GRENOUILLE

Measuring ultrashort laser pulses—the shortest events ever created—has always been a challenge. For many years, it was possible to create ultrashort pulses, but not to measure them. Techniques such as spectrometry and autocorrelation were available but provided only a vague measure of a pulse. Worse, autocorrelation is actually a fairly *difficult* measurement to make. It requires splitting the pulse into two replicas and then focusing and recombining them (overlapping them in space and time) in a second-harmonic-generation (SHG) crystal. This involves carefully aligning three sensitive degrees of freedom (two spatial and one temporal). It is also necessary to maintain this alignment while scanning the delay. Worse, the phase-matching-bandwidth condition mandates a thin SHG crystal, yielding a very weak signal and poor measurement sensitivity. This latter problem compounds alignment difficulties. As a result, an autocorrelator is a time-consuming and high-maintenance undertaking; it requires significant table space; and commercial devices cost ~ $20,000 or more.

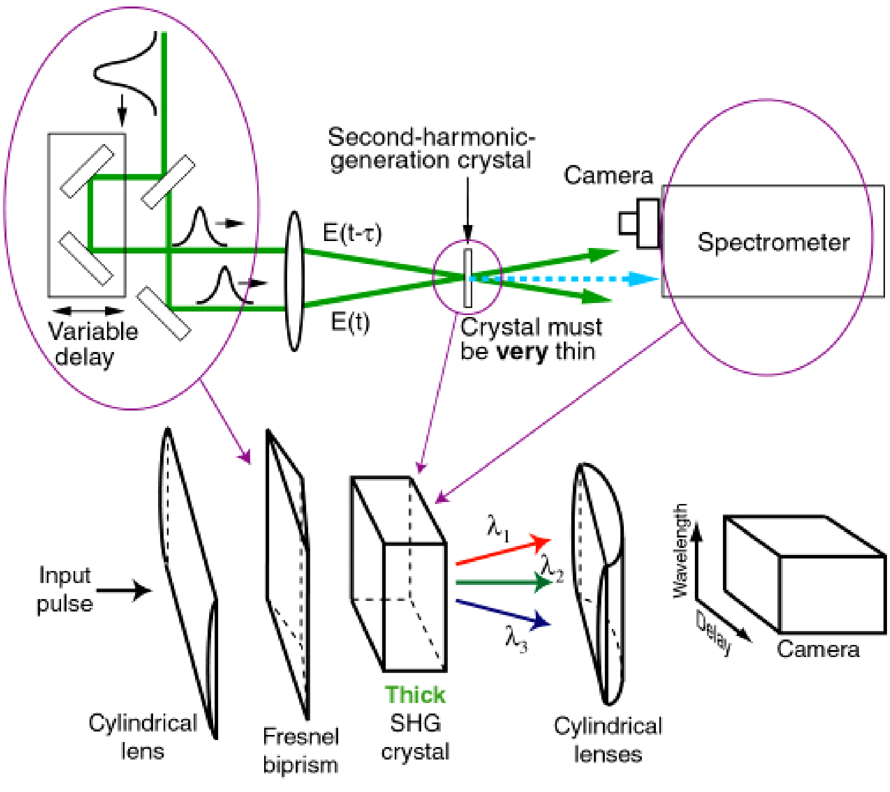

Fig. 1. Top: SHG FROG. While SHG FROG is the simplest intensity-and-phase ultrashort-pulse-measurement device, there are a few components of it that we'd like to eliminate to simplify it. Bottom: GRENOUILLE, which involves replacing the complex elements of SHG FROG with simpler ones. GRENOUILLE uses a Fresnel biprism to replace the beam splitter, delay line, and beam-recombining optics. It maps delay to position at the crystal. GRENOUILLE also utilizes a thick SHG crystal acting as both the nonlinear-optical time-gating element and the spectrometer. A complete single-shot SHG FROG trace results. Most importantly, however, GRENOUILLE has zero sensitive alignment parameters.

In the past decade, great advances in the field of ultrashort-pulse measurement have occurred. New classes of more powerful methods now yield much more information, in particular, the full intensity and phase of the pulse vs. time. But simplicity has never been the goal. In fact, these new techniques have actually *increased* in complexity. They all incorporate an autocorrelator and add—sometimes a great many—additional components.

