The Abdus Salam
International Centre
for Theoretical Physics

2474-3

School and Workshop on New Light in Cosmology from the CMB

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Planck Products: From timelines to frequency maps and null tests

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From timelines to Frequency Maps

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LFI DPCM

on behalf of the Planck Collaboration

School on New Light in Cosmology from the CMB

ICTP

Overview

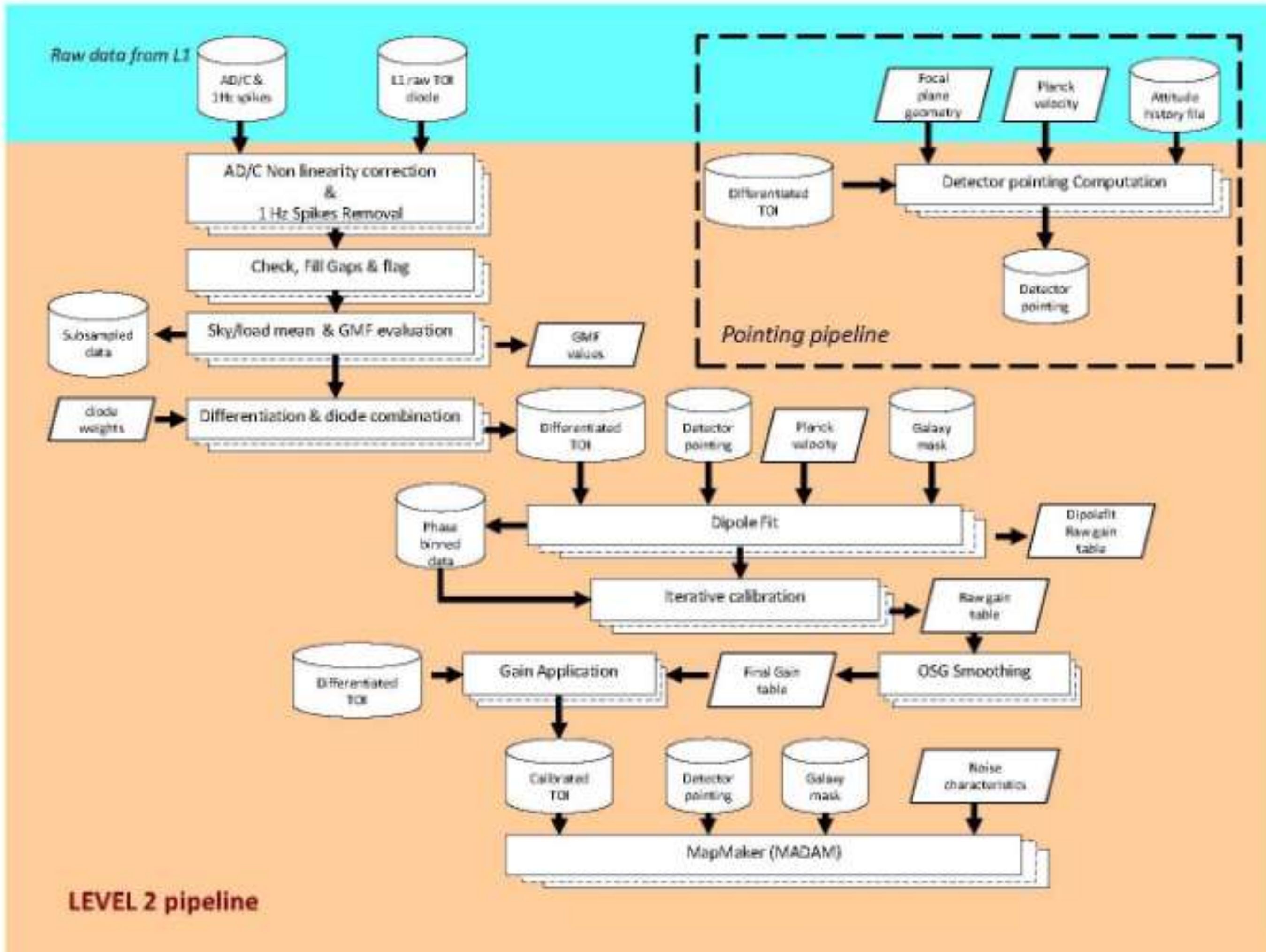
- Data Processing Overview
- Flagged Data
- Beam reconstruction
- Photometric Calibration
- Noise estimation
- Mapmaking
- Systematics effects
- Instrument internal validation
- Intra instrument validation
- Maps characteristics
- Next Steps

Data Processing Overview

- Both DPC follows the same overall approach to the data reduction with specific tasks aimed to correct instrument dependent systematics;
- Process has been logically divided in three main levels:
  - Level 1 where HK and Science telemetry received from the satellite are transformed in raw timelines and stored in dedicated database with time information associated;
  - Level 2 is dedicated to synthesize the instrument information in the Instrument Model, remove the systematics, flag the data that are considered not to be usable, calibrate the data and finally create the maps and all associated products;
  - Level 3 is dedicated to the more scientific analysis with the responsibility to separate components into catalogues and specific astrophysical emissions, and evaluate CMB spectra and likelihood.
- Each step is internally validated and most of the DPC time is spent to cross check all the results first internally and then between instruments.
- NOTE that pipeline and entire process was developed independently at each DPC adding **strong** value to the cross-instrument validation;

LFI Pipeline

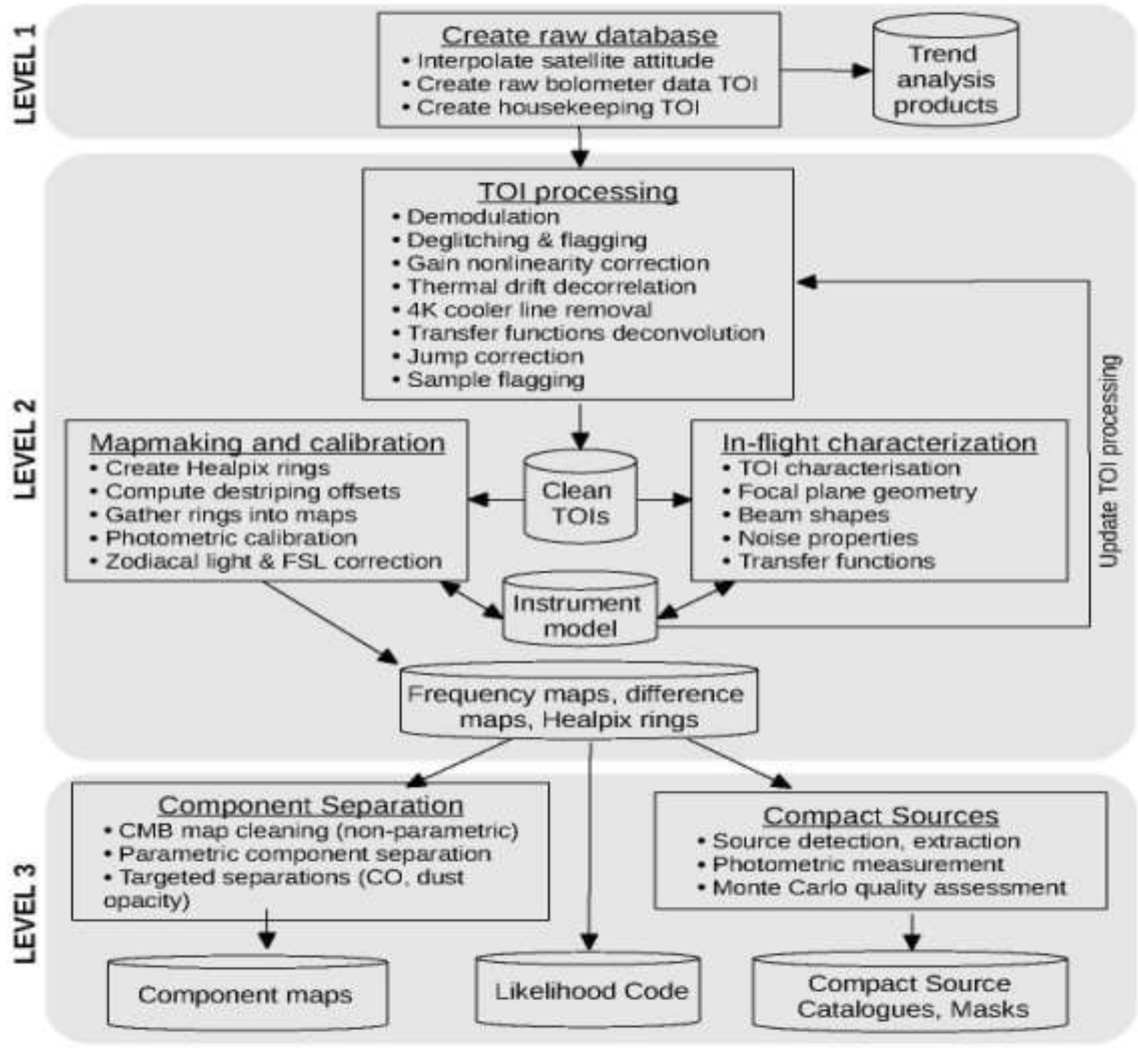
Main task of LFI L2 DPC pipeline are shown. Special pipeline is dedicated to the determination of detector pointing based on auxiliary data provided by the Flight Dynamics team.



HFI Pipeline

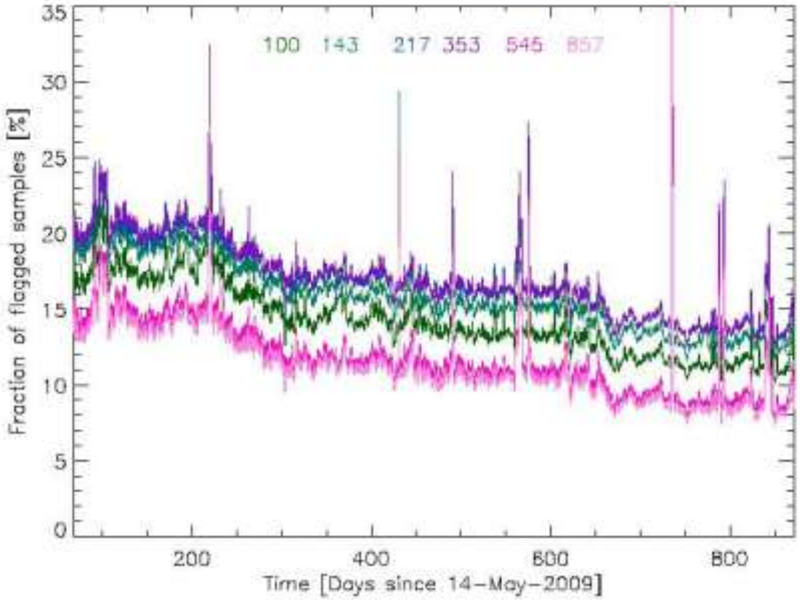
Main steps of HFI DPC pipeline from Level 1 to Level 3. Raw telemetry is cleaned from instrument effect and stored before applying the mapmaking and calibration process.

Output is then stored in to a database and made available to the Level 3 to continue with the scientific analysis



Flagged data

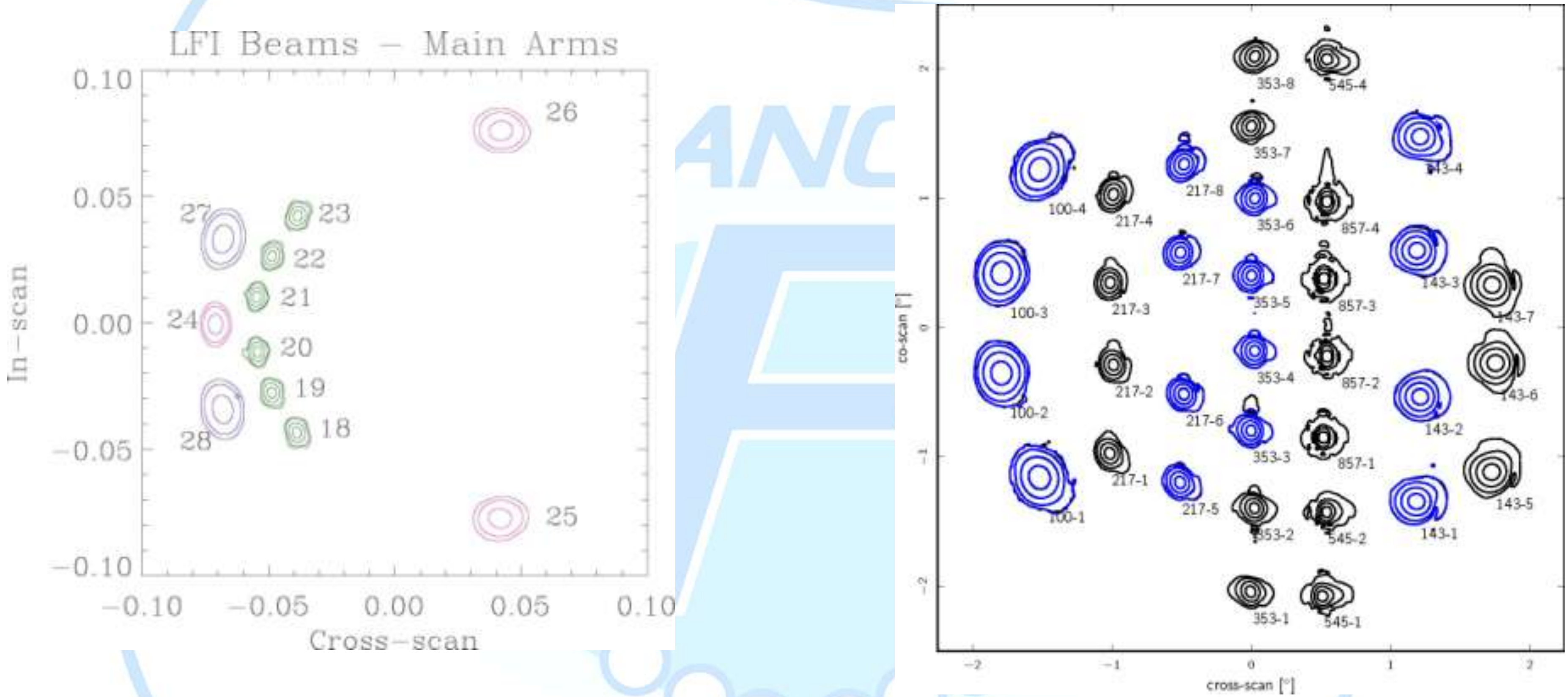
	30 GHz	44 GHz	70 GHz
Missing [%]	0.00014	0.00023	0.00032
Anomalies [%]	0.82220	0.99763	0.82925
Maneuvers [%]	8.07022	8.07022	8.07022
Usable [%]	91.10744	90.93191	91.10021



During Level 1 and Level 2 pipeline all the data are checked sample by sample, unusable samples and data acquired during maneuvers or special operations (e.g. Sorption cooler switch-over) are flagged.

- In LFI about 1% of the data has been flagged due to instrument anomaly;
- In HFI most of flagged data are due to “glitches”, special processing to identify and flag has been developed.

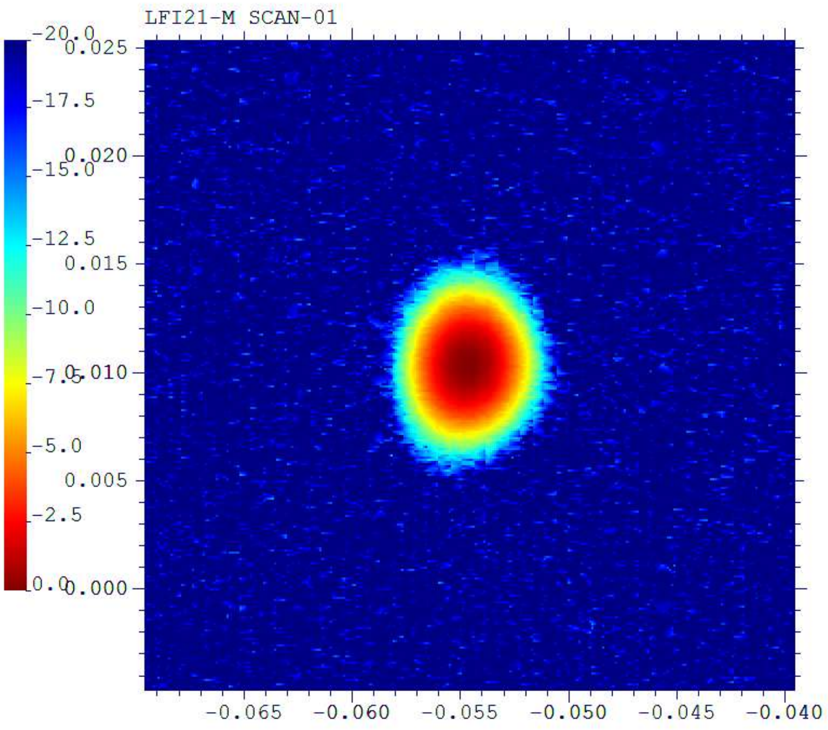
Beam reconstruction



Using Jupiter transits for LFI and Mars for HFI, we were able to measure the (scanning) beam profile. Solar system planets were used to reconstruct the focal plane geometry that represent the pointing direction and its related polarization for each beam centre in the field of view. Beam has been reconstructed to about -20 db(LFI), -30 db (HFI).

