HFI detection chain

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Bolometers

The heart of the HFI - the detectors - are bolometers, solid-state devices in which the incoming radiation dissipates its energy as heat that increases the temperature of a thermometer. The instrument Flight Model total number of bolometers is 52, split into six channels at central frequencies of 100, 143, 217, 353, 545, and 857 GHz. Two extra bolometers, not optically coupled to the telescope, are added to the focal plane to monitor thermal noise (dark bolometers).

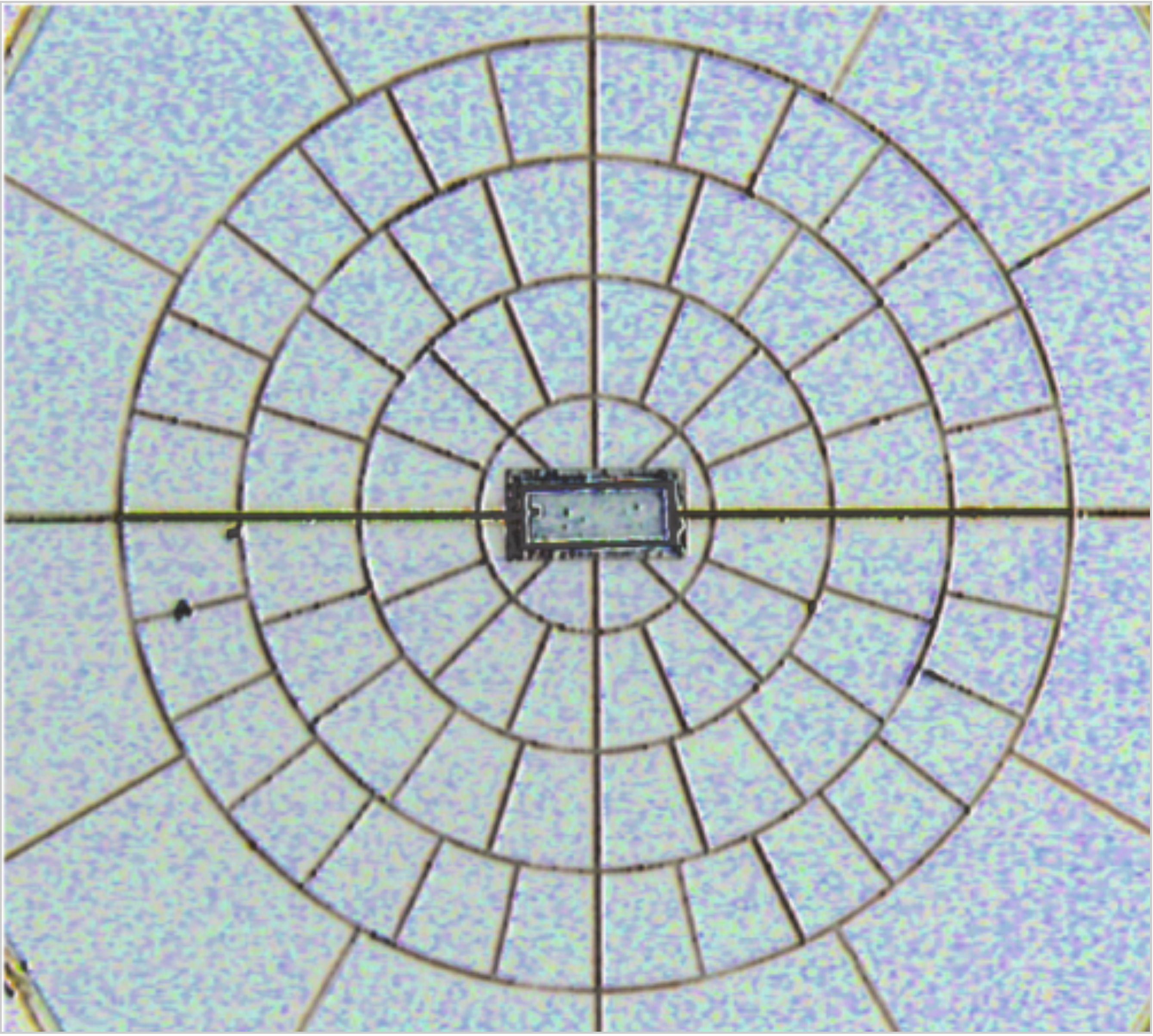
The bolometers consist of:

- an absorber that transforms the in-coming radiation into heat;
- a semi-conducting NTD thermistor that is thermally linked to the absorber and measures the temperature changes;
- and a weak thermal link to a thermal sink, to which the bolometer is attached.

