

# COSMOGLOBE I. Improved Wilkinson Microwave Anisotropy Probe frequency maps through Bayesian end-to-end analysis

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## ABSTRACT

We present the first joint analysis of *WMAP* and *Planck* LFI time-ordered data, processed within the Bayesian end-to-end COSMOGLOBE framework. This framework builds directly on a similar analysis of the LFI measurements by the BEYONDPLANCK collaboration, and approaches the CMB analysis challenge through Gibbs sampling of a global posterior distribution. The computational cost of producing one complete *WMAP*+LFI Gibbs sample is 581 CPU-hr, including calibration, map-making, and component separation, of which 389 CPU-hr is spent on *WMAP* low-level processing; this demonstrates that end-to-end Bayesian analysis of the *WMAP* data is computationally feasible. We find that our *WMAP* posterior mean temperature sky maps are largely consistent with the official maps, and the resulting CMB power spectrum is in excellent agreement with previous results. The most notable difference is a slightly lower CMB quadrupole amplitude of  $\sigma_2 = 98^{+14}_{-6} \mu\text{K}^2$ , as compared to  $\sigma_2 = 229 \pm 97 \mu\text{K}^2$  from LFI alone. In contrast, our *WMAP* polarization maps differ more notably from the official results, and in general they exhibit weaker transmission imbalance residuals; it is particularly noteworthy that our *W*-band sky maps appear statistically consistent with the *V*-band maps. At a higher level, *WMAP*-minus-LFI frequency map differences appear for the first time visually consistent with instrumental noise over most of the sky. Still, we identify three specific issues that require additional work, namely 1) noise mismodelling at high temporal frequencies, 2) a quadrupolar *V*-band temperature residual at the  $2 \mu\text{K}$  level; and 3) a strong degeneracy between the absolute *K*-band calibration and the dipole of the anomalous microwave emission component. Nevertheless, we believe that the reprocessed *WMAP* maps presented here are significantly cleaner in terms of systematic uncertainties than the official *WMAP* maps, and they should be preferable for most scientific analyses that rely on *WMAP* measurements. Both sky maps and the associated code are made publicly available through the COSMOGLOBE web page.

**Key words.** ISM: general – Cosmology: observations, polarization, cosmic microwave background, diffuse radiation – Galaxy: general

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## 1. Introduction

The discovery of the Cosmic Microwave Background (CMB) by Penzias & Wilson (1965) marked a genuine paradigm shift in the field of cosmology, giving direct evidence that the Universe was once much hotter than it is today, effectively ruling out the steady-state theory of the universe (Dicke et al. 1965). Aside from a fundamental shift in the astrophysical history of the universe, this discovery spurred a series of cosmological experiments, which culminated in the Nobel Prize-winning measurements by COBE’s FIRAS and DMR experiments that confirmed the blackbody nature of the CMB and measured temperature variations from the primordial gravitational field (Smoot et al. 1992; Mather et al. 1994).

The *Wilkinson Microwave Anisotropy Probe* (*WMAP*) mission directly superseded the DMR, with the goal of making maps of the CMB that were 45 times more sensitive and 33 times higher angular resolution, all with the goal of measuring the physics of the universe at recombination (Bennett et al. 2003a). It can be argued that *WMAP*’s measurements of the CMB heralded a paradigm shift of similar magnitude to the 1965 discovery of the CMB. As quantified in Bennett et al. (2013), the volume of parameter space in standard  $\Lambda$ CDM allowed before *WMAP* was 68,000 times larger than after, with 99.9985 % of six-parameter  $\Lambda$ CDM ruled out. As a concrete example, the best determination of the age of the CMB before *WMAP* came from Boomerang (Lange et al. 2001) and constrained  $t_0 < 14$  Gyr, with peak values of 9–11 Gyr, in contradiction with direct measurements of the oldest globular clusters (Hu et al. 2001).

The *Planck* satellite was developed concurrently with *WMAP*, and their operation lifetimes briefly overlapped, with *Planck* observing from 2009–2013 and *WMAP* from 2001–2011 (cite). *Planck*’s stated goal was to (check overview papers) fully characterize the temperature fluctuations from recombination, as well as to characterize the polarized microwave sky on large angular scales. Overall, the *Planck* experiment’s sensitivity to the CMB was an improvement in white noise sensitivity of a factor x, and a factor of y improvement in angular resolution. Overall, the raw sensitivity of *Planck* was an order of magnitude lower than *WMAP*. As opposed to *WMAP*, which used minimal COBE data in its fiducial analysis, *Planck*’s initial release calibrated off of *WMAP*’s Solar dipole solution, and the Galactic component separation solution found in Planck Collaboration X (2016) by Commander (Jewell et al. 2004; Eriksen et al. 2004, 2006, 2008) made use of *WMAP* frequency maps. Most crucially, the *Planck* and *WMAP* maps are of similar quality that meaningful comparisons can be made between them. This last aspect has been critical, especially for the *Planck* Low Frequency Instrument (LFI), whose channels lie between those of *WMAP*.

As became clear in the LFI analysis (2018 LFI analysis), there was a circular dependency between the instrument calibration and the sky – a robust sky model made from *Planck* LFI maps was required to calibrate the timestreams sufficiently accurately. It was from this need that the BEYONDPLANCK project grew (BeyondPlanck 2022), powered by Commander3 (Galloway et al. 2022), a Gibbs sampling software that performs high-level and low-level parameter estimation in a single integrated framework. This analysis demonstrated the feasibility of a full end-to-end Gibbs sampling analysis in the CMB framework, while providing the highest-quality LFI maps to date.

The success of this paradigm, using properly characterized external datasets to improve TOD processing, led to the COSMOGLOBE initiative. As part of the BEYONDPLANCK suite of papers, Watts et al. (2022) integrated *WMAP* *Q*-band TODs into the Commander3 framework, calibrated off of the BEYONDPLANCK sky model. Beyond demonstrating that Commander3 can be applied to non-*Planck* data, this analysis uncovered an instrumental effect not previously described in the literature, namely a spurious polarization signal induced by the coupling of the Solar dipole, sidelobes, and horn transmission imbalance.

This paper is the next logical step in the set of previous developments, and presents the first end-to-end TOD analysis of multiple datasets. In this work, we analyze the full *WMAP* dataset at the raw TOD level alongside the *Planck* LFI TODs. As described in Sect. 2, this takes into account the fact that *Planck* and *WMAP* observed the same sky, and hence uses the sky as determined from a component separation using these data as a given in each stage of the Gibbs chain. We describe the underlying data

and computational resources in Sect. 3. We describe the posterior distribution of instrumental parameters in Sect. 4, and describe the properties of the output astrophysical and frequency maps in Sect. 6. Section 7 includes a thorough discussion of systematic error treatment in both frameworks, and Sect. 8 covers the outstanding issues that will be addressed in future analyses. We conclude in Sect. 9, and lay a path forward for the COSMOGLOBE project.

## 2. End-to-end Bayesian CMB analysis

We begin by discussing the *WMAP* analysis from uncalibrated TOD to maps. Section 2.1 gives an overview of the BEYONDPLANCK project’s reanalysis of *Planck* LFI data, Sect. 2.2 provides a brief overview of the official *WMAP* pipeline, and Sect. 2.3 constructs the data model that is used in the end-to-end Gibbs sampling analysis.

### 2.1. LFI and BEYONDPLANCK

The BEYONDPLANCK project (BeyondPlanck 2022) was the first true application of end-to-end Gibbs sampling in the framework of CMB data analysis. The *Planck* Low Frequency Instrument data had been gradually improved through each *Planck* data release, specifically PR1 (Planck Collaboration II 2016), PR2 (Planck Collaboration II 2016), PR3 (Planck Collaboration II 2020), and PR4 (Planck Collaboration II 2016). Even after PR4, the LFI data still failed polarization null tests and contained visually striking poorly measured modes corresponding to relative gain uncertainty between different detectors. During the PR3 analysis, it became clear that there was a degeneracy between the assumption of the sky’s polarization and the gain differences.

The BEYONDPLANCK analysis generated the first clean LFI maps by Gibbs sampling the sky components and underlying instrumental parameters jointly (BeyondPlanck 2022; Galloway et al. 2022; Basyrov et al. 2022). The Commander3 pipeline was used to perform the low-level data analysis conditioned on a sky model that was created through component separation, and the reprocessed maps were used to perform component separation once again. This Gibbs chain not only allowed for the true instrumental properties to be determined thus creating the best LFI maps to date – it fully explored the degeneracies between the low-level instrumental parameters themselves and our knowledge of the sky (Andersen et al. 2022; Svalheim et al. 2022).

### 2.2. Official WMAP pipeline

The *WMAP* satellite carried forty differential polarization-sensitive radiometers grouped as differencing assemblies (DAs), where one pair was sensitive to the difference in signal at one polarization orientation and the other pair sensitive to the orthogonal polarization. In total, the DAs were allocated as: 1 *K* (23 GHz), 1 *Ka* (30 GHz), 2 *Q* (40 GHz), 2 *V* (60 GHz), and 4 *W* (90 GHz).

The *WMAP* pointing solution was determined using the boresight vectors of individual feedhorns in spacecraft coordinates, in combination with on-board star trackers. Thermal flexure of the tracking structure introduced small pointing errors, as discussed by Jarosik et al. (2007). Using the temperature variation measured by housekeeping data, the quaternion pointing solution was corrected using a linear model that depends on arcsecond per temperature change. The residual pointing errors were computed using observations of Jupiter Saturn, and the reported

upper limit was given by 10” (Bennett et al. 2013; Greason et al. 2012).

The *WMAP* bandpasses were measured directly pre-launch, sweeping a signal source through 201 frequencies and recording the output (Jarosik et al. 2003b). The bandpass responses have not been updated since the initial data release. However, as noted in Bennett et al. (2013), there has been an observed drift in the center frequency of *K*, *Ka*, *Q*, and *V*-band corresponding to a  $\sim 0.1\%$  decrease over time. In practice, this did not affect the *WMAP* data processing because each year was mapped separately and co-added afterwards. An effective frequency calculator was delivered in the DR5 release as part of the IDL library to mitigate this effect during astrophysical analyses.<sup>1</sup>

The beams were characterized in the form of maps, with separate products for the near-field and far-field. The main beam and near sidelobes were characterized using a combination of physical optics codes and observations of Jupiter for each horn separately. The maps of Jupiter were then combined with the best-fit physical optics codes to create a map of the beam response (Hill et al. 2009; Weiland et al. 2011; Bennett et al. 2013). Far sidelobes were estimated using a combination of laboratory measurements and Moon data taken during the mission (Barnes et al. 2003), as well as a physical optics model describe in Hinshaw et al. (2009). To remove the far sidelobe in the TOD, an estimate was calculated by convolving the intensity map and the orbital dipole signal with the measured sidelobe signal (Jarosik et al. 2007). Although the sidelobe pickup was modeled in Barnes et al. (2003), it was determined that the results were small enough to be neglected, and have not been reported in any of the *WMAP* data releases.

The *WMAP* data were calibrated by jointly estimating the time-dependent gains and baselines, as describe in Hinshaw et al. (2007), Hinshaw et al. (2009), and Jarosik et al. (2011). The TOD are intially modelled as having constant gain and baseline for a 1–24 hour period, and are fit to the orbital dipole assuming  $T_0$  from Mather et al. (1999) and a map made from a previous iteration of the mapmaking procedure. Once the gain and baseline solution has converged, the data are fit to a parametric form of the radiometer performance as a function of housekeeping data, given in Appendix A of Greason et al. (2012).

Transmission imbalance, i.e., the effect of different sky signal transmission from the A-side and B-side optics, is parameterized using  $x_{im}$ , which is zero in the case of an ideal differential radiometer. In practice, an unpolarized sky map generates a timestamp

$$d_t^{imbal} \propto (1 + x_{im})T_{p_A} - (1 - x_{im})T_{p_B} \quad (1)$$

$$= (T_{p_A} - T_{p_B}) + x_{im}(T_{p_A} + T_{p_B}). \quad (2)$$

If the  $x_{im}$  value is inaccurate, this yields a spurious polarization component, and creates imbalance modes due to coupling with the Solar dipole (Jarosik et al. 2007). The transmission imbalance factors are fit by using the Solar dipole in TOD space and fitting the common-mode and differential signals in TOD space directly (Jarosik et al. 2003a, 2007).

Data are flagged and masked before the final mapmaking step. In particular, station-keeping manuevers, solar flares, and unscheduled events caused certain data to be unusable – the full catalog of these events is listed in Table 1.8 of Greason et al. (2012). In addition, data are masked depending on the channel frequency and the planet itself, with the full list of exclusion radii enumerated in Table 4 of Bennett et al. (2013).

<sup>1</sup> [https://lambda.gsfc.nasa.gov/product/wmap/dr5/m\\_sw.html](https://lambda.gsfc.nasa.gov/product/wmap/dr5/m_sw.html)







This equation can be solved using the BiCG-STAB algorithm for a non-symmetric matrix  $\mathbf{A}$  where  $\mathbf{Ax} = \mathbf{b}$ . We apply a preconditioner  $\mathbf{M}$  by numerically inverting the same problem with  $N_{\text{side}} = 16$  maps and applying a diagonal noise matrix. Numerically, we define convergence as when the residual  $\mathbf{r} \equiv \mathbf{b} - \mathbf{Ax}$  satisfies  $\mathbf{r}^T \mathbf{M}^{-1} \mathbf{r} / \mathbf{b}^T \mathbf{M}^{-1} \mathbf{b} < 10^{-10}$ , which typically takes about 20 iterations for producing frequency maps.

### 2.6.3. Transmission imbalance estimation

Transmission imbalance, i.e., the differential power transmission of the optics and waveguide components, can be parameterized as

$$d_{t,j} = g_{t,j}[(1 + x_{\text{im},j})s_{t,j}^{\text{tot,A}} - (1 - x_{\text{im},j})s_{t,j}^{\text{tot,B}}] + n_t. \quad (49)$$

This can be decomposed into a differential (d) and common-mode (c) signal such that

$$d_{t,j} = g_{t,j}[s_{t,j}^{\text{d}} + x_{\text{im},j}s_{t,j}^{\text{c}}] + n_t. \quad (50)$$

In this form, the imbalance parameters can be estimated by drawing Gaussian samples from the standard mean and standard deviation over the entire mission. To draw samples for  $x_{\text{im},j}$ , we construct the sampling routine analogous to Eqs. (34) and (36) with  $\mathbf{r} = \mathbf{d} - \mathbf{gs}^{\text{d}}$ ,

$$[(\mathbf{gs}^{\text{c}})^T \mathbf{N}^{-1} \mathbf{gs}^{\text{c}}]x_{\text{im}} = (\mathbf{gs}^{\text{c}})^T \mathbf{N}^{-1} \mathbf{r} + (\mathbf{gs}^{\text{c}})^T \mathbf{N}^{-1/2} \boldsymbol{\eta}, \quad (51)$$

essentially cross-correlating the common-mode signal with  $\mathbf{r}$  with appropriate weights and adding a Gaussian random variable with the correct weighting. Note that we are marginalizing over the correlated noise here by using  $\mathbf{N} = \mathbf{N}_{\text{wn}} + \mathbf{N}_{\text{corr}}$ . This mitigates any baseline drifts being erroneously attributed to the common-mode signal and biasing the estimate of  $x_{\text{im}}$ .

The *WMAP* procedure, described in Jarosik et al. (2003a), fit for common-mode and differential coefficients along with a cubic baseline over 10 precession periods at a time, corresponding to 10 hours of observation. The mean and uncertainty were then calculated by averaging and taking the standard deviation of these values. This approach has the benefit of allowing for the tracking of possible transmission imbalance variation throughout the mission. However, none of the *WMAP* suite of papers have indicated this, and it has not arisen in our analysis, so we model this as an effect whose value is constant throughout the mission.

### 2.6.4. Baseline sampling

The data model adopted in Hinshaw et al. (2003) can be written in raw digital units (du) as

$$\mathbf{GPBM}\mathbf{a} + \mathbf{n} + \mathbf{b}, \quad (52)$$

where  $\mathbf{b}$  is the instrumental baseline and  $\mathbf{n}$  is the total instrumental noise. As detailed in Ihle et al. (2022), Commander3 divides the noise into  $\mathbf{n} = \mathbf{n}^{\text{w}} + \mathbf{n}^{\text{corr}}$ , a white noise term and a correlated noise term. By definition, the white noise does not have any correlations between adjacent pixels, so that any pixel-pixel covariance should be fully described by realizations of the  $\mathbf{n}^{\text{corr}}$  timestream.

Commander estimates the baseline using the full estimate of the current sky model,  $\mathbf{r} = \mathbf{d} - \mathbf{gs}^{\text{tot}} = \mathbf{b} + \mathbf{n}$ . Modeling  $\mathbf{b} = b_0 + b_1 \Delta t$ , we solve for  $b_0$  and  $b_1$  using linear regression in each timestream while masking out samples that lie within the processing mask. Strictly speaking, this is breaking the Gibbs

chain, as we are not formally sampling  $b_0$  and  $b_1$  for each TOD chunk. In practice, baseline estimation uncertainty propagates to correlated noise realizations and PSD parameters, as discussed below.

The approach detailed in Hinshaw et al. (2003) and the Commander implementation differ mainly in the assumed stable timescale – the initial *WMAP* baseline is estimated over one hour timescales, whereas Commander assumes constant values throughout the entire timestream, 3–7 days depending on the band in question. As noted in Hinshaw et al. (2003), residual baseline variations manifest as correlated noise stripes in the final maps. *WMAP9* solves this using a time-domain filter, downweighting the data based off of the noise characterization. This approach is equivalent to the Commander3 procedure of removing a constrained realization of correlated noise from the timestream directly, based on the best-fit to the noise PSD.

## 3. Data and data processing

We describe the delivered *WMAP* data in Sect. 3.1, then describe the treatment we apply it to make them compatible with Commander3 in Sect. 3.2, then describe the computational requirements in Sect. 3.3.

### 3.1. Publicly available WMAP products

The full *WMAP* dataset is hosted at the Legacy Archive for Microwave Background Data Analysis (LAMBDA).<sup>4</sup> In addition to the primary scientific products, e.g., cosmological parameters, CMB power spectra and anisotropy maps, and frequency maps, the time-ordered data (TOD) can be downloaded, both in uncalibrated and calibrated form.<sup>5</sup> In principle, thanks to these data and the explanatory supplements (Greason et al. 2012), the entire data analysis pipeline can be reproduced from TOD in digital units (du) to frequency maps.

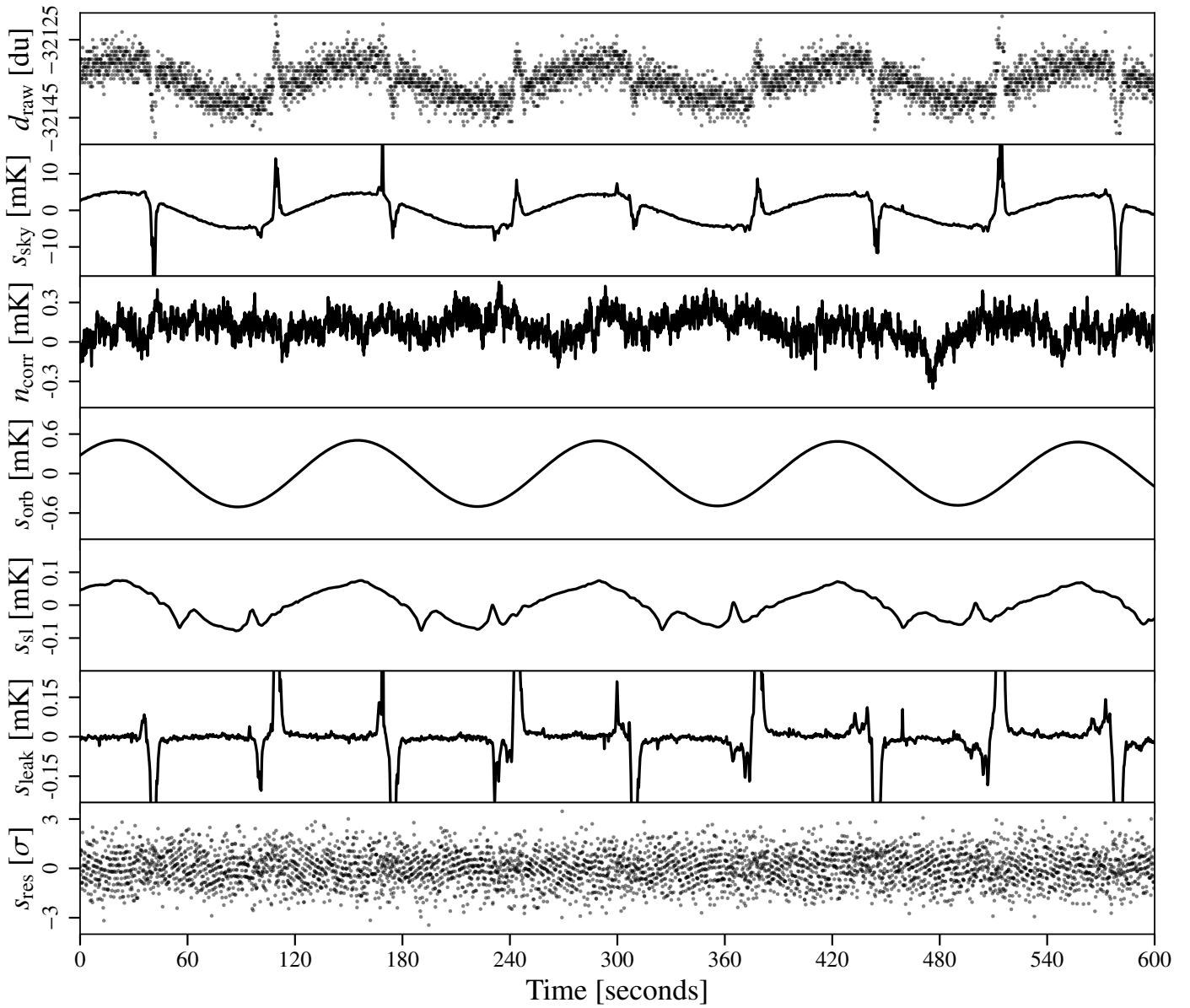
For this analysis, we keep certain instrumental parameters fixed to the reported values. For example, we have made no attempts to rederive the pointing solutions, re-estimate the main beam response and far sidelobe pickup, or recover data that was flagged in the *WMAP* event log. These and other analyses, such as estimating the bandpass shift over the course of the mission, are certainly possible within the larger Gibbs sampling framework. However, in this work we limit ourselves to recalibrating the TOD, estimating the noise properties, and applying bandpass corrections to the data before mapmaking.

### 3.2. TOD pre-processing and data selection

The full nine-year *WMAP* archive spans from August 10, 2001 to August 10, 2010, with the raw uncalibrated data spanning 626 GB. A little over 1 % of the data were lost or rejected due to incomplete satellite telemetry, thermal disturbances, spacecraft anomalies, and station-keeping maneuvers, with an extra 0.1 % rejected due to planet flagging (Bennett et al. 2003b; Hinshaw et al. 2007, 2009; Bennett et al. 2013). The final results reported in Bennett et al. (2013) included roughly 98.4 % of the total data volume. A full accounting of all data cuts can be found in Table 1.8 of Greason et al. (2012). In total, we flag the same data

<sup>4</sup> [https://lambda.gsfc.nasa.gov/product/wmap/dr5/m\\_products.html](https://lambda.gsfc.nasa.gov/product/wmap/dr5/m_products.html)

<sup>5</sup> [https://lambda.gsfc.nasa.gov/product/wmap/dr5/tod\\_info.html](https://lambda.gsfc.nasa.gov/product/wmap/dr5/tod_info.html)



**Fig. 1.** Each of the timestreams that go into the model. Note the varying dynamic ranges of each plot.

**Table 1.** Flagging statistics

Band	Flagged (%)	Discarded (%)	Used (%)
$K$	1.72	0.87	97.4
$Ka$	1.64	0.88	97.5
$Q1$	1.84	0.84	96.5
$Q2$	1.62	0.81	97.6
$V1$	1.62	1.10	97.3
$V2$	1.61	1.01	97.4
$W1$	1.76	1.03	97.2
$W2$	1.60	0.81	97.6
$W3$	1.61	0.87	97.5
$W4$	1.60	0.81	97.6

indicated in the fiducial *WMAP* analysis, and use the same planet flags.

