DETECTION OF NEW POINT SOURCES IN WMAP 7 YEAR DATA USING INTERNAL TEMPLATES AND NEEDLETS

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ABSTRACT

We have developed a new needlet-based method to detect point sources in cosmic microwave background (CMB) maps and have applied it to the Wilkinson Microwave Anisotropy Probe (WMAP) 7 year data. We use both the individual frequency channels as well as internal templates, the latter being the difference between pairs of frequency channels and hence having the advantage that the CMB component is eliminated. Using the area of the sky outside the Kq85 galactic mask, we detect a total of 2102 point sources at the 5σ level in either the frequency maps or the internal templates. Of these, 1116 are detected either at 5σ directly in the frequency channels or at 5σ in the internal templates and ≥3σ at the corresponding position in the frequency channels. Of the 1116 sources, 603 are detections that have not been reported so far in WMAP data. We have made a catalog of these sources available with position and flux estimated in the WMAP channels where they are seen. In total, we identified 1029 of the 1116 sources with counterparts at 5 GHz and 69 at other frequencies.

Key words: cosmic background radiation – cosmology: observations – methods: data analysis – methods: statistical

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The Wilkinson Microwave Anisotropy Probe (WMAP; Bennett et al. 2003) measured the cosmic microwave background (CMB) fluctuations at high resolution and signal-to-noise ratio in five frequency bands. The detailed study of the CMB and its anisotropies gives information enabling us to comprehend the universe we live in and how it came to be. It is therefore very important to get the maximum accuracy of the data we have at present. For the moment, the best publicly available data of the CMB are the seven-year WMAP data (Jarosik et al. 2011), but the ongoing Planck mission is expected to improve the quality even more. The data are contaminated by foregrounds; on larger scales the dominating foregrounds are diffuse galactic emissions, while on smaller scales the main contaminants are extragalactic point sources (see, for instance, Toffolatti et al. 1998; De Zotti et al. 1999, 2005; Hobson et al. 1999). Clearly the WMAP mission, in addition to measuring the CMB and its anisotropies, provides an all-sky, high-frequency survey of diffuse galactic foregrounds and extragalactic sources. Independently of whether one is interested in studying the CMB anisotropy, diffuse galactic emissions, or extragalactic point-source measurements, it is crucial to be able to separate the different components. In this paper, we are mainly interested in disentangling extragalactic point sources from the WMAP data. This has been done by the WMAP team and other teams; here we present a new approach.

In Gold et al. (2011), the WMAP collaboration presents two point-source catalogs of detected sources obtained from the 7 year data. WMAP finds a total of 542 distinct sources, most of which also have a 5 GHz counterpart. They used two different methods: a global filtering method in the five bands (where they find 471 sources) and a CMB-free method (ILC based, introduced and previously applied by Chen & Wright 2008 to 1 year and 3 year data and applied to 5 year data by Chen & Wright 2009 for the Q, V, and W band (where 417 sources are found); for more details on these approaches we refer to Gold et al. 2011, and references therein). Subsequently, other approaches have been used by different teams on real data or simulations. The most relevant one to our approach is the one where Mexican wavelets are used to detect sources, introduced by Cayón et al. (2000); this approach has then been developed further to the Mexican Hat Wavelet (MHW) Family (González-Nuevo et al. 2006). Subsequently, López-Caniego et al. (2007) successfully applied the MHW technique to make a non-blind search in 3 year WMAP data, where at 3σ level they detect 381 sources at the 5σ level (98 of which were not present in the WMAP 3 year catalog). Massardi et al. (2009) then apply the MHW to WMAP 5 year data, obtaining 516 point sources at the 5σ level.

Other approaches that have been applied include via cross-correlation (Nie & Zhang 2007), via matched filters (Vikhlinin et al. 1995; Tegmark & de Oliveira-Costa 1998; Barreiro et al. 2003; López-Caniego et al. 2006) and matched multilters (Herranz et al. 2002; Lanz et al. 2011), and Bayesian techniques with prior information about source distribution (Hobson & McClachlan 2003; Carvalho et al. 2009; Argüeso et al. 2011); see also Schmitt et al. (2010), Starck et al. (2010), and the references therein for general results on wavelet-based methods to search for point sources in astrophysical data.

Here, we present a method for the point-source detection that is novel in two ways: (1) it uses the family of standard (Marinucci et al. 2008) and Mexican (Scodeller et al. 2011) needlets optimized for point-source detection on the given channels, and (2) we search for point sources both in the individual WMAP channels and in the CMB-free internal templates (Hansen et al. 2006) constructed from the difference between two frequency channels.

The outline of the paper is as follows: in Section 2 we present in detail how our method for detecting point sources works, in Section 3 we present our results on simulations, and in Section 4
for the real data. Eventually in Section 5, we summarize. In Table 6, we list the 1116 sources that we detected in the five WMAP channels.

2. METHOD

2.1. A Short Introduction to Needlets

Needlets were introduced in the mathematical literature by Narcowich et al. (2006) and have recently become a very popular tool for a wide range of CMB analysis tasks, as proved from the variety of statistical procedures where they have been exploited. A partial list includes testing for non-Gaussianity, estimating the angular power spectrum, testing for asymmetries, testing for cross-correlation among CMB and large-scale structure data, map reconstruction, and testing for Bubble universes; see, for instance, Pietrobon et al. (2006), Baldi et al. (2009a), Baldi et al. (2009b), Marinucci et al. (2008), Fay et al. (2008), Rudjord et al. (2009a, 2009b), Cabella et al. (2009), Feeney et al. (2011), and Basak & Delabrouille (2012). We review briefly their construction, as follows.