There are two kinds of detector modules: polarization-sensitive bolometers (PSBs) and spider-web bolometers (SWBs).

Spider-web bolometers [1][2]

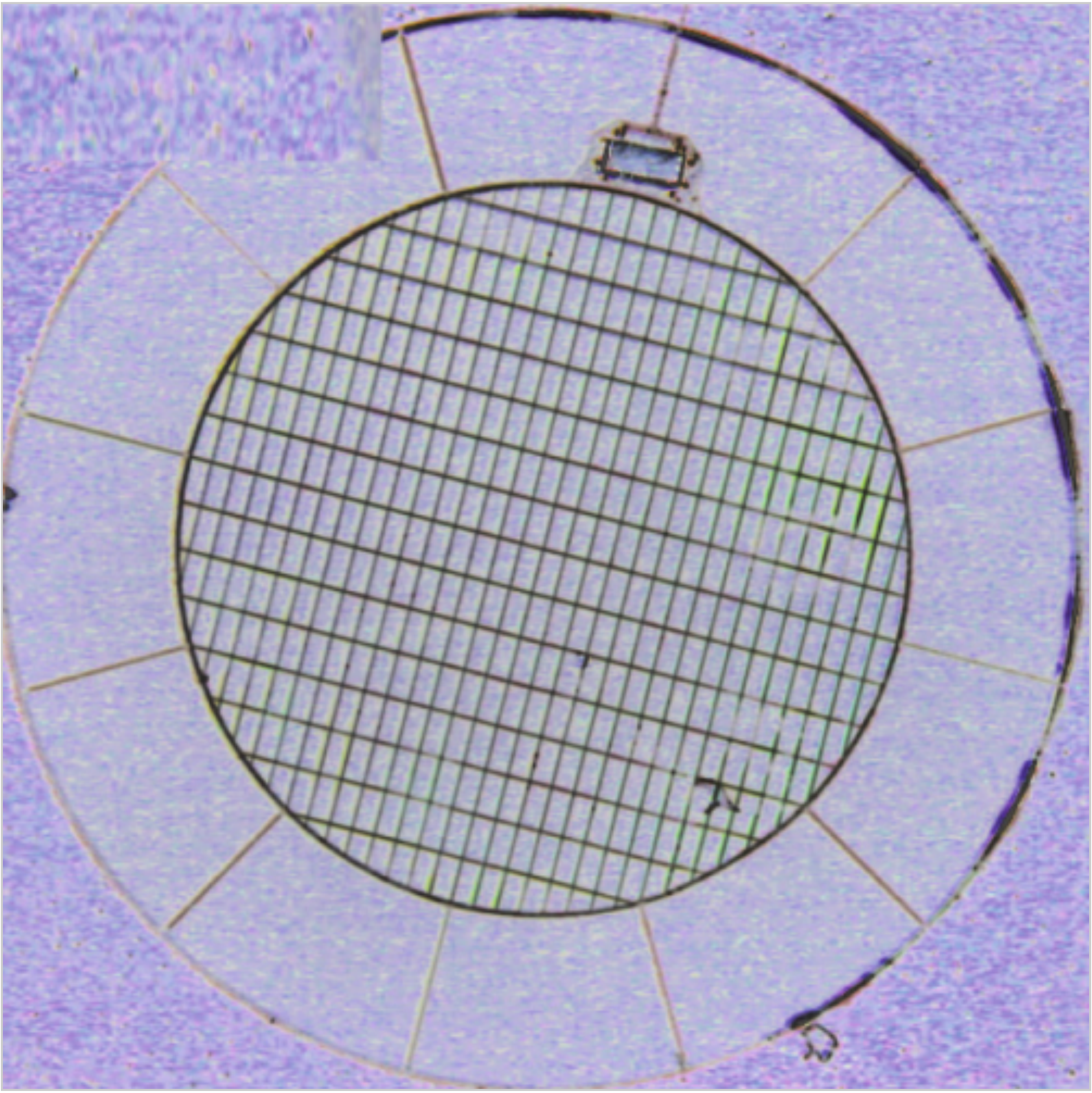
In these bolometers, the absorber consists of a metallic grid deposited on a Si3 N4 substrate in the shape of a spider web. The mesh design and the impedance of the metallic layer are adjusted to match vacuum impedance and maximize the absorption of millimetre waves, while minimizing the cross-section to particles. The absorber is designed to offer equal impedance to any linearly polarized radiation. Nevertheless, the thermometer and its electrical leads define a privileged orientation that makes the SWBs slightly sensitive to polarization, as detailed in Planck-PreLaunch-IX (http://www.aanda.org/articles/aa/pdf/2010/12/aa13054-09.pdf#page=1) [3]. The thermometers are made of neutron transmutation doped (NTD) germanium [4], chosen to have an impedance of about 10 MΩ at their operating temperature.



