Matched filtering for EASIER data

Abstract

We introduce in this note the method of matched filtering to EASIER data.

1 Introduction

The current signal search for EASIER event is based on a peak detection. To be considered as an event, a peak also needs to arrive in coincidence with the trigger given by the particle signal and above a fixed threshold. It is robust but it is not the best technique for the search of small signals. We study in this note the improvement of the signal to noise ratio when a matched filter is applied to the radio trace.
In the first section we present briefly the detector simulations needed to test the effect of the filters. Then we study quantitatively the improvement in sensitivity with mock signals. Finally, we apply these methods to realistic simulation data.

2 Signal simulation

In this section, we describe briefly the detector simulation. More details on this study can be found in a separated note [1]. Here, we only deal with the detector simulation, we assume that we know the power received (the signal after the antenna).

2.1 Detector simulation

The skeleton of an EASIER detector is the same for all the versions :EASIER/GIGADuck C-band, GIGADuck Helix. It is composed of an antenna, an amplification stage, a power detection, an adaptation stage and finally the SD FADC. To simulate a realistic radio trace we simulate these stages one by one. We first simulate an RF (radio frequency) waveform according to the receiver's bandwidth. This RF waveform is then processed by the power detector and the board response. Finally we sample this waveform in time and amplitude to obtain a trace we can compare to actual data. We sum up here the methods used to simulate these parts:

- **antenna + LNA:** The antenna and LNA (or LNB) association is the RF (radio frequency) part, it sets the bandwidth of the receiver. The spectrum of the association antenna+LNA(or LNB) was measured for all the detector types and are shown in the figure 1. From the spectrum and an random phase, a RF waveform is generated by inverse FFT. The amplitude of the waveform is set according to the system noise temperature.

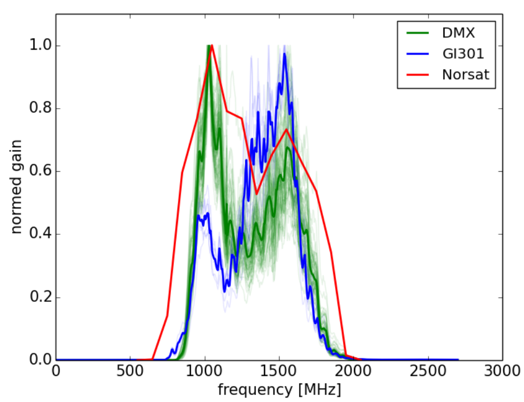

Figure 1 gain spectra for the three types of LNB in the C-band.

- **power detection:** the power detector output is simulated by a convolution of an exponential decay function and the RF waveform in dBm unit. The parameters of the exponential function were deduced from lab measurements. In the figure 2 (left) we show an example of the measured RF waveform (top), the power detector response (measured in blue and simulated in red) and the difference for this particular waveform (bottom). The difference between measured and simulated for a set of waveforms is shown in the figure 2 (right) for a power detector with capacitor (in green) and without (in blue).

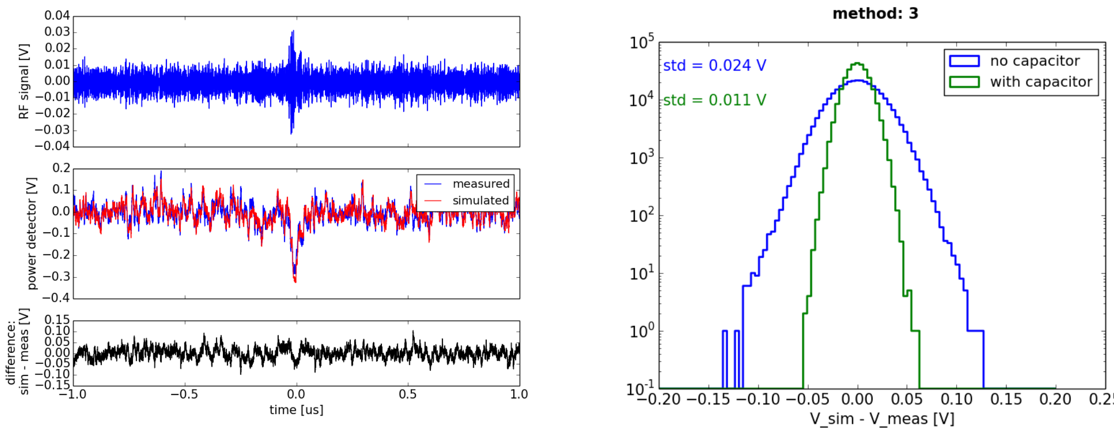

Figure 2 power detector simulation. left: superposition of measured and simulated. right: distribution of the difference measured-simulated.

