NPIPE — Planck data processing pipeline

On behalf of Planck and the international NPIPE team
Reijo Keskitalo
Lawrence Berkeley National Laboratory and University of California Berkeley

NPIPE

- is a data processing pipeline built on TOAST[1] time-ordered data processing framework
- is a collaborative effort leveraging two decades of software, analysis techniques and expertise developed in Planck
- runs at the National Energy Research Scientific Computing Center (NERSC) in Berkeley, California, *and (almost) any other cluster or supercomputer*
- processes raw, digitized signal into calibrated frequency maps
- is the first pipeline to handle both Planck LFI and HFI data in a common framework

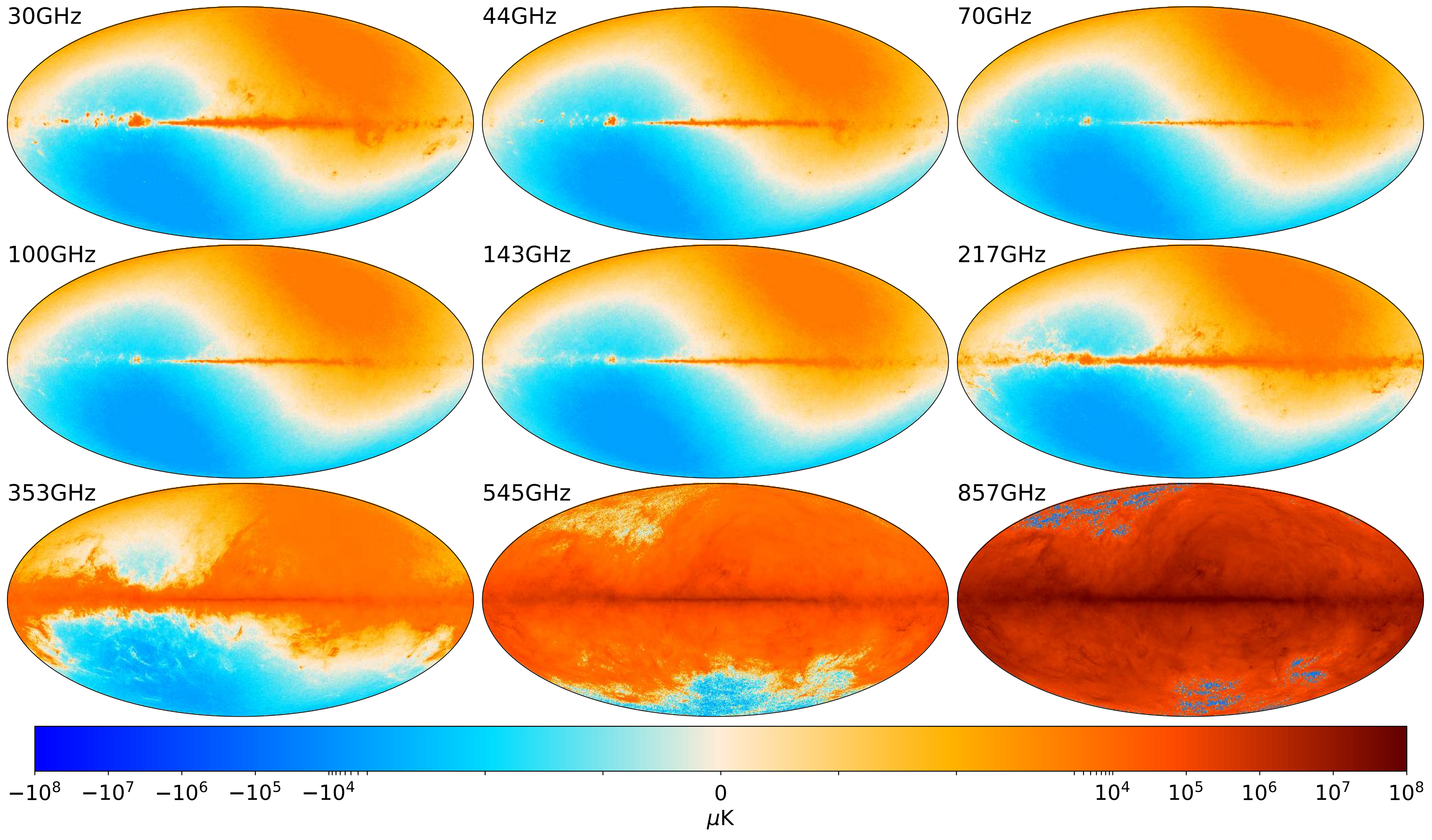


Fig. 14. NPIPE temperature maps, including the Solar dipole. The scaling is linear between −3 and 3 mK.