Picture of a spider-web bolometer. This a 143 GHz module. The temperature sensor is at the centre of the absorbing grid.

Polarization-sensitive bolometers

The absorber of PSBs is a rectangular grid with metallization in one direction [5]. Electrical fields parallel to this direction develop currents and then deposit some energy in the grid, while perpendicular electrical fields propagate through the grid without significant interaction. A second PSB, perpendicular to the first one, absorbs the other polarization. Such a PSB pair measures two polarizations of radiation collected by the same horns and filtered by the same devices, which minimizes the systematic effects; differences between polarized beams collected by a given horn are typically less than −30 dB of the peak. The differences in the spectral responses of a PSB pair have also proved to be a few percent in the worst case. Each pair of PSBs sharing the same horn is able to measure the intensity Stokes parameter and the Q parameter associated with its local frame. An associated pair of PSBs rotated by 45° scans exactly the same line (if the geometrical alignment is perfect), providing the U Stokes parameter.



Picture of a polarization-sensitive bolometer. This is a 217 GHz module. The temperature sensor is located at one edge of the absorbing grid.

The detectors operate at a temperature close to 100 mK, while the filters are distributed on the 100-mK, 1.6-K, and 4-K stages, in such a way that the heat load on the coldest stages is minimized, to limit the heat load on the detectors and to decrease the heat lift requirement and thus enhance the mission lifetime. The self-emission of the 4-K stage is minimized to limit the photon noise contribution on the detectors from the instrument. The HFI Focal Plane Unit accommodates sub-millimitre absorbing material in order to decrease the scattering inside it.

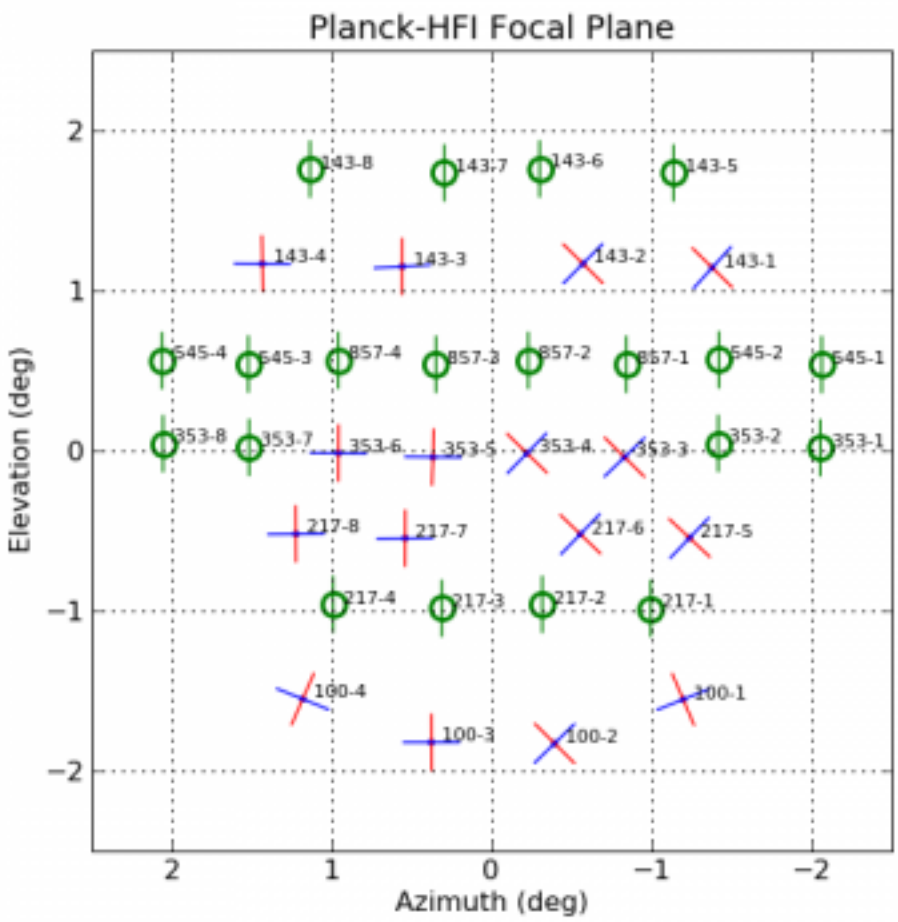
Table 1. The HFI receivers.

