Non-linear transient response of bolometers: direct model and correction

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Abstract

The classical non linear dynamical model for bolometers describing the response of the system to a change of the incident flux has been implemented in order to check whether HFI bolometers on-board Planck satellite may exhibit non linear response. It is confirm that Jupiter is close to the limit between linear and non-linear domains.

Corrections of the effects have also been studied. Excellent reconstruction are obtained for all cases. This may be used for beam reconstruction.

Four bolometers have been mainly studied: Planck bolometers at 100, 545 and 800 GHz, and also the bolometer described and used in (Woodcraft et al., 2003).

Version 2.0 in relation with SimuDyna package Version 0.3 rc 3

1 Introduction

Incoming flux for large majority of sources to be observed by HFI Planck bolometers are in the range where the bolometer' response is linear to a high degree. That means that in static case (i.e. after stabilization) we have a linear relationship between measured temperature (above bath temperature) and incoming flux. That also means that in dynamical case bolometer responses to a change of incoming flux follow the relation of linearity:

$$f(\lambda x) = \lambda f(x)$$

Nevertheless several points should be checked:

- planets are in the upper range
- relationship between real and observed beams and strategy for beam measurement and reconstruction
- response to High Energetic Particles (HEPs, also called glitches)
- dynamical behavior of such bolometers and its possible correction

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2 The direct model

2.1 Physical model and its equation

Despite the fact that they need to operate at very low temperature (close to 0.1 K), bolometers have the property to response quasi linearly to the optical incident signal in a large range.

We have used the direct model described in (Chanin and Torre, 1984). Let T be the measured temperature of the system (also called $bolometer temperature$), T_{bath} the temperature of the bath, t the time, P_J the Joule power dissipated in the bolometer polarized under current i, P_f the leakage power, C the heat capacity and $signal$ the incoming signal (can be optical of).

The main equation is:

$$P_j(T) + signal = P_f(T) + P_c(T)$$

The differential equation is:

$$\frac{dT}{dt} = \frac{P_j(T) - P_f(T) + signal}{C(T)} \tag{1}$$

with:

- the Joule power $P_j(T) = R_{\inf}\ i^2\ exp[(A/T)^m]$ dissipated in the bolometer resistance $R_{\inf}$ under the polarization current i. Coefficient m is usually 1/4, 1/2 or 1. For all the HFI bolometers the value is now 1/2.
- the loss power

  $$P_f(T) = \frac{g_{s0}}{T_{100mk}^{\beta}(\beta+1)}(T^{\beta+1} - T_{100mK}^{\beta+1})$$

  in order to be able to take into account any temperature variation of the so-called 100 mK stage, we use instead:

  $$P_f(T) = \frac{g_{s0}}{T_{100mk}^{\beta}(\beta+1)}(T^{\beta+1} - T_{bath}^{\beta+1})$$

  where T_{100mk} is fixed at 0.1 K and T_{bath} is the effective temperature of the 100mK stage bath.
- the heat capacity:

  $$P_c(T) = \frac{dT}{dt}C(T)$$

  where

  $$C(T) = C_0[\frac{T}{T_0}]^d$$

2.2 Numerical equation

We have choosen the simplest way to implement Eq. 1. We use recursive equation with constant time step Δt. Then we write:

$$\frac{dT}{dt} \sim \frac{T_{n+1} - T_n}{\Delta t}$$

and any other T in Eq. 1 are T_n. Then, if we have initial value of temperature at time 0, and a sampled incoming optical signal S_n we can compute any T_{n+1} from previous T_n and S_n.

It is also obvious to invert this equation, when we know the current,T_{bath} and all the parameters of a bolometer, in order to compute the incoming flux.

2.3 Numerical consistency

It at been check carefully that this direct model is numerically stable in the expected range for Ground Based Tests (GBT) and in-flight operation. Minimal range is a current at 0.1 nA and a background at $1.\times 10^{-13}$ W. In this extreme case, with sampling time $\Delta t = 1.\times 10^{-4}$ s, we have a numerical problem, which is solved by using a white noise with rms $1.\times 10^{-16}$ on background. As soon as background is above $2.\times 10^{13}$ W (sampling $1.\times 10^{-4}$ s and current at 0.1 nA), no numerical problem have been evidenced.

2.4 Experimental parameters

We summerized in the following table the values of mandatory parameters we have to know in order to do simulations.

The background level of HFI following the Planck documentation is around $\sim 5.\times 10^{-13}$ W at 100 GHz and increase to $\sim 5.\times 10^{-12}$ W at 545 GHZ and $\sim 15.\times 10^{-12}$ W at 857 GHz. Three cases have been used for computing these background levels: a satellite at 40 K, at 60 K and at business agreement.

