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# Noise analysis, noise reduction and covariance estimation for Time domain Spectroscopy

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**Abstract**—Time domain spectroscopy is now 30 year old and spread more and more along many fields of analytical sciences. The specificity of this technique reads in its name: measurements are not done in the frequency domain using a dispersive element, but in the time domain. One of the consequences is that the data processing is specific as well and shows both complexity and opportunities. In this conference, we will present a thorough noise analysis as well as a method to reduce it in order to take the full benefit of the dynamic range in the case of relatively strong signals.

## I. INTRODUCTION

Time domain spectroscopy (TDS) is now 30 years old and spread more and more along many fields of analytical sciences. The specificity of this technique reads in its name: measurements are not done in the frequency domain using a dispersive element, but in the time domain. One of the consequences is that the data processing is specific as well and shows both complexity and opportunities.

In this conference, we will discuss this data processing. First all data processing depends on the noise on the signal and we will analyze this noise. Second, we will propose a method to reduce this noise. Finally, as explained by [1], it is important to evaluate this noise to enable the estimation of the precision of the measurements in TDS and this is the focus of our last part.

## II. RESULTS

The datasheet of the TDS systems includes dynamic range data that compares the signal at the peak frequency to the noise at frequency where the system does not operate or when the THz beam is blocked [2]. This clearly helps make the difference from a first generation system with the new ones. However, it is not a clear figure on how reliable your measurements will be in presence of a relatively strong signal. To go further towards this direction, we propose a statistical approach in which the noise is defined as the standard deviation of the signal. We took the benefit of our system being able to record several time traces per seconds to record each time trace and extract the mean and standard deviation. We did it in four different configurations: (i) the laser did not eliminate any of the antenna; (ii) the laser illuminated the receiver; (iii) the laser illuminated the receiver and emitter but the beam was blocked; and finally (iv) in normal configuration with the full signal as plotted in figures 1 versus time and 2 versus frequency.

The major conclusion when comparing these noises is that most of the noise in the absence of the THz signal comes from the receiver noise and corresponds to the well-known dynamic range limitation.

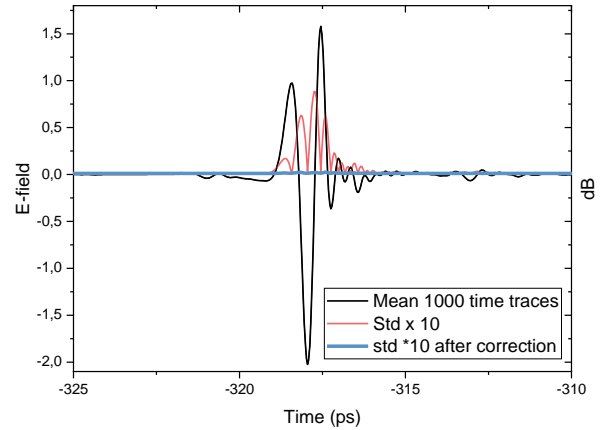


Figure 1 : Mean and standard deviation of 1000 time traces before and after correction in the time domain.

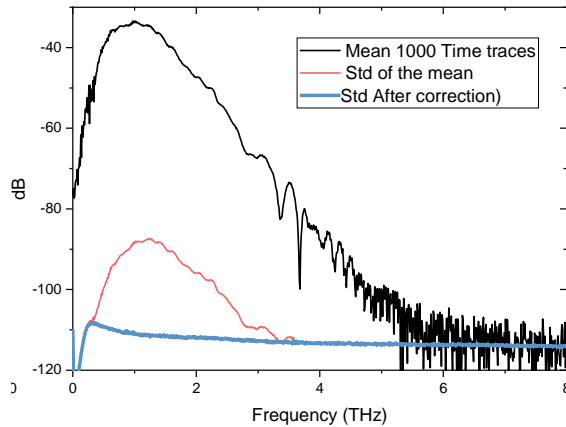


Figure 2 : Mean and standard deviation of 1000 time traces before and after correction in the frequency domain.

We further analyse the noise proportional to the derivative of the signal and figured out that the time traces were slightly time shifted ( $\sim 10$ fs) mostly due to a thermal drift in the optical fibers caring the laser pulses. We developed a method and software `correct@tds` to correct this shift. Since the shift is smaller than a time step, a simple correlation is not enough. We use an optimization algorithm where the time shift ( $dt$ ) is implemented by multiplying the Fourier transform by  $e^{i\omega dt}$ . The algorithm chooses one different  $dt$  per time trace with the goal to synchronize all the time trace to a single one. After this operation, we reduce the noise by about a factor 100 as shown on figure 1 & 2.

Finally, it is important to know that a quantitative evaluation of the noise is indispensable if one wants to get uncertainties when fitting data, again as explained in [1]. More precisely, the figure of merit of a fit includes the multiplication of the residue vector by the precision matrix. This precision matrix is

simply the inverse of the covariance matrix of the signal. However, these two matrices would need much more accumulated time traces than the number of points in a time trace, which is barely possible in many cases. Thankfully, TDS is not the first signal recorded in this situation and several algorithms exist to infer both the covariance and precision matrix. We implemented several of these methods based on matrix shrinkage and sparse inversion in `correct@tds` and now provides both matrix estimation as output of the software.

#### CONCLUSION

TDS is now a mature system spreading in several fields of analytical sciences. To expand its use, it is important to provide the user with not only comprehensive information, as done in several analytical tools [3-5], but also the corresponding uncertainties. To achieve this goal, we performed a thorough analysis of the noise in the TDS traces and proposed a method and software to remove the one link to the drift of the delay line. Additionally, we offer the possibility to infer both the covariance and precision matrix from the data. In the future, it will allow the fitting software to implement uncertainties calculation and fulfil the community needs.

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