Band	ν_{center} [GHz]	Bandwidth [%]	Number of bolometers
100P	100	33	8
143P	143	32	8
143	143	30	4
217P	217	29	8
217	217	33	4
353P	353	29	8
353	353	28	4
545	545	31	4
857	857	30	4

Notes. The "P" identifies the polarisation sensitive bolometers.

Focal plane layout

The layout of the detectors in the focal plane is defined in relation to the scanning strategy. The HFI horns are positioned at the centre of the focal plane, where the optical quality is good enough for the high frequencies. The curvature of rows compensates for the distortion of images by the telescope. A pair of identical SWBs will scan the same circle on the sky to provide redundancy. Similar horns feeding PSBs are also aligned so that two PSBs rotated by 45° with respect to each other scan the same line. This will provide the *Q* and *U* Stokes parameters with minimal correction for the pointing Planck-PreLaunch-IX (http://www.aanda.org/articles/aa/pdf/2010/12/aa13054-09.pdf#page=1) [3]). Residual systematics will come from the differences between the beam shapes of the two horns. In all cases, except for the 100 GHz horns, a measurement is also done by a pair of similar channels shifted by 1.25 arcminutes in the cross-scan direction, to ensure adequate sampling. The focal plane layout is reported in the figures.



Focal plane layout as seen from outside the celestial sphere. PSB orientations are indicated, with a red rod for the "a" elements and a blue rod for the "b" elements. The scan direction is from left to right.