We have used a gaussian beam (Field of view) of resp. 9.5 (@ 100 GHz), 7,2 (@ 143 GHz) and 5 ArcSec (all others frequencies) and a scanning speed of 6 ArcMin/s.

Jupiter temperature at such wavelength is around 180K. Jupiter sized was between 39 to 44 ArcSec.

Spectral window is set to 1/3 of the central frequency. Optical efficiency is assumed to be 0.36.

Before looking in detail the values of all these parameters, it should be understood that the main parameter is the applied current, which was in the range 0.1 to 1 nA.

Bolometer Name	Woodcraft	HFI 100 GHz	HFI 545 GHz	HFI 857 GHz
Temp. Bath (K)	0.1	0.1	0.1	0.1
Pol. Curr. (nA)	0.36	3.6.	1.0	1.0
Frequency (GHz)	100.	100.	545.	857.
Rinf (Ohms)	143.	120.48	84.	101.
Ttrans	13.30	16.54	16.40	16.79
α	0.5	0.5	0.5	0.5
Gbol ($\times 10^{11}$)	150.	6.	27.8	25.9
β	1.0	1.5	2.36	2.46
c0 ($\times 10^{-13}$)	29.	8.0	4.4	5.8.
Dcapa	1.2	2.1	2.1	2.1
Field of View (ArcSec)	9.5	9.5	5.0	5.0
Nb of modes	1	1	9	16

Table 1: Parameters of real bolometers considered in the simulations.

3 Response to bright sources

For most of the scientific sources to be observed by Planck HFI, it is expected that the bolometer will operated in linear range. Nevertheless (1) it was not clear Jupiter nor Mars are inside the linear range and (2) it is not clear what means non-linear response of a bolometer.

The simulations clearly shown that :

- we always have a *simple* no linear effect which transform a symmetrical (Gaussian) signal to a non symmetrical one. Because of the delay introduce by the bolometer, the position of the peak is slightly shifted (exact position can be accurately predicted by model. Such effect will have to be carefully corrected when beam profile measurement and beam corrections will have to be done
- the critical parameter is the current.
- at 100 GHz, no error on direct estimation of the incoming flux amplitude is made, even if the incoming flux is ten time Jupiter
- for bolometers operating at 545 and 857 GHz, a significant non linear effect affecting the amplitude appears for flux in the range of half Jupiter. At Jupiter value, up to 7% of the flux can be loose on direct measurement.

4 Response to high energetic particles

Recent GBT (Woodcraft et al., 2003) report comparison between the model described in Section 2, especially concerning the NL response after impact of High energetic particles (HEP). The bolometer used in this paper is a fast one in comparison to Planck bolometers. HEP hitting the bolometer or around are generated by ^{241}Am γ-ray source outside the cryostat. Energy of generated photons is $\sim$ 60 keV.

5 Can we invert this model ?

As mention in SubSect. 2.2, the direct model can be used directly in order to estimate the incoming flux if others values are know.

5.1 Without noise

The case without noise is obvious since we know T_n and T_{n-1}, then P_J, P_f and C

This correction works perfectly well to simulations in small signal case, large signal case and HEP case. We do not provide figures since the inversion perfectly overlap the original input signal.

5.2 With noise

No serious problems have occurs when doing inversion tests with small level of noise (white or uniform). Nevertheless, no estensive study under realistic noise configuration has been made up to now.