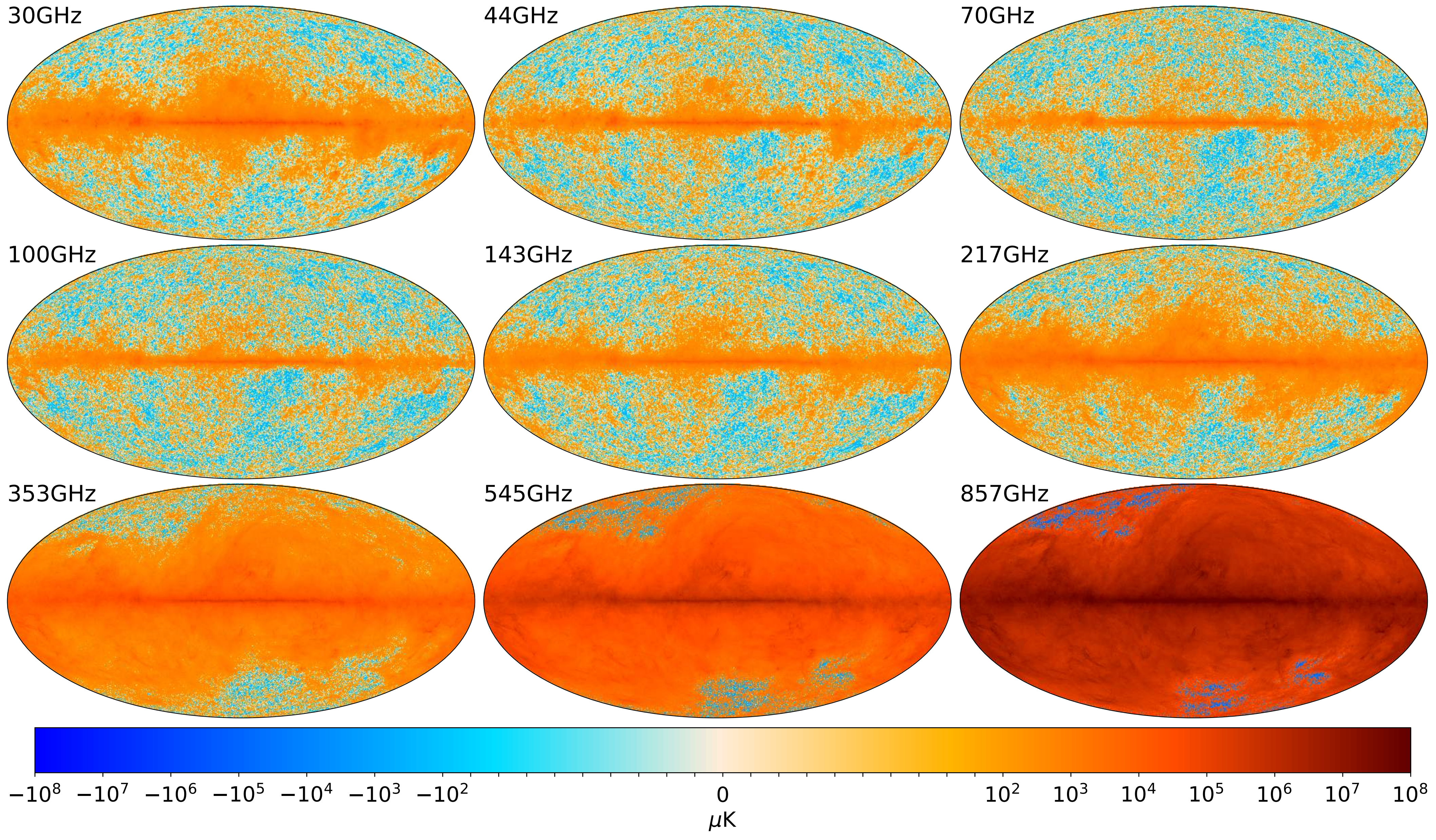


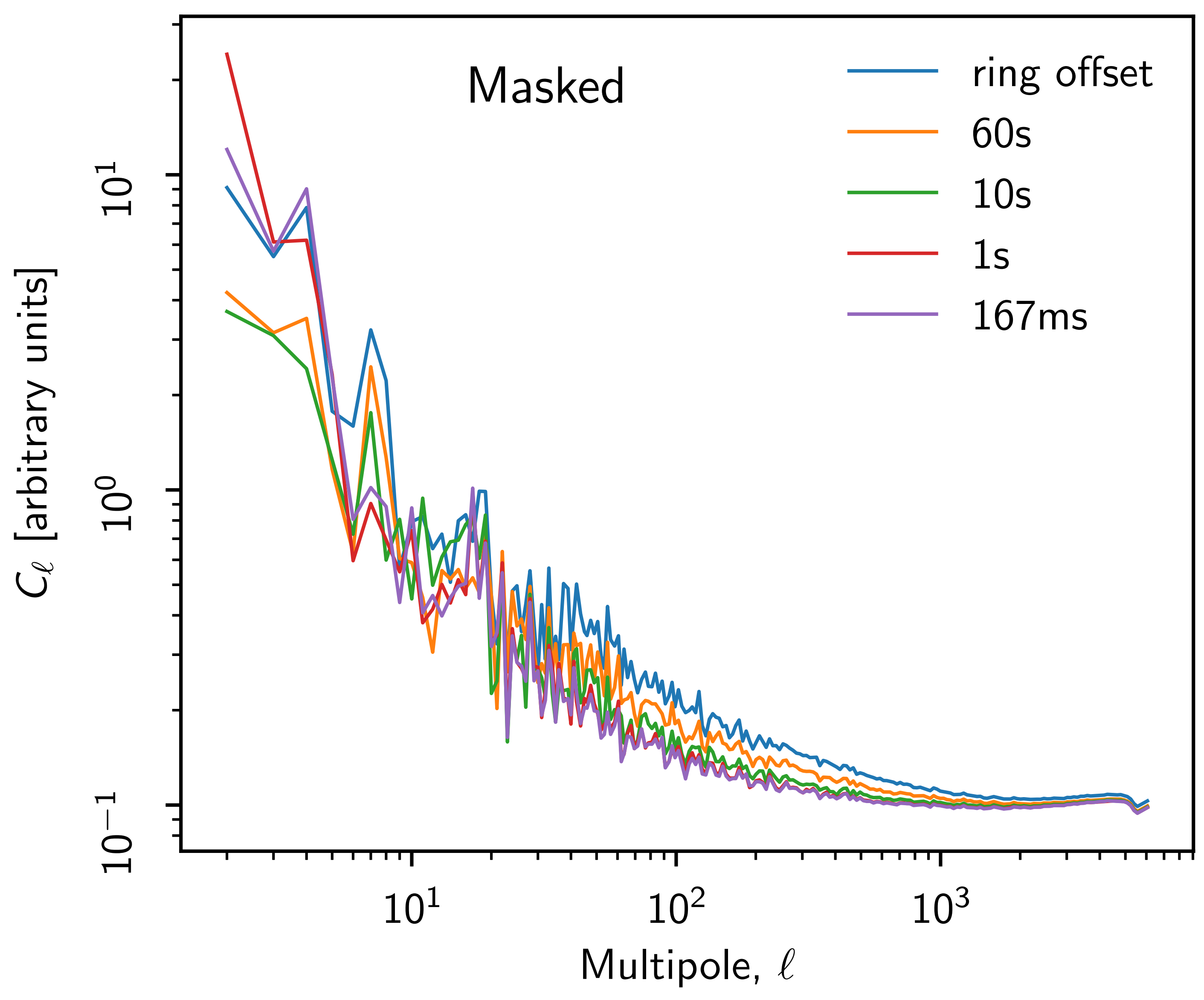
Fig. 15. NPIPE temperature maps, with the *Planck* 2015 dipole removed. The scaling is linear between −100 and 100 μK.

[1] : https://github.com/hpc4cmb/toast

What makes NPIPE special?

NPIPE combines the best parts of the independent LFI and HFI data processing pipelines. Most notably NPIPE:

- breaks large scale polarization degeneracies in calibration by using polarized sky templates (from LFI)
- performs a global fit of gain fluctuations, systematics templates and time-dependent sky signal (from HFI)
- uses the generalized destriper, *Madam*[1], to approximate minimum noise solution using short, 166ms noise steps (from LFI)

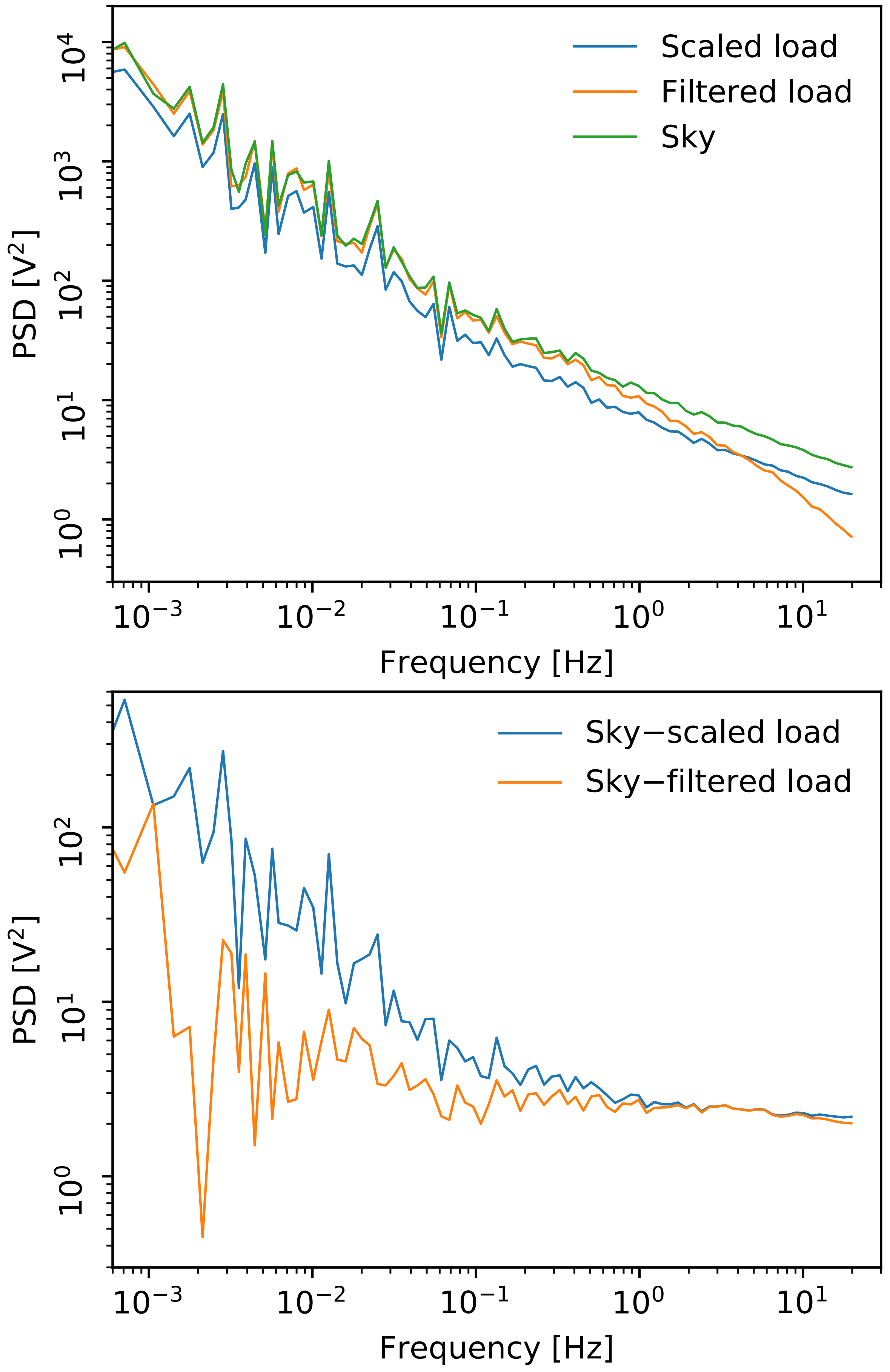


Dark bolometer signal destriped and projected onto a map with various noise step (baseline) lengths