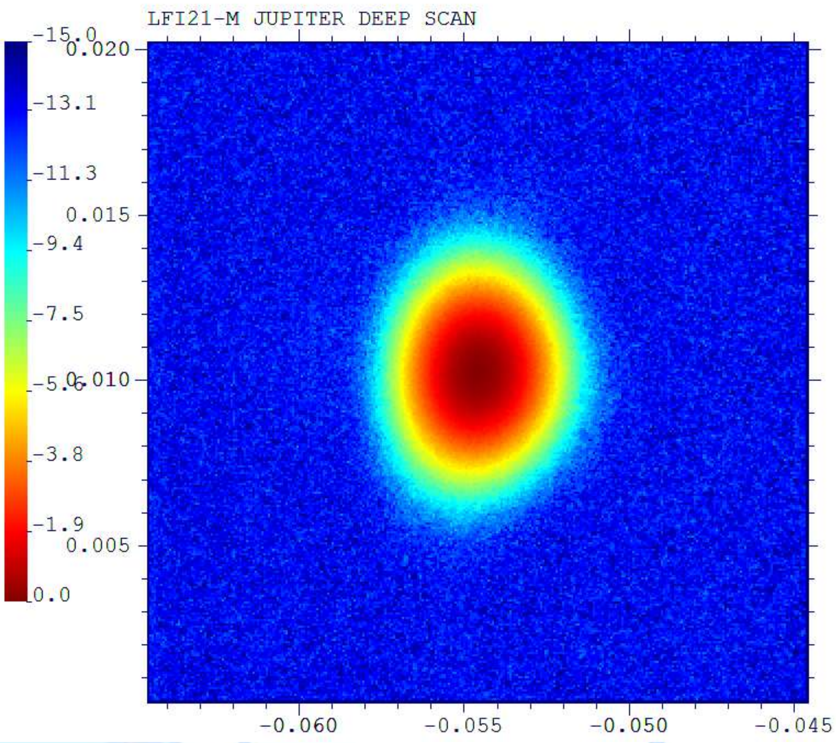
LFI *Real* Beam

Jupiter Scan



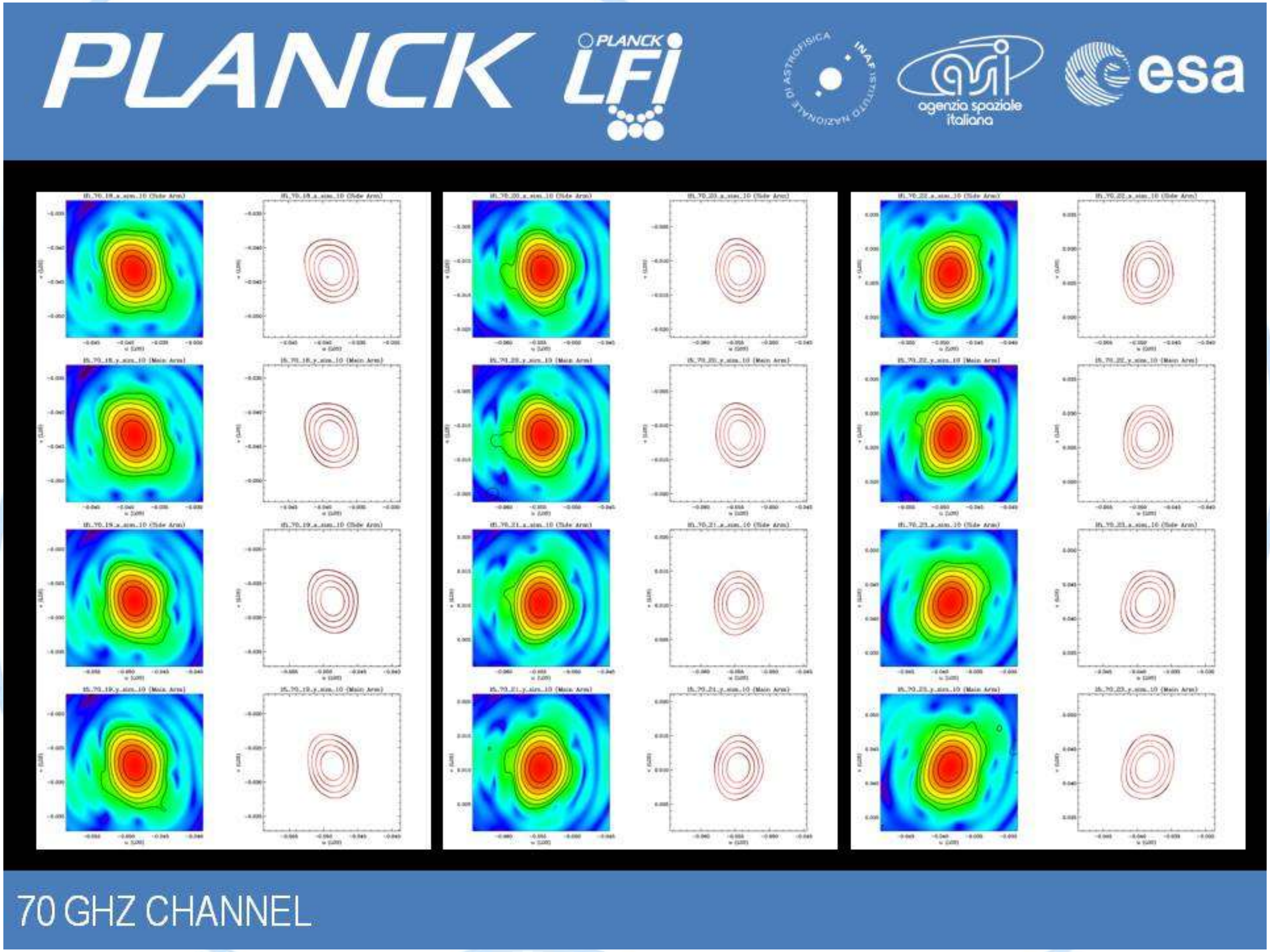
2 arcmin, 3600 sec

Jupiter deep Scan

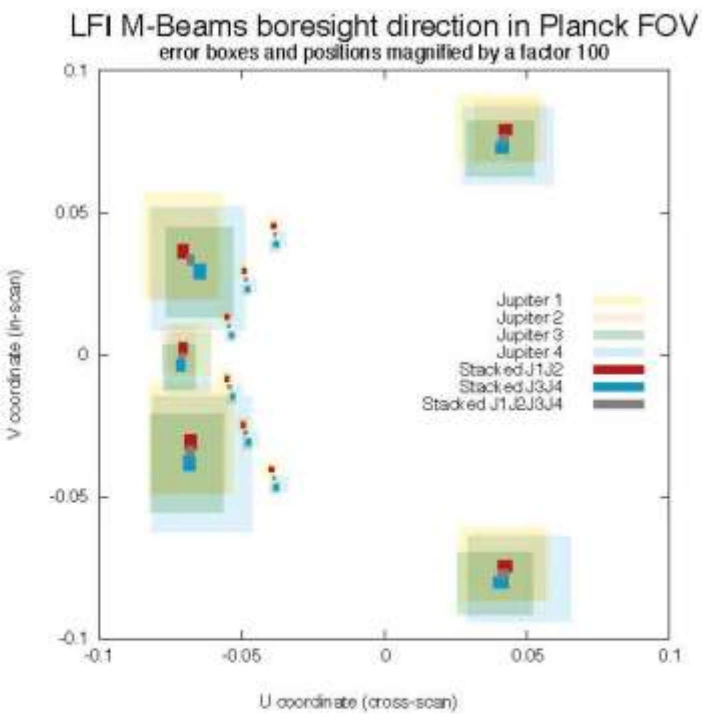


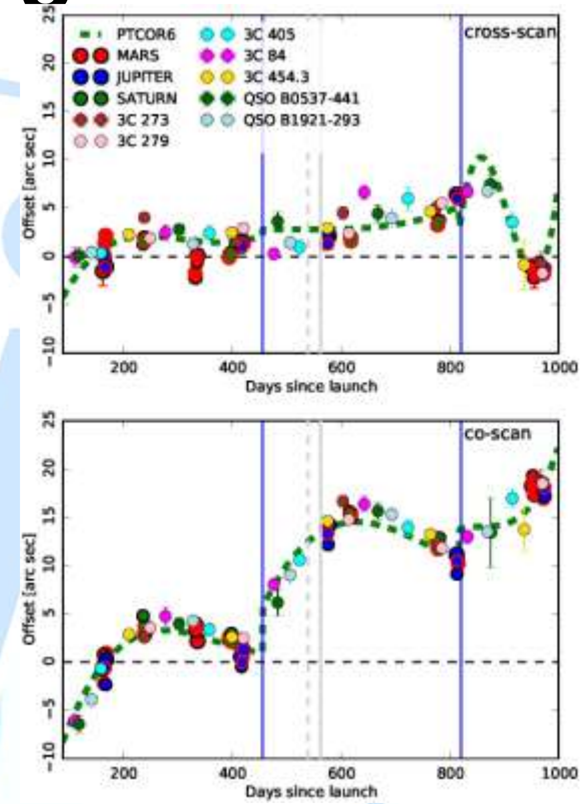
0.5 arcmin, 2900 sec

LFI *Optical* Beam



Detector Pointing



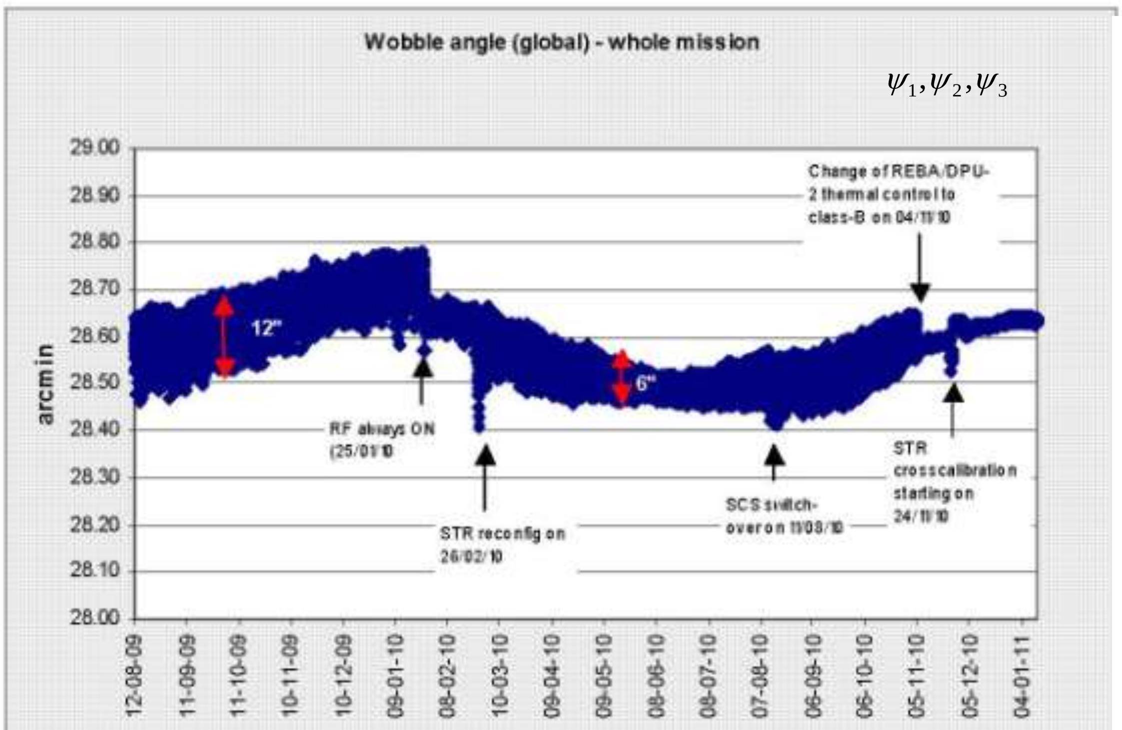


Pointing reconstruction was determined with an error to less than 0.5''. Different corrections has been applied as the Stellar aberration and wobble angle (due to an apparent variation produced by thermoelastic deformation which change the relative orientation of the start tracker respect the reference body frame).

DPCs had a different approach to the detector pointing reconstruction, HFI applied (on the right) a model (PTCOR6) taking in account all the planets and introducing discontinuity due to special operation done at Spacecraft level, LFI introduced only one discontinuity using a flat model. Those are compatible inside the errors.

Wobble

- It is due to misalignment between the StarTracker LOS and the Telescope LOS (it is represented by three angle ψ_1, ψ_2, ψ_3)
- Part of the wobble angle is linked to thermal events.
  - Seasonal effect
  - Spacecraft thermal events (Trasponder etc …)



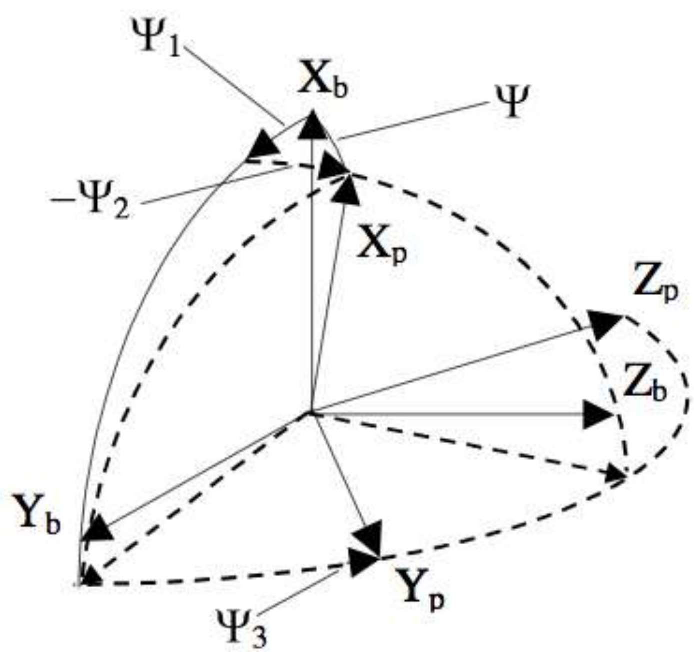
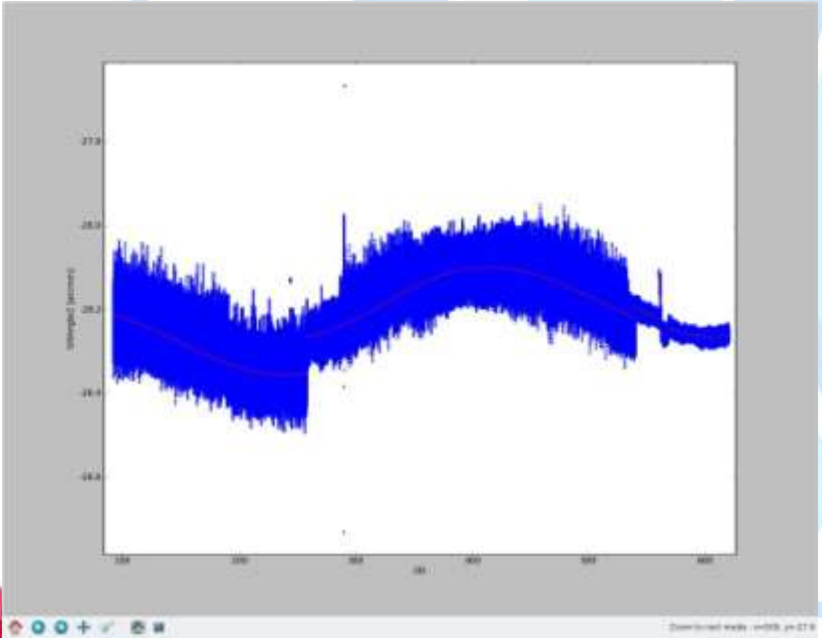
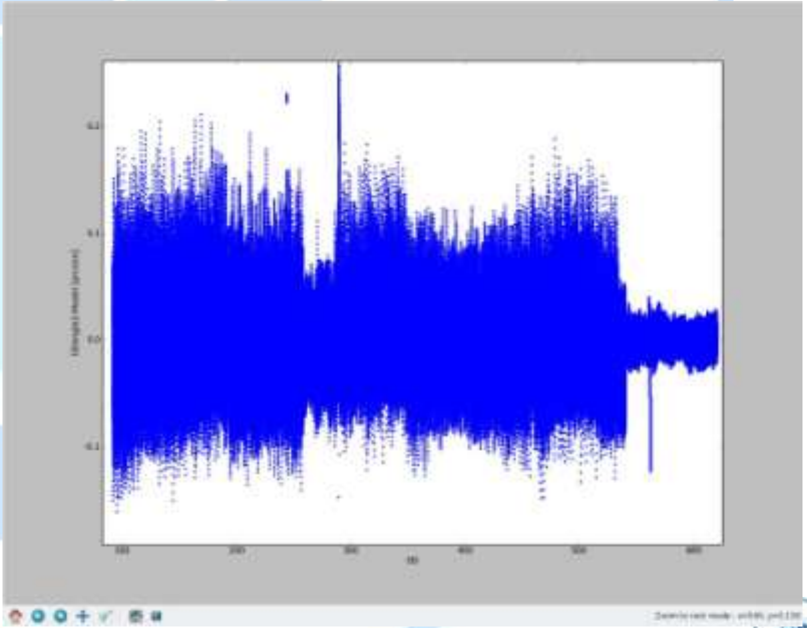


Figure 13.4.3.7-1: Principal Axis Reference Frame (wobble angles)

Wobble

- The basic Idea is to model the seasonal variation of phi2 (we start from the worst angle), remove from the original quaternion (AHF) and apply the median of phi2 → new quaternion → detector pointing.
- The model was built taking in account the solar distance (common LFI and HFI approach).

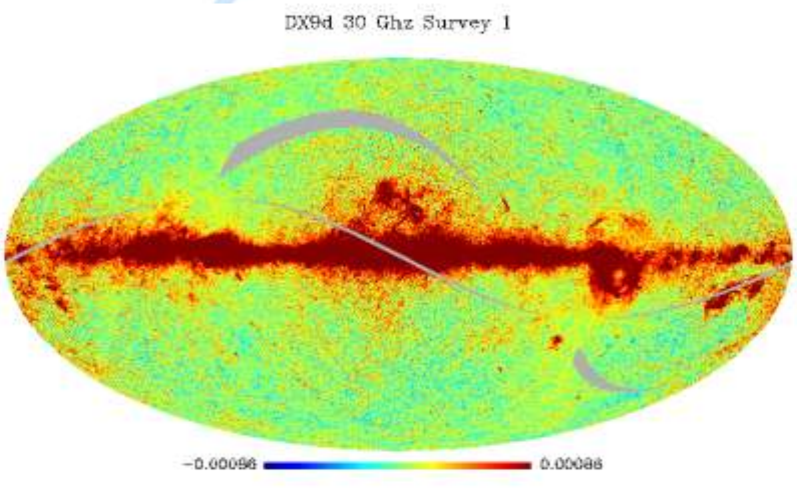




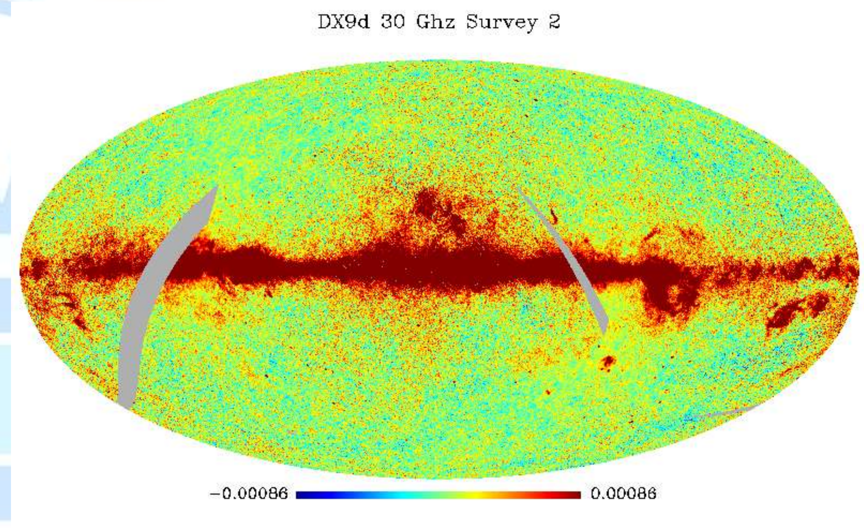
Wobble correction

How we can VERIFY that the pointing solution is good enough ?