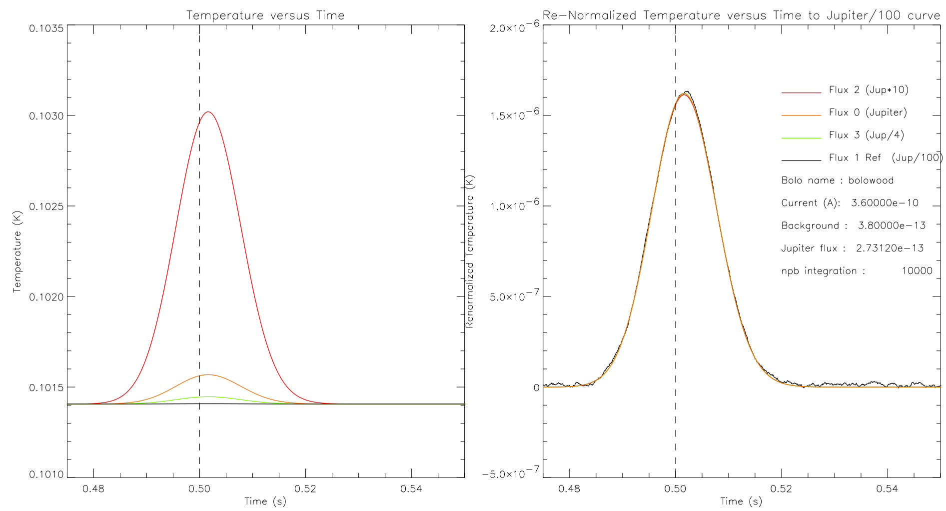

Figure 1: Example of response of the fast bolometer to a incoming flux in the range of Jupiter. We used the values is (Woodcraft et al., 2003), especially for the current, put to 0.36 nA. No non linear behavior is visible, by comparison to the response at level hundred time lower (the dark noisy curve which is a reference curve in a linear regime). It can only be noticed that the position of the maxima is slightly shifted in comparison to the in-sky position of the maximum (0.5). Brightest flux is for Jupiter. We have done the same for fluxes a 10 and 100 times Jupiter. Non linear effects become to appear for 100, but amplitude of the decreasing of the peak is below 5% for 100 and 1% for 25 Jupiter.

5.3 Possible Improvements

Such readout per readout correction method is adequate only if the model is close to the real response and also if we can estimate accurately all the parameters.

We have now to check whether this model is in good agreement with the GBT which have been done by CalTech and Cardiff team, and also to check whether some valuable informations can be extract from IAS GBT (Nov 2004).

We also have to think how to be able to monitor any possible variation of these parameters, not only during GBT, but also during such a long space mission. The availability of the model give the opportunity to check quickly what may be the consequence of any change of the parameters, and how it can be observed on brilliant point sources during flight.

Other more robust methods can be also derived from the equation, but if the stability of the nine parameters is good, such correction method should be enough.

W also have soon to include realistic model of the Readout Unit Electronic, where the signal is sampled then integrated. Since data rate after integration is ∼180 less than raw signal, a clear smoothing effect will be added, which may give significant complexity during the reconstruction of the incoming flux.

Influence of no-perfect current shape can be also study.

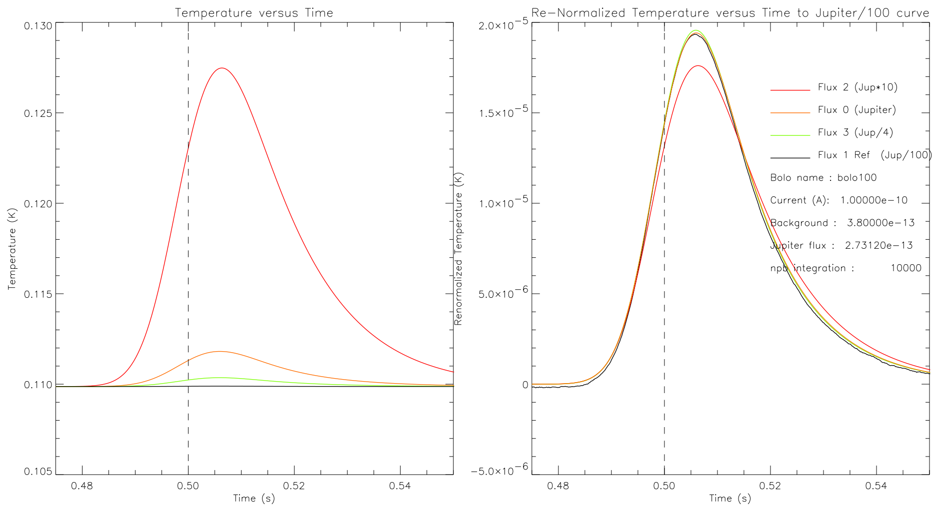

Figure 2: Simulation of response of one bolometer of HFI Planck operating in a spectral window centered at 100 GHz to a incoming flux in the range of 10 Jupiter. Polarization current is 0.1 nA. The dynamical non linear behavior is clearly visible, by comparison to the previous case (where a faster bolometer is used). For range closer to expected flux of Jupiter, no significant non linear effect are visible.

