GRENOUILLE User's Guide

Swamp Optics

R&D100
Award Winner
2003

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Fellow Ultrafast Researcher,

Thank you for purchasing GRENOUILLE! We hope you're as excited about it as we are. We're sure that, as you use it and make measurements with it, you'll be impressed by it. It's the world's simplest, most compact, least expensive, and most powerful ultrashort laser pulse measurement device. It's a member of the FROG family, the most powerful class of pulse-measurement techniques ever invented. It measures the pulse intensity and phase vs. time and the spectrum and spectral phase vs. wavelength. And with the flip of a switch, it measures the beam spatial profile.

Unlike other pulse-measurement devices, GRENOUILLE is very easy to use. It comes pre-aligned, and aligning your beam into it is trivial. The instructions are simple: simply set GRENOUILLE to measure the beam spatial profile, send a fraction of your beam into it, connect the camera output to a video monitor or frame-grabber, and generate the spatial profile. Then switch to temporal mode and you're already generating FROG traces of pulses! Even better, using either VideoFROG or the Spiricon/Femtosoft frame-grabber/software, you'll have the full intensity and phase of your pulse and a host of other information. Even better, GRENOUILLE will never become misaligned; there are no alignment knobs to turn!

GRENOUILLE also automatically measures spatio-temporal distortions, which are more common than first realized. Spatio-temporal distortions, such as spatial chirp and pulse-front tilt, can badly distort experimental data. Fortunately, GRENOUILLE measures both: spatial chirp yields a tilt in the GRENOUILLE trace, and pulse-front tilt yields a GRENOUILLE trace displaced along the delay axis. Indeed, GRENOUILLE is the most accurate measure of these distortions that money can buy.

There's not much more to know about your laser output!

If you have any questions, just give us a call. We're available every day from 10 a.m. to 6 p.m. (USA, eastern time), and many evenings until 10 p.m.

Sincerely,

Rick P. Trebino

Rick P. Trebino

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Introduction

The world's most powerful ultrashort-laser-pulse measurement device, GRENOUILLE combines full-information pulse measurement with much-needed experimental simplicity.[1] It requires only a few simple optical elements and has no intricate alignment procedure.

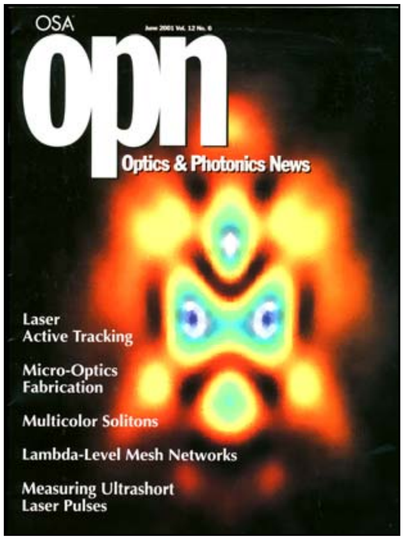
GRENOUILLE tells you more about your pulse with less effort than ever thought possible. And it can measure pulses from a wide variety of sources, from the lowest-energy oscillator to the highest-intensity amplifier. GRENOUILLE is available in two models: the Model 8-50, for pulses as short as 50 fs, and Model 8-20, for pulses as short as 20 fs.

GRENOUILLE is also extremely compact and more sensitive than other pulse diagnostics, including even those that don't yield the full intensity and phase. GRENOUILLE's operating range (~ 700 to 1100 nm) nicely matches that of most ultrafast Ti:Sapphire lasers and amplifiers, so it should be ideal for most everyday diagnostics as well as many more exotic applications.

For complete details on GRENOUILLE's operation, refer to the GRENOUILLE Tutorial in the appendix.

GRENOUILLE Features at a Glance

- Operating range of ~ 700 to 1100 nm
- Models for 20-200 fs & 50-500 fs pulses
- Yields the pulse intensity and phase vs. time
- Yields the pulse spectrum and spectral phase
- Measures the beam spatial profile
- Measures the spatial chirp
- Measures the pulse-front tilt
- Makes no assumptions about the pulse
- Requires no alignment
- High sensitivity
- Offers real-time operation (10 pps)
- Features minimal effort, weight, size, and cost
- Available in five bold **colors**



GRENOUILLE as Featured in Optics & Photonics News

GRENOUILLE was featured in the cover story of OPN in June 2001. Refer to the FROG Web site to read a reprint of the article:

http://www.physics.gatech.edu/gcuo/SubIndex.html

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[1] GRENOUILLE is the French word for "frog," and it's pronounced gra-NEW-ee.

Frequency-Resolved Optical Gating (FROG)

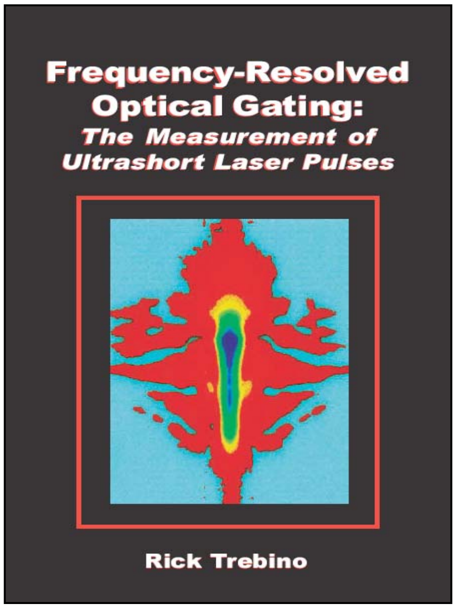
The subject of five patents, FROG is a well-established method for accurately determining critical pulse information, including the time-dependent (or, equivalently, frequency-dependent) intensity and phase of an ultrashort laser pulse. FROG is rigorous, general, and accurate, and it is a widely used technique with many applications.

GRENOUILLE is, in essence, a remarkably streamlined FROG design that employs only a few simple optical elements and completely eliminates the intricate and time-consuming alignment procedure required by other pulse measurement techniques.

The Swamp Optics and FROG Web sites have extensive information on FROG (and GRENOUILLE). The tutorials and articles published there contain everything you need to know about these powerful and versatile techniques. The relevant sites are

- www.swampoptics.com, for Swamp Optics
- www.physics.gatech.edu/gcuo/subindex.html, for FROG

Frequency-Resolved Optical Gating: *The Measurement of Ultrashort Laser Pulses*



Written by Rick Trebino (and others), this book is devoted to FROG and GRENOUILLE and is available from Kluwer Academic Publishers and Amazon.com. It contains more than everything you could possibly ever need to know about FROG and GRENOUILLE.

The book also features chapters on ultrashort pulses (lots on the intensity and phase and what can happen to these quantities if you're not careful) and nonlinear optics. And it has a nice CD with PowerPoint presentations on pulse measurement and FROG and GRENOUILLE (also translated into French!).

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Using GRENOUILLE: An Overview

Unlike other pulse-measurement devices, GRENOUILLE is very easy to use. It comes pre-aligned, and aligning your beam into it is trivial. Plus, GRENOUILLE will never become misaligned for the simple reason that there are no alignment knobs to turn! And it's very tolerant of input beam wander.

> **Note**: This chapter introduces the ways in which GRENOUILLE can be used. If you're already familiar these options and want to set GRENOUILLE up right away, skip to the next chapter: Setting Up Your GRENOUILLE.

Using GRENOUILLE Alone

Simply use GRENOUILLE in the beam spatial profile mode, connect its camera output to a video monitor or frame-grabber, send a fraction of your beam into it, and walk your beam to the center of the camera. Then switch to the temporal mode and you're already generating FROG traces of pulses!

Since the output of GRENOUILLE's camera is a spectrogram, you can tell a lot by just looking at it on a video monitor. For example, since it's a spectrally resolved autocorrelation, just visually integrating over wavelength (the vertical axis) yields the autocorrelation.

Or, better, the trace width along the delay axis is proportional to the pulse length, and the trace width along the wavelength axis is proportional to the spectral width (the proportionality factors are the same autocorrelation factors you're used to). Also, the trace area is proportional to the pulse time-bandwidth product. And, of course, by simply switching modes, GRENOUILLE also provides the beam spatial profile, too.

Combining GRENOUILLE with Pulse Analysis Tools

Using pulse analysis tools, you'll have the full intensity and phase of your pulse and just about everything else you could imagine about it. This includes the spatio-temporal distortions—spatial chirp and pulse-front tilt—which are more common than first realized and can badly distort experimental data. Spatial chirp yields a tilt in the GRENOUILLE trace, and pulse-front tilt yields a GRENOUILLE trace displaced along the delay axis. Indeed, GRENOUILLE is the most accurate measure of these distortions that money can buy.

No algorithm exists for retrieving the intensity or any other quantitative information from an autocorrelation, but it's possible to retrieve an incredible amount of useful quantitative information from a GRENOUILLE trace. Indeed, inexpensive software exists that can compute and display the pulse intensity vs. time, the phase vs. time, the spectrum, the spectral phase, the spatial profile, the spatial chirp, and pulse-front tilt. And, of course, you can also get the autocorrelation (which is trivially derived from the intensity, but there's no need to compute it if you already have the intensity!).

To take advantage of the extended information available from a GRENOUILLE trace, it's necessary to get the pulse trace into a computer. This involves using a frame-grabber (basically, a board that fits in your computer and which grabs a frame from GRENOUILLE's camera) and some computer code to analyze the trace. Because GRENOUILLE provides both temporal and spatial pulse information, it's best to use both temporal-profile (FROG) code and spatial profile code.

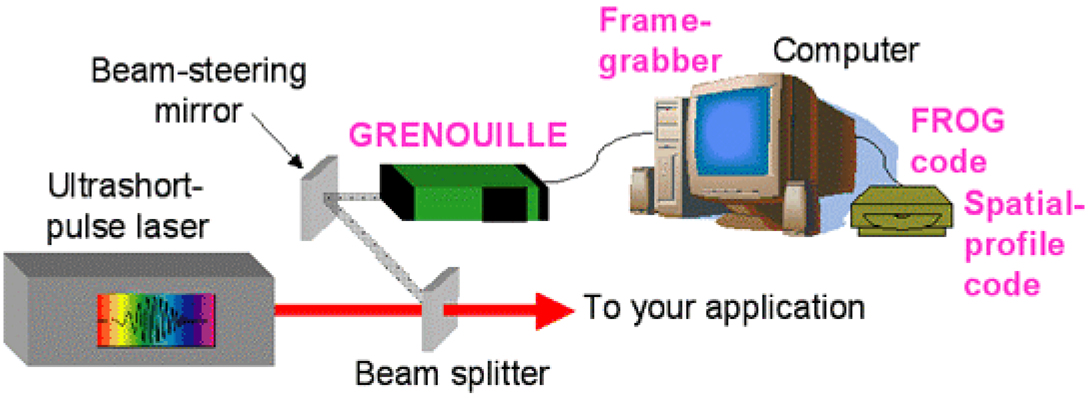


Figure 1: Setup for using GRENOUILLE with pulse analysis tools. The devices labeled in black are already in your lab, and those labeled in magenta represent devices or software that will give you the most detailed and effortless measurements of your ultrashort pulses ever available.

As described below, there are currently two third-party options for the frame-grabber hardware and software combinations. When purchased with a GRENOUILLE device, Swamp Optics can offer some of these products at discount. For availability information, refer to the Swamp Optics Web site: www.swampoptics.com.

No matter which you choose, you will have the best, most informative measure of an ultrashort laser pulse ever.

Mesa Photonics Video FROG

Mesa Photonics' VideoFROG provides everything needed after the GRENOUILLE in one integrated package: the frame grabber, the FROG code, and the spatial-profile code.

VideoFROG incorporates very fast FROG code which can retrieve the pulse intensity and phase vs. time, the spectrum, spectral phase, and the spatio-temporal distortions from the FROG trace at about 10 pulses per second. It also incorporates spatial-profile software, which allows you to view your beam's spatial profile, and easily switches between temporal and spatial beam property displays.

Spiricon Frame Grabber/Spatial Profile Software and Femtosoft FROG Code

This approach combines Spiricon's frame grabber and spatial profile software with FROG software from Femtosoft. Both the Spiricon and Femtosoft software are highly polished programs with many features.

For example, the Spiricon spatial-profile software offers many display options and can compute a wide range of quantities related to your beam spatial profile. And the Femtosoft

FROG code allows you to modify many aspects of the FROG algorithm and watch the algorithm converge.

Femtosoft's code also allows you to use alternative versions of FROG to perform other highly accurate measurements, including fluorescence measurements or measurements of pulses at odd wavelengths. Such extended pulse analysis is possible by first saving the trace from within the Spiricon code and then running the FROG code on the saved file.

What FROG and GRENOUILLE Do and Do Not Measure

FROG measures the pulse intensity and phase vs. time and the spectrum and spectral phase vs. frequency (or wavelength). These two pairs of quantities are equivalent (a Fourier transform relates them), so you only need the intensity and phase or the spectrum and spectral phase to completely specify the pulse. GRENOUILLE also measures the spatial profile and the spatial chirp and pulse-front tilt (which are described later). But there are some quantities in the intensity and phase that FROG doesn’t measure, so you should be aware of them now.

In fact, generally, you don’t want to measure these quantities because if you did, it’d be a pain. These are the absolute phase (the constant phase term in both the time and frequency domains) and the pulse arrival time in the time domain, which is the linear phase term in the frequency domain. We go to some length to always set the absolute phase to zero and to center the pulse in time, but you will occasionally see some jitter due to meaningless variations in these quantities. Just ignore them and be glad you don’t need to know them. If FROG measured these quantities, you’d have to stabilize them in your set up, and that’d suck up a good bit of your time and money.

Also, always remember that when the intensity is zero, the phase is meaningless and so doesn’t need to be measured (indeed, it *cannot* be measured). And when the intensity is nearly zero, the phase is nearly meaningless. This is true in both the time and frequency domains. So, of course, FROG doesn’t measure the phase when the intensity is zero, like way out in the wings of the pulse. So please don’t worry about the random phase values way out in the wings of the pulse. All computer inversion algorithms just return random numbers for the phase when the intensity is zero. Just blank these phase values out in any paper you write using these measurements.

Pulse Analysis Tool Setup & Calibration

As described in the Overview, combining GRENOUILLE with pulse analysis tools extends the information you can retrieve from the pulse trace and includes the pulse intensity vs. time, the phase vs. time, the spectrum, the spectral phase, the spatial profile, the spatial chirp, and pulse-front tilt.

Before using these tools with GRENOUILLE, you'll need to calibrate them for your particular configuration. GRENOUILLE itself is fully calibrated during the final phase of its production, using the POLKADOT FROG technique. This involves placing an etalon in the beam and measuring the GRENOUILLE trace's fringes in delay and frequency, which determine very accurately the delay and wavelength calibrations. Appendix A contains the measured traces and relevant plots for this calibration.

This chapter describes configuration for the following frame-grabber and software tool options:

- Mesa Photonics' VideoFROG real-time pulse measurement frame-grabber and FROG/spatial-profile software

- Spiricon's frame-grabber/spatial-profile software combined with Femtosoft's FROG software

VideoFROG Setup

The VideoFROG software and hardware must be installed before GRENOUILLE can be set up. Please refer to the VideoFROG manual for installation and setup instructions, and follow the instructions in the Calibrating VideoFROG section below to calibrate VideoFROG for your specific GRENOUILLE and application.

Should you encounter any difficulties installing the VideoFROG software or hardware, a call to Dan Kane at Southwest Sciences, 505-984-1322, or to Mutech, 978-663-2400, should resolve any installation issues. You may also want to check the support section of the Mesa Photonics Web site: www.mesaphotonics.com.

The following sections outline VideoFROG setup by GRENOUILLE model.

VideoFROG Setup for the GRENOUILLE Model 8-50

<u>Note</u>: The instructions provided here correspond to Mesa Photonics VideoFROG.

1. Install the Mutech frame-grabber hardware and software and Mesa Photonics VideoFROG software following the directions outlined in the VideoFROG manual. Plug the color-coded, 5-wire cable shipped with the frame-grabber into the connector on the back plane of the Mutech frame grabber.

2. Find the round multi-pin connector on the GRENOUILLE power supply cable. Plug the connector into the GRENOUILLE camera.

3. Find the individual co-axial cable running from the round multi-pin connector used in step 2. This is the video out cable from the GRENOUILLE camera. Plug this cable into the green lead of the color-coded frame-grabber cable.

4. Double click on the VideoFROG Configuration icon which was placed on your desktop during the VideoFROG installation.

5. Select the VideoFROG Configuration tab and select 0 degrees for Raw Video Orientation. Close VideoFROG configuration, and then save changes when prompted.

6. Double click on the VideoFROG icon located on your desktop to open the VideoFROG program. Select the pull-down menu labeled View, and select FROG camera = Green. Then select Spatial Camera = Green.

7. Select the pull-down menu labeled Application, and select VideoFROG. Position your cursor on top of one of the axis numbers surrounding the live video window and click. This opens the Set Coordinates window where you can enter your calibration values. Find these values handwritten in the GRENOUILLE user manual on the page titled "Using GRENOUILLE with VideoFROG"

8. Refer to the VideoFROG manual for detailed descriptions of all of the VideoFROG features.

VideoFROG Setup for the GRENOUILLE Model 8-20

Note: The instructions provided here correspond to Mesa Photonics VideoFROG.

1. Install the Mutech frame-grabber hardware and software and Mesa Photonics VideoFROG software following the directions outlined in the VideoFROG manual. Plug the color-coded, 5-wire cable shipped with the frame-grabber into the connector on the back plane of the Mutech frame grabber.

2. Find the (2) round multi-pin connectors on the GRENOUILLE power supply cable labeled camera 1 and camera 2. Plug the connector labeled camera 1 into the top camera located on the back panel of the GRENOUILLE 8-20 device. Plug the connector labeled camera 2 into the lower camera located on the back panel of the GRENOUILLE 8-20 device. Plug the flat multi-pin power supply cable halves together. Now plug the power supply into an AC power outlet.

3. Find the 2 individual coaxial cables leading from the flat multi-pin power supply connector, labeled camera 1 and camera 2. These are the video out leads from the cameras. Plug the camera 1 BNC connector into the mating connector on the green frame grabber lead. Plug the camera 2 BNC connector into the mating connector on the blue frame grabber lead.

4. Double click on the VideoFROG Configuration icon which was placed on your desktop during the VideoFROG installation.

5. Select the VideoFROG Configuration tab and select 90 degrees for Raw Video Orientation. Close VideoFROG configuration, and then save changes when prompted.

6. Double click on the VideoFROG icon located on your desktop to open the VideoFROG program. Select the pull-down menu labeled View, and select FROG camera = Green. Then select Spatial Camera = Blue.

7. Select the pull-down menu labeled Application, and select VideoFROG. Position your cursor on top of one of the axis numbers surrounding the live video window and click. This opens the Set Coordinates window where you can enter your calibration values. Find these values handwritten in the GRENOUILLE user manual on the page titled "Using GRENOUILLE with VideoFROG"

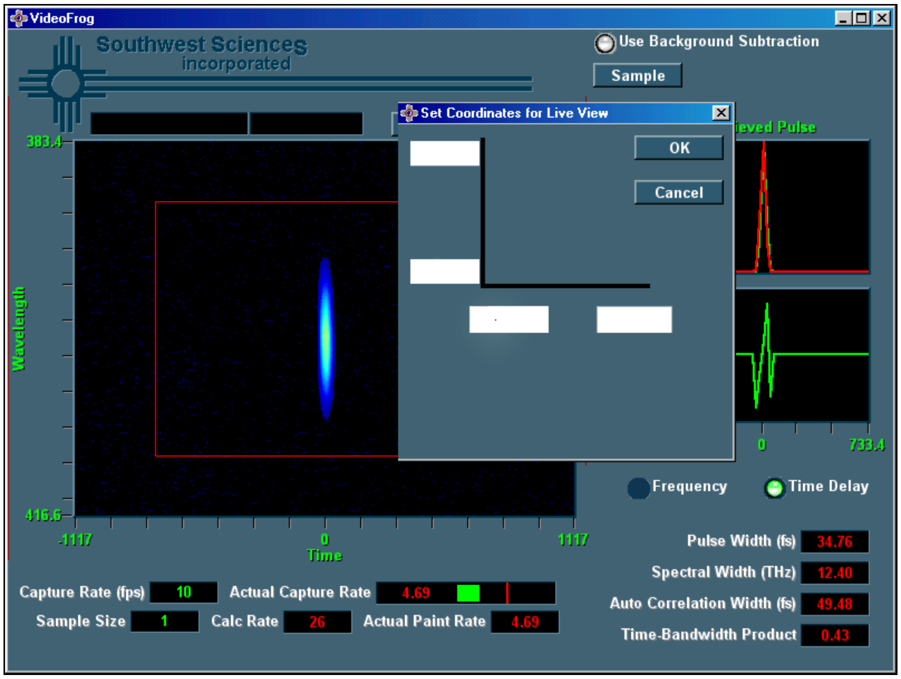
8. Refer to the VideoFROG manual for detailed descriptions of all of the VideoFROG features.

Calibrating VideoFROG

VideoFROG calibration steps vary slightly according to the GRENOUILLE model in use; refer to section appropriate to the GRENOUILLE model you're using.

VideoFROG Calibration for GRENOUILLE Model 8-50

1. Once VideoFROG has been installed, run the program and position the mouse cursor over one of the axis limit numbers, on either the x- or y-axis around the live display window, and left-click. The "Set Coordinates for Live View" window will appear. The VideoFROG window should look like Figure 2 below, where we've replaced the calibration numbers with white rectangles:



Capture Rate (fps) 10

Actual Capture Rate 4.69

Sample Size 1

Calc Rate 26

Actual Paint Rate 4.69

Pulse Width (fs) 34.76

Spectral Width (THz) 12.40

Auto Correlation Width (fs) 49.48

Time-Bandwidth Product 0.43

Figure 2: The main VideoFROG screen, with the "live view" configuration dialog displayed.

You will need to type the correct calibrations into these rectangles. This will involve taking numbers off the calibration chart in Appendix A and then perhaps making a wavelength correction.

Typical calibrations for VideoFROG on the calibration page look like:

$\Delta\tau$ = 3.53 fs/pixel (640 pixels)

$\Delta\lambda$ = 0.0754 nm/pixel (480 pixels) for a center wavelength, λ_0,of 800 nm

Note that these are not the calibrations for your particular GRENOUILLE; they're just an example. We'll now use them to show how to input the VideoFROG calibrations.

Note: The wavelength calibration depends on the central wavelength λ_0, which was 800 nm in our measurement of the calibration. If your laser operates at a wavelength other than 800 nm, you must multiply the $\Delta\lambda$ calibration by the Calibration Adjustment Factor found on the graph in Appendix A.

2. Use the central wavelength λ_0 to compute the central second harmonic wavelength, which is simply $\lambda_0/2$. Use this wavelength and the wavelength increment $\Delta\lambda$ to compute the minimum signal wavelength ($\lambda_{min} = \lambda_0 / 2 - 240\ \Delta\lambda$) and maximum wavelength ($\lambda_{max} = \lambda_0/2 + 240\ \Delta\lambda$). This is a lot of computing, but you only have to do it once (or until you change the wavelength).

Example: Suppose that your laser is tuned to 750 nm. The Calibration Adjustment Factor (from the graph in Appendix A) is 0.85. Your minimum and maximum wavelengths for use with VideoFROG are therefore as follows:

375 nm – 240 pixels x 0.85 x .0754 nm/pixel = 346.8 nm

375 nm + 240 pixels x 0.85 x .0754 nm/pixel = 389.1 nm

Note: The smaller wavelength appears on the top of the y-axis, and the larger wavelength appears on the bottom. In other words, wavelength decreases along the y-axis. So for this example, you'd input the y-axis limits of 346.8 nm for the upper value, and 389.1 nm for the lower value.

VideoFROG Calibration for GRENOUILLE Model 8-20

The GRENOUILLE Model 8-20 uses the same VideoFROG calibration procedure as outlined above for the Model 8-50 with this important difference: The Model 8-20 uses two cameras and does not have a Space/Time switch. Switching between temporal and spatial modes (temporal vs. spatial) is done by switching the camera input through VideoFROG. To switch between the Space and Time cameras, use VideoFROG's Application menu to select the Spatial Profile application for Space, and the Temporal Profile for Time.

Spiricon & Femtosoft Setup

The following setup steps are described in detail in the Help file in the Femtosoft Technologies FROG software and the Spiricon manuals, but we provide them here in addition for your convenience.

Before you can calibrate these tools for use with GRENOUILLE, you need to set up the Spiricon and Femtosoft FROG software to work with GRENOUILLE's camera. Follow these steps:

1. On the Spiricon menu bar and select the "Options" pull-down menu and choose "Camera."

2. Now find the "Camera" menu, and select "TM-7" for your camera. While in the "Camera" pull down, select your resolution.

   A setting of "1x" provides the full 512x480 resolution of the Spiricon frame-grabber. Use 1x resolution if you have a complicated FROG trace with a lot of structure. For simpler pulses, use "2x" resolution, which provides a 256x240 FROG trace. You could even use "4x" resolution, for a 128x120 trace, though it's better to use greater resolution; you can always reduce the resolution of a dataset, but you can't increase it after it's taken.

3. To save a FROG trace, go to the "File" pull down menu, and select "Save FROG as." A dialog box appears to prompt you for calibration information. (Note that the GRENOUILLE calibration varies according to wavelength!) Enter appropriate calibration settings from the plot in Appendix A, and ensure that the "Use header information" checkbox is checked.

4. Enter a file name for your FROG data and click the "OK" button.

5. Now open the Femtosoft Technologies FROG code. Select the "F" box in the upper left-hand corner, just under the "File" pull-down. This opens the FROG dialog box. Now select the grid size. The trick here is to use the smallest grid size that will contain the data, with no clipping. Start with a grid of 128. You can modify it later if necessary (if your pulses become more complex). Select "GRENOUILLE" as your beam geometry choice. Select "Experimental FROG trace" as your data source. Notice that a new "Exp.Data" dialog box appears. Type in the location and name of your data file, or click "Select file" and browse for the location. Click the "Use header information" if you typed in the calibrations when you saved the file, or enter your calibrations now. Select "Wavelength" as your order, and read in as "Constant wavelength." Take a moment to select a location for the code's "Outputs." After you are finished with this, click the "OK" button.

6. Now you will see the data grid with the experimental FROG trace. We usually use some sort of noise subtraction or filtration, if the data are noisy due to pulse shot-to-shot jitter, and these options are available under the "Noise subtraction" pull-down menu. The Femtosoft FROG software's Help file gives excellent details on the noise-suppression options. Basically, use filters to remove any background and noise in your trace, but try not to distort any of its large-scale features. We find that GRENOUILLE traces have so little noise that noise filtering is usually unnecessary.

    Nevertheless, we usually use some Background subtraction: first “Lowest-pixel” subtraction and then “Edge” subtraction.

    If the data don’t fill the grid, you may extract the data by placing your cursor in the grid, in the upper left hand corner of the data area, and, while holding down the left mouse button, move the mouse to draw a box around the FROG trace. When you have drawn the box, release the left mouse button, go to the “Data” pull-down, and select “Extract.” You should see the data that appeared in the box now occupying the entire grid.

7. When you are ready to launch the algorithm, click “Grid data.” Now the FROG algorithm screen appears. The experimental FROG trace (in a box labeled “Original”) is displayed in the upper left-hand corner, with the box for the retrieved trace just below it. Check to make sure that 1) your experimental data are not being clipped, and 2) that they are not occupying only a small section of the grid (i.e., the data should fill the frame).

    If clipping is evident, then you must go back and select a larger grid size, by clicking on the “F” box located just below the “File” pull-down in the upper left-hand corner and repeating the above process.

8. Now launch the FROG algorithm by clicking on “Begin.” Allow the algorithm to run until the FROG error stabilizes at a low value, typically less than 0.01. You can determine this by watching the “FROG error vs. Iteration” feedback box. When the FROG error has stabilized, and the retrieved FROG trace looks identical to the original FROG trace, click on “Stop.” Now, the retrieved pulse parameters appear in the “Results” dialog box.

9. The pulse intensity, phase, spectrum, and spectral phase will be placed in output files, which you can use later to plot, learn from, and publish. The measured trace, retrieved traces, and “marginals” are also available. Be sure to save these in a safe place.

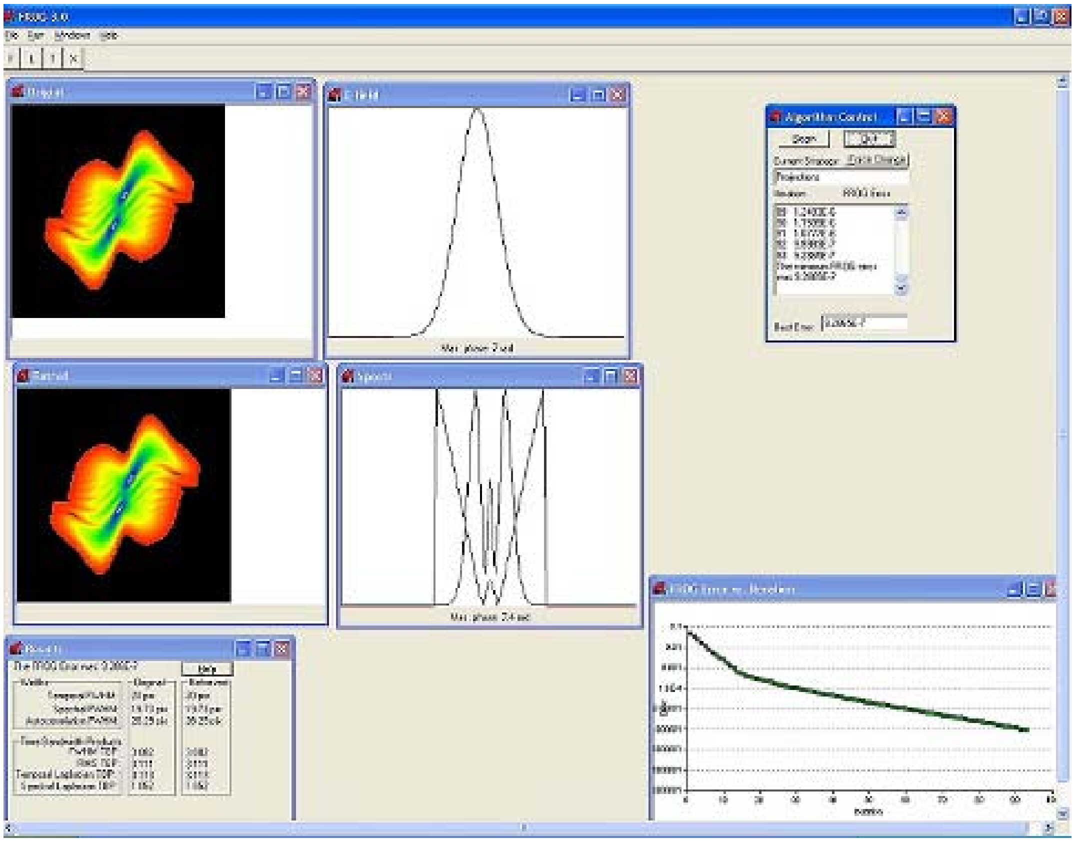


Figure 3: The main Femtosoft FROG software user interface showing original and retrieved FROG traces along with E-field and spectrum graphs. FROG algorithm controls, results, and error information appears in separate program windows.

Calibrating the Femtosoft FROG Code

GRENOUILLE Model 8-50 Calibration

In order to retrieve your pulse from its FROG trace, it is necessary to provide several parameters to the Femtosoft FROG code.

First, you need to provide the central wavelength of your pulse. It needn't be exact. Second, the FROG code requires the delay increment per pixel and the wavelength increment per pixel used. Fortunately, we have carefully calibrated your GRENOUILLE to determine the base numbers prior to shipping. What have to enter into the FROG code depends on the resolution selected in the Spiricon software, so be sure to enter the correct number:[2]

Resolution:	1x (512 x 480)	2x (256 x 240)	4x (128 x 120)
Number of delay points:	512	256	128
Number of frequency points:	480	240	120
Delay increment, in femtoseconds/pixel:			
Wavelength increment, in nanometers/pixel:			

The precise calibration of your GRENOUILLE was performed very accurately using the POLKADOT FROG technique. This involves placing an etalon in the beam and measuring the GRENOUILLE trace's fringes in delay and frequency, which very accurately determines the delay and wavelength calibrations. A page has been inserted into this manual with the measured traces and relevant plots for this calibration.

Note that the calibration depends on the wavelength, which we measured at 800 nm. If your laser operates at a wavelength other than 800 nm, you must multiply the $\Delta\lambda$ calibration by the Calibration Adjustment Factor found in Appendix A.

> **Example**: Suppose that your laser is tuned to 750 nm. The Calibration Adjustment Factor (from the graph in Appendix A) is 0.85. If your calibration is 0.0754 nm/pixel, the actual calibration for 750 nm for use with the Femtosoft FROG code is: 0.85 x 0.0754 nm/pixel.

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[2] The Spiricon code allows you to change the camera's resolution in software. The 1x resolution approximately corresponds to the camera's actual-sized pixels. For 2x resolution, the code just averages neighboring pixels, does a bit of interpolation, and divides the same physical area of the camera's CCD chip by fewer pixels. The same is true for 4x resolution, just more of it. So, if the camera's actual sized pixels were 13micron square, then for 2x resolution the code makes pixels that are 26 micron square, and for 4x resolution they are 52 micron square. The FROG code requires a per-pixel calibration value, so if the pixels are larger, then the calibrations must reflect that change.

GRENOUILLE Model 8-20 Calibration

The procedure for the 8-20 is the same as for the 8-50 above.

Basically the calibration is the same for the model 8-20. We made design changes to the Grenouille 8-20 which makes use with Spiricon a bit more complicated. For instance, we rotated the cameras in the 8-20 by 90 degrees to make better use of the camera's rectangular array. VideoFROG automatically transposes the array to put the saved trace in the correct format. Spiricon doesn't do this. So, in order to use a Spiricon-saved trace from the 8-20 in Femtosoft code, one must use another program (like Matlab) to transpose the array first. Another design is that we use two cameras in the 8-20. The Spiricon device supports one camera, which means that the user must switch cables between spatial and temporal measurements. However, Spiricon has an optional accessory that allows mulitiple cameras.

Setting Up Your GRENOUILLE

Adding GRENOUILLE to your Optical Table

GRENOUILLE's base features both ¼"-20 and #8-32 mounting holes. Use these holes to secure GRENOUILLE to your optical table using the mounting posts of your choice, and then adjust GRENOUILLE's height so that the center of its input aperture matches your beam height.

Cable Connections

GRENOUILLE Model 8-50

1. Connect the camera power supply to the GRENOUILLE CCD camera using the cable provided.

2. Using a coaxial cable (or other appropriate cable), connect the camera to a video monitor, or to the input connector of your frame grabber hardware if using VideoFROG or Spiricon/Femtosoft pulse analysis tools. Note that many video monitors have a "video-out" feature allowing simultaneous video feed to both a monitor and a frame grabber with no reduction of signal level.

GRENOUILLE Model 8-20

1. Find the two round multi-pin connectors labeled Camera 1 and Camera 2 on the GRENOUILLE power supply cable.

2. Plug the connector labeled Camera 1 into the top camera located on the back panel of the GRENOUILLE 8-20. Plug the connector labeled Camera 2 into the lower camera located on the back panel of the GRENOUILLE 8-20. Plug the flat multi-pin power supply cable halves together.

3. Plug the power supply into an AC power outlet.

4. Find the two individual coaxial cables leading from the flat multi-pin power supply connector, labeled Camera 1 and Camera 2. These are the video out leads from the cameras. You may connect these leads to video monitors, or directly to PC-based frame grabber hardware as described in the Model 8-20 sections of the VideoFROG and Spiricon configuration chapters.

Polarization and Input Beam Requirements

All GRENOUILLE models expect horizontal polarization when arranged with the GRENOUILLE logo at the side (i.e., when the camera(s) are above or below the beam entrance). As a helpful reminder, a two-headed arrow label on the input face of GRENOUILLE indicates the required input polarization. If your beam polarization is vertical, just rotate GRENOUILLE by 90° so that the GRENOUILLE logo is on top.

GRENOUILLE likes ~20 mW for 100-fs pulses from a 100-MHz rep-rate oscillator, or ~1 mW for 100-fs pulses from a 1-kHz rep-rate regen, but it can get by with about 1/10 that much if necessary. If your pulses are longer than 100 fs, you may need to send slightly more power into GRENOUILLE.[3] GRENOUILLE also likes a clean collimated input beam with a diameter of 2 to 4 mm.

To avoid saturating GRENOUILLE's camera during spatial profile measurements, GRENOUILLE includes a neutral density filter wheel in front of the camera, with several thicknesses of BG40 blue-transmitting filter glass. GRENOUILLE itself has an internal attenuation of about ND2 for spatial profile measurement, but you'll probably need more; [illegible] precise amount will depend on whether you're measuring low-energy pulses from an oscillator or high-energy pulses from an amplified system. You may, in the initial stages of alignment, set this wheel for no attenuation and then later rotate it to achieve additional attenuation.

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[3] Remember that GRENOUILLE uses second-harmonic generation (SHG), in which the signal intensity scales as the square of the input intensity, so longer pulses, which have correspondingly less intensity, will yield less signal power.

Aligning Your Beam into GRENOUILLE

GRENOUILLE is internally pre-aligned and should never misalign. To set it up to measure pulses, it's only necessary to get your beam into it. And you'll be amazed how easy this is. We'll measure the beam spatial profile first, which sends the beam directly onto the camera and bypasses the temporal-pulse-measurement optics.

1. Pick off a fraction of your beam setting up two alignable beam-steering mirrors to direct the beam into GRENOUILLE's entrance iris. It's probably best not use the pick-off optic as one of the beam-steering mirrors because tilting it will walk the transmitted beam that you plan to use in an important experiment.

2. Set GRENOUILLE to its spatial mode. If you're using GRENOUILLE Model 8-50, slide the "space-time switch" to the "space" position; on the Model 8-20, monitor the video output of the spatial camera (Camera 2).

3. Align the two beam-steering mirrors so that the beam enters the GRENOUILLE through the center of the entrance aperture. Try to align the beam so that it is also parallel to GRENOUILLE's sides in both the horizontal and vertical planes, not at an angle.

4. While monitoring the display, walk the beam, using the two beam-steering mirrors so that the beam spatial profile is precisely centered on the camera. Make sure that the beam also continues to be precisely centered in the entrance aperture. You can use GRENOUILLE's input iris to help center the beam by closing it down until you see diffraction rings.

5. Rotate GRENOUILLE's filter wheel to achieve a spatial profile that achieves the full dynamic range of the camera but doesn't saturate it. You're now measuring your beam spatial profile. It should be smooth and structureless, or else temporal (and other) measurements won't be accurate. (If it isn't smooth, check the Troubleshooting section at the end of this chapter.)

6. Finally, set GRENOUILLE to temporal mode. On the Model 8-50, slide the space-time switch to "time;" on the 8-20, monitor the output of the temporal camera (Camera 1). Set the wavelength knob to your pulse's wavelength, and you should now see the FROG trace of your pulse. If it's too high or low, tweak the wavelength knob a bit until it's nicely centered.

Congratulations! You've just set up your GRENOUILLE!

Troubleshooting

What if I don't see a trace at this point?

1. A missing trace is almost always due to incorrect input polarization. Check to see that your pulse polarization matches GRENOUILLE's orientation. The required input polarization is shown near GRENOUILLE's input aperture with a two-headed arrow. For more information, look back to the Polarization and Input Beam Requirements section.

2. Check to see that your laser is mode-locking (i.e., emitting short pulses). The laser should also have a broad spectrum. If it doesn't, tweak it according to the manufacturer's instructions.

3. Verify that your input pulse train has sufficient power. Refer to the GRENOUILLE specifications in Appendix C, and above, in the Polarization and Input Beam Requirements section.

4. Check that you've set GRENOUILLE's wavelength dial to the correct wavelength.

Also, although no Swamp Optics GRENOUILLE has ever become misaligned, if you're still having trouble after checking the above, it's possible that gorillas have stomped on it in shipping and caused some internal damage. Give us a call or send an e-mail; our contact information is listed in Appendix B.

I've read that tilt in the FROG trace indicates the pulse chirp. Why aren't my traces tilted when I send the pulse through a thick piece of glass and I know there's chirp in the pulse?

In some versions of the FROG technique, such as the polarization-gate (PG) version, the pulse slope mirrors the frequency vs. time. GRENOUILLE uses the second-harmonic-generation version of FROG, which necessarily yields a symmetrical trace without tilt. It still yields the pulse phase vs. time (and hence the frequency vs. time). Tilt in a GRENOUILLE trace indicates instead a spatio-temporal distortion: spatial chirp.

I've centered the beam spatial profile on the camera, but my GRENOUILLE trace is off center. Why?

Your beam may not be passing through the center of the input aperture. Close down GRENOUILLE's aperture iris to verify that the beam is centered on both the input aperture and the camera. That should do it. If your trace is still displaced, and the displacement is along the wavelength axis, just tweak the wavelength knob, and you'll be able to center your trace easily. If your trace is still displaced along the delay axis, your pulse has pulse-front tilt! This is how GRENOUILLE measures this quantity. If you're trying to create a pulse with pulse-front tilt, congratulations, you've done it. If, however, like most people, you're not, you may wish to re-align your pulse compressor and any other dispersive optics in the beam.

What if my beam spatial profile isn't smooth?

If your beam spatial profile isn't nice and smooth, then your pulse measurement could be biased, since GRENOUILLE, like other single-shot methods, assumes constant input-beam intensity across the trace area. Fortunately, GRENOUILLE requires so little input power, you can probably afford to invest some power in cleaning up the beam. So you can spatially filter the beam before GRENOUILLE or just expand the beam, taking only the middle region. You could expand it before the GRENOUILLE and just let GRENOUILLE's input aperture do this for you. This has the nice feature that it automatically centers your beam on the input aperture!

Helpful Procedures

Obtaining Very Precise Intensity and Phase Measurements

If you desire a very precise pulse measurement, be careful not to distort the pulse before it arrives at GRENOUILLE. It's best to use a thin substrate that's uncoated on the front and AR-coated on the back to pick off a few per cent of the beam. If you use the leakage from a high-reflector, perform a test to verify that it doesn't distort the pulse spectrum.

Also, place as little material in the beam as possible to minimize the group-velocity dispersion and resulting distortions in the pulse spectral phase (and hence in both the intensity and phase vs. time). Any such material in the beam before GRENOUILLE can distort very short pulses. Fortunately, this effect is exactly computed by theoretical back-propagation. There is MATLAB code for making this correction on the FROG web site (see www.physics.gatech.edu/gcuo/propagation.html).

There is some material inside GRENOUILLE (the cylindrical lens and Fresnel biprism), but each component is very thin, and their material dispersion is very small, so, as long as your pulse is longer than the minimum pulse length specified for the model you're using (see the device specifications, Appendix C), there should be negligible pulse distortion due to these components.

Using the FROG Trace to Align Your Laser

The real-time FROG trace displayed on your video monitor is quite useful for helping you align your laser and, in particular, your pulse compressor. Simply viewing the FROG trace while tweaking the compressor gives excellent qualitative feedback. On the GRENOUILLE Model 8-50,t he FROG trace is displayed on your monitor with delay as the horizontal axis, and frequency (wavelength) as the vertical axis. On the GRENOUILLE 8-20, the axes are reversed; delay is the vertical axis, and frequency (wavelength) is the horizontal axis.

You can minimize your pulse length by aligning your pulse compressor to minimize the FROG trace width of the horizontal axis. Or you can try to maximize the pulse spectral width by aligning to maximize the vertical width of the FROG trace. Also, the FROG trace area is roughly proportional to the pulse time-bandwidth product (TBP), so you can minimize the TBP by aligning to minimize the trace area.

Finally, a simple round FROG trace corresponds to a simple near-transform-limited pulse (possibly with some linear chirp), and a complex FROG trace corresponds to a complex pulse, and you can use this information to advantage as well.

Measuring Spatio-temporal Pulse Distortions: Spatial Chirp

Spatial chirp is a very common pulse distortion in which the different colors of the pulse are spatially dispersed across the beam. Because pulse compressors deliberately introduce massive spatial chirp in the beam (with the first two prisms) and then compensate for it (with the next two), this distortion usually results from an imperfectly aligned pulse compressor (see Figure 4). But it can also result simply from propagation through a simple tilted plane-parallel window (see Figure 5).

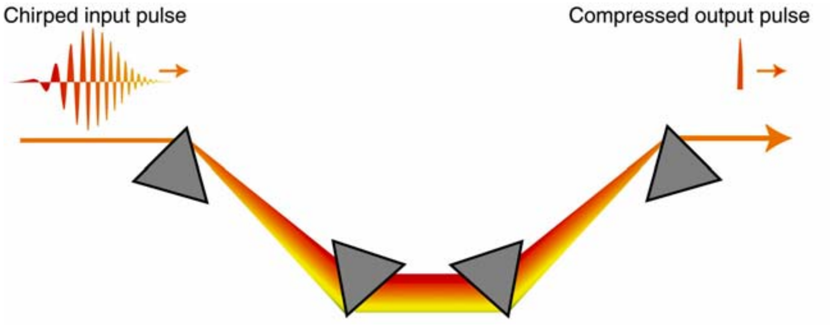


Figure 4: A prism pulse compressor, which uses four identical Bewster prisms (or two and a mirror), which often yields spatial chirp in a pulse. If the prism separations, apex angles, or incidence angles are not precisely the same, spatial chirp results. Even slight amounts of beam divergence or expansion inside this device can yield significant spatial chirp in the output pulse.

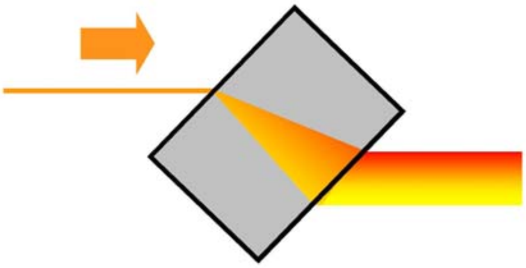


Figure 5: An ultrashort pulse propagating through a simple plane-parallel window. Even slight tilt of the window yields spatial chirp in the pulse, despite the absence of angular dispersion.

Note that a beam need not have angular dispersion in it to have spatial chirp. Note also that, at each point in the beam, a pulse with spatial chirp will be narrower-band than expected and hence can be longer than expected.

Unfortunately, it is difficult to measure spatial chirp. Autocorrelators do not measure it. It requires measuring a spatially resolved spectrum, but spectrometers can introduce this distortion themselves and hence are not reliable for this purpose. As a result, spatial chirp goes undetected on most ultrashort laser pulses.

Fortunately, GRENOUILLE automatically measures this pulse distortion, which appears as a tilt in the measured trace (which should otherwise be symmetrical with respect to delay. The magnitude and direction of the tilt yields the magnitude and direction of the spatial chirp (see Figure 6).

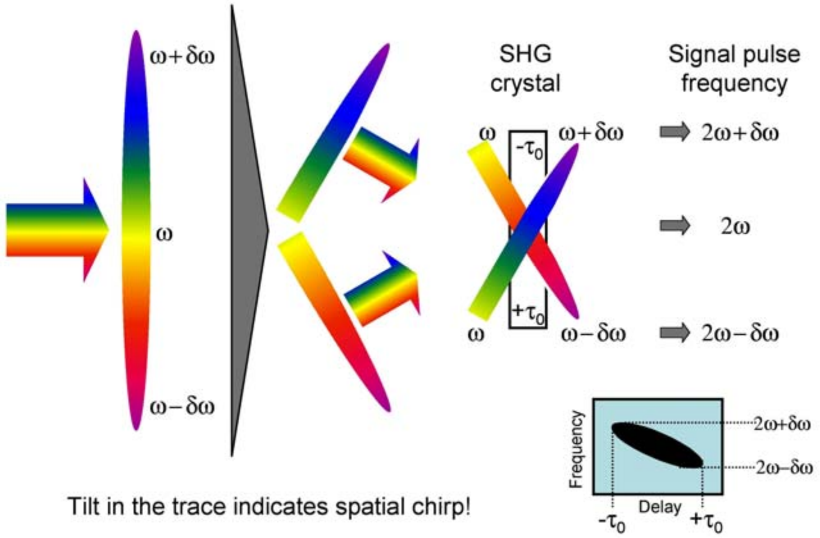


Figure 6: Spatial chirp and GRENOUILLE. A spatially chirped pulse enters the Fresnel biprism from the left. The Fresnel biprism splits the pulse into two, which then cross in the SHG crystal. While the crystal yields the autocorrelation signal of the pulse for the purpose of measuring its intensity and phase vs. time, spatial chirp causes a variation of the autocorrelation signal wavelength vs. distance (i.e., vs. delay). This yields a tilt in the GRENOUILLE trace proportional tot he magnitude of the spatial chirp.

A quantitative evaluation of spatial chirp from the GRENOUILLE trace is available in both Mesa Photonics' VideoFROG and Femtosoft FROG code. In the mean time, you can use the tilt in the trace as an indicator of this spatio-temporal distortion in order to align your laser and remove it.

Measuring Spatio-temporal Pulse Distortions: Pulse-front Tilt

Another spatio-temporal pulse distortion is pulse-front tilt. It involves the constant-intensity contours being tilted with respect to the propagation direction and results from uncompensated angular dispersion in the beam (see Figure 7).

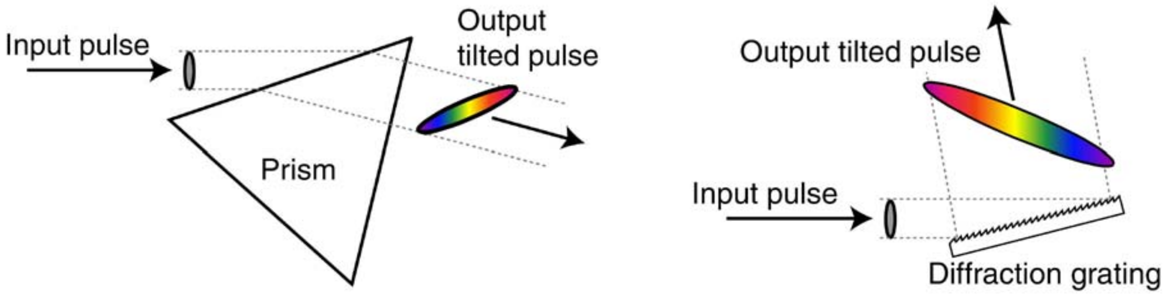


Figure 7: Pulses with the spatio-temporal distortion, *pulse-front tilt*. When a prism refracts a pulse, the rays that traverse more glass are slowed more by the prism than rays that traverse less glass. This is because the group velocity is less than the phase velocity. In a grating, the path is simply less for rays that strike the near edge of the grating. In general, pulse-front tilt results from dispersion of any sort. Note that these pulses also have spatial chirp.

It is also difficult to measure pulse-front tilt. You could try making two autocorrelations, one with the pulses spatially reversed, and one without, and comparing them. But since autocorrelation doesn't really tell you all that much about your pulse in the first place, you wouldn't really learn all that much from such a measurement.

Better is to realize that GRENOUILLE also *automatically* measures pulse-front tilt, which corresponds to a displacement of the GRENOUILLE trace in delay. If you carefully align your beam into GRENOUILLE, this works very precisely. Both the VideoFROG and Femtosoft FROG products provide this information.

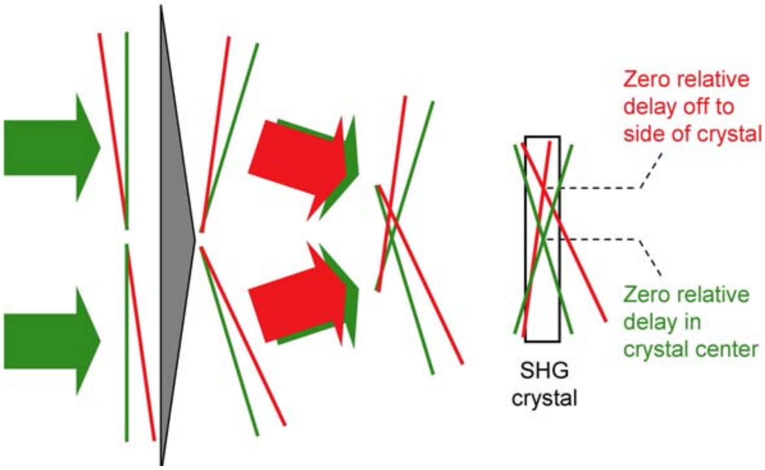
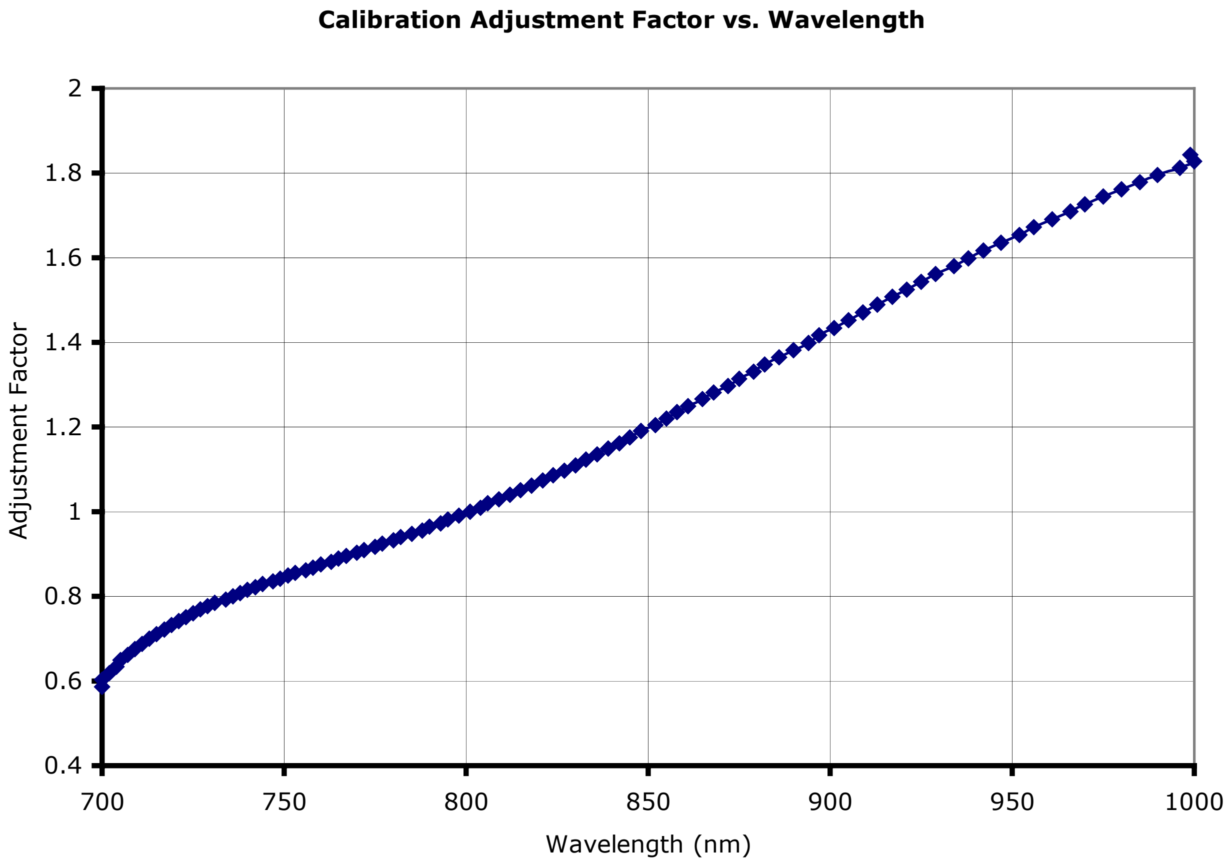


Figure 8: Pulse-front tilt and GRENOUILLE. Pulse-front tilt yields a displaced trace along the delay axis. The green-colored pulse has no pulse-front tilt; the red-colored pulse does. Note that this causes the zero-delay point to shift laterally in the SHG crystal (along the delay axis).

Appendix A: Calibration vs. Wavelength Plot

The wavelength increment is given here at 800 nm. It's different at different central wavelengths, so use this plot to correct this number if you're working at a different central wavelength.

To use the plot, just multiply the wavelength calibration (not the delay calibration!) by the value you pull from it for the wavelength you're using. For example, if you're working at 700 nm, multiply the calibration by 0.6. By the way, the plot includes both theoretical and experimental values.



Appendix B: Technical Support

Your GRENOUILLE should perform very well and be free of irritations. We've worked hard for several years to make GRENOUILLE a great and very polished product. And we've also worked hard to make this manual a complete, helpful, and polished piece of writing.

Nevertheless, if you have any problems with GRENOUILLE or anything related to GRENOUILLE, please let us know. We'll do everything we can to fix them for you. We'd like very much for you to be happy with GRENOUILLE. And anything we fix for you will be something we'll also fix for our future customers. Even more importantly, you and our future customers are also our colleagues, collaborators, and friends. We really want to do a great job.

By telephone, GRENOUILLE support is available Monday through Friday, from 10 a.m. to 6 p.m. eastern time. Please call us at

+1.404.54.SWAMP (+1.404.547.9267)

Via e-mail, support is available by sending a message to

support@swampoptics.com

When you contact us for help, please provide the following information:

- the GRENOUILLE model you're using
- your pulse width
- your laser's wavelength
- the laser model you're using
- the laser pulse repetition rate
- the average power of the beam aligned into the GRENOUILLE

Mesa Photonics VideoFROG

For help specific to VideoFROG installation and operation, contact Mesa Photonics. On the Web, you'll find them at www.mesaphotonics.com.

Spiricon/Femtosoft

For help specific to Spiricon or Femtosoft product installation or operation, please refer to them at www.spiricon.com and www.femtosoft.com.

Appendix C: GRENOUILLE Layout & Specifications

Inside GRENOUILLE

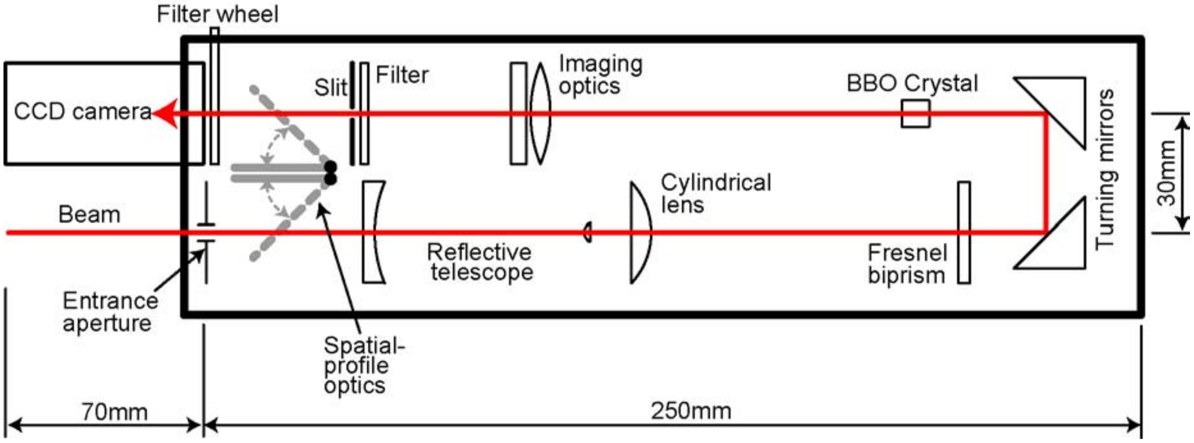


Figure 9: Schematic of GRENOUILLE internal components.

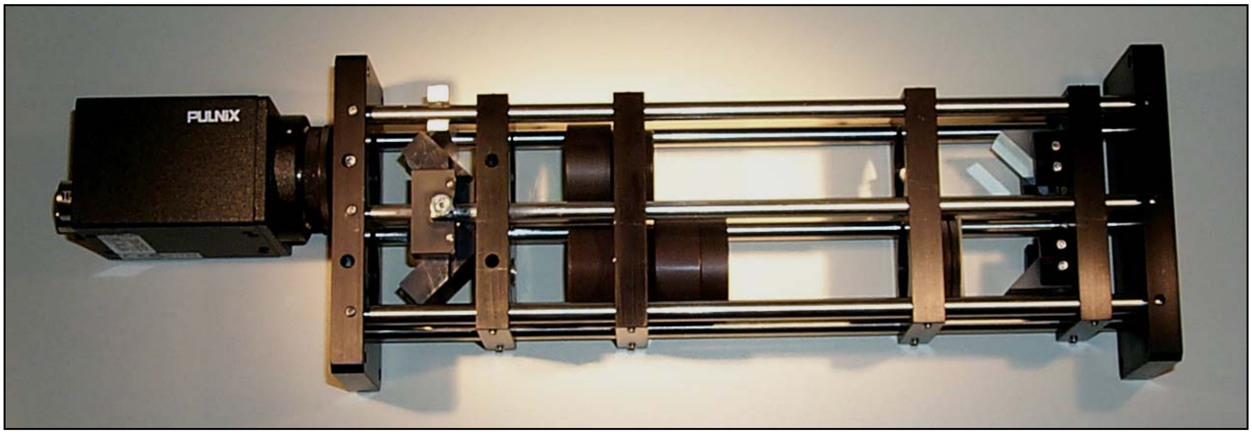


Figure 10: GRENOUILLE, without its colorful outer covering.

GRENOUILLE Specifications

GRENOUILLE model:	**Model 8-10**	**Model 8-20**	**Model 8-50**	**Model 8-500**
Wavelength range:	700 – 1100 nm			
Pulse-length range:	10 – 200 fs	18 – 120 fs	50 – 500 fs	500 – 5000 fs
Maximum pulse bandwidth:	150 nm	100 nm	35 nm	10 nm
Spectral resolution:	2 nm	4 nm	2 nm	0.1 nm
Pulse complexity:	Time-bandwidth product < 10			
Intensity accuracy:	2%			
Phase accuracy:	0.01 rad (intensity-weighted phase error)			
Sensitivity (at 10^8 pps):	10 mW (100 pJ)			
Sensitivity (at 10^3 pps):	100 μW (100 nJ)			
Sensitivity (single-shot):	n/a	1 μJ		
Spatial profile accuracy:	< 0.2 %			
Spatial chirp accuracy (dx/dλ):	1 μm/nm			
Pulse-front tilt accuracy (dt/dx):	0.05 fs/mm			
Required input polarization:	Any (just rotate GRENOUILLE!)			
Required input-beam diameter:	2 – 4 mm			
Input-beam lateral-displacement tolerance:	1 mm			
Number of alignment knobs:	Zero			
Time to set up:	~ 10 minutes			
Dimensions (L x W x H) w/camera:	33 cm x 7.5 cm x 16.5 cm	33 cm x 7.5 cm x 16.5 cm	33 cm x 4.5 cm x 11.5 cm	33 cm x 7.5 cm x 16.5 cm
Weight:	3 kg	3 kg	1.2 kg	3 kg
Available colors:	**Red**, **Yellow**, **Green**, **Blue**, **Black**			

Additional Notes

- Spatial chirp is easily and accurately revealed by tilt in the otherwise symmetrical measured trace.
- Pulse-front tilt is easily and accurately revealed by a displacement of the trace along the delay axis.
- Absolute wavelength is determined to a few nanometers by the accurately calibrated crystal-angle dial.
- GRENOUILLE is a second-harmonic-generation (SHG) FROG, and hence has an ambiguity in the direction of time, but this one-bit ambiguity can be removed using any of several simple methods.
- Feedback on measurement quality is obtained from the retrieved trace (as well as additional optional marginal measurements). Only FROG offers these assurances that a measurement is absolutely correct.
- The input-beam mode quality should be good, and GRENOUILLE's spatial-profile measurement capability helps you to ensure this.
- Single-shot measurement is available without modifying the device.
- Finally, GRENOUILLE is so easy to use that even aligning your beam into it involves an amazingly simple (~10 minute) procedure.

Appendix D: Frequently Asked Questions

How compact is GRENOUILLE?

So compact, you can carry it in your hip pouch. The GRENOUILLE Model 8-50, for example, measures 33 cm x 4.4 cm x 11.5 cm and weighs just 1.2 kg. GRENOUILLE's highly portable size is important because you never know when you might have to measure an ultrashort laser pulse! For full specifications, see the GRENOUILLE Specifications chapter.

Do FROG and GRENOUILLE require any assumptions about the pulse shape?

Absolutely not! FROG and GRENOUILLE yield the pulse intensity and phase vs. time (and vs. frequency) even for complex pulses.

How reliable are FROG and GRENOUILLE?

FROG is universally considered the most reliable ultrashort-pulse-measurement technique. The shortest pulse ever generated at the time of this writing (4.0 fs) was measured using FROG. Indeed, autocorrelation measurements (interferometric or otherwise) are no longer acceptable to claim a world's record short pulse.

GRENOUILLE is a simplified version of FROG and has similar performance, although it can't be used for pulses shorter than ~10 fs. Fortunately, Swamp Optics will soon offer a FROG for measuring pulses as short as 10 fs.

Can I use FROG or GRENOUILLE without buying the FROG software?

Yes! The FROG trace is a spectrogram of the pulse, a measure often preferred to the intensity and phase (especially in acoustics). Its horizontal width is a measure of the pulse width; its vertical width is a measure of its spectral width; and its area is a measure of the time-bandwidth product. You can, for example, align your laser in real time for the shortest pulse length by minimizing the horizontal width.

Why do I need the FROG software to determine the pulse intensity and phase when there is no such software to buy with an autocorrelator?

There is no software for an autocorrelator because it's impossible to determine the intensity or phase from an autocorrelation trace. The autocorrelation doesn't contain enough information to determine these quantities. The FROG trace, on the other hand, does. Of course, as we said above, you can use FROG or GRENOUILLE without the software, and you still have a lot more information than there is in an autocorrelation.

I've heard that the FROG software is complicated. Is this true?

Yes, the code is complex, but using it isn't. Your computer's Web browser is also a complex piece of code, but it's also easy to use.

Can measuring only the autocorrelation and spectrum (the so-called TIVI and PICASO methods) determine a pulse intensity and phase?

Occasionally this works; usually it doesn’t. You never know. Imagine a thermometer whose temperature reading might or might not be right….

I have an autocorrelator and spectrometer; must I buy a FROG or GRENOUILLE?

No! Just place the spectrometer behind the autocorrelator, and measure the spectrally resolved autocorrelation, and you have a FROG. You can then just buy the FROG software from Mesa Photonics, Femtosoft, MakTech, or Spiricon. We just saved you a bunch of money (not to mention the benefit to your research from such improved measurements)!

Another company’s pulse-measurement device requires the entire beam to operate. Is this true for FROG and GRENOUILLE?

No! FROG and GRENOUILLE are much more sensitive than other intensity-and-phase methods. GRENOUILLE, for example, requires only about 10 milliwatts of average power from a Ti:sapphire oscillator and about 100 microwatts from a regen.

Which option is better for me, Mesa Photonics' VideoFROG or Spiricon/Femtosoft?

Mesa Photonics' VideoFROG is specifically designed to operate with GRENOUILLE. It performs the retrieval of the pulse intensity and phase vs. time and frequency as rapidly as 20 pulses per second (depending on the computer) from the GRENOUILLE trace. It will also automatically compute the pulse spatio-temporal distortions from the measured trace. It also contains spatial-profile software, allowing you to see the beam spatial profile with just a flip of a switch. It's one integrated program that matches GRENOUILLE's capabilities.

Spiricon's spatial profile frame-grabber and software is one of the world's leading spatial-profile packages, offering tremendous power and a very user-friendly interface. When measuring the pulse's FROG trace, it allows the trace to be saved as a FROG trace for input into Femtosoft's FROG code for pulse retrieval. Femtosoft's FROG code is the gold standard of pulse-retrieval codes and is extremely versatile and complete, yielding numerous additional measures of the pulse that can be retrieved from the intensity and phase. It also can also be used with other FROG beam geometries that might be required for measuring pulses at unusual wavelengths or very low energies.

Okay, so FROG yields the intensity and phase vs. time. How about the spectrum, spectral phase, and group delay?

Simply Fourier transforming the time-domain electric field (fully determined by the intensity and phase vs. time) yields their frequency-domain equivalents, the spectrum and spectral phase. The derivative of the spectral phase is the group delay. The FROG software gives all of these quantities, except the group delay, which is easily calculated from the spectral phase. We can put it in the code if you like.

Is there an ambiguity in the direction of time in GRENOUILLE?

Yes, this is the case in all SHG-based pulse-measurement devices. Unlike autocorrelation, which has unaccountably many ambiguities, the direction-of-time ambiguity is essentially the only one in GRENOUILLE. If you’d like to remove it, just place an etalon in the beam before the GRENOUILLE [this is our POLKADOT (Procedure for Objectively Learning the

Kalibration And Direction Of Time)] option, which will be available soon. You can check out our paper on the subject: E. Zeek, A. P. Shreenath, M. Kimmel, and R. Trebino (2002). "Simultaneous automatic calibration and direction-of-time removal in frequency-resolved optical gating," *Applied Physics B (Lasers and Optics) B74(Suppl.)*, p.S265-71.

I understand that optics, crystals, and cameras aren't so broadband that one GRENOUILLE will work for all wavelengths, but will there be GRENOUILLEs for other wavelength ranges?

Yes. In fact, GRENOUILLEs for visible and the 1- to 2-micron wavelength range are on the way.

I have pulses at exotic wavelengths. Can you design a FROG to measure them?

Yes. Check the Custom Design Services page on our Web site (at www.swampoptics.com, under the Services menu) to learn more about our custom design capabilities.

What does the word "GRENOUILLE" stand for?

GRENOUILLE stands for "GRating Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields." It's the French word for "frog." We've chosen it to honor all the great French and French-speaking scientists who have contributed to the field of ultrashort laser pulse measurement, including Jean-Claude Froehly, J. A. Giordmaine, and Jean-Claude Diels.

I need to measure supercontinuum, and it's a very complex pulse. Autocorrelator company reps just laughed when I asked about this. Can you design a device to measure it?

Yes! Continuum is the most complex ultrafast light ever generated, but it's measurable. Only FROG can do it, and we can design one for you.

Why is GRENOUILLE so much less expensive than an autocorrelator? Am I really getting more for less?

GRENOUILLE is a very recent invention (by Rick Trebino) that takes advantage of two new and clever pulse-measurement ideas: a thick crystal as a spectrometer and the Fresnel biprism for beam-splitting and recombining. Swamp Optics has the exclusive rights to the relevant patent, so you are getting more. But Swamp Optics has no overhead, ruthless business ethic, or bloated middle-management. In fact, Swamp Optics has no managers at all! So you are in fact getting more for less! And, due to our small size, we can give you personal service and help.

Were any graduate student careers harmed in the formation of Swamp Optics?

No! In fact, GRENOUILLE was a student thesis project. So a grad student actually benefited from this endeavor!

Will I need an all-day intensive training session to use FROG or GRENOUILLE?

No! Setup is straightforward and takes less than 10 minutes on average. (See GRENOUILLE Overview chapter at the beginning of this manual.)

Will I need a specialist to come and set up the FROG or GRENOUILLE?

No! A simple setup procedure and clear instructions make this an easy, do-it-yourself job.

Does the GRENOUILLE box have a color selection?

Yes! The GRENOUILLE box comes in classic black, blood red, bright yellow, navy blue, and emerald green.

Can I get a job at Swamp Optics?

Sorry. To keep prices down, we're limiting our size. And no managers under any circumstances. But feel free to e-mail, call, or visit.

Do you have international distributors?

Yes. Our international distributors include:

- Hikari, Inc. for Japan
- Optoprim for France, Belgium, and Switzerland
- Photonic Solutions for UK and Eire
- Sesim Photonics Technology for Korea
- SUPER Optronics for China and Taiwan

Does Swamp Optics have a snappy slogan?

Yes! "Size doesn't matter; it's how you measure it!"

Appendix E: GRENOUILLE Tutorial

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.

