Wideband Noise Envelope-Transient Simulation in Radiometers operating with multiple time-scales

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Abstract: - A radiometer simulation procedure with special emphasis on high frequencies and switched system performance is discussed. The whole system simulation is implemented in Envelope-Transient, a combination of frequency domain and time domain, on the same software platform which is used to design separate microwave components, allowing the use of measured S parameters and measured current-voltage characteristics of the detectors. 1/f gain fluctuations are introduced in the simulations and switched differential operation is implemented and validated as a way to minimize their impact. Low frequencies are scaled-up to allow the simulator a reasonable CPU time and memory handling without losing generality. Coupling between a base-band equivalent solution and a complete mm-wave solution is provided by the proposed simulation, providing a step beyond typical separate analysis of RF parts and base-band equivalent in this kind of systems.

Key-Words: - Radiometers, Envelope-Transient, 1/f noise, wideband circuits and systems

1 Introduction

Radiometers employ RF and microwave technology extensively to provide remote sensing data like content of the soil, salinity of the oceans and astronomical data for scientific models of the universe. The level of signals received by radiometers (basically broadband noise) is extremely low, which makes low noise operation and stability of the radiometric system basic requirements which must be properly simulated.

1.1 30 GHz PLANCK radiometer

Simulation procedures for radiometers will be presented, with application to the 30 GHz Planck Mission radiometer. There are different types of radiometers for radio-astronomy which respond to a common principle of operation [1]. The basic one is called total power radiometer and most other types are variations of it to improve some features. This work focuses on the referred 30 GHz radiometers of the Planck Mission, which is a mission of the European Space Agency (ESA) Science Program [2], to perform astronomical investigations in the sub millimeter and millimeter wave range. The mission will produce calibrated maps of the whole sky with high sensitivity. Planck mission will characterize small fluctuations in the Cosmic Microwave Background by mapping its anisotropies. The Planck Low Frequency Instrument (LFI) receiver is a form of differential radiometer that minimizes 1/f noise due to low frequency gain and noise fluctuations.

The Planck 30 GHz radiometers consist of Front End Modules (FEM) formed by cryogenic amplifiers cooled at 20 K and Back End Modules (BEM) with amplifiers, filters and detectors at room temperature (300 K) (figure 1).

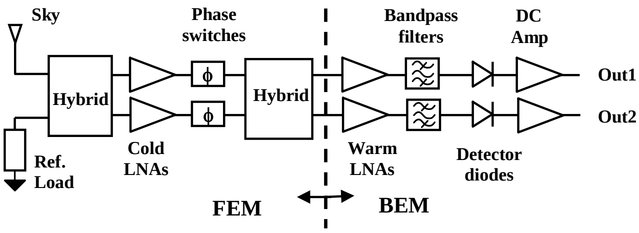


Fig. 1. Block diagram of a Planck radiometer

The radiometers operate as direct detectors in which the signal is first sufficiently amplified in the band of interest, band-pass filtered with 20% effective bandwidth (around 6 GHz), not -3 dB bandwidth, and then detected with a diode. Stability of the amplification chain (in gain and noise temperature) is desired. Differential operation is required for a good suppression of systematic errors. Also BEM amplifiers behavior in terms of 1/f noise is important for this suppression. One input is connected to a 4 K reference load; the other input comes from a feed horn receiving the sky signal (2.7 K). The hybrid couplers act as a divider and a combiner respectively, in a balanced structure containing two branches with low noise amplifiers and switching phase shifters (180 degrees difference in both states). The output signals in the second hybrid are separated into a sky signal and a reference load signal. The use of hybrids leads to have the same noise contribution in both signals. Each time the phase shifter switches, the sky signal and the reference load signal change their position at the second hybrid outputs. Each BEM branch can provide an independent set of measurement data subtracting successive measurements of each detector output in different phase states. In such case the suppression of 1/f noise due to gain fluctuations in the Back End amplifiers and detectors is expected to be the best possible. Expected values of equivalent noise temperature of the radiometer cryogenic Front End Module (FEM) are around 12 or 15 K, above measured signal. Only after a complex statistical data processing based on repetitive measurements it is possible to extract valuable data from these measurements. For the stability of the measure, gain and noise level must be almost constant during a whole cycle of the satellite sweeping the sky; therefore spin frequency of the satellite defines the upper bound of the acceptable system knee frequency. Analytical studies of the Planck system performance have been done [3] addressing all these requirements.