[1] : E. Keihänen, H. Kurki-Suonio and T. Poutanen: Madam - A Map-making method for CMB experiments, MNRAS 360 (2005) 390, astro-ph/0412517

Differences between NPIPE and PR3 processing (1/2)

- Include re-pointing maneuvers and incomplete survey 9
- Apply pointing model corrections developed for Herschel
- Apply low-pass filter to reduce small scale noise in the sky-load differenced LFI signal
- Improve the HFI cosmic ray glitch removal to reduce noise bias and scan-synchronous glitch residuals
- Fit for 1Hz spikes, including aliased modes, in all LFI detectors
- Add new 4-Kelvin cooler interference templates and track the time evolution of the more intense harmonics (HFI)



Top: power spectral density (PSD) of sky and load signals for one 44GHz detector
Bottom: PSD of the differenced signal.

Differences between NPIPE and PR3 processing (2/2)

- Retain the solar system dipole in the frequency maps
- Provide maximally independent detector set (A/B) splits
- Add more transfer function harmonics in HFI templates
- Interpolate map-based templates to sample positions to avoid low resolution pixelization artifacts
- Provide depolarized single-detector maps for all Planck detectors and horns, use 0.86 arc minute resolution for 217–857GHz
- Measure and correct HFI polarization angles and efficiencies

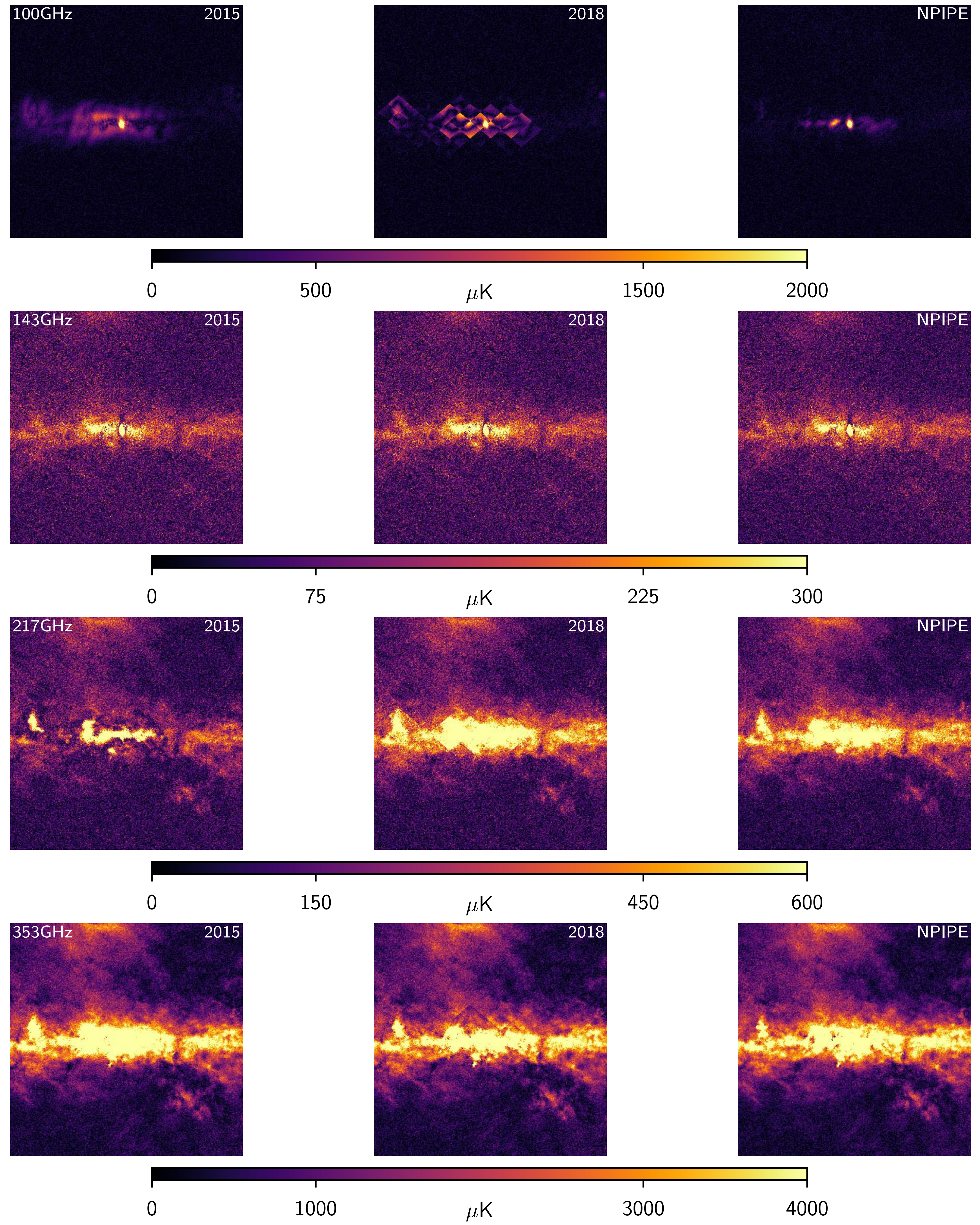


Fig. D.1. Polarization amplitude in an 8° × 8° patch centred around the Galactic centre. The linear colour scale was chosen to demonstrate the low-resolution CO template residuals in the 2018 maps. The residuals are most pronounced at 100 GHz, where the CO corrections are largest, and absent at 143 GHz, where there is no CO correction needed. Since the 2015 maps are not corrected for bandpass mismatch, they do not display the same artefacts..

Destriper (NPIPE) formalism

time-domain templates

All detector samples

template amplitudes

$$\boldsymbol{d} = \mathrm{P}\,\boldsymbol{m} + \mathrm{F}\,\boldsymbol{a} + \boldsymbol{n}$$