As shown in Galloway et al. (2022), a large fraction of Commander3’s computational time is spent performing FFTs on individual scans. Rather than truncating datastreams to have

lengths equal to “magic numbers” for which FFTW (Frigo & Johnson 2005) is fastest, as in Galloway et al. (2022), we split the data into scans of length  $2^N$ , where  $N = 22$  for  $K-Q$ ,  $N = 23$  for  $V-W$ . This yields scans with lengths of 6.21 days for  $K$ - and  $Ka$ -band, 4.97 days for  $Q$ -band, 7.46 days for  $V$ -band, and 4.97 days for  $W$ -band. These datastream lengths are short enough to be processed quickly and distributed efficiently across multiple processors, while being long enough to properly characterize the noise properties of the timestreams, whose  $f_{\text{knee}}$ ’s are on the order 1 mHz. Most importantly, FFTW performs fastest when the datastream is of length  $2^N$ .

When rechunking the data, timestreams of length  $2^N$  were interrupted by events logged in Table 1.8 of Greason et al. (2012). When we encountered these events, TOD segments that were interrupted by the event were appended to the previous TOD, in most cases creating TODs with lengths  $> 2^N$ . We found that events of length  $< 2^N$  were too short to accurately estimate the noise PSD parameters. This criterion led us to discard these otherwise useful data. In addition, when  $> 10\%$  of the TOD was flagged, the large number of gaps in the data made the con-

strained realizations unreliable, as well as biasing the noise PSD parameters. Together, these two effects led to  $\simeq 1\%$  of the data to be discarded despite being of acceptable quality. We present the full flagging statistics for our maps in Table 1. In total, the COSMOGLOBE maps use slightly less data than the *WMAP9* official products, which had a total efficiency of  $\simeq 98.4\%$  (Bennett et al. 2013). The total difference in data volume can be entirely accounted for by the cuts described in this paragraph.

### 3.3. Computational resources

A key motivation of the COSMOGLOBE project is to evaluate whether it is feasible to perform a joint analysis of two datasets simultaneously, each with its own particular processing requirements and algorithmic treatment. One of the results from Watts et al. (2022) was that most of the data processing procedures for *WMAP* and *Planck* LFI overlapped, with the notable exception of mapmaking. While the algorithmic requirements have been discussed in Sect. 2, we have not yet quantified the requirements in terms of RAM and CPU hours. In Table 2, we enumerate the RAM requirements and CPU time for each sampling step using the local cluster at the Institute of Theoretical Astrophysics at the University of Oslo. The node that these numbers come from used 128 cores of an AMD EPYC 7H12, 2.6 GHz machine with 2 TB of memory. As Commander3 is parallelized and used 128 cores, wall hours in Table 2 can be obtained by dividing by 128.

Despite the relatively small data volume spanned by *WMAP*, the CPU time is comparable to each of the LFI channels. By far the largest reason for this is the mapmaking step, which requires looping over the entire dataset for each matrix multiplication, a process which must be repeated  $\sim 20$  times. This is vastly sped up by the use of a low resolution preconditioner, reducing the number of iterations by an order of magnitude.

Additionally, operations that require creating timestreams for each detector, i.e., TOD projection, sidelobe evaluation, and orbital dipole projection, take much longer than expected from a pure data volume scaling. Part of this is due to each *WMAP* radiometer needing to evaluate the sky in two pixels simultaneously, doubling the expected workload. The operations of gain sampling and correlated noise sampling include multiple FFTs. Typical LFI TODs are of length  $\sim 200\,000$ , an order of magnitude smaller than the *WMAP* TODs of length  $2^{22-23}$ .

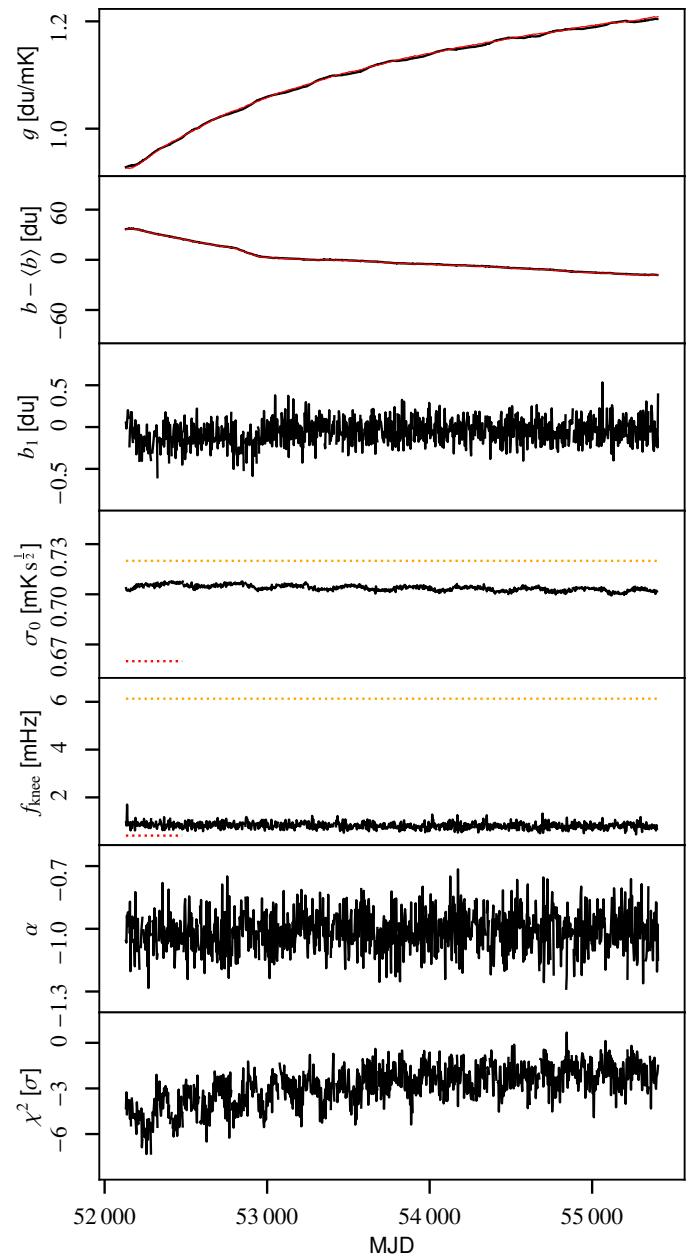
## 4. Posterior distributions

### 4.1. Gain and baselines

To compare the calibrated TODs from *WMAP* versus COSMOGLOBE, it is important to look at the *WMAP* gain model,

$$g = \alpha \frac{\bar{V} - V_\circ - \beta(T_{\text{RXB}} - 290\text{ K})}{T_{\text{FPA}} - T_\circ} + (m\Delta t + c), \quad (53)$$

where  $\alpha$ ,  $V_\circ$ ,  $\beta$ ,  $T_\circ$ ,  $m$ , and  $c$  are fit to a constant value across the mission for each radiometer.  $\bar{V}$  are radio frequency bias powers per detector, and  $T_{\text{RXB}}$  and  $T_{\text{FPA}}$  are the receiver box and focal plane assembly temperatures, which are recorded every 23.04 s. Evaluating the model as a function of  $T_{\text{RXB}}$  and  $T_{\text{FPA}}$  requires finding the housekeeping data for the thermistor that was physically closest to the relevant radiometer's focal plane on the satellite. As this requires detailed technical information about the specifications of the satellite's schematics layout that can easily be misunderstood, we do not attempt to reproduce the gain model given in Eq. (53) in this work. Although we are unable to

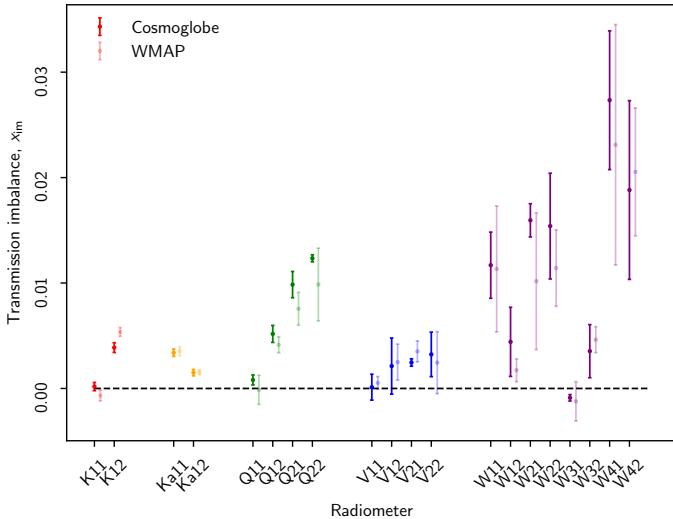


**Fig. 2.** Overview of K113. The red solid lines in first and second panel are the delivered gain and baselines from *WMAP9*, while the black lines in all panels are samples from the COSMOGLOBE Gibbs chain. The red dashed and yellow dashed lines are reported  $\sigma_0$  and  $f_{\text{knee}}$  values from the first-year *WMAP* data analysis and GSFC measurements, respectively.

reproduce the exact gain model parametrized in Greason et al. (2012), the 23.4 s time dependence of the gain model on housekeeping data is a plausible explanation for the time-dependent noise variation in the different calibrated data solutions.

As reported in Hinshaw et al. (2007), the calibrated data archive has been calibrated using the procedure listed above, with a baseline subtracted each hour and the sidelobe subtracted. Figure 3 shows the COSMOGLOBE timestream  $d/g - s_{\text{sl}} - b$  with the *WMAP* delivered calibrated signal subtracted. The most prominent feature is a  $\sim 25\,\mu\text{K}$  offset, which is unsurprising, given the different treatment of baselines in our two pipelines. The second obvious difference is a series of spikes associated with Galactic plane crossings. The differences of order  $50\,\mu\text{K}$  correspond to sky brightness of order 10 mK, equivalent to  $\sim 0.5\%$  devi-





**Fig. 5.** Transmission imbalance

calibrated and uncalibrated data can be related by

$$d_t^{\text{raw}} = g(d_t^{\text{cal}} + s_t^{\text{sl}}) + \sum_{i=0}^3 c_i(t - t_0)^i. \quad (54)$$

We find that  $d_t^{\text{raw}}$  is consistent with the expression on the right at the level of  $< 0.1$  du for all radiometers, suggesting that this estimate of  $g$  and the baseline  $c_0$  is a good approximation of the *WMAP9* calibration solution. An initial estimate using a linear baseline gave an unacceptably poor fit. Given that Eqn. (2) of [Jarosik et al. \(2003a\)](#) employed a cubic baseline fit while fitting for transmission imbalance parameters, it is reasonable to assume that the official calibrated archive was created using a similar procedure.

The morphological characteristics of the *WMAP9* and COSMOGLOBE gain solutions are similar, with a general trend to increase with time. Both solutions also follow a sinusoidal pattern, corresponding to temperature change due to L2's motion around the Sun ([Greason et al. 2012](#)). However, we do find the amplitude of the COSMOGLOBE  $K$ -band gain is slightly lower than the *WMAP9* solution, and with fewer oscillatory features. Other than the absolute calibration shift in  $K$ -band, the gains are consistent between COSMOGLOBE and *WMAP9* within 1 %. For completeness, the full gain comparisons can be found in Fig. A.3.

#### 4.2. Transmission imbalance

The transmission imbalance parameters  $x_{\text{im}}$  are crucial to measure correctly because their mis-estimation can induce a large polarized signal that is coupled to the Solar dipole ([Jarosik et al. 2007; Watts et al. 2022](#)). The uncertainty in  $x_{\text{im}}$  was quoted as the source of large-scale polarized features in the *WMAP9* maps, and a template of this effect was explicitly projected out in the pixel-space polarized covariance matrix.

We find  $x_{\text{im}}$  values that are largely consistent with the values reported in [Bennett et al. \(2013\)](#), albeit with some outliers. We find in general that the 68 % confidence intervals from COSMOGLOBE are smaller than the fiducial values, although we caution against a direct comparison of these values since such different procedures were used for estimating the uncertainties.

#### 4.3. Instrumental noise and goodness-of-fit

The noise fitting, as outlined in Sect. 2.6, inherently depends the data being fit well by both the sky model and the instrument model. In practice, correlated noise fitting can model any unmodelled signals, so the power spectrum and TODs must be carefully scrutinized before any conclusions can be made about the corresponding maps.

The white noise level in raw du is not strictly sampled, but is estimated conditioned on the instrumental parameters and the sky parameters. However, the calibrated white noise level  $\sigma_0[\text{K}] = \sigma_0[\text{du}]/g$  does depend on the gain quite directly, which allows us to test the effects of the calibration on the instrument sensitivity itself. The calibrated white noise level follows a biaannual trend indicative of a system temperature variation, which is to be expected given the radiometer equation

$$\sigma_0[\text{V}] \propto gT_{\text{sys}}. \quad (55)$$

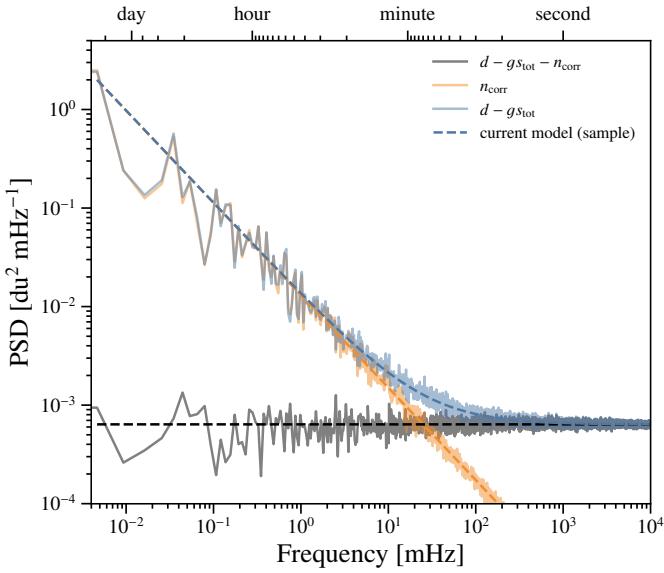
Aside from an overall amplitude shift due to the absolute calibration variation, the shape of the white noise level is stable throughout the Gibbs chain.

The knee frequencies for each channel lie between the reported values in [Jarosik et al. \(2003a\)](#) for both the Goddard Space Flight Center (GSFC) laboratory measurements and those from the first year of data collection. Nearly all radiometers have constant  $f_{\text{knee}}$  throughout the mission, with a few notable exceptions. First, all  $W$ -band channels display some amount of temporal variation that does not seem to be associated with any sinusoidal features. Second, all  $Q2$  channels,  $V223$ , and  $V224$  all display a similar asymptotic drift in time. We have not found any instrumental effects that share this feature. The PSD slope  $\alpha$  is around  $-1$  for each radiometer, albeit with high scatter for the lower frequencies. As expected, the uncertainty in  $\alpha$  decreases as  $f_{\text{knee}}$  increases, since there are more datapoints to fit below  $f_{\text{knee}}$  where the constraining power on  $\alpha$  is the strongest.

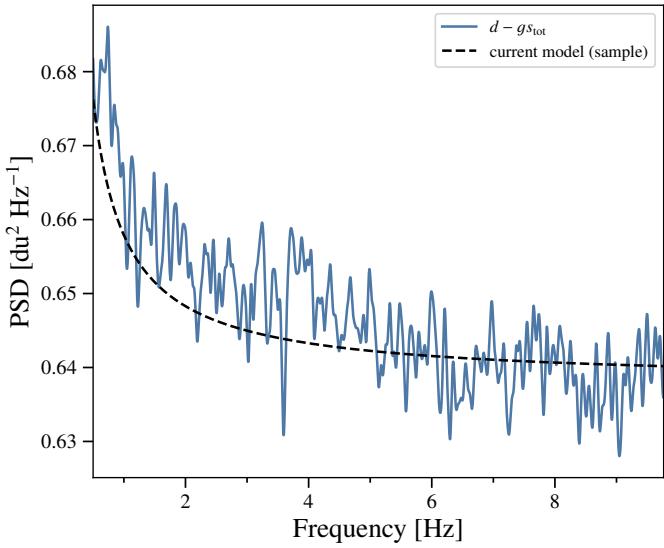
The most striking feature of the reduced normalized  $\chi^2$  is its amplitude and its semiannual periodicity. Given the noise model and data residual, we can evaluate the goodness-of-fit in the form of the relative  $\chi^2$ . Here, we find that approximately half of the radiometers have a  $\chi^2$  value at least  $6\sigma$  above or below the expected value. Given perfect Gaussian residuals, we would expect the reduced sum of squares to be  $n_{\text{TOD}} = 2^N$  and be within  $\sqrt{2n_{\text{TOD}}} = 2^{(N+1)/2}$  68 % of the time. For a typical  $W$ -band scan of length  $n_{\text{TOD}} = 2^{22}$ , a  $10\sigma$  model failure corresponds to  $\chi^2/n_{\text{TOD}} = 1.003$ . Therefore, it is exceedingly difficult to look at any given *WMAP* scan in the time domain and identify a model failure. In power spectrum space, i.e., in Fig. 6, the data are still characterized well at all scales, despite this scan having a  $\chi^2/7\sigma$  above the expectation value.

Only with aggressive smoothing, as in Fig. 7, does the model failure become apparent at frequencies 1–10 Hz. Here, it is clear that despite fitting the data well at the highest and lowest frequencies, it is in the intermediate range of 1–5 Hz where the power spectrum is a less accurate fit to the power spectrum. Part of the cause of this failure is that the white noise level is essentially fixed by the value of the power spectrum at the Nyquist frequency, as it was computed by differencing adjacent samples. The power spectrum has a downward trend beyond above 1 Hz, indicating that the data would be better fit by one or more terms proportional to  $f^\alpha$ . This is phenomenologically similar to the *WMAP* collaboration's approach of describing the time-space autocorrelation as a cubic polynomial in  $\log \Delta t$  ([Jarosik et al. 2007](#)).





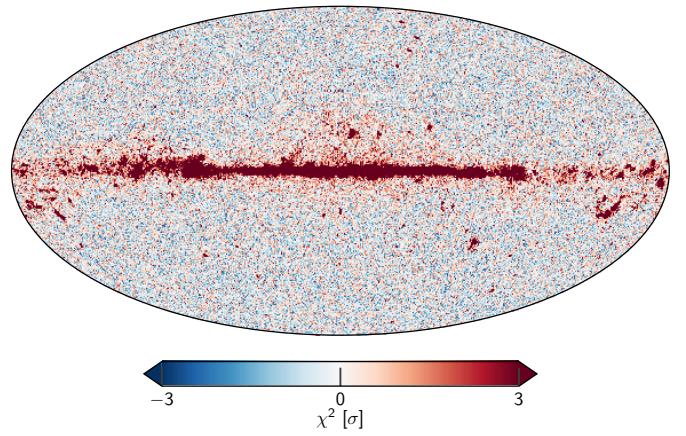
**Fig. 6.** PSD for radiometer W413 that spans MJDs 52252.3–52254.8. The power spectrum of the blue line corresponds to the residual, while the gray line is the residual with a correlated noise realization removed.



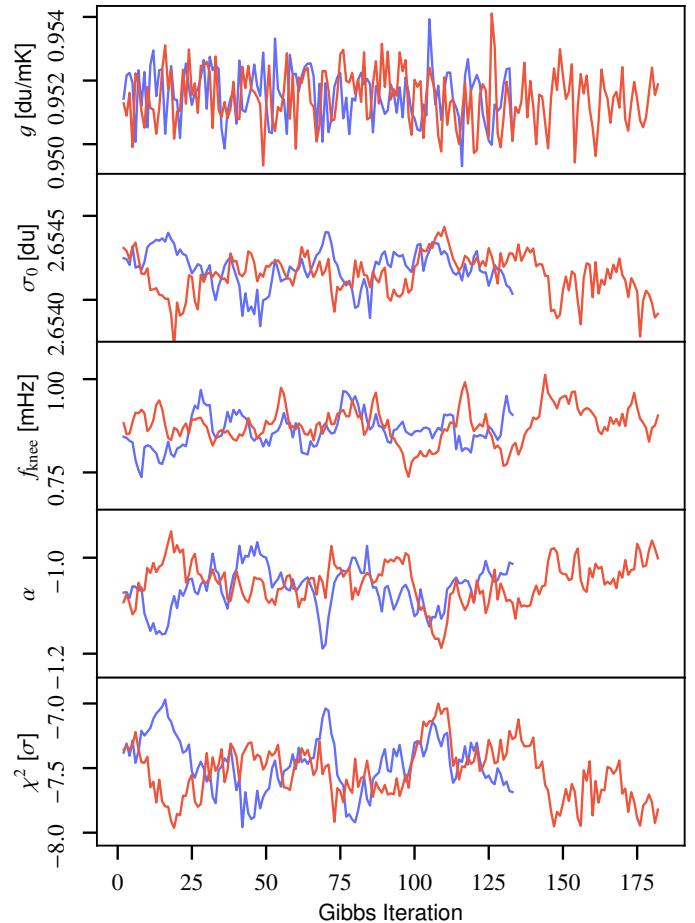
**Fig. 7.** PSD for radiometer W413 that spans MJDs 52252.3–52254.8. The black dashed line is a sample of the theoretical PSD, while the blue line is the smoothed residual power spectrum.

## 5.2. Parameter correlations

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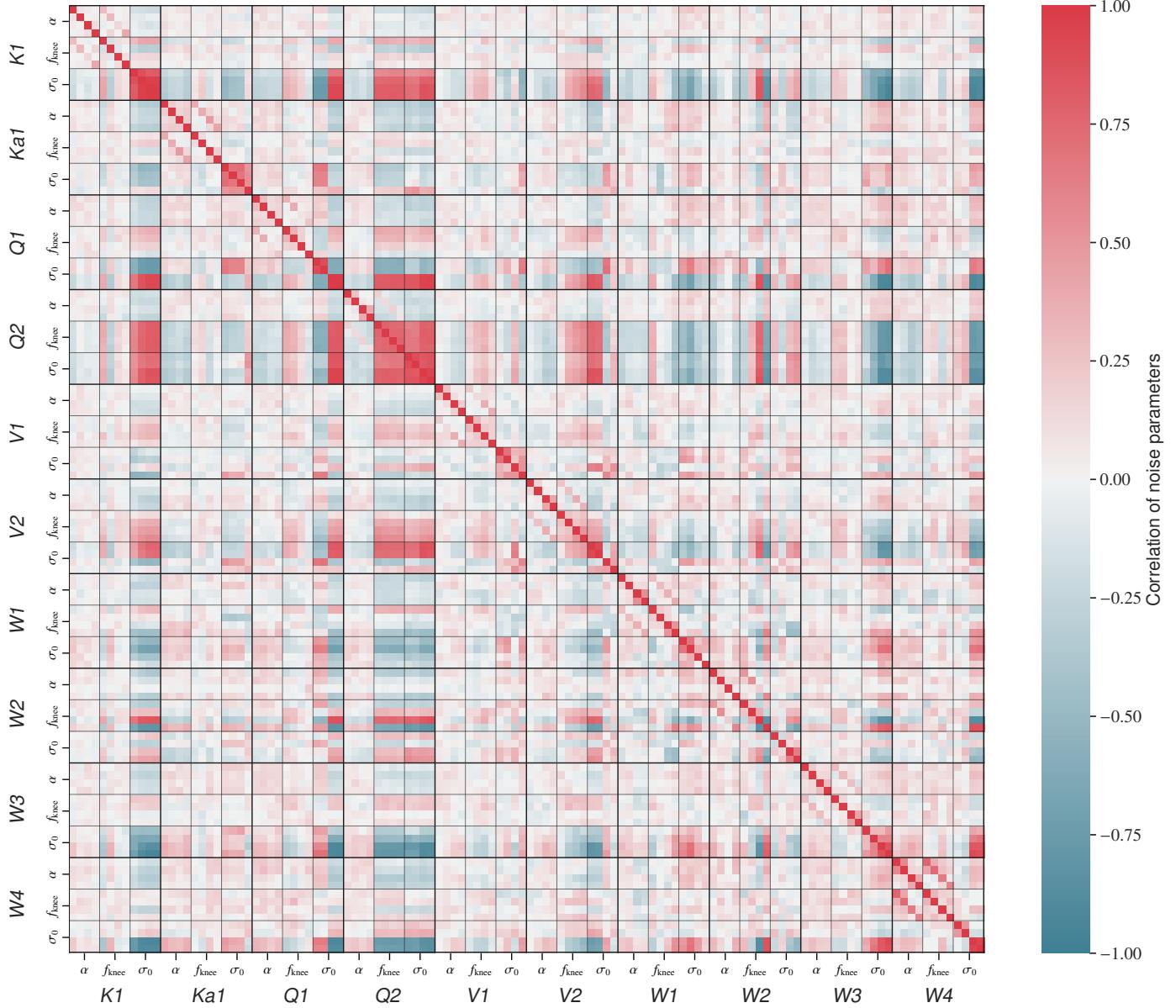
**Fig. 8.** Reduced- $\chi^2$ , using  $n_{\text{dof}} = 300$ , which comes from fitting to the regions outside of the  $K$ -band processing mask.