1.2 Radiometer Simulation

Radiometer simulation is a difficult task, specially compared to conventional communication system simulation due to:

- Radiometer signals (for example sky or cryogenic loads) are noise-like, compared with modulated carriers in communication systems
- Frequencies involved in radiometers cover a wide range, from required f-knee around mHz to microwave noise-like signals (up to tenths of GHz). In the case of communication systems there is a clear distinction between base band and band pass signals. Envelope-Transient simulation allows this broad range to be handled, once the carriers are specified. In our radiometric problem there is no such clearly defined carrier, but the centre frequency could be chosen. The bandwidth is too wide (6 GHz) to allow enough simulation time to reach the mHz range.
- Mathematical simulation tools [4] using different kinds of transforms not only Fourier but also Wavelets or multiple time scales are suitable for theoretical analysis, but they are neither prepared nor suitable for introducing parameters of the practical implementation (like S parameters, power compression, current voltage and non-linear capacitances, etc.).

Small signal frequency domain simulation is required to test gain, matching and balance between branches for each state of switching. Large signal harmonic balance allows evaluation of detector sensitivity in the conversion from RF to DC and gain compression of the amplifiers using single tone excitation. Both, small and large signal simulations are fundamental to test microwave performance. But simulation with single tones is different from real operation. Next it will be shown how Envelope-Transient tool can be used to perform more realistic simulations of radiometers. The models used in the simulations according to the type of simulation will be discussed. Then results obtained will be shown probing the principles of operation of the radiometer and the reliability and usefulness of the simulations, and setting the basis for further improvements in the simulation techniques of such systems.

2 Envelope-Transient Radiometer Simulations

The two inputs of the radiometer system are the sky signal (with a power level corresponding to sky temperature of 2.7 K) and the 4-K reference load, both of which are noise-like signals. To test switched differential operation with realistic noisy input signals, time domain simulation is required. In a pure transient simulation with maximum frequencies involved around 40 GHz (to include filter edges), the time step has to be very small. Simultaneously, a sufficiently long simulating time is required to reach the mHz range. It is not possible to handle both requirements with ordinary computers due to memory restrictions. The use of Envelope-Transient provides a noticeable improvement. Actually, there is no single carrier defined because high frequencies lie between 27 GHz and 33 GHz (with 20% of bandwidth around 30 GHz). A first reasonable attempt could be to choose 30 GHz as carrier, but 6 GHz is too wide a band around the carrier and the computer memory cannot handle a simulation time, which is long enough to reach the mHz range. These limitations do not mean that Envelope-Transient simulation of the radiometer becomes useless. Accurate quantitative and qualitative results may be obtained in the microwave range and qualitative results may be achieved for low frequency range.

Without a generic three-time-scale envelope tool available, priority has to be given to simulating one of the frequency bands. This can be done by defining a procedure for frequency scaling. Frequencies involved start almost at DC and reach values around 40 GHz. A linear compression would be a waste of valuable spectrum. Capability limitations of current

computers mean the real-time operation of a system is faster than its virtual simulation on a PC, even for the fastest CPU. According to this, classic frequency scaling divides the maximum frequencies, keeping the lowest unchanged [4]. However, in our approach to the system simulation, the main emphasis is the accurate emulation of the microwave parts. Therefore, the scaling method proposed here maintains high frequencies unchanged and only shifts the lower frequencies. This shifting has to be taken into account for the values of DC-low frequency filters. Another possibility is the re-definition of the time base, once simulated data are obtained, to a longer time of simulation with wider sampling time, but with the same number of points.
Transient simulation is considered to be as the closest to "the true behavior" of circuits and systems. Transient simulation of the radiometer has the highest computer cost. A portion of irrelevant bandwidth between a few MHz and ~25 GHz is analyzed consuming valuable memory. Therefore, unless transient simulations are also performed, it is preferable to use Envelope-Transient simulations. Irrelevant bandwidth is avoided this way and lower frequencies are reached, leaving memory available for longer simulations, but not long enough to decrease the simulated knee frequencies to real values. Envelope-Transient [5] is based on the expression of circuit/system signals in terms of a Fourier series with time-varying phasors of limited bandwidth (1).