Let $b(t)$ be a weight function satisfying three conditions, namely,

1. **Compact support**: $b(t)$ is strictly larger than zero only for $t \in [B^{-1}, B]$, some $B > 1$.
2. **Smoothness**: $b(t)$ is $C^\infty$.
3. **Partition of unity**: for all $l = 1, 2, \ldots$, we have
   $$ \sum_{j=0}^{\infty} b^2 \left( \frac{l}{B^j} \right) = 1. $$

Recipes to construct a function $b(t)$ that satisfy these conditions are easy to find and are provided, for instance, by Marinucci et al. (2008) and Marinucci & Peccati (2011). Consider now a grid of points $\{\xi_{jk}\}$ on the sphere and a grid of weights $\lambda_{jk}$; in practice, the points can be viewed as the pixel centers for HEALPix, while the weights can be taken to be constant and equal to the pixel area. The needlet system is then defined by

$$ \psi_{jk}(x) = \sqrt{\lambda_{jk}} \sum_{l=0}^{L} \sum_{m=-l}^{l} b \left( \frac{l}{B^j} \right) Y_{lm}(x) Y_{lm}(\xi_{jk}), $$

with the corresponding needlet coefficients provided by

$$ \beta_{jk} = \int_{S^2} f(x) \psi_{jk}(x) dx = \sqrt{\lambda_{jk}} \sum_{l=0}^{L} \sum_{m=-l}^{l} b \left( \frac{l}{B^j} \right) a_{lm} Y_{lm}(\xi_{jk}). \quad (1) $$

The main features of needlets have now been widely discussed in the literature; here, we simply recall the **reconstruction property** (see Narcowich et al. 2006) entailing that

$$ f(x) = \sum_{jk} \beta_{jk} \psi_{jk}(x). $$

More recently, the needlet idea has been extended by Geller & Mayeli (2009a, 2009b), introducing the so-called Mexican needlets; loosely speaking, the idea is to replace the compactly supported kernel $b(l/B^j)$ by a smooth function of the form

$$ b \left( \frac{l}{B^j} \right) = \left( \frac{l}{B^j} \right)^{2p} \exp \left( - \frac{l^2}{B^{2j}} \right), $$

for some integer parameter $p$; see Scodeller et al. (2011) for numerical analysis and implementation in a cosmological framework. Mexican needlets have extremely good localization properties in real space, and for $p = 1$ they provide at high frequencies a good approximation to the so-called spherical MHW construction.

2.2. Choosing the Needlet Bases

In order to amplify the point-source signal, we use the needlet transform on the maps and search for needlet coefficients with a value larger than five times the standard deviation expected from CMB and noise in a given channel or template. As mentioned in the introduction, we will look for point sources not only in the individual WMAP channels but also in internal templates (first introduced by Hansen et al. 2006). The internal template between channel $c$ and channel $c'$, assuming that $c'$ has a smaller beam than $c$, is constructed by smoothing the $c'$ map by the beam $b^{-1}/b^{'-1}$. In this way both channels have the same beam, and hence by constructing the difference map between the two, the CMB component disappears. We are thus left with an internal template containing only noise and foregrounds/point sources. The advantages/disadvantages with the two approaches are as follows:

1. **Individual channels**. The background consists of both CMB and noise. The CMB is dominated by large-scale fluctuations, and therefore a needlet basis with small extension (high value of $j$) on the sphere is necessary in order to separate the point sources from local CMB fluctuations. Such needlet coefficients of a point source will therefore have a $5\sigma$ deviation only on a small number of pixels, since the point source in this case will be very localized in needlet space.
2. **Internal templates**. The background consists of only noise, but the noise level is higher than in the individual channels, since noise from both channels is present in the template. The absence of dominant large-scale fluctuations makes needlets with a larger extension (lower $j$) more efficient. The advantage is that more needlet coefficients will be at $5\sigma$ for a given source and the probability of a detection is therefore larger. Whereas for the individual channels a point source must have a large amplitude in at least one channel in order to be detected, for the internal template it suffices that the difference in amplitude between the two channels is large. This also implies that we cannot estimate the source amplitude in the template, but we can use the position of a source found in the template to estimate the amplitude in the channel.

For each channel and each internal template, we have calculated the needlet coefficients of a simulated point source and the standard deviation of needlet coefficients due to CMB and noise (at the given frequency). In that way we are able to calculate the signal-to-noise ratio for a large set of different needlets and find the needlet with the optimal signal-to-noise ratio for point sources for a given channel. In Table 1, we show which needlets we found optimal for a given channel and template. The templates presented in this table are the templates for which we found the highest signal-to-noise ratio. In addition, we will also use the $K - Ka$ template, which, even though it does not contain the highest signal-to-noise ratio, is expected to reveal many sources being in the synchrotron-dominated frequency range. In the table, we also show the distance of influence (for details, see Scodeller et al. 2011; we used a threshold of 3%), which is a...
measure of angular extension of the needlet on the sphere and is in particular an indication of how extended a point source will appear in a given needlet basis.

