Intensity Autocorrelation

In order to measure an event in time, you need a shorter one.
So how do you measure the shortest one?

The *intensity autocorrelation* was the first attempt to measure an ultrashort pulse's intensity vs. time. Early on (the 1960's), it was realized that no shorter event existed with which to measure an ultrashort pulse. And the autocorrelation is what results when a pulse is used to measure itself. It involves splitting the pulse into two, variably delaying one with respect to the other, and spatially overlapping the two pulses in some instantaneously responding nonlinear-optical medium, such as a second-harmonic-generation (SHG) crystal (See Fig. 1). A SHG crystal will produce "signal light" at twice the frequency of input light with a field envelope that is given by:

$$E_{sig}^{SHG}(t,\tau) \propto E(t)\, E(t-\tau)$$

where τ is the delay. This field has an intensity that's proportional to the product of the intensities of the two input pulses:

$$I_{sig}^{SHG}(t,\tau) \propto I(t)\, I(t-\tau)$$

Detectors are too slow to resolve this beam in time, so they'll measure:

$$A^{(2)}(\tau) = \int_{-\infty}^{\infty} I(t)\, I(t-\tau)\, dt$$

This is the intensity autocorrelation. The superscript (2) implies that it's a second-order autocorrelation; third-order autocorrelations are possible, too.

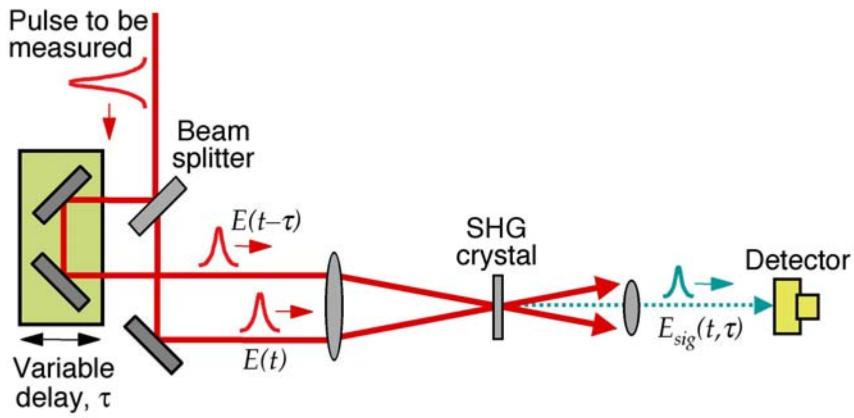

Fig. 1. Experimental layout for an intensity autocorrelator using second-harmonic generation. A pulse is split into two, one is variably delayed with respect to the other, and the two pulses are overlapped in an SHG crystal. The SHG pulse energy is measured vs. delay, yielding the autocorrelation trace. Other nonlinear-optical effects, such as two-photon fluorescence and two-photon absorption can also yield the autocorrelation, using similar beam geometries.

Figure 2 shows some pulses and their intensity autocorrelations.