Surveys Maps



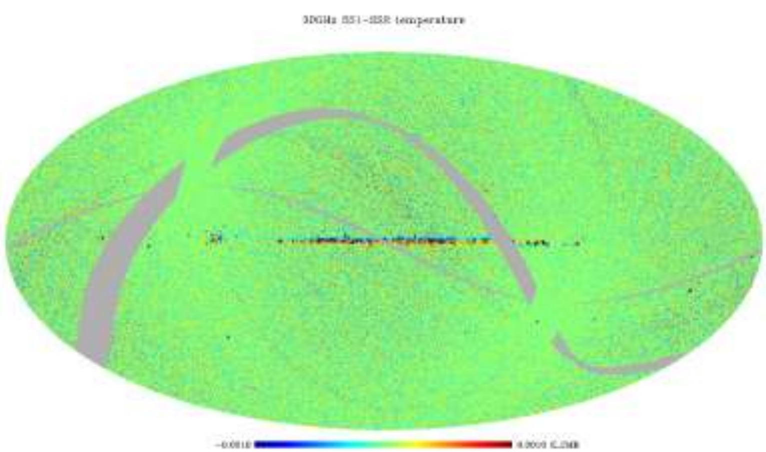
30 GHz Survey 1



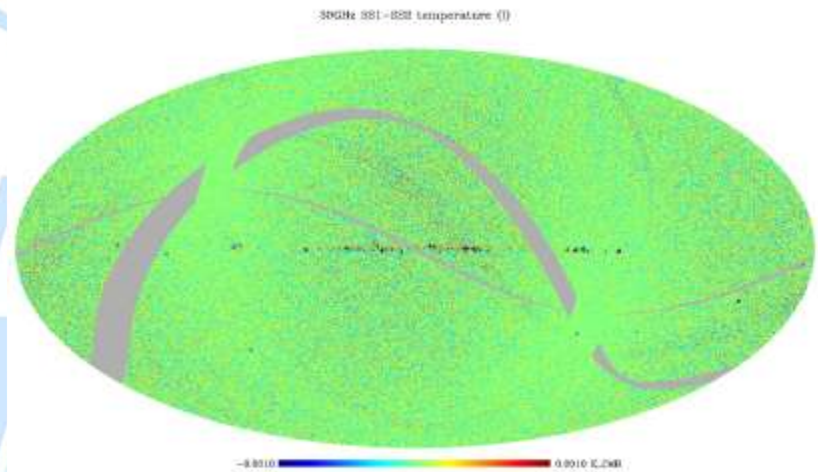
30 GHz Survey 2

Just making the difference between Survey 1 and Survey 2 you have an estimation on how is good your pointing BUT because the beam (especially at 30 GHz) is NOT symmetric and the scan between Survey 1 and Suvey2 change of 90 Degree, you should expect a butterfly image

Wobble correction

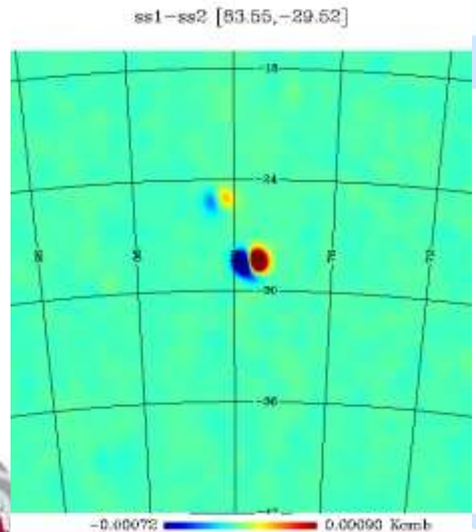


SS1-SS2 30 GHz BEFORE wobble correction

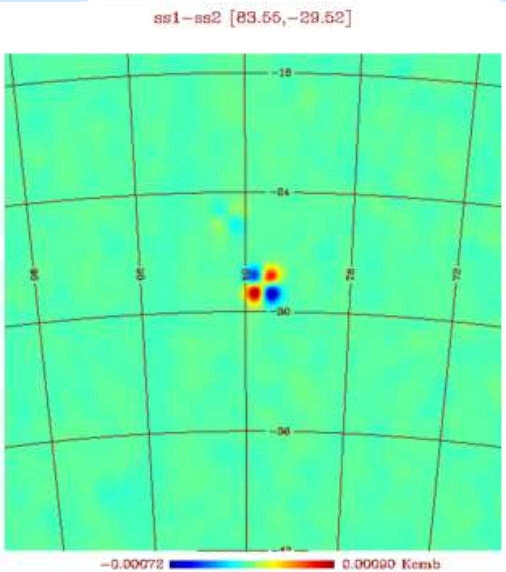


SS1-SS2 30 GHz AFTER Wobble correction

The minimization of the galaxy split is clearly visible due to the Stellar Aberration Correction and introduction of wobble correction

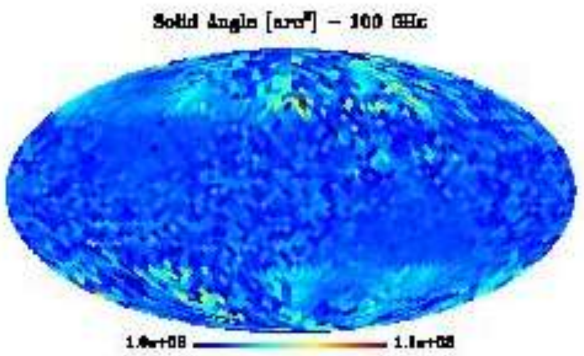


Same object in SS1-SS2 maps smoothed at 1 degree.
Left SS1-SS2 before
Right SS1-SS2 after



Effective Beam

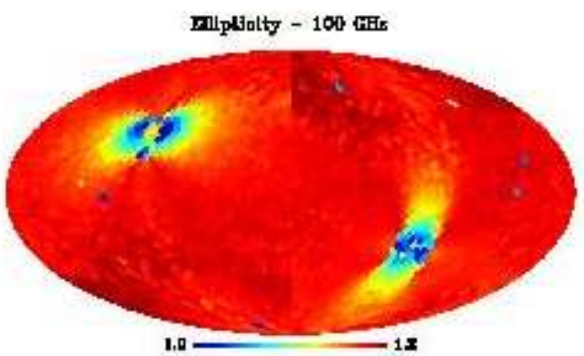
Eff Beam solid angle



Band	FWHM[a] [arcmin]	Ellipticity	Ω [arcmin²]
30......	32.239 ± 0.013	1.320 ± 0.031	1189.51 ± 0.84
44......	27.01 ± 0.55	1.034 ± 0.033	833 ± 32
70......	13.252 ± 0.033	1.223 ± 0.026	200.7 ± 1.0
100.....	9.651 ± 0.014	1.186 ± 0.023	105.778 ± 0.311
143.....	7.248 ± 0.015	1.036 ± 0.009	59.954 ± 0.246
217.....	4.990 ± 0.025	1.177 ± 0.030	28.447 ± 0.271
353.....	4.818 ± 0.024	1.147 ± 0.028	26.714 ± 0.250
545.....	4.682 ± 0.044	1.161 ± 0.036	26.535 ± 0.339
857.....	4.325 ± 0.055	1.393 ± 0.076	24.244 ± 0.193

[a] Mean of best-fit Gaussians to the effective beams.

Eff Beam ellipticity



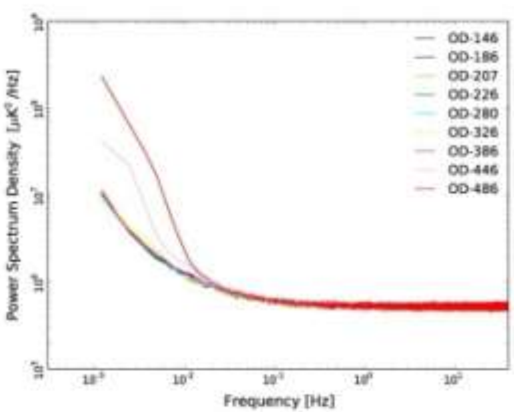
Scanning beams are then used to compute the effective beam. Effective beam give pixel by pixel the shape of the beam project in the sky taking in account the scanning strategy applied. This was used as base for the point sources extraction algorithm and for the computation of the beam window function.

LFI TOI Noise Estimation

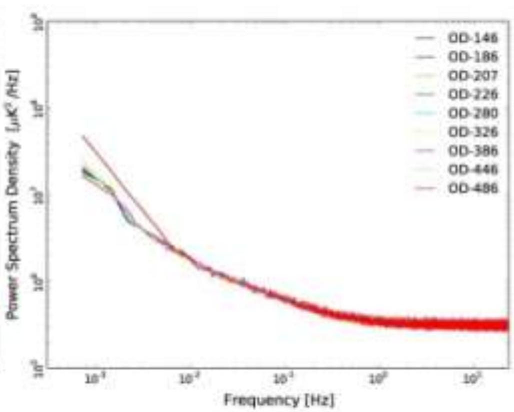
To estimate instrument noise proprieties in LFI, useful for Monte Carlo simulations and determine the proper horn weights to be employed during the map-making process, we implement a Monte Carlo Markov Chain approach. Results has been check with respect the withe noise level obtained subtracting half-rings maps and are compatible at 1% level.

The values are computed taking the median of the five estimation made for different ranges of OD over the nominal mission.

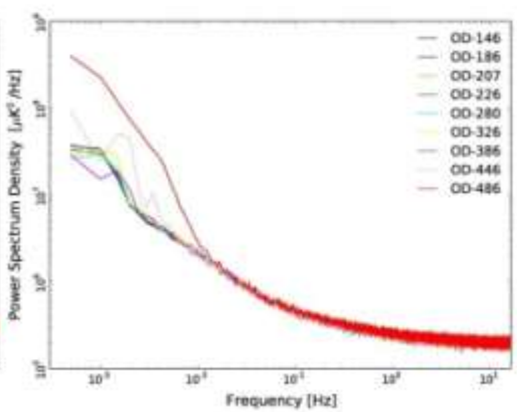
70-18M GHz Noise spectra



44-24S GHz Noise spectra



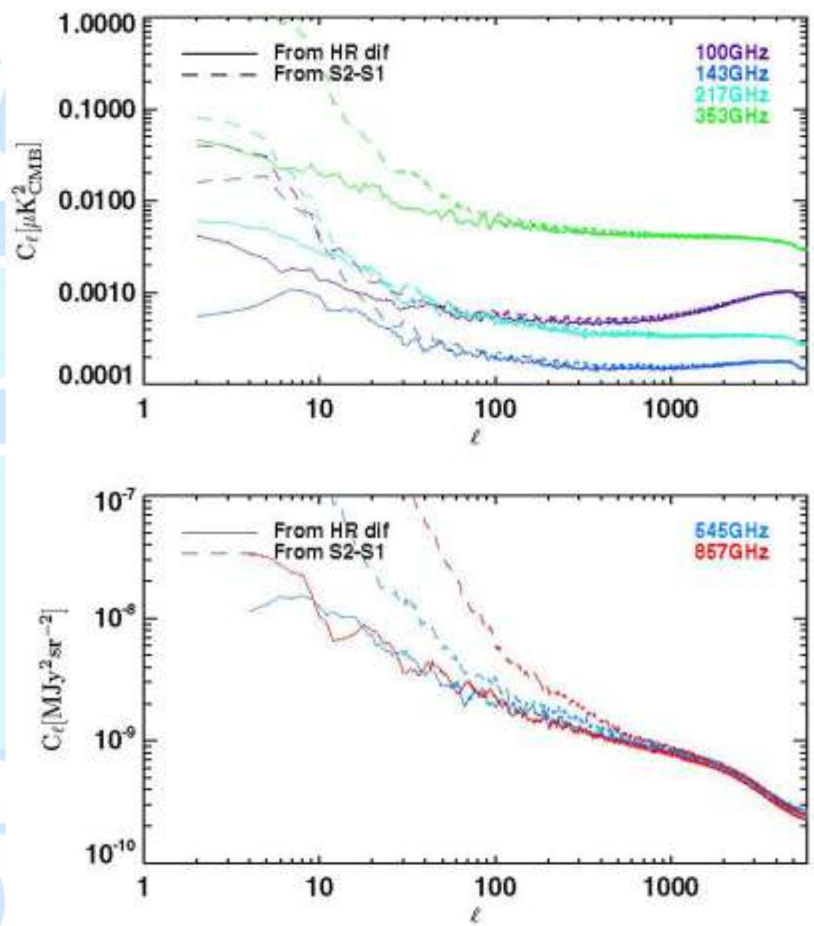
30-28M GHz Noise spectra



HFI Noise estimation

The map noise properties are evaluated from the half ring maps differences which give a good estimate rendition of the noise at map level.

The power spectra of these difference show that at high l the noise is flat thanks to the use of better low pass noise filter in the TOI processing

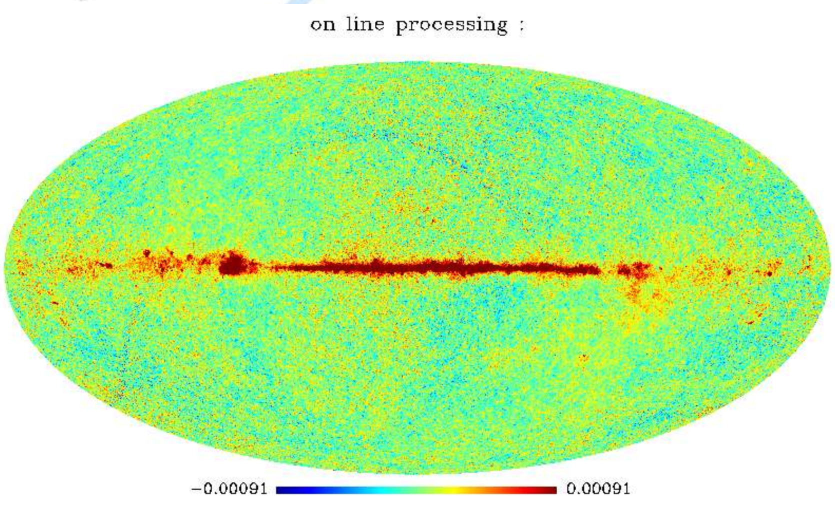


•Continuous line half-ring difference
•Dashed line survey difference

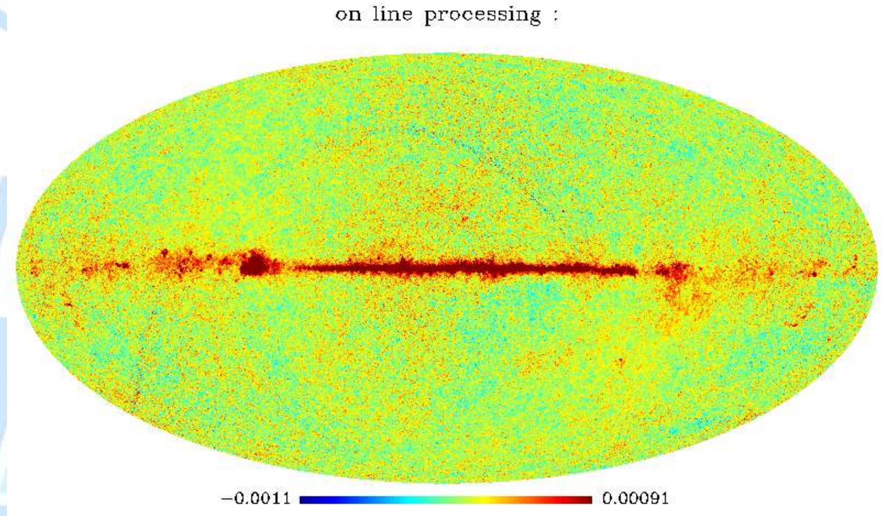
Wobble correction

How we can VERIFY the Noise proprieties ?

