

Ambiguities in FROG? Fortunately, Not.

Lina Xu,¹ Daniel J. Kane,² and Rick Trebino¹

¹Georgia Institute of Technology, School of Physics, Atlanta, GA 30339

²Mesa Photonics, Santa Fe, NM 87505

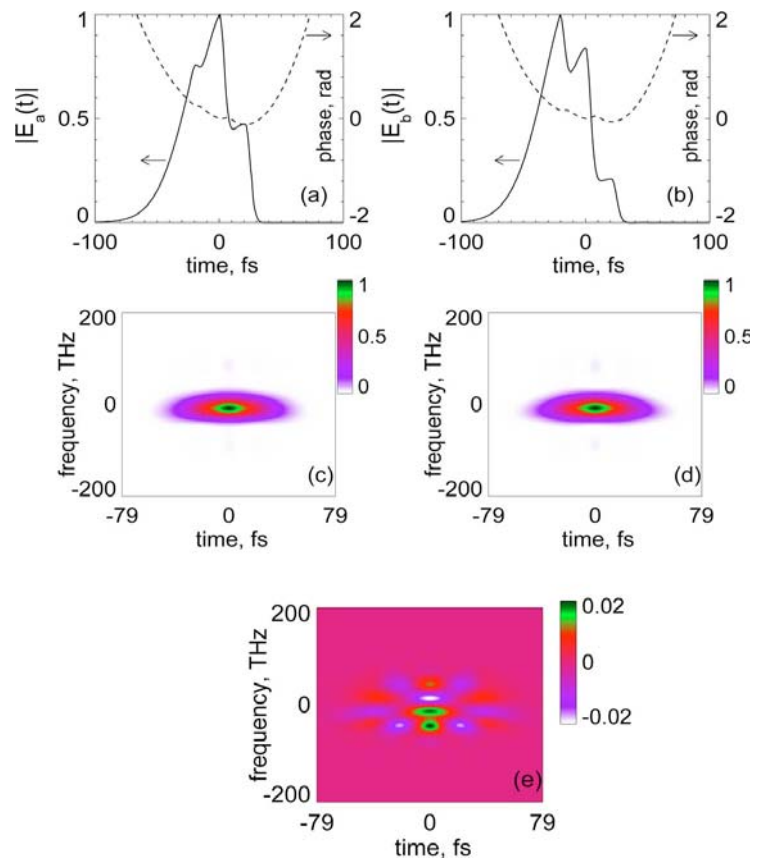
*Corresponding author: rick.trebino@physics.gatech.edu

OCIS codes: 320.7100, 320.7110, 120.1880.

A December 2007 Optics Letter¹ reported two nontrivial “ambiguities” in second-harmonic-generation (SHG) frequency-resolved-optical-gating (FROG). And a December 2008 “Erratum” on this paper by the same authors² reiterated this claim and the conclusions of the initial publication (it reported no errors). However, the first “ambiguity” is clearly wrong—the result of computational error by the authors of that paper. The other is well-known, trivial, and common to most pulse-measurement techniques (except for XFROG and SEA TADPOLE). It is also easily removed in FROG (but not in other methods) using a simple, well-known FROG variation. Finally, their main conclusion—that autocorrelation can be more sensitive to pulse variations than FROG—is also wrong. This article is an expanded version, including figures, of a one-page Comment that has been accepted for publication in Optics Letters, and which will appear soon. It is reprinted here with the permission of the editor.

The most important characteristic of any measurement technique is the avoidance of ambiguities. Alas, all ultrashort-pulse measurement techniques have ambiguities. Fortunately, all known ambiguities in FROG are *trivial* (unimportant or easily removed). In their December 2007 Optics Letter, however, Yellampalle, Kim, and Taylor (YKT)¹ claim to have found a *nontrivial* ambiguity in SHG FROG: two pulses with different substructure, whose SHG FROG traces they claim cannot be distinguished in practice. Computing the traces’ rms difference (usually called the FROG error), they report a tiny value: $G = 7 \times 10^{-6}$, indicative of an ambiguity.