**Fig. 9.** Subset of K113 Gibbs samples for both chains, arbitrarily colored red and blue. The parameters correspond to MJDs 52285.2–52290.6.

### 5.2.1. K-band calibration and AME

In a preliminary Commander3 run, we discovered an unbounded rise in the  $K$ -band absolute calibration,  $g_0$ , and the dipole in the AME component of the sky. Because the AME is strongest among all bands at  $K$ -band, any increase in the  $K$ -band absolute calibration can easily be accounted for by changing the amplitude of the AME, while leaving goodness-of-fit tests such as relative- $\chi^2$  and residual maps unaffected.



**Fig. 10.** Noise parameter correlation matrix. We average over all Gibbs samples of the noise parameters  $\xi^n = \{\alpha, f_{\text{knee}}, \sigma_0\}$  for each PID. We then find the correlation in time between these averages for the different bands and detector. The results here are for the calibrated white noise level,  $\sigma_0$ [mK]. The values for each detector are ordered 13, 14, 23, and 24

In order to break this degeneracy, it was necessary to impose a prior either on the AME itself or on the absolute calibration. The AME prior we explored followed the approach of [Andersen et al. \(2022\)](#), in which the prior mean was the *Planck* DR4 857 GHz map scaled by  $3 \cdot 10^{-5}$ , and the variance is given in angular scales by a parameter  $q$ . We found that a prior of  $q = 10^{-2} \mu\text{K}^2$  was necessary to stabilize the gain, resulting in an AME map that was nearly identical to the *Planck* 857 GHz band. As this gave a result that was inconsistent with many previous results, we opted instead to sample the absolute calibration instead.

Any error in  $g_0$  leads to a residual due to the large Solar dipole. In practice, we found that the typical variation of  $g_0$  was 0.002, giving a relative error of  $\sim 0.1\%$ . This variation induces a  $\sim 6 \mu\text{K}$  Solar dipole uncertainty, which is easily attributed to AME during component separation. In Figure 37, we demonstrate this effect on recovered AME maps using extreme  $g_0$  values of 1.175 and 1.9. We find that AME maps consistent with

those presented in [Bennett et al. \(2013\)](#) and [Planck Collaboration X \(2016\)](#) are recovered when  $g_0$  is between 1.180 and 1.182. Based on this analysis, we sample  $g_0$  from a Gaussian with mean 1.1815 and standard deviation 0.001.

[Bennett et al. \(2013\)](#) and [Planck Collaboration X \(2016\)](#) find AME peak frequencies 12.0–17.5 GHz and 17–23 GHz, respectively, both with low signal-to-noise at high Galactic latitude and with structure along the plane. The Q-U-I JOint Tenerife Experiment (QUIJOTE) has recently released maps of the sky with approximately 70 % sky coverage at frequencies 11, 13, 17, and 19 GHz ([Rubiño-Martín et al. 2023](#)). QUIJOTE is optimized for characterizing the polarized sky, and constraints from, e.g., [de la Hoz et al. \(2023\)](#), will be critical for future polarized synchrotron SED characterization and polarized AME limits. While in principle the AME SED can be constrained by a joint *WMAP/LFI/QUIJOTE* analysis, we consider this outside of the scope of the paper, which aims to evaluate the effect of jointly

analyzing *WMAP* and *Planck* LFI at the TOD level. Future analysis will include the QUIJOTE data, and hopefully break the  $g_{0-a}$  degeneracy.

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*The second main deviation...* is in the treatment of the noise power spectra. As shown in Sect 2.5 of [Jarosik et al. \(2007\)](#), the noise autocorrelation spectrum is fit on a year-by-year basis to a polynomial in  $\log(\Delta t)$ , where  $\Delta t$  is the time lag between data points. This method is very similar to the Commander3 approach, which fits for the power spectrum in Fourier space using a correlated noise model of the form  $\sigma_0^2(f/f_{\text{knee}})^\alpha$ . Properly parameterized, these two approaches should yield similar results, albeit with different levels of uncertainty and time resolution. However, we have confirmed that in many cases the simple  $1/f$  noise model does not fit the signal-subtracted TOD, yielding  $\chi^2$  values that are up to  $10\sigma$  discrepant from their expected values. [Show, discuss figure with the PSDs, residual spectrum, and Bessel filter.]

Deviations from the  $1/f$  model consist either of a linear increase or downturn above 10 Hz. This can be partially explained by the use of a two pole Bessel low-pass filter just prior to signal quantization, which introduces a 2.62% correlation between 25.6 ms sample integrations ([Jarosik et al. 2003b](#), Sect. 5.3). The exact form of the Bessel filter was not used on flight data, but rather the parametric fit as discussed above. However, the filter is designed to reduce the signal by half at 100 Hz, and as such has a negligible effect.

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## 6. Frequency maps and astrophysical components

### 6.1. Map summary statistics

Will combine these spectra shortly

Want to compare the *QU* correlation in *WMAP* and *Planck* LFI, get a quantitative number. Point out that the polarization solution itself is much better, but the covariance between pixels themselves is much higher. This wasn't an issue for LFI, so we had to take that into account here.

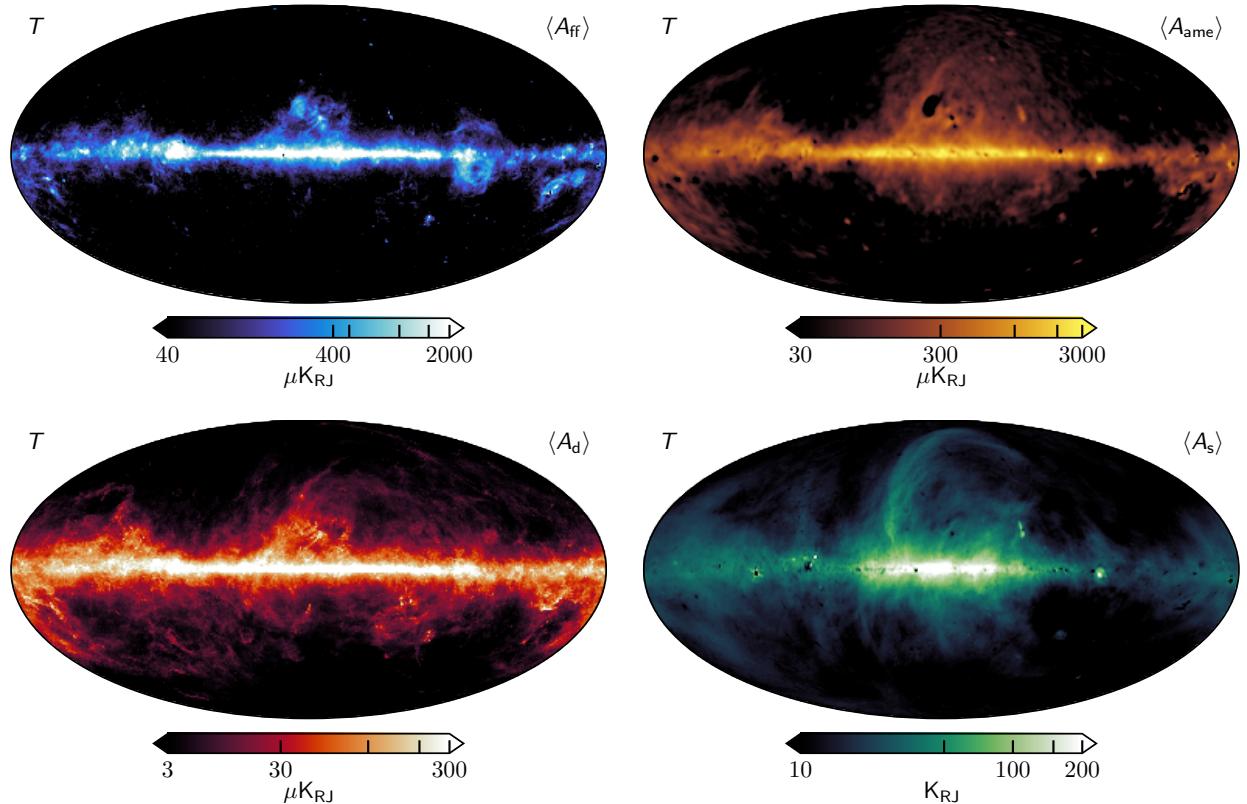
I also want to put a bit here on why the low- $\ell$  approach needed to be done separately, how correlated noise sampling addresses it, to what extent it's mitigated, etc.

Note that LFI's 30 and 70 GHz *QU* correlation is  $\sim 0.1$ , whereas 44 GHz is much larger,  $\sim 0.5$ . This discrepancy is due to the number of horns with differing polarization orientation. Both 30 and 70 GHz have an even number of horns, allowing for pairs of datastreams to be combined to give independent polarization measurements. Conversely, 44 GHz has one horn pair and an unpaired horn, the latter of which induces more correlation in the *QU* observation matrix. An example for *Ka* and 30 GHz is shown in Fig. ???. Aside from the obvious morphological changes due to the two experiments' different observing strategies, the magnitude of *WMAP*'s correlation is much larger than *Planck*'s.

The BEYONDPLANCK project took this covariance structure into account using the dense  $N_{\text{side}} = 16$  noise covariance matrix provided by the *WMAP* team.<sup>7</sup> Properly sampled correlated noise only leaves white noise in the maps, so the noise properties of each map's sample do not require a dense pixel-pixel covariance, even at low resolution ([BeyondPlanck 2022; Basyrov et al. 2022](#)). The *WMAP9* inverse noise covariance matrices were computed using the full time-space noise matrix  $\mathbf{N} = \mathbf{N}^{\text{w}} + \mathbf{N}^{\text{corr}}$ , so the full pixel-pixel covariance matrix  $\Sigma^{-1} = \mathbf{P}^T \mathbf{N}^{-1} \mathbf{P}$  took into account the correlation between neighboring samples. The COSMOGLOBE maps, by subtracting a realization of correlated noise before mapmaking, estimates an inverse noise covariance matrix

$$\Sigma_{pp'}^{-1} = \sum_{t_1, t_2} \mathbf{P}_{t_1, p_1}^T \mathbf{N}_{t_1, t_2}^{-1} \mathbf{P}_{t_2, p_2} = \sum_t \mathbf{P}_{t, p_1}^T \mathbf{N}_{t, t}^{-1} \mathbf{P}_{t, p_2} \quad (56)$$

<sup>7</sup> [https://lambda.gsfc.nasa.gov/product/wmap/dr5/ninv\\_info.html](https://lambda.gsfc.nasa.gov/product/wmap/dr5/ninv_info.html)

**Fig. 11.** Foreground intensity maps**Table 4.** Difference map  $\chi^2$  statistics.

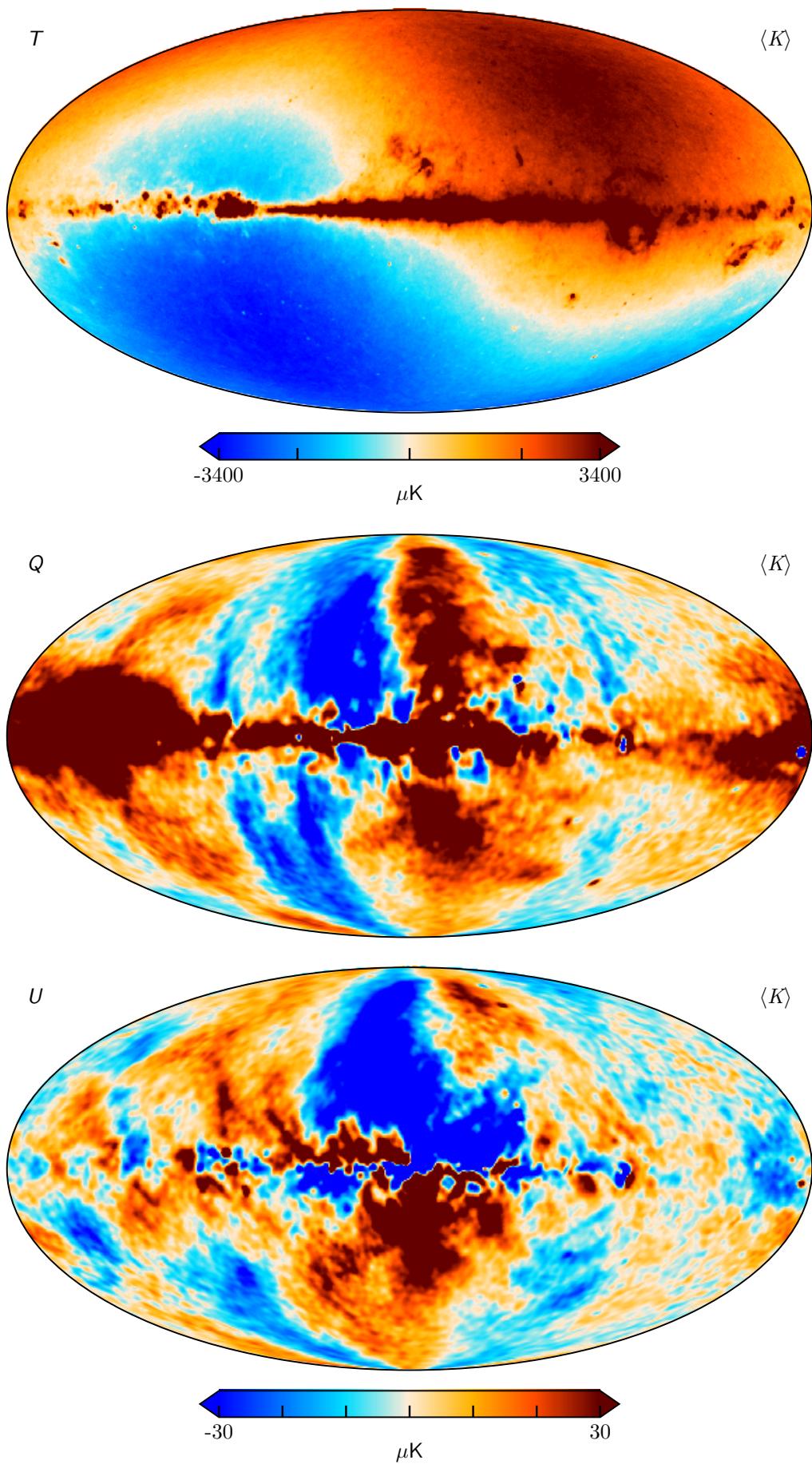
DIFFERENCE	$\chi^2_{\text{uncorr}}$	$\chi^2_{\text{corr}}$	$\Delta\chi^2$
$0.32 \times K1 - K1$ . . .	4291	4287	4
Q1 – Q2 . . . . .	4500	4380	120
V1 – V2 . . . . .	4490	4429	61
W1 – W2 . . . . .	4328	4270	68
W3 – W4 . . . . .	4257	4145	112

**Table 5.** Transmission imbalance template amplitudes for each *WMAP* radiometer as estimated by fitting the official templates to low-resolution difference maps between COSMOGLOBE and *WMAP*. The templates are provided in mK, and the template amplitudes are therefore dimensionless. The fourth column lists the relative decrease in standard deviation,  $\sqrt{\sigma_{\text{raw}}^2 - \sigma_{\text{corr}}^2}/\sigma_{\text{raw}}$ , after subtracting the best-fit templates in percent.

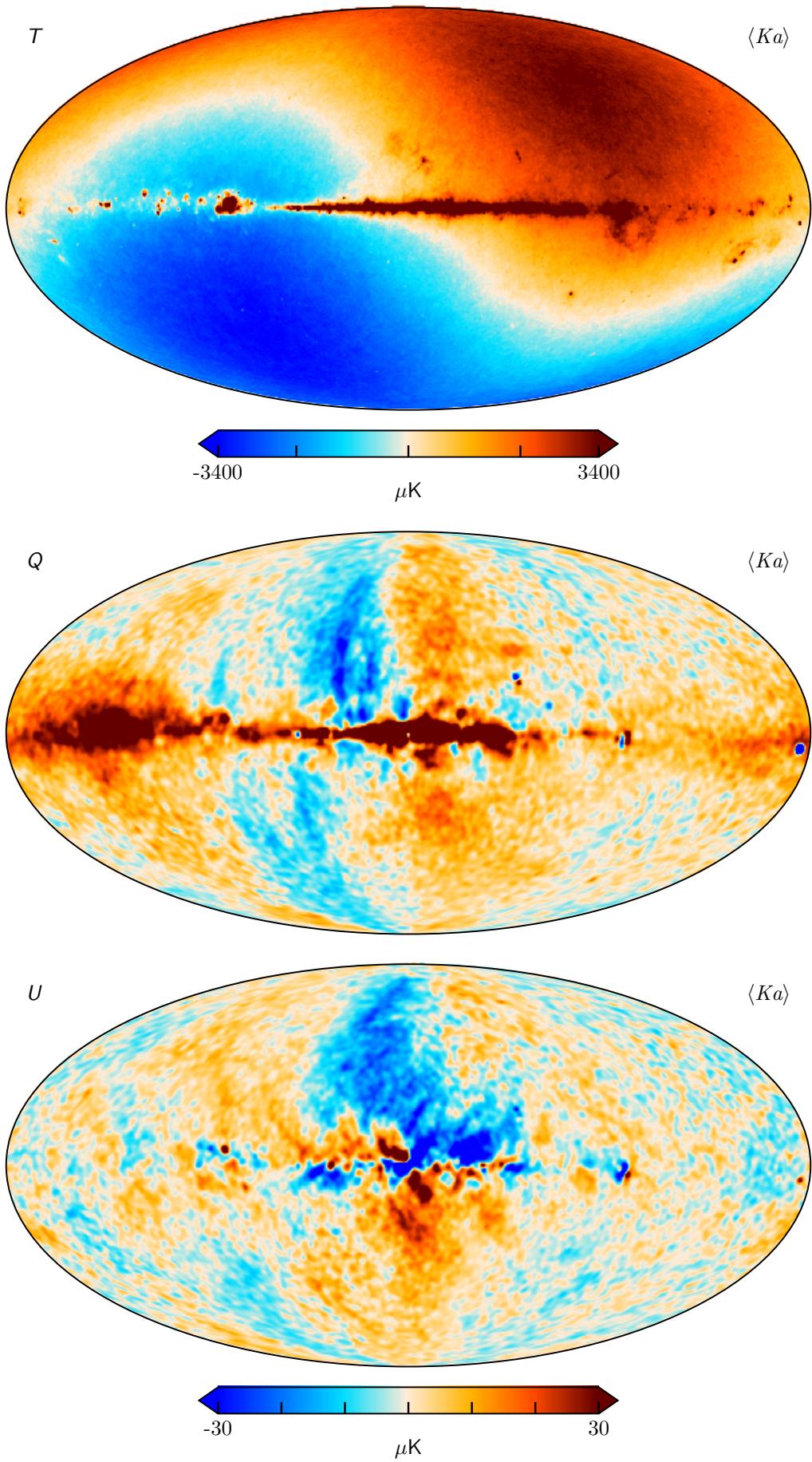
DA	$a_1$	$a_2$	$\Delta\sigma[\%]$
K1 . . . . .	-27.5	-50.6	30
Ka1 . . . . .	-1.4	-1.9	25
Q1 . . . . .	-30.0	-71.6	11
Q2 . . . . .	-7.1	-1.5	20
V1 . . . . .	-32.8	-53.4	6
V2 . . . . .	8.8	-4.1	16
W1 . . . . .	-2.8	4.6	8
W2 . . . . .	-6.9	-3.5	11
W3 . . . . .	29.1	53.4	12
W4 . . . . .	15.5	-6.8	52

How much off-diagonal pixel covariance is there here?

dense noise covariance matrix also explicitly projected out the poorly-measured imbalance modes, but because we find no trace of these modes in our sky maps or residual maps, this treatment is not necessary in our approach. However, the correlation between Stokes  $Q$  and  $U$  was not taken into account in the BEYONDPLANCK LFI analysis. This was not a significant oversight in the LFI analysis because the 30 and 70 GHz maps only had a 10% correlation, and 44 GHz's 50% correlation was subdominant to other systematic effects. We have updated Commander3 to take  $QU$  correlation into account for LFI.

