



HAL
open science

Noise sources, data process and uncertainties in terahertz time domain spectroscopy

Jeyan Bichon, Nouredin Osseiran, Jean-Francois Lampin, Romain Peretti

► To cite this version:

Jeyan Bichon, Nouredin Osseiran, Jean-Francois Lampin, Romain Peretti. Noise sources, data process and uncertainties in terahertz time domain spectroscopy. 12th International Symposium on Terahertz-Related Devices and Technologies: TeraTech 2025, Jun 2025, Salamanque, Spain. ⟨hal-05160933⟩

HAL Id: hal-05160933

<https://hal.science/hal-05160933v1>

Submitted on 14 Jul 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

Noise sources, data process and uncertainties in terahertz time domain spectroscopy

Jeyan Bichon¹, Nouredin Osseiran¹, Jean François Lampin¹,
Romain Peretti^{1,2}

¹Univ. Lille, CNRS, Univ. Polytechnique Hauts-de-France,
UMR 8520 IEMN - Institut d'Electronique de Microélectronique et de Nanotechnologie, F-59000 Lille,
France

²CNRS, INSA Lyon, Ecole Centrale de Lyon, Université Claude Bernard Lyon 1, CPE Lyon, INL,
UMR5270, CP et Ville de l'établissement dans lequel le chercheur est installé, France
E-mail: romain.peretti@cnrs.fr

Abstract: The first terahertz time domain spectroscopy (THz-TDS) experiments are now well-established, and fully autonomous systems have been commercially available for over a decade. This has led to the increasing adoption of THz-TDS by research groups outside the core THz community, as well as by industrial actors. With this broader use, the need for more standardized experimental and data processing methods has become crucial, exemplified by the publication of standards for specifying THz-TDS systems. THz-TDS uniquely performs measurements in the time domain, while the information of interest often resides in the frequency domain. This necessitates a minimum level of data processing, typically starting with a fast Fourier transform. Various strategies exist to extract the desired information, and the field continues to evolve rapidly, lacking a definitive standard. In this conference, we will briefly discuss the different sources of noise and uncertainties in a THz-TDS setup, followed by a review of proposed methodologies for extracting information from time traces, and finally, a discussion on obtaining better insight into the uncertainties of the retrieved information.

Keywords – terahertz time-domain spectroscopy, data processing, noise, uncertainties, standardization

I. INTRODUCTION

The first terahertz time domain spectroscopy (THz-TDS) experiments are now in their forties [1, 2, 3, 4] and fully autonomous systems have been commercially available for more than a decade. The spread of this technique has begun, with research groups outside the traditional terahertz community, as well as industrial actors, now utilizing THz-TDS setups.

With this increasing adoption, the need for more standardized experimental and data processing methods has grown. This is evidenced by the publication of standards defining the characteristics and measurement methods for THz-TDS systems [5].

Still, THz-TDS has the distinct characteristic of performing measurements in the time domain, while in most cases, the information of interest lies in the frequency domain. The direct consequence is the intrinsic necessity of a minimum of data processing, primarily starting with the application of a fast Fourier transform on the recorded time traces. From this point, different strategies are employed to access the information of interest. However, the field continues to evolve quite rapidly, and a universal standard is still lacking.

In this conference, we will briefly discuss the different sources of noise and uncertainties in a THz-TDS setup, followed by a review of the proposed methodologies to extract information from the time traces, and finally, a discussion on how to gain better insight into the uncertainties of the retrieved information.

II. Sources of uncertainties in THz-TDS systems

In line with the general definition by Tuzlukov [6], we choose here to consider noise as any unwanted modification that the signal undergoes during capture, storage, transmission, processing, or conversion. This encompasses: Artifact-noise (misleading disturbances from the experiments); deterministic noise (any non-signal feature having a consistent and repeatable behavior; for instance, artifact noise or any non-zero average part of any noise); and correlated or nonwhite noises.

Noise analysis in THz-TDS has been performed from the beginning of the technique [7]. To analyze the sources of noise we recorded numerous consecutive single time traces in different configuration [8, 9]. We conclude that the main source of standard deviation while averaging the time traces including the signal was linked to an artifact noise: small delay between consecutively recorded time traces (on the order of ~10 fs) we attributed to a variation of temperature in the optical fiber bringing the laser signal to the antennas. To address this, we implemented a resynchronization feature in our software, Correct@TDS, to correct this shift and remove this significant source of uncertainties. Another important source of noise, again an

artifact, was a low-frequency component present in the recording even when the THz beam was properly blocked. We attributed this contribution to parasitic radiation and mitigated it by applying a 200 GHz high-pass filter during data processing.