2.3. The Detection Algorithm

Given the needlet coefficients of a channel or a template at $N_{\text{side}} = 512$, we use the following procedure to detect point sources and estimate amplitudes:

1. We divide the needlet coefficients by their standard deviation due to CMB and noise to get the normalized needlet coefficients.
2. We loop on detection threshold starting with $50\sigma$ and gradually going down to $5\sigma$.
3. For a given threshold, we loop on the pixels of the $N_{\text{side}} = 512$ map of normalized needlet coefficients. When a pixel with a value above the threshold is found, we identify a disk of radius equal to the distance of influence for the given needlet around this pixel. Possible amplitudes of the point source are estimated using as possible source positions the centers of all pixels in an $N_{\text{side}} = 2048$ map within this disk. Thus, for all $N_{\text{side}} = 2048$ pixels within the disk, we obtain the amplitude of the point source assuming that each of these pixels is the center. The center of the pixel that gives the highest estimate of the amplitude is identified as the most likely position of the source.
4. Using the best-fit source center, we subtract the best-fit point-source model from the $N_{\text{side}} = 512$ needlet map. This is done in order to avoid further detections of the same source as we continue looping through the pixels.
5. After the loop on pixels and detection thresholds, we are left with a list of positions and amplitudes.
6. Finally, we need to identify the cases where residual diffuse foregrounds, close sources, or extended sources give rise to a false detection or detections of sources where we are unable to estimate a reliable amplitude. We use a $\chi^2$ goodness-of-fit test to eliminate these detections from the list.

To avoid further detection of the same source, we use the following procedure:

- We loop on the pixels of the $N_{\text{side}} = 512$ map of normalized needlet coefficients. When a pixel with a value above the threshold is found, we identify a disk of radius equal to the distance of influence for the given needlet around this pixel. Possible amplitudes of the point source are estimated using as possible source positions the centers of all pixels in an $N_{\text{side}} = 2048$ map within this disk. Thus, for all $N_{\text{side}} = 2048$ pixels within the disk, we obtain the amplitude of the point source assuming that each of these pixels is the center. The center of the pixel that gives the highest estimate of the amplitude is identified as the most likely position of the source.

3. RESULTS ON SIMULATIONS

3.1. Creating the Simulations

The aims of the simulations are as follows:

- To test if the estimates of source amplitudes are unbiased.
- To find error bars on amplitude and position of the sources.
- To find the detection limits for the different channels and templates.
- To identify problems with the detection algorithm.

We thus try to make simulations that are simple, fast, and mainly fitted to fulfill these goals more than to make simulations with realistic point-source amplitudes and numbers of sources.
But in order to have a range of amplitudes that are not too unrealistic, we choose to use 464 sources detected in a first run in the WMAP 7 year $K$-band data. To test the lower limit of detection, we added 71 sources slowly decreasing in amplitude from the smallest of the 464 $K$-band sources.

We simulate the positions in such a way that the minimum distance between the sources is always larger than 1°. As we show later, there are some problems with the detection and estimate of the amplitude of sources that are very close. In order to obtain reliable error estimates from simulations, we need to reduce this problem here by simulating source positions that are more than 1° apart. The centers of the sources are taken to be centers of pixels at HEALPix resolution $N_{\text{side}} = 2048$. The amplitudes of the sources on other channels than the $K$ channel are obtained assuming a synchrotron spectral index of $-2.7$. Again, this is not completely realistic but sufficient to satisfy the goals of the simulations. We now make a pure point-source map with the above-defined positions and amplitudes.

Finally, we make 3000 different realizations of noise and CMB fluctuations and add the pure point-source map to them, obtaining maps with CMB, noise, and point sources, but no extended foregrounds. To generate CMB and noise realizations, we use the best-fit WMAP7 power spectrum and the WMAP noise rms models. The choice of the number of simulations was motivated by the trade-off between available CPU time and the necessary accuracy on the error bars obtained from simulations.

### 3.2. Analyzing the Simulations

First, we used 3000 simulated maps to estimate the error $\sigma_{\text{Pos}}$ on the estimated position. Only input sources that are detected in at least 1000 simulations are used to estimate error bars. In order to identify a detected source with an input source when estimating the error on position, we needed to ensure that we used a search radius that was much larger than the 1σ error on position. An identification radius of 0.5 deg was found to be sufficient. Now that the error bars on position have been found, we will in all further analysis of the simulations use a new identification radius of 0.25 deg for the individual channels and the $K_a - V$ and $Q - V$ templates and 0.3 for all other internal templates. This corresponds to a maximum of about 5$\sigma_{\text{Pos}}$ (taking the error for the weakest sources); very few sources are expected to be found outside a radius of 5$\sigma$. For some channels the 5$\sigma_{\text{Pos}}$ distance is less than 0.25 deg: we still use 0.25 deg as the identification radius in order to include at least 2 pixels on $N_{\text{side}} = 512$. When deciding whether a source detected in one channel may be the same source as one detected in another channel at a slightly different position, we will use a maximum distance of $\sqrt{2} \times 5\sigma_{\text{Pos}}$ ≈ 0.4 deg for the identification, taking into account the 5σ error on position for both sources.

We then used 3000 simulated maps to estimate the error $\sigma^A$ on estimated amplitude now using the new identification radius. We find that the error on the amplitude is independent of its value (but fluctuates around a constant value, due to noise) whereas the error on position grows with decreasing amplitude. To be conservative, we will use the error bars for the weakest sources. The mean error bars on amplitude, the mean value of the error bars on position, and the error bars on the position for the weakest sources are all shown in Table 3 for individual channels and in Table 4 for the templates (in the latter table we do not list an error on the amplitude, since this is an amplitude difference between two channels, which is never used).