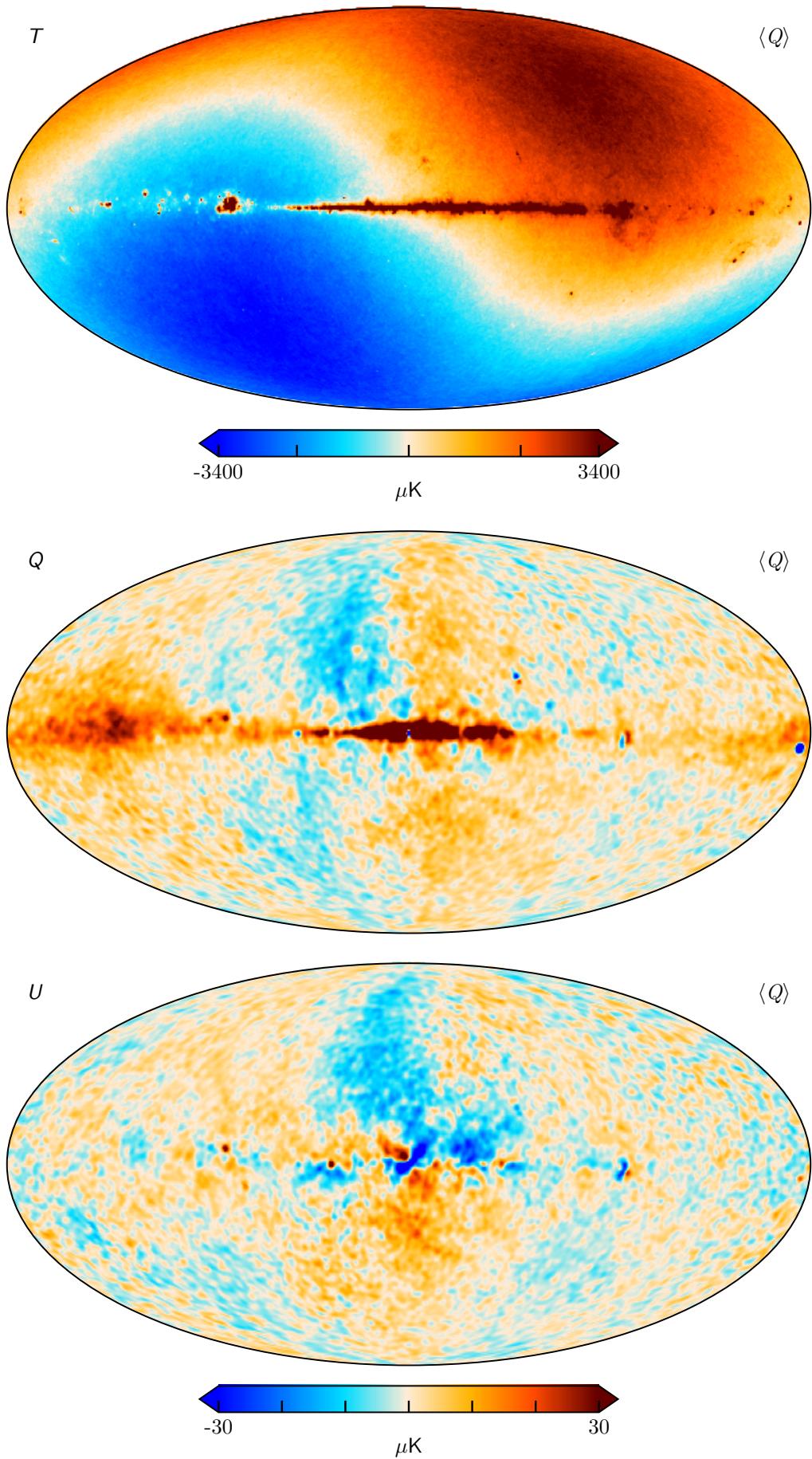


**Fig. 12.**  $K$ -band

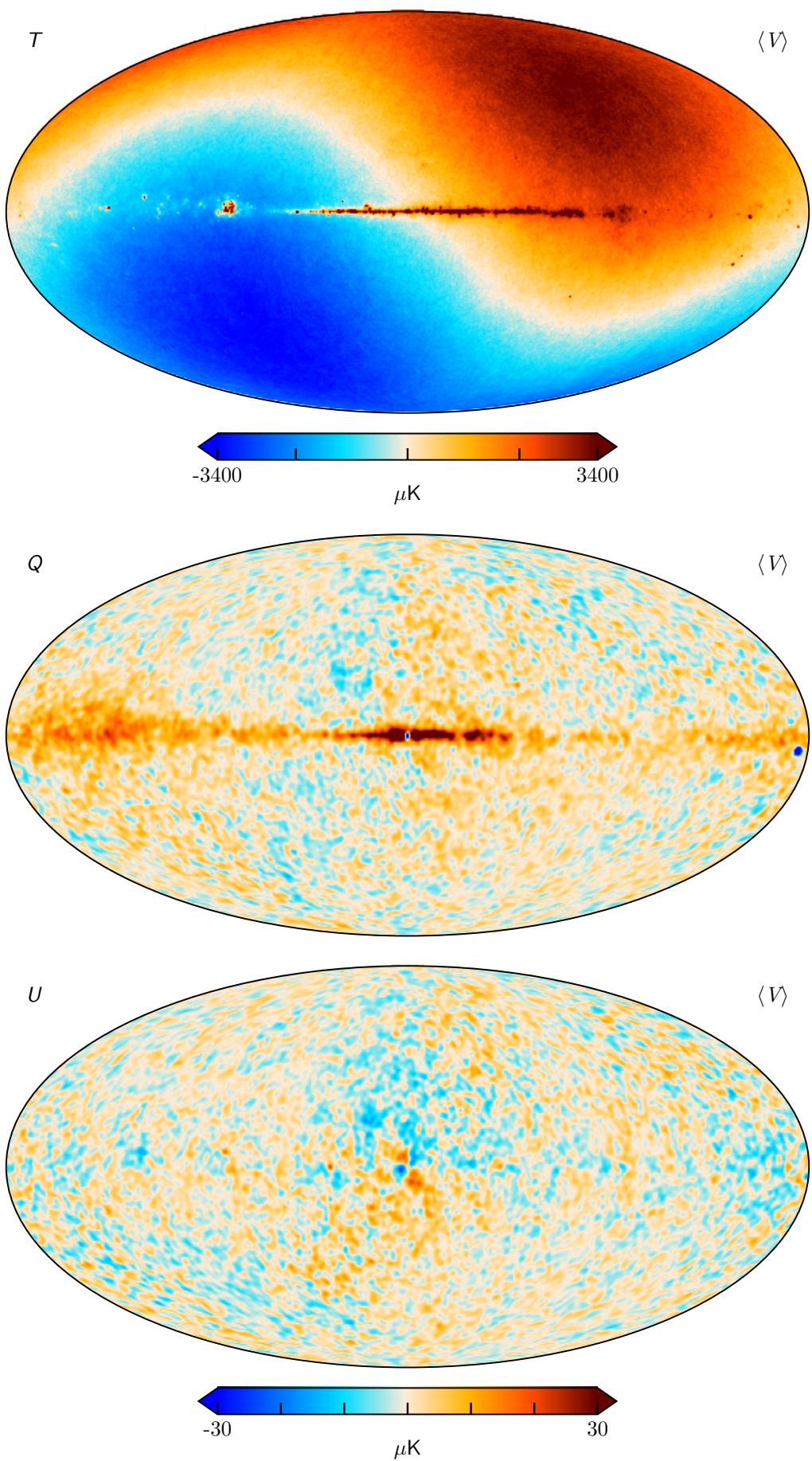


**Fig. 13.**  $Ka$ -band

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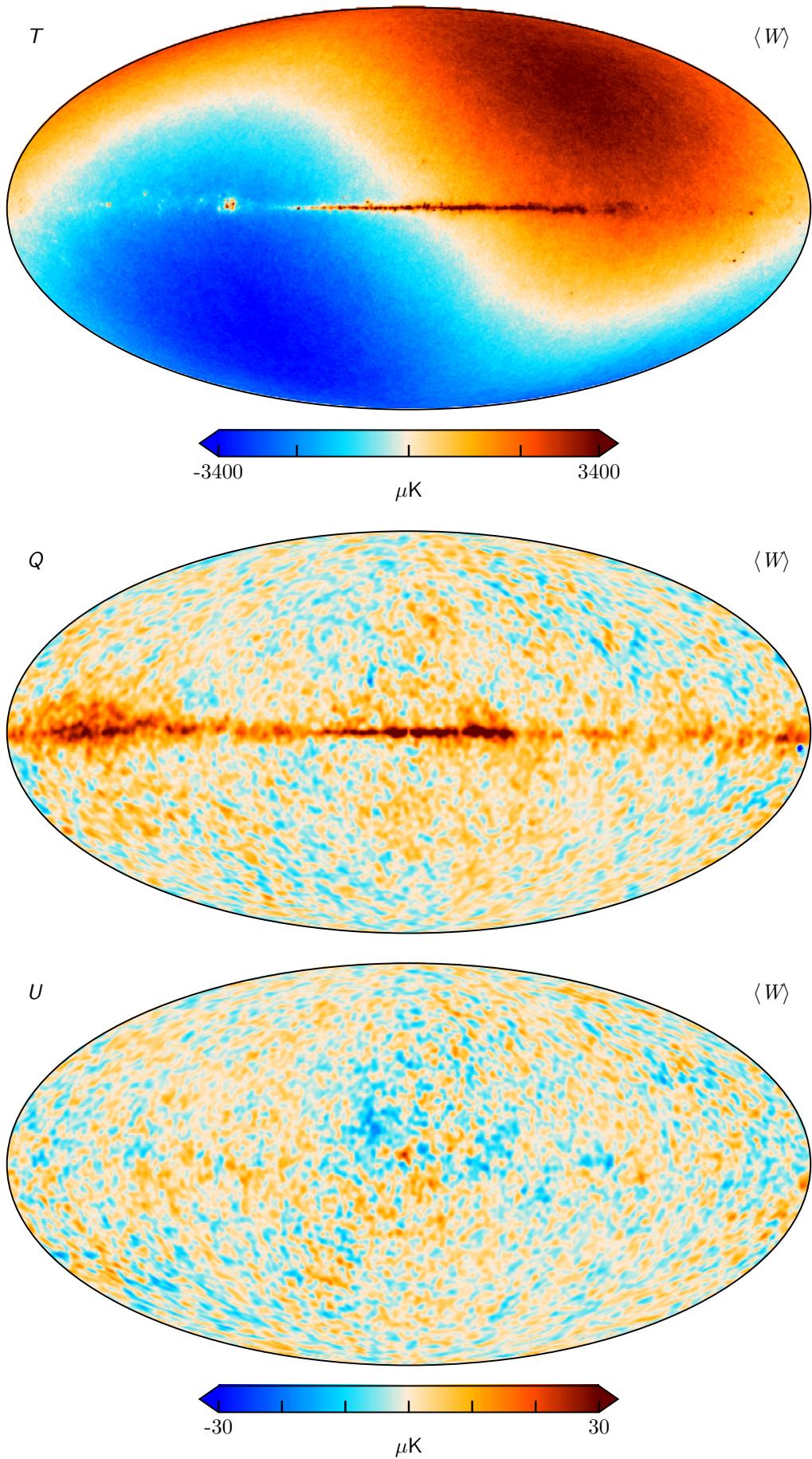


**Fig. 14.**  $Q$ -band



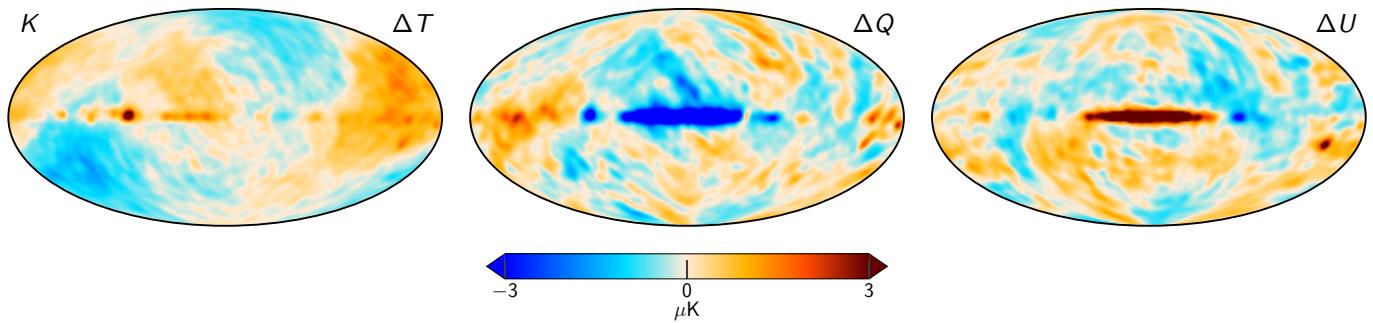
**Fig. 15.**  $V$ -band

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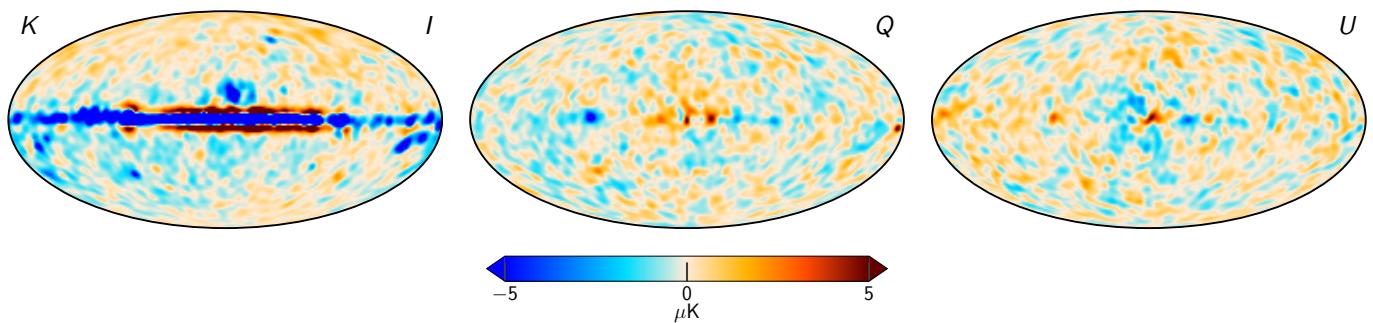


**Fig. 16.**  $W$ -band

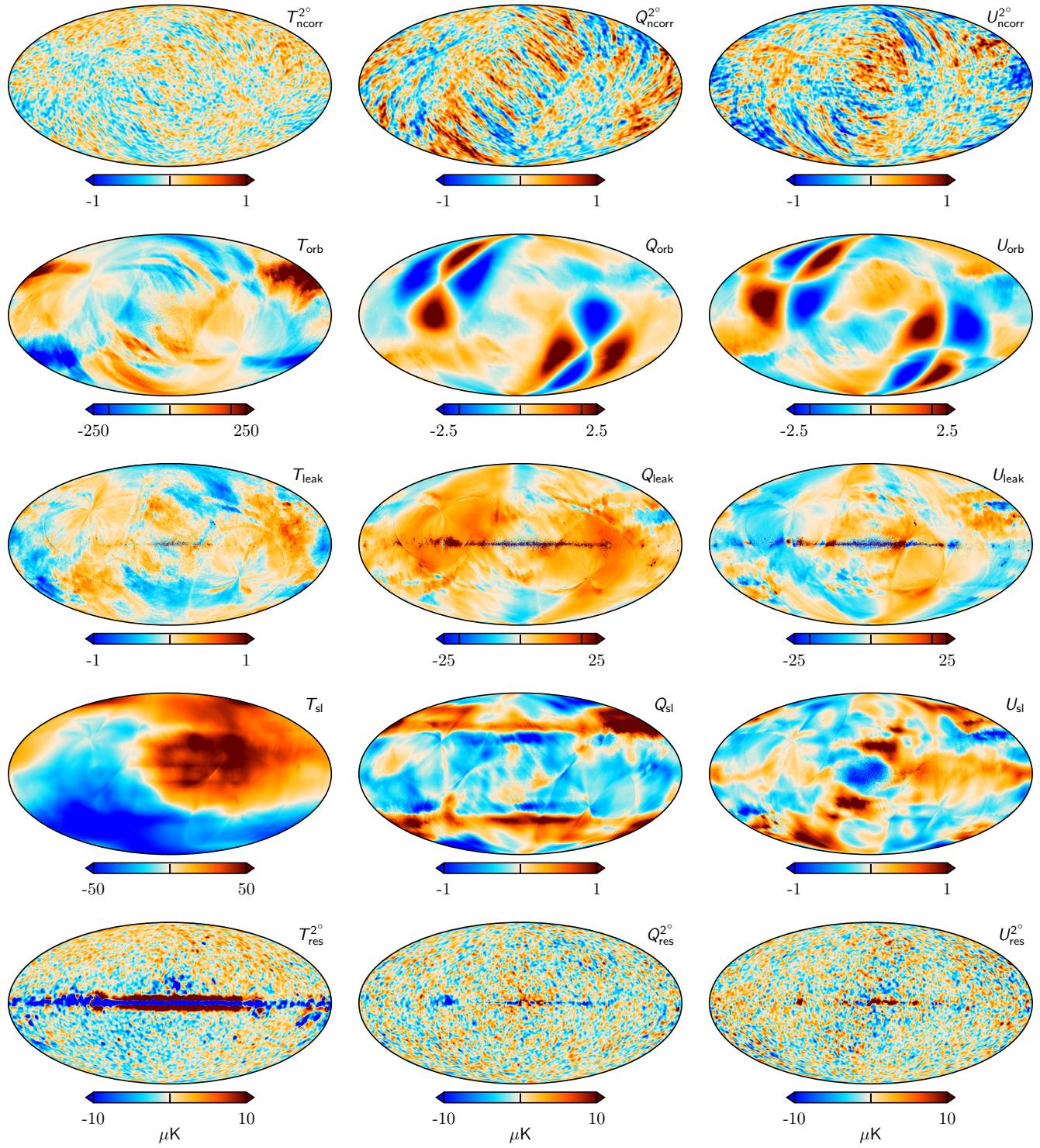


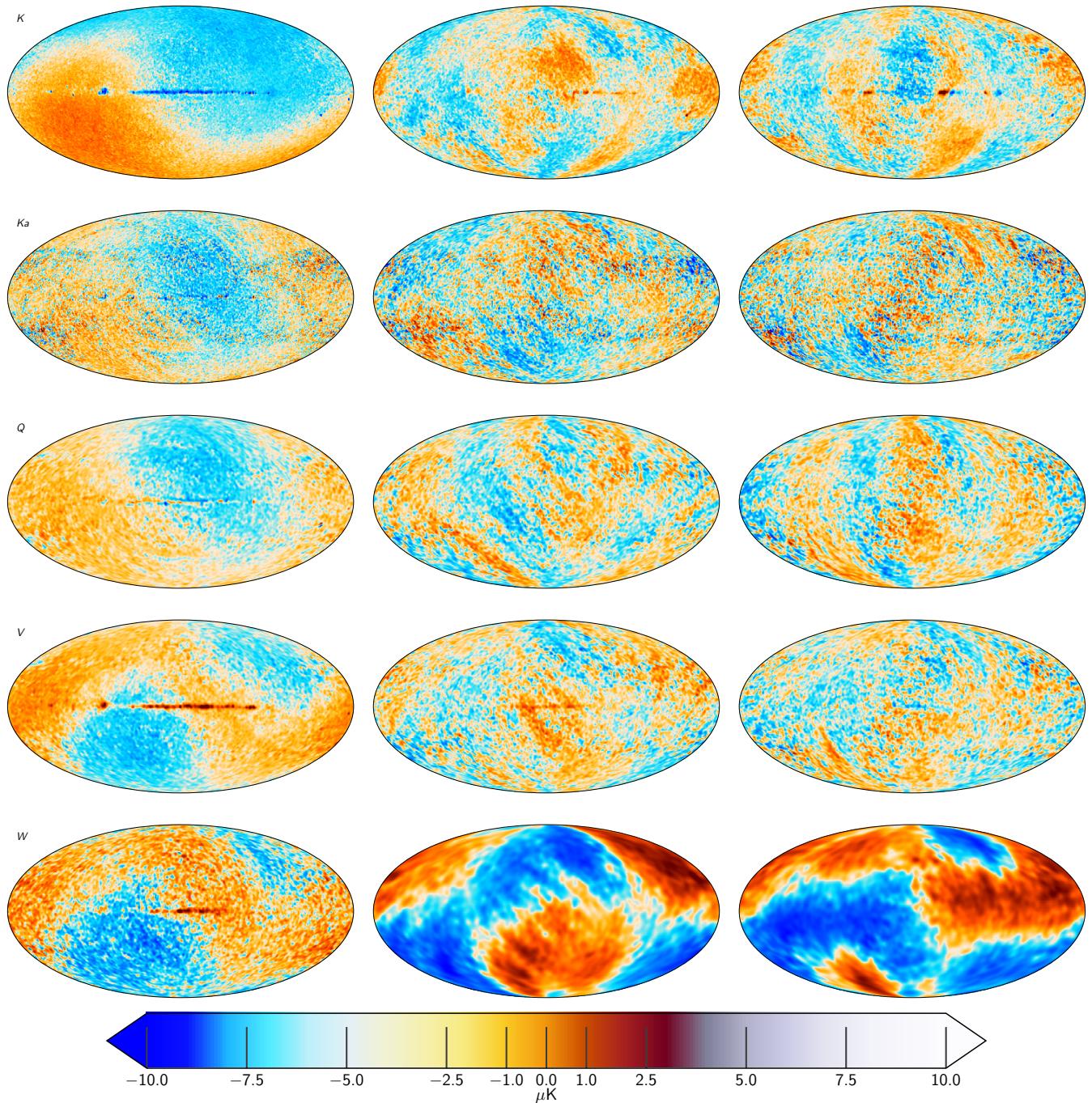


**Fig. 19.** K sample diff

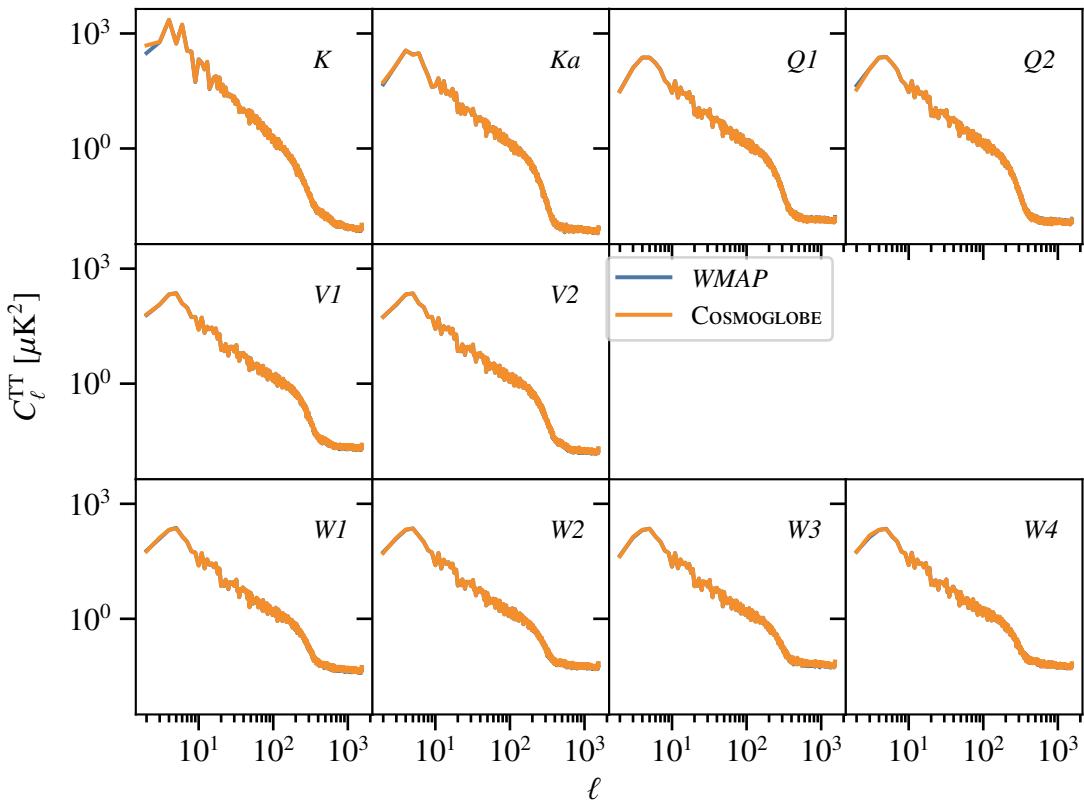
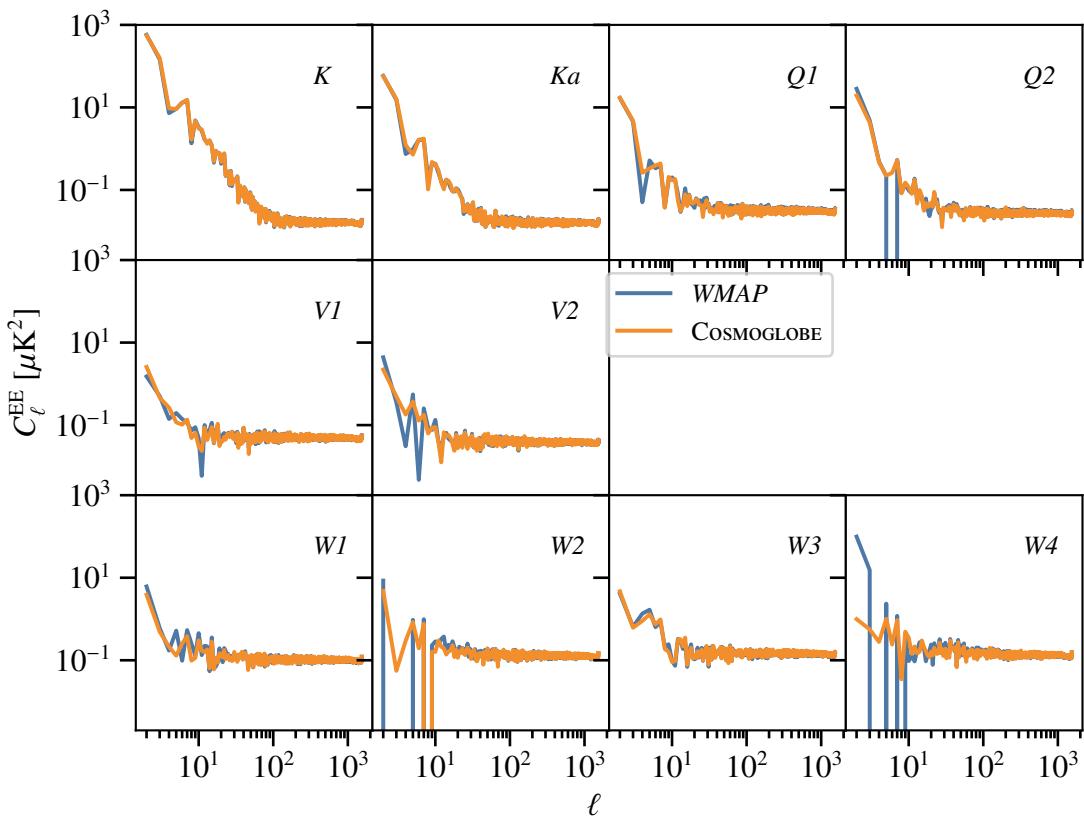