- **adaptation stage:** this stage amplifies the power detector output in order to adjust the dynamic range. The stage is simulated with the transfer function measured in lab. The gain as a function of the frequency for this amplifier is shown in the figure 3 (left) and an example of simulation in the figure 3 (right)

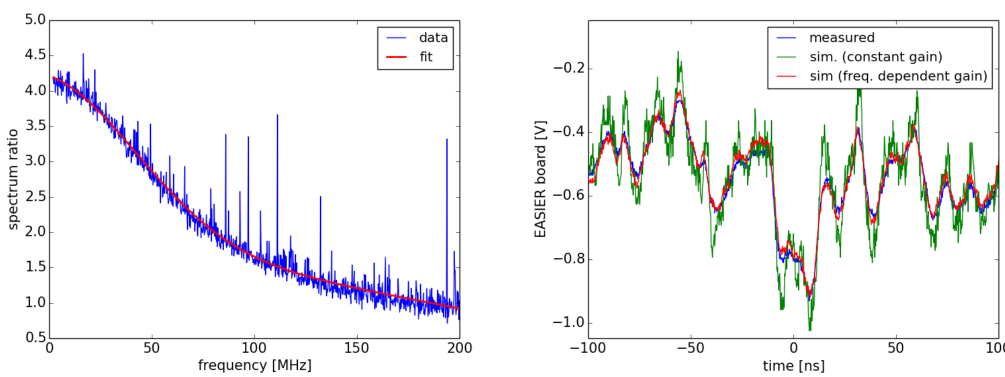

Figure 3 left: the board transfer function. right: example of board simulation, in green the board is simulated with a constant gain (simple linear relation between the power detector and the board.), in red it is simulated using the measured transfer function.

- **SD FADC:** The input of the Auger SD front end has anti aliasing filter. It is simulated with a 4^{th} order low pass filter with a cut frequency of 20 MHz. The signal is then sampled in time at 40MSamples/s and in amplitude over 1024 ADC counts on 1V.

The comparison of the simulation with data is shown in the figure 4. It shows the distribution in ADC counts of the measured and simulated traces (after baseline subtraction). In the simulation described above, we haven't mentioned the system noise temperature or the absolute gain of the system. In fact these parameters will only change the value of the average baseline, they won't change the RMS.

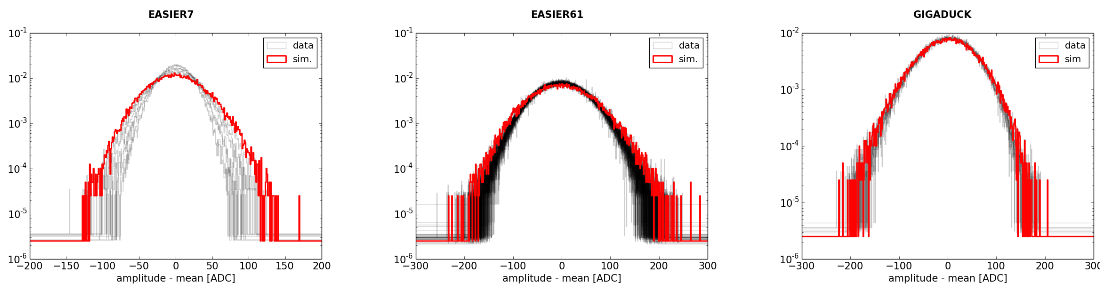

Figure 4 comparison of the measured distribution of amplitude and the simulated one.