We compare the mean value of the estimated amplitudes in the simulations with the corresponding input amplitude. We find that the estimated amplitudes are unbiased with the exception of the very weakest sources, which are influenced by the Eddington bias (Eddington 1940). In Section 4, we will show how we correct for the Eddington bias in the WMAP data.

In Table 3 (for individual channels) and Table 4 (for templates), we show the mean number of sources found in the 3000 simulated maps (entry “Found total”). We list both the number of 5$\sigma$ detections and the mean number of sources remaining after applying the $\chi^2$ acceptance criterion (entry

### Table 3

| WMAP channel $i$ | $K$ | $K_a$ | $Q$ | $V$ | $W$ |
|------------------|-----|-------|-----|-----|-----|
| $(\sigma_{\text{Pos}}^A)$ (Jy) | 0.165 | 0.158 | 0.173 | 0.225 | 0.315 |
| $\sigma_{\text{Pos}}$ (arcmin) | 3.03 | 2.88 | 1.74 | 1.40 | 1.24 |
| $\sigma_{\text{Pos}}$ (arcmin) | 1.87 | 1.57 | 1.29 | 1.18 | 0.95 |
| Found total (535 input sources) | 424 | 353 | 216 | 87 | 24 |
| After $\chi^2$ elimination | 420 | 351 | 215 | 87 | 24 |
| Identified | 419 | 350 | 213 | 85 | 22 |
| Unique | 82 | 12 | 1 | 0 | 0 |
| Avg. false positives$^b$ | 1.7 | 1.6 | 1.9 | 1.8 | 1.7 |
| Detected in int. temp | 462 | 448 | 373 | 191 | 65 |
| Amplitude detection limit (Jy) | 0.519 | 0.501 | 0.491 | 0.522 | 0.991 |
| Avg. 99% completeness flux, channels (Jy)$^c$ | 1.07 | 1.59 | 1.12 | 1.40 | 1.79 |
| Avg. 99% completeness flux, int. temp. (Jy)$^c$ | 1.01 | 0.883 | 0.932 | 1.09 | 1.46 |
| Avg. 99% completeness flux, combined (Jy)$^c$ | 0.775 | 0.747 | 0.830 | 1.08 | 1.46 |

**Notes.**

$^a$ NB: this error on the amplitude does not take into account the error of the effective area (used to convert kelvin to jansky), since this error is dependent on the value of the amplitude.

$^b$ Represents the average number of detections not identified with an input source; discrepancies from "After $\chi^2$ elimination" minus "Identified" come from rounding.

$^c$ Represents the average input flux limit from where 99% of the simulated input sources are detected. "Channels" stands for the sources detected directly in the five channels; "int. temp." for those detected in internal templates and being non-zero in channels at the $3\sigma$ level; "combined" for those detected in either the channels or the templates.
“After $\chi^2$ elimination”). The mean number of these accepted sources that are identified with input sources is also shown (entry “Identified”). The detections that are not identified are found to be either random fluctuations or sources whose input position is further than 5$\sigma_{\text{Pos}}$ away from the detected position; they are shown in entry “Avg. false positives.” We also show the mean number of unique detections (entry “Unique”), for the individual channels this refers to sources that are detected only in one channel, while for the templates this refers to sources detected only in one template and no others. A given source is a unique detection in the channels (respectively, templates), if no other channel (respectively, template) has detected a source within 0.4$\sigma$ from the position of this source, where 0.4$\sigma$ comes from the error on positions as explained above.

It may seem surprising that while the $Ka - V$ and $Q - V$ templates overall detect less sources than the other templates, they detect on average more unique sources, not detected in other templates. The reason for this is that the needlets used for these templates have smaller spatial extension and can hence better resolve point sources that are very close. This is also the reason why there are many fewer sources that are eliminated by $\chi^2$ elimination. This is also the consequence of the fact that in templates we measure a temperature difference between two channels at different frequencies and hence there is no obvious way to transform such an amplitude to jansky.

In the same tables, we also show the mean (input) amplitude of the weakest detected sources in the simulations. This is the amplitude limit below which very few sources will be detected. For the internal templates, we show the weakest differences in amplitude rather than the amplitude itself. In the five frequency channels, an average of 435 sources are found in total among all the channels; for the templates, the corresponding number is 491. Thus, on average 56 more sources are found in the templates; this indicates that the lower background level (pure noise versus noise+CMB) of the templates increases the number of detections, in spite of the fact that the amplitudes in the templates are differences and not absolute values. The simulations show that this is true for synchrotron sources; in real data we will see that this effect is even stronger and that using the internal templates gives the possibility to discover many more sources than when using only the individual channels.

We also follow up the point sources that are detected in the templates by amplitude measurements at the same position in the individual channels. We first use the two templates with the smallest error in position ($Ka - V$ and $Q - V$). For all sources detected in these templates, we look for the maximum amplitude in a radius of 0.25 deg in the five individual channels. For the sources detected only in the remaining three templates, we use a radius of 0.3 deg. The radii of 0.25 and 0.3 deg correspond again to roughly five times the error on the position as explained above. In order to make sure that the given source is actually seen in a given channel, we only accept the detection and use the amplitude if it is non-zero at least at the 3$\sigma$ level. In Table 3, we show the number of sources detected by this method in each of the channels.

