Point source extraction

M. López-Caniego
Planck Science Office & ESAC Science Data Centre

CMB foregrounds for B-mode studies 15-18 Oct. 2018
CMB experiments have to deal with not only the diffuse galactic foregrounds but also compact source emission from our galaxy and from distant galaxies and clusters of galaxies.

The goal is to separate these components in order to do cosmology with the CMB and galactic and extragalactic science with the diffuse and compact emissions.
Different approaches have been proposed to detect and characterize compact sources in maps of the microwave sky in intensity and polarization.

In some cases there is a clear distinction between the detection of a source and its characterization, in some other cases they are part of the same process.

Using one technique or another depends on the complexity of the problem, complexity of the implementation, or personal taste.

One tool fits all does not apply here: difficult to find a technique equally effective detecting and characterizing point sources in very clean regions of the sky at low and extended non-circular sources in the vicinity of galactic plane in a high-frequency high-resolution map where the dust emission dominates at many different scales including that of the compact sources.
In terms of detection, we typically speak of:

- Blind detection
- Non-blind (detection?)

Both the blind and non-blind detection can be generally improved pre-processing the data.

One approach is to filter out the large scale diffuse structures, and, to some extent, the small-scale noise, one frequency at the time.
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30 GHz Planck simulation before and after filtering with MHW at the scale of the sources
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By filtering at this particular scale you remove structures with other angular scales and at the same time increasing the signal to noise of the sources, improving completeness.
30 GHz Planck simulation before and after filtering with MHW at the scale of the sources

By doing this we also increase the SNR of structures with angular scales similar to that of the sources, and there is a trade off between completeness and reliability.
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One approach is to filter out the large scale diffuse structures and to some extent the small-scale noise, one frequency at the time.

Another approach is to combine multiple frequencies into a new combined map “optimal” for detection.

This multi-frequency approach has been very successfully applied to the detection of SZ clusters using the Matched Multi Filter (MMF) from Herranz et al. 2002, to PS (MMF-PS, Lanz et al. 2014).

MTXF, Herranz et al 2009  This image: Herranz, Argüeso and Carvalho, 2012, AdAst. 22H
There are many types of filters, operating on the sphere and on flat patches, some examples:

- **Matched-filter or matched-filter-like filters**

  \[ \widetilde{\Psi}_{MF} \propto \frac{\tau(q)}{P(q)} \]

  For a Gaussian profile and a Scale-free Power Spectrum \( P(q) \) prop. \( q^{-\gamma} \), the MF is

  \[ \widetilde{\Psi}_{MF} \propto x^{\gamma} e^{-\frac{1}{2}x^2} \]

  MF in CMB: Tegmark & Oliveira-Costa, 1998;
  MF in CMB: WMAP Point source catalogue
  MMF for SZ: Herranz et al 2002;
  Other imp. of MMF: Schaefer et al 2005, Melin et al. 2006

  MTF for PS: L-C et al 2004;
  BSAF for PS: L-C et al. 2005;
  MMF for PS: Lanz et al. 2010
  FF for PS in P: Argüeso et al. 2010

- **Bayesian methods**

  Using a Bayesian formalism, these methods look for maxima in the posterior and decided if these maxima correspond to a real object performing a Bayesian model selection. As Spiderman would say: “With great **power** comes great **responsibility**”.

  BeeP: Carvalho, L-C and Tauber PCCS2 annex in preparation.
The Mexican Hat Wavelet (MHW) used as a filter

In 2D:

\[ \psi_{MH}(x) \propto \left( 1 - \frac{x^2}{2} \right) e^{-\frac{1}{2}x^2}, \quad x \equiv |\vec{x}| \]

Vielva et al. 2001, Cayón et al. 2003
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\]

Vielva et al. 2001, Cayón et al. 2003

The Mexican Hat Wavelet Family
- MHW1 and MHW2 (1st and 2nd order Laplacian of the Gaussian)
- CMHW (perfect reconstruction of a function at any scale).

\[
\begin{align*}
\varphi(x) &= \frac{1}{2\pi} e^{-\frac{x^2}{2}}, \\
\psi_{\varphi h}(x) &= \frac{1}{2\pi} \left(1 - \frac{x^2}{2}\right) e^{-\frac{x^2}{2}}, \\
\psi_d(x) &= \frac{1}{2\pi} \left(1 - \frac{x^2}{2} + \frac{x^4}{8}\right) e^{-\frac{x^2}{2}}, \\
\psi_c(x) &= \delta(x) - \frac{1}{2\pi} \left(3 - \frac{3x^2}{2} + \frac{x^4}{8}\right) e^{-\frac{x^2}{2}}
\end{align*}
\]

\[
\begin{align*}
\varphi(q) &= e^{-\frac{q^2}{2}}, \\
\psi_{\varphi h}(q) &= \frac{q^2}{2} e^{-\frac{q^2}{2}}, \\
\psi_d(q) &= \frac{q^4}{8} e^{-\frac{q^2}{2}}, \\
\psi_c(q) &= 1 - \left(1 + \frac{q^2}{2} + \frac{q^4}{8}\right) e^{-\frac{q^2}{2}}
\end{align*}
\]


MHW2 used to extract PS in WMAP, Planck and QUIJOTE. In Planck: PCCS and PCCS2 and SEVEM PS masks.
### Table 1. PCCS characteristics.

