^2}{2} (A_j - \hat{A}_j)^2 \right], \quad (26)$$

where \hat{A}_j is the MMF estimate of the flux (18). The same result could have been obtained directly using formula (22). Thus, the prior on the flux must be locally uniform:

$$\pi(A_j) \propto c, \quad (27)$$

⁷ The patch is just the atom of a more general region of statistical homogeneity, the ‘homogeneous zone’ (see Section 4.1).

where j indexes the source. For a more general and rigorous treatment, see Box & Tiao (1992).

(ii) *Informative*. Owing to the different statistical properties of point sources and SZ galaxy clusters, a different prior applies in each case. For point sources, we adopt the flux prior first suggested by Argüeso et al. (2011),

$$\pi(A_j) = \Pr(A_j | A_0 p \gamma) \propto \left[1 + \left(\frac{A_j}{A_0} \right)^p \right]^{-\frac{\gamma}{p}}, \quad (28)$$

where A_0 is the ‘knee’ flux, p is some positive number and γ is the exponent controlling the shape of the power law for fluxes much larger than the ‘knee’. This provides a good model for the observed distribution of fluxes, fitting the de Zotti model almost perfectly (de Zotti et al. 2005). Moreover, the distribution can be properly normalized as required for evidence evaluation. PwS truncates the distribution faint tail and re-normalizes the remaining range as a result of the early selection effect (see Section 3.3.6), a practice the proponents of the distribution also followed. For galaxy clusters, the derivation of the prior follows a different approach. The *Planck* Sky Model (PSM v1.6) (Delabrouille et al. 2012) was used to draw realistic simulations of the cluster populations assuming a standard *WMAP* best-fitting cold dark matter cosmology (Hinshaw et al. 2009) and the Jenkins mass function (Jenkins et al. 2001). We found that the fluxes in the sample cluster catalogues were quite well fitted by a power law:

$$\pi(A_j) \propto A_j^{-\gamma}. \quad (29)$$

To deal with the early selection threshold and to provide a properly normalized distribution, once again a minimum and, this time, a maximum flux also were assumed.

3.3.4 Prior on size

(i) *Point sources*. Point sources are best modelled by imposing the prior $\pi(r) = \delta(r)$ on the ‘radius’. This condition might, however, be too restrictive, since to simplify the implementation of the code and to make it faster, PwS assumes the instrument beams are circularly symmetric, which is only an approximation to the true beam shapes. Thus, even for point sources, allowing the source radius to vary over a small range of values allows a better fit between the template and the pixel intensities and consequently a higher likelihood ratio/SNR value. Thus, in both the informative and non-informative cases, our preferred radius prior for point sources is

$$\pi(r_j) = \begin{cases} 1/\Delta & r_j \leq \Delta \\ 0 & r_j > \Delta \end{cases}, \quad (30)$$

where $\Delta \ll \text{FWHM}$ (the full width half-maximum of the beam).

(ii) *Galaxy clusters*. Turning to galaxy clusters, a significant fraction of the clusters *Planck* will detect will be unresolved, and thus appear as point sources with a distinctive spectral signature. In many cases, however, galaxy clusters are large enough to be mapped as extended objects and a parameter controlling the scale of the cluster profile, the radius, needs to be included. The informative prior on the radius was derived using the same procedure as in Section 3.3.3 and an exponential law

$$\pi(r_j) \propto \exp \left(-\frac{r_j}{\ell} \right) \quad (31)$$

was found to fit the simulated catalogues very well. We truncate the distribution outside a minimum and maximum radius.

The non-informative prior follows a different law from that expected from the cosmological models. Our model for an individual

source is the convolution of the source profile with the beam PSF. The radius parameter r'_s that scales the resulting shape is a ‘hybrid’ parameter, as it shifts and scales the likelihood at the same time (Jaynes 2003, ch. 12). After applying the Jeffreys rule, the non-informative prior on r'_s reads

$$\pi(r'_s) \propto \frac{1}{r'_s^2}. \quad (32)$$

Assuming that either the profile or the beam has centroids at the origin and the profile is a scaling profile $\tau(r/r_s)$ then

$$r'_s = \sqrt{B^2 + \kappa^2 r^2}, \quad (33)$$

where B^2 is a constant known as the function variance of the beam (Bracewell 1965) and κ^2 is another dimensionless constant, the variance of the dimensionless variable r/r_s over the profile. The non-informative prior for the radius parameter then reads:

$$\pi(r) \propto \frac{r}{(\mathcal{B}^2 + r^2)^{\frac{3}{2}}}, \quad (34)$$

where $\mathcal{B} = B/\kappa$. For the general case B^2 , the variance of the beam, should be replaced by the variance of $\sqrt{\mathcal{P}_j(\eta)}$. For unresolved objects, narrow clusters with radii smaller than the beam size, the prior grows linearly with r . For well resolved objects, $r \gg \mathcal{B}$, the prior decreases proportionally to r^{-2} .

3.3.5 Prior on spectral parameters

There is an extensive literature on the distribution laws of radio-source spectral indexes: de Zotti et al. (2010) (Planck Collaboration et al. 2011c,d). In general, Gaussian distributions, or Gaussian mixtures with two modes, fit the available data reasonably well. However, the most interesting sources are exactly those that do not follow the canonical laws of emission. To avoid narrowing the range of possible alternatives too much, uniform priors are probably better choices unless we choose to target a very specific family. The same holds for dusty galaxies.

By applying our standard procedure, the non-informative prior on the spectral parameters reads

$$\pi(\alpha_j) \propto \sqrt{\sum_v \left(\frac{\partial S_v(\phi)}{\partial \alpha_j} \right)^2}, \quad (35)$$

where $S_v(\alpha_j)$ is the SED of the source as a function of the parameters and the sum extends over all frequency channels.

3.3.6 Prior on the models

The prior ratio $\Pr(H_1)/\Pr(H_0)$ on the models is often neglected (i.e. assumed to equal unity), but plays a very important role in the PwS detection criterion. To give a proper account of its nature, let us imagine the simplest possible detection problem, where we know in advance all the true values of the parameters that define an object, which translates into delta-function priors. Substituting this condition into (7) and making use of (19), we obtain the following inequality:

$$\text{SNR} \stackrel{H_1}{\gtrless} \sqrt{2 \left[\xi + \ln \left(\frac{\Pr(H_0)}{\Pr(H_1)} \right) \right]}. \quad (36)$$

One may interpret the term $\ln(\Pr(H_0)/\Pr(H_1))$ as an extra ‘barrier’ added to the detection threshold because we are expecting more fake objects than the objects of interest, due to background fluctuations.