The remaining noise component was primarily white noise originating from both the amplifier and the receiving antenna, superimposed with a periodic sampling error [10]. This periodic sampling error was also corrected using Correct@TDS.

This thorough analysis was performed on a fiber-coupled system, and other sources of noise may or may not be present in different systems and families of systems. Nevertheless, we want to emphasize that in THz-TDS, uncertainties can arise from the laser source, the emitter and detector antennas, the delay line precision, and the data acquisition electronics. Understanding and mitigating these noise sources is crucial for improving the reliability and reproducibility of THz-TDS measurements.

III. Extraction of the information

Once the reference and sample time traces are recorded, several methodologies are employed to extract meaningful information about the studied material or metamaterial. Traditionally, the initial step involves computing the complex transmittance \tilde{T} by taking the ratio of the Fourier Transforms (FFT) of the sample and reference pulses, ensuring that the necessary requirements for FFT are met [11]. This can then be used to retrieve the complex refractive index of the material \tilde{n} as a function of frequency by solving an inverse problem that typically incorporates a photonic model accounting for the sample's thickness and refractive index:

$$\arg(\tilde{T}(\omega)) = \arg\left(\frac{4\tilde{n}(\omega)}{(\tilde{n}(\omega)+1)^2}\right) - \frac{\omega d}{c}(\tilde{n}(\omega) - 1) + \arg(\tilde{F}\tilde{P}(\omega)), (1)$$

Where $\tilde{F}\tilde{P}$ is the frequency domain function depicting the Fabry P erot effect [8].

The historical process to retrieve $\tilde{n}(\omega)$ from this equation is to neglect the $\tilde{F}\tilde{P}$ and the interfaces terms to get a first value and then insert this value in the equation and iterate the process [12]. This gives satisfactory results most of the time but this equation still does not have a single solution for $\tilde{n}(\omega)$. Therefore, a combination of this approach together with a minimization [13] has been used. Still this approach does not fulfil the Kramers-Kronig equations and an additional step has been proposed [14].

Following the extraction of the refractive index, a common practice is to fit these frequency-domain data with analytical dispersion models, such as the Drude-Lorentz model, to gain insight into the material's physical properties, like electronic or vibrational resonances. This allows for the determination of crucial parameters for material identification, which is vital in applications like drug quality control and anti-counterfeiting. Traditionally, parameter retrieval in the frequency domain has been achieved using optimization routines. However, this approach has limitations, particularly when the signal is noisy or when absorption peaks saturate the spectrum, and it can also involve complicated phase unwrapping issues and loss of phase information in cases of strong absorption.

To address these drawbacks, more recent approaches emphasize direct fitting of the time-domain data. Software like Fit@TDS implements this method, where a physical model (e.g., Drude-Lorentz for materials, time-domain coupled mode theory for metamaterials) is used to simulate the time-trace of the THz pulse after interacting with the sample. An optimization algorithm is then used to iteratively adjust the parameters of the physical model until the simulated time-trace closely matches the experimentally measured one [8].

One of the advantages of this approach is that the difference between the model and the measurands is expressed in the measurement domain. Therefore, one can normalize this discrepancy, serving as an objective function, by the noise [15, 16], following the good practice of information processing [8].

This methodology enables as well the derivation of a quantitative criterium for the comparison of two different models allowing to know which one is the most probable. For instance, when analyzing a α -lactose monohydrate pellet with Fit@TDS, incorporating noise considerations and advanced fitting routines, we found that the absorption peak around 1.3 THz likely corresponds to a doublet rather than a single line, consistent with DFT simulations [17]. This approach also allows for the implementation of super-resolution algorithms, capable of overcoming the Fourier transform limit and significantly improving the spectral resolution, as demonstrated with ammonia gas lines [18].