$$x(t) = \sum_{K} X_K(t) e^{j\omega_K t} \qquad (1)$$

This simulation tool is especially well suited for modulated signals, start-up of oscillators, etc. In all cases there are one or several high frequency carriers (ω_K) and one or several time-varying low-frequency envelopes ($X_K(t)$). The high frequency components are analyzed with harmonic balance, providing results in the frequency domain, and the envelope phasors are analyzed in the time domain. Compared to conventional transient simulation the saving in time-steps is clear because sampling rate is fixed by the low frequency envelope, not by the high frequencies.
In the case of the millimeter wave radiometer under study there are two "virtual" carriers: 0 Hz and 30 GHz and a noisy wideband modulating envelope. As was explained, due to the high bandwidth (over 20%), the application of Envelope-Transient forces a still high sampling rate which limits the maximum time of simulation and therefore the minimum frequency. However, useful data are obtained from simulations, and can be processed in the same simulator or stored and processed in other applications which allow the modification of time scales to make results closer to real time scales (see example of time-frequency scales in figure 2).

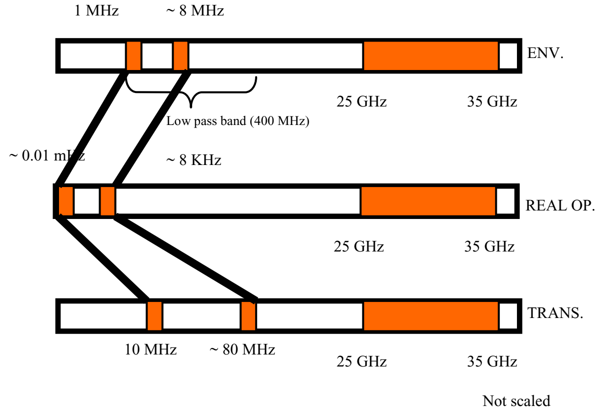


Fig. 2. Time-frequency scales in real operation (center bar), Envelope-Transient (upper bar) and Transient (lower bar).

The output bandwidth must be below the Envelope-Transient bandwidth (proportional to 1/Δt) and above the knee frequency range to allow a proper representation of the spectrum.
Models for transient simulation could be suitable for Envelope-Transient simulation. The only aspect which must be adjusted moving from transient to Envelope-Transient is the shape of the system low pass filters (1/f noise generation and in the output of the system after detection). A detailed description of models for these simulations is presented in [6]. As an example, in figure 3 it is shown an amplifier model including input thermal noise and 1/f fluctuating gain.

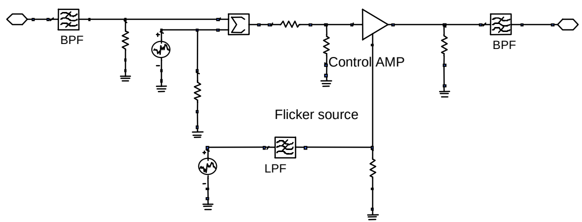
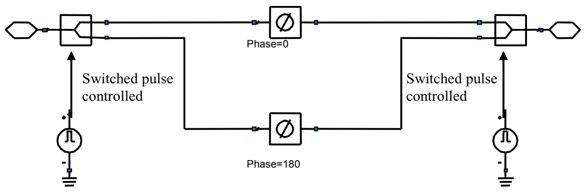


Fig.3. Amplifier model for the FEM.