We saw earlier that, when an object is present, a local maximum in the likelihood is always present in the position parameter sub-space. This condition immediately implies that only likelihood maxima need be analysed. Nonetheless, one expects other likelihood maxima to occur as a result of background fluctuation ‘conspiracies’. Assuming Poisson statistics for the number of sources and the number of likelihood maxima resulting from the background fluctuations, then the ratio of the probabilities is given by

$$\frac{\Pr(H_1 | N_s)}{\Pr(H_0 | N_s)} = \left(\frac{\lambda_1}{\lambda_0} \right)^{N_s}, \quad (37)$$

where λ_0 is the expected number of maxima per unit area resulting from background fluctuations above the minimum limit of detection of the experiment, and λ_1 the expected number density of sources above the same limit.

If only background is present, the density of maxima, λ_0 , resulting from the filtering procedure that creates the likelihood manifold can be estimated using the 2D Rice formula:

$$n_b(v, \kappa, \epsilon) = \frac{8\sqrt{3}\tilde{n}_b}{\pi\sqrt{1-\rho^2}} \epsilon(\kappa^2 - 4\epsilon^2) e^{-\frac{1}{2}v^2 - 4\epsilon^2 - \frac{(\kappa-\rho v)^2}{2(1-\rho^2)}}, \quad (38)$$

where $v \equiv A/\sigma$ is the ‘normalized peak amplitude’, κ the ‘normalized curvature’, ϵ the ‘normalized shear’, and $\rho = \sigma_1^2/(\sigma_1\sigma_2)$, with $\sigma_n^2 = (2\pi)^{1+2n} \int_0^\infty \eta^{1+2n} |\mathcal{P}(\eta)|^2 d\eta$ (Lopez-Caniego et al. 2005). Marginalizing over all parameters we obtain the expected density of maxima of a Gaussian filtered field, which reads

$$\tilde{n}_b = \frac{\sigma_2^2}{8\pi\sqrt{3}\sigma_1^2}. \quad (39)$$

One is not interested, however, in all peaks, but only in those above a certain level v_0 , since PwS pre-selects the putative detections by imposing a minimum SNR level before attempting the evidence evaluation. The main reason for adopting this early selection is computational efficiency. The SNR alone provides a good proxy (see formula 19) for deciding whether a candidate peak is the result of the presence of a source or just a background fluctuation. Moreover, low SNR peaks tend to be ‘badly shaped’, making the sampler very inefficient and resulting in a very large fraction of the samples being rejected. To make the things even worse, in most cases, these peaks themselves end up being rejected as objects.

The applied flux cut must be taken into consideration to evaluate the correct expected number counts, which define the prior $\Pr(H_1)$ as well. Thus, λ_0 will read:

$$\lambda_0 = \int_{v_0}^{\infty} n_b(v) dv, \quad (40)$$

where $n_b(v)$ is given by

$$n_b(v) = \frac{\tilde{n}_b \sqrt{6}}{2\sqrt{\pi}\rho_1} \left\{ \left(1 + \operatorname{erf} \left(\frac{\rho}{\rho_1\rho_2} v \right) \right) e^{-v^2 \left(\frac{1}{2} + \left(\frac{\rho}{\rho_2} \right)^2 \right)} \left(\frac{\rho}{\rho_2} \right) \right. \\ \left. + \left(1 + \operatorname{erf} \left(\frac{\rho}{\rho_1} v \right) \right) e^{-\frac{v^2}{2}(v^2 - 1)\rho^2\rho_1^2} \right\} \\ + \frac{v e^{-v^2 \left(\frac{1}{2} + \left(\frac{\rho}{\rho_1} \right)^2 \right)}}{\sqrt{\pi}} \rho\rho_1^2 \left\} , \quad (41)$$

where $\rho_1 = \sqrt{2(1-\rho^2)}$ and $\rho_2 = \sqrt{2(\frac{3}{2}-\rho^2)}$. The expected number count of targeted objects above a certain flux threshold S , $\lambda_1 \equiv \langle N(>S) \rangle$, may be easily derived from their differential counts.

Now a distinction must be made because the dominant type of extragalactic point sources in *Planck* maps are galaxies which, in principle, do not follow the same statistics as the galaxy clusters. From general cosmological assumptions it is possible to derive that the expected differential counts for a certain population type of galaxies per flux interval at a certain frequency always follow a power law: $dN_\phi/dS = A_\phi S^{-b}$ (de Zotti et al. 2005). For clusters of galaxies, however, one must instead use a realistic set of simulations, such as the ‘*Planck Sky Model*’ (PSM v1.6) (Delabrouille et al. 2012). Using a properly normalized mass function (Jenkins et al. 2001), one finds that a power law also fits quite well the expect number counts of clusters above a certain threshold. So, in either case, point sources or clusters, λ_1 may be written as

$$\lambda_1 = N(>S_0) = \int_{S_0}^{\infty} \frac{dN_\phi}{dS} dS = A_\phi (1-b)^{-1} S_0^{1-b}, \quad b \neq 1, \quad (42)$$

where we keep the parameters $\{A_\phi, b\}$ free. These parameters are usually provided by the user to target a specific type of object and/or instrumental setup.

4 OBJECT DETECTION STRATEGY

So far, we have only developed the logic and probabilistic underpinnings of PwS. It is now time to bring all the pieces together into a consistent strategy for the detection and characterization of discrete objects. Our aim is to construct a robust, controlled and predictable algorithm. Some caveats will be identified and solutions suggested, always justified within the framework presented above.

4.1 The single object approach

Let us return to formula (7). At a first look, the evaluation of (7) seems quite a daunting task. In order to apply the full Bayesian approach, many complex integrals, over a very high dimensional volume (at least $4 \times N_s$), need to be evaluated.⁸ Clearly a brute force method is not efficient and perhaps not possible, even with the massive computing resources generally available.

To find an effective solution, we begin by making two important assumptions: (i) the objects of interest are ‘well separated’, so that (17) holds; and (ii) all variables pertaining to each individual source are mutually independent, which has already been implicitly assumed throughout the exposition of our inferencial infrastructure.

These conditions allow us to separate the integrals associated with each source. This is a very important simplification because it is now possible to deal with each source independently, one at a time. This is the ‘single object approach’ (Hobson & McLachlan 2003) and replaces a single $N_{\text{param}} \times N_s$ -dimensional integral with a sequence of N_s integrals, each of dimension N_{param} .

The complete likelihood expression may now be replaced by the much simpler ‘single source’ form. However, we should exercise some care in defining the limits of integration in position space, since no significant likelihood mass can be shared among position integration domains. Apparently, this requirement creates such a wealth of complexity to the integral evaluation that the single source approach might at first be considered a poor choice. Fortunately, the method PwS uses to evaluate the evidence integrals automatically enforces this rule if the fields are not too crowded (see section 4.2).

⁸ Even when working with one small patch at a time, N_s is seldom smaller than 4.