2.2 Signal simulation

The RF noise is simulated according to the spectra of the figure 1 and the absolute noise level is given by:

$$\mathrm{P_{noise}} = \mathrm{k_B T_{sys}} \Delta\nu \tag{1}$$

where $\Delta\nu$ is the bandwidth (i.e. the normalized integrated power cf [1]).
The signal is generated with a power envelope, an example of a gaussian envelope is presented in the fig 5 (left). To obtain a RF signal waveform we generate another normalized noise waveform and we multiply it by the amplitude envelope. The results is shown in the fig 5 (middle). When added to the noise, we obtain the waveform shown in the fig 5 (right).
This RF waveform is then processed according to the electronics simulation described before.

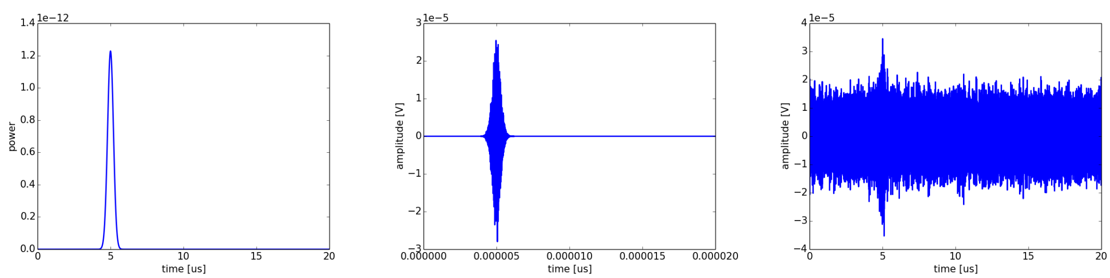

Figure 5 steps of the RF waveform simulation

2.3 Power estimate

We described the signal simulation in the previous paragraph. Now we are able to simulate a EASIER trace signal from a RF trace. We want to know if we can actually come back to the input power with the EASIER trace.
We produce a set of simulation with a Gaussian envelope as input signal with an SNR varying from 1 to 10 and the width from 10 ns to 500 ns. To estimate the power, we multiply the ADC waveform with the board and the power detector DC characteristics (that mean we don't account for any frequency dependence). This gives us the estimated power in dBm, so finally we convert this power in Watt. The output SNR is found by fitting the retrieved power trace, see for example the figure 6, and the comparison of input and output SNR is shown

in the figure 7. For very short signal (10ns), the output SNR is underestimated because of the filtering of the power detector, this is clear when comparing the results in the case we simulate the power detector with capacitor or without. The case with capacitor filters at lower frequencies and cuts more the short signals. For longer signal the output SNR is slightly overestimated by 10 to 15 %. I still don't understand the reason but the study presented in this note will compare methods to improve the SNR it is not critical to have a systematic bias.

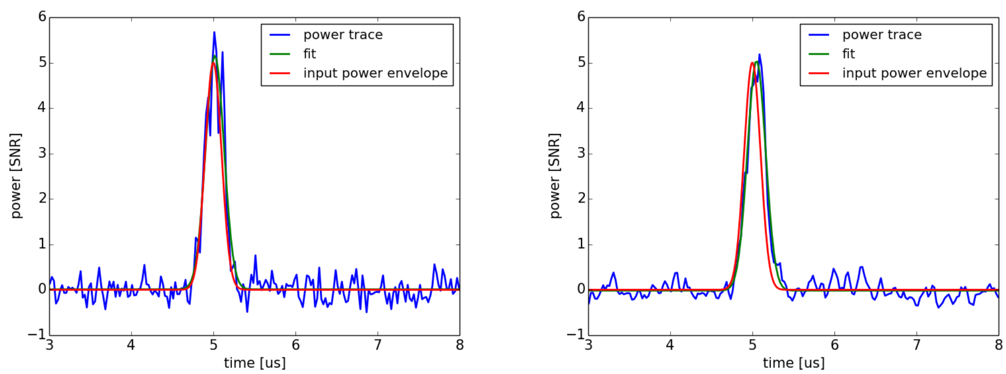

Figure 6 Output after detector simulation and back to power. In green the gaussian fit and in red the input. Left: for Norsat and no capacitor case. Right: for GI antenna and with capacitor case.