<table>
<thead>
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<th>Channel</th>
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<td>$</td>
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<tr>
<td>$N(&gt;S)^c$</td>
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<tr>
<td>Full sky</td>
<td>934</td>
</tr>
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<td>b</td>
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<tr>
<td>$</td>
<td>b</td>
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<tr>
<td>Flux densities:</td>
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<td>Uncertainty [mJy]</td>
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<tr>
<td>Position uncertainty$^e$ [arcmin]</td>
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</table>

$^a$ FWHM: Full Width at Half Maximum.

$^b$ Galactic and Extragalactic zones defined as in Table 1 of [ref].

$^c$ Number of sources fulfilling $S/N > 1$.

$^d$ Minimum flux density per pixel.

$^e$ Uncertainty estimated from the pointing errors.
Detection on Planck: PCCS2 (full mission)

2015 PCCS2: 3 lists of sources 30-70 GHz & 6 lists of sources 100-857 GHz.

Galactic coordinates Mollweide projection

PCCS2 T 30, 143 and 857 GHz
Detection on Planck: PCCS2/PCCS2E full mission

2015 PCCS2E: 6 lists of sources 100-857 GHz, 45,000 sources
### Summary Total Intensity

<table>
<thead>
<tr>
<th>Channel</th>
<th>30</th>
<th>44</th>
<th>70</th>
<th>100</th>
<th>143</th>
<th>217</th>
<th>353</th>
<th>545</th>
<th>857</th>
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<td>44.1</td>
<td>70.4</td>
<td>100.0</td>
<td>143.0</td>
<td>217.0</td>
<td>353.0</td>
<td>545.0</td>
<td>857.0</td>
</tr>
<tr>
<td>$\lambda$ [(\mu\text{m})]</td>
<td>10561</td>
<td>6807</td>
<td>4260</td>
<td>3000</td>
<td>2098</td>
<td>1382</td>
<td>850</td>
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### Number of sources

<table>
<thead>
<tr>
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<th>70</th>
<th>100</th>
<th>143</th>
<th>217</th>
<th>353</th>
<th>545</th>
<th>857</th>
</tr>
</thead>
<tbody>
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<td>934</td>
<td>1296</td>
<td>1742</td>
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<td>43290</td>
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<tr>
<td>Union PCCS2+PCCS2E</td>
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<td>...</td>
<td>...</td>
<td>4229</td>
<td>6299</td>
<td>18977</td>
<td>24009</td>
<td>52762</td>
<td>48181</td>
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<tr>
<td>PCCS(^a)</td>
<td>1256</td>
<td>731</td>
<td>939</td>
<td>3850</td>
<td>5675</td>
<td>16070</td>
<td>13613</td>
<td>16933</td>
<td>24381</td>
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Detection on Planck: PCCS2/PCCS2E full mission
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Detection on Planck: Polarization
• “Detecting” and characterizing polarized sources in Planck was really hard, not many sources, low SNR, systematics, etc.

• To prepare for Planck we used simulations from the Planck Sky Model and the filtered fusion method from Argüeso et al. 2010 we built IFCAPOL. The trick here is applying MF’s on the Q and U maps before building P, reducing the biases to a level below our own uncertainties in the flux density determination down to low flux densities
IFCAPol (Filtered Fusion) technique to assess the significance of the detection and estimate the flux density of sources embedded in early LFI polarization maps:

Source 2: Pictor A

The source is in the center of the patch and in many cases it is hardly visible in the unfiltered maps.

We have applied the FF technique to WMAP5yr maps and to Planck simulations and data maps, recovering unbiased fluxes down to 300 mJy for the 30 GHz case.
IFCAPol (Filtered Fusion) technique to assess the significance of the detection and estimate the flux density of sources embedded in early LFI polarization maps:

Source 9: 3C279

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We have applied the FF technique to WMAP5yr maps and to Planck simulations and data maps, recovering unbiased fluxes down to 300 mJy for the 30 GHz case.
Detection on Planck: Non-blind analysis in Polarization

PCCS2 in Polarization 30, 44 and 70 GHz
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To prepare for Planck we used simulations from the Planck Sky Model and the filtered fusion method from Argüeso et al. 2010 we built IFCAPOL. The trick here is applying MF’s on the Q and U maps before building P, reducing the biases to a level below our own uncertainties in the flux density determination down to low flux densities.

This was very successfully applied to WMAP (L-C et al. 2009) and later to Planck PCCS2 and now to QUIJOTE data (see D. Herranz and J. González-Nuevo talks).

