

Retrieving spatio-temporal distortions in ultrashort pulses from FROG traces

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For decades, ultrashort-pulse-measurement community has used an often oversimplified model for an ultrashort laser pulse, in which the space and time field dependences are assumed to be separable. In reality, coupling may occur between the electric field's space and time dependences, which is referred to as a spatio-temporal distortion. Two of the most common such distortions are spatial chirp (in which the average wavelength of the pulse varies spatially across the beam) and pulse-front tilt (in which the pulse intensity front is not perpendicular to the propagation direction). These distortions are very common in ultrafast optics because the generation, amplification, and manipulation of ultrashort pulses all involve the deliberate introduction (and hopefully the subsequent removal) of massive spatio-temporal distortions. Researchers have struggled to make resulting pulse 'clean' (free of such distortions), but minor misalignments are common in these operations, and as a result, ultrashort pulses are often contaminated with spatio-temporal distortions. Indeed, the broadband nature of ultrashort pulses makes them particularly vulnerable to these distortions.

Frequency-resolved optical gating (FROG) is one of the most popular and effective ways to measure the temporal evolution of the intensity and phase of ultrashort laser pulses [1]. It involves the generation of a spectrally resolved autocorrelation with a corresponding iterative phase-retrieval algorithm to retrieve the pulse intensity and phase. A new variation of FROG, called grating-eliminated no-nonsense observation of ultrafast laser-light e-fields (GRENOUILLE) [2], is known for its low cost, compact size, and user-friendly operation. We have recently shown that in addition to measuring temporal pulse characteristics, GRENOUILLE may also reveal spatial chirp and pulse-front tilt [3,4], without a single modification in its hardware. Specifically, spatial chirp causes a shear, and pulse-front tilt causes a delay shift to a FROG or GRENOUILLE trace, which is otherwise symmetrical with respect to delay. However, such intuitive descriptions are only valid for pulses having a simple form of spatial chirp, called frequency gradient. For more realistic pulses, which are usually contaminated with a type of spatial chirp, called spatial dispersion, the distortion to the FROG or GRENOUILLE trace is more complicated, which not only prevents one from retrieving spatio-temporal distortions in a simple manner, but also affects the accurate measurement of the pulse's temporal characteristics.

In this work, we establish a rigorous GRENOUILLE model with spatio-temporal distortions. Using this model, the GRENOUILLE trace of an arbitrary input spatio-temporal field can be calculated. We then demonstrate a new FROG retrieval algorithm, which is capable of accurately retrieving both the pulse temporal characteristics and spatio-temporal distortion parameters from the distorted GRENOUILLE trace. Such an

algorithm is a major modification of the current commercial FROG retrieval programs. The core of the algorithm must be completely rewritten to accommodate the effects imposed by input spatio-temporal distortions. Optimization is performed on both the temporal field and the spatio-temporal distortion parameters to achieve best results.

To test the performance of our new retrieval algorithm, we theoretically generated the GRENOUILLE trace of a fairly complicated pulse under spatial chirp, as shown in Figs. 1 and 2. The distortion to the GRENOUILLE trace was quite severe. With our new algorithm, we were able to retrieve both the temporal pulse form and the spatial chirp value very accurately, which corresponded to a reconstructed trace in perfect agreement with the input distorted trace.

In conclusion, we have developed a new ultrashort pulse electric field retrieval algorithm that retrieves not only the temporal evolution of the pulse, but also spatio-temporal distortion parameters of the input beam from the distorted GRENOUILLE trace. With this work, we now have a more complete view of an ultrashort pulse than ever—and with the simplest measurement device ever devised.

- [1] R. Trebino, Frequency-Resolved Optical Gating: the measurement of Ultrashort Laser Pulses (Kluwer Academic Publishers, Boston, 2002).
- [2] P. O'Shea, M. Kimmel, X. Gu, R. Trebino, "Highly simplified device for ultrashort-pulse measurement", Opt. Lett., **26**, 932 (2001).
- [3] S. Akturk, M. Kimmel, P. O'Shea, R. Trebino, "Measuring spatial chirp in ultrashort pulses using single-shot Frequency-Resolved Optical Gating " Opt. Express, **11**, 68 (2003).
- [4] S. Akturk, M. Kimmel, P. O'Shea, R. Trebino, "Measuring pulse-front tilt in ultrashort pulses using GRENOUILLE " Opt. Express, **11** 421 (2003).

Acknowledgement: This research is sponsored by National Science Foundation grant #ECS-0200223.

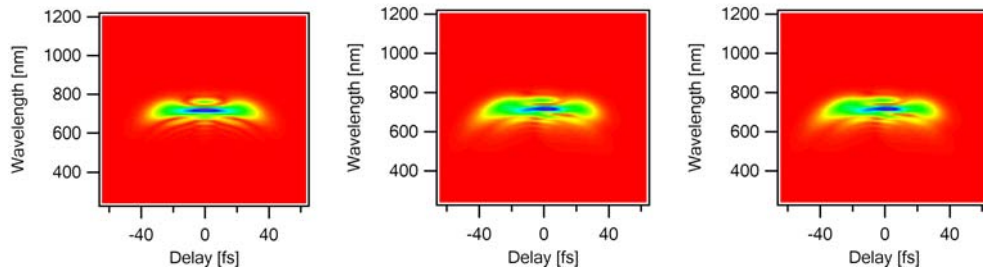


Fig.1. Left: GRENOUILLE trace of a spatio-temporal-distortion-free pulse. Middle: GRENOUILLE trace of the same pulse in the presence of spatial chirp (input spatial chirp: $dx/d\omega = 7.654321 \times 10^6$ nm fs). Right: Reconstructed GRENOUILLE trace using the algorithm described in the text, with the trace in the middle as the input. (retrieved spatial chirp $dx/d\omega = 7.654327 \times 10^6$ nm fs).

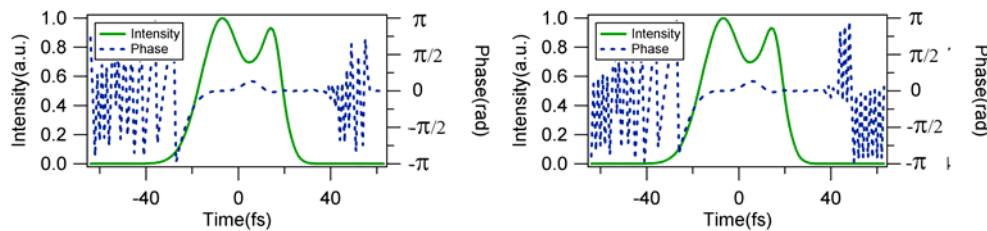


Fig.2 Simulated (left) and retrieved (right) electric field of the pulse that is used to generate traces in Fig. 1.