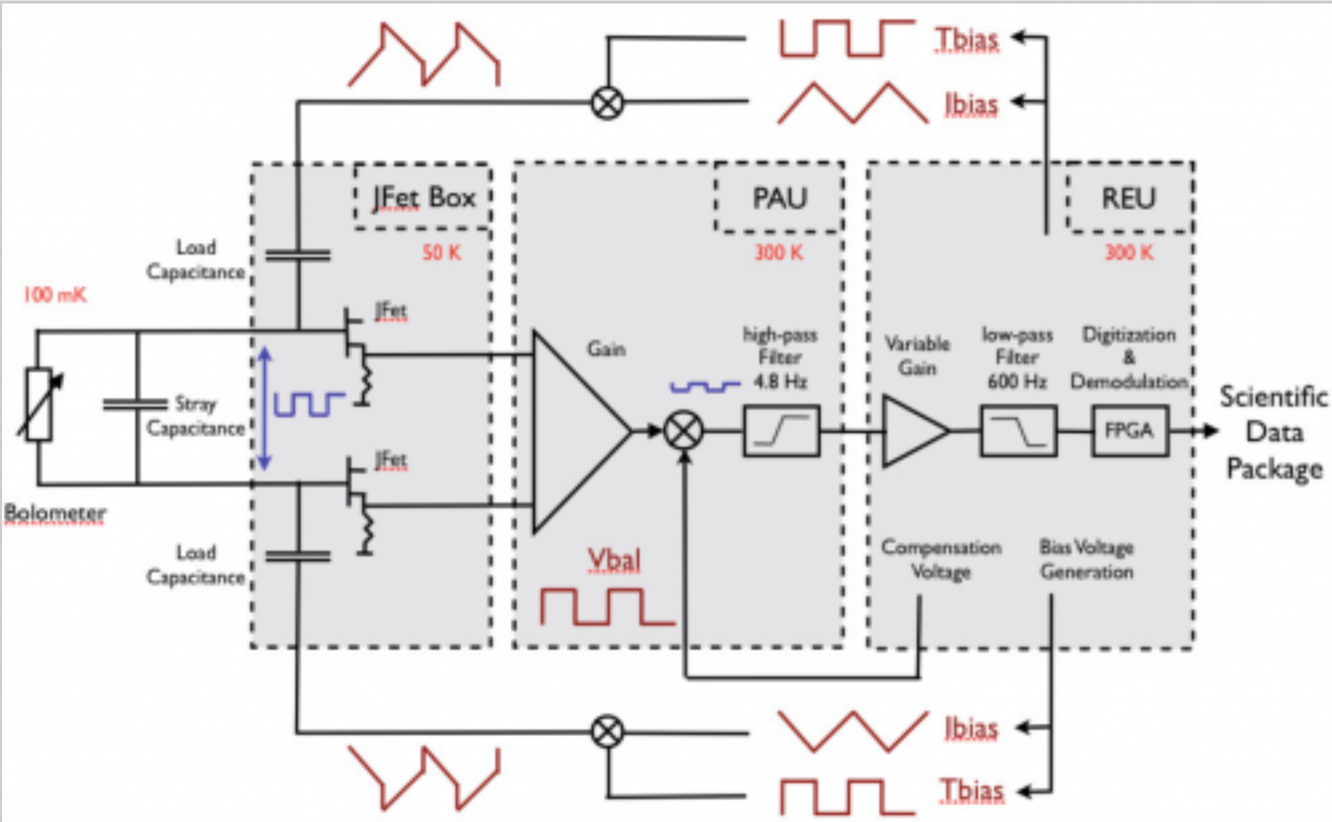
Readout

The AC bias readout electronics of the HFI instrument [6] includes the following features:

- the cold load resistors were replaced by capacitors because they have no Johnson noise;
- the detectors are biased by applying a triangular voltage to the load capacitors, which produces a square current (I-bias) in the capacitors, and a square voltage (T-bias) that compensates for the stray capacitance of the wiring (producing a nearly square bias current into the bolometer);
- a square offset compensation signal is subtracted from the bolometric signal to minimize the amplitude of the signal that has to be amplified and digitized;
- the electronic scheme is symmetrical and uses a differential amplification scheme to optimize the immunity to electromagnetic interference;
- and finally every parameter of the REU can be set by commands, which is made possible by extensively using digital-to-analogue and analogue-to-digital converters.

The readout electronics consists of 72 channels designed to perform low noise measurements of the impedance of 52 bolometers, two blind bolometers, and 16 accurate low-temperature thermometers, all in the 10 MΩ range, together with one resistor of 10 MΩ and one capacitor of 100 pF. The semiconductor bolometers and thermometers of Planck-HFI operate at cryogenic temperatures around 100 mK on the focal plane, with impedance of about 10 MΩ when biased at the optimal current. The readout electronics, on the other hand, has to operate at “room” temperature (300 K). The distance between the two extremities of the readout chain is about 10 m and this could bring about an extreme susceptibility to electromagnetic interference. The readout electronics chain was therefore split into three boxes. These are the JFET box, located on the 50-K stage of the satellite at 2.2 m from the focal plane, the pre-amplifier unit (PAU), located

1.8 m further at 300 K, and the REU, located on the opposite side of the satellite, 5 m away. Each of the three boxes (JFET, PAU and REU) consists of 12 belts of six channels. The first nine belts are dedicated to the bolometers, and the three last ones to the accurate thermometers, the resistor, and the capacitor.



Principles of readout electronics. The three modules of the chain are shown: JFET box; Pre-Amplifier Unit (PAU); and Readout Electronic Unit (REU)

Nbelt / Nchannel	0	1	2	3	4	5
0	100-1a	100-1b	143-1a	143-1b	217-1	353-1
1	143-5	217-5a	217-5b	353-2	545-1	Dark 1
2	100-2a	100-2b	217-2	353-3a	353-3b	857-1
3	143-2a	143-2b	353-4a	353-4b	545-2	857-2
4	100-3a	100-3b	143-6	217-6a	217-6b	353-7
5	143-3a	143-3b	217-3	353-5a	353-5b	545-3
6	143-7	217-7a	217-7b	353-6a	353-6b	857-3
7	143-8	217-8a	217-8b	545-4	857-4	Dark 2
8	100-4a	100-4b	143-4a	143-4b	217-4	353-8
9	Ther_0.1K 1	Ther_PID2 N	Ther_PID1 N	Ther_PID1.6 N	Ther_1.6K 1	Ther_PID4 N
10	Resistor	Capa 2	Ther_0.1K 2	Ther_PID1.6 R	Ther_4KH 1	Ther_4KL 1
11	Ther_PID2 R	Ther_PID1 R	Ther_1.6K 2	Ther_PID4 R	Ther_4KH 2	Ther_4KL 2

Organization of the HFI readout. Each row represents a belt. Each belt has six channels.