Unfortunately, this value is wrong. In fact, $G = 2.4 \times 10^{-3}$. A quick glance at YKT’s plot (YKT Fig. 3e) of the trace difference, which is $\sim 2\%$ over 10% of the trace area and near zero elsewhere, easily confirms this value. It is likely that YKT



YKT Fig. 3e. a. Pulse #1. b. Pulse #2. c, d. SHG FROG traces of pulses #1 and 2. e. the difference between the two traces. Note that the difference is about $\sim 2\%$ over 10% of the trace area and hence clearly about .002, not .000007, as reported by YKT.

neglected to take the square root in computing the rms value. Such traces are easily distinguished in practice. In their “erratum,” YKT computed the rms error normalized by the nonzero trace area and obtained $G' = 8 \times 10^{-4}$, again wrong. The correct value is $G' = 2.6\%$. Again this larger value is consistent with their figure, in which the difference is about 2% over the nonzero area of the trace. Again it appears that they neglected to take the square root in computing the rms.

More importantly, simply quoting a difference between two FROG traces is simplistic. That, of course, is all that can be done in autocorrelation-based methods. FROG, on the other hand, enjoys a powerful pulse-retrieval algorithm. Thus the issue is *not* how the traces appear to the eye or even their difference, but whether the *pulses retrieved from them* would be confused.

To test the two pulses, we generated SHG FROG traces of the two “ambiguous” pulses and added up to 2% additive noise to simulate a noisy experiment. We ran the usual SHG FROG algorithm using random noise as the initial guess. Also, to attempt to fool the algorithm, we also used the *other “ambiguous” pulse* as the initial guess in each case. Despite this deception, the algorithm achieved excellent and rapid convergence to the correct pulse in all cases. Clearly, such pulses are not ambiguities in SHG FROG.

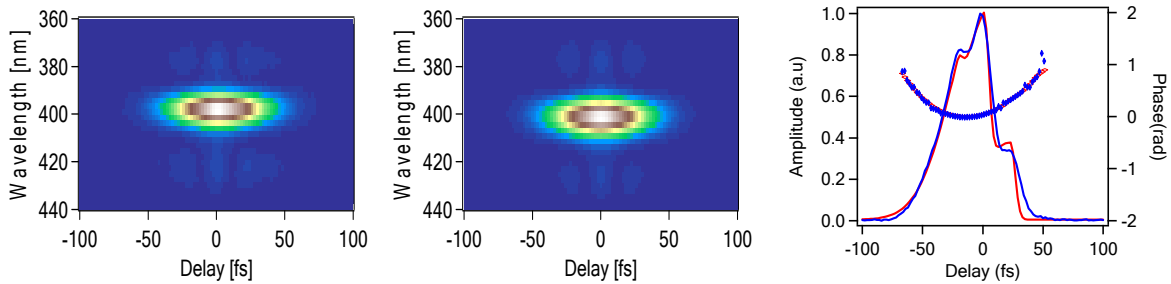


Fig.1. From left: SHG FROG trace of YKT’s pulse #1 with 1% noise added, retrieved SHG FROG trace, and the generated and retrieved pulses in the time domain. The red curve indicates the generated pulse and the blue curve indicates the retrieved pulse. The initial guess for the algorithm was the “ambiguous” pulse. The array size was 128 x 128, the FROG G error of the retrieval is 0.0036, and the (intensity-weighted) G' error is 0.0824.