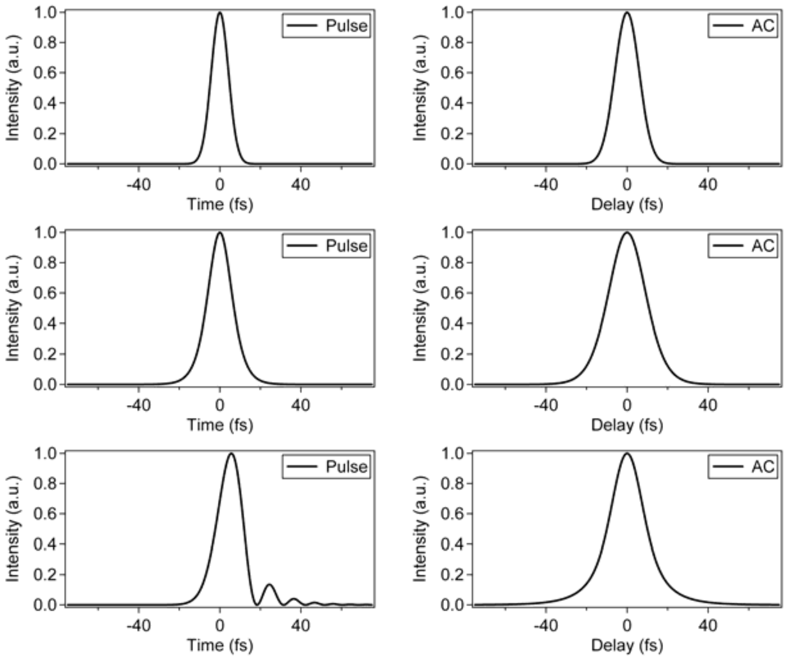

Fig. 2. Examples of theoretical pulse intensities and their intensity autocorrelations. Left: Intensities vs. time. Right: The intensity autocorrelation corresponding to the pulse intensity to its left. Top row: A 10-fs Gaussian intensity. Middle row: A 7-fs sech^2 intensity. Bottom row: A pulse whose intensity results from 3^{rd}-order spectral phase, a very common occurrence in ultrafast optics labs. Note that the autocorrelation loses details of the pulse, and, as a result, all of these pulses have similar autocorrelations.

Notice that the autocorrelation doesn't reveal the satellite pulses in the pulse in the bottom row. Indeed, it is easy to show that the autocorrelation doesn't yield the pulse intensity because many different intensities can have the same autocorrelation (and, of course, it says nothing about the pulse phase).

It can be shown that the problem of retrieving the pulse intensity from the intensity autocorrelation is equivalent to a mathematical problem called the one-dimensional phase-retrieval problem, which is the attempt to retrieve the Fourier-transform phase for a function when only the Fourier-transform magnitude is available. This problem is unsolvable because typically many solutions ("ambiguities") exist, and it isn't possible to determine which is the correct one.

The autocorrelation's tendency to wash out structure in the intensity is well known. But this shortcoming is most evident in the measurement of complicated pulses. In fact, for complex pulses, it can be shown that, as the intensity increases in complexity, the autocorrelation actually becomes *simpler* and approaches a simple shape of a narrow spike on a pedestal, *independent of the intensity structure*.

For a discussion of this remarkable fact, see *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses* by Rick Trebino. But here we'll illustrate it with a few plots (See Fig. 3).

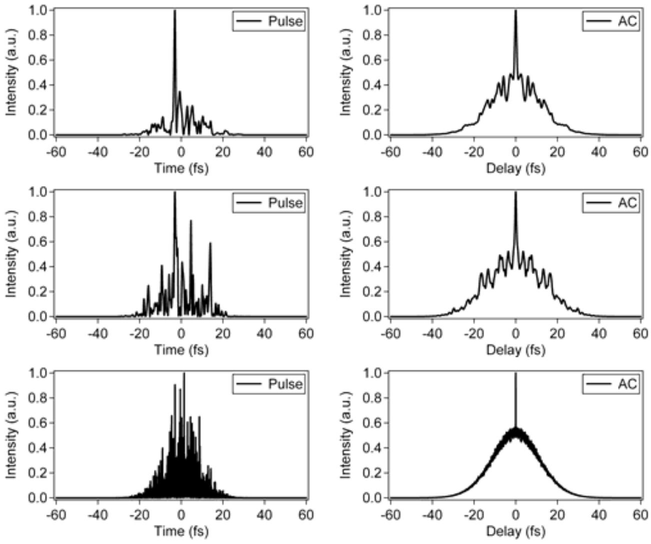

Fig. 3. Complicated intensities with Gaussian slowly varying envelopes with increasing amounts of intensity structure (left) and their autocorrelations (right). As the pulse increases in complexity (from top to bottom), the autocorrelation approaches the simple narrow-spike-on-a-pedestal shape, independent of the pulse intensity structure. Note that the spike narrows along with the structure, while the pedestal always reveals the approximate width of the envelope of the intensity and approaches a perfect Gaussian (the autocorrelation of a Gaussian is a Gaussian) as the structure increases in complexity.

Interestingly, this autocorrelation trace simultaneously yields rough measures of both the pulse spectrum and intensity autocorrelation. Unfortunately, that's all it yields. It says nothing of the actual spectrum or the intensity structure.

The "interferometric autocorrelation," which involves placing an SHG crystal at the output of a Michelson interferometer, is better, yielding some information about the pulse phase. But no one has ever found a way to extract the full pulse intensity and phase from it, and, worse, very different pulses (even pulses with very different pulse lengths) can have very similar interferometric autocorrelations.

Thus, a pulse intensity shape and phase must typically be assumed when using any type of autocorrelation. And the resulting pulse length will depend sensitively on the shape chosen. Worse, in view of these issues, it generally isn't possible to sense from an autocorrelation when other pulse distortions (such as spatio-temporal distortions like spatial chirp or pulse-front tilt) or systematic error are present. Thus, autocorrelation is no longer an acceptable measure of most ultrashort pulses.