Finally, we also show in Table 3 the average limiting flux from where the detection is 99% complete, meaning from where we detect on average 99% of the source with a greater flux than the reported limit. We report this average completeness limit for the detections directly done in the five WMAP channels, for $5\sigma$ detections in the templates that are non-zero at least at the 3$\sigma$ level in the channels, and for the combined unique detections of the two preceding approaches. This shows well how the two approaches are complementing each other.

### 4. RESULTS ON WMAP 7 YEAR DATA

In Table 5, we show the results of the above procedure on the WMAP data. Note that we only search for sources outside the Kq85 galactic mask (to be exact, we use the WMAP point-source catalog mask, which is similar but not equal to the Kq85 galactic mask; see Gold et al. 2011). The table is divided into three parts: first we show the source detection in the internal templates only, then in the individual channels only, and finally the sources detected at $5\sigma$ in the templates and then found at more than $3\sigma$ amplitude in the channels. In each case, we show the number of detections before (entry “Found total”) and after elimination with the above $\chi^2$ criterion (entry “After $\chi^2$ elimination”). For each channel and template, we show how many sources are uniquely detected in this particular channel or template (entry “Unique”).

In the following, all references to detected sources refer only to those that passed the $\chi^2$ criterion. The table clearly shows the power of using the internal templates. The number of detected sources is substantially increased when including the templates. In total 522 sources were found using the channels only, whereas 2052 were found using the templates only. Overall, 1116 sources are detected in at least one frequency, either as $5\sigma$ directly on the map or as $5\sigma$ in the template and $\gtrsim 3\sigma$ at the corresponding

| Template $i$ | $K - Ka$ | $K - V$ | $K - W$ | $Ka - V$ | $Q - V$ |
|--------------|----------|----------|----------|-----------|---------|
| $\sigma_{\text{Pos}}$ (arcmin) | 3.46     | 3.31     | 3.34     | 2.94      | 2.65    |
| $\langle\sigma_{\text{Pos}}\rangle$ (arcmin) | 2.00     | 1.36     | 1.36     | 1.67      | 2.06    |
| Found total (535 input sources) | 494      | 550      | 549      | 481       | 288     |
| After $\chi^2$ elimination | 444      | 458      | 460      | 456       | 285     |
| Found identified | 442      | 457      | 459      | 455       | 282     |
| Unique | 1        | 1        | 0        | 6         | 5       |
| Avg. false positives$^a$ | 1.8      | 1.0      | 1.1      | 1.8       | 2.2     |
| Amplitude difference, det. limit ($10^{-2}$ mK)$^b$ | 3.96     | 4.67     | 4.98     | 5.17      | 5.76    |

**Notes.**

$^a$ Represents the average number of detections not identified with an input source; discrepancies from “After $\chi^2$ elimination” minus “Identified” come from rounding.

$^b$ As previously, the minimum amplitude difference is reported in temperature units rather than jansky. This is a consequence of the fact that in templates we measure a temperature difference between two channels at different frequencies and hence there is no obvious way to transform such an amplitude to jansky.
522 detections in the channels. We start by taking all the detected sources in the K-channel (where we detect most), then we add those detected in the $K-a$-channel that are not also detected in the $K$-channel (meaning further than 0.4 from the positions of the detections in $K$). Then we iterate till the $W$-channel. Note that this procedure just counts how many different sources we detect, independently of whether they are unique or detected in more than one channel.

2052 detections in templates. Same approach as for the 522 detections in the channels, starting from the sources detected in $K-a$, then adding those not already present iteratively from $Q-V$, $K-W$, $K-V$, and $K-a$.

1116 detections in at least one frequency. As for the 5σ detections in the channels, we combine the different sources we detect at 5σ in the templates and at 3σ in the channels. We keep all 522 sources detected directly in the channels and add those from the templates that are further than 0.4 from the ones directly detected in the channels.

Note that with a 5σ detection criterion, we would expect about 18 false detections in total, considering that we have 5 channels and 5 templates. In the simulations we had an average of nine false detections in the channels and eight in the templates. Furthermore, for the sources that are detected at 5σ in the templates only, a total of 2052, one should expect about 6 false 3σ detections for each channel. We therefore expect about 30 false detections among the sources that are only detected at 5σ in the templates and 3σ at the same position in the channels. We exclude some of these by noting that some detections in the $V$ and $W$ band are positive 3σ detections whereas at the same positions in the internal templates $K-V$ and $K-W$ there are positive 5σ detections, meaning that the source should be much stronger in $K$ than in $V$ or $W$. If, at the same position, there is no 2σ detection in either of the two other bands among $Q$, $V$, and $W$, we assume that the detection is due to a fluctuation and is excluded. We find in total 30 such cases.

### 4.1. Comparison with Catalogs at the Same Frequencies

In order to test our method, we will first compare the sources to those found by the WMAP team using the WMAP 7 year point-source (Gold et al. 2011) catalogs, sources found in the NEWPS_5yr_5s catalog (Massardi et al. 2009) based on WMAP 5 year data, and the Early Release Compact Source Catalogue (ERCSC) based on Planck observations (Planck Collaboration 2011) at frequencies 30, 44, 70, and 100 GHz. The WMAP catalogs contain 542 independent sources, the NEWPS_5yr_5s catalogs contain 533, and the ERCSC catalogs contain 705, 452, 599, and 1381 sources at, respectively, 30, 44, 70, and 100 GHz (adding up to 1585 distinct sources if we identify them among themselves when they are within the identification radius of 0.4).