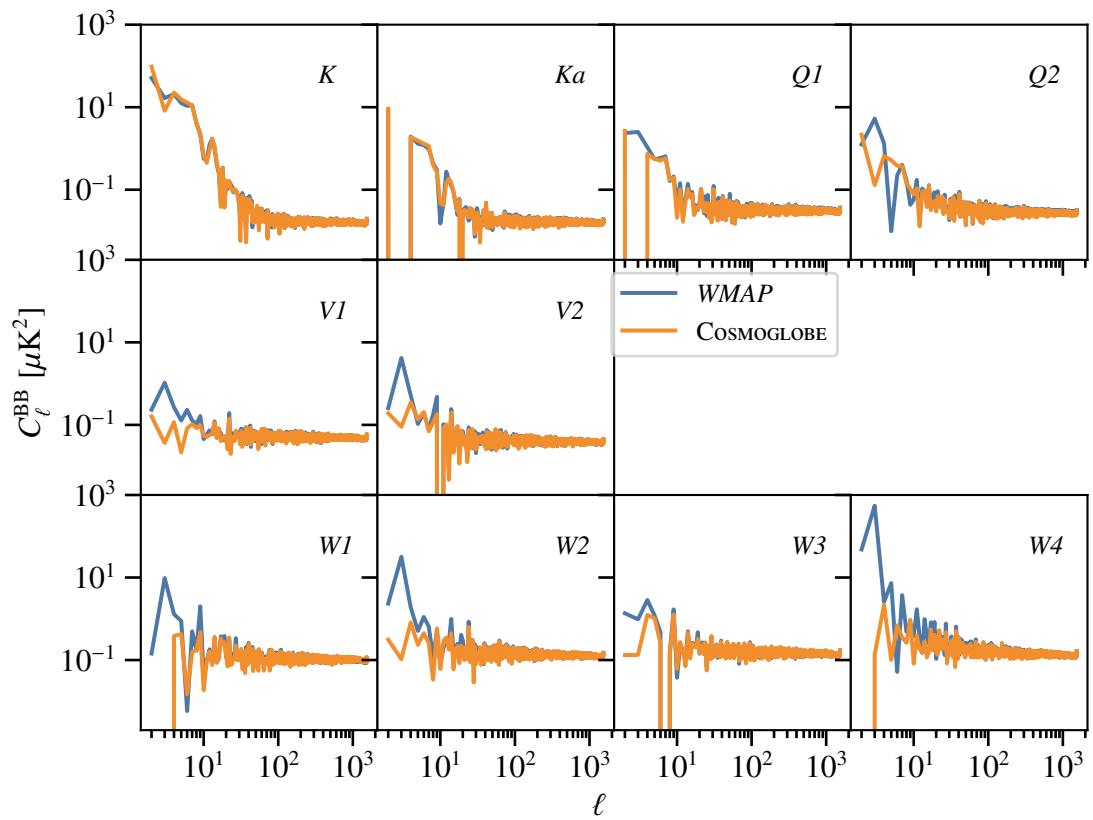
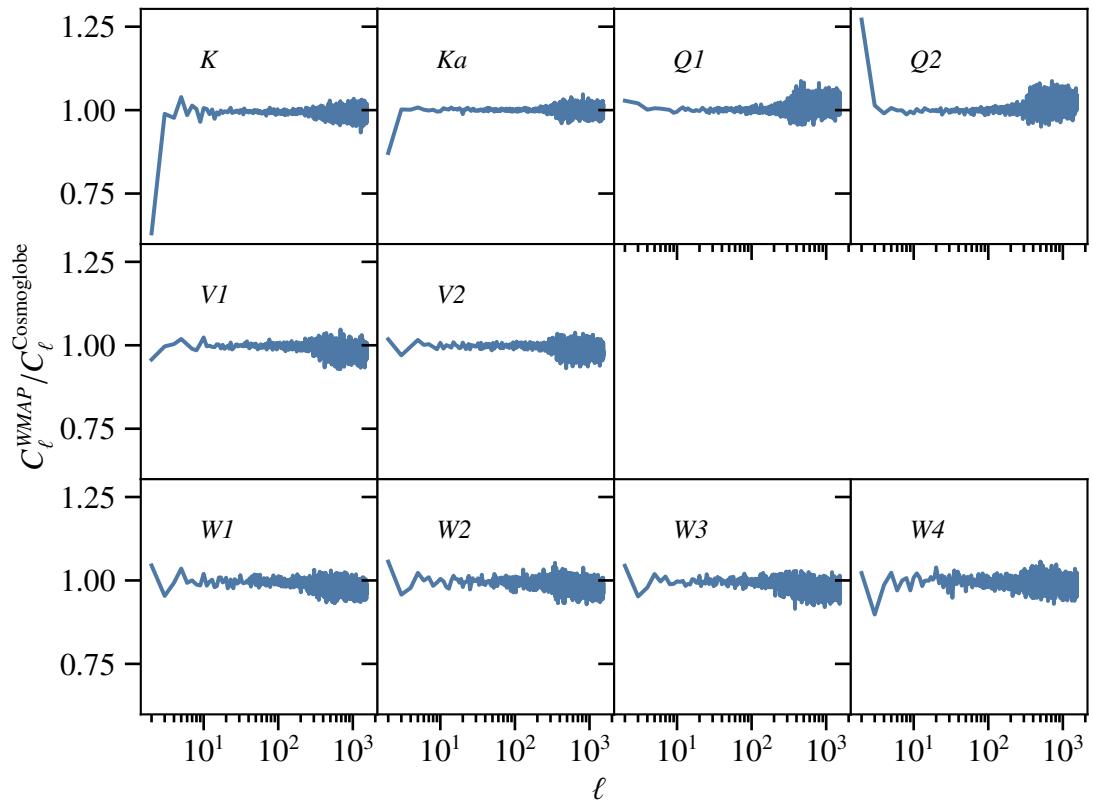
**Fig. 20.** K residual

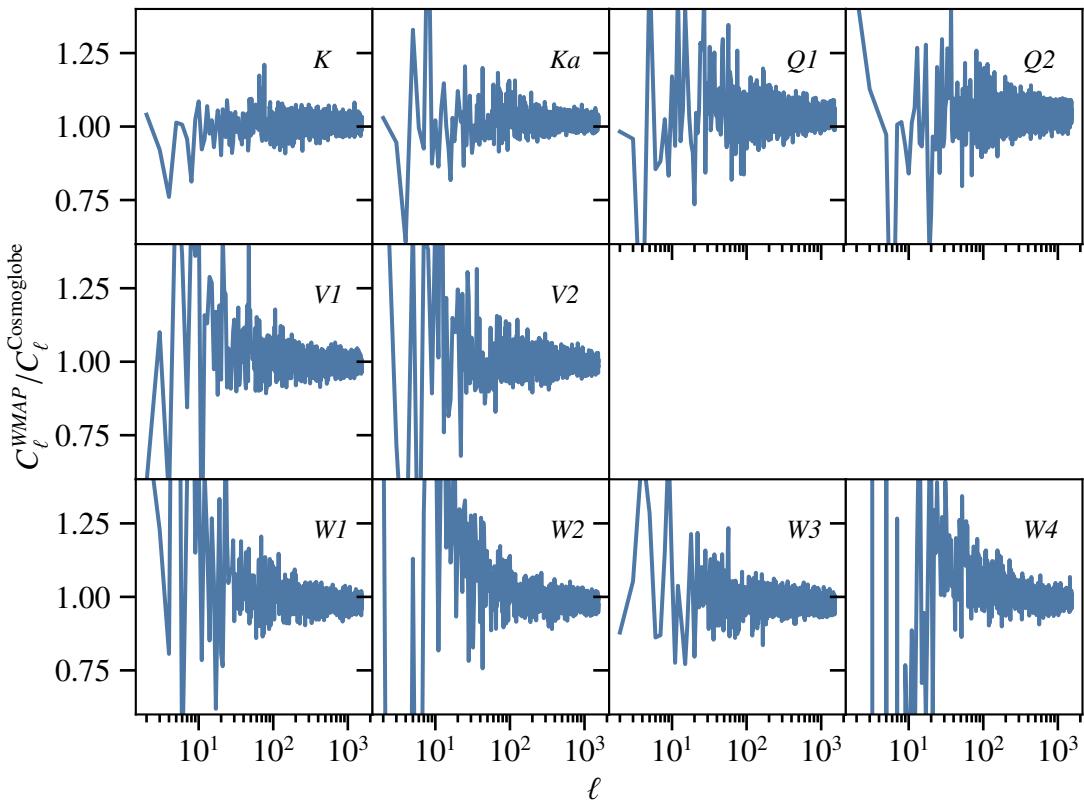
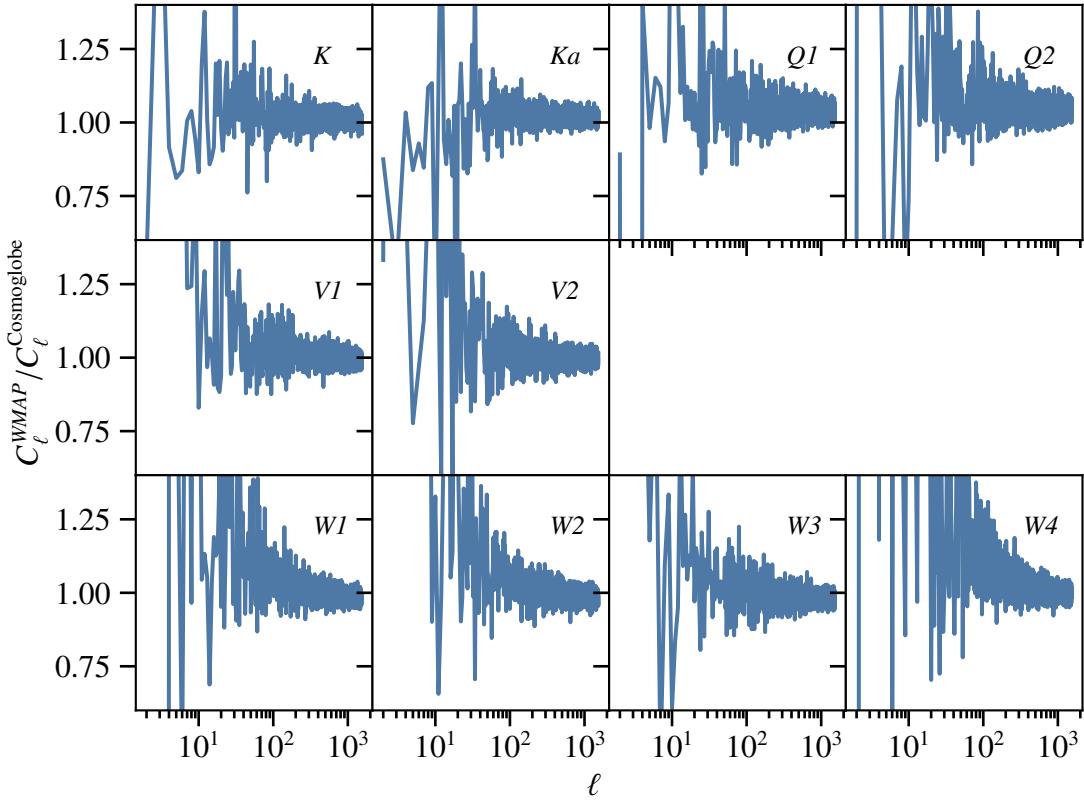
**Fig. 21.** Time-ordered components projected

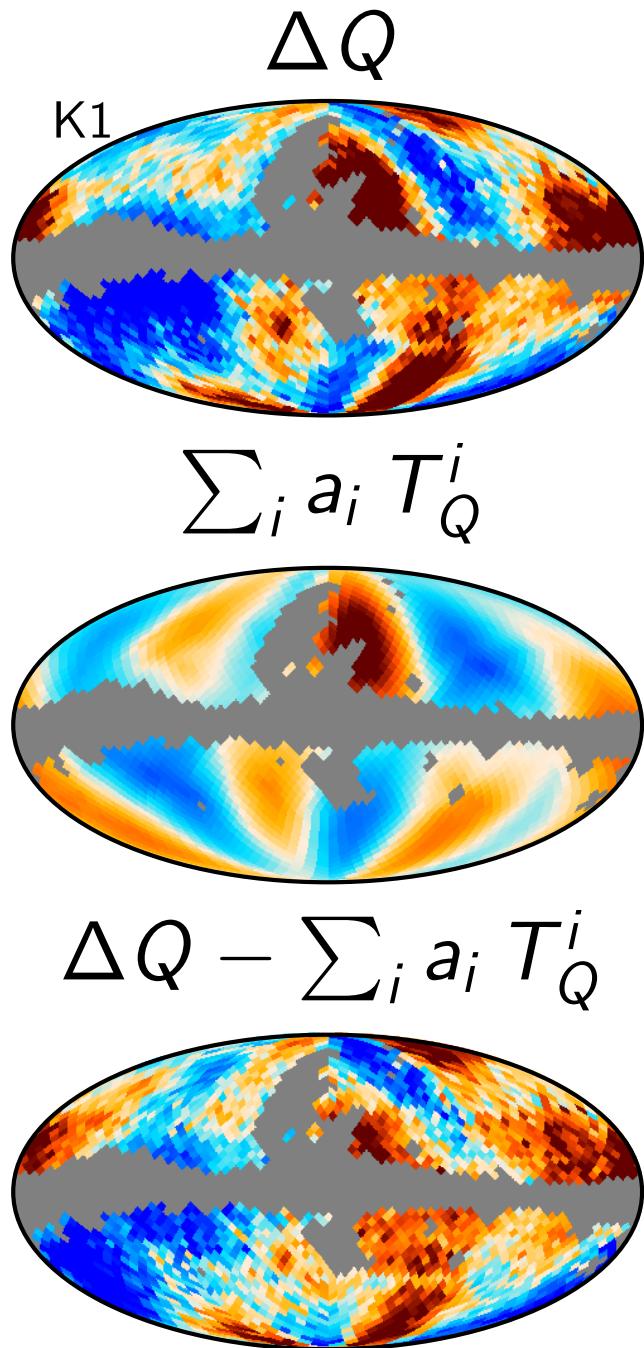


**Fig. 22.** Difference maps between the COSMOGLOBE and 9-year WMAP frequency maps. Columns show Stokes  $T$ ,  $Q$ , and  $U$  parameter maps, while rows show  $K$ -,  $Ka$ -,  $Q$ -,  $V$ -, and  $W$ -band maps. The temperature maps are smoothed to an angular resolution of  $1^\circ$  FWHM, while the polarization maps are smoothed to  $5^\circ$  FWHM.

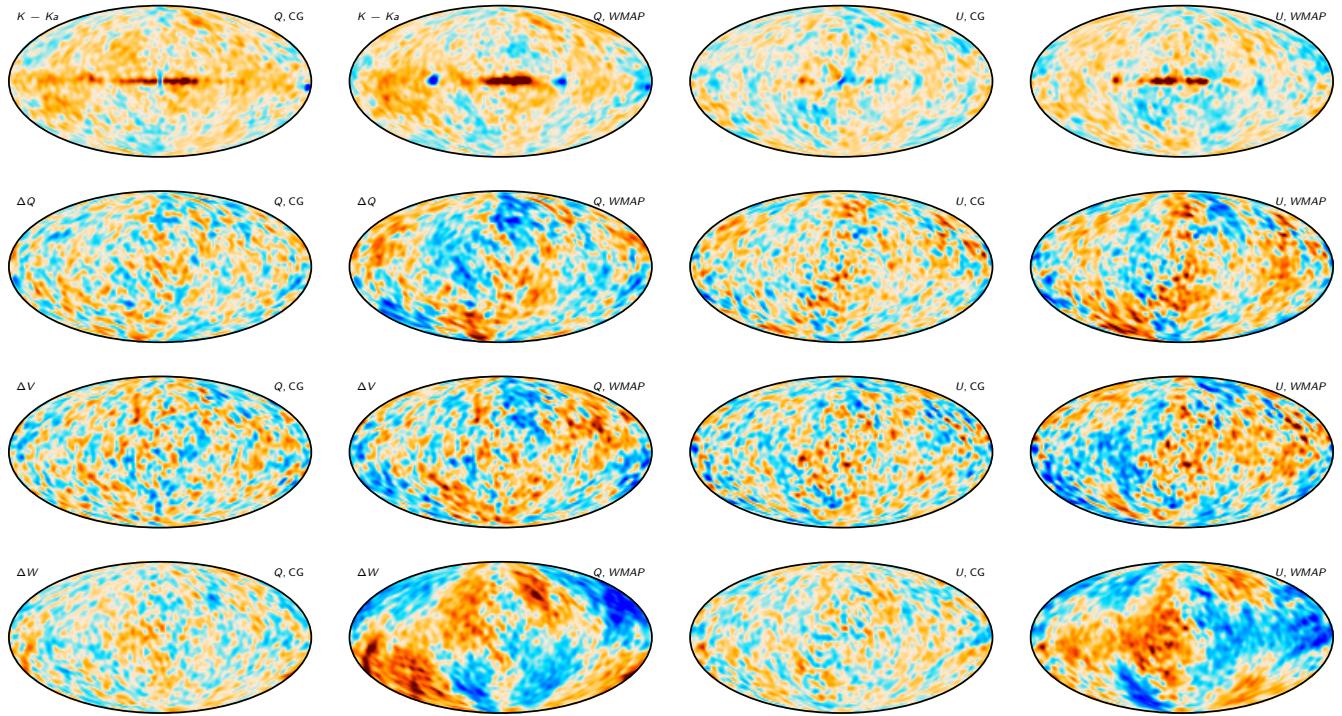
**Fig. 23.** TT power spectra**Fig. 24.** EE power spectra

**Fig. 25.** BB power spectra**Fig. 26.** TT ratios

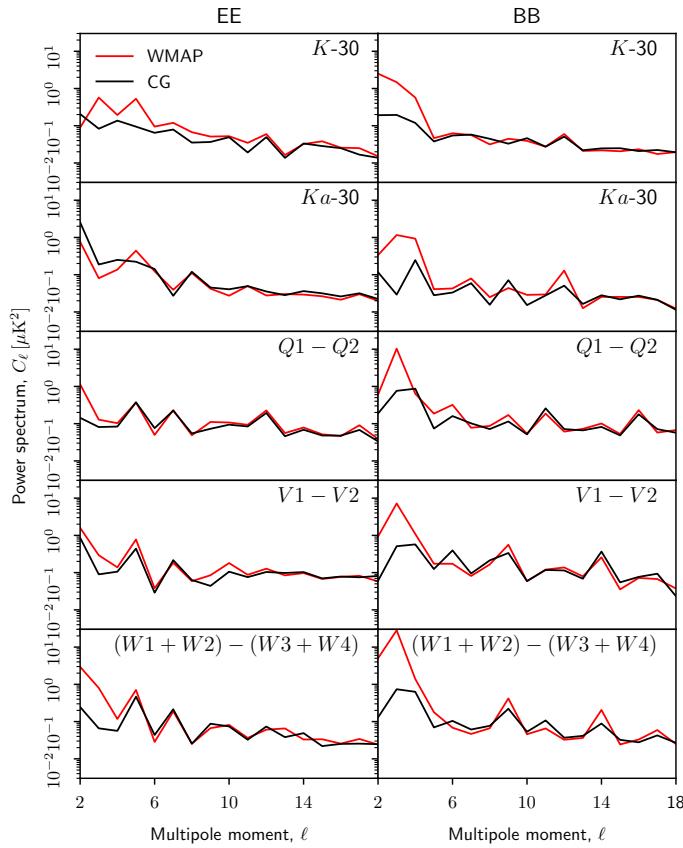
**Fig. 27.** EE ratios**Fig. 28.** BB ratios



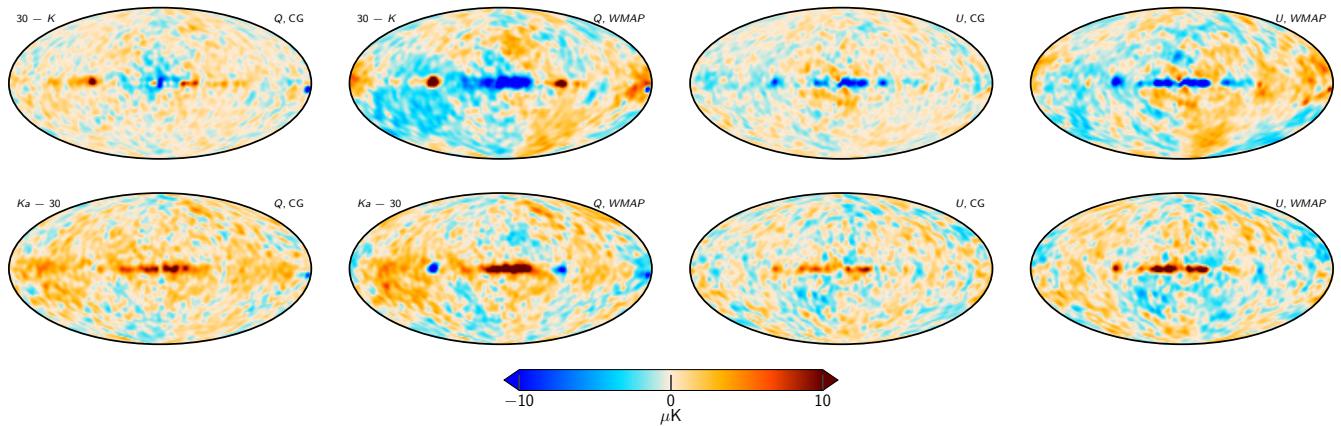
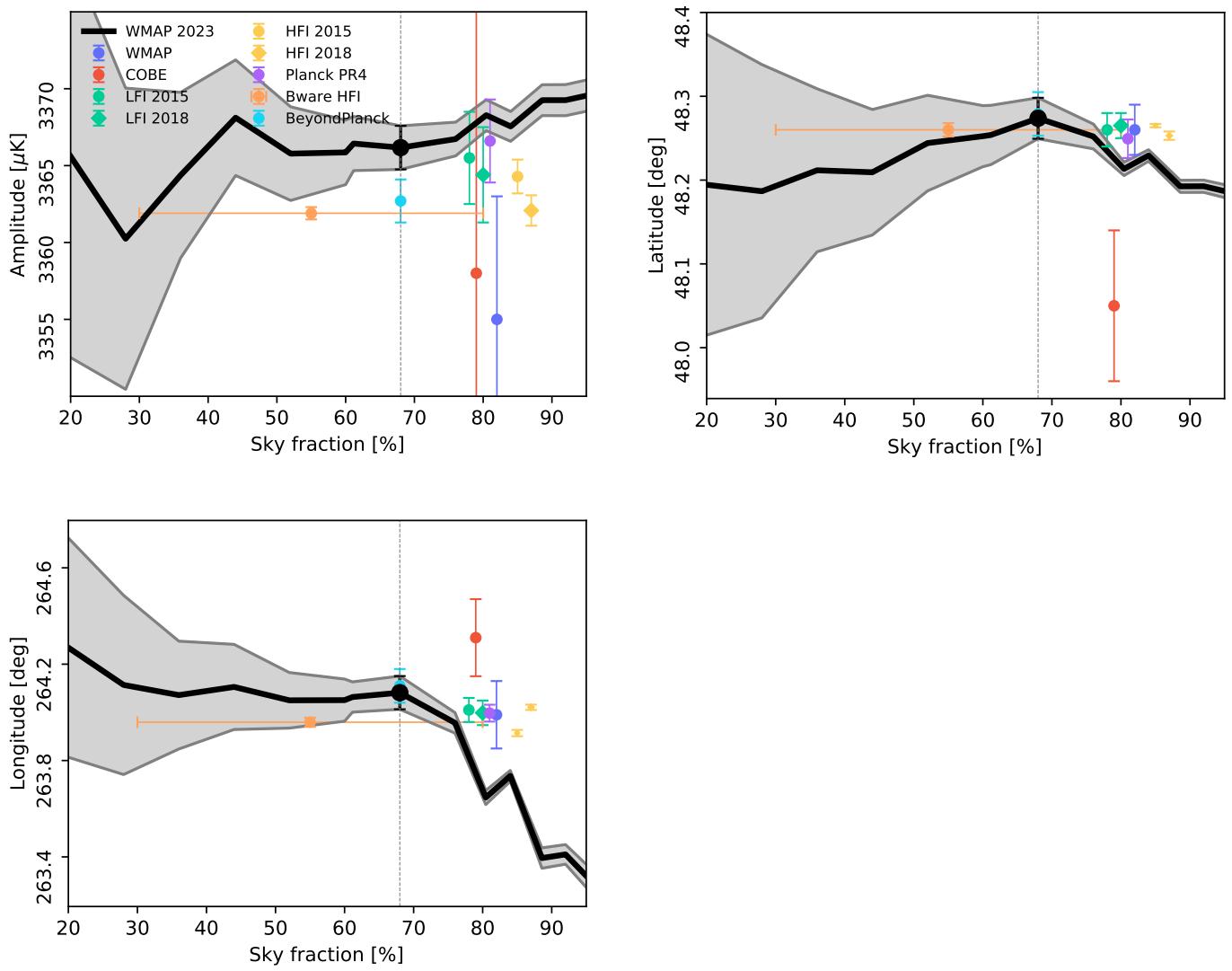
**Fig. 29.** K-band transmission imbalance templates

