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# Deliverable 5.1

*Beam deconvolution map maker*

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**Work Package** WP5 - Beam deconvolution map making

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# Revision History

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|---|---|---|---|
| Version | Authors | Date | Changes |
| 1.0 | Anna-Stiina Suur-Uski<br>Elina Keihänen | 1 September 2019 | Initial Version |
| 1.1 | Anna-Stiina Suur-Uski | 22 October 2019 | Results from BeyondPlanck deconvolution tests |

# Contents

# Overview

Standard maps, such as Madam maps (E. Keihanen et al., Astron. Astrophys., 510: A57, 2010), are not corrected for beam shape, but each data sample is assigned entirely to the pixel where the center of the beam falls. The beam shape will affect the maps in several ways: image of a point source does not appear symmetric, and part of the temperature signal is misinterpreted as polarization (leakage of temperature signal to polarization through beam shape mismatch).

Beam deconvolution aims to remove the effects of beam asymmetry. We use ArtDeco beam deconvolver to produce beam deconvolved maps (E. Keihänen et al., Astron. Astrophys., 548: A110, 2012). The effective beam is symmetric and leakage from temperature to polarization due to asymmetric beams has been eliminated in the beam deconvolved maps.

ArtDeco has been previously successfully applied to Planck LFI data (E. Keihänen et al., Astron. Astrophys., 587:A27, 2016; E. Keihänen et al., arXiv:1905.05440v1, 2019).

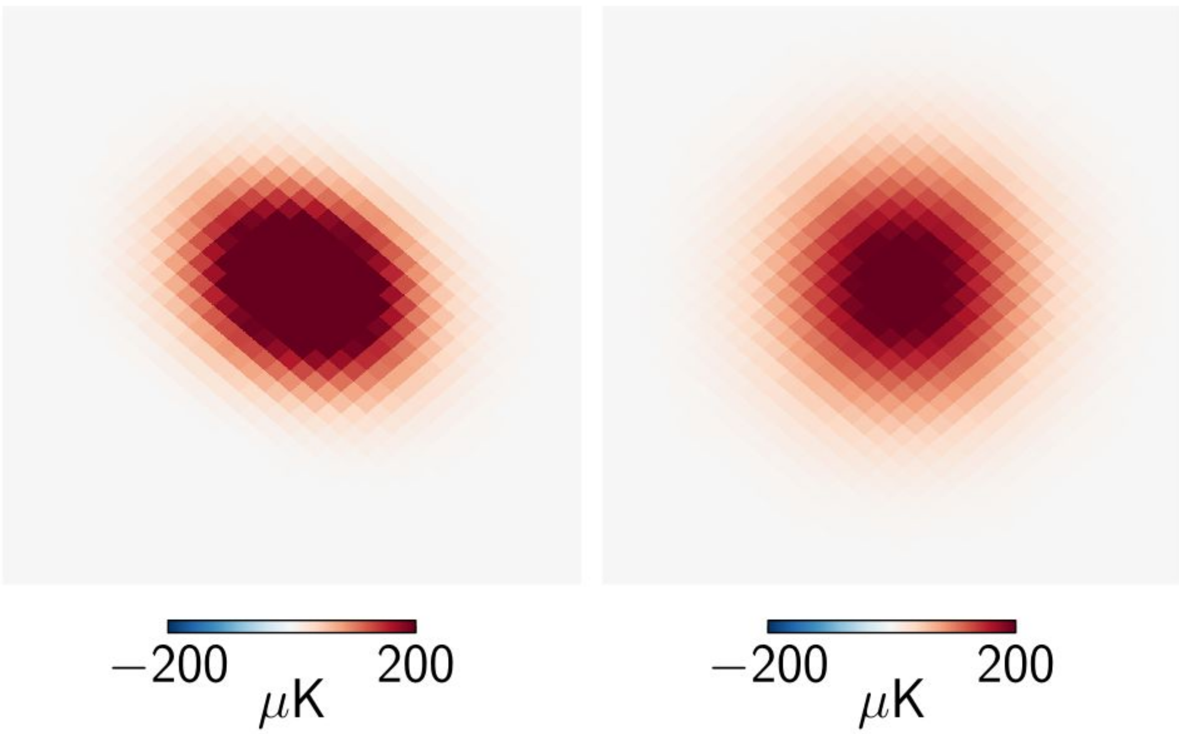


**Figure 1**: The effect of beam deconvolution for a point source. *Left:* Ordinary map. A point source appears elliptical. *Right:* Beam deconvoled map. The effective beam is symmetrized.

# Beam deconvolution in BeyondPlanck

Beam deconvolution is not part of the official BeyondPlanck pipeline. Beam deconvolution can be either run at the end of the pipeline or for example after every 100 iterations.

Beam deconvolved maps provide an additional data set for cross-checks and validation.

BeyondPlanck pipeline has been updated to output 4D maps for every *n*th sample. These 4D maps are input to the deconvolution.