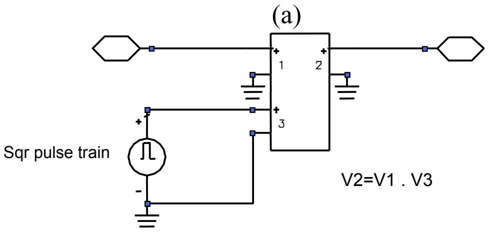
Other elements relevant to be properly modelled are the phase-switches. In figure 4 two alternatives are proposed. The second (b) is a mathematical block which multiplies the input signal by a pulsed signal (switching between –1 and +1) providing the phase change (0-180).
There are different possibilities to combine the outputs of the radiometer, but the final goal is the same, to make a comparison between sky and reference signal by cancelling the difference with a correction factor (usually designed "r"), which contains the information. The expression of the gain modulation factor is given by (2).

$$r = \frac{T_{sky} + T_n}{T_{load} + T_n} \qquad (2)$$

where Tsky is the sky noise temperature, Tload is the reference load temperature and Tn is the system noise temperature. The r-factor will be adjusted periodically; therefore stability of the system is required.



(a)



(b)

Fig. 4. Models for phase switch: Two-path switched structure (a) and multiplier structure (b).

It is possible to compare both outputs in the same phase switch state, only one output in consecutive phase switch states and even to take a difference between both channels, but taking differences of consecutive phase switch states (a kind of "difference of differences").

Output signal of the radiometer has been analyzed in switched operation. Two kinds of spectra have been obtained: a raw spectrum and a processed spectrum. In the raw spectrum data from each output of the system at different phase switch states have been integrated. In the processed spectrum, data have been averaged in each phase switch state and then differences calculated between consecutives states. These last results have been Fourier-transformed.

2.1 Special cases of simulations: switching frequency and gain fluctuations

In the simulation, depending on the level of the noisy signals and the shape of the low pass filters used in the 1/f generation, gain fluctuation is controlled in amplitude and speed.

A minimum post-detection bandwidth is required to ensure that both phase-switch states are clearly distinguished at the output, therefore several harmonics of the switching signal must pass the output filter. Commutation of the phase switches may take place in two ways: switching both branches to a fixed frequency (ie.: 4 KHz) or leaving a fixed phase in one branch and switching the other with double the frequency (8 KHz). In both cases sky and reference signals alternate at the outputs. If a switching frequency of 8 KHz is considered, a well defined square-wave would require at least five harmonics (40 KHz). Therefore a simulation must be defined to check if the post-detection bandwidth is enough to fulfill the bandwidth condition. In these simulations the Envelope-Transient becomes quite useful, because magnitude of the fundamental tone can be plotted versus time and superimposed with the switching signal and output signal. But here the limitations in maximum time (minimum frequency) arise, which force us to simulate not with real frequencies (KHz) but with higher frequencies (MHz). One possibility is to introduce pulsed RF in one input and check the DC output without switching. Figure 5 shows the magnitude of the fundamental tone versus time at the input of the radiometer and at the input of the detector (RF) and superimposed with the output signal (DC).

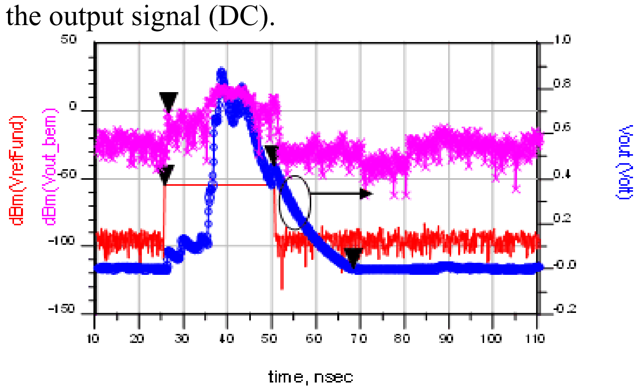


Fig. 5. Magnitude of the fundamental tone at the input of the radiometer (line) and at the input of the RF detector (x) and superimposed with output signal (circles), all versus time.

The estimation of "fknee" from simulations is easy due to the possibility of performing two different analyses: one with gain fluctuations "off" and the other with gain fluctuations "on". The value of fknee is estimated by integrating the raw output spectrum of the second simulation as far from the DC as possible (but below the roll-off of the post detection bandwidth) up to the frequency at which power is twice the power corresponding to the first simulation (white noise sources). In figure 6 the raw spectrum of one output for the two cases is superimposed: only thermal noise and thermal noise plus gain-noise fluctuations. The flat line represents the numerically averaged in-band thermal noise power density. The value of fknee is numerically estimated to be 83 MHz for this case.