In our work, we have concentrated the search outside the Kq85 galactic mask; the corresponding numbers of sources found in these three catalogs are thus 536 (WMAP), 430 (NEWPS), and 678 (ERCSC).

Of the 536 sources in the WMAP catalogs, we find 487 (combining individual channels and templates) with our procedure. Of the 49 missing WMAP sources, 24 are detected but rejected by our conservative $\chi^2$ criteria, and another 12 are detected but not identified as they are offset by more than our 5σ identification radius. Only 13 of the WMAP sources are not detected at all. These are all very weak and close to other stronger sources and therefore not resolved by the needlet coefficients. For the NEWPS catalog, we find 415 of the 430 sources; the remaining 15 sources are detected but excluded by our $\chi^2$ criterion. Among the 678 ERCSC sources, we detect in total 517 by our procedure. For the 1116 sources which are found either directly at 5σ in the channels or at 3σ in the templates and 3σ in at least one channel, 506 are new sources that are not listed in the WMAP, NEWPS, or ERCSC catalogs. In Table 5, we show channel by channel the number of sources identified with sources in these
three catalogs (entries “Identified in WMAP catal.”, “Identified in NEWPS_5yr_5s,” and “Identified in ERSC”).

### 4.2. Comparison with Catalogs at Other Frequencies

For all these 1116 sources, we run the identification procedure with catalogs at other frequencies. In Table 6, we show the relevant data. The first column corresponds to the source number, the second and third to right ascension (J2000) and declination in degrees, given by the weighted average of the positions in all frequencies where the source is found. Columns 4–8 correspond to the flux densities estimated at the given frequency. For converting the source temperature and errors from Kelvin to Jy, we use the effective beam area and relative error as presented in Table 4 of Jarosik et al. (2011). For the very weakest sources, we are unable to correct the flux for Eddington bias due to the low signal-to-noise level (see Section 4.3 below).

For these sources, we use the internal template to estimate the flux as explained in Section 4.3. These fluxes are in italic in the table. In the ninth column there are five flags, one for each catalog, indicating whether we detected the source at 5σ in the individual channel (“C”), or in the template with a 3σ detection in the channel (“F”), or not at all (“.”). In the 10th column, there are flags indicating if the found source is identified with one in a given catalog in at least one frequency: “W” for WMAP catalogs, “N” for the NEWPS_5yr_5s catalogs, and “P” for the ERCSC catalogs (at 30, 44, 70, 100 GHz only). This table is also available at http://fol.uio.no/frodekh/PS_catologue/Scodeller_PS_catalogue.txt.

The last two columns contain the identification with the GB6 (Gregory et al. 1996), Parkes-MIT-NRAO (PMN, Griffith et al. 1994, 1995; Wright et al. 1994, 1996), 1 Jy (Kühr et al. 1981) when possible or with the lower-frequency catalogs NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and SUMSS (Mauch et al. 2003) catalog counterparts, the offset from the position in the given catalogs, a flag “M” if there are multiple identifications possible (where we took the brightest one), and a flag “A” if the listed counterpart has a flux density below 100 mJy.

Of the 1116 detected sources, 1021 have a 5 GHz counterpart (either GB6 or PMN); counting also the sources identified with ones from Kühr et al. (1981), there are 1029 having a rather high-frequency counterpart. Sixty-nine sources have only a counterpart in the NVSS (61) or SUMSS (8) catalogs, and 16 sources have no known counterpart. Some of the identifications with weak sources in the catalogs (i.e., the ones with flag “A”) may be misidentifications. There are in total 104 sources with this flag. The mean distance between the position of our sources and the counterparts in catalogs is 12.1. Excluding the sources with a weak counterpart (with flag “A”), the mean distance to the counterpart for the remaining 1012 sources becomes 3.7, substantially lower than the upper limit for identification (15).

Among the 16 found sources that have no known counterpart, 14 are unique (meaning detected only in one channel) and all 16 are new (meaning not in the WMAP, NEWPS_5yr_5s, or ERCSC-catalogs); 6 of them are detected in K, 4 in Ka, 1 in Q, 5 in V, and 2 in W. With the numbers in mind of false detections due to Gaussian fluctuations at 5σ level (≈1.8 for \( N_{\text{side}} = 512 \)), these 16 are most likely spurious detections due to Gaussian fluctuations.

Of the 506 new detections (meaning not in the WMAP, NEWPS_5yr_5s, or ERCSC-catalogs) 235, 195, 8, and 52 have a counterpart in, respectively, GB6, PMN, SUMSS, and NVSS catalogs, and 46 of these have an identification with a weak counterpart (flag “A”). The mean distance to the counterpart for the new detections only is also 12.1, and if excluding the 46 new sources with flag “A,” it becomes 8.1. When considering only the sources that do not have flag “A,” we see that the mean distance to the counterpart is larger when using only new sources than when using all detected sources. This is to be expected since the new detections tend to be rather weak (most of them are less than 5σ in the channels) and hence resolve the position worse.