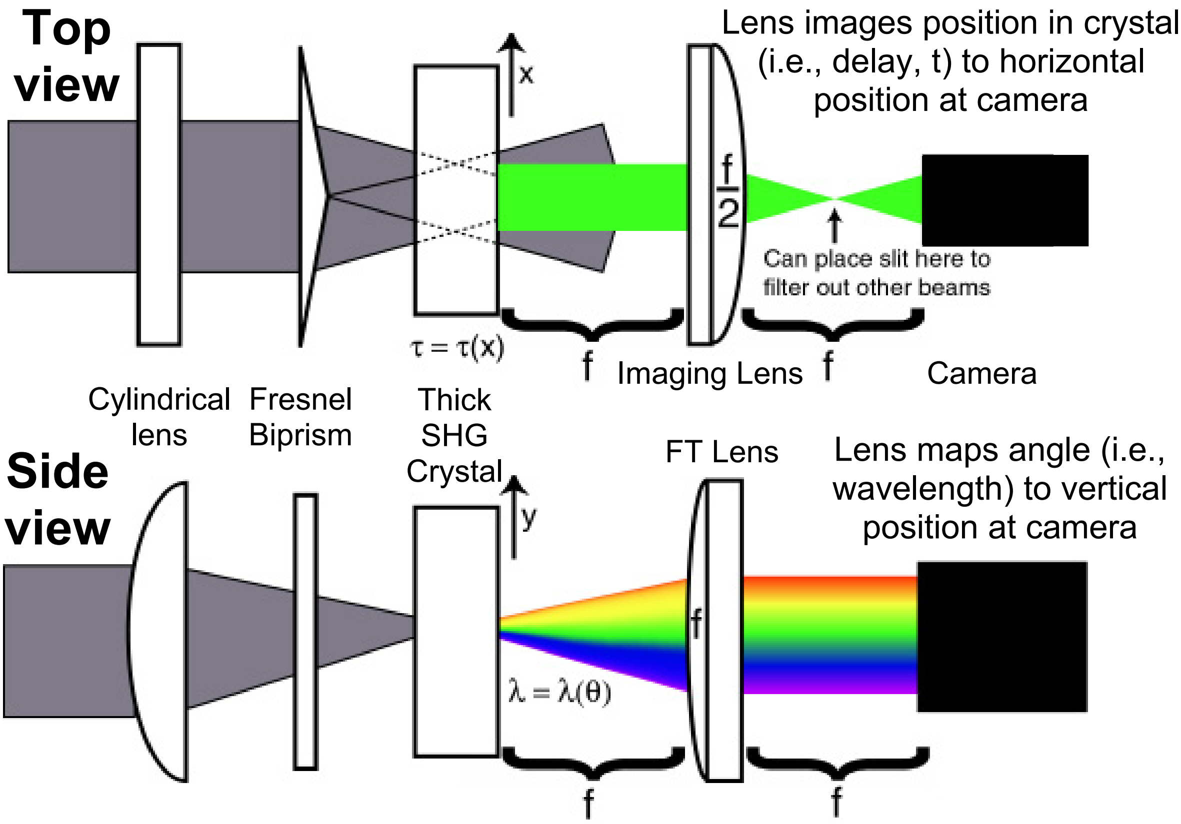

Fig. 2. Side and top views of the GRENOUILLE beam geometry of Fig. 1. Here, convenient focal lengths are shown for the two final cylindrical lenses (f and f/2).

The most popular full intensity-and-phase measurement technique, Frequency-Resolved Optical Gating (FROG)[1], adds a spectrometer to an autocorrelator (see Fig. 1). A simple grating-lens home-made spectrometer that introduces no additional sensitive alignment degrees of freedom can be appended to an autocorrelator to make an excellent FROG, but FROG still inherits the autocorrelator's complexity, size, cost, maintenance, and alignment issues. Alternatives to FROG are, unfortunately, even more complex. Some involve two beams propagating collinearly with a precisely given delay, which by itself introduces no less than *five* sensitive alignment degrees of freedom (four spatial and one temporal). Furthermore, alternative devices often contain numerous additional components, such as frequency filters, additional delay lines, and even interferometers within interferometers, yielding as many as a dozen or more sensitive alignment degrees of freedom and increasing significantly the complexity, size, cost, maintenance, and potential for systematic error. And most lack much-needed feedback as to measurement accuracy.