HalfRing Maps



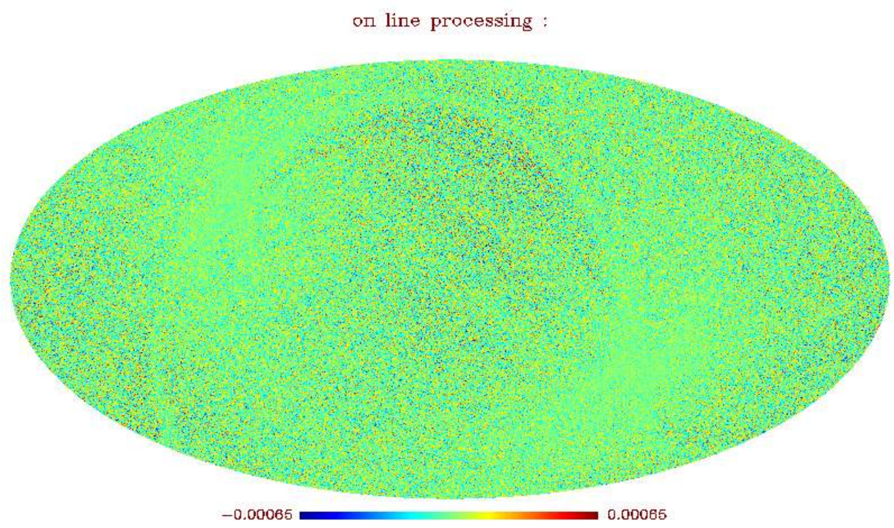
70 GHz HalfRing 1



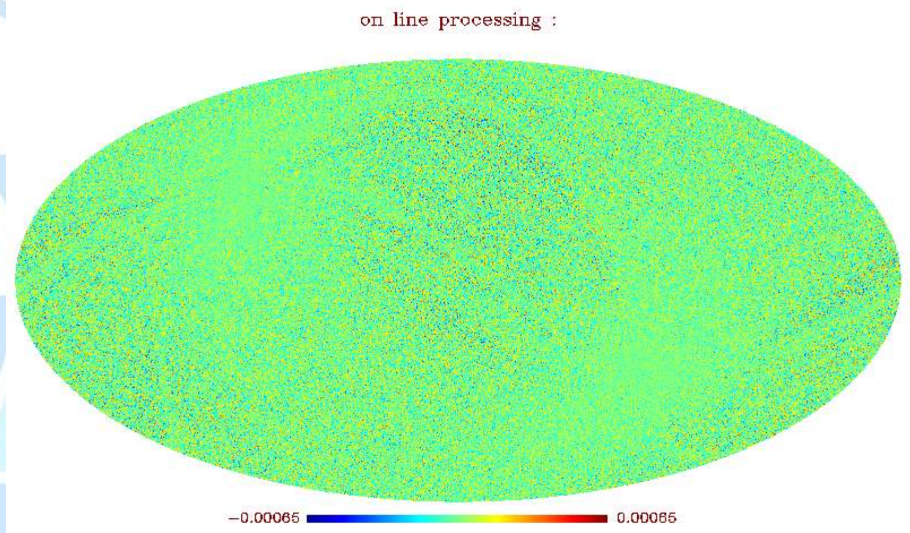
70 GHz HalfRing 2

Just making the difference between halfring 1 and halfring 2 you cancel all the data. What should remain is just the withe noise.

HalfRing Maps



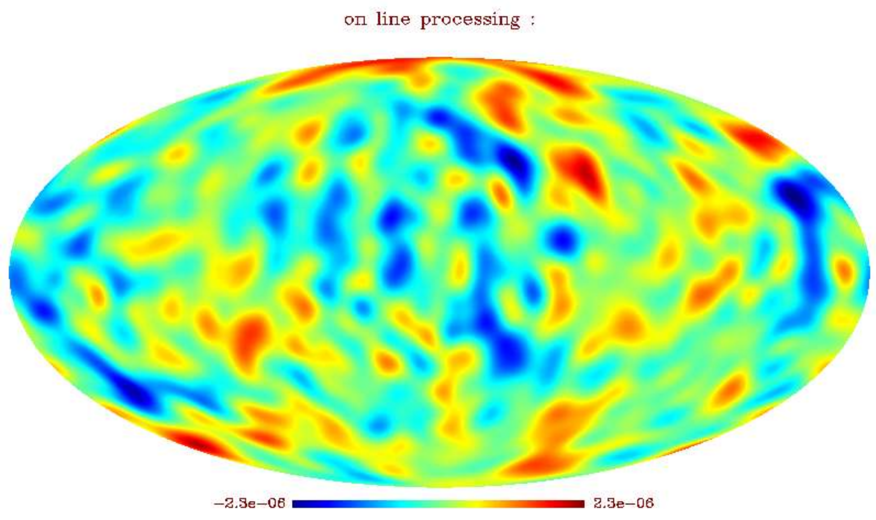
70 GHz HalfRing 1 – halfring 2 DX9D



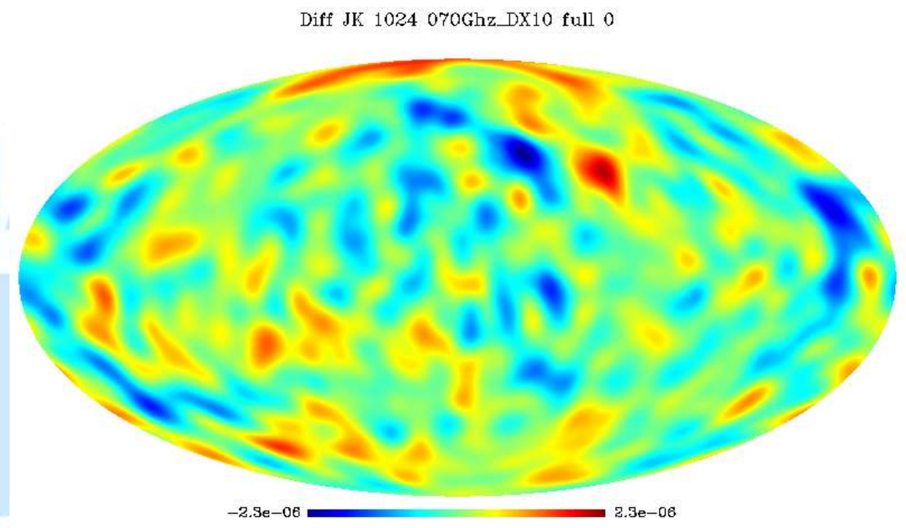
70 GHz HalfRing 1 – halfring2 DX10

As you can see no clear structure are present (left jk Dx9d, right DX10). BUT if you smooth at 10 degrees ….

HalfRing Maps



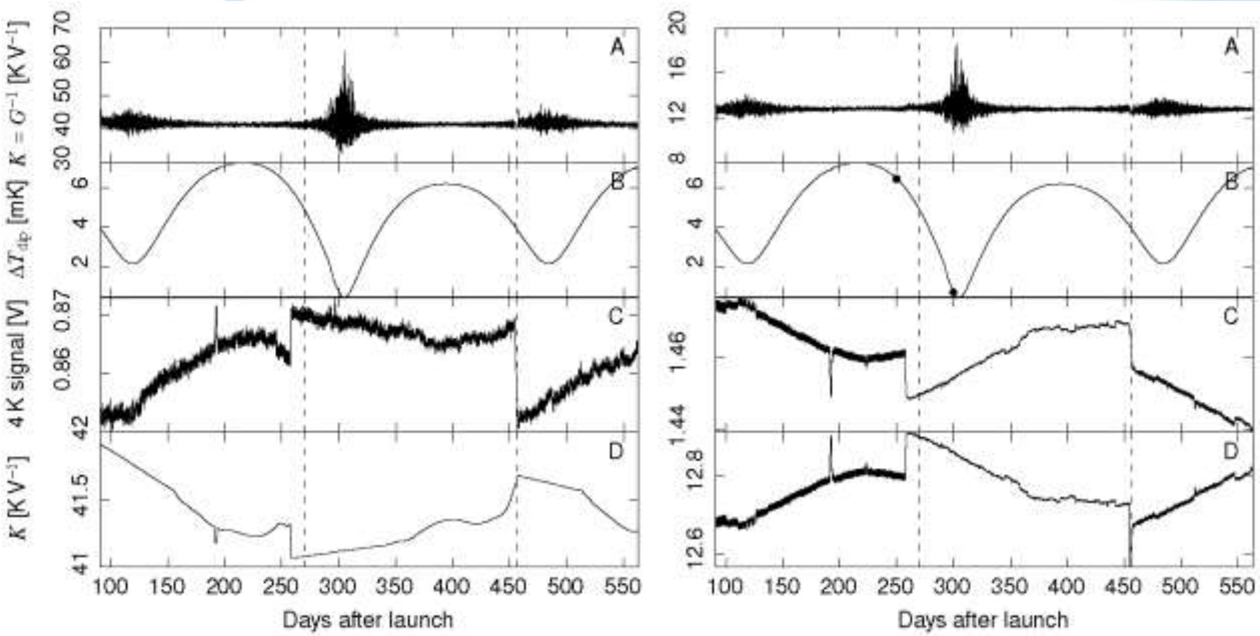
70 GHz HalfRing 1 – halfring 2 DX9D



70 GHz HalfRing 1 – halfring2 DX10

Same amps but Smoothed at 10 degrees → you can see that the maps at the right seems to be better (ideal map is completely FLAT), range is of about 2 microK. Statistics on the noise indicate that is purely white.

LFI Photometric Calibration



Example in time (left horn at 70GHz, right horn at 30 GHz) of:

A- Calibration constant estimated using the expected amplitude of CMB dipole;

B- Expected amplitude of the dipole;

C- 4k Total-power output voltages;

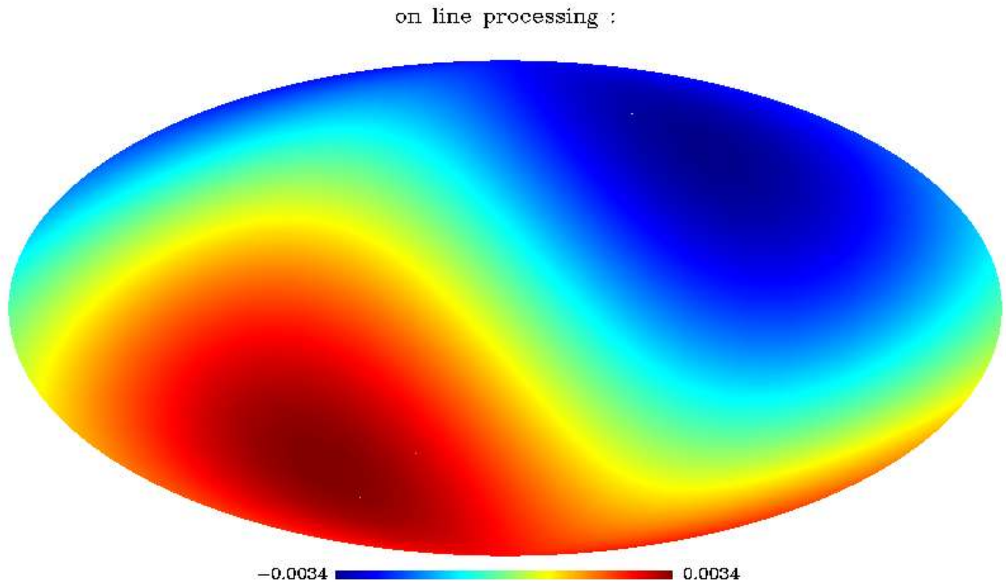
D- Calibration constant applied.

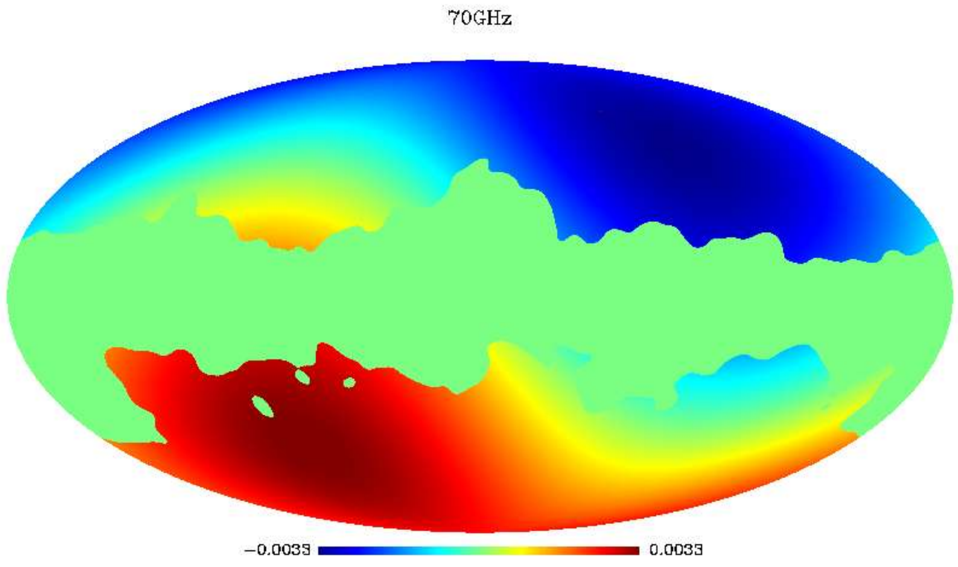
The calibration accuracy is estimated for LFI to be: 30 GHz ~0.82%, 44GHz ~ 0.55%, 70GHz ~0.62%

Photometric calibration results to be one of the most important element in the pipeline. LFI approach can summarized by the following points:

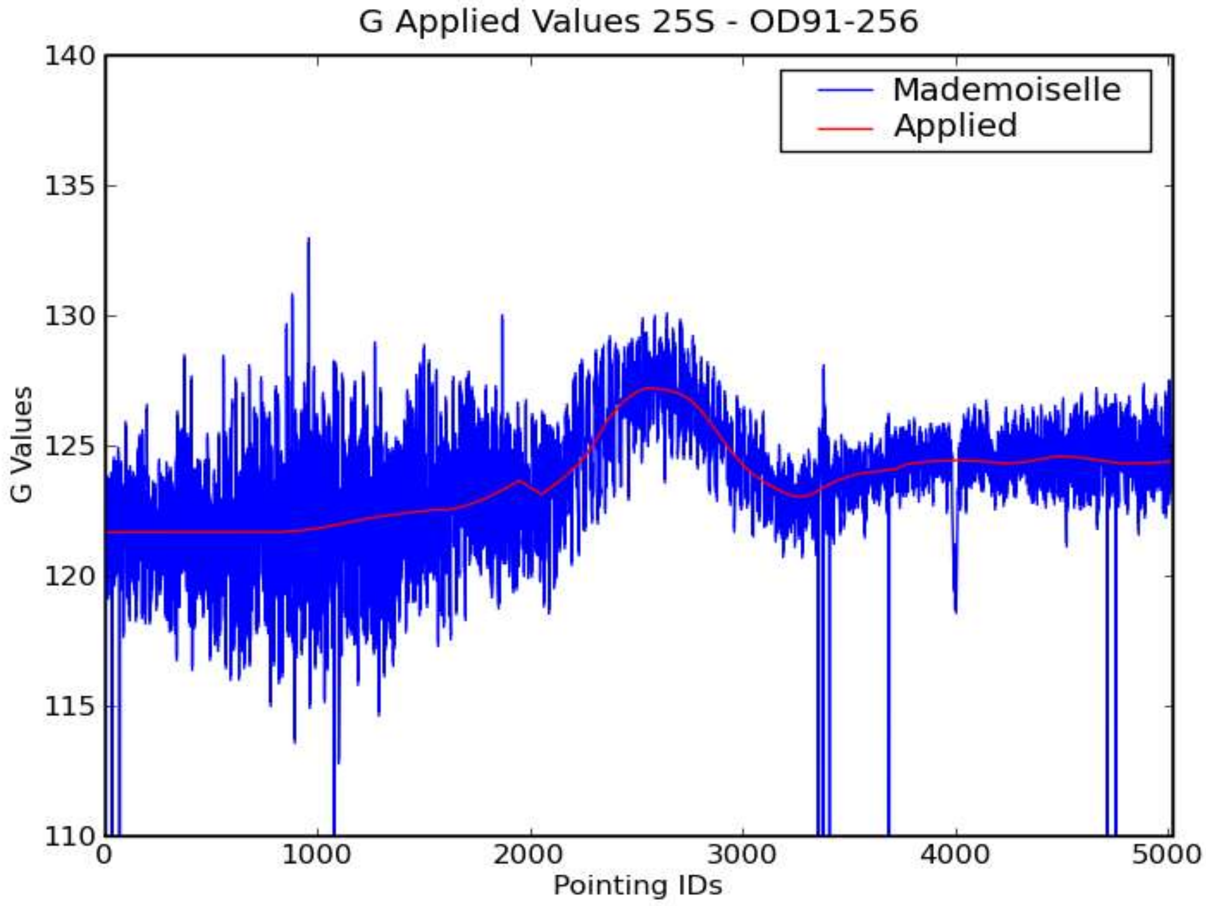
- estimate the amplitude and alignment of the dipole in the sky in a given direction;
- produce discrete TOD of the expected overall dipole signal, taking in account the beam shape;
- fit the obtained dipole with the real data;
- use an iterative algorithm to regularize the solution obtained;
- gain produced are processed by an adaptive smoothing filter to reduce the statistical noise;
- final gain is then applied to the timelines and the dipole signal is removed.

The Dipole, our reference





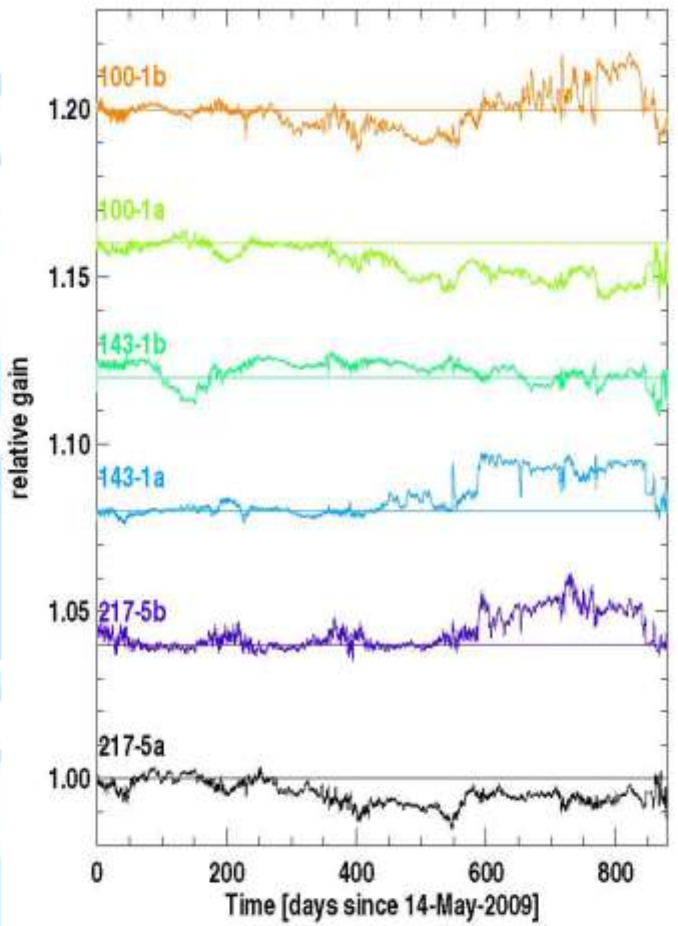
Row Gain and applied gain



HFI Photometric Calibration

HFI used two techniques to perform the photometric calibration, one for lower frequencies (100-353 GHz) achieved by comparing the measured data against the expected signal from the solar and orbital dipole. It yields three parameters per ring: a dipole gain, a Galactic gain and an offset. An initial gain model consists of a fixed gain averaged over a contiguous set of 4000 rings. An iterative schema is then applied that fits for relative variations of the gain over the whole mission. Relative variations are typically about 0.2%, except for a systematic bias of 0.5% probably due to the ADC non linearity (currently not corrected).