Under our assumptions, the odds of the model H_1 (for a given source type), given N_s such sources, reads

$$\frac{\Pr(H_1 | \mathbf{d}, N_s)}{\Pr(H_0 | \mathbf{d}, N_s)} = (N_{\text{pix}} \Delta_p)^{-N_s} e^{-\lambda_1} \frac{\lambda_1^{N_s}}{N_s!} \left(\frac{\lambda_1}{\lambda_0} \right)^{N_s} \prod_{j=1}^{N_s} \mathcal{Z}_{1j}, \quad (43)$$

where we have defined the ‘partial evidence’ for each individual source as

$$\mathcal{Z}_{1j} \equiv \int \frac{\mathcal{L}_1(\Theta_j)}{\mathcal{L}_0} \pi(\Theta_j) d\Theta_j. \quad (44)$$

Taking logarithms and rearranging, one finds

$$\ln \left[\frac{\Pr(H_1 | \mathbf{d}, N_s)}{\Pr(H_0 | \mathbf{d}, N_s)} \right] = \sum_{j=1}^{N_s} \ln(\mathcal{Z}_{1j}) - N_s P_s, \quad (45)$$

where we have defined the ‘penalty per source’ P_s as

$$P_s \equiv \ln \Lambda_s^{-1} + \ln \left(\frac{\lambda_0}{\lambda_1} \right) + \frac{1}{N_s} [\lambda_1 + \ln N_s!]. \quad (46)$$

Thus, the total $\ln(\text{odds})$ for a single patch is the sum of the partial $\ln(\text{evidence})$ for each source, plus an extra global penalty term that contributes, in the majority of the cases, negatively to the final balance and does not depend on any particular source, but exclusively on the ensemble properties. Let us further define a new entity which will soon prove very helpful, the ‘homogeneous zone’. A homogenous zone is an arbitrary ensemble of patches across which all statistical properties of the data and the object models may be assumed approximately invariant. The homogeneous zones should be appropriately sized to keep the expected number of sources (λ) on each mostly invariant.⁹ The most robust source catalogue is that which maximizes the $\ln(\text{odds})$ in (45), but we do not know the value N_s . Moreover, we have not yet addressed how many or which candidate detections will be finally selected for inclusion in the catalogue. Nonetheless, expression (45) is a sum, so its maximum value is reached when only the positive terms are included. Thus, one possible procedure to select the optimal set of sources is as follows:

- (i) evaluate \mathcal{Z}_j for each source;
- (ii) partition the candidate detections into the pre-defined homogenous zones. For each zone:
 - (a) sort the candidate detections in descending order of \mathcal{Z} and number them ($j = 1 \dots$);
 - (b) with N_s , iterate down the list of catalogue lines evaluating formula (45);
 - (c) stop when moving from $N_s = k$ to its successor ($N_s = k + 1$) makes expression (45) decrease.
 - (d) This means, \widehat{N}_s (the value of N_s that maximizes the evidence ratio) has been found and the ‘proto-catalogue’ is formed from the first k lines.

This quantity, the $\ln(\text{odds})$ for each object

$$\ln(\text{odds})_j \equiv \ln \left[\frac{\Pr(H_1 | \mathbf{d})}{\Pr(H_0 | \mathbf{d})} \right]_j = \ln(\mathcal{Z}_{1j}) - \widehat{P}_s, \quad (47)$$

(\widehat{P}_s is the penalty per source evaluated at \widehat{N}_s or the catalogue penalty per source), has a pivotal role in catalogue making (see Section 4.6).

We are not finished yet, however, because we have only selected the set of detections that maximizes the odds. Other constraints

⁹ Denser regions should be made smaller than sparsely populated ones. An homogeneous zone may contain from one single patch (the ‘area atom’) to the full set.

may yet apply. For instance, we may impose a threshold per line different from zero as a result of the loss criteria or, as we shall see, a prescribed contamination for the catalogue.

4.2 Evaluation of the odds ratio

Even using the simplified form of the likelihood assumed in the single-object approach, a ‘brute force’ evaluation of the resulting evidence integrals is still not feasible. One must instead use a Monte Carlo approach to the numerical integration. Evidence integrals are usually evaluated using MCMC methods and thermodynamic integration. Such methods can fail, however, when the posterior distribution is very complex, possessing multiple narrow modes¹⁰ that are widely separated. We therefore instead use ‘nested sampling’ (Sivia & Skilling 2006), which is much more efficient, although not without its difficulties. Feroz et al. (2009) have developed a very efficient implementation of the nested sampling algorithm, called ‘MultiNest’, which is capable of exploring high-dimensional multi-modal posteriors. Nonetheless, MultiNest is designed to be a general sampling and evidence evaluation tool and it is not particularly tuned for *Planck*.

In the interest of speed, PwS instead tries to take full advantage of the properties of the astronomical data sets. As already stated (see Section 3.3), if our model explains the data well then the likelihood should peak steeply around the parameter true values, decay very rapidly to zero and have most of its mass concentrated around the maxima vicinities. Thus, if one can first find the likelihood maxima, then one does not need a sophisticated multi-modal sampling algorithm like MultiNest. A much simpler nested sampling scheme such as that mentioned in Mukherjee, Parkinson & Liddle (2006) would perform equally well. Moreover, reasonably high SNR¹¹ maxima develop ‘well-shaped’ peaks, in the sense they are close to Gaussian, rendering the sampling highly efficient. Two other significant advantages are: (i) we can reduce our data set to a small neighbourhood enclosing the maxima, so that only a very small number of pixels close to the maxima contribute appreciably to the evidence value; and (ii) a much reduced parameter volume allows the same number of ‘live points’ to deliver a considerably higher accuracy on the evidence value, since they do not split among the several posterior peaks. This is the approach adopted in PwS, which we now outline in more detail.

4.2.1 Locating the likelihood maxima

Our first goal is to find the likelihood maxima. For illustration, let us focus on the example of galaxy clusters, each of which is described by four parameters: $\{X, Y, S, R\}$. An efficient four-dimensional minimizer implementation is straightforward and immediately available (Press, Teukolsky & Vetterling 2007). However, our manifold has many maxima and we need to check all of them, otherwise we might lose some sources.

One possibility would be to follow the approach used in PwS I, where the Brent line minimizer was ‘enhanced’ with an ancillary step to allow it to ‘tunnel’ from one minimum to the next one using a scheme closely related with the equivalent quantum mechanical effect. To increase the effectiveness of the procedure, PwS I started a Powell minimization chain (hence the name ‘PowellSnakes’) in

¹⁰ At least one central maximum per source plus other secondary maxima around the central higher peaks (Carvalho et al. 2009).

¹¹ SNR $\gtrsim 4.2$.

many different locations of the manifold in an attempt to find all the maxima. It should be remembered, however, that the likelihood only exhibits multiple maxima in the position sub-space; the other sub-spaces are ‘well behaved’. Moreover, the likelihood in the position sub-space is merely the MMF filtered field. We therefore instead use a brute force peak finding algorithm that scans all pixels in this sub-space, which is very easy to implement and almost instantaneous. Then, after collecting a list of peak positions, we start a four-dimensional PwS optimization at each such location to find the ML parameters for that particular peak.