Recently, however, we introduced a remarkably simple FROG device that overcomes all of these difficulties [2]. It (see Figs. 1 and 2) involves first replacing the beam splitter, delay line, *and* beam combining optics with a *single* simple element, a Fresnel biprism[3]. Second, in seemingly blatant violation of the phase-matching-bandwidth requirement, it uses a *thick* SHG crystal, which not only gives considerably more signal (signal strength scales as the approximate square of the thickness), but also simultaneously replaces the spectrometer. The resulting device, like its other relatives in the FROG family of techniques, has a frivolous name: GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields (GRENOUILLE, which is the French word for "frog").

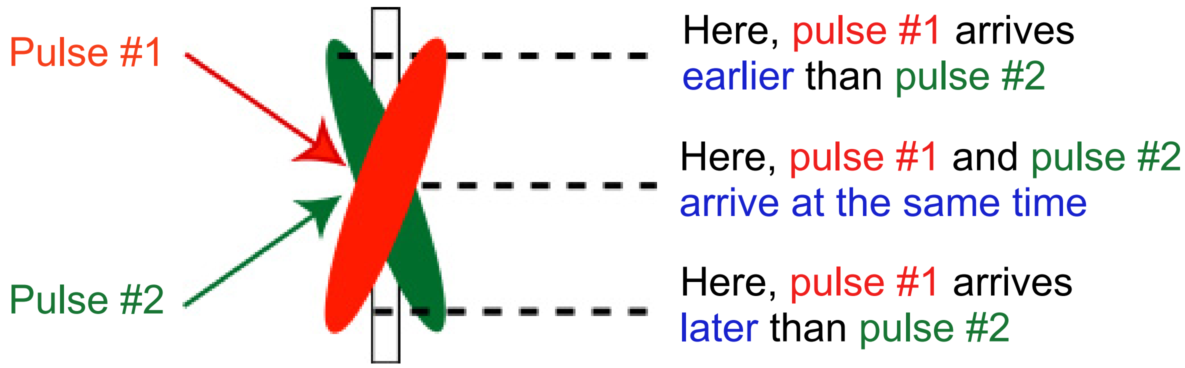

Fig. 3a. Crossing beams at an angle maps delay onto transverse position.

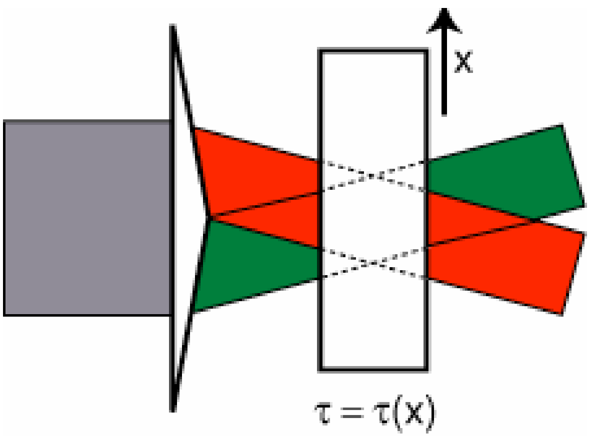

Fig. 3b. Crossing beams at an angle using a Fresnel briprism (different colors are used to distinguish the beams). Note that the beams are automatically aligned in space and time.

A Fresnel biprism [3] (a prism with an apex angle close to 180˚) is a device usually used in classrooms to illustrate interference. When a Fresnel biprism is illuminated with a wide beam, it splits the beam into two beamlets and crosses them at an angle yielding interference fringes. While fringes aren't relevant to pulse measurement, crossing beams at an angle is exactly what is required in conventional single-shot autocorrelator and FROG beam geometries, in which the relative beam delay is mapped onto horizontal position at the crystal (See Fig. 3). But, unlike conventional single-shot geometries, beams that are split and crossed by a Fresnel biprism are *automatically aligned* in space and in time, a significant simplification. Then, as in standard single-shot geometries, the crystal is imaged onto a camera, where the signal is detected vs. position (i.e., delay) in, say, the horizontal direction.