At higher frequency (545 and 857 GHz) the calibration is based on fitting the HFI measurements of the flux density of Uranus and Neptune to planetary emission modes which have an absolute accuracy of about 5% and a relative accuracy of ~ 2%



MapMaking

LFI

- Calibrated TOI of each radiometer are used as input to the MADAM mapmaking code together with pointing data. The algorithm estimates in a maximum-likelihood fashion the amplitude of the baseline, subtract them from the timelines and simply bins the results in to a map.

HFI

- Maps for HFI channels are made projecting the processed HEALPix rings built from TOI onto HEALPix map. First, maps of individual rings are created by averaging filtered and baseline-subtracted TOIs in to HEALPix pixels. Second, these ring maps are used for the photometric calibration of each detector. Then, these calibrated ring maps are combined via least-squares destripping procedure.

Both DPCs produced a set of maps composed by:

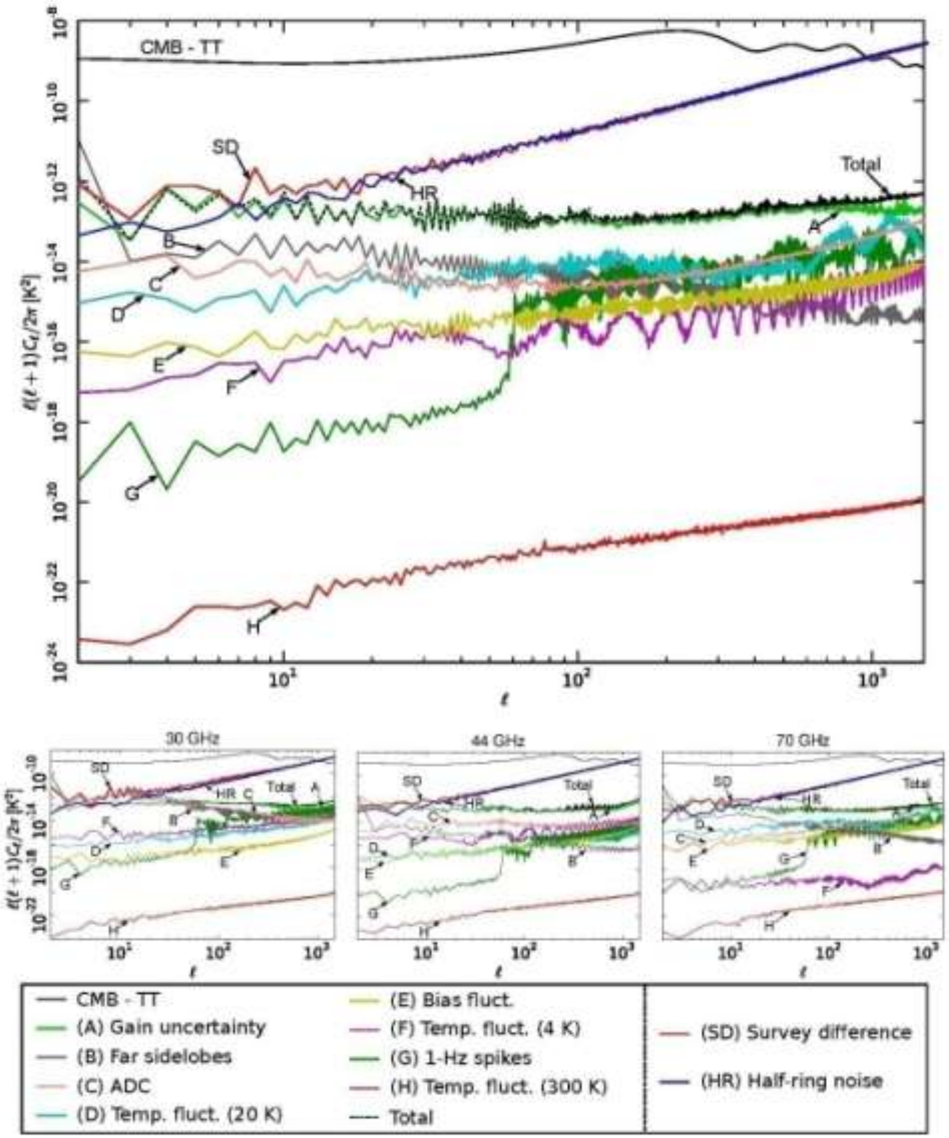
- Frequency maps, Half-ring maps and Survey maps
- LFI DPC, for its internal use, produced too low resolution noise covariance matrix maps
- HFI DPC produced and delivered an additional set of maps with the first estimation of Zodiacal light emission removed.

Systematics effect

Analysis of know systematics effect was pursued following two strategies:

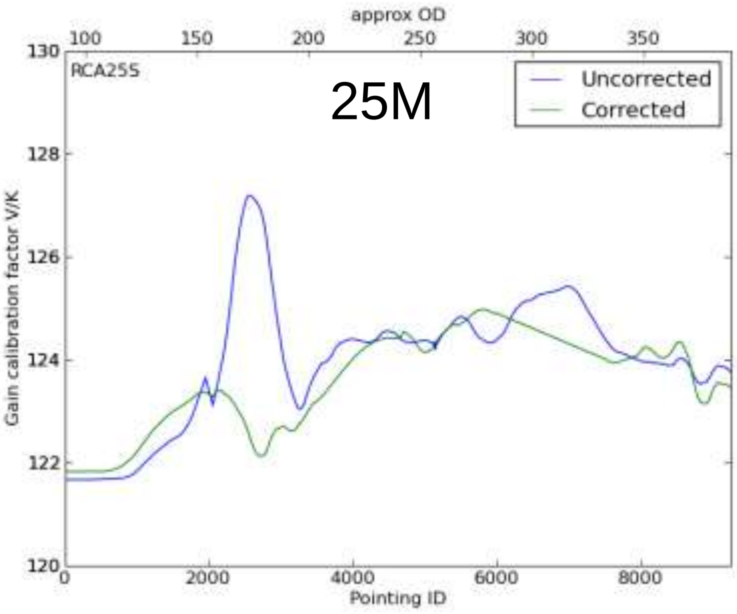
- Null test were the primary tool to check for systematic effect residual exceeding the white noise level
- We then assessed their impact on timelines, even if below the white noise limit, by exploiting in-flight housekeeping and scientific data.

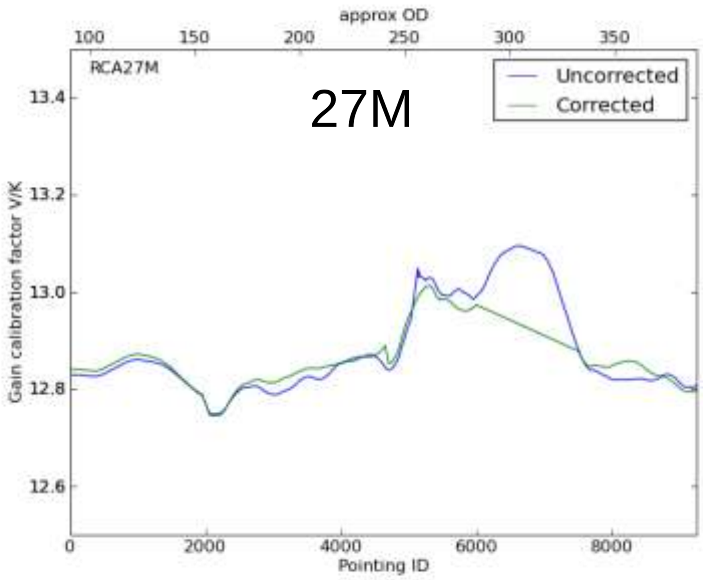
This latter approach, that combine flight data with ground-measured instrument properties, provided a powerful tool to check for systematic effect.



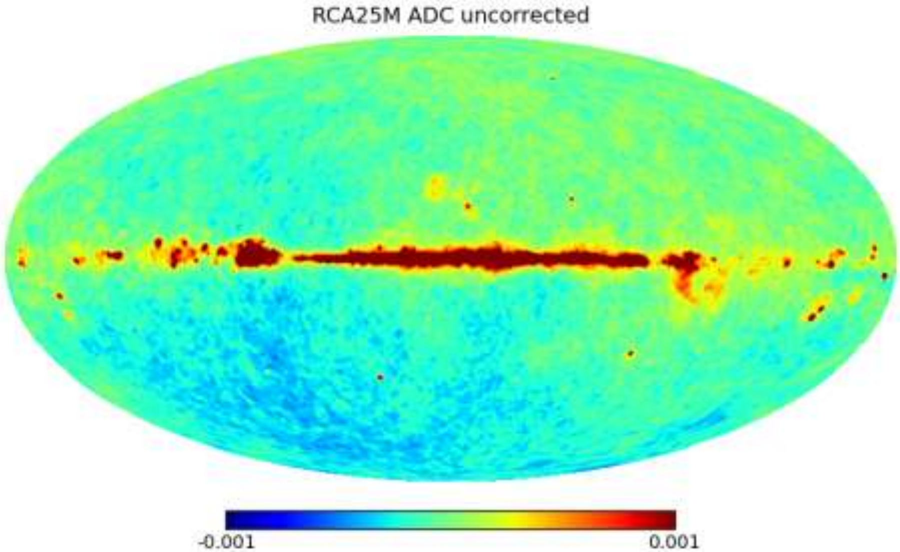
Systematic ADC Correction

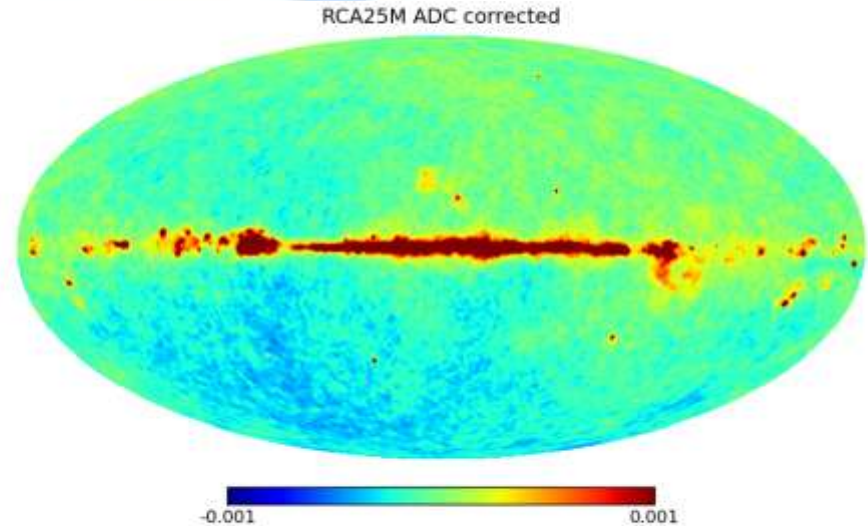
- To correct not liner response showed by some horn during certain period, a special task was introduced in the LFI pipeline.
  - *Ad hoc solution was* adopted developing a special pipeline

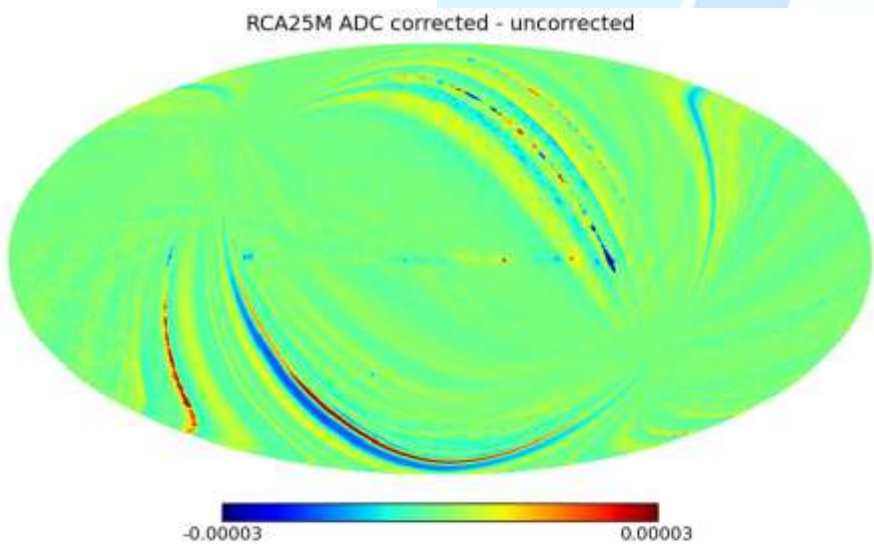




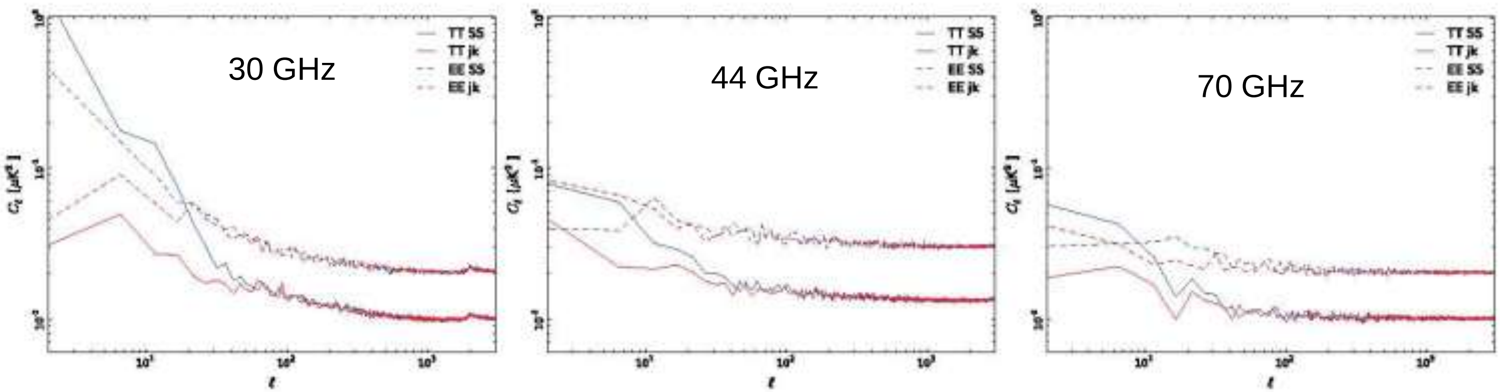
Systematic ADC Correction







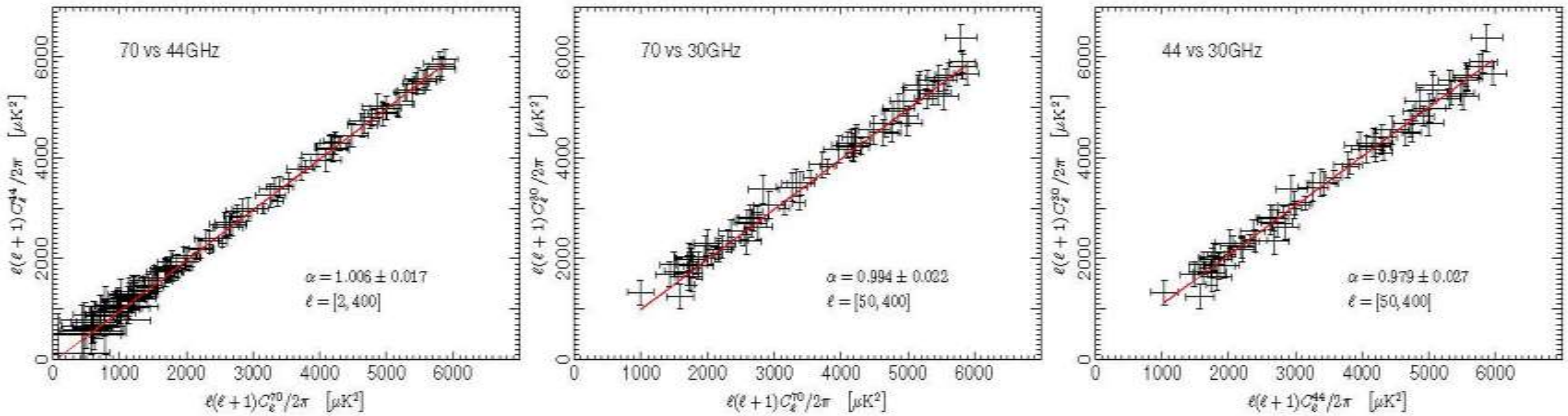
LFI Internal Validation



In order to asses and verify the quality of our maps, a set of null tests was performed in a semi automatic way by a dedicated team. We made all the possible combination in term of time and sources (radiometer, horn, horn-pairs within a given frequency and between frequency). The kind of effects probed by null test depends from the data under analysis. For example, differences in LFI at horn level between odd and even surveys reveal the impact of sidelobes since the sky covered is the same BUT not the beam orientation.

Null test power spectra are used to check the total level of systematic effect, results at frequency level of survey difference for TT and EE spectra compared to the noise level from half-ring differences maps shown something strange that was identified to be due to the sidelobes effect as well as the band effect, now included in the new pipeline.