III. Uncertainties and information's, towards errors bars

Many research groups worldwide are exploring the use of THz-TDS in analytical fields. A critical requirement in these applications is not only the estimation of a result but also the precision of that result, often expressed as error bars. Uncertainties in THz-TDS measurements have been studied, revealing multiple sources and a complex

pattern [19]. However, there is a relative lack of propositions in the literature for the direct estimation of uncertainties on extracted parameters. In a Bayesian framework, a common approach to assess the uncertainties of parameters obtained from a fit is to relate them to the uncertainties in the measurements themselves. By combining the uncertainties estimation on the measurements we have developed [9], along with our fitting software Fit@TDS, we aim to provide error bars for the extracted material parameters. This methodology showed good results as far as the main source of discrepancy from the model to the signal came from the signal. On the spectral region where the signal to noise ratio is very good, the discrepancy comes from other sources specifically the approximation with the model (i.e. Gouy phase [20, 21], parallelism of the sample side ...), making the uncertainties' estimation over optimistic.

IV. CONCLUSIONS

Several efforts are underway to establish good practices, for example, in sample thickness determination [22] and, more recently, in recorded data format standardization [23], alongside improved analysis of system components [24]. These initiatives demonstrate the community's early recognition of these needs and ongoing efforts to achieve these standards.

We hope that these combined efforts will soon enable THz-TDS to reach its full potential in various analytical and industrial applications by providing reliable measurements with quantified uncertainties. The development of tools like Correct@TDS and Fit@TDS, which address noise reduction, signal estimation, and uncertainty quantification, represents a step towards this goal. We envision future work involving closer collaborations between the THz and signal processing communities to develop even more sophisticated data processing methods for the evolving landscape of THz-TDS technologies.

ACKNOWLEDGMENTS

This work was financially supported by THE ERC COG TUSCANY ERC-2022-COG GRANT AGREEMENT 101089040

REFERENCES

[1] G. Mourou, C. V. Stancampiano, and D. Blumenthal, "Picosecond microwave pulse generation," *Applied Physics Letters*, vol. 38, no. 6, pp. 470–472, 1981. [Online]. Available: <https://doi.org/10.1063/1.92407>

[2] D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting hertzian dipoles," *Applied Physics Letters*, vol. 45, no. 3, pp. 284–286, 1984. [Online]. Available: <https://doi.org/10.1063/1.95174>

[3] R. Sprik, I. Duling III, C.-C. Chi, and D. Grischkowsky, "Far infrared spectroscopy with subpicosecond electrical

pulses on transmission lines," *Applied physics letters*, vol. 51, no. 7, pp. 548–550, 1987.

[4] D. Grischkowsky, S. Keiding, M. Van Exter, and C. Fattinger, "Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors," *JOSA B*, vol. 7, no. 10, pp. 2006–2015, 1990.

[5] S. Becker, J. Beckmann, O. Cojocari, V. Feige, B. Fischer, F. Friederich, B. Globisch, G. Hechtfisher, K. Hens, H.-W. Hübers, J. Jelonnek, J. Jonuscheit, A. Keil, T. Kleine-Ostmann, M. Mayr, D. Nüßler, M. Peichl, O. Peters, J. Schür, T. Sprenger, A. Steiger, S. van Frank, N. Vieweg, and R. Wilk, "deuTerahertzsysteme - zeitbereichsspektrometer (tds-systeme)," Verein Deutscher Ingenieure, pp. 1–22. [Online]. Available: <https://www.vdi.de/5590>

[6] V. Tuzlukov, *Signal processing noise*. CRC Press, 2018.

[7] L. Duvillaret, F. Garet, and J.-L. Coutaz, "Noise analysis in thz time-domain spectroscopy and accuracy enhancement of optical constant determination," in *Optoelectronics' 99-Integrated Optoelectronic Devices*. International Society for Optics and Photonics, 1999, pp. 38–48.

[8] M. Lavancier, N. Vindas-Yassine, J. Vlieghe, T. Hannotte, J.-F. Lampin, F. Orieux, and R. Peretti, "A new metric for the comparison of permittivity models in terahertz time-domain spectroscopy," *IEEE Transactions on Terahertz Science and Technology*, pp. 1–10, 2024.

[9] E. Denakpo, T. Hannotte, N. Osseiran, F. Orieux, and R. Peretti, "Signal estimation and uncertainties extraction in terahertz time domain spectroscopy," *IEEE Transactions on Instrumentation and Measurement*, 2025.

[10] A. Rehn, D. Jahn, J. C. Balzer, and M. Koch, "Periodic sampling errors in terahertz time-domain measurements," *Opt. Express*, vol. 25, no. 6, pp. 6712–6724, 2017. [Online]. Available: <http://www.opticsexpress.org/abstract.cfm?URI=oe-25-6-6712>

[11] J. Xu, T. Yuan, S. Mickan, and X.-C. Zhang, "Limit of spectral resolution in terahertz time-domain spectroscopy," *Chinese Physics Letters*, vol. 20, no. 8, p. 1266, 2003.