FROG also involves spectrally resolving a pulse that has been time-gated by itself. GRENOUILLE combines both of these operations in a single *thick* SHG crystal. As usual, the SHG crystal performs the self-gating process: the two pulses cross in the crystal with variable delay. But, in addition, the thick crystal has a relatively small phase-matching bandwidth, so the phase-matched wavelength produced by it varies with angle (See Fig. 3). Thus, the thick crystal also acts as a *spectrometer*.

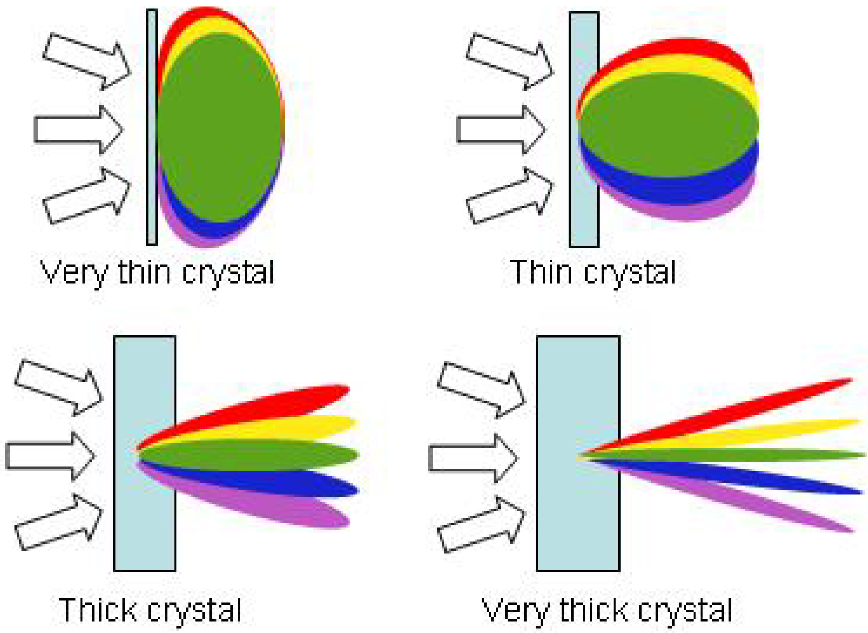

Fig. 4. Thin and thick SHG crystals illuminated by converging broadband light and polar plots of the generated colors vs. crystal exit angle. Note that the very thin crystal (ordinarily required in pulse-measurement techniques) generates the second harmonic of all colors in the forward direction. The very thick crystal, on the other hand, does not and, in fact, acts like a spectrometer. The thick crystal thus acts like a thin crystal *and* a spectrometer.

Two additional cylindrical lenses complete the device. The first cylindrical lens must focus the beam into the thick crystal tightly enough to yield a range of crystal incidence (and hence exit) angles large enough to include the entire spectrum of the pulse. After the crystal, a cylindrical lens then maps the crystal exit angle onto position at the camera, with wavelength a near-linear function of (vertical) position.

GRENOUILLE has many advantages. It has few elements and so is inexpensive and compact. It operates single-shot. And it is considerably more sensitive than current devices. Furthermore, since GRENOUILLE produces (in real-time, directly on a camera) traces identical to those of SHG FROG, it yields the full pulse intensity and phase (except the direction of time). In addition, several feedback mechanisms on the measurement accuracy that are already present in the FROG technique work with GRENOUILLE, allowing confirmation of—and confidence in—the measurement. And it measures the beam spatial profile. Even better, it measures the most common spatio-temporal pulse distortions, spatial chirp and pulse-front tilt. But best of all, GRENOUILLE is extremely simple to set up and align: it involves no beam-splitting, no beam-recombining, and no scanning of the delay, and so has *zero* sensitive alignment degrees of freedom!

GRENOUILLE: The details

The key issue in GRENOUILLE is the crystal thickness. Ordinarily, achieving sufficient phase-matching bandwidth requires *minimizing* the group-velocity mismatch, GVM: the fundamental and the second harmonic must overlap for the entire SHG crystal length, L. If τ_p is the pulse length, $GVM \equiv 1/v_g(\lambda_0/2) - 1/v_g(\lambda_0)$, $v_g(\lambda)$ is the group velocity at wavelength λ, and λ_0 is the fundamental wavelength, this condition is: $GVM \cdot L \ll \tau_p$.