LFI Internal Validation

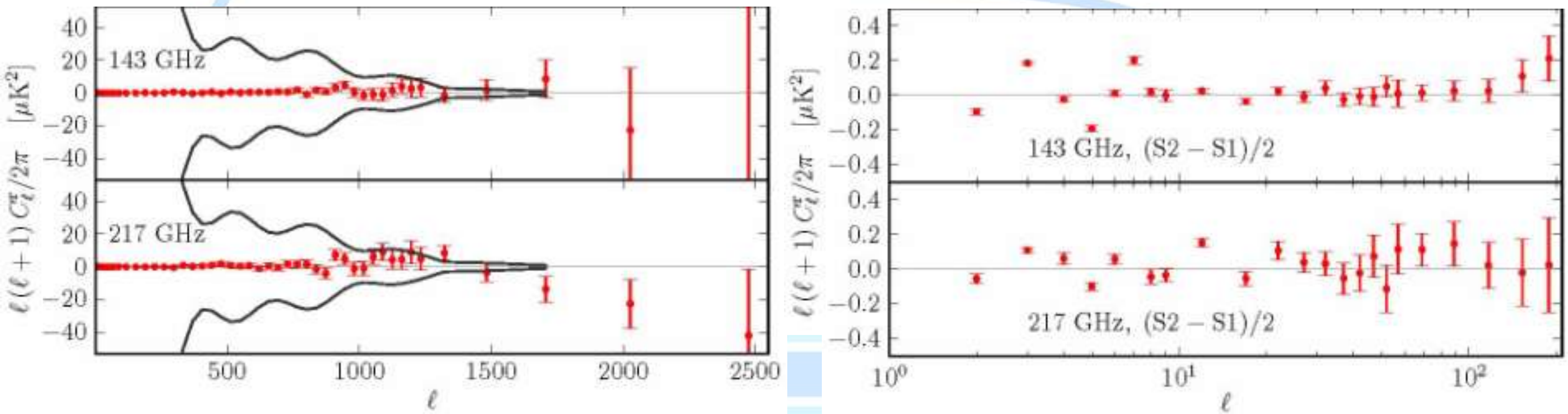


- To test the consistency between 30, 44 and 70 GHz maps we compare the power spectra in the multiple range around the first acoustic peak removing the estimated contribution from unresolved point sources. The three power spectra are well consistent inside the errors.

- We used the Hausman test to asses the consistency of auto and cross spectral estimates at 70 GHz, this test didn't shows any statistically significant inconsistency.

- We then estimate the temperature power spectra for each of the three horn-pair map, and we compared the results with the spectra obtained from all the 12 radiometers. The chi^2 analysis of the residual show that they are compatible with the null hypothesis, confirming the strong consistency.

HFI Internal Validation



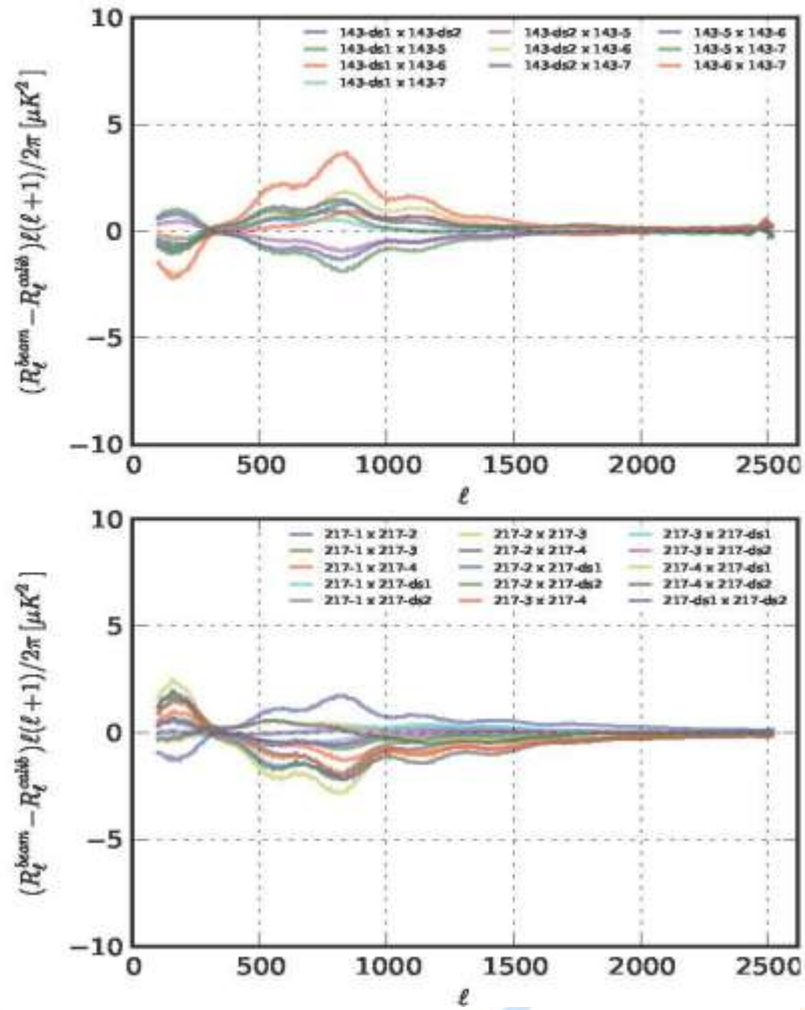
We perform a series of difference map consistency tests to evaluate the contribution of residual systematics effects to the angular power spectra:

- Half-ring maps differences has been subtracted from systematics-free Yardstick realization → the amplitude of the remaining power in each bin can be used as estimation of residuals.
- Half-focal plane difference is particular sensitive to relative gain error, that give also some sensitivity to sidelobes pickup.

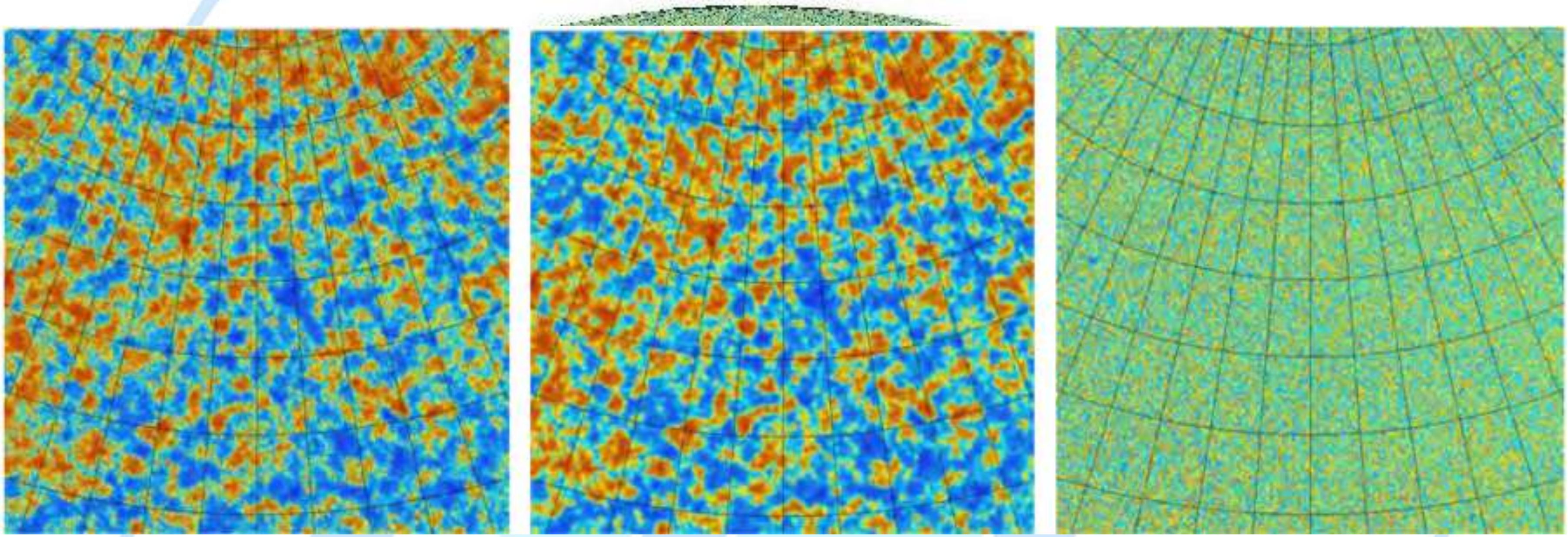
The survey difference test is the most stringent, (survey1-survey2)/2 cross power spectra is show. Note that the amplitude of the residual is under the binned sample variance envelope.

HFI Internal Validation

Other power check of the data follows from assessing the signal consistency between detectors at the same frequency. On the right is shown the overall beam correction of each detector set which minimizes their mismatch. These corrections are very small.



HFI-LFI Validation

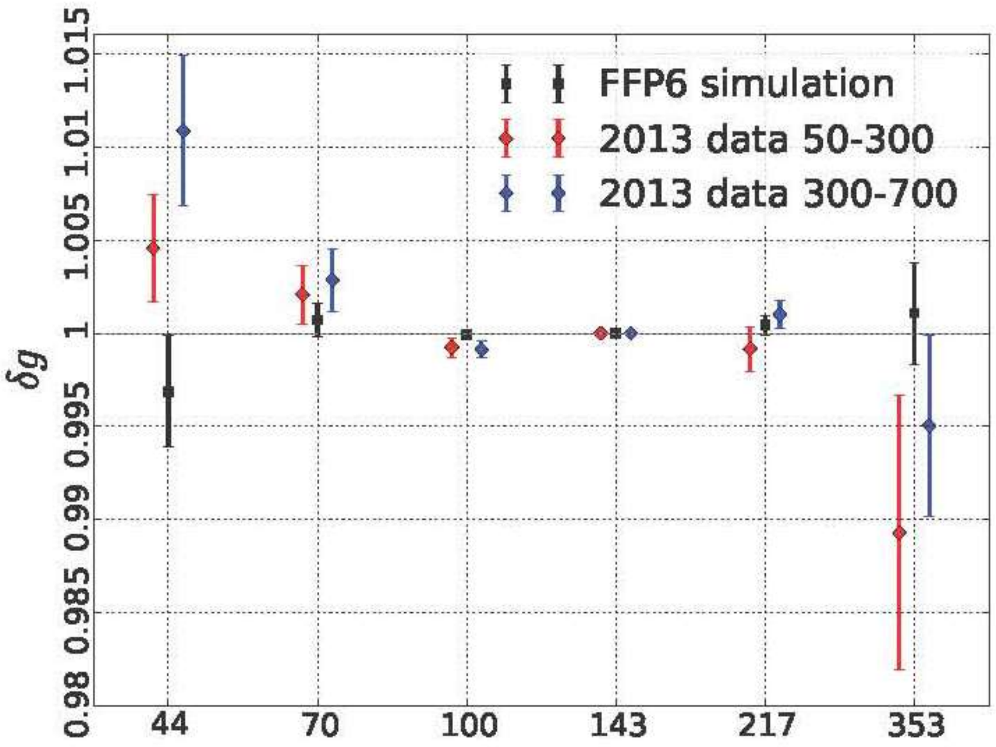


To verify the consistency between LFI and HFI we compare sky maps by pairs of frequency from 44 to 217 GHz and then we investigate the power spectra of these maps in various ways.

Key comparison between 70 and 100 GHz is shown. The CMB structure at high galactic latitude disappears in the difference demonstrating very good agreement.

HFI-LFI Validation

We can further broaden our consistency checks using SMICA (CMB component separation method) from 44 to 353 GHz, in effect intercalibrating on common CMB anysotropies themselves, taking the 143 GHz as reference. This analysis suggests that HFI Maps are consistent inside 0.2% and 70 GHz Maps and HFI 100 GHz are inside 0.3%



Maps Characteristics

Uncertainty	Applies to	Method used to assess uncertainty: LFI	Method used to assess uncertainty: HFI
Gain calibration standard	All sky	*WMAP* dipole	100–353 GHz: *WMAP* dipole 545–857 GHz: Planet model
Zero level	All sky	Galactic cosecant model Comparison with *WMAP*	Galactic zero: correlation to HI CIB: empirical model
Beam uncertainty	All sky	GRASP models via Febecop	Beam MC realizations via Quickbeam
Color corrections	non-CMB emission	Comparison of ground/flight bandpass leakages	Ground measurements
Beam Color corrections	non-CMB emission	GRASP models	GRASP models
Residual systematics	All sky	Null tests	Null tests

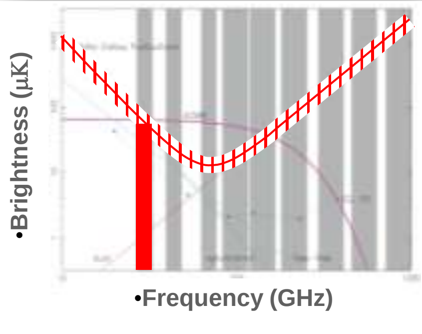
Property	Applies to	Frequency [GHz] 30	44	70	100	143	217	353	545	857
Effective frequency [GHz]	Mean	28.4	44.1	70.4	100	143	217	353	545	857
Noise rms per pixel [μK_{CMB}]	Median	9.2	12.5	23.2	11	6	12	43	...	...
[$MJy\,sr^{-1}$]	Median	...	...	...	...	...	...	...	0.0149	0.0155
Gain calibration uncertainty[b]	All sky	0.82 %	0.55 %	0.62 %	0.5 %	0.5 %	0.5 %	1.2 %	10 %	10 %
Zero level[c] [$MJy\,sr^{-1}$]	All sky	0	0	0	0.0047	0.0136	0.0384	0.0885	0.1065	0.1470
Zero level uncertainty [μK_{CMB}]	All sky	±2.23	±0.78	±0.64	...	...	...	...	...	...
[$MJy\,sr^{-1}$] . . .	All sky	...	...	...	±0.0008	±0.001	±0.0024	±0.0067	±0.0165	±0.0147
Color correction unc.[d]	non-CMB emission	0.1β %	0.3β %	0.2β %	0.11$\Delta\alpha$ %	0.031$\Delta\alpha$ %	0.007$\Delta\alpha$ %	0.006$\Delta\alpha$ %	0.020$\Delta\alpha$ %	0.048$\Delta\alpha$ %
Beam Color correction unc.[e]	non-CMB emission	0.5 %	0.1 %	0.3 %	<0.3 %	<0.3 %	<0.3 %	<0.5 %	<2.0 %	<1.0 %

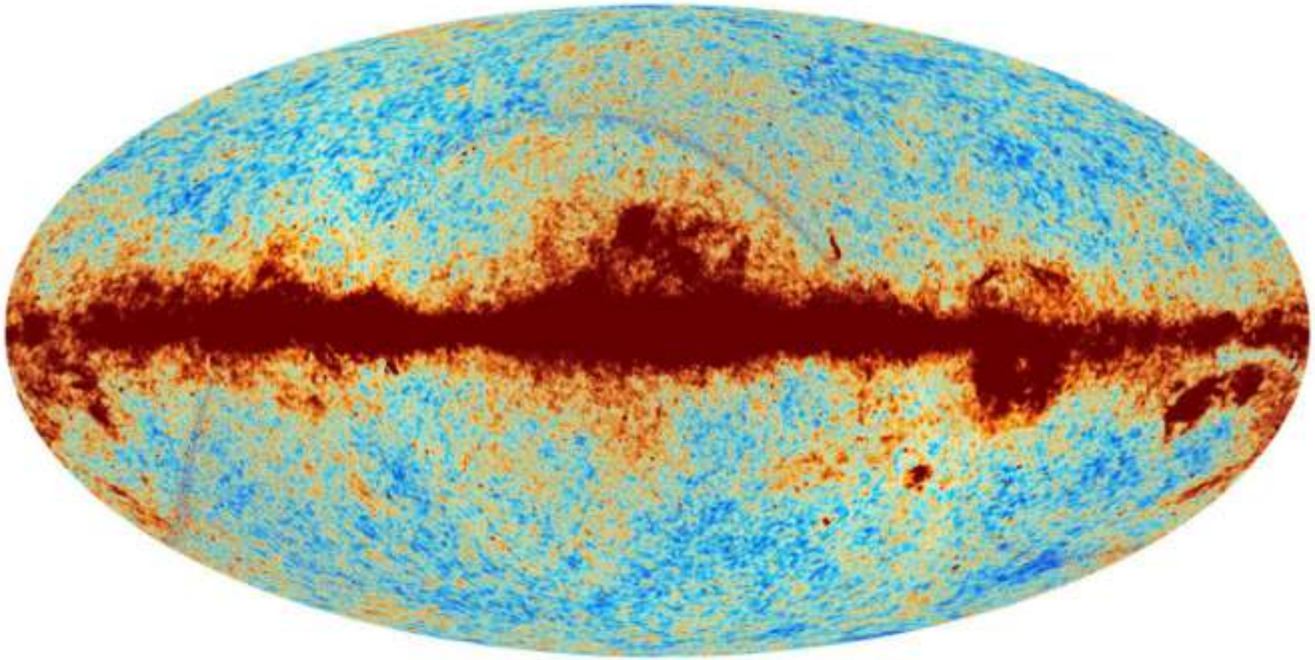
The Planck focal Plane

- **LFI**
-
- 44 GHz
- 70 GHz

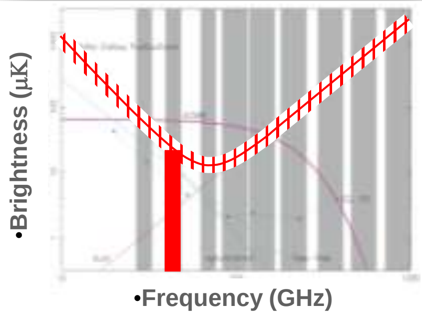
- **HFI**
- 100 GHz
- 143 GHz
- 217 GHz
- 353GHz
- 545 GHz
- 857 GHz