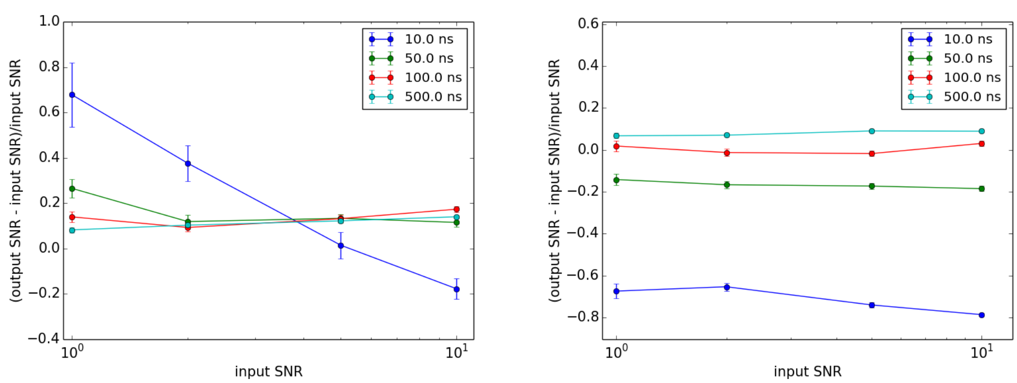

Figure 7 comparison of input and output SNR (after detector simulation and back to power). Left: for Norsat and no capacitor case. Right: for GI antenna and with capacitor case.

3 Signal to Noise Ratio improvement

3.1 Convention and previous method

The purpose of this section is to investigate signal processing methods to increase the detection capability.
In the following section we will only deal with SNR. We won't deal with the system noise temperature, at least not directly, because it is included in the SNR. All of the following study is done in a relative way, with no need to set the noise temperature or the gain. What we need to set is the antenna/LNB spectrum (the frequency bandwidth) and the electronics parameters (cf section 2).
The input SNR is defined as the ratio of the maximum of the signal power envelope over the system noise average (not its RMS). However after the detector, what we want to compare is the maximum signal with the fluctuation of the noise, so we will look at the waveform in unit of its fluctuation (we will plot the ratio of signal minus the average noise over the noise fluctuation). We define $\mathrm{SNR}_{\mathrm{det}}$ as the maximum power in unit of noise fluctuation.
To study the effect of filtering, we use input signals with Gaussian envelope. Examples of simulated traces are shown in the figure 8. The signal is clearly seen when the width of the gaussian is large enough, of a few hundreds of ns, and the SNR is of the order of the unity. If we decrease one of these parameters we start loosing the signal into the noise.
The method implemented in [2] was a simple peak search method. We would insure the background to be null by setting a high threshold (around 7 sigmas) and asking the maximum of the trace to be in a window of $4\,\mu$s. We can now compute the efficiency, that is to say the percentage of simulated event that would pass the criteria, with this method. Figure 9 shows the detection efficiency for such a peak search.