In all cases it is a non-blind analysis at the positions of the sources detected in intensity, where we assess the significance level of the “detections” and stay above 99.90%.

In Planck we also modified the Powelsnakes code turning off all the Bayesian machinery and keeping the MF part to have a second independent analysis.
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### Summary Polarization

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<tbody>
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<td>34</td>
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<td>25</td>
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<td>Minimum polarized flux density(^a) [mJy]</td>
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<td>181</td>
<td>284</td>
<td>138</td>
<td>148</td>
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<td>453</td>
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<td>Polarized flux density uncertainty [mJy]</td>
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<td>88</td>
<td>91</td>
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<td>81</td>
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<td>397</td>
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<td>100</td>
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<td>347</td>
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<tr>
<td>Minimum polarized flux density completeness 95% [mJy]</td>
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<td>454</td>
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<td>111</td>
<td>153</td>
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<td>700</td>
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<td>Minimum polarized flux density completeness 95% [mJy]</td>
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<td>893</td>
<td>464</td>
<td>590</td>
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<td>Minimum polarized flux density completeness 100% [mJy]</td>
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<td>...</td>
<td>...</td>
<td>835</td>
<td>893</td>
<td>786</td>
<td>958</td>
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</tbody>
</table>
However, it also common to skip the pre-processing step and perform the characterization of the source, when the position is known, with the most appropriate tool or tools.

In Planck we see several types of populations of extragalactic radio and infrared galaxies, galactic compact regions, SZ clusters and lots of small scale galactic emission at higher frequencies that looks like a compact source, specially after you filter it with a circularly symmetric filter.

For example, in the Planck Catalogue of Compact Sources, both the nominal mission PCCS and the full mission PCCS2, one detection method and four different photometries where used in intensity:

- DETFLUX (MHW2 photometry) coming from the filtered maps
- APERTURE PHOTOMETRY
- 2D ELLIPTICAL GAUSSIAN FITTING
- EFFECTIVE BEAM FITTING
Impact of PS in the CMB angular power spectrum
Impact of PS in the CMB angular power spectrum

![Graph showing the impact of PS in the CMB angular power spectrum](image-url)
Impact of PS in the CMB angular power spectrum
Impact of PS in the CMB angular power spectrum
Impact of PS in the CMB angular power spectrum
Impact of PS on higher order moments used in NG
Impact of PS on higher order moments used in NG

Planck 2015 Component Separation

Polarised intensity skewness evaluated from Planck simulations (histograms) and the fiducial map at Nside 1024, 256 and 64 outside the mask.

Coloured vertical lines correspond to:

- Before using Pol PS
- Masking Pol PS

D. Molinari
Planck Component Separation WG
Planck 2015 Component Separation

Polarised intensity skewness evaluated from Planck simulations (histograms) and the fiducial map at Nside 1024, 256 and 64 outside the mask.

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Planck Component Separation WG
### SEVEM 2018

Iterative SEVEM template fitting + MHW2 PS detection and masking

<table>
<thead>
<tr>
<th>Map</th>
<th>30 GHz</th>
<th>44 GHz</th>
<th>70 GHz</th>
<th>100 GHz</th>
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<td>$P$ (full-sky)</td>
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<tr>
<td>$P$ ($</td>
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<td>&gt; 20^\circ$)</td>
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<td>...</td>
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<td>93</td>
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<td>48</td>
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<tr>
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<td>&gt; 20^\circ$)</td>
<td>...</td>
<td>...</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>16</td>
<td>...</td>
</tr>
</tbody>
</table>

### COMMANDER 2018

Starting from a long list of sources compiled at low frequency, source by source fit the Planck effective beam at that frequency at the position in the sky to the data. If the low frequency source is not visible anymore, this results in a bad fit, if there is something there, this results in a fit with it associated uncertainties in the fitted parameters.
Conclusions

- The compact sources are a very important source of contamination in CMB analyses and their detection and proper characterization in intensity and polarization is necessary.

- These analyses allow us to minimize the residual PS contamination in the CMB map reconstruction, reduce its impact in CMB angular power spectrum, reduce the uncertainties in the determination of cosmological parameters and in NG analyses.

- Residual compact source emission is the only foreground at the level of the lensing B-modes, and uncertainties in the level of compact source residual can impact delensing of primordial B-modes.

- The times of simple detection techniques are now gone. For the next generation of experiments we need to use all the artillery available: multifrequency information, Bayesian techniques, joint diffuse and compact foreground separation, and any other tool that allow us to understand the objects we are looking, like ESASky.

- As a by product, these catalogues are used for compact source science.
Theoretically the matched filter is optimal (among the class of linear filters) in the sense of signal-to-noise ratio amplification.

In practice, implementation issues could degrade the performance and some precautions need to be taken into account.
Filters: Comparison of the MHW1 and MHW2 with the MF
Filters: Comparison of the MHW1 and MHW2 with the MF