### 4.3. Bias Correction

Flux estimation is subject to the Eddington bias (Eddington 1940), which has the effect that with a given detection threshold the amplitudes of the weakest sources are overestimated. Using a power-law model \((\propto S^{-1/(1+q)}\) for \( S > S_m \), with \( S \) being the source flux and \( S_m \) a minimum flux from where the power law is valid) for the differential number count of galaxies, Herranz et al. (2006) present a Bayesian approach to correct for the bias. Their procedure allows us to estimate both the slope of the power law and the bias. The method is in two steps:

1. Estimate the slope via equation

   \[
   \frac{1}{q} = \frac{1}{N} \sum_{i=1}^{N} \left( \ln \left( \frac{S_i'}{S_m'} \right) + \ln \left( \frac{1 + \sqrt{1 - 4(1+q)/r_i}}{1 + \sqrt{1 - 4(1+q)/r_m}} \right) \right)
   \]

   where \( S_i' \) and \( S_m' \) are the observed (and hence biased) fluxes and minimum flux (which depends on the threshold),

\[\text{...}\]

\[\text{...}\]
Figure 1. All four plots show the same region on the sky. We show the needlet coefficients of the K- and V-band maps and the Ka−V template. We also show the V-band map in real space. In the band maps, red circle indicates source at \( \geq 5\sigma \) in the K band, blue circle indicates \( \geq 5\sigma \) in a template and \( \geq 3\sigma \) in the K channel, and gray circle means \( \geq 5\sigma \) in a template and \( < 3\sigma \) in the K channel. In the internal template, the three gray circles indicate sources that are \( \geq 5\sigma \) in the template but rejected (considered extended source/foreground) by the \( \chi^2 \) test. (A color version of this figure is available in the online journal.)

respectively, and \( r_i \) is the observed signal-to-noise ratio of the source.

This equation can be solved numerically, if \( r_m^2 \geq 4(1 + q) \).

2. Then obtain the unbiased fluxes \( S_i \) via

\[
S_i = \frac{S_i^o}{2} \left( 1 + \sqrt{1 - \frac{4(1 + q)}{r_i^2}} \right). \tag{3}
\]

For sources detected directly at \( 5\sigma \) in the WMAP channels, we find slopes \( 1+q \), respectively \( (2.04, 2.07, 2.06, 2.14, 2.12) \), while for the sources detected in the templates and then found at \( \geq 3\sigma \) in the channels we find \( (2.04, 2.08, 2.06, 2.15, 2.22) \). The two approaches give values of \( q \) in good agreement with each other and with other estimates; see for instance, on WMAP data (Chen & Wright 2009) or López-Caniego et al. (2007) and other rather high-frequency surveys such as ATCA 18 GHz survey (Ricci et al. 2004), 9C survey at 15 GHz (Waldram et al. 2003), or 33 GHz Very Small Array (VSA) survey (Cleary et al. 2005).

For sources with very low signal-to-noise ratio (in total for 71 different flux estimations corresponding to 71 different sources), the likelihood does not have a peak \( (r_m^2 < 4(1 + q)) \) and Equation (2) does not have a solution. In this case, we are unable to estimate the bias and therefore also the flux. In order to solve this problem, we use the internal templates where the source has a much higher signal-to-noise ratio. To find the flux in channel \( c \) where it is detected, then, if the source is not detected in channel \( c' \) (where the distance in frequency between \( c \) and \( c' \) is as large as possible), we assume that the flux is zero in \( c' \).
Figure 2. Two figures show the needlet coefficients of sources in the \( K \) band in two different parts of the sky. Gray dot indicates the source center as detected by the WMAP team. In our procedure these two sources are detected but rejected by the \( \chi^2 \) test. (A color version of this figure is available in the online journal.)

Figure 3. Two projections show the same part of the sky. In the center, we see one of our new sources (not found in other catalogs taken at the same frequencies, but identified with a source in catalogs at different frequencies) detected in the internal templates and found at \( \geq 3 \sigma \) in several frequency channels. (A color version of this figure is available in the online journal.)

With this assumption, we can use the amplitude estimated in the internal template and a corresponding bias correction to obtain the amplitude. To test this approach, we used a set of weak sources where we are able to estimate the bias correction with Equation (2). For these sources, we estimated the amplitude both directly in the channel and using the internal template approach and found full agreement (within error bars) between the two methods. Nevertheless, in Table 6 we have written the fluxes estimated only from the internal templates in italic.

### 4.4. Some Examples

In Figure 1, we show four projections, all of the same part of the sky. The needlet coefficients for the \( K \) - and \( V \)-band maps and the internal template \( Ka - V \) are shown. For reference we also show the \( V \)-band temperature map. The sources that are detected (i.e., above 5\( \sigma \)) in the \( K \) band are marked with a red circle; the sources that are detected (\( \geq 5 \sigma \)) in a template only and found \( \geq 3 \sigma \) in the \( K \) band are marked with a blue circle. Finally, the sources that we detect (\( \geq 5 \sigma \)) in the template but are below 3\( \sigma \) in the \( K \) band are marked with gray circles in the \( K \)-and \( V \)-band needlet maps. Comparing the \( K \)-band coefficients with the coefficients of the template, we see clearly how many more sources are seen in the template. Note also that some of the sources detected in the template seem off-center in the \( K \)-band circles. The reason for this is that the circles are made based on the centers detected in the template, which, due to fluctuations,
are often displaced with regard to the frequency maps. Looking at the V-band coefficients, we see that several of the detected sources are still present but at a much smaller amplitude.