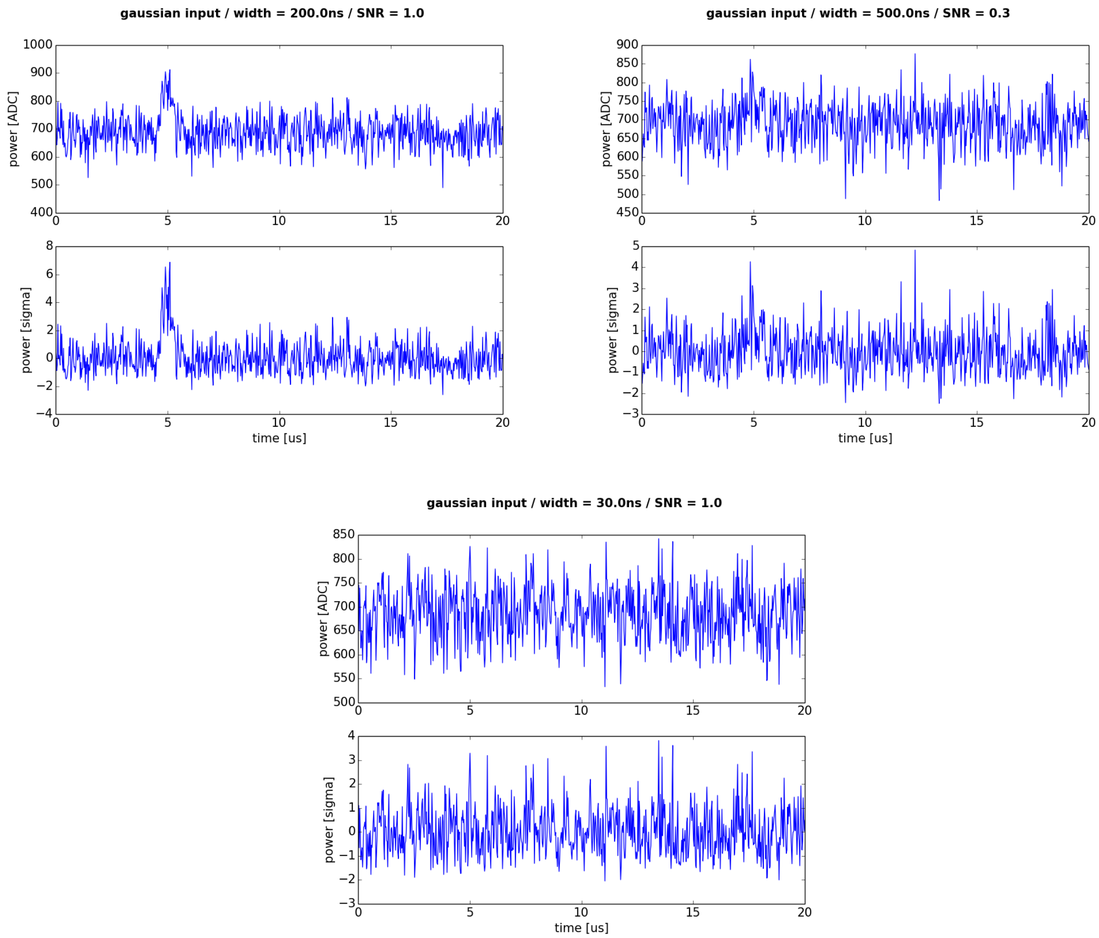

Figure 8 three example of simulated trace with on top of each figure the signal in ADC counts, and on the bottom the signal in sigma

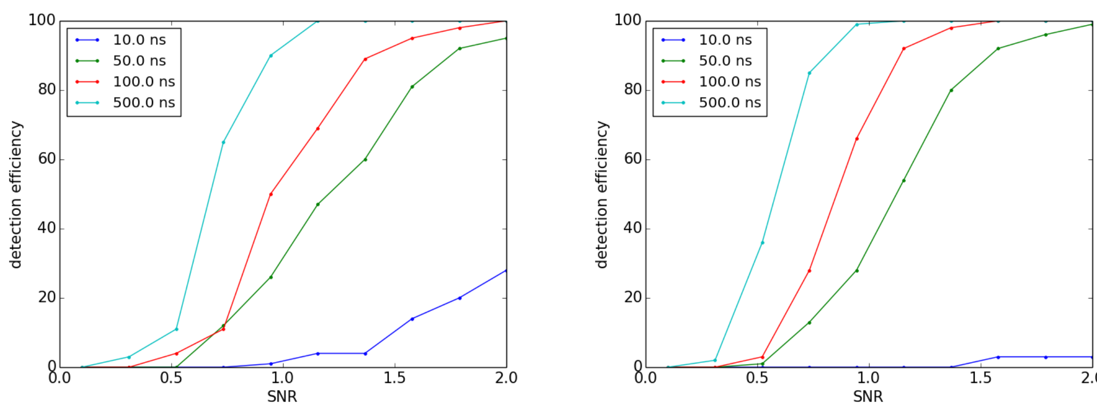

Figure 9 Detection efficiency with peak search (left: without capacitor, right: with capacitor)

3.2 Filtering

The point of filtering is to keep the signal and remove the noise. We have simulated trace with a large SNR and produced their spectrum in the figure 10. The shorter the signal , the flatter the spectrum. When the signal is too short the spectrum has no specific structure anymore so the filtering is useless. However, we see that for the longer signal we can filter out the high frequencies and keep only the signal part at low frequency.