Subtlety does arise in this approach, however, since to obtain the MMF filtered field, one needs to assume a size R for the objects to define the filter. Since we expect different clusters to have different radii, we might lose some peaks because of the mismatch between the true value of the cluster radius and that used in the filtering template. A simple solution would be that suggested by the MMF authors: apply the filter repeatedly using a different radius each time. Although practical, this is, however, not the most efficient approach. Fortunately, if the instrument beams and the sources possess reflection symmetries in both axes, then one can show that the Fisher matrix at each likelihood peak is block-diagonal [assuming the likelihood (16) and using the single-source approach assumption (17)], such that there is no correlation between the position sub-space and the other parameters (flux and size) of the cluster. This has two important consequences: (i) regardless of the radius used to construct the filter, a likelihood peak will always be present at the location source and its position will not change positions as the filter scale varies; (ii) we do not need to perform a full four-dimensional maximization but can (at least) separate the position variables from all others, which brings a tremendous simplification to the problem of finding the likelihood maxima. Thus, we can indeed start by finding the maxima in the position sub-space using a brute force ‘check-all-pixels’ approach and then, after pinpointing the position of the source, search the remaining sub-spaces associated with the other variables.

A couple of final comments on this approach are worth making. First, it is well known that MFs are excellent at finding and locating sources, but not as good at estimating fluxes. If the beam shape/size is not completely known but symmetric, even when building up a filter with the wrong beam geometry, the filter will correctly recover the positions of the objects. In general, however, the element in the Fisher matrix corresponding to the correlation between the radius and the flux of an object is non-zero. Therefore, if the filter is assembled using wrong beam parameters, bias in the flux estimates must be expected. Second, and perhaps more subtle, is that the symmetries of the Fisher matrix only hold on average. Thus, for each individual peak some residual correlation between the position and the other variables is expected. According to our current accumulated experience, however, this correlation is usually very small. Nonetheless, PwS still includes the option to use the peak positions obtained from the MMF filtered fields just as initial hints for a full N -dimensional Powell minimization.

4.2.2 Exploring the posterior distribution

Our initial step provides the ML estimates and the SNR of each detection candidates. This has a very useful side effect, since we do not need to explore the posterior distribution around all the maxima we find. Only a much smaller sub-set is chosen based on an SNR threshold. This SNR threshold should be low enough not to reject any substantial fraction of peaks associated with true detections and

high enough to make the selected sample contain a large percentage of true sources and to include most ‘well-shaped’ maxima. This shorter list is then sorted in descending order of SNR and one-by-one the maxima are sent to the nested sampler, which returns an evidence estimate and a set of weighted samples that we use to model the full joint posterior distribution. The final catalogue is almost completely independent of the SNR threshold if this is not too high.¹² From these samples we can compute any parameter estimate, draw joint distribution surfaces, predict HPD intervals of any content over the marginalized distributions to infer the parameter uncertainties, etc., as in the example presented in Planck Collaboration et al. (2011b, fig. 9). The current released implementation of PwS (v3.6) computes the ML, the expected value over the posterior estimates and 1σ error bars.¹³

4.3 Non-Gaussianity of the background

It is clear that our model of the observations, like any model, is only an approximation to the real data. This is true both for our model of the discrete objects and for our model of the background. For the latter, it is clear that the background emission in real observations is neither Gaussian nor statistically homogeneous. Regarding non-Gaussianity, we do not mean that of a primordial origin, which, if exists, would have an insignificant effect in our analysis. We are instead alluding to the non-Gaussianity induced by the Galactic emission components, the confusion noise created by the sources below the detection threshold, the instrumental noise artefacts coming from the incomplete removal of the cosmic ray glitches and, of course, a wealth of other possible sources.

Many authors simply ignore this issue and many others dismiss its importance. A very strong argument, used many times, is that despite the sky emission being admittedly non-Gaussian, the effect of the finite PSF of beams will combine many different sky locations into a single pixel. In addition, signal de-noising procedures further combine more samples. Some authors then appeal to the Central Limit Theorem (CLT) to claim that non-Gaussian effects in the final data must be completely negligible.

This argument seems particularly appealing, but a deeper analysis of the CLT shows that, in our particular problem, namely detection and separation of two signals, the effects of the CLT are not as important as those authors claim. Formally, the CLT only applies when $N \rightarrow \infty$, where N is the number of random deviates in the sum. For finite N , the CLT only guarantees the Gaussian approximation is good for ‘*a region around the mode*’ (Bouchaud & Potters 2009). The size of this Gaussian region grows very slowly. In the worst case, the distributions of the individual deviates are skewed and have ‘fat tails’. Let us focus on a real example: the Galactic emission. If the spectral brightness distribution follows a power law with a finite first moment, to guarantee the field has physical behaviour, the normalized central Gaussian region, $|u|$, only grows very slowly with N :

$$|u| \ll u_0 \propto \sqrt{\ln N}, \quad (48)$$

where u_0 is the tail lower boundary. This means that the sum must have more than 1000 terms to make the Gaussian approximation

¹² This initial selection by SNR thresholding is only applied on computation efficiency grounds. Very low SNR maxima take much longer to sample as the likelihood manifold peaks are not properly shaped and in the end most of the time end up being rejected.

¹³ The ML estimates from the maximization step are updated, if necessary, during the sampling phase.

acceptable up to about $|u| \sim 2.6$. In detection problems, where we want to separate the maxima created by the sources from the background fluctuations, we are dealing all the time with the background distribution upper tail:

$$\mathcal{P}_{\geq u_0} \equiv \int_{u_0}^{\infty} \Pr(u) du. \quad (49)$$

If the background field intensity distribution follows a power law: $\Pr(I_v) \propto I_v^{-\mu}$, with $\mu > 2$, to guarantee its energy is finite, then the probability that a sum of N deviates falls into the upper tail region of the sum normalized distribution is

$$\mathcal{P}_{\geq u_0} \propto \frac{1}{N^{\mu/2-1} \ln^{\mu/2} N}. \quad (50)$$

This is a very serious problem. Object detection methodologies are designed typically to suppress the background and amplify what does not fit its model. The non-Gaussianity component is not a part of our background model, so its effect on the detection process is doubly pernicious: not only it is not removed, it is amplified.

There seem to be only two ways of circumventing this problem: (i) to include the non-Gaussian effects in the statistical models; and (ii) to manipulate and add as much data as possible to make it more Gaussian. Owing to the complexity of *Planck* data it is almost impossible to give a proper account of the non-Gaussian effects without making the problem unsolvable. So, a workable solution must necessarily combine as much data as possible, and then analyse the outcome. The only possible way of doing this is to use multi-channel analysis all the time.

Our own experience corroborates this view. The SNR values of the PwS selected detections and the thresholds the frequentist methods normally employed ($\gtrsim 4.0$) are much higher than what would be expected according to the purity levels of the catalogues if the statistics were purely Gaussian. However the channels with the largest beams, where each pixel is the result of a much higher number of different contributions, do indeed have detection thresholds lower and closer to those expected from the Gaussian theory. A good practical example of how the multi-channel processing can help the reduction of the impact of the non-Gaussian distributions on the detection process is the recovery of the SZ signal (Melin et al. 2011).