In the figure showing the needlet coefficients for the internal template, there are three gray circles. These indicate sources that are detected at $\geq 5\sigma$ in the template but then rejected by the $\chi^2$ test. We can clearly see how some of these appear more elongated than the accepted sources, and according to the $\chi^2$ test these do not resemble the beam shape; this may indicate that the sources are extended, but also simply that the mean beam shape is not a good approximation in this part of the sky. In Figure 2, we show two more examples of sources that are detected but rejected by the $\chi^2$ test. Both of these are detected by the WMAP team; the gray dot indicates the center as detected by WMAP. In the first case, there seem to be two similar but very close sources, producing the elongated shape that the $\chi^2$ interprets as not being a point source. In the second case, there is a weak source close to a very strong one; the needlet amplification of the strong source distorts the vicinity of the weak source, making it fail the $\chi^2$ test.

Finally, in Figure 3, we show an example of one of our new sources that are not listed in the WMAP, NEWPS, or ERCSC catalogs, but identified with a 5 GHz counterpart (in PMN). The source is clearly seen above $5\sigma$ in the $K-Ka$ template, but in the figure we see that it is also above $3\sigma$ in the V-band needlet coefficients.

In Figure 4, we highlight the advantage of combining the direct detections with detections in internal templates. Both plots provide the (logarithmic) integral counts for $5\sigma$ detections in the channels and for the combination of detections that are either $5\sigma$ in the channels or $5\sigma$ in the templates and $3\sigma$ in the channels. For visibility reasons, the top plot shows these integral counts for the

Figure 4. Integral number counts of detected sources in WMAP 7 year data. “Direct” means only detections at 5$\sigma$ in the channels; “combined” means detections either at 5$\sigma$ in the channels or at 5$\sigma$ in the templates and 3$\sigma$ in channels. The lines represent a linear fit to the number counts. Top: for $K$, $Q$, and $W$ band. Bottom: for $K$ and $V$ band. NB: counts are computed in bin sizes of $\Delta S = 0.1$ (Jy), and the axes are clipped in order to enhance the most interesting part.
sources being parts of the diffuse galactic emission, we use many cases. In order to distinguish point sources from extended background of the internal templates makes detection easier in difference in amplitude from one frequency to another are In the internal templates, however, the sources with the largest templates where the CMB is eliminated. In the frequency maps, noise as background, we also use needlet coefficients of internal sources in CMB data. First, we use needlet coefficients of frequency maps optimized for point-source detection, and sources in CMB data. For the combined integral counts, we obtain complete sets of detections till approximately 0.60, 0.64, 0.72, 0.80, 0.84 Jy in the respective channels. In both plots the lines represent a linear fit to the number counts, starting at the approximate completeness limit (of the combined counts).

5. CONCLUSIONS

We have developed a new procedure for detecting point sources in CMB data. First, we use needlet coefficients of the frequency maps optimized for point-source detection, and second, in addition to the frequency maps having CMB and noise as background, we also use needlet coefficients of internal templates where the CMB is eliminated. In the frequency maps, only the sources with the strongest amplitude can be detected. In the internal templates, however, the sources with the largest difference in amplitude from one frequency to another are more easily detected. In addition, the pure instrumental noise background of the internal templates makes detection easier in many cases. In order to distinguish point sources from extended sources being parts of the diffuse galactic emission, we use \( \chi^2 \) tests to eliminate point-like structures that do not have a beam-like shape. In this paper, we have applied this new point-source detection procedure on the WMAP 7 year data.

We first used the beam and noise properties of the WMAP channels to optimize the kind of needlet to use for point-source detection for each of the five WMAP frequency channels, as well as for the five internal template combinations with the highest signal-to-noise ratio. We then produced a set of simulated maps with simulated point sources, in order to test the detection procedure and to estimate error bars on amplitude and position. We used a 5\( \sigma \) detection limit on the needlet coefficients in the frequency bands as well as in the internal templates. We detected in total 522 sources in the frequency bands only, and 2052 sources in the internal templates only, which all passed the rather conservative \( \chi^2 \) test. For sources that we detected at 5\( \sigma \) in the frequency maps, or at 5\( \sigma \) in the templates and at the same time \( \geq 5\sigma \) in the frequency maps, we estimated flux and position and attempted to identify them with sources found in other catalogs. All these 1116 sources are listed in Table 6, of which 1029 have a 5 GHz or 1 Jy counterpart. Of the remaining, 69 have only lower-frequency catalog counterparts and 16 have no known lower-frequency counterpart. When comparing to catalogs based on WMAP data (the two catalogs obtained by the WMAP team (Gold et al. 2011) and the NEWPS catalogs (Massardi et al. 2009)) or other observations at similar frequencies (the ERCSC based on Planck data (Planck Collaboration 2011)), we find 487 sources also found in the WMAP catalogs, 415 also found in the NEWPS_5yr_5s catalog, and 517 found also in the ERCSC (at least one frequency of either 30, 44, 70, 100 GHz). We point out that among the 49 sources in the WMAP catalogs that we do not detect/accept, only 13 are not detected; the remaining are either excluded by the \( \chi^2 \) test or the position is offset such that we are unable to identify it with our source. Finally, of the 1116 sources in Table 6 (also available at http://folk.uio.no/frodekh/PS_catalogue/Scodeller_PS_catalogue.txt), 506 are not identified with sources in any of the catalogs based on WMAP or WMAP-like frequencies, but most are identified with a 5 GHz counterpart. And 603 of 1116 sources have not been previously detected in WMAP data.

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