pointing matrix

stationary sky map

detector noise not included in the noise offsets

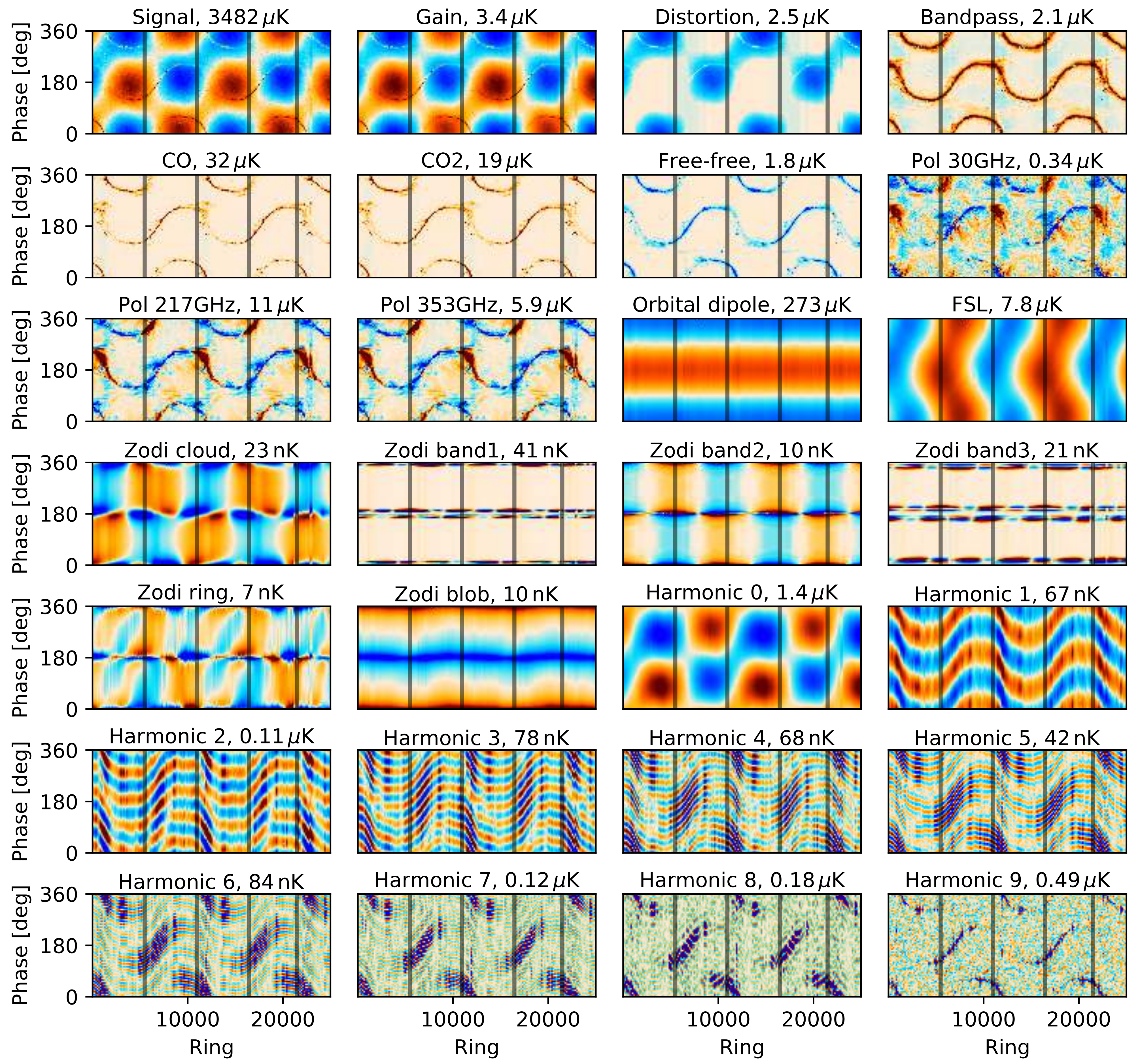


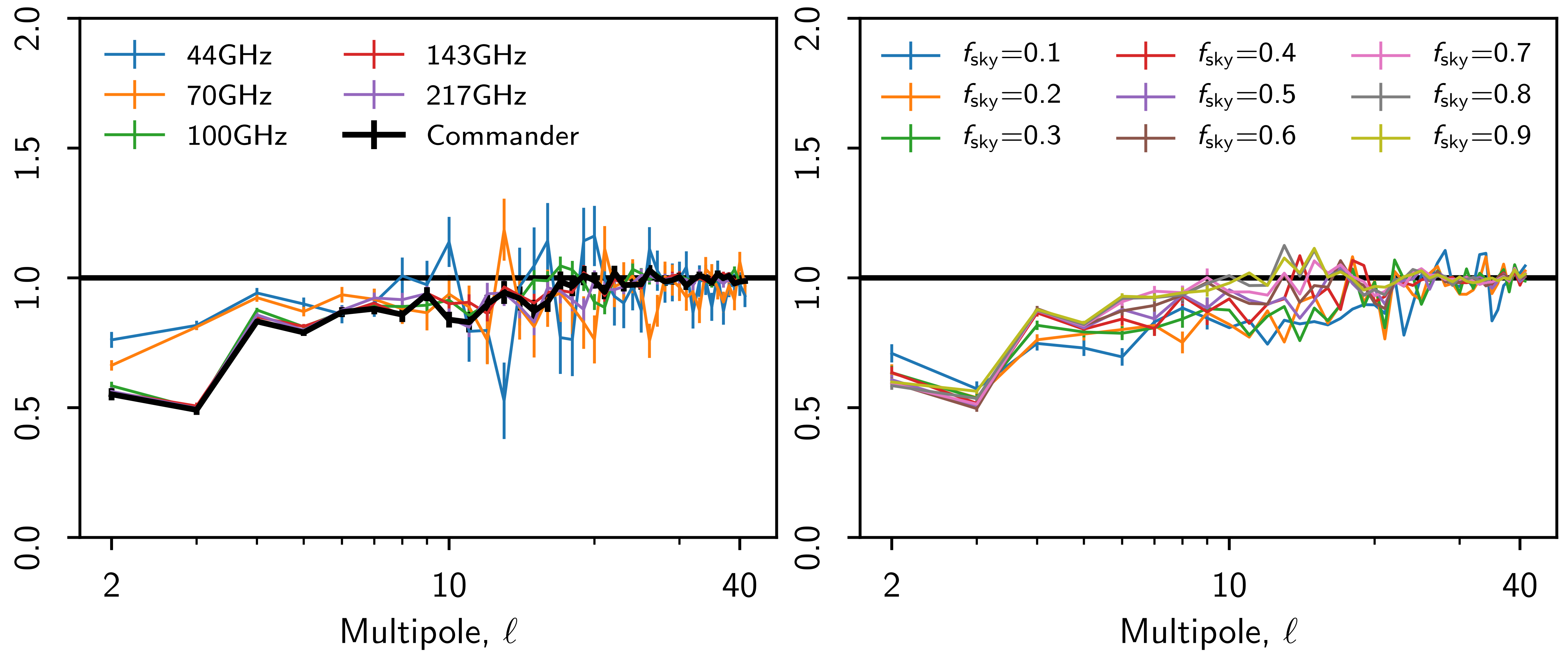
Fig. E.1. Signal and systematics templates for detector 100-1a, plotted as a function of pointing period (ring) and spacecraft spin phase. The gain and signal distortion templates are actually split into several disjoint steps that vary in length depending on the S/N. The templates for 100-1b are otherwise identical, but the 30, 217, and 353 GHz polarization templates are multiplied by −1. The far sidelobe (FSL) template is not fitted because of degeneracies, but it is estimated and subtracted. The polarization templates across all detectors share a single fitting amplitude. The zodiacal emission-template amplitudes are similarly shared. For 353 GHz and above, the harmonic templates are doubled to include frequency-dependent gain. At 100–217 GHz, only relative time-shift between frequency bins is modelled. The last harmonic template includes all frequencies not included in the other harmonic templates. The templates are scaled to match the rms amplitude of each systematic across the 100 GHz detectors, and the plotting ranges are chosen to match the $2\,\sigma$ range of each panel. To save space, the amplitude is reported in the title of each panel rather than as a colour bar. The grey vertical lines indicate the survey boundaries. Figure E.2 shows `HEALPix` maps of these templates that include only the first survey.