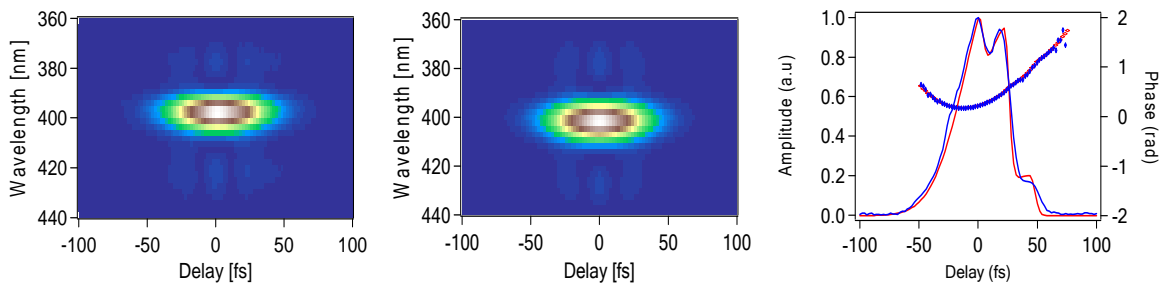


Fig.2. From left: SHG FROG trace of pulse #2 with 1% noise added, retrieved SHG FROG trace and the generated and retrieved pulse in the time domain. The initial guess for the algorithm was the “ambiguous” pulse. The FROG G error of the retrieval is 0.004, and the G' error is 0.0803.

YKT also reminded us of a trivial SHG FROG ambiguity, described earlier, by one of the authors herself^{3, 4} and also by one of us.^{5, 6} It involves pulses well-separated in time (YKT Fig. 1). It’s well known that relative phases, amplitudes, and directions of time (DOT) for well-

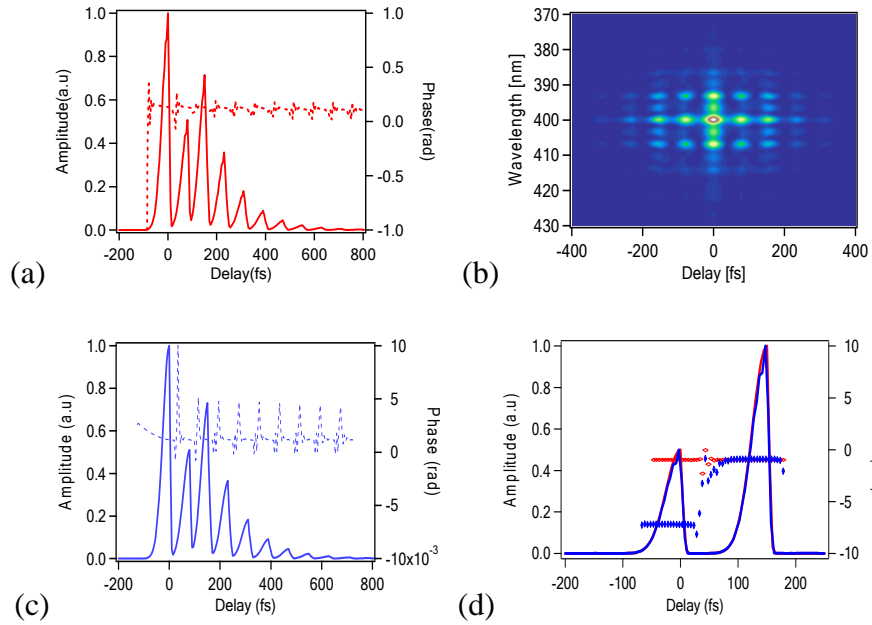


Fig. 3. (a) the double pulse train after the etalon, (b) the SHG FROG trace of the etalon-transmitted pulse train, (c) the retrieved pulse train from the trace, (d) the original generated double pulse and the double pulse retrieved using $E(t) = E_{train}(t) - \varepsilon E_{train}(t-T)$. The solid line indicates the generated pulse and the dashed line indicates the retrieved pulse. The FROG G error of the retrieval is 0.00027, and the G' error is 0.0056.