Owing to the residual non-Gaussianity left in the background, especially close to the Galactic plane, we should now expect a higher number of background fluctuations reaching above the evidence threshold level than those predicted by the Gaussian model. So, eventually, we need to correct the prior on the models: $\frac{\Pr(H_1)}{\Pr(H_0)}$, as this prior was derived assuming that the background had purely Gaussian statistics. The simplest way, we believe, is just to count the total number of fluctuations above the SNR threshold adopted, before embarking on the evaluation of the evidence. In particular, one should compare this number with what would be expected from the Gaussian model plus the predicted source counts above the SNR threshold and then take the larger quantity. Denoting this value by T , a corrected estimate of λ_0 (see formula 37) would read

$$\lambda_0 \simeq T - \lambda_1. \quad (51)$$

This very simple ‘trick’ provides a first-order correction to the effects of background non-Gaussianity.

4.4 Statistical inhomogeneity of the background

Real observations will also inevitably exhibit some statistical inhomogeneity of the background, in contradiction to our assumed

model. Consequently, the conditions of optimality derived therefrom no longer hold. This can lead to a number of difficulties in detecting and characterizing discrete objects, particularly in regions of the sky that contain bright, very inhomogeneous and anisotropic backgrounds. Indeed, this general expectation has been borne out in applying earlier versions of PwS to detailed simulations of *Planck* observations (PSM v1.6) (Delabrouille et al. 2012). In particular, the presence of bright diffuse Galactic dust emission was found to lead to the PwS SZ catalogue (in common with catalogues produced by other methods, such as MMF) containing bright spurious detections. Hence one did not obtain a regular cumulative purity curve that slowly approaches unity as the $\ln(\text{evidence})$, or the SNR, increases (Melin et al. 2011), in contradiction to what would be expected from theory if our model explained the data properly.

Indeed, the detection of SZ galaxy clusters highlights further problems. Again in the analysis of *Planck* simulations using previous versions of PwS, one finds that bright spurious SZ signals are not only concentrated in complex background regions, with a fraction of the bright spurious detections spread all across the sky. By cross-correlating the resulting SZ catalogues with ancillary point source data sets, one finds that bright spurious cluster detections matched bright point source locations. In our preliminary attempts to address this problem, we therefore first performed a point source extraction step and subsequently subtracted/masked the best-fitting point source profiles in the maps. This pre-processing step greatly helped in reducing the number of spurious detections, especially those with very high evidence values. Another approach has been suggested by the *Planck* WG5 team, namely the ‘ χ^2 test’ (Planck Collaboration et al. 2011b). This performed very well, although, once more, there is no easy way to choose a robust acceptance/rejection threshold for the test. Another difficulty occurs when extracting the SZ effect at each individual channel. The SNR was usually so low that the measurements ended up being quite noisy.

Can we do any better using Bayesian logic? The apparent failure of the ‘best’ test can be immediately explained using the main Bayesian decision equation, equation (7). Our decision criterion is based on the $\ln(\text{odds})$, namely

$$\ln \left[\frac{\Pr(H_1 | \mathbf{d})}{\Pr(H_0 | \mathbf{d})} \right]. \quad (52)$$

The problem comes from the denominator $\Pr(H_0 | \mathbf{d})$. When we find a point source, its probability of being a cluster, $\Pr(H_1 | \mathbf{d})$, is very low, but the probability of those pixels being part of the background, $\Pr(H_0 | \mathbf{d})$, is also very low, because point sources do not fit our model of the background either. We have already mentioned that the binary model is too simple to handle realistic astronomical situations. To secure the optimality of our methodology we must ensure that the data are well described by our model, and employ a multi-model approach, as described in Section 4.5.

4.5 The solution: multi-model, multi-frequency detection

For the reasons outlined above, we believe that a deeper and purer catalogue can only be obtained through multi-frequency analysis. An excellent example of the power of such an approach is provided by the detection of SZ clusters. Despite the SZ signal being sub-dominant on all *Planck* channels (the signal level is below that of the background), an optimal combination of the different frequencies can boost these extremely faint signals to the point where one can now build reliable catalogues of many hundreds of such objects.

We have also demonstrated above that our simple binary decision making approach is too naïve to handle ‘real-life’ situations. The

introduction of a multi-model (more than two models) decision rule cannot, however, be achieved simply by extending the binary case (Jaynes 2003, ch. 3), although it is always possible to reduce the general multi-model decision rule to a succession of binary ones. We start by choosing one of the hypothesis, say $H_0 \equiv \text{‘this maximum is a background fluctuation’}$, and making it the ‘null’ or ‘reference hypothesis’. Then we iterate through all the hypotheses associated with different source families and compute the $\varrho_i \equiv \text{odds}_i$:

$$\varrho_i \equiv \frac{\Pr(H_i | \mathbf{d})}{\Pr(H_0 | \mathbf{d})}; \quad i \neq 0. \quad (53)$$

The optimal way of deciding between $M + 1$ different hypothesis (M source types plus the null hypothesis) is by evaluating the odds for each type of source against the null hypothesis, pick up the largest ϱ_i , which we denote by ϱ_{i^*} , and then check for the following inequality

$$\frac{\varrho_{i^*}}{1 + \sum_{i \neq i^*} \varrho_i} \stackrel{H_{i^*}}{\gtrless} \xi', \quad (54)$$

where $\xi' = L_{\text{spurious}}/L_{\text{miss}}$ is the ratio of the losses when accepting a false positive (spurious) and when missing a source. A source assigned to a wrong catalogue is a ‘spurious’ in that catalogue and at the same time a ‘miss’ in its true catalogue. This setup might be interpreted as a ‘classification engine’ since it selects a proposition among multiple choices. After running through all putative detections it will end up with as many catalogues as the initial contender hypothesis.¹⁴ Equation (54) defines the condition which minimizes the expected loss when the loss matrix reads

$$L_{ij} = \begin{cases} 0 & \text{if } i = j \text{ (no penalty if correct)} \\ L_{\text{miss}}(>0) & \text{if } i = 0, j \neq 0 \text{ (miss)} \\ L_{\text{spurious}}(>0) & \text{if } i \neq 0, j = 0 \text{ (spurious)} \\ L_{\text{miss}} + L_{\text{spurious}} & \text{if } i \neq 0, j \neq 0, i \neq j \text{ (spurious + miss).} \end{cases} \quad (55)$$

An important difference between the multiple option case (more than two options) and the binary case is that of the different role of the ‘null’ model in either case. In the binary case the ‘null’ catalogue will only contain those lines preferring it. However in the multiple option case if the preferred option cannot reach the desired acceptance/rejection level, the putative detection will be assigned to the ‘null’ even if this was not the most favoured.