For GRENOUILLE, however, the opposite is true; to resolve the spectrum, the phase-matching bandwidth must be *much less than* that of the pulse:

$$GVM\ \ L \gg \tau_p \tag{1}$$

which ensures that the fundamental and the second harmonic *cease* to overlap well before exiting the crystal, which then acts as a frequency filter. Interestingly, in contrast to all other pulse-measurement devices, GRENOUILLE operates best with a highly dispersive crystal.

On the other hand, the crystal must not be too thick, or group-velocity *dispersion* (GVD) will cause the pulse to spread in time, distorting it:

$$GVD\ \ L \ll \tau_c \tag{2}$$

where $GVD \equiv 1/v_g(\lambda_0 - \delta\lambda/2) - 1/v_g(\lambda_0 + \delta\lambda/2)$, $\delta\lambda$ is the pulse bandwidth, and τ_c is the pulse coherence time (~ the reciprocal bandwidth, $1/\Delta\nu$), a measure of the smallest temporal feature of the pulse. Since GVD < GVM, this condition is ordinarily already satisfied by the usual GVM condition. But here it is not necessarily satisfied, so it must be considered.

Combining these two constraints, we have:

$$GVD\ (\tau_p/\tau_c) \ll \tau_p/L \ll GVM \tag{3}$$

There exists a crystal length L that satisfies these conditions simultaneously if:

$$GVM / GVD \gg TBP \tag{4}$$

where the time-bandwidth product (TBP) of the pulse is τ_p/τ_c. Equation (4) is the fundamental equation of GRENOUILLE.

For a near-transform-limited pulse (TBP ~ 1), this condition is easily met because GVM >> GVD for all but near-single-cycle pulses. Consider typical near-transform-limited (i.e., $\tau_p \sim \tau_c$) Ti:Sapphire pulses of ~100-fs duration, where λ_0 ~800-nm, and $\delta\lambda$ ~10-nm. A 5-mm BBO crystal—about 30 times thicker than is ordinarily appropriate—satisfies Eq. (3): 20 fs/cm << 100 fs/0.5 cm = 200 fs/cm << 2000 fs/cm. Note that, due to GVD, shorter pulses require a thinner, less dispersive crystal, but shorter pulses also generally have broader spectra, so the same crystal will provide sufficient spectral resolution, in view of GVM. Less dispersive crystals, such as KDP, minimize GVD, providing enough temporal resolution to accurately measure pulses as short as 50 fs. Conversely, more dispersive crystals, such as $LiIO_3$, have larger GVM, allowing for sufficient spectral resolution to measure pulses as narrowband as 4.5 nm (~200-fs transform-limited pulse length at 800 nm). Still longer or shorter pulses will also be measurable, but with less accuracy (although the FROG iterative algorithm can incorporate these effects and extend GRENOUILLE's range).

GRENOUILLE measurements of simple pulses have proven extremely accurate [2]. But just because GRENOUILLE is simple doesn't mean that it can only measure simple pulses. Indeed, we have measured a complex "double-chirped pulse:" two strongly chirped pulses separated by about one pulse width. With structure in its trace in both delay and frequency, it puts GRENOUILLE to the test; if the GVM is too small, frequency resolution will be inadequate; if the GVD is too large, the pulse will spread, and the temporal structure will be lost. Figure 5 shows these measurements (which use Femtosoft Technologies' FROG code for pulse retrieval). All traces were 128 by 128 pixels, and the FROG errors (the rms difference between the measured and the retrieved-pulse traces—one of the checks of the quality of the experimental trace) were 0.031 and 0.013 for the GRENOUILLE and FROG measurements respectively, which is quite good for such complex pulses. The GRENOUILLE signal strength was ~1000 times greater than that of a single-shot FROG and also much greater than that of an autocorrelator.

In summary, GRENOUILLE combines full-information pulse measurement with much-needed experimental simplicity. Only a few simple optical elements are required, and no sensitive alignment is required. It is also extremely compact and more sensitive than other pulse diagnostics, including even those that don't yield the full intensity and phase. Its ability to measure elusive spatio-temporal distortions is also remarkable (see the tutorial on spatio-temporal distortions). Finally, GRENOUILLE's operating range nicely includes that of most ultrafast Ti:Sapphire lasers and amplifiers, so it should be ideal for most everyday diagnostics as well as many more exotic ones.