[12] L. Duvillaret, F. Garet, and J.-L. Coutaz, "A reliable method for extraction of material parameters in terahertz time-domain spectroscopy," *IEEE Journal of selected topics in quantum electronics*, vol. 2, no. 3, pp. 739–746, 1996.

[13] O. S. Ahmed, M. A. Swillam, M. H. Bakr, and X. Li, "Efficient optimization approach for accurate parameter extraction with terahertz time-domain spectroscopy," *J. Lightwave Technol.*, vol. 28, no. 11, pp. 1685–1692, 2010. [Online]. Available: <http://jlt.osa.org/abstract.cfm?URI=jlt-28-11-1685>

[14] M. Bernier, F. Garet, J. L. Coutaz, H. Minamide, and A. Sato, "Accurate characterization of resonant samples in the terahertz regime through a technique combining time-domain spectroscopy and kramers-kronig analysis," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 3, pp. 442–450, 2016.

[15] L. Mohtashemi, P. Westlund, D. G. Sahota, G. B. Lea, I. Bushfield, P. Mousavi, and J. S. Dodge, "Maximum-likelihood parameter estimation in terahertz time-domain spectroscopy," *Opt. Express*, vol. 29, no. 4, pp. 4912–4926, 2021. [Online]. Available: <http://www.opticsexpress.org/abstract.cfm?URI=oe-29-4-4912>

[16] J. P. Loaiza, S. Higuera-Quintero, A. Noori, L. Mohtashemi, R. P. Hall, N. A. Yimam, and J. S. Dodge, "Thztools: data analysis software for terahertz time-domain spectroscopy," *Journal of Open Source Software*, vol. 9, no. 104, p. 7542, 2024. [Online]. Available: <https://doi.org/10.21105/joss.07542>

- [17] S. Mitryukovskiy, D. E. P. Vanpoucke, Y. Bai, T. Hannotte, M. Lavancier, D. Hourlier, G. Roos, and R. Peretti, "On the influence of water on thz vibrational spectral features of molecular crystals," *Phys. Chem. Chem. Phys.*, vol. 24, no. 10, pp. 6107–6125, 2022.
- [18] S. Eliet, A. Cuisset, F. Hindle, J.-F. Lampin, and R. Peretti, "Broadband super-resolution terahertz time-domain spectroscopy applied to gas analysis," *IEEE Transactions on Terahertz Science and Technology*, vol. 12, no. 1, pp. 75–80, 2021.
- [19] W. Withayachumnankul, B. M. Fischer, H. Lin, and D. Abbott, "Uncertainty in terahertz time-domain spectroscopy measurement," *J. Opt. Soc. Am. B*, vol. 25, no. 6, pp. 1059–1072, Jun 2008. [Online]. Available: <https://opg.optica.org/josab/abstract.cfm?URI=josab-25-6-1059>
- [20] P. Kužel, H. Nemeč, F. Kadlec, and C. Kadlec, "Gouy shift correction for highly accurate refractive index retrieval in time-domain terahertz spectroscopy," *Opt. Express*, vol. 18, no. 15, pp. 15338–15348, Jul 2010. [Online]. Available: <https://opg.optica.org/oe/abstract.cfm?URI=oe-18-15-15338>
- [21] P. Koleják, K. Postava, M. Micica, P. Kužel, F. Kadlec, and J. Pištora, "Experimental gouy phase shift compensation in terahertz time-domain spectroscopy," *Photonics and Nanostructures-Fundamentals and Applications*, vol. 31, pp. 129–133, 2018.
- [22] W. Withayachumnankul, B. M. Fischer, and D. Abbott, "Material thickness optimization for transmission-mode terahertz time-domain spectroscopy," *Opt. Express*, vol. 16, no. 10, pp. 7382–7396, 2008. [Online]. Available: <http://www.opticsexpress.org/abstract.cfm?URI=oe-16-10-7382>
- [23] J. Lee, C. K. Leung, M. Ma, J. Ward-Berry, S. Santitewagun, and J. A. Zeitler, "The dotthz project: A standard data format for terahertz time-domain data," vol. 44, no. 11, pp. 795–813.
- [24] T. Vogel and C. J. Saraceno, "Advanced data processing of thz-time domain spectroscopy data with sinusoidally moving delay lines," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 45, no. 11, pp. 967–983, 2024.