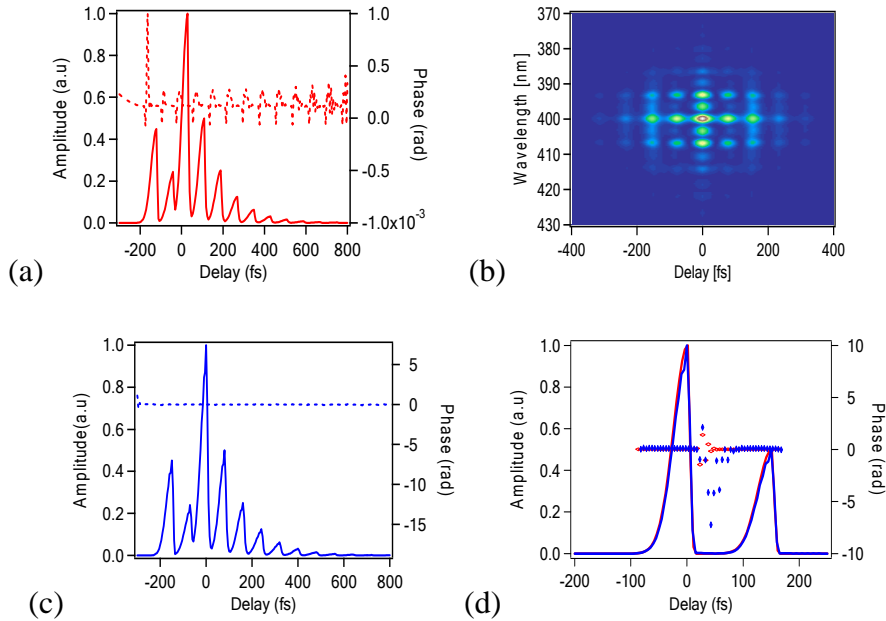


Fig. 4. (a) the double pulse train after the etalon, (b) the SHG FROG trace of the etalon-transmitted pulse train, (c) the retrieved pulse train from the trace, (d) the original generated double pulse and the double pulse retrieved using $E(t) = E_{train}(t) - \varepsilon E_{train}(t-T)$. The solid line indicates the generated pulse and the dashed line indicates the retrieved pulse. The FROG G error of the retrieval is 0.00024, and the G' error is 0.0049.

separated pulses or modes confuse most pulse-measurement techniques.⁵⁻⁷ But SEA TADPOLE and a FROG variation, XFROG, easily avoid them.⁷ Also, in our paper on the issue^{5, 6} (and unfortunately not mentioned by YKT), we also showed how to *remove* all such ambiguities and also SHG FROG's DOT ambiguity: using an *etalon* for the beam splitter yields an easily measured train of overlapping pulses. Such a train of pulses is easily measured by FROG, and retrieving the individual waveform (E) from the train (E_{train}) is trivial:

$$E(t) = E_{train}(t) - \varepsilon E_{train}(t-T),$$

where T is the round-trip time of the etalon and ε is the ratio of field strengths of successive individual pulses in the train. This method also removes the overall DOT ambiguity in SHG FROG and in addition automatically calibrates any FROG device. We called it Procedure for Objectively Learning the Kalibration And Direction Of Time (POLKADOT) FROG. In Figs. 3 and 4, we show how this approach easily removes the ambiguity in the case of the double pulses mentioned by YKT.