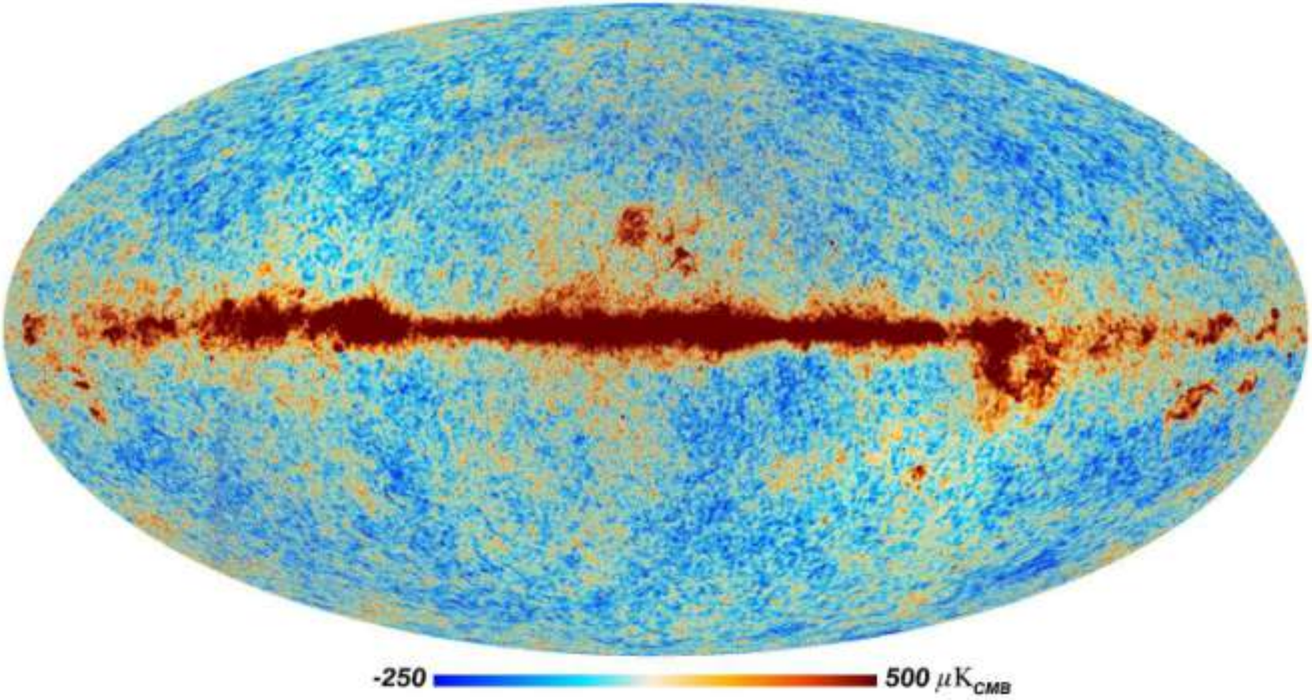
Planck-LFI – 30 GHz frequency map



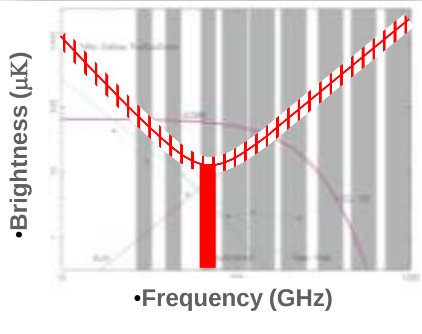


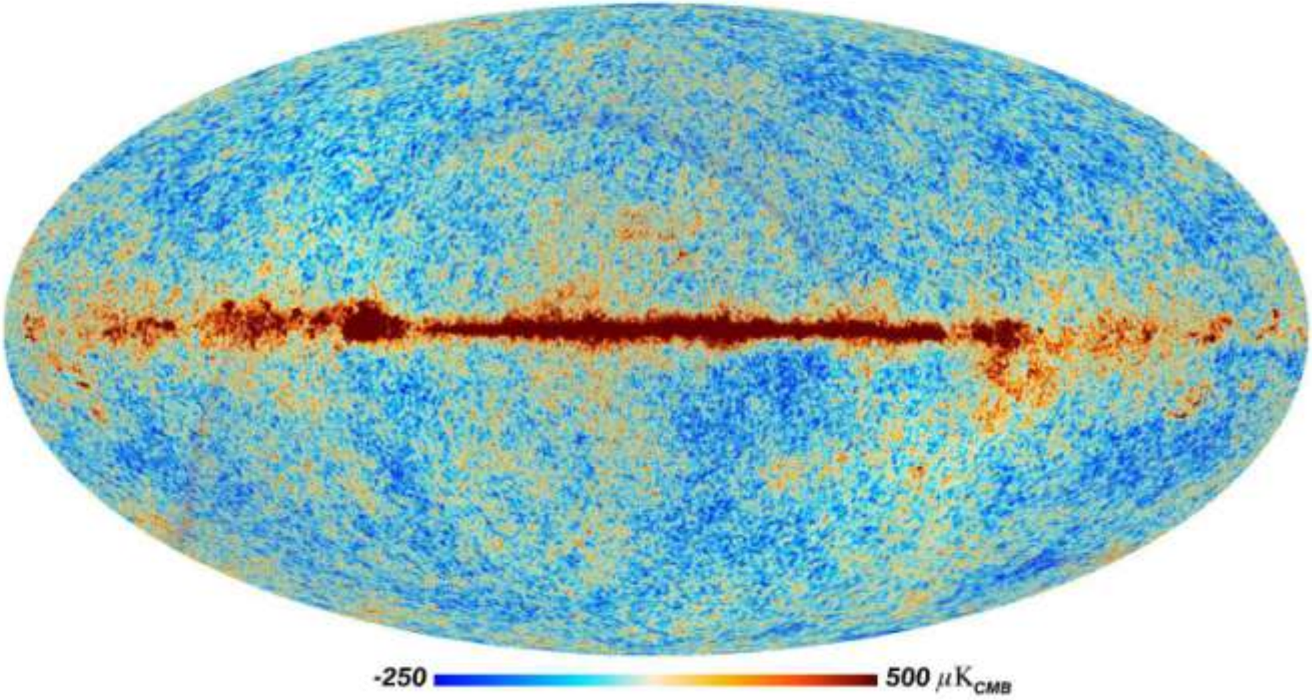
Planck-LFI – 44 GHz frequency map



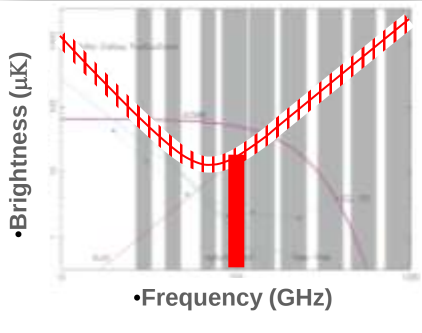


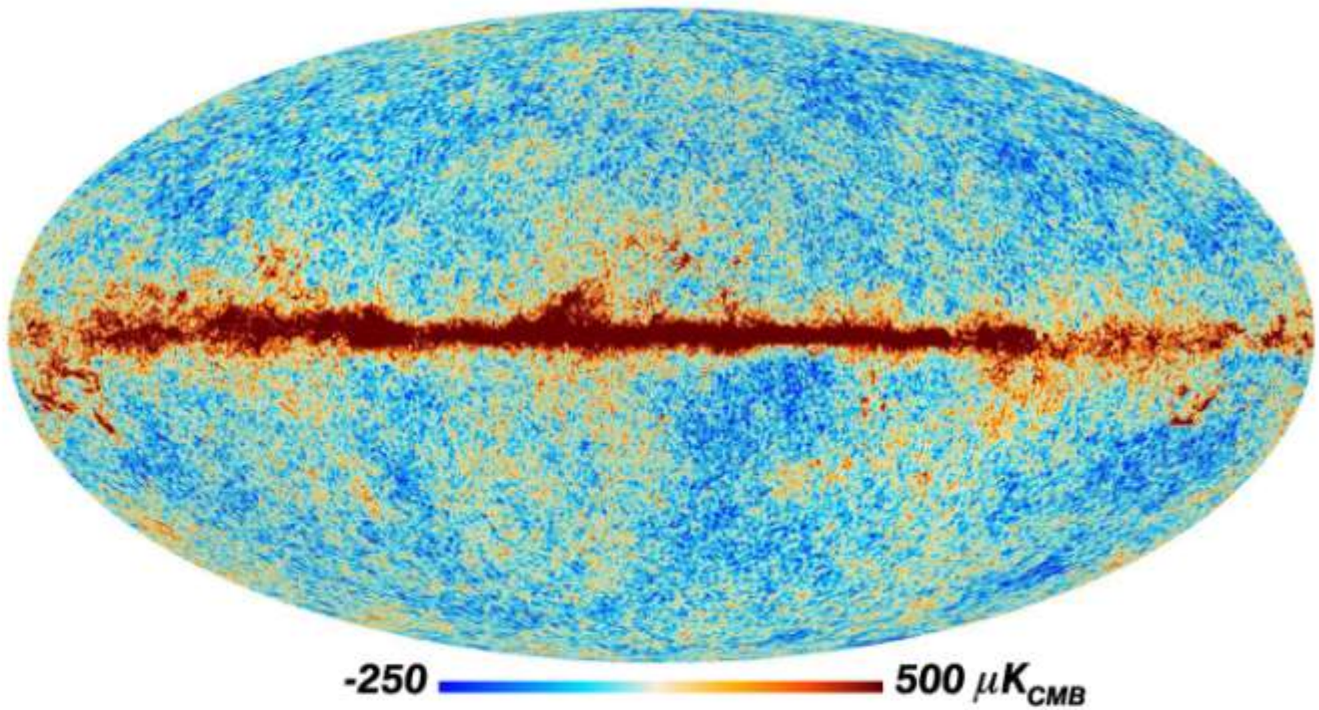
Planck-LFI – 70 GHz frequency map



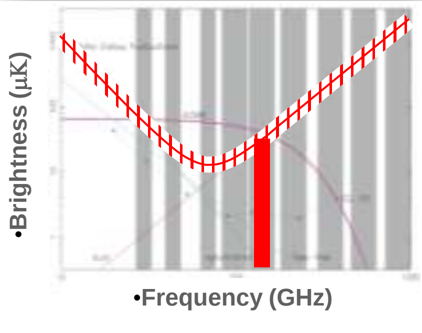


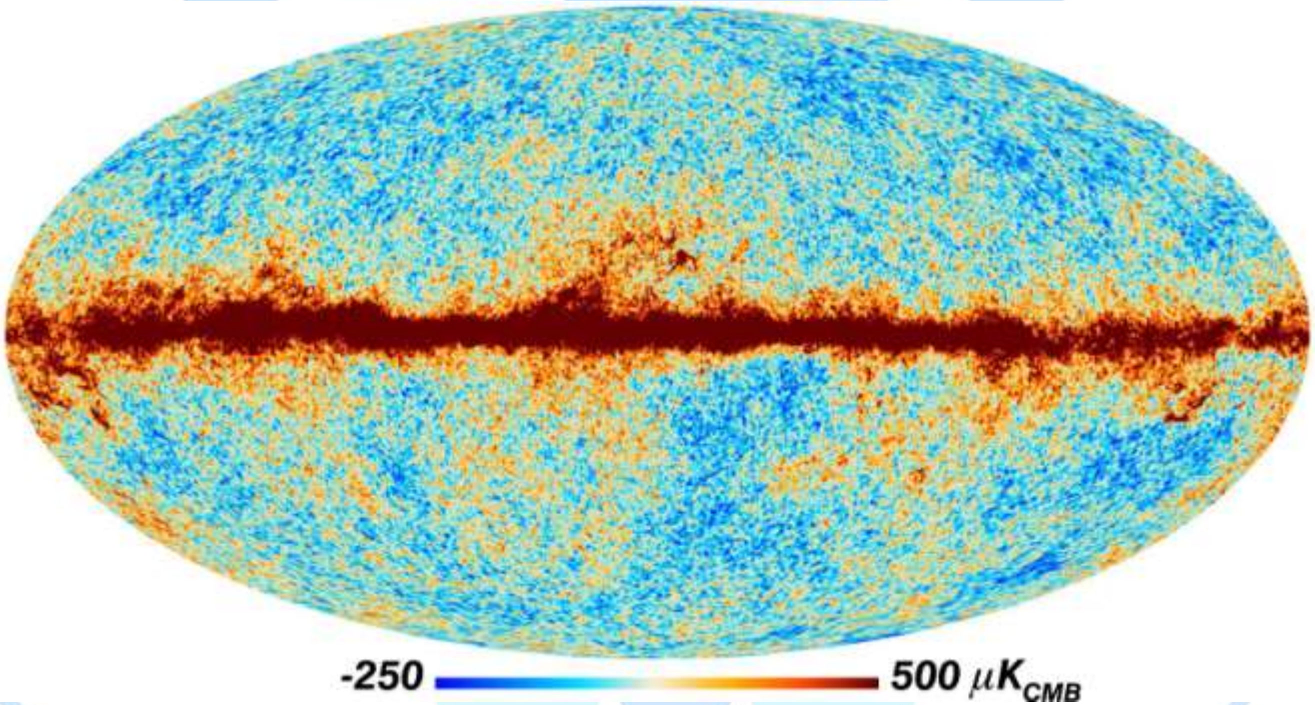
Planck-HFI – 100 GHz frequency map



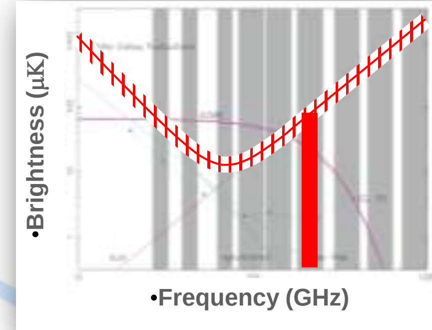


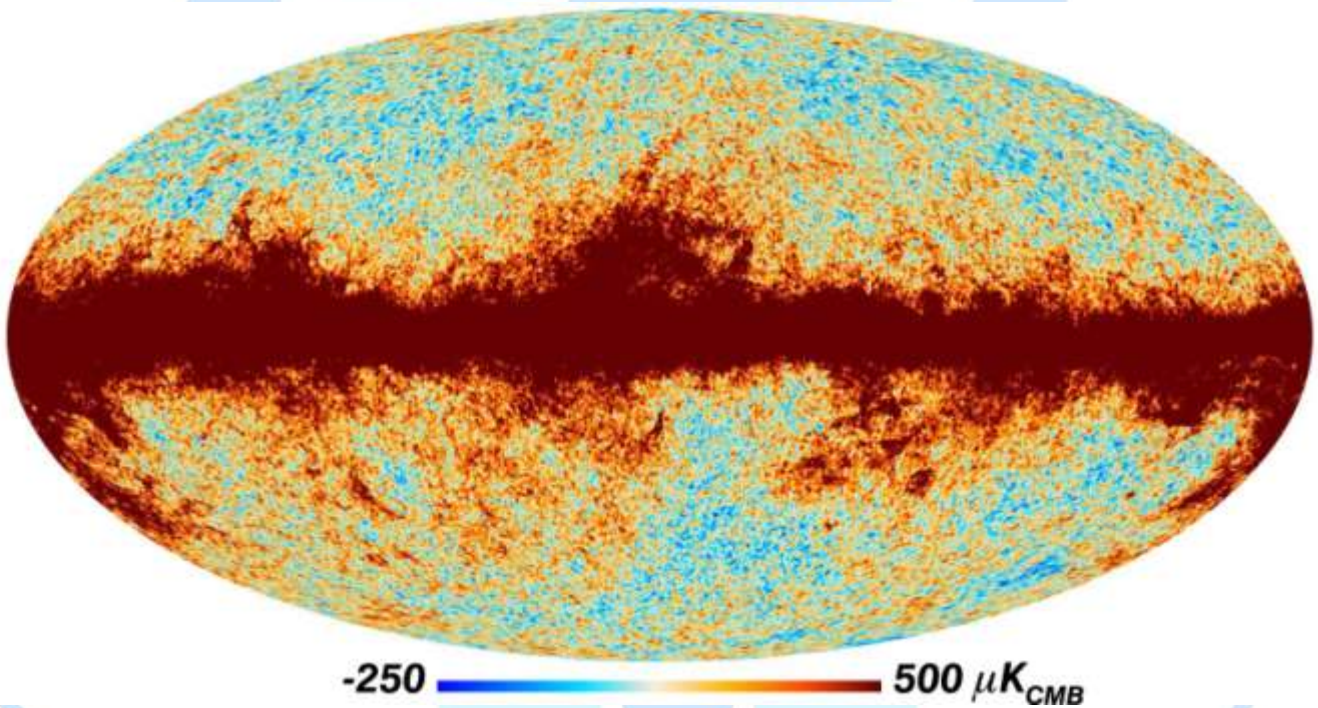
Planck-HFI – 143 GHz frequency map



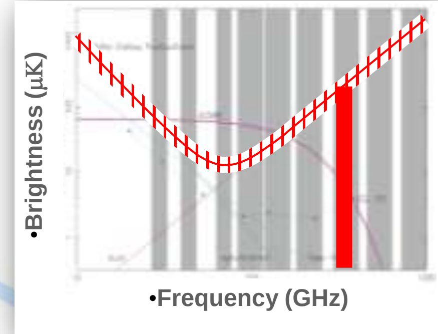


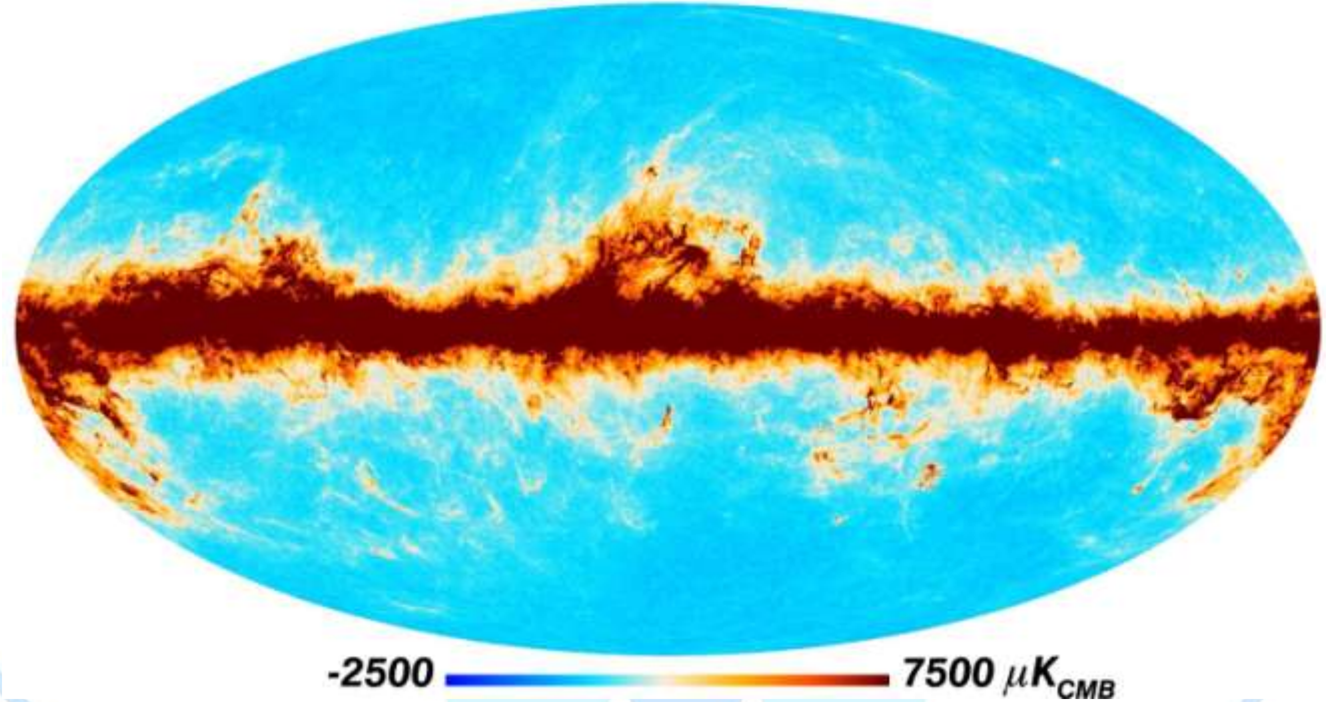
Planck-HFI – 217 GHz frequency map



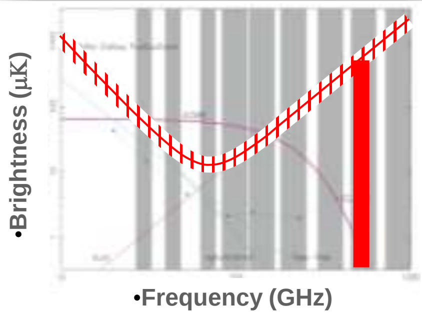


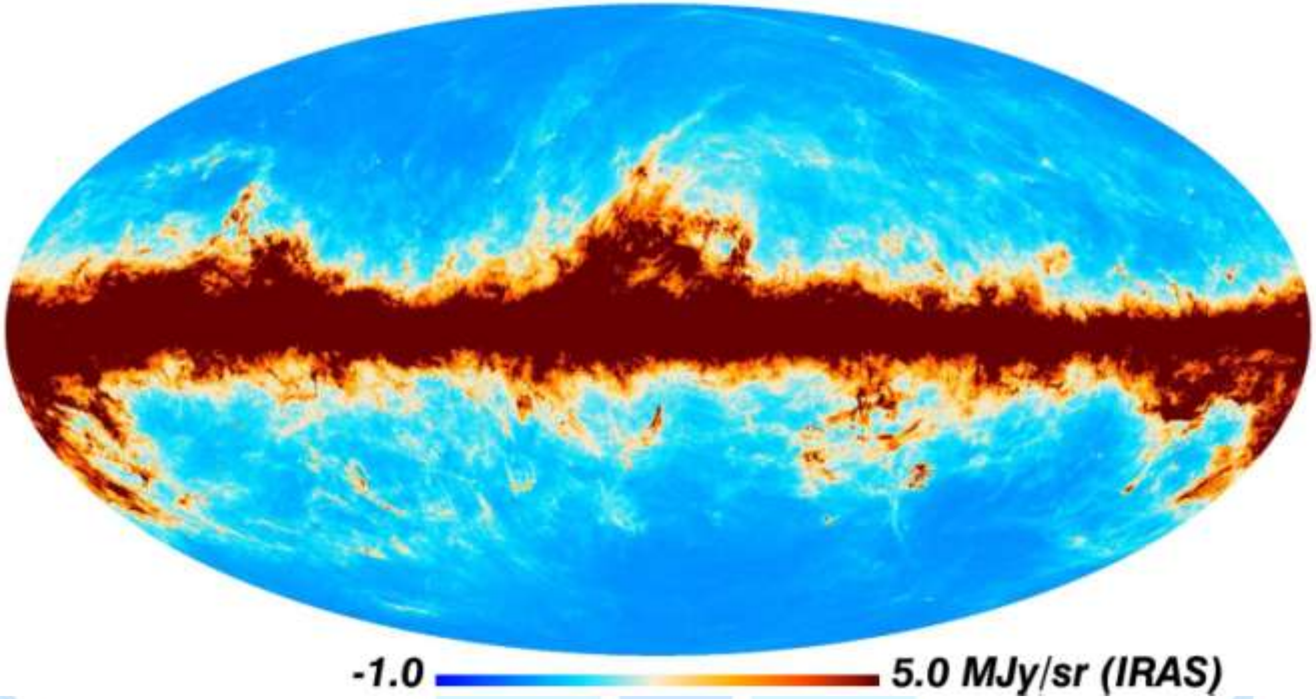
Planck-HFI – 353 GHz frequency map



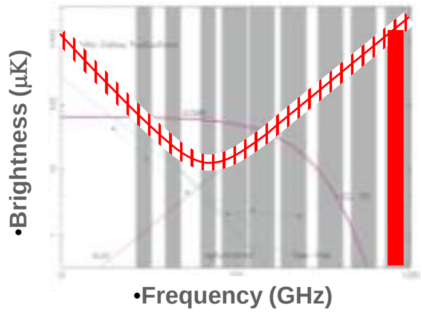


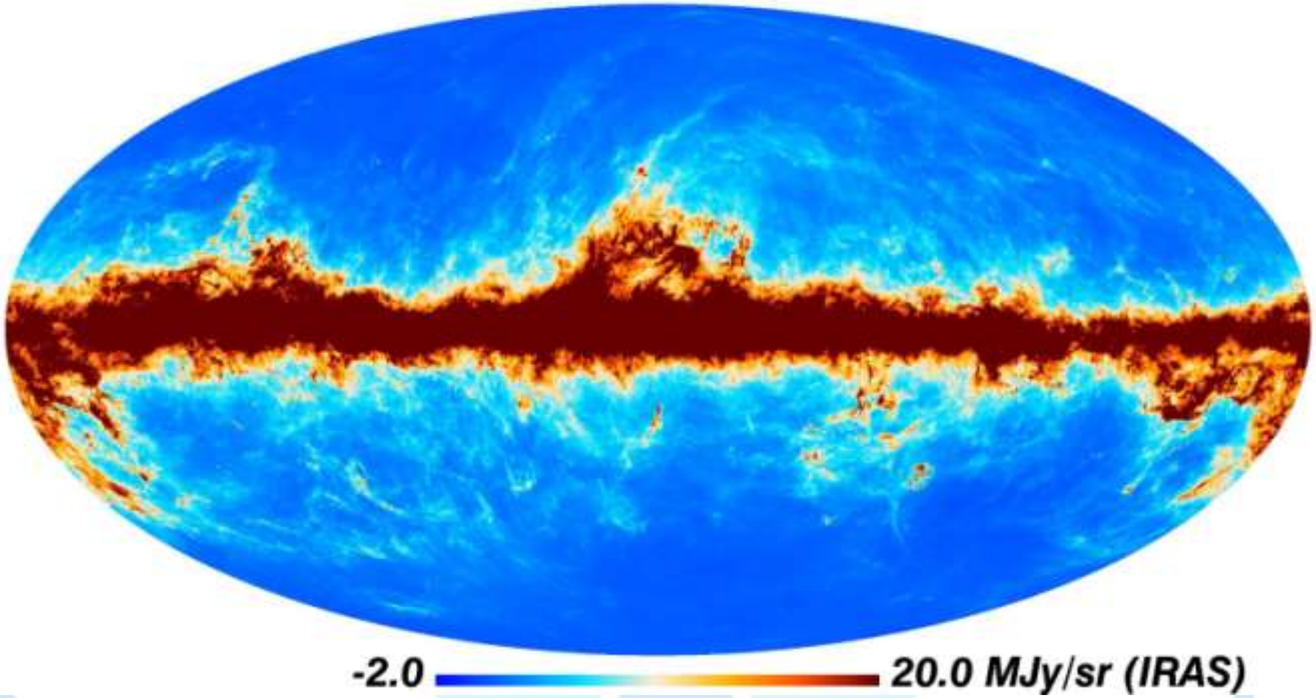
Planck-HFI – 545 GHz frequency map



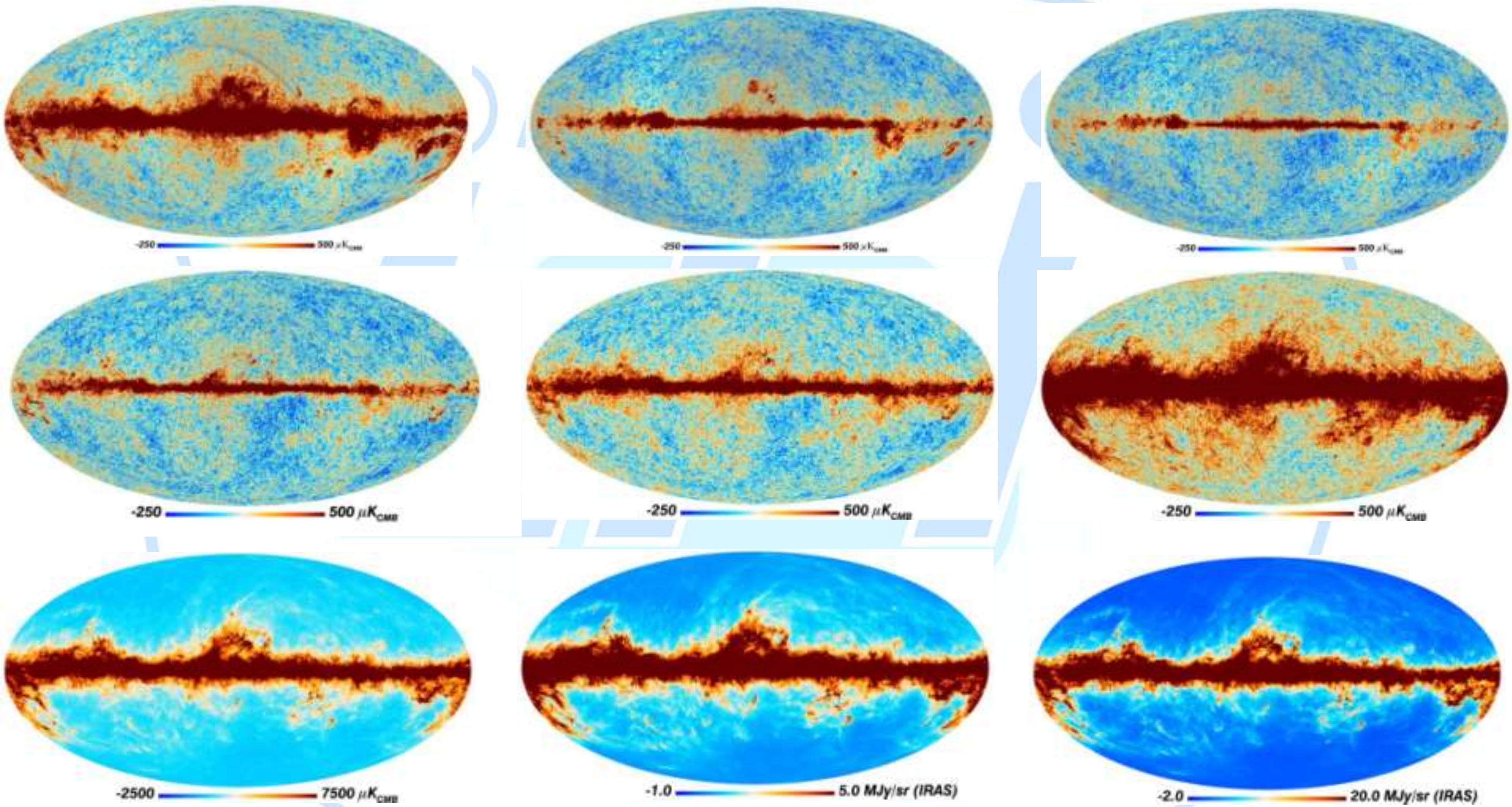


Planck-HFI – 857 GHz frequency map





Planck - frequency map



Future Steps

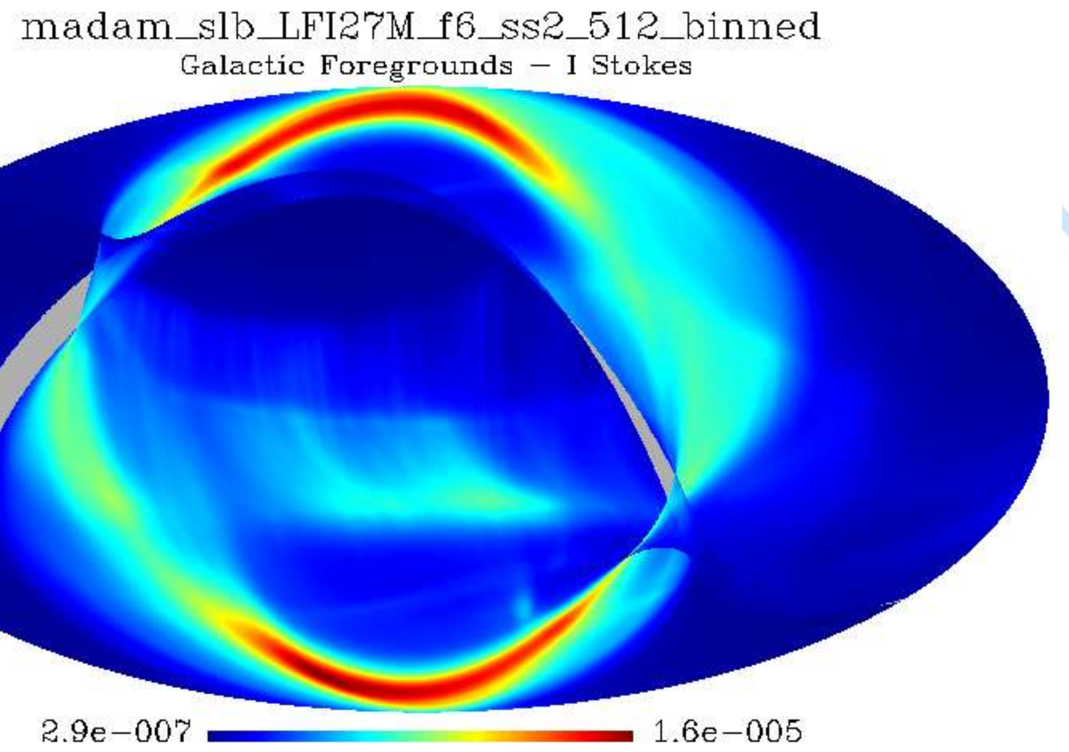
- Maps and products delivered in March 2013 are at very high quality and consistency was one of the key element that has been pursued.

- Next goal will be the analysis in polarization that will imply, at least, the following elements:
  - include Sidelobes in the calibration process;