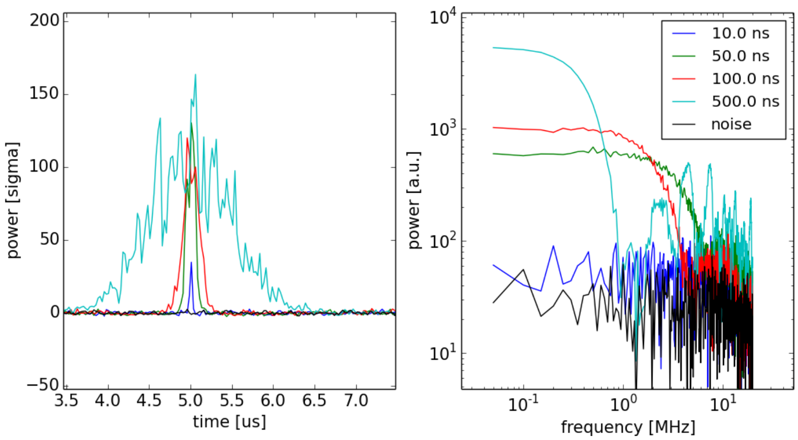

Figure 10 spectra for various width of input and a SNR of 20.

low pass filter One method is to filter at a given frequency. From the spectra shown in the figure 10 we see that for a 500 ns signal we would need to filter with a cut frequency around 1 MHz and for a 50 ns long signal a cut frequency of 10 MHz. We apply these filter to simulated traces, and then convert the trace in sigma units, some examples are shown in the figure 11. We can improve the signal to noise ratio $\mathrm{SNR}_{\mathrm{det}}$ when the correct filter (matching the signal...) is chosen: low cut frequency for long signals and high cut frequency for short signals.

matched filter The best way to find a known signal into a measured (noise + signal) waveform is to cross correlate the measured waveform with the expected signal itself. It is equivalent to filter it with the expected signal spectrum. (in principle you also want to weight your filter's coefficient with the noise spectrum but in our case the noise spectrum is really flat so the improvement won't be important). The matched filter is a very effective technique when the signal has a distinct signature in the frequency spectrum. In our case, the expected signals are rather simple, and the matched filter will look like a low pass filter. But by applying the matched filter we are sure to use the right filter, see for instance in the figure 12. We can now compute the detection efficiency, shown in the figure 13, using the same parameters than in section 3.1.

The largest improvement is obtained for long signals, 500 ns, for which we reach 100% efficiency for an input SNR of around 0.5 instead of 1 when no processing filter is applied. For shorter signals the improvement is clear especially when no capacitor is present after the

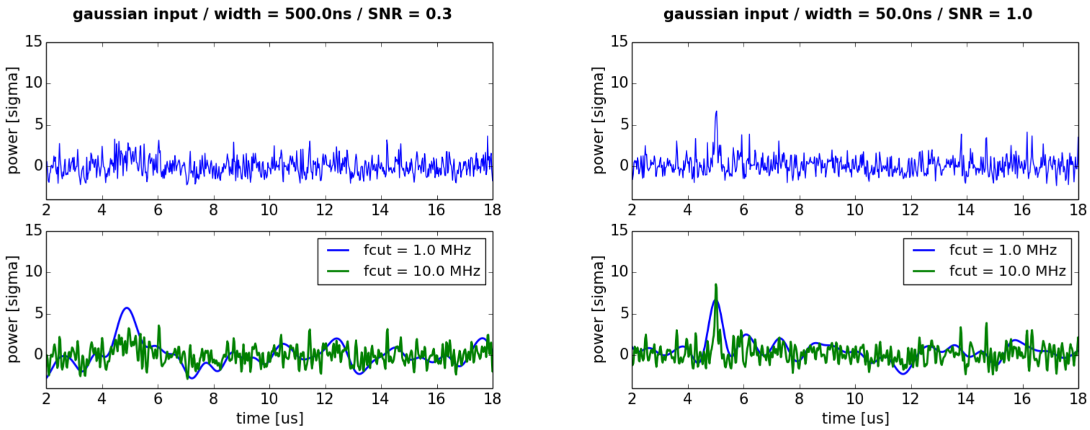

Figure 11 Examples of filtered trace with low pass filter. The best filter depends on the input signal.