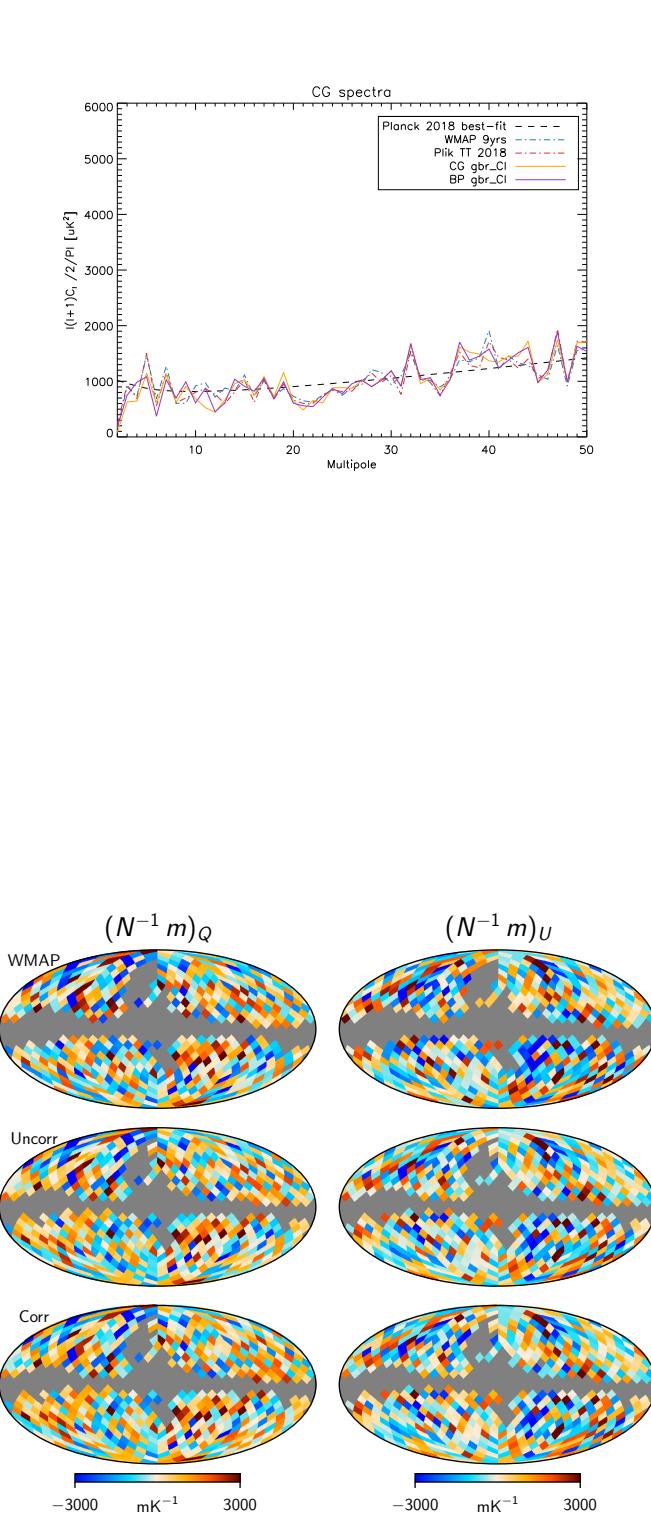
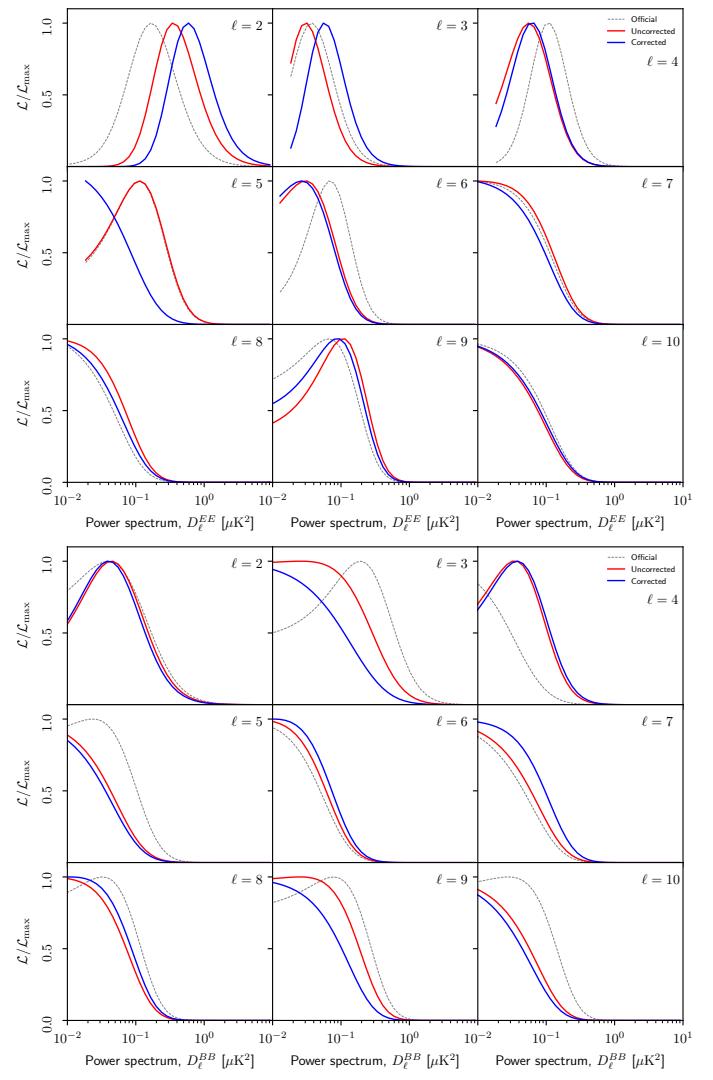


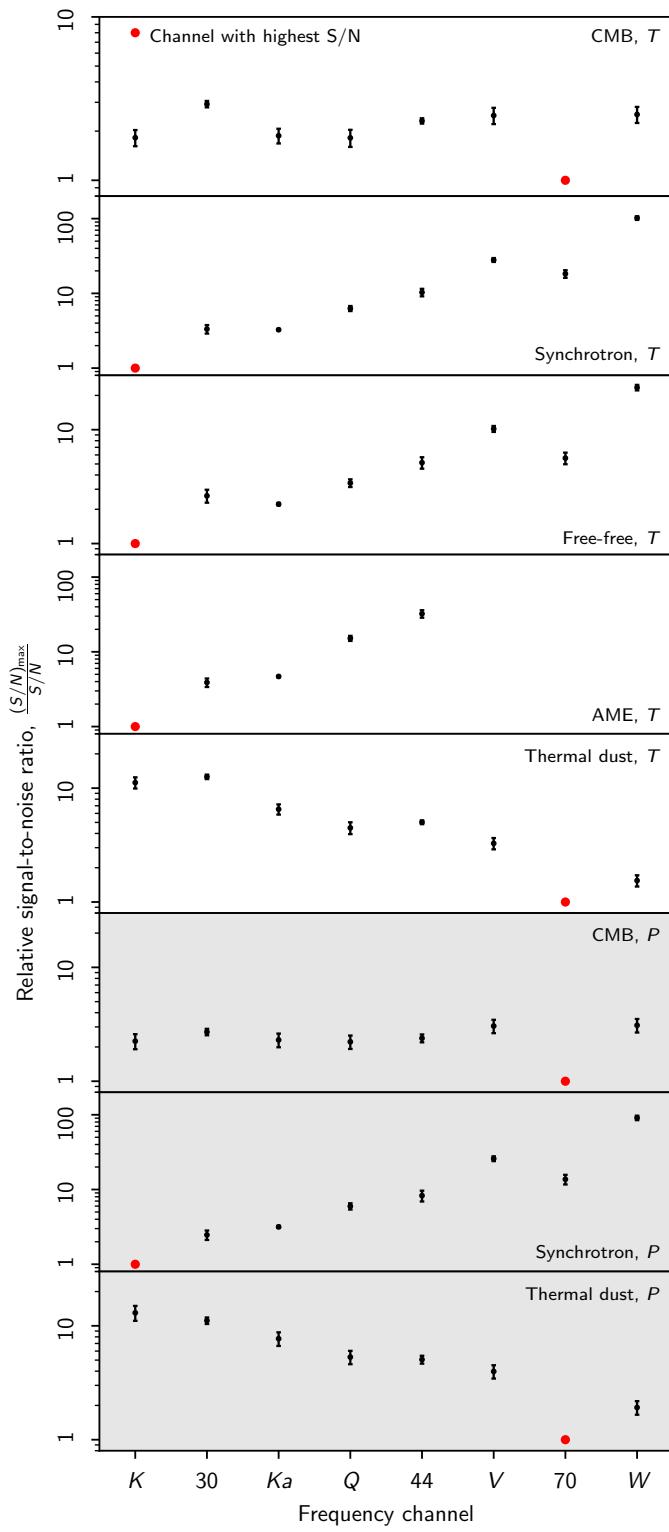
**Fig. 30.** Half-difference maps, smoothed by  $10^\circ$ .



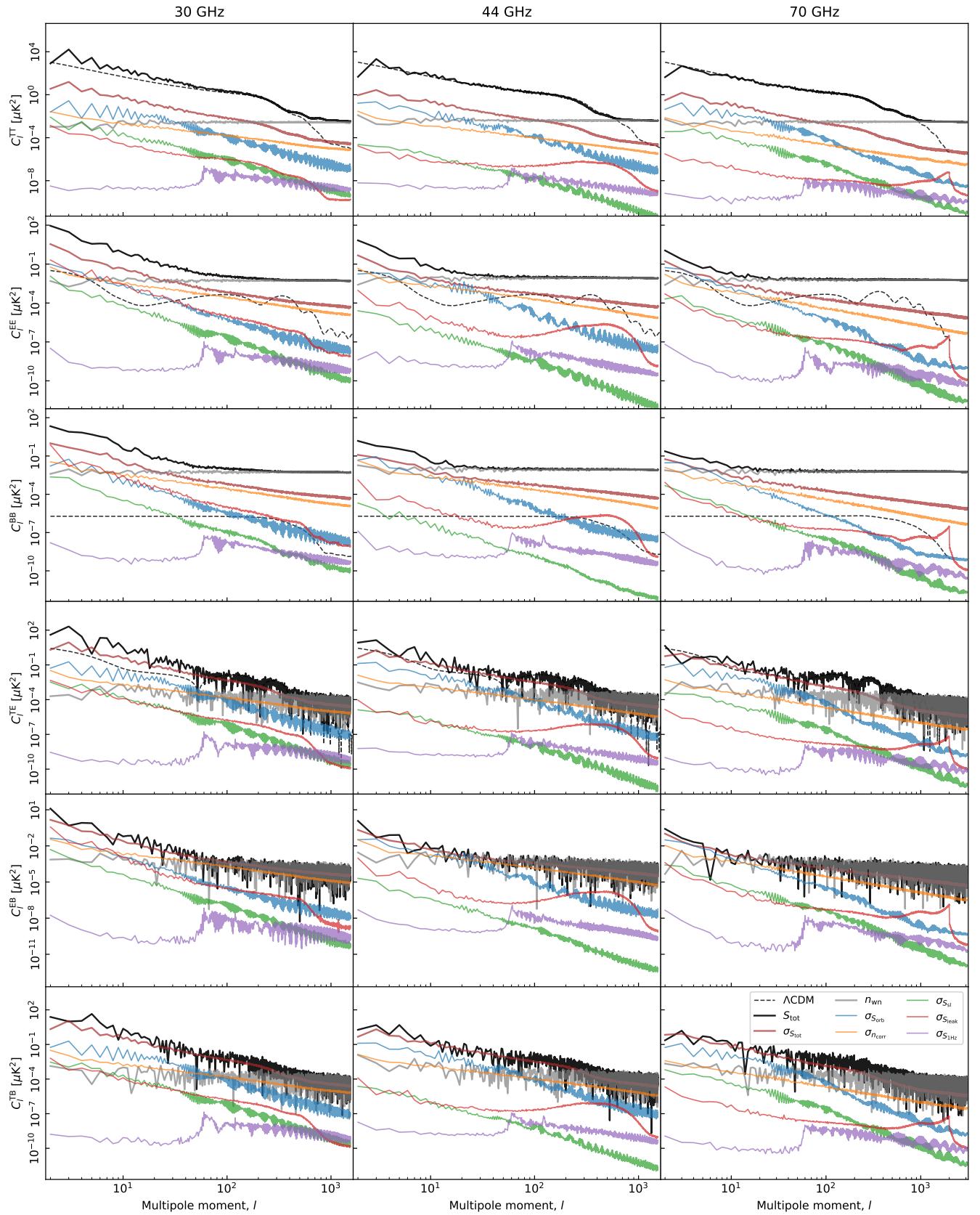
**Fig. 31.** Half-difference spectra.

**Fig. 32.** Mean of WMAP+LFI bands

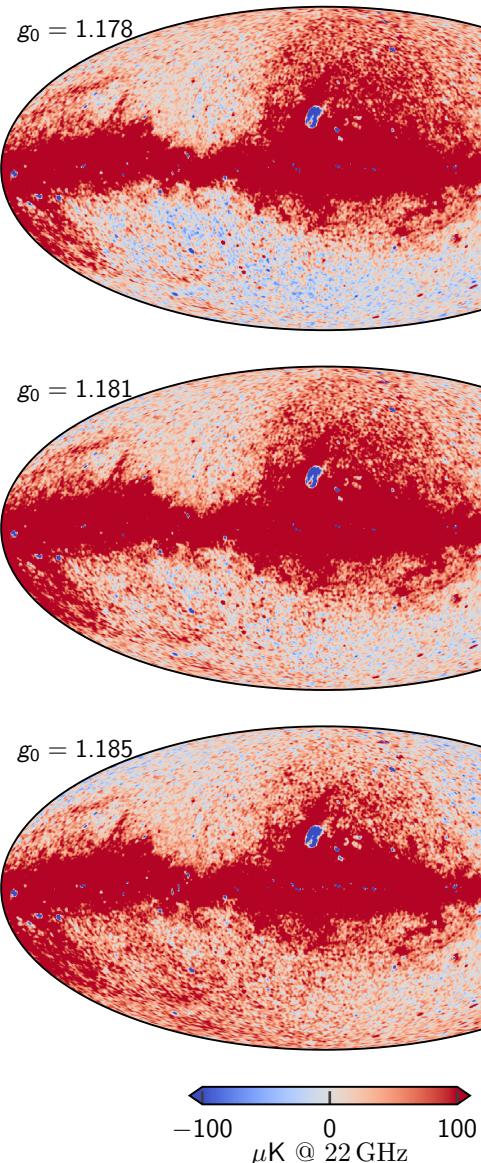
**Fig. 33.** Noise-weighted likelihood input maps.**Fig. 34.** Likelihood slices



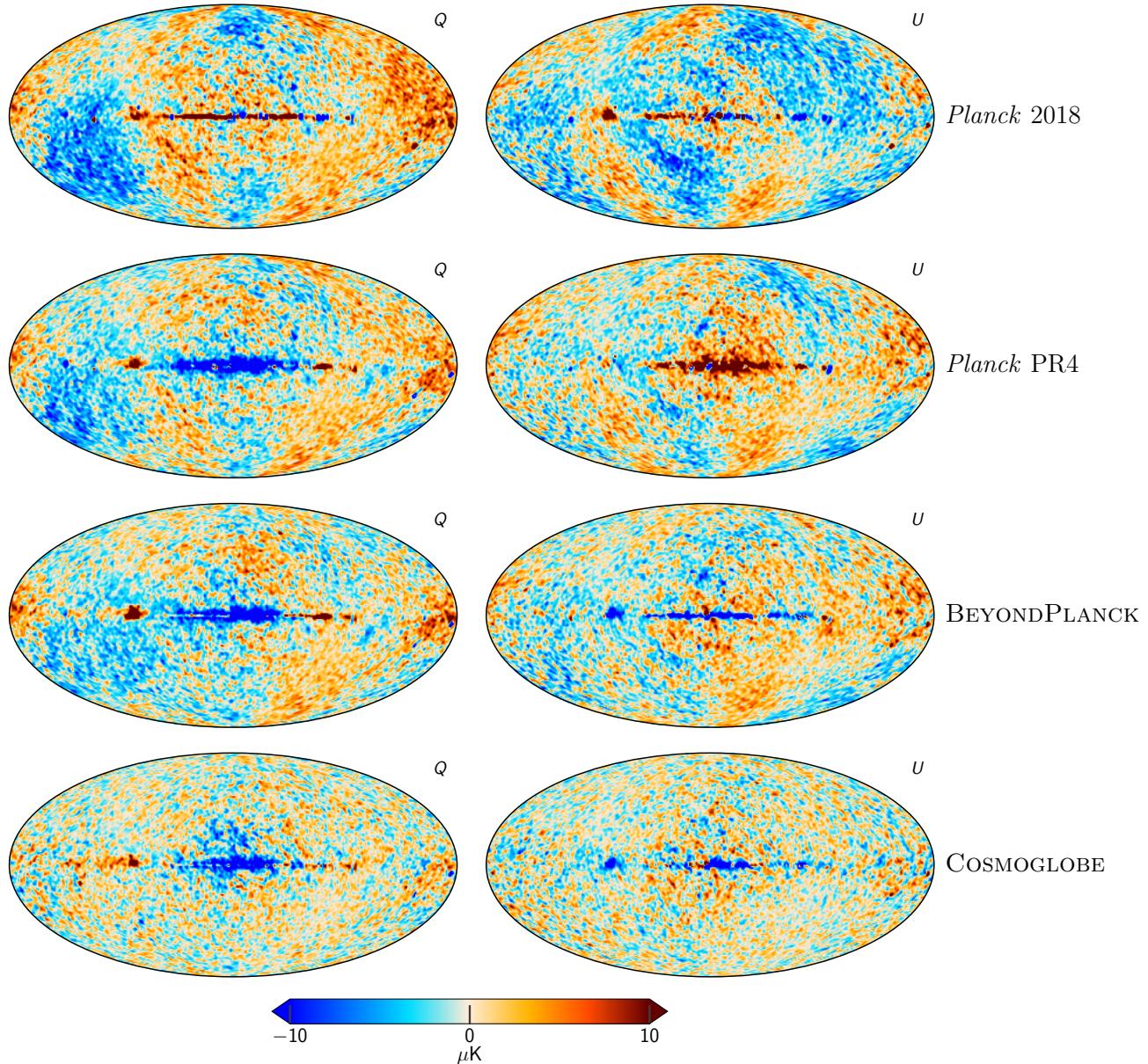
**Fig. 35.** Relative signal-to-noise ratios for WMAP and LFI channels and various components.



**Fig. 36.** Pseudo-spectrum standard deviation for each instrumental systematic correction shown in Figs. ??–?? (thin colored lines). For comparison, thick black lines show spectra for the full coadded frequency map; thick red lines show the standard deviation of the same (i.e., the full systematic uncertainty); gray lines show white noise; and dashed black lines show the best-fit *Planck* 2018  $\Lambda\text{CDM}$  power spectrum convolved with the instrument beam. Columns show results for 30, 44 and 70 GHz, respectively, while rows show results for each of the six polarization states ( $TT$ ,  $EE$ ,  $BB$ ,  $TE$ ,  $TB$ , and  $EB$ ). All spectra have been derived outside the CMB confidence mask presented by [Andersen et al. \(2022\)](#) using the HEALPix `anafast` utility, correcting only for sky fraction and not for mask mode coupling.



**Fig. 37.** Dependence on AME amplitude evaluated at 22 GHz as a function of absolute calibration. Each map comes from the fifth iteration of a dedicated `Commander` run that fixed  $g_0$  while letting all other TOD parameters be fit. The values of  $g_0 = 1.178$  and  $g_0 = 1.185$  represent  $3.5\sigma$  draws from the prior distribution with mean 1.1815 and standard deviation 0.001. The dipole visible in the top and bottom panels is aligned perfectly with the Solar dipole, and is directly due to variations in the  $K$ -band absolute calibration.



**Fig. 38.** Difference maps between the *Planck* 30 GHz and *WMAP* K-band maps. The columns are (1) *Planck* 2018 v. *WMAP*9, (2) *Planck* PR4 v. *WMAP*9, (3) BEYONDPLANCK v. *WMAP*9, and (4) COSMOGLOBE *Planck* 30 GHz and *WMAP* K-band both produced in this paper. All maps have been smoothed to a common resolution of  $2^\circ$  FWHM, and the K-band map has been scaled by 0.495 to account for different central frequencies, assuming a synchrotron spectral index  $\beta_s = -3.1$ .