# Data

ArtDeco **inputs**:
- Cleaned TOD (calibrated and destriped TOD)
- Detector pointing
- Beam model

TOD and pointing are imported as 3D objects, which are compressed TOD objects. While a usual two-dimensional Healpix map is a function of two angles $\theta,\varphi$ (latitude and longitude), a 3D map adds to these the third pointing angle $\psi$, which specifies the detector orientation. 3D objects are constructed from Madam 4D maps. Beams shapes are given in the form of the harmonic expansion of the beam shape, $b\_slk$.

ArtDeco **output**:
- Harmonic coefficients *a_slm* representing the beam-free sky.

The harmonic coefficients can be converted into a conventional two-dimensional sky map with a spherical harmonic transform. Because the harmonic representation is limited up to a cut-off *l_max* that depends on a beam width, the resulting maps must be smoothed with a Gaussian window to eliminate ringing artefacts.

# Software and compilation

**ArtDeco:**

- ArtDeco is available in the BeyondPlanck GitLab repository
    - https://gitlab.com/BeyondPlanck/repo/tree/master/artdeco
- To compile ArtDeco, the user must have access to the following compilers and libraries:
    - C MPI compiler
    - FFTW, http://www.fftw.org/
    - Level-S, http://adsabs.harvard.edu/abs/2006A%26A...445..373R
    - CFITSIO, https://heasarc.gsfc.nasa.gov/fitsio/fitsio.html
    - HEALPix, https://healpix.jpl.nasa.gov/
- Following modules need to loaded before compiling:
    - module load Intel_composer_xe/2017/1.132
    - module load openmpi/Intel/2.1.3
    - module load Intel_parallel_studio/2018/3.051
- To compile the code:
    - cd <your_path>/artdeco
    - make deconvolver_cxx
- The resulting executable is <your_path>/artdeco/deconvolver_cxx.

**Map4Dtools:**

- Map4Dtools are available in the BeyondPlanck GitLab repository
    - https://gitlab.com/BeyondPlanck/repo/tree/master/Map4Dtools
- To compile Map4Dtools, the user must have access to the following compilers and libraries:
    - C MPI compiler
    - FFTW, http://www.fftw.org/
    - Level-S, http://adsabs.harvard.edu/abs/2006A%26A...445..373R
    - CFITSIO, https://heasarc.gsfc.nasa.gov/fitsio/fitsio.html
- HEALPix, https://healpix.jpl.nasa.gov/Following modules need to loaded before compiling:
    - module load Intel_composer_xe/2017/1.132
    - module load openmpi/Intel/2.1.3
    - module load Intel_parallel_studio/2018/3.051
- To compile the code:
    - cd <your_path>/Map4Dtools
    - make
- The resulting executables are in <your_path>/Map4Dtools/bin.

# Usage

One of the Madam map-maker outputs are 4D maps. 4D maps contain additionally time information in the form of a pointing period index. First run map4Dto3D to compress 4D maps into 3D maps, which are used as an input in the ArtDeco.

Run **map4Dto3D**:
- In: One 4D map from Madam per horn
- Out: One 3D map per detector
- Example script is https://gitlab.com/BeyondPlanck/repo/blob/master/artdeco/examples/map4Dto3D_v2.sh

Run **deconvolver_cxx** (part of ArtDeco):
- In: one 3D map per detector, harmonic expansions of beam shape
- Out: Harmonic coefficients a_slm representing the beam-free sky
- Example script for running deconvolution is: https://gitlab.com/BeyondPlanck/repo/blob/master/artdeco/examples/Deconvolve.sh
    - For 30GHz we have chosen following parameters (see E. Keihänen et al., arXiv:1905.05440v1, 2019): *l_max=800, k_max=600, Pol=T, N_side=1024, FWHM=40*

# Validation

We have run the deconvolution software successfully on the BeyondPlanck pipeline products. We have also run the deconvolution on data corresponding the Planck PR3 data release (DX12), and compared the results with PR3 deconvolved maps from E. Keihänen et al., arXiv:1905.05440v1, 2019.

In Fig. 2 we show both the BeyondPlanck deconvolved and undeconvolved maps, and their difference.  The difference shows three main features:
1. White noise from the undeconvolved map, since the deconvolved map is smoothed more strongly.
2. The difference in smoothing gives also rise to the red-blue structure at the galactic plane.
3. Deconvolution scales the overall signal level up to compensate the missing beam power and thus we see a faint copy of dipole in the difference map.

All these are expected features for this particular run.

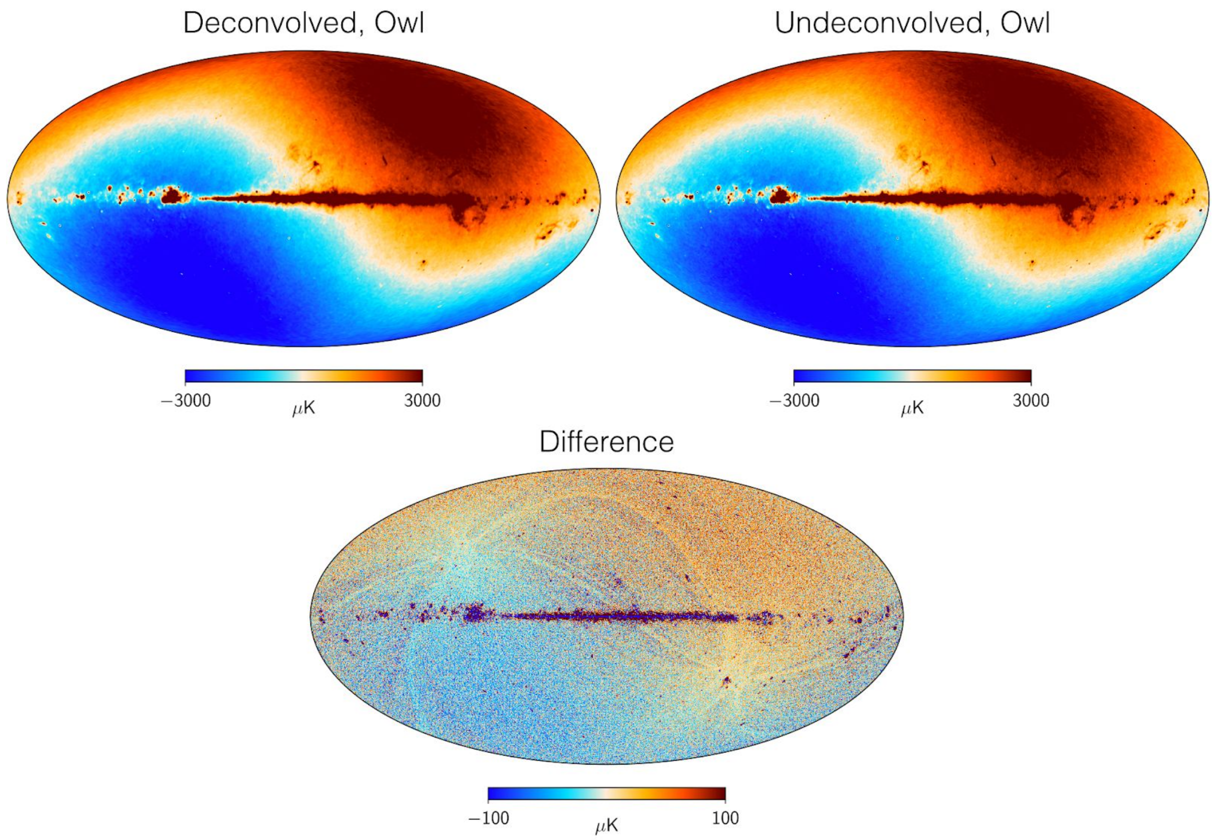


**Figure 2**: Top row: Deconvolved and undeconvolved maps. Bottom row: Difference map. Difference is similar to the one in E. Keihänen et al., arXiv:1905.05440v1, 2019, except for the dipole pattern.

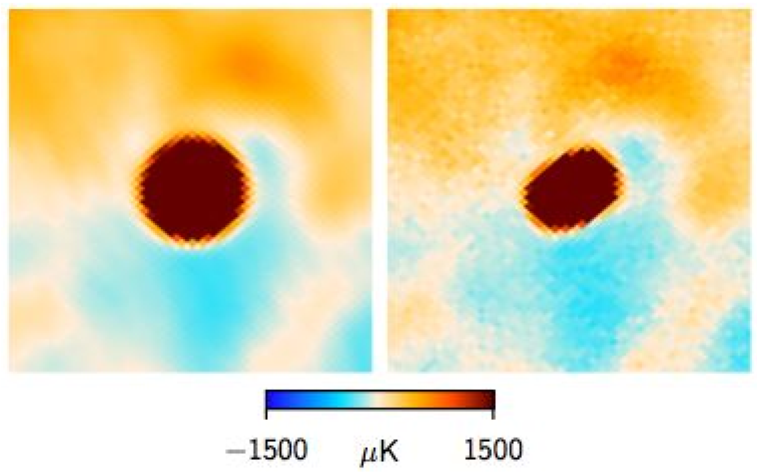


**Figure 3**: A 10 degree patch around the Tau A in the 30 GHz temperature map. *Left*: deconvolved. *Right*: Undeconvolved map.

Fig 3. Illustrates the effect of deconvolution on a given point source, and the source indeed appears symmetric.

The ArtDeco beam deconvolver is ready to be used for BeyondPlanck work on the Oslo cluster.

# Refrences

E. Keihanen et al. Making cosmic microwave background temperature and polarization maps with MADAM, Astron. Astrophys., 510: A57, 2010
E. Keihänen and M. Reinecke. ArtDeco: a beam-deconvolution code for absolute cosmic microwave background measurements, Astron. Astrophys., 548: A110, 2012

E. Keihänen et al. Impact of beam deconvolution on noise properties in CMB measurements: Application to Planck LFI, Astron. Astrophys., 587:A27, 2016

E. Keihänen et al. Beam deconvolved Planck LFI maps, arXiv:1905.05440