References

[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, and R. Trebino, Opt. Lett., vol. 26, p 932 (2001).
[3] E. Hecht, in *Optics,* 3rd edition (Addison Wesley, Reading, Massachusetts), 391 (1998).

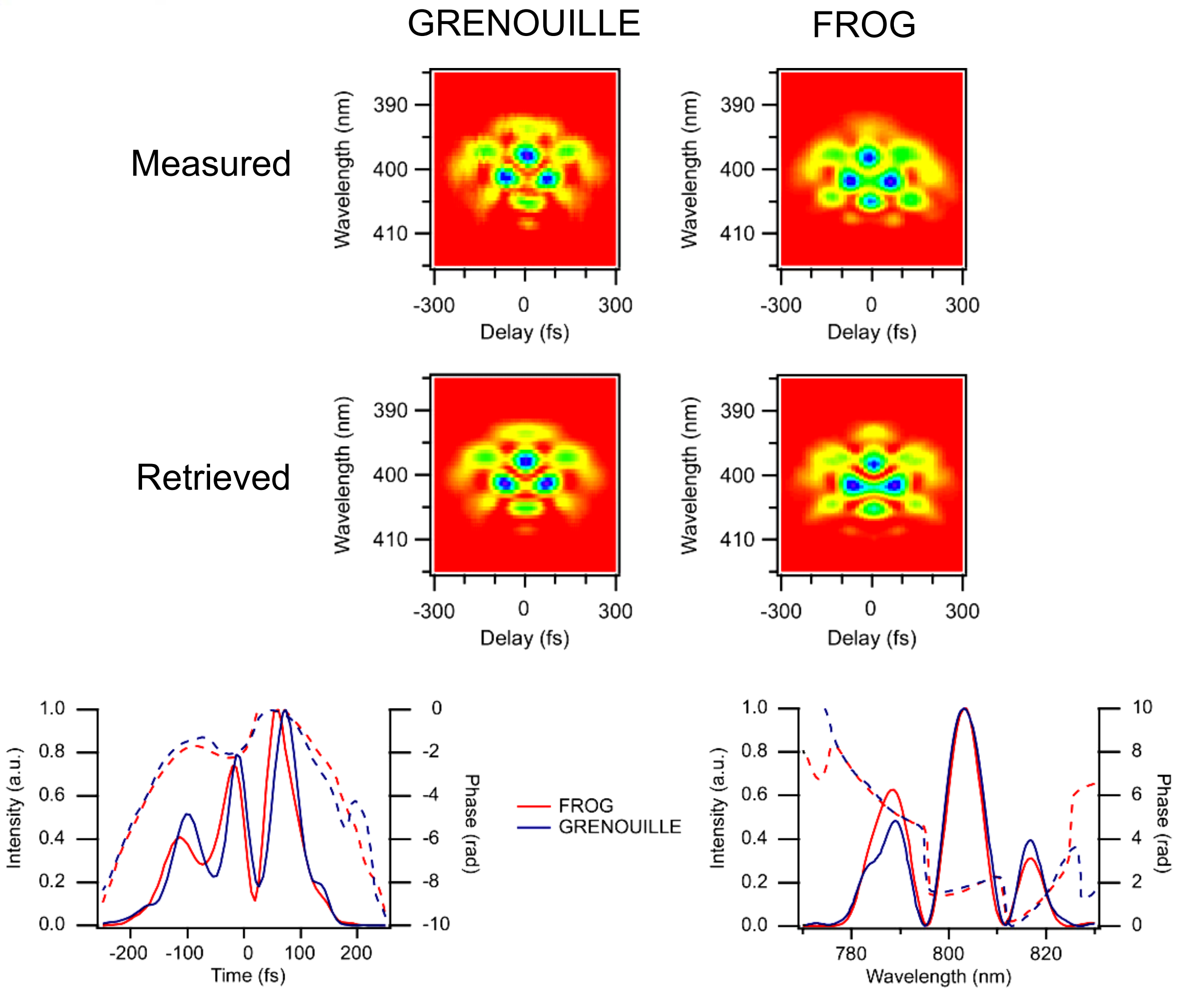

Fig 5. Comparison between GRENOUILLE and FROG measurements of a complex test pulse.