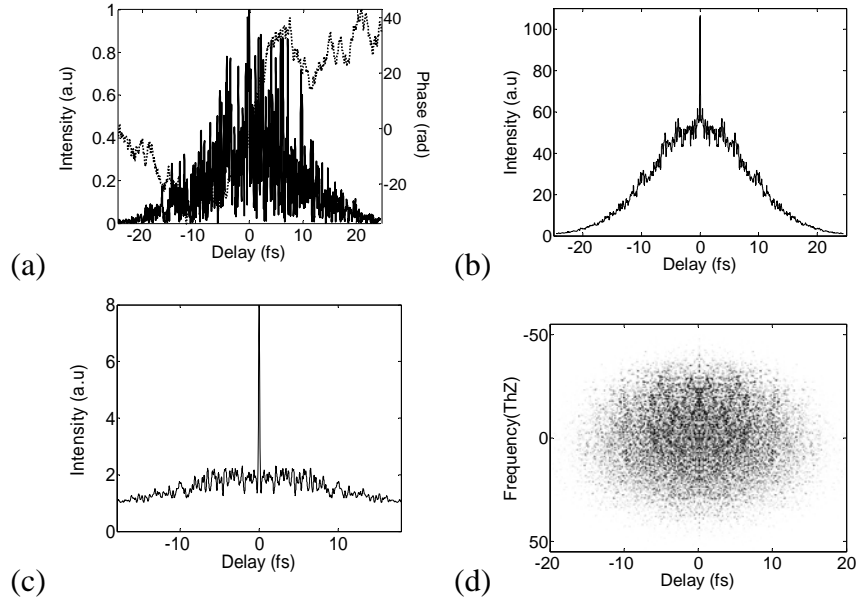


Fig 5. (a) Generated complex pulse with TBP of 475, (b) Intensity autocorrelation trace of this complex pulse, (c) Interferometric autocorrelation trace of this complex pulse, (d) SHG FROG trace of this complex pulse. While the structure (which contains the pulse information) in the autocorrelation and interferometric autocorrelation is nearly washed out, the highly complex structure in the FROG trace has a visibility of close to 100%.

In general, intensity and interferometric autocorrelation are not appealing alternatives to FROG. It's well known that pulses (including all those of YKT) *cannot* be retrieved from either type of autocorrelation trace, even when additional measures (such as the spectrum) are included, unless arbitrary assumptions are made or the pulse is trivially simple.^{5, 8} The complexity of the mathematics in autocorrelation in autocorrelation prevents even knowing the ambiguities. Finally, both types of autocorrelation traces blur features as pulses become more complex,

clearly losing much information and so rendering them *fundamentally* unable to measure complex pulses. FROG traces, on the other hand, grow appropriately more complex, thus retaining the necessary information about the pulse. Indeed, FROG easily measures and retrieves extremely complex pulses without ambiguity.^{5, 9} This cannot be said of any other technique available, except for XFROG and SEA TADPOLE, which require reference pulses.

Acknowledgments

We thank Reviewer #1 for confirming our calculations.

References

1. B. Yellampalle, K. Y. Kim, and A. J. Taylor, "Amplitude ambiguities in second-harmonic-generation frequency-resolved optical gating," *Opt. Lett.* **32**, 3558-3561 (2007).
2. B. Yellampalle, K. Y. Kim, and A. J. Taylor, "Amplitude ambiguities in second-harmonic generation frequency-resolved optical gating: erratum," *Opt. Lett.* **33**, 2854 (2008).
3. C. W. Siders, A. J. Taylor, and M. C. Downer, "Multipulse Interferometric Frequency-Resolved Optical Gating: Real-time Phase-sensitive Imaging of Ultrafast Dynamics," *Opt. Lett.* **22**, 624-626 (1997).
4. C. W. Siders, J. L. W. Siders, F. G. Omenetto, and A. J. Taylor, "Multipulse Interferometric Frequency-Resolved Optical Gating," *IEEE J. Quant. Electron.* **35**, 432-440 (1999).
5. R. Trebino, *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses* (Kluwer Academic Publishers, Boston, 2002).
6. E. Zeek, A. P. Shreenath, M. Kimmel, and R. Trebino, "Simultaneous Automatic Calibration and Direction-of-Time-Ambiguity Removal in Frequency-Resolved Optical Gating," *Appl. Phys. B* **B74**, S265-271 (2002).
7. D. Keusters, H.-S. Tan, P. O'Shea, E. Zeek, R. Trebino, and W. S. Warren, "Relative-phase ambiguities in measurements of ultrashort pulses with well-separated multiple frequency components," *J. Opt. Soc. Amer. B* **20**, 2226-2237 (2003).
8. J.-H. Chung, and A. M. Weiner, "Ambiguity of ultrashort pulse shapes retrieved from the intensity autocorrelation and power spectrum," *IEEE J. Sel. Top. Quant. Electron.* **7**, 656-666 (2001).
9. L. Xu, E. Zeek, and R. Trebino, "Simulations of Frequency-Resolved Optical Gating for measuring very complex pulses," *J. Opt. Soc. Am. B* **25**, A70-A80 (2008).