Often real data present us with (mostly unwanted) surprises (see Section 4.4). That is when our generic model (see Section 3.1) is useful. It is there not only for the most exciting sources, those not falling in any of the known SED models, but also for the least interesting, the localized artefacts. Some might question whether this ‘safety net’ might on the contrary misguide us. Because the physical SED models are just a special case of the generic, what prevents our ‘decision machine’ not picking it even when one of the other models is present. The generic SED is necessarily more complex (has more adjustable parameters) than any of the physical ones.¹⁵ In theory the Bayesian evidence should account for this. Either the generic model fits the data much better (higher SNR) or owing to the enlarged prior volume of the parameter space, the generic model will be disfavoured.¹⁶ An important point to consider

¹⁴ Some of those catalogues might stay empty.

¹⁵ Otherwise the physical SED models would only be a re-parametrization of the generic.

¹⁶ For a very detailed and elegant exposition why this happens, please refer to Jaynes (2003, ch. 20) and Jeffreys (1961, ch. 5.2).

is the reliability of the source parameter estimates, especially when an object is classified as ‘something else’ or the chosen model is only marginally favoured over the set of competitors. Once again, the Bayesian methods provide a good safety net against possible bias in the estimates as result of mis-modelling. By inspecting the posterior probability distributions one may check whether the probability mass concentrates close to the boundaries of the priors, denoting they might have had a major impact on the estimates. In this case, as we are not completely sure about the correct description of the object’s data, the parameter estimates should always be read with some caution. A possible way of circumventing this problem is through a guided (non-blind) re-extraction of the source with an even more general model, for instance, by relaxing the priors of the preferred model in the case that a better data description is not yet available.

A pivotal quantity in catalogue making, as we shall shortly see, is the probability that a certain entry in the putative catalogue is a spurious detection: $\Pr(\widetilde{H}_{i^*} | D)$. Providing this value is a unique capability of the Bayesian approach. It is very simple to show that, when extending the binary test to multiple hypotheses, the probability of a spurious detection now reads:

$$\Pr(\widetilde{H}_{i^*} | \mathbf{d}) = \frac{1}{1 + \psi}, \quad \text{with } \psi \equiv \frac{\varrho_{i^*}}{1 + \zeta}, \quad \zeta \equiv \sum_{i \neq i^*} \varrho_i. \quad (56)$$

In some extreme cases, ‘complex regions’ (Small Large Magellanic Cloud, Large Magellanic Cloud, Orion, etc.) or the Galactic plane, for instance, the splitting into small patches is not enough to satisfy either the homogeneity of the background or the source number counts. Moreover, the background statistics deviate so much from the assumed model and/or source blending is so acute that the operation of the code may break and the results stop being reliable. In this case we apply a mask to those regions (see Appendix A). In our view, the exclusion of these regions has only very limited impact on the usefulness of PwS products especially when aiming at extragalactic science products (Planck Collaboration et al. 2011b,c,d). In the case of point sources, however, PwS can accommodate moderate source blending (no more than three sources per beam). In this case the ‘one source at a time’ approximation no longer holds. Thus, we have now to employ the full likelihood expression and expand the single source parameter space to the Cartesian product of the spaces of the individual sources we aim to de-blend. This extension of PwS will be addressed in a forthcoming publication.

4.6 Catalogue making

The last step of PwS is to assemble the final catalogue from a list of candidates. During this stage, PwS performs the following steps:

- (i) maps flat sky patches back on to the sphere at the positions of the putative detections;
- (ii) applies a detection mask, if any;
- (iii) merges multiple detections of the same source obtained in different patches into a single candidate detection; and
- (iv) makes the final catalogue by rejecting those lines that do not meet the pre-established criterion of purity or loss.

The last step is critical to the success of our methodology. We already gave some indication in Section 2.2.3 about how to address the difficult task of selecting a sub-set of detections from our initial list of candidates. If the selection criterion is based on losses, then we just need to trim the ‘proto-catalogue’ further by applying the decision rule (54). But, as we mentioned previously, it is much more common in astronomy to require a catalogue to have an expected

contamination ratio or that the contamination does not exceed a prescribed value. We are now finally in a position to show how the Bayesian logic framework can give us exactly that.

The number of false positives in a catalogue may be represented as a sum of Bernoulli variables. Assuming all catalogue entries are statistically independent, the sum of N of those variables is distributed as a Poisson-binomial distribution:

$$\mu = \sum_{i=1}^n p_i, \quad \sigma^2 = \sum_{i=1}^n p_i(1 - p_i), \quad (57)$$

where $p_i = \Pr_i(\widetilde{H}_{i^*} | \mathbf{d})$, is the probability of source i being a false positive.

Therefore, one way to proceed is as follows:

- (i) sort the list of candidate detections in $\ln(\text{odds})$ descending order (p_i ascending order);
- (ii) for each candidate, accumulate p_i until μ (see formula 57) exceeds the prescribed contamination $\alpha \equiv (\text{spurious detections})/(\text{total lines in catalogue})$ times the total number of lines already included; and
- (iii) discard the last line.

As μ is a sum of independent variables and N is usually a large number (hundreds), it is perfectly reasonable to assume that the distribution converges to a Gaussian as result of the CLT.¹⁷ So, a good estimate of the number of spurious detections in the catalogue is

$$\sum_{i=1}^N p_i \pm \sqrt{\sum_{i=1}^N p_i(1 - p_i)}, \quad (58)$$

and an estimate of the fraction of spurious detections in the catalogue, α , reads:

$$\left(\widehat{\alpha} = \frac{\sum_{i=1}^N p_i}{N} \right) \pm \frac{\sqrt{\sum_{i=1}^N p_i(1 - p_i)}}{N}. \quad (59)$$

A problem still remains, however, since our calculation of $\Pr_i(\widetilde{H}_{i^*} | D)$ is only an approximation, although we do have an estimate of the $\ln(\text{odds})$ evaluation uncertainty [for a rigorous treatment see Keeton (2011)]. We therefore need to introduce corrections into the above formulas to account for the uncertainty on p_i . It is easy to verify that, to a first approximation, the error on p_i , reads

$$|\Delta p_i| \simeq \gamma p_i(1 - p_i) \quad (60)$$

where the value of γ is the average evidence evaluation fractional error. The corrected value of the catalogue’s variance on the number of spurious, σ'^2 , is always less than

$$\sigma'^2 \lesssim (1 + \gamma) \sum_{i=1}^n p_i(1 - p_i), \quad (61)$$

and the variance on μ reads

$$|\Delta\mu|^2 \simeq \gamma^2 \sum_{i=1}^n p_i^2(1 - p_i)^2 < \gamma \sum_{i=1}^n p_i(1 - p_i). \quad (62)$$

Thus, we get the final expression of predicted contamination of the catalogue by adding both contributions in quadrature:

$$\left(\widehat{\alpha} = \frac{\sum_{i=1}^N p_i}{N} \right) \pm \frac{\sqrt{1 + 2\gamma} \sqrt{\sum_{i=1}^N p_i(1 - p_i)}}{N}. \quad (63)$$

¹⁷ Note this time we are working around the distribution mode.

The uncertainty on the contamination of the catalogue for commonly accepted levels (~ 10 per cent), catalogue size ($\gtrsim 1000$) and γ as large as 0.32, is always $\lesssim 1.2$ per cent.