Principles of the readout electronics

The bolometer is biased by a square wave AC current obtained by the differentiation of a triangular voltage through a load capacitance, in a completely differential architecture. The presence of stray capacitance due to losses of charge in the wiring requires a correction of the shape of the square bias current by a transient voltage. Thus the bias voltage generation is controlled by the two parameters I-bias and T-bias that express the amplitude of the triangular and transient voltage. The compensation voltage added to the bolometric signal to optimize the dynamics of the chain is controlled by the V-bal parameter.

The following parameters of the Readout Unit can be set to optimize the detector performance:

- fmod, the modulation frequency of the square bias current, which was set to 90.18685;
- Nsample, which defines the number of samples per half period of modulated, which signal was set to 40.

Each channel has its own settings for the following parameters:

- I-bias, the amplitude of the triangular bias voltage;
- T-bias, the amplitude of the transient bias voltage;
- V-bal, the amplitude of the square compensation voltage;
- G-amp, the value of the programmable gain of the REU [1/3, 1, 3, 7.6];
- N-blank, the number of blanked samples at the beginning of each half period not taken into account during integration of the signal;
- S-phase, the phase shift when computing the integrated signal.

All these parameters influence the effective response of the detection chains, and were optimized during the calibration campaigns and confirmed during the calibration and performance verification phase following the launch of Planck. The scientific signal is provided by the integral of the signal over each half-period, between limits fixed by the S-phase and N-blank parameters.

The interaction of modulated readout electronics with semiconductor bolometers is rather different from that of a classical DC bias readout [7]. The differences were seen during the calibration of the HFI, although the readout electronics was designed to mimic the operation of a DC-biased bolometric system as far as possible. With the AC readout the maximum of responsivity is lower and is obtained for higher bias current in the bolometer with respect to the DC model. This is caused by the stray capacitance in the wiring, which has negligible effects for a DC bias and a major effect for an AC bias. In our case, a stray capacitance of 150 pF induces increases of NEP, ranging from 4% (857 GHz bolometers) to 10% (100 GHz bolometers), and also affects the HFI time response. Details of the effect of the HFI AC bias system on the time response of the detectors are discussed in the time response section.

JFETs

Given the high impedance of the bolometers and the length of the connecting cables, it is essential that the impedance of the signal is lowered as close as possible to that of the detectors. In our system this is accomplished by means of JFET source followers, located in boxes connected to the 50-K stage [8]. There are two JFETs per channel, since the readout is fully differential, and they provide a current amplification of the signal while keeping the voltage amplification very close to unity.

Inside the box, the JFETs are mounted on a thermally insulated plate with an active temperature control to keep them at the optimal temperature of 110 K. With a dissipated power lower than 240 mW, mainly produced by the JFETs and the source resistors, we obtained a noise power spectral density of less than 3 nV

Hz$^{1/2}$ for the frequency range of interest. This increases the total noise of all bolometer channels by less than 5%.

Time response

The HFI bolometers and readout electronics have a finite response-time to changes of the incident optical power, modelled as a Fourier domain transfer function (called the LFER4 model). LFER4 has two factors. The first one represents the bolometer thermal response, driven by its heat capacity, by the thermal link to the bolometer plate at 100 mK, and by the thermo-electrical feed-back [9] resulting from the heat deposited in the bolometer by the readout electronics. This factor is empirically obtained from the observation of sources. The second factor is simply the time response of the part of the readout electronics that amplifies and digitizes the signal. It is obtained by modelling the electronics using only a very few free parameters.

The time response of the HFI bolometers and readout electronics is modelled as a Fourier domain transfer function (called the LFER4 model), consisting of the product of a bolometer thermal response $F(\omega)$ and an electronics response $H'(\omega)$:

$$TF^{LFER4}(\omega) = F(\omega)H'(\omega).$$

Due to Planck's nearly constant scan rate, the time response is degenerate with the optical beam. However, because of the long timescale effects present in the time response, the time response is deconvolved from the data in the processing of the HFI data (see TOI processing). $F(\omega)$ is tuned to optimize the "compactness" of the beams reconstructed with the deconvolved signal from planets.

Details about the time response model are to be found in this annex.

Data compression

The output of the readout electronics unit (REU) consists of one value for each of the 72 science channels (bolometers and thermometers) for each modulation half-period. This number, S_{REU}, is the sum of the 40 16-bit ADC signal values measured within the given half-period. The data processor unit (DPU) performs a lossy quantization of S_{REU}.

Details about the data compression scheme, performance of the data compression during the mission, setting the quantization step in flight, and the impact of the data compression on science, are given in this annex.

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Category: HFI design, qualification and performance