Gain-noise fluctuations have been measured and simulated for BEM alone without phase switching, to adjust the levels of fluctuations supposing a 290 K matched load at the input. Both spectra must be compared taking into account low frequency shift of simulations (figure 7 and 8).

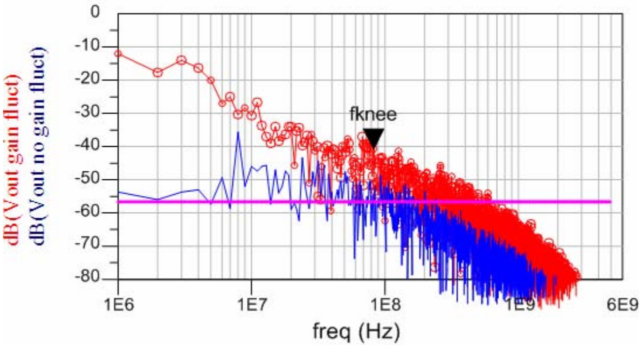


Fig. 6 Raw spectrum of one output for several cases: thermal noise only and gain-noise fluctuations. Flat line: averaged in-band thermal noise power density. fknee is numerically estimated to be 83 MHz.

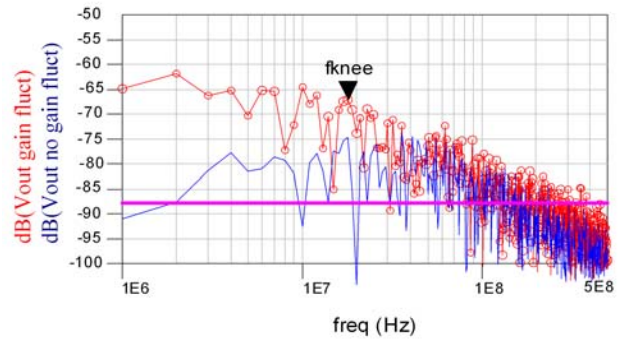


Fig. 7: Simulated BEM output spectrum without gain-noise fluctuations and with gain-noise fluctuations included (circles). Horizontal line is the average in band white noise level.

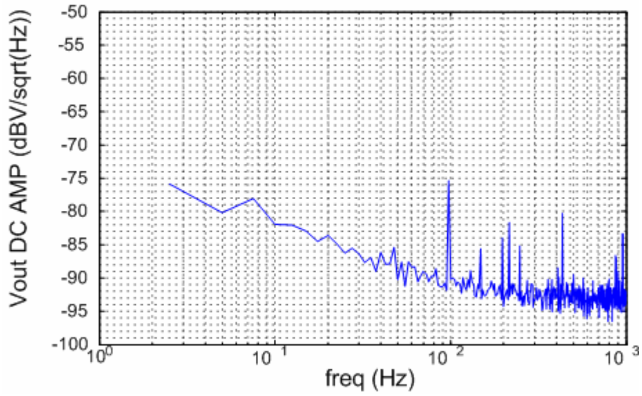


Fig. 8: Measured BEM output spectrum.

Faster and slower gain controlling signals were used, and different switching frequencies were compared in terms of output signal spectrum. As could be expected, simulations of differential system operation performance show that differencing both outputs decreases fknee, compared to differencing consecutive states in the same output. This can be explained as, in the first case, compared sky and ref signal flow simultaneously through the system (same gain), but in the second case, compared signals flow in consecutive moments (possibly different gain). Another result is that the minimum fknee corresponds to differencing both outputs with fast switching frequency and slow gain fluctuation. This can be explained considering that in this case, switching happens without giving the gain time to vary.

3 Conclusion

Envelope-Transient has been proposed and tested to emulate the behavior of a differential radiometer (Planck 30 GHz) on a standard RF simulation tool. Procedures have been proposed to overcome limitations in built-in models of elements, spectrum coverage and in memory use obtaining quantitative and qualitative results.

Acknowledgments

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