Finally, we are now in position to answer the key question all the frequentist methods must at some point face, ‘*what threshold should one use for accepting the candidates for inclusion in the final catalogue?*’, although the question is no longer relevant in our Bayesian approach, since it is an output of our catalogue-making method, rather than an input. The answer is just “*the ln(odds) estimate of the last line of the final catalogue*”, since the initial list of putative detections was sorted in descending order of ln(odds) and all those with a higher or equal ln(odds), and only those, were selected for inclusion.

4.6.1 Estimation of the catalogue completeness

In the last section we devoted ourselves to the design of a catalogue with a prescribed ‘purity’.¹⁸ As important, however, is ‘completeness’, the percentage of objects above a certain amplitude/flux, present in our data that we successfully included in our catalogue. In DT language, $\Pr(D_j | H_j)$.¹⁹ Curiously, the purity of the catalogue may be represented just by swapping H_j with D_j , $\Pr(H_j | D_j)$. These quantities can be related using Bayes theorem, but the other quantities involved are difficult to define and quantify in a practical problem. Purity is intrinsically a Bayesian quantity, a posterior probability, by virtue of the decision, $D_j = D_j(\mathbf{d})$, being a function of the data only. Completeness is very closely related with the likelihood. Fortunately, point source detection can be accurately modelled by (i) a one-sided test, (ii) a distribution belonging to the exponential family (a Gaussian in our case) and (iii) a monotone likelihood ratio (Van Trees 2001). This set of conditions guarantees a ‘*Uniform Most Powerful*’ (UMP) test exists with significance, α and ‘Power’, P . Translating from the frequentist dialect into that of the astronomers, this means that one *single* SNR threshold is enough to assure a catalogue has a certain purity, α and completeness, P . Recalling the equivalence between Bayesian posterior probabilities, when using non-informative priors, and the equivalent sampling distributions from the orthodox theory (Box & Tiao 1992, ch. 2), we define a new variable

$$\hat{\zeta} = \frac{\hat{A} - A}{\sigma_A} \sim N(0, 1), \quad (64)$$

where A is the true value of the source amplitude, assumed non-random in this context, and σ_A is the variance of the random variable \hat{A} defined in (20). The $\hat{\zeta}$ statistic (frequentist dialect) is normally distributed (see equation 26). Now let us define $\gamma \sigma_A$ as the amplitude threshold for rejection/acceptance. So the completeness, $\Pr(D_j | H_j)$, reads

$$\int_{\gamma - \frac{A}{\sigma_A}}^{+\infty} N(0, 1) d\zeta = \frac{1 + \text{erf}\left[\frac{\sqrt{2}}{2} \left(\frac{A}{\sigma_A} - \gamma\right)\right]}{2}, \quad (65)$$

where erf() is the Gauss error function. However when dealing with extended objects, the conditions for a UMP do not hold anymore. The acceptance/rejection threshold now depends, at least, on the

¹⁸ Some authors prefer ‘reliability’.

¹⁹ In this context H_j identifies not only the source family but also the flux cut, i.e. different flux cuts map into different j . This probability in frequentist language is the ‘*Power of the test*’.

geometrical parameter that controls the extension of the objects and the completeness estimate of the sample is no longer trivial.

To give a proper assessment of the purity, except on the simplest cases, frequentist methods ought to resort to simulations. The simulations need to emulate the most realistic astronomical backgrounds at the frequencies of interest and the instrumental effects as closely as possible. Modern cosmological data sets are increasingly larger and more complex, rendering this task immensely resource consuming. Apparently it seems that PwS still relies on a SNR cut to predict/define the completeness of the catalogue. That means we would be throwing away most of the advantage of using a Bayesian detection method, as any catalogue is essentially useless unless it provides a measure of how representative it is of the population of the objects under scrutiny. Fortunately, this apparent limitation may be easily overcome by very realistic simulations that at the same time are simple and fast to construct: injecting mock source populations into the real maps and then recovering them. These simulations might not be optimal to assess purity but they provide the most realistic possible test bed for measuring completeness (Planck Collaboration et al. 2011a).

4.6.2 Validation (follow-up)

No science quality catalogue is complete without a proper validation. Validation tests the assumptions, physical and statistical, and whether our models are actually a truthful representation of reality. Only a thorough validation can actually provide a sensible way to assess how systematics, mis-modelling and statistical bias impair the properties of the catalogue and its estimates. Further analysis of formula (47) shows that the catalogue penalty per source, \tilde{P}_s , concentrates into a single number the least well defined prior quantities, namely the expected number counts of a population above a certain flux (λ_1), the expected number of background fluctuations above the same threshold (λ_0), etc. The non-Gaussianity of the background, the instrumental or map-making artefacts and the uncertainty on the priors most likely alter this value from the fiducial prediction. A properly calibrated \tilde{P}_s may be easily found initially by using simulations and later consolidated through validation.

Of particular note is how detection/estimation in Bayesian methods can unleash the power of validation by bringing together different instrumental capabilities into a unified and coherent analysis. Joint variate analyses are natural inside the Bayesian logic framework. They are the most powerful way to cross-validate and enhance the quality of catalogues. An example may be found in Planck et al. (2012) where a joint Bayesian analysis has allowed us to impose tighter and better defined constraint on the estimates, Y_{500} and Θ_{500} , of an 11 cluster subset of the *Planck* Early SZ galaxy cluster catalogue.

5 IMPLEMENTATION HISTORY

The data analysis philosophy and a set of algorithms described in this paper have not so far been fully implemented in a coded version of PwS. We are working towards this aim, and the release corresponding to the full set of features described here will be PwS v4.0. The versions that have been used in published data analyses so far are v1.5 and v3.1 for the SZ Challenge (Melin et al. 2011), v2.01 for the lower frequency point sources in the *Planck* ERCSC (Planck Collaboration et al. 2011a) and for all frequency channels in the Compact Source Investigation (CSI) workshop (Rocha et al., in preparation), v3.6 in application to the SZ cluster detection in the

Planck ESZ sample (Planck Collaboration et al. 2011b) and to characterize single cluster parameters in a non-blind exercise (Planck Collaboration et al. 2011e). It is worth noting that these versions include a pre-processing tool specifically designed to convert data sets distributed within the *Planck* collaboration into the format required by PwS. The main tasks performed by this tool are:

- (i) taking account of the masking and/or flagging of ill-observed pixels and contaminated regions;
- (ii) projecting the spherical maps into flat patches;²⁰
- (iii) mapping of coordinates from the sphere into the patches and back;
- (iv) removal of multiple detections of the same source in different patches;
- (v) assembly of the output catalogues into the required format.

The existing released versions of PwS differ from what will be available in v4.0 mainly in the limitation to a binary model selection step in determining when to accept a putative source detection and a non-parametrized frequency spectrum in multi-frequency detection. The latter restriction meant that, while the SZ cluster detection could be carried out using all *Planck* frequencies simultaneously, point source detections, in common with the other methods available, were carried out for each frequency channel separately. PwS v4.0 will aim at genuine multi-frequency and indeed multi-model detection, using all the available data simultaneously.