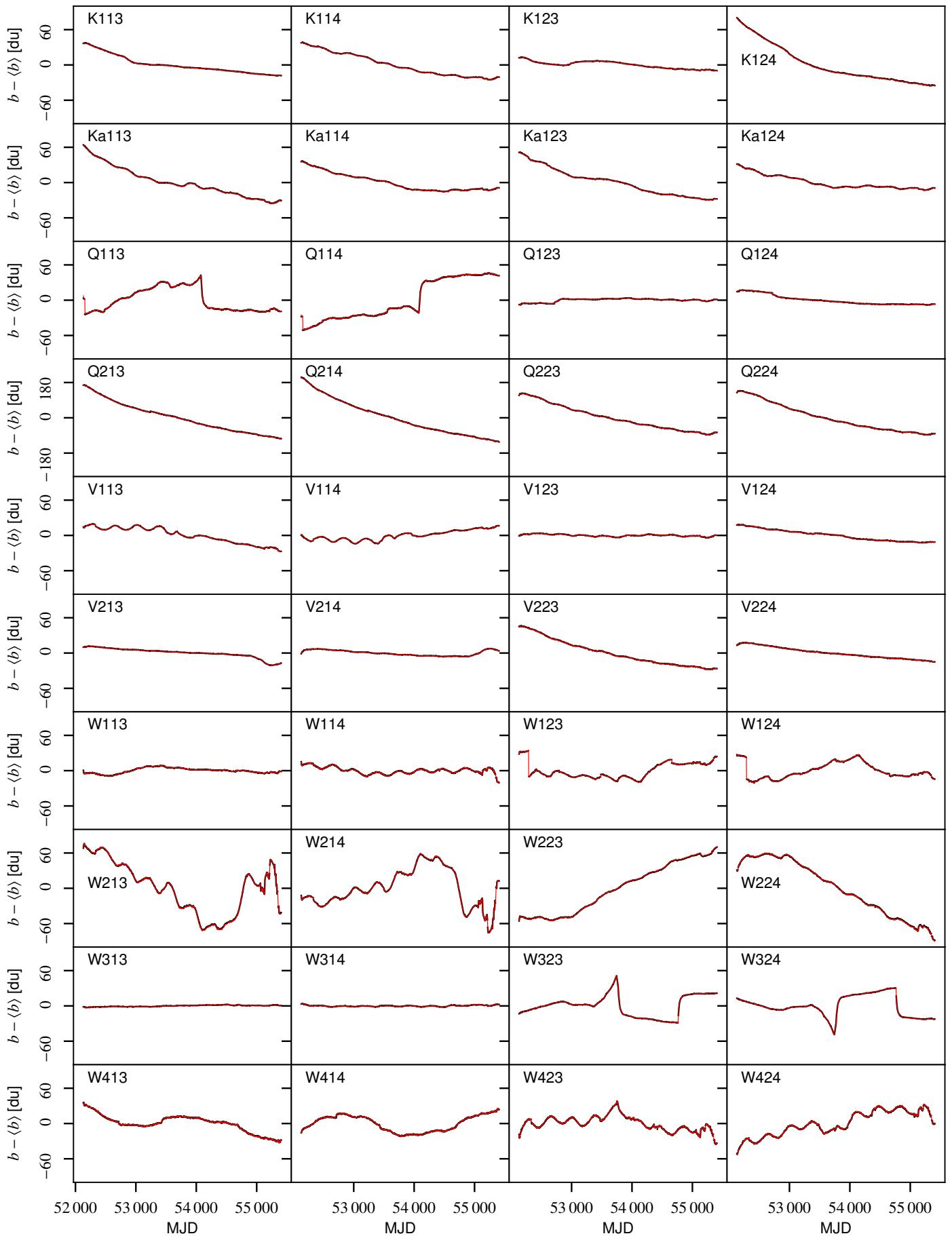
## **Appendix A: Survey of instrumental parameters**

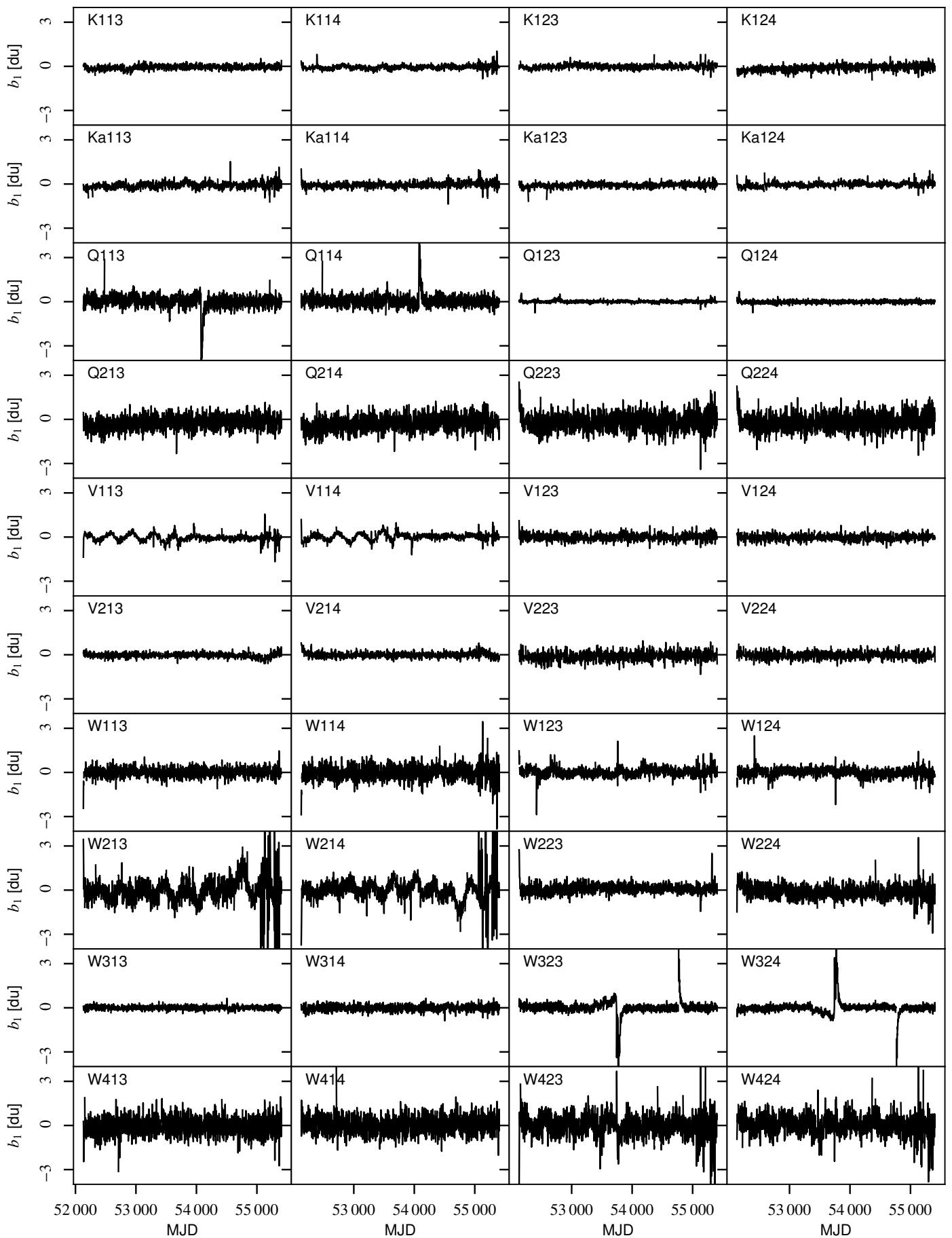
*Appendix A.1: Gain, baselines, noise and  $\chi^2$*

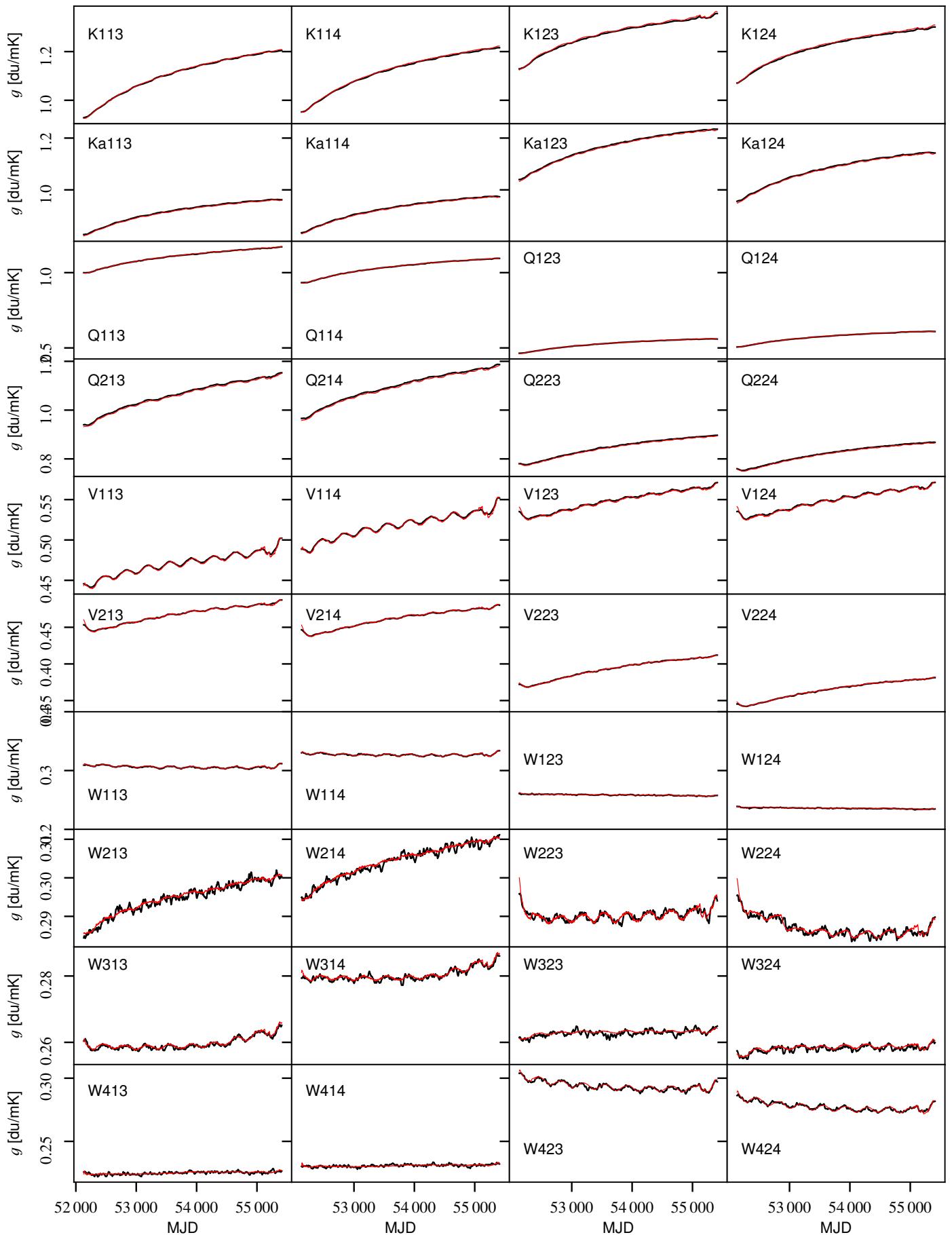
*Appendix A.2: Transmission imbalance*

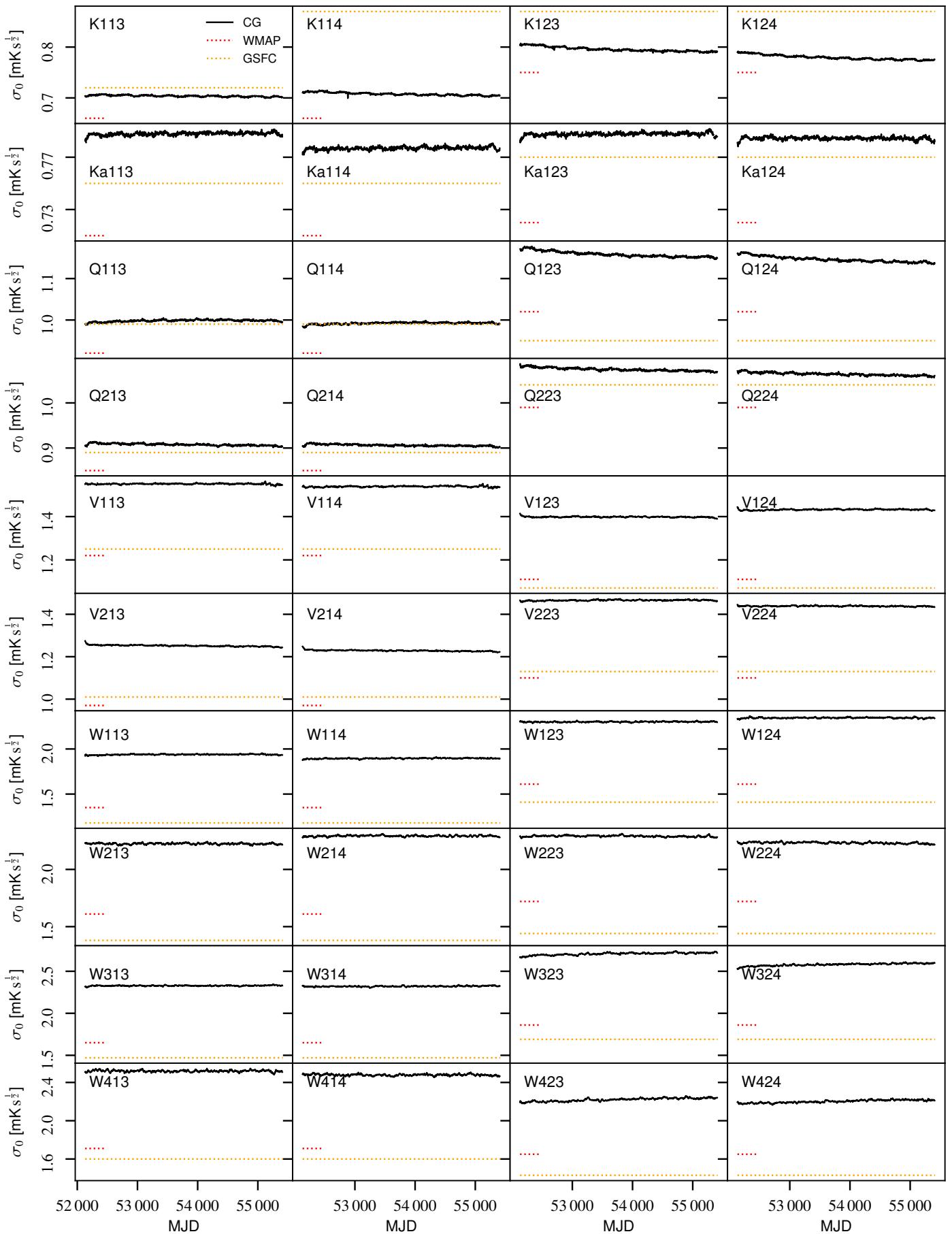
## **Appendix B: *WMAP* frequency map survey**

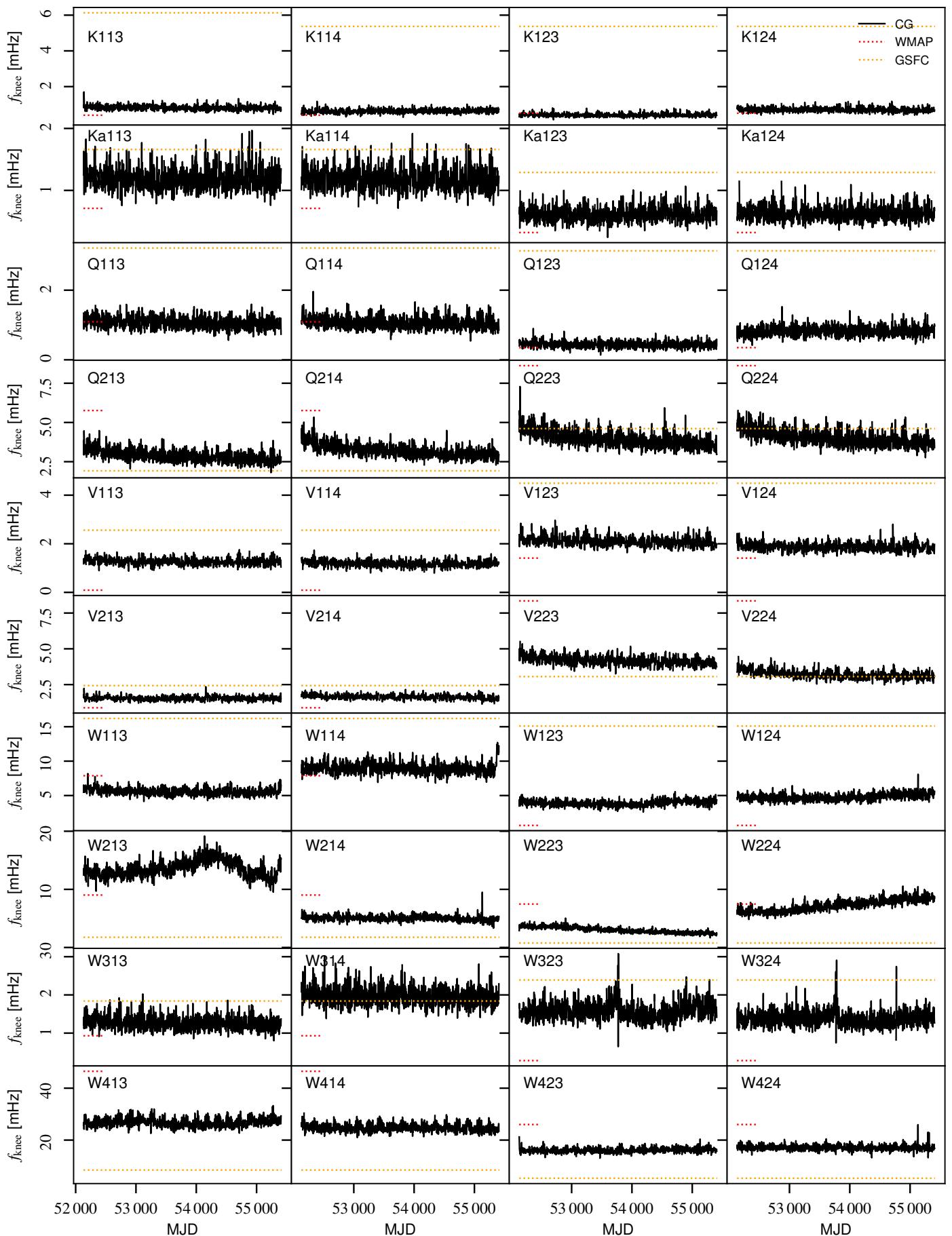
## **Appendix C: Comparison with BEYONDPLANCK LFI results**

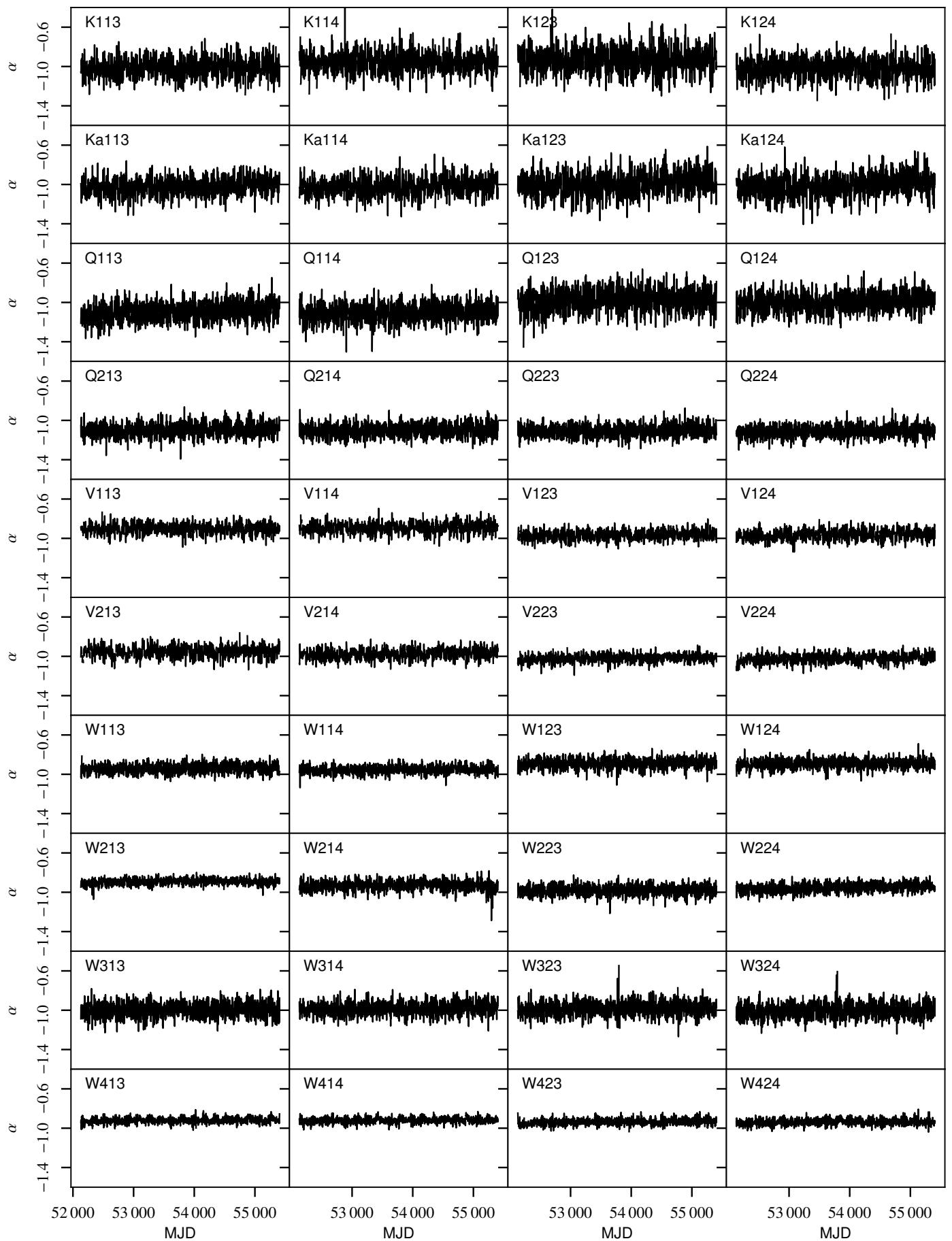
**Fig. A.1.** baseline.

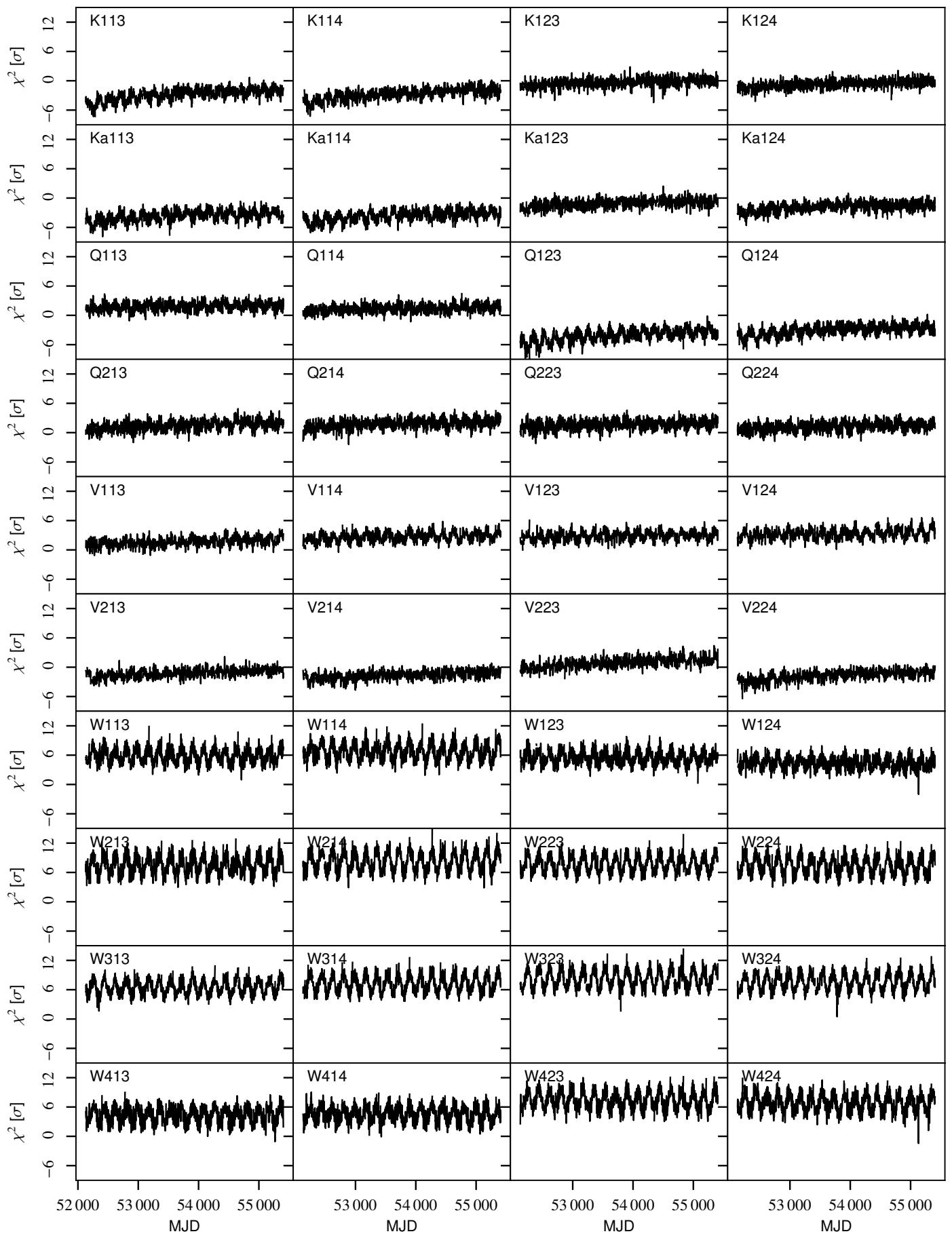
**Fig. A.2.** baseline slopes.