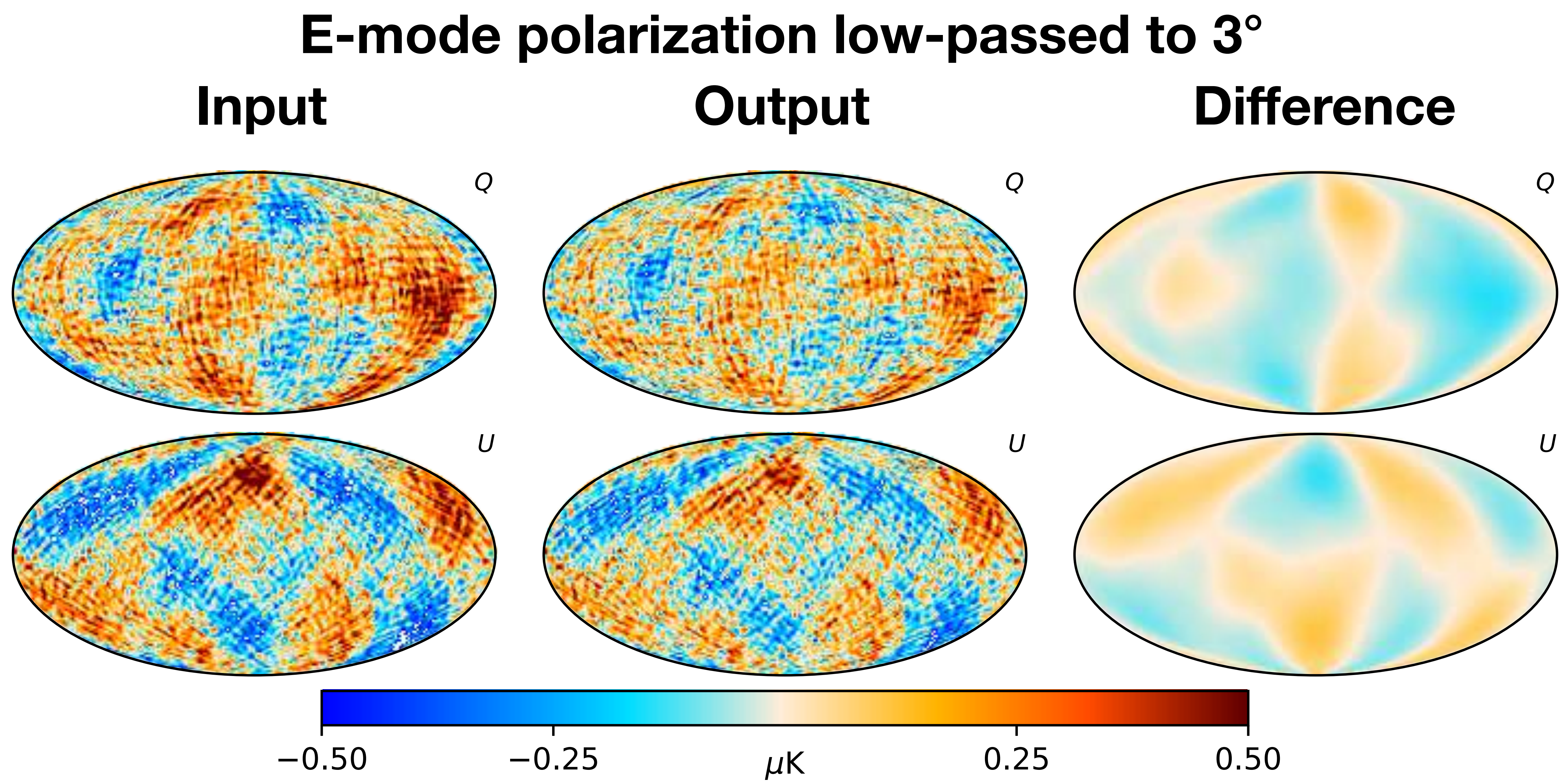
Templates included in F:

- noise offsets
- gain fluctuations
- HFI ADC nonlinearity
- orbital dipole
- HFI transfer function residuals
- Zodiacal emission components
- bandpass mismatch
- polarization templates

NPIPE transfer function

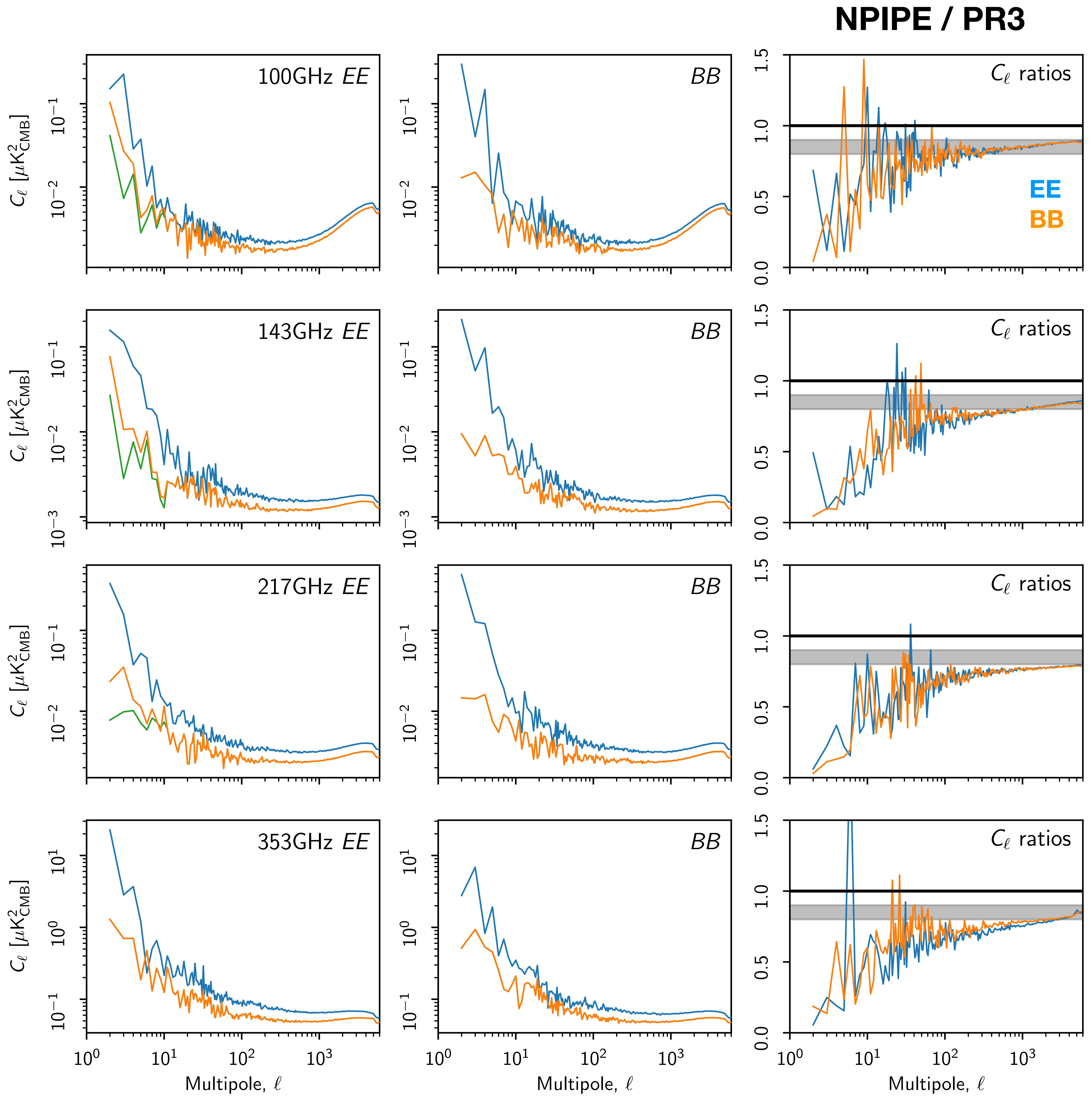
- The polarization prior breaks degeneracies and substantially reduces large scale polarization uncertainty
- The downside is that polarization power at ell < 20 is suppressed
- The pipeline transfer function seems remarkably stable across frequency and sky fraction





Null map comparison

- Here we compare detector set differences between PR3 and NPIPE
- These power spectra comprise only noise and systematics and demonstrate improvements at all angular scales
- NPIPE EE spectra are corrected for transfer function. Uncorrected spectrum in green