6 CONCLUSIONS

The *Planck* satellite and many other modern cosmological data sets present completely new challenges for the detection and description of compact objects. Two important traits of such observations are (i) low or very low SNRs; and (ii) strongly correlated backgrounds with typical scales similar to those of the objects being sought. These attributes render traditional object detection methods sub-optimal, since: (i) it is difficult to separate the sources from the background fluctuations; and (ii) the uncertainties on derived source parameters are important and traditional methods do not provide them.

A better strategy is to develop an object detection methodology from a strong statistical foundation first. The linear filtering family of tools is the attempt by the orthodox frequentist school of probability to overcome these limitations. The MF and all its derivatives are based on the Neymann–Pearson likelihood ratio, although their optimal performance is extremely dependent on the choice of the acceptance/rejection threshold and on implementation details. Despite their widespread use, the actual practical designs of these tools do not yet implement a sound framework to handle the uncertainties on the parameter estimates.

Bayesian methods have the great advantage of providing a coherent probability methodology with the option to include, in a completely consistent way, all ancillary information. But probability theory by itself only gives us a degree of belief. In order to produce a catalogue, decisions must be made as well. DT is unambiguous: $\ln[\frac{\Pr(H_1 \mid d)}{\Pr(H_0 \mid d)}]$ is the optimal decision tool (in the binary case), although the binary model is manifestly not powerful enough to handle a real data set. The necessary extension to a multi-model foundation is mandatory for an operational and viable solution. PwSII builds up on top of PwSI in the sense that it inherits its strong probability

and Bayesian legacy. Furthermore, it complements it with a fast detection/characterization Bayesian methodology based on ln(odds) and extends it to a multi-channel, multiple model decision rule. Simultaneously, the evaluation of the evidence is no longer based on a multi-dimensional Gaussian approximation to the posterior manifold but instead on a single-nested sampling scheme mostly independent of the manifold geometry. To achieve our goal we focused on taking advantage of the symmetries of the multi-channel likelihood manifold to design an efficient, though rigorous, exploration tool. Owing to its full, consistent probability foundation, PwS can provide a sound, generally applicable,²¹ and complete statistical characterization of its results. Simultaneously, we can offer effective solutions for the difficulties accompanying real data, without compromising any of our goals.

Some might question that conditioning our reasoning by priors might actually impair or even mislead the inference, especially if these are neither complete nor accurate. We are partially sympathetic with this, but:

- (i) if the data contain enough information and can actually constrain the object parameter estimates, the priors are mostly irrelevant.²²
- (ii) PwSII Bayesian modelling is still incomplete. Fundamental physics can most of the time constrain the general shape of the priors but not the actual parameter values they depend upon. Bayesian methods allow not only the estimation of each object parameters but also the parameters in the priors that provide the population laws. These probability models are commonly called ‘*hierarchical*’ or ‘*random effect*’ (see Box & Tiao 1992, ch. 5; Jaynes 2003, ch. 6) and will constitute the main subject of a future publication.

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²¹ If the assumptions of our data model are met (see section 3.1), PwS, or any similarly implemented Bayesian detection tool, can be used in any instrumental setup scenario, from radio to gamma-ray frequencies.

²² In the sense that any eventual bias induced by the prior will always much smaller than the statistical uncertainty.

²⁰ The patch set usually contains about $12\,000 7^\circ 33 \times 7^\circ 33$ flat patches or $3000 14^\circ 66 \times 14^\circ 66$.

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APPENDIX A: PWS ALGORITHM IMPLEMENTATION

PwS operation may be broadly divided in three main steps.

(i) Pre-processing

Makes the masks, creates the flat patches geometry and computes the pixel values.

(ii) Detection/estimation

Performs the detection by creating a list of candidates and respective parameter estimates.

(iii) Post-processing

Removes repeated detections of the same source across different patches, selects the candidates to be included in the catalogue, formats and writes it to the media.

A1 PwS step by step

A1.1 Pre-processing

(i) Reads in the data channel maps together with those defining the masks, and galactic and point sources (SZ). Renders auxiliary maps to flag heavily contaminated areas and possible ill-defined pixels.

(ii) Defines the patches' geometry using a gnomonic projection. Patches are squares, usually 256 or 512 pixels wide and the pixel area is $\sim 1.718 \times 1.718$ arcmin². The pixel values are computed using a bilinear interpolation. With the mask information from the first step, the pixels flagged as 'not usable' are filled with values that preserve the statistical properties of the background ('in-painting').

A1.2 Detection/estimation

(i) For each one of the patches repeat the next steps at least twice:

(a) Estimate the cross-power spectrum matrix and invert each Fourier mode.

(b) Create the likelihood manifold.

(c) Scan the likelihood manifold searching for its maxima using a grid. Store the maxima coordinates as initial hints.

(d) Sort the putative detections in descending order of likelihood ratio.

(e) For each one of the candidates do:

(1) use a Powell minimizer to estimate the optimal values (likelihood maximum estimate) of the source's parameters: position, flux and radius.²³

(2) If this is not the last iteration:

(A) If the SNR of the candidate is above a certain threshold (high) mask it. Go back to the beginning of the processing of this patch and start all over again.²⁴

(B) Subtract the object from the maps. Continue with the next iteration (candidate source).

(C) If running in *The Generalized Likelihood Ratio Test* (GLRT) mode.

Test the computed SNR value against the threshold for acceptance/rejection. If the detection is accepted then add it to the intermediate catalogue.

²³ Even when doing point source extraction PwS *never* assumes the objects as point like and shapeless. A narrow, but with finite dimensions, Gaussian is employed instead.

²⁴ This operation is restricted to point source detection only.

(D) If running in $\ln(\text{odds})$ (Bayesian) mode.

With the estimates from the previous step predict an initial bounding parameter volume and explore the posterior distribution using a simple nested sampling algorithm. Evaluate the $\ln(\text{odds}) \equiv [\ln(\frac{\Pr(H_1 | d)}{\Pr(H_0 | d)})]$.

Several sets of priors can be used. With the samples drawn from the posterior compute the best parameter estimates, mode or expected value estimators and the uncertainties on the parameters and the $\ln(\text{odds})$. Always add the detection to the intermediate catalogue. If necessary it will be removed during the post-processing stage.

(3) Subtract the object from the maps and continue with the next candidate.

A1.3 Post-processing

- (i) Map the position coordinates of the detections from the patch pixels back on to sphere coordinates.
- (ii) Using the auxiliary mask maps filter the intermediate catalogue removing those detections laying on top of the flagged areas.
- (iii) Remove repeated detections from the intermediate catalogue choosing always that one with the largest SNR (GLRT) or $\ln(\text{odds})$ (Bayesian). Generate the catalogue using a SNR cut (GLRT) or probability of a false positive (Bayesian).

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