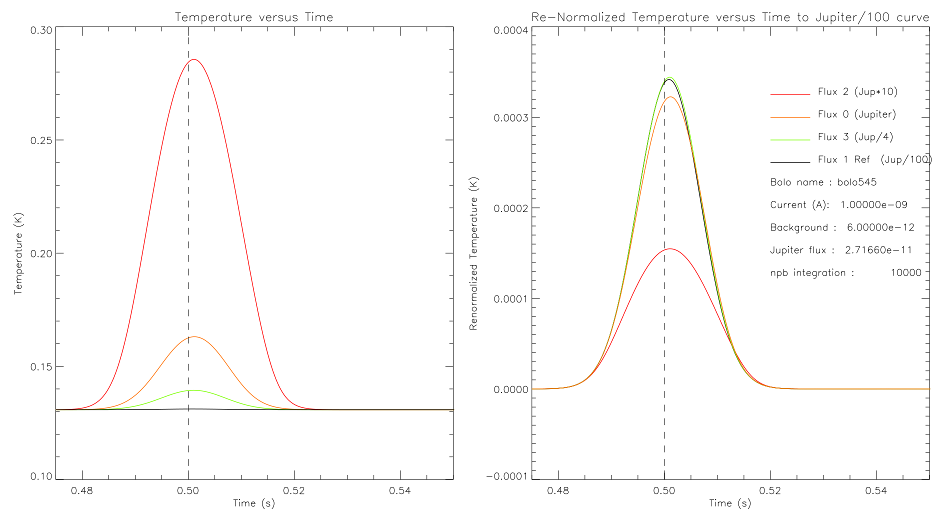

Figure 3: Simulation of response of one bolometer of HFI Planck operating in a spectral window centered at 545 GHz to a incoming flux in the range of Jupiter. Polarization current is 1 nA. The dynamical non linear behavior is clearly visible, by comparison to the previous case (where a faster bolometer is used).

6 Conclusion

A dynamical direct model for HFI bolometers is mandatory to provide realistic end to end simulations for Planck mission, not only for GBT but also for accurate

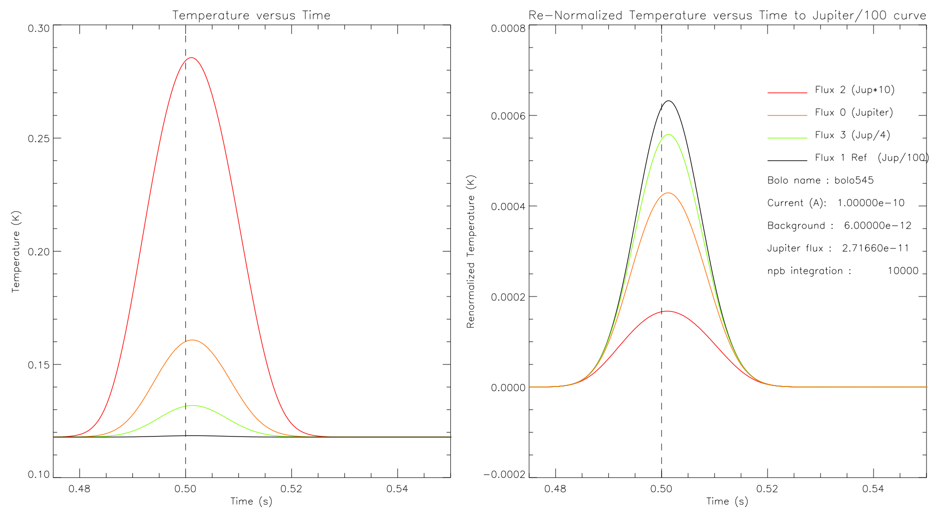

Figure 4: Simulation of response of one bolometer of HFI Planck operating in a spectral window centered at 545 GHz to a incoming flux in the range of Jupiter. Polarization current is this time 0.1 nA. The dynamical non linear behavior is also clearly visible, by comparison to the first two cases.

reconstruction of the real incoming sky during scientific observations. This model is non linear but we confirm that non linear effects should remain very limited for the brightest sources to be observed by Planck HFI, like planets Jupiter or Mars.

A simple correction method was also derived form the direct model. Up to now, this approach is stable even in presence of glitches and noise, and is simple and quick.

It should be noticed also that we know all the mandatory parameters for the direct model for most of the bolometers. Future GBT will give the opportunity to compare experimental data and simulations. Using this simple direct model and with simple tests, we should be able to check whether all work at the expect working point during GBT or flight. Using the correction model during GBT, we should be able to exhibit simply and quickly any depart between observations and this model.

Another major step is to plug after the output of the direct model the model for the readout electronic (RAU), including in-flight integration and integrator non linearities. Then we will be very close to real measurements and realistic inversion approaches can start, including glitches removing and correction around the beam shape.

References

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Woodcraft, A. L., Sudiwala, R. V., Ade, P. A. R., Griffin, M. J., Wakui, E., Bhatia, R. S., Lange, A. E., Bock, J. J., Turner, A. D., Yun, M. H., and Beeman, J. W., 2003, Appl. Opt. 42, 5009