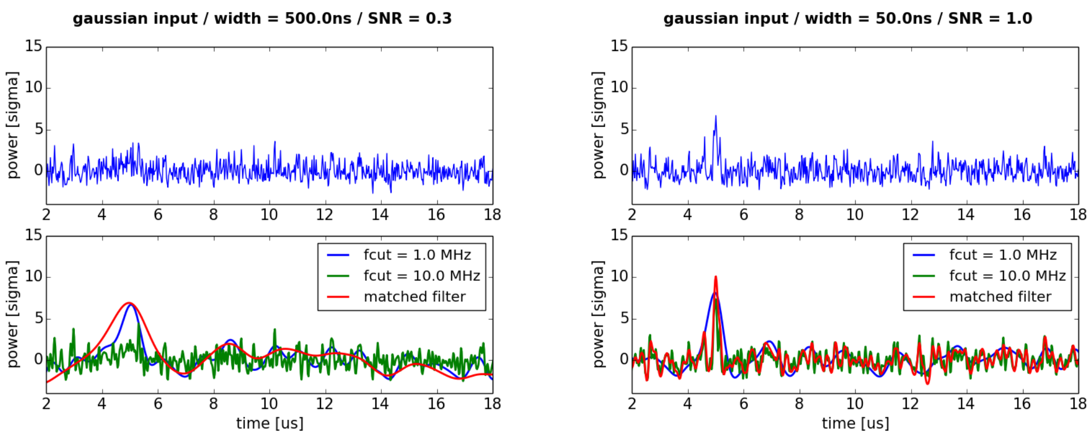

Figure 12 Examples of filtered trace with low pass filter and matched filter. In both cases the matched filter gives the best SNR_{det}

power detector (figure 13 left). When the capacitor is present, the signal is already filtered analogically and the numerical filter that we apply has less effect. 132

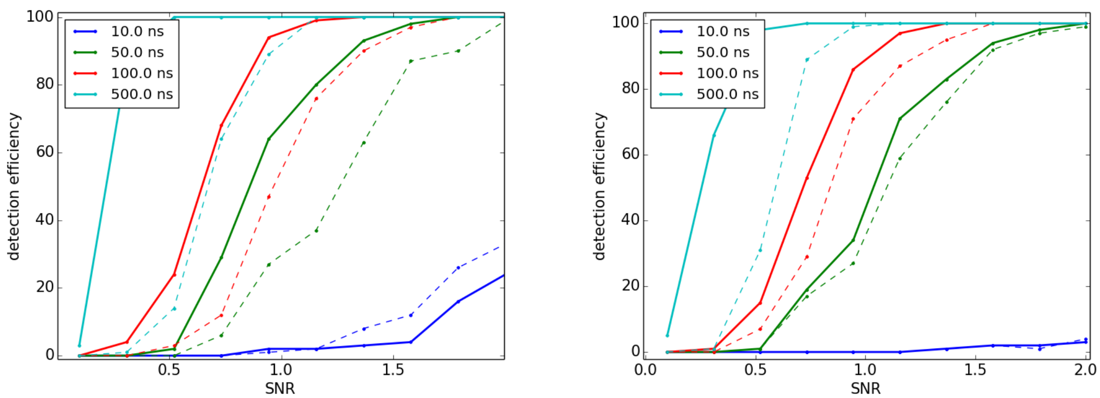

Figure 13 Detection efficiency after the matched filter processing in solid line. The dashed line represents the results found without filtering.

References

[1] R. Gaior, Detector simulation and validation with data. (https://atrium.in2p3.fr/nuxeo/nxdoc/default/3dafcfbd-e8ee-435b-91a0-b80c5cfff21f/view_documents).

[2] R. Gaior, thesis.