  - use of 4pi beam in the calibration based on band response;
  - removal of Galatic strylight;
  - correction of ADC non linearity effect;
  - assessment of know systematic in polarization;
  - optimization of Zodiacal light removal.

SideLobes correction

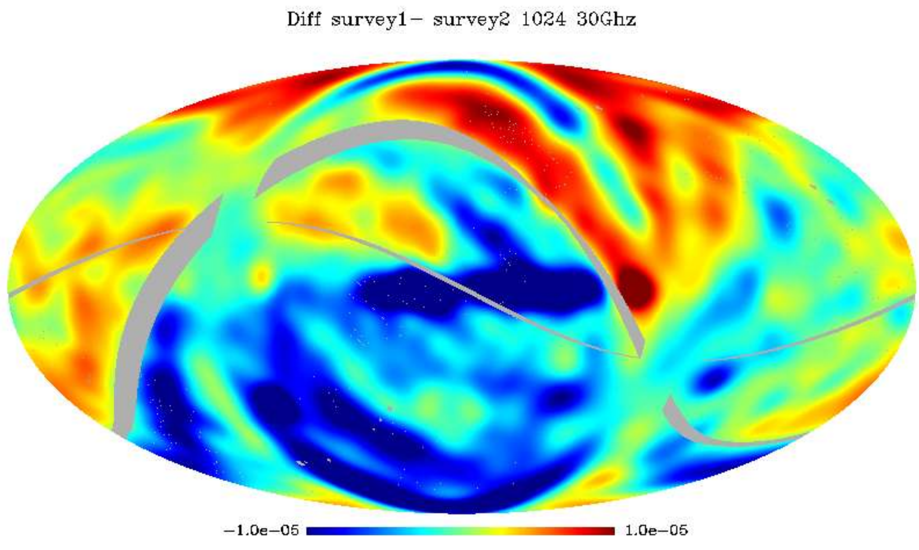
- As stated before we introduced in the pipeline the 4pi beam (in the previous release pencil beam was assumed).
- Then in the calibration process we convolve the dipole and the Galactic emission with this 4pi beam
- After calibration the convolved dipole and convolved Galactic emission with the 4pi are removed from the timelines before the mapmaking
- This is necessary to remove the SideLobes effect.

SideLobes correction Simulation

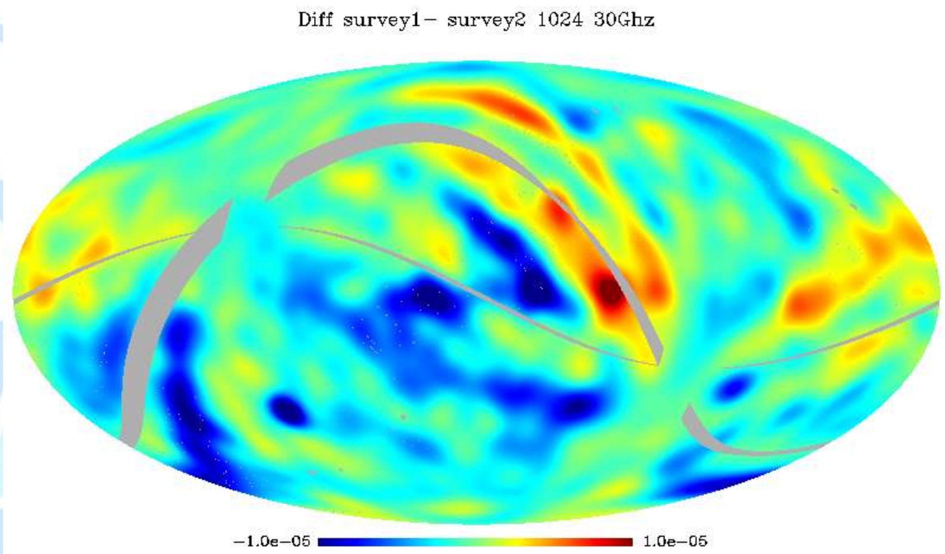


Before creates the code to be used in the official pipeline, we perform a simulation to understand the impact of the sidelobes in our maps

Side Lobes Reality



30 GHz Survey 1 – Survey 2 DX9D smoothed



30 GHz Survey 1 – Survey 2 DX10 smoothed

In this difference you can see how the sidelobes removal affect the map and how we are now removing the effect. This is not so important in Temperature but seems to be relevant in polarization. Some large structure are still to be understood but we are in the right path !!!!

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Bandpass 21M 70GHz