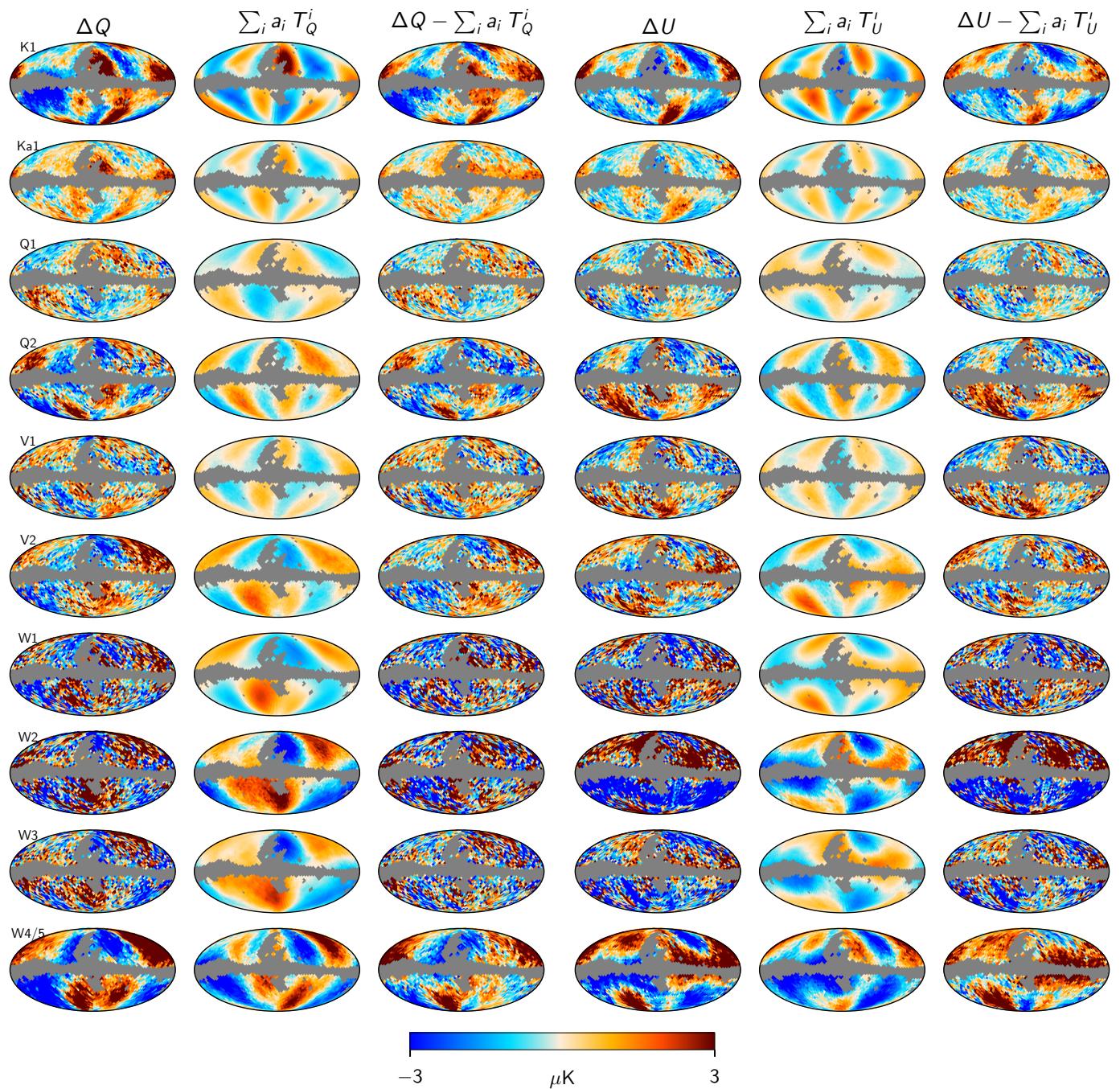
**Fig. A.3.** Gain.

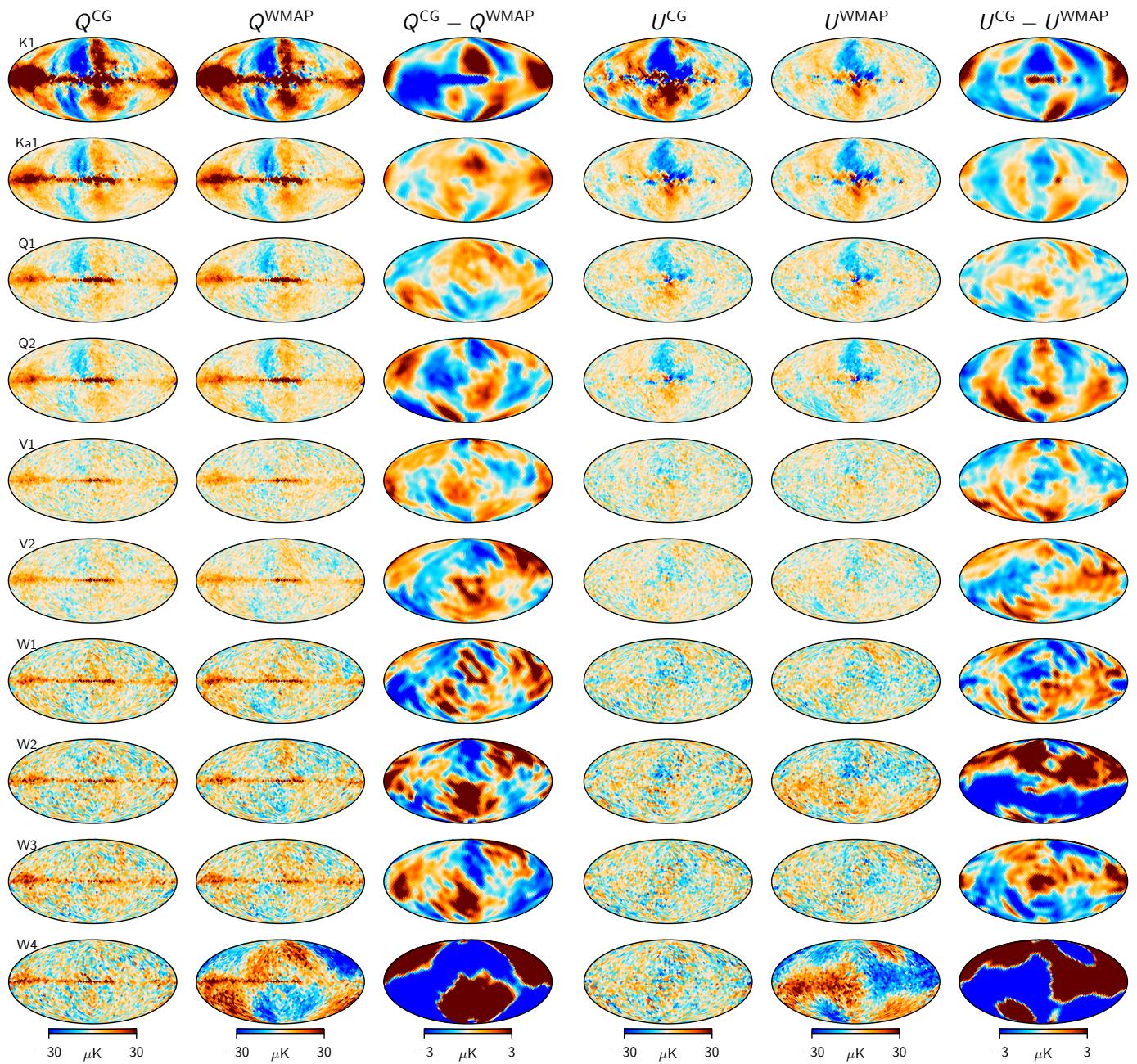
**Fig. A.4.**  $\sigma_0$ .

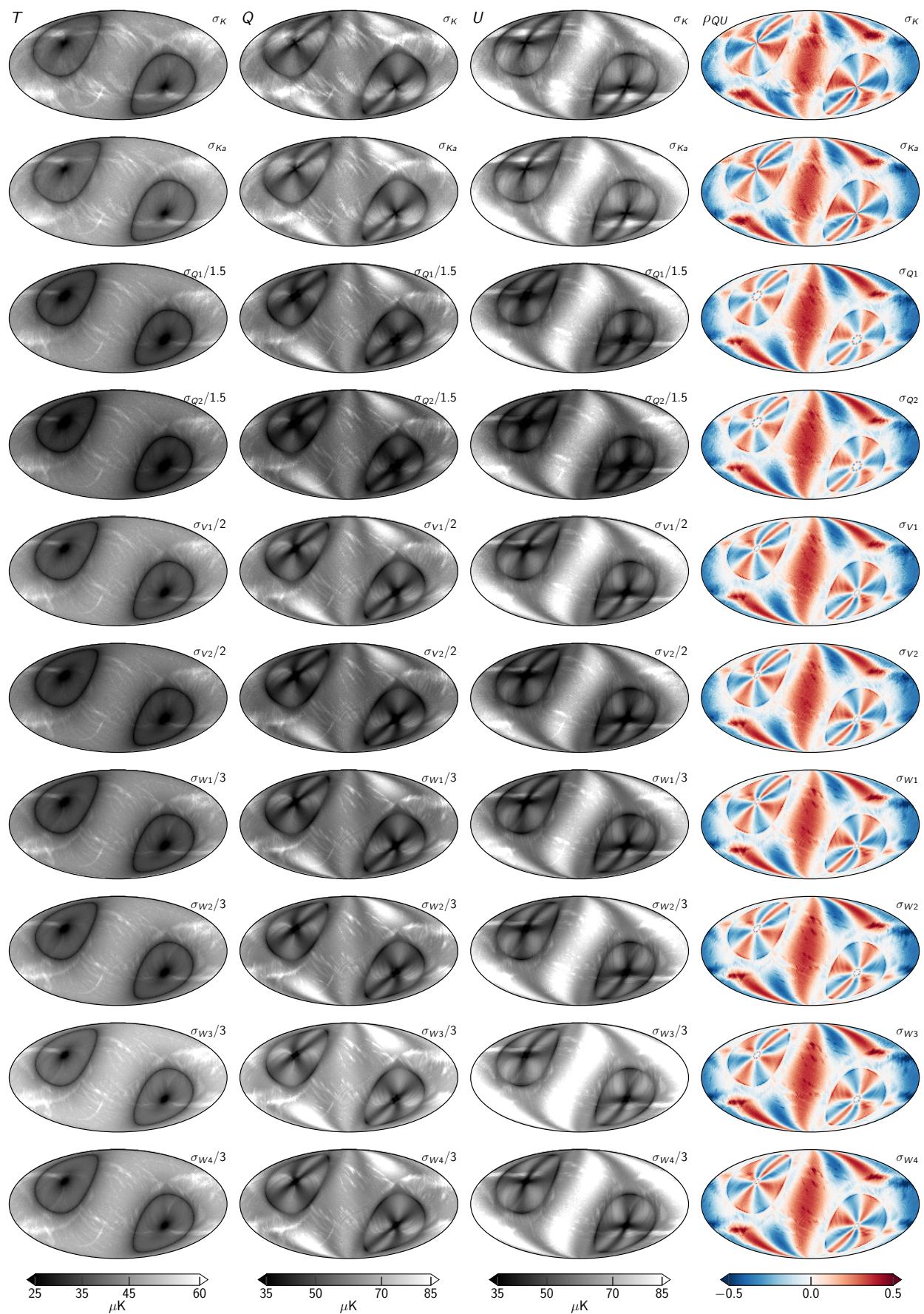
**Fig. A.5.** Fknee.

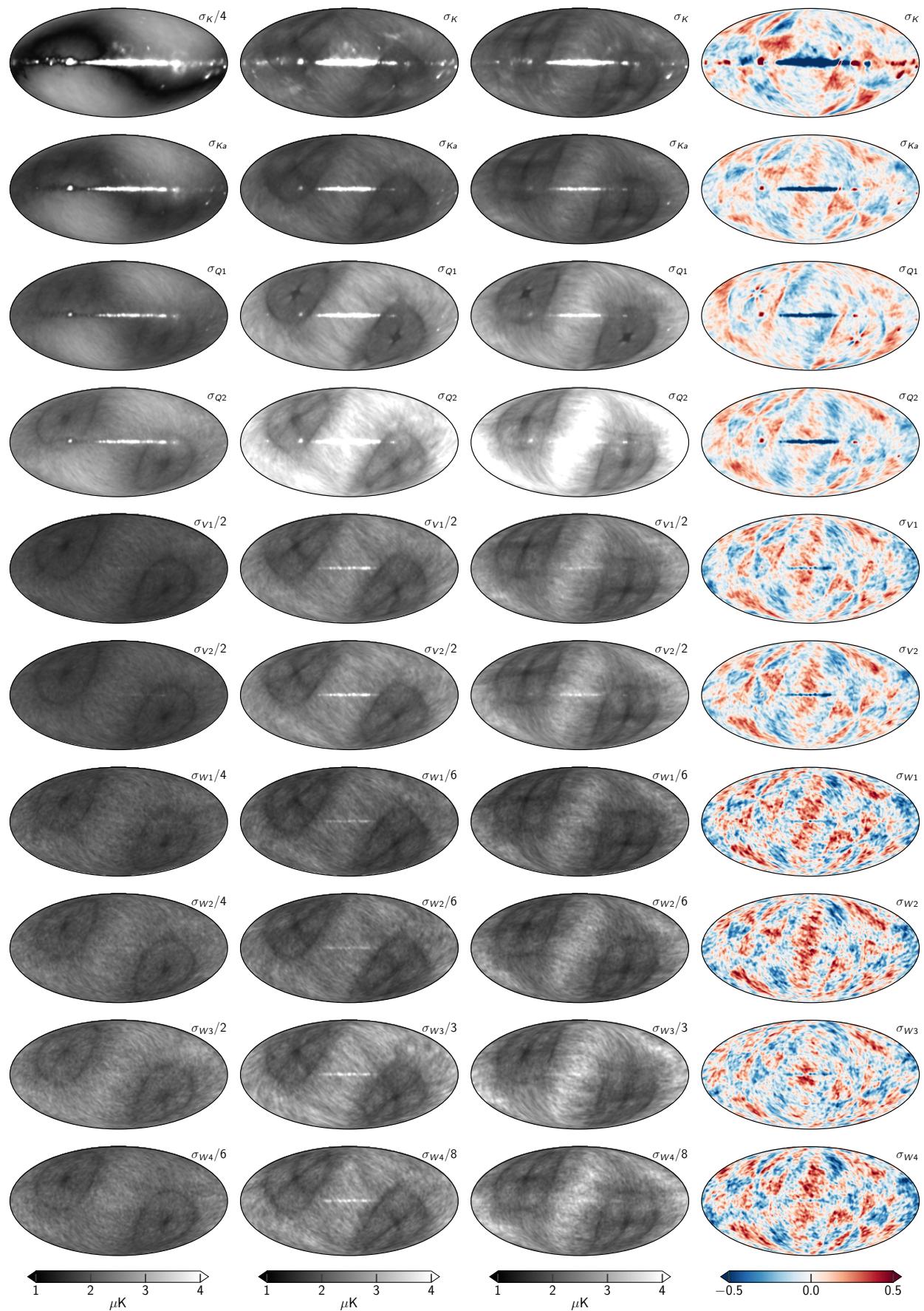
**Fig. A.6.**  $\alpha$ .

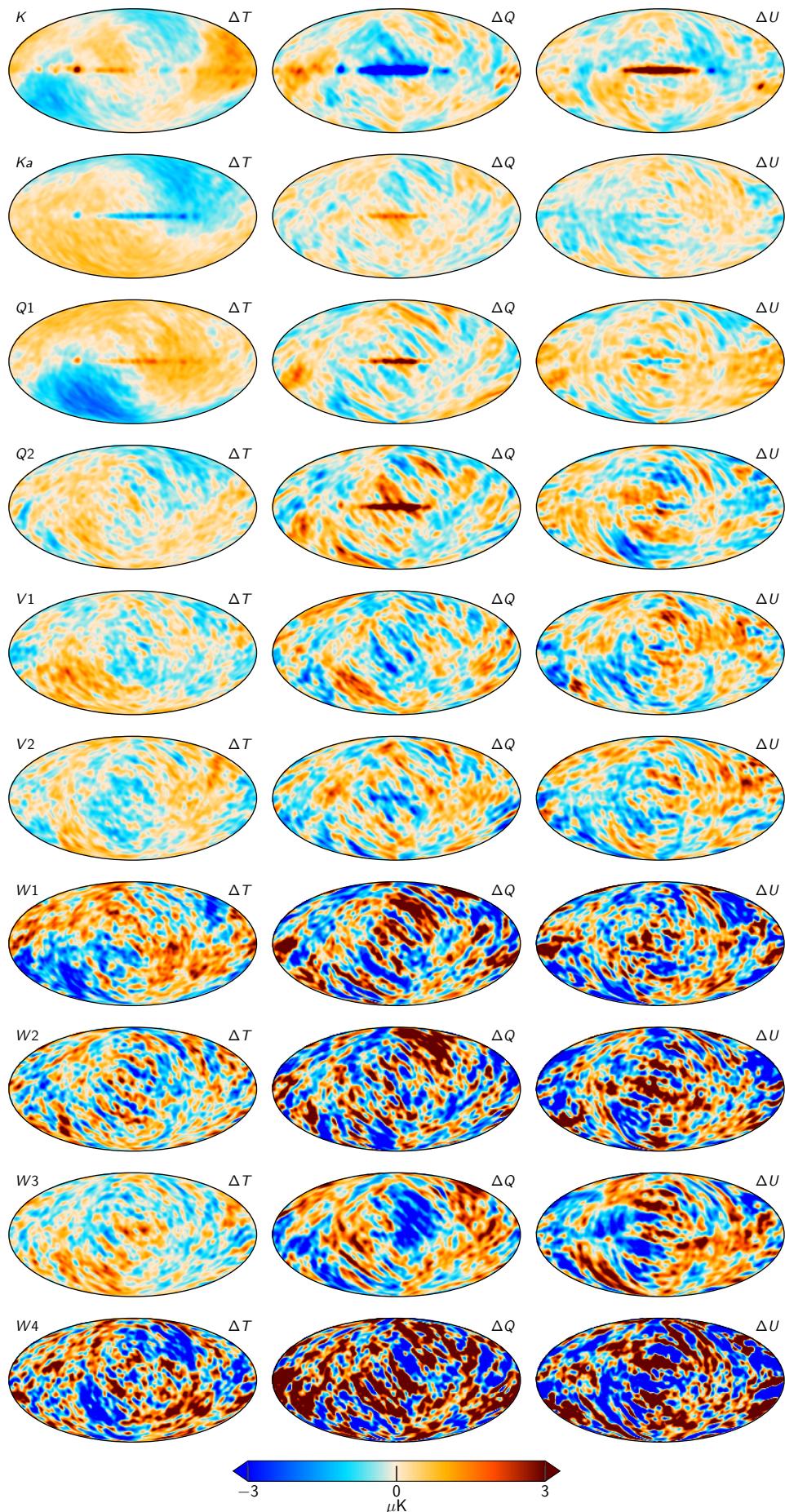
**Fig. A.7.** chisq.

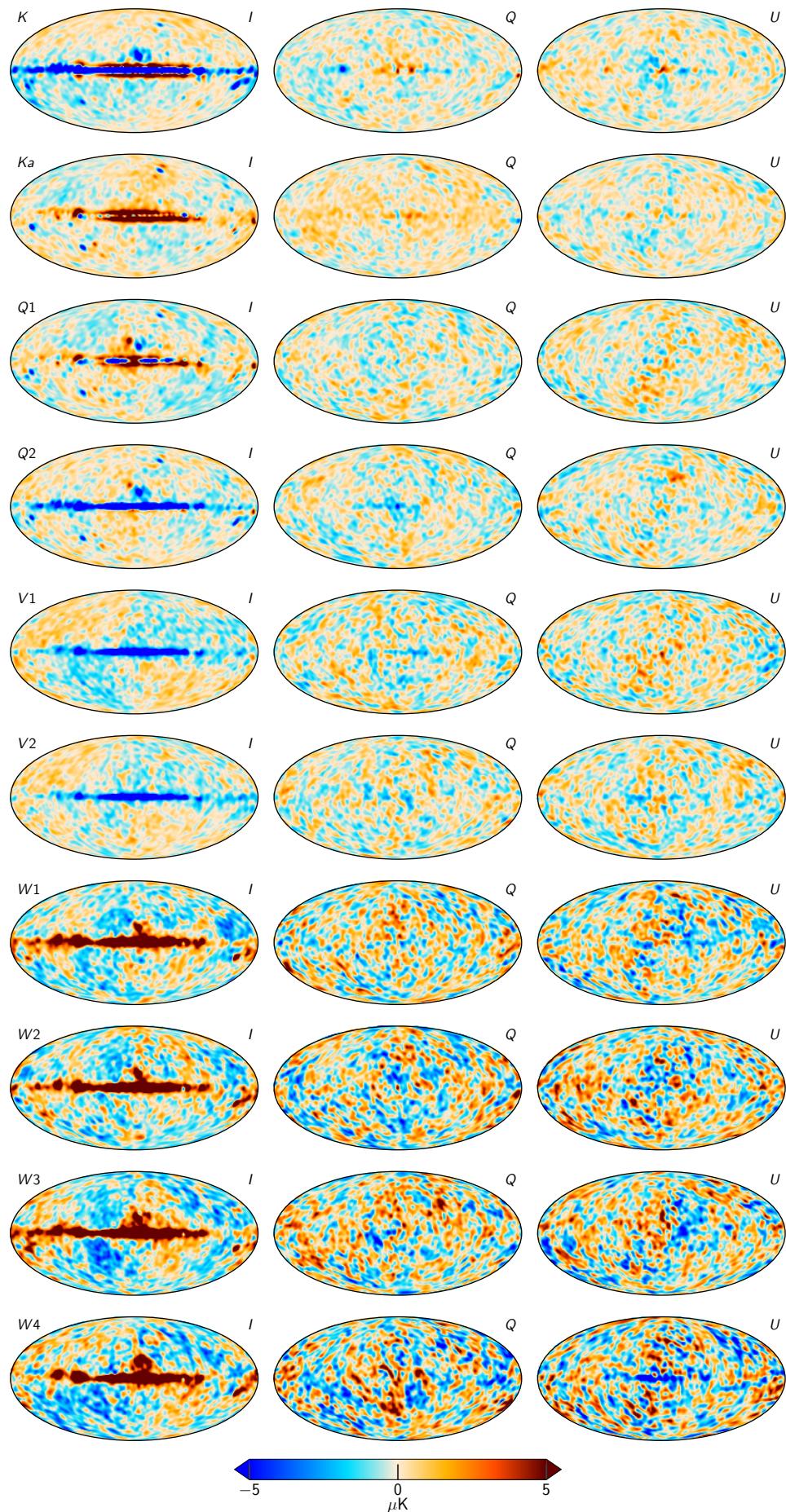
**Fig. A.8.** Transmission imbalance templates

**Fig. B.1.** Sky maps

**Fig. B.2.** RMS maps

**Fig. B.3.** STD std

**Fig. B.4.** Differences between two samples



**Fig. B.5.** TOD Residuals for each of the WMAP channels, smoothed by  $5^\circ$ .  
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