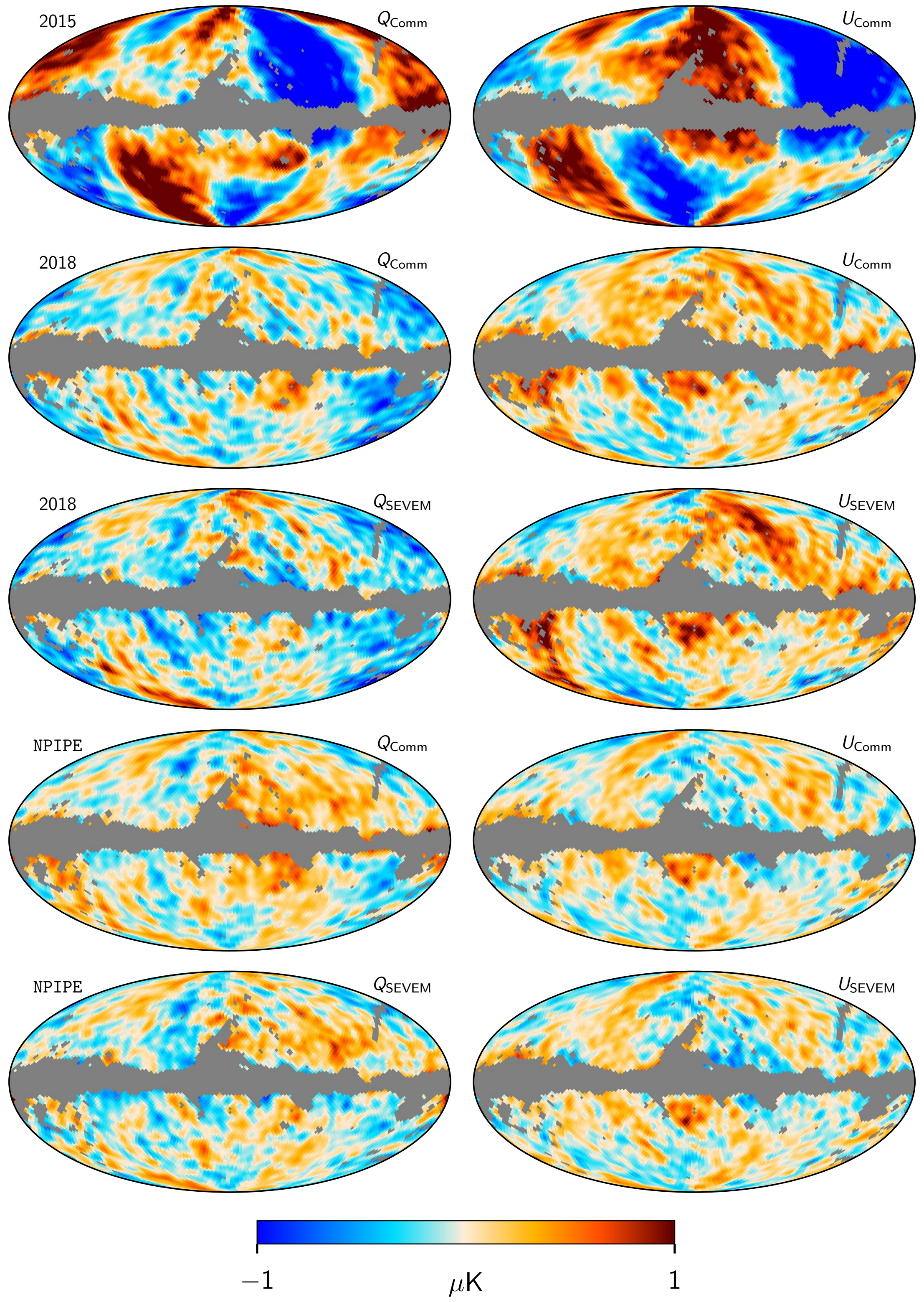


Fig. 59. Comparison of large-scale CMB Q and U maps from, *top to bottom*: `Commander` *Planck* 2015; `Commander` *Planck* 2018; `SEVEM` *Planck* 2018; `Commander NPIPE`; and `SEVEM NPIPE`. Note that the large-scale *Planck* 2015 CMB map in the *top row* was never publicly released, due to the high level of residual systematic effects. The grey region corresponds to the *Planck* 2018 common component-separation mask (Planck Collaboration IV 2020). All maps are smoothed to a common angular resolution of 5° FWHM.

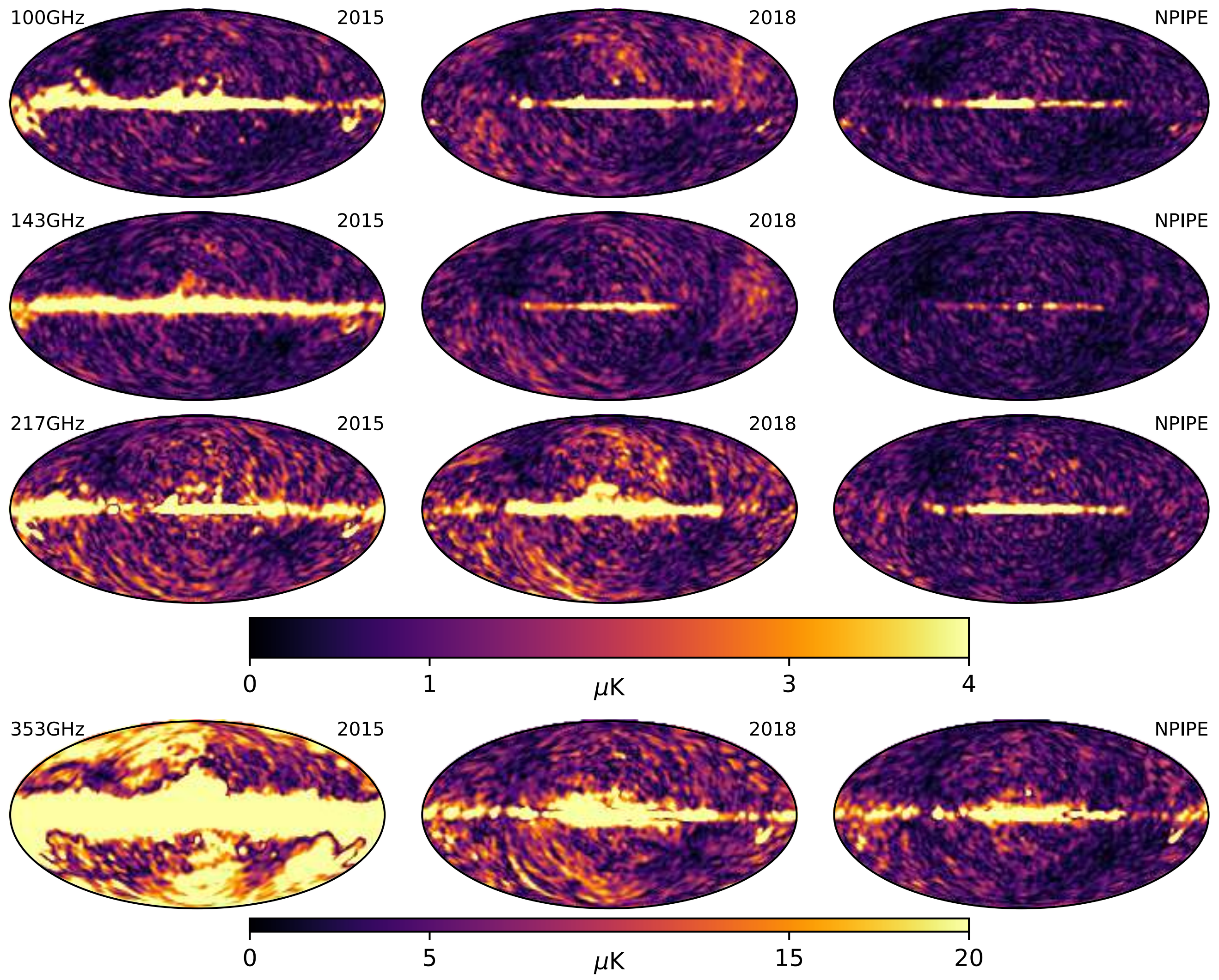


Fig. 39. Polarization amplitudes of the detector-set difference null maps. The angular power spectra of PR3 and `NPIPE` maps are shown in Fig. 40. Independent processing of the two detector-sets means that these maps reflect the level of total residuals in the frequency maps.

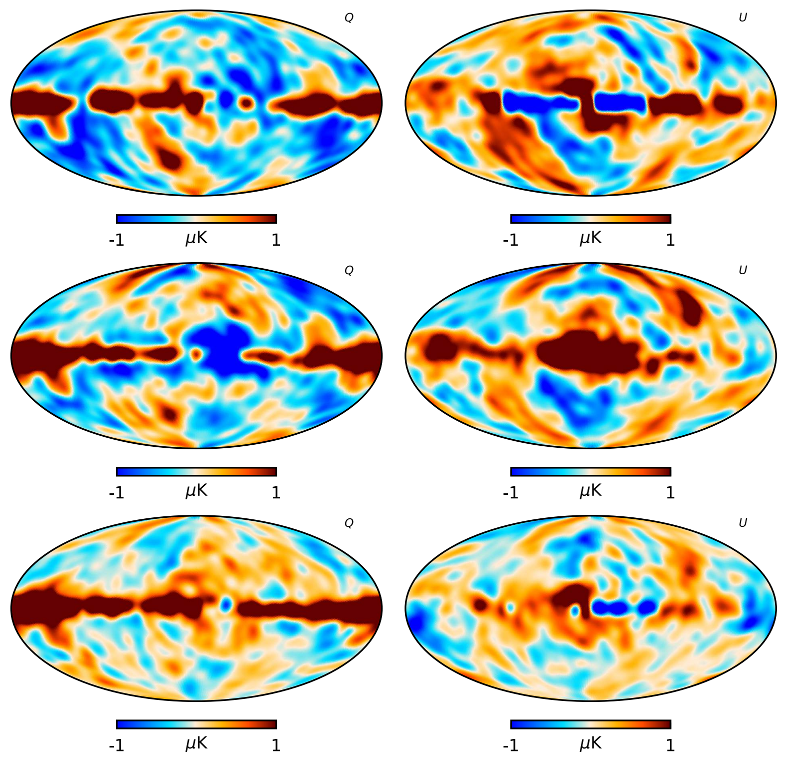


Fig. 48. Internal frequency-difference polarization maps of the form $\boldsymbol{m}_{217} - 0.128\,\boldsymbol{m}_{353}$, where the 353 GHz scaling factor is designed to suppress thermal dust emission at 217 GHz. From top to bottom, the three rows show difference maps based on `SRoll`, `SRoll2`, and `NPIPE`. The left and right columns show Stokes Q and U parameters, respectively. All maps have been smoothed to a common angular resolution of 10°.

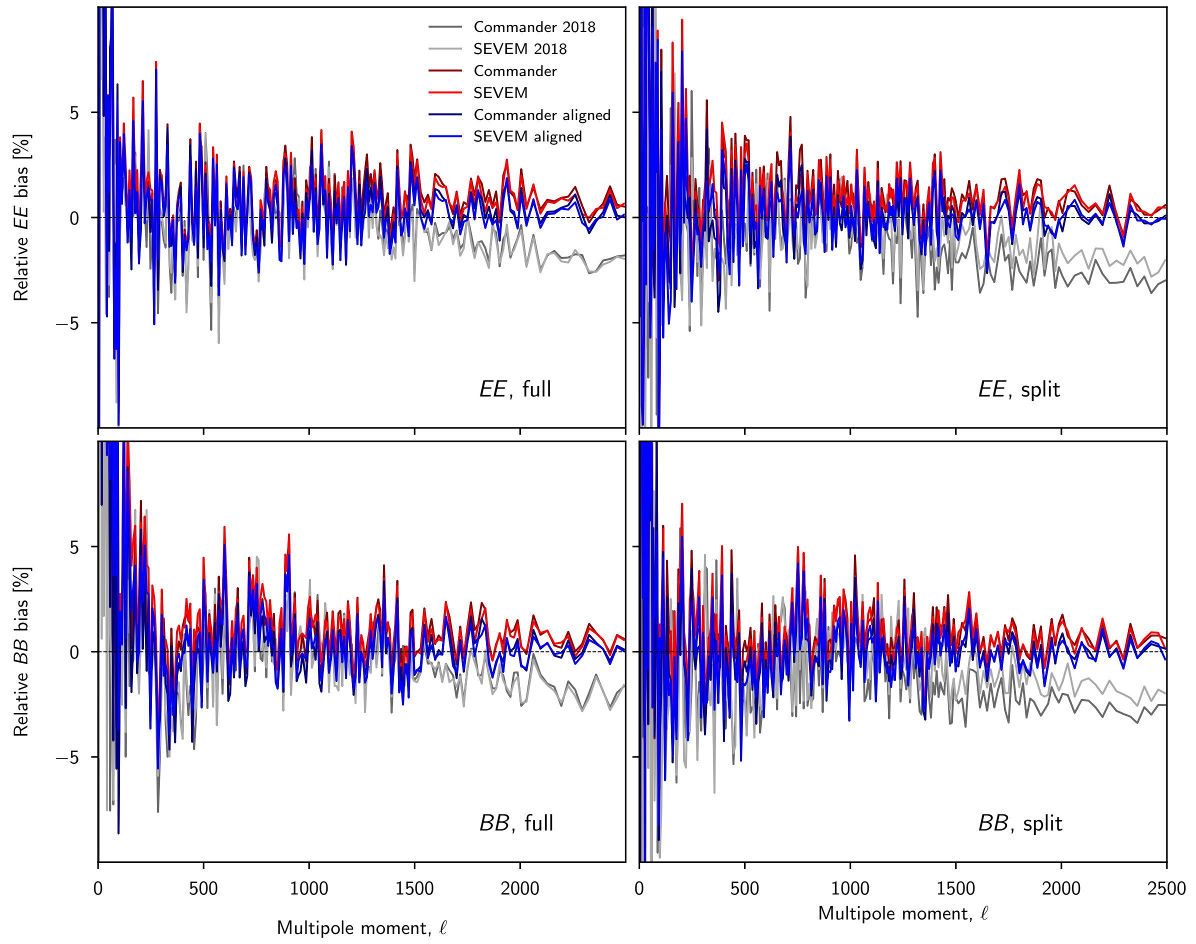


Fig. 73. Power spectrum consistency between the foreground-cleaned `Commander` (dark curves) and `SEVEM` (light curves) CMB polarization map and corresponding end-to-end-simulations. Each panel shows the fractional difference between the angular power spectrum computed from the observed data and the mean of the simulations. Blue and red curves show results derived for `NPIPE` data using simulations *with* and *without* noise alignment, respectively, while grey curves show similar results derived from *Planck* 2018 data using simulations *with* noise alignment. Rows show results for EE (*top*) and BB (*bottom*) spectra, while columns show results for full-mission (*left*) and split (*right*) data. In the latter case, A-B split results are shown for `NPIPE`, while half-mission splits are shown for *Planck* 2018.

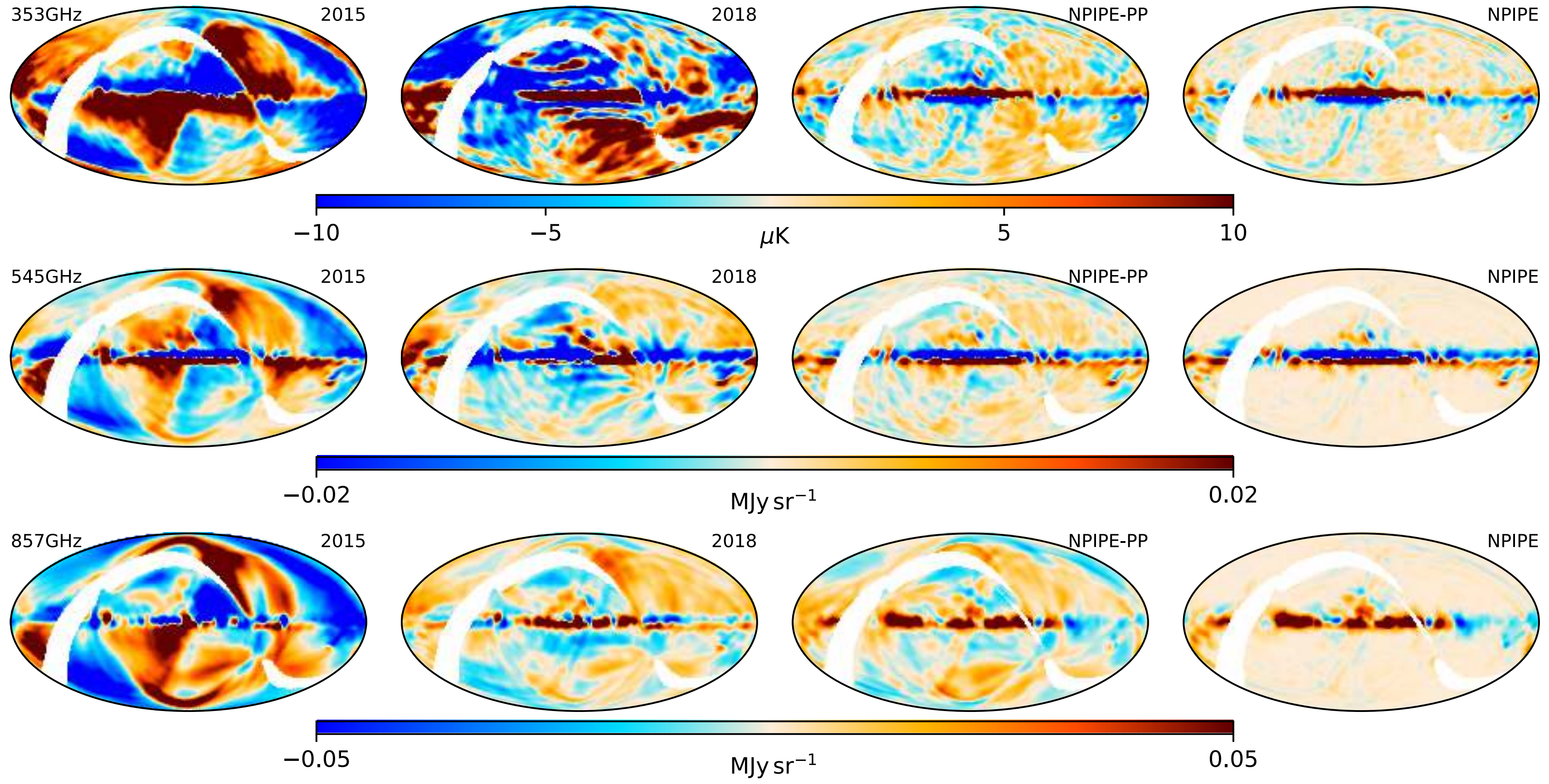


Fig. 47. Same as Fig. 46, but for 353, 545, and 857 GHz. The S-shaped residual along the Ecliptic equator, especially in the 353 GHz `NPIPE` results, is residual zodiacal emission.

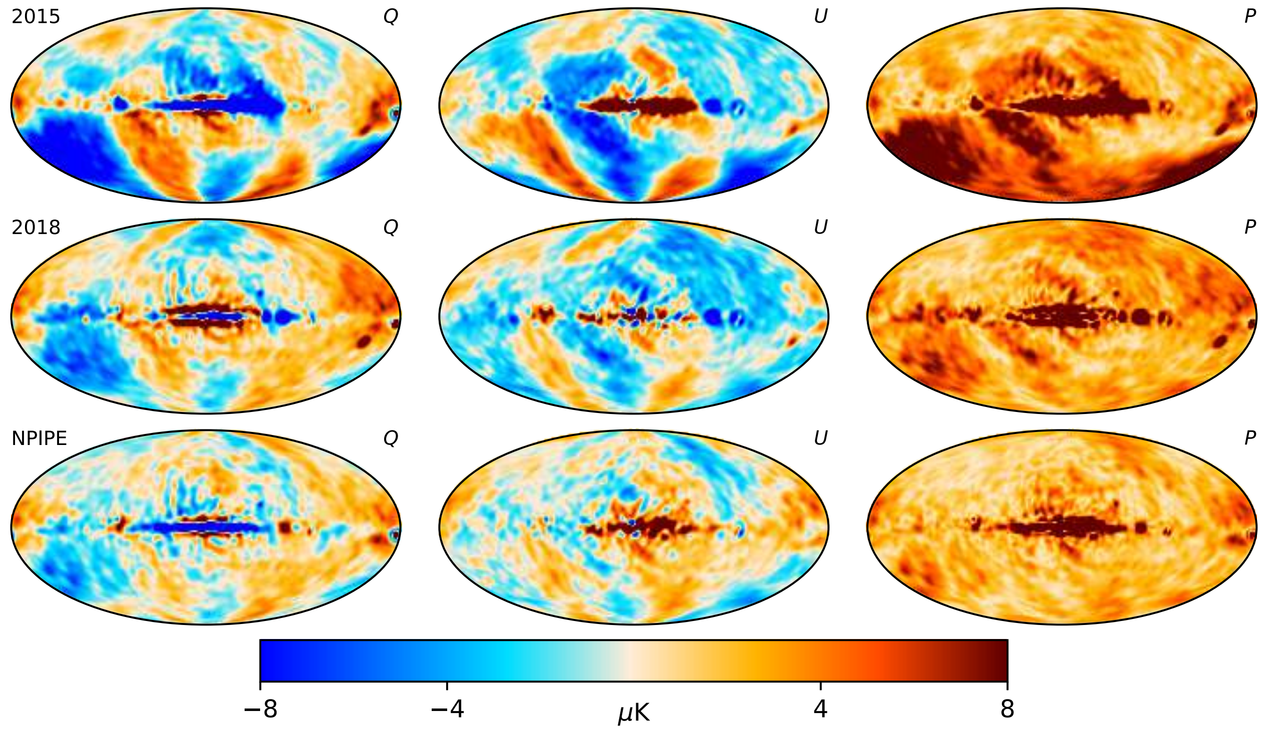


Fig. 50. *Planck* 30 GHz – WMAP *K*-band difference. The *K*-band regression coefficients by row (*top* to *bottom*) are 0.406, 0.451, and 0.462.

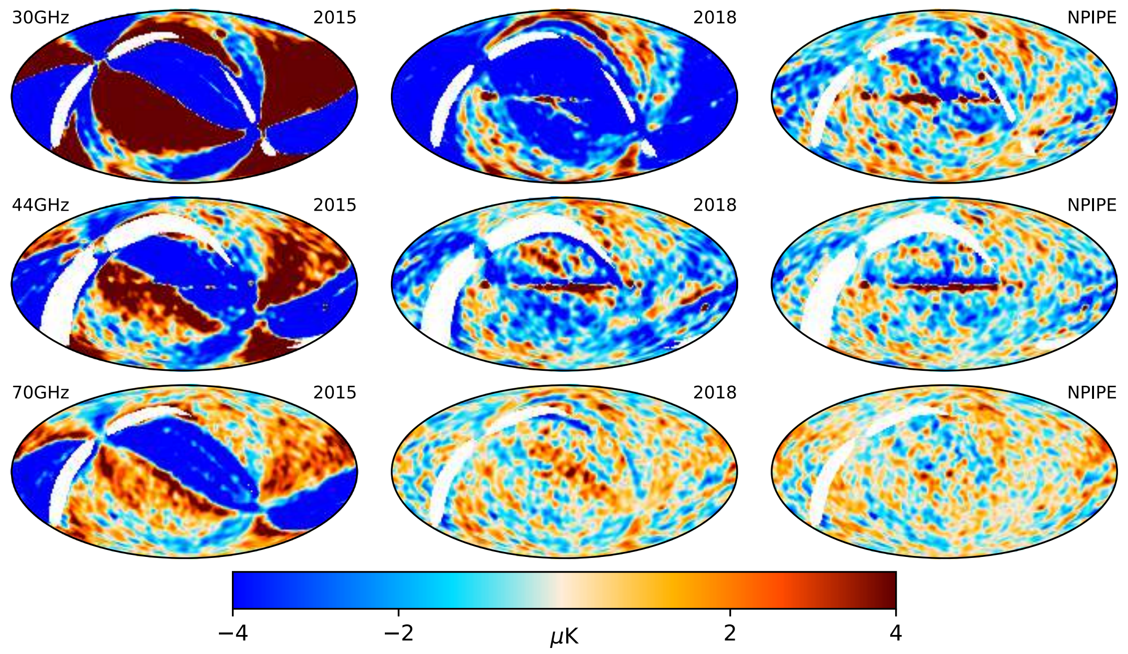


Fig. 45. Odd–even survey intensity differences for LFI smoothed to 5°. These maps reflect the internal consistency achieved, not the total residuals, since the calibration errors are correlated between the surveys. To match the 2015 and 2018 processing, the `NPIPE` 167 ms baseline offsets for this plot are solved using individual survey data.

NPIPE release

- Planck Collaboration : "*Planck intermediate results LVII. Joint Planck LFI and HFI data processing*", A&A 643, A42 (2020), arXiv:2007.04997

- Time-ordered data, maps and 600 end-to-end simulations are *soon* available on the Planck Legacy Archive (PLA): http://pla.esac.esa.int/pla *and* already available at NERSC. If you need a NERSC account, see https://crd.lbl.gov/departments/computational-science/c3/c3-research/cosmic-microwave-background/cmb-data-at-nersc

- NPIPE software is available on GitHub: https://github.com/hpc4cmb/toast-npipe

Conclusion

- NPIPE (PR4) offers significant improvements over earlier Planck data releases
- Much of the advantage comes from treating the Planck dataset as a whole and leveraging the extensive frequency coverage
- Despite its success, the internal NPIPE sky model is crude and affects a non-trivial transfer function on large scale CMB polarization
- Developing the sky model directly from the time-ordered data is a natural next step in multifrequency data analysis
- There is lots to explore in NPIPE. See Tristram et al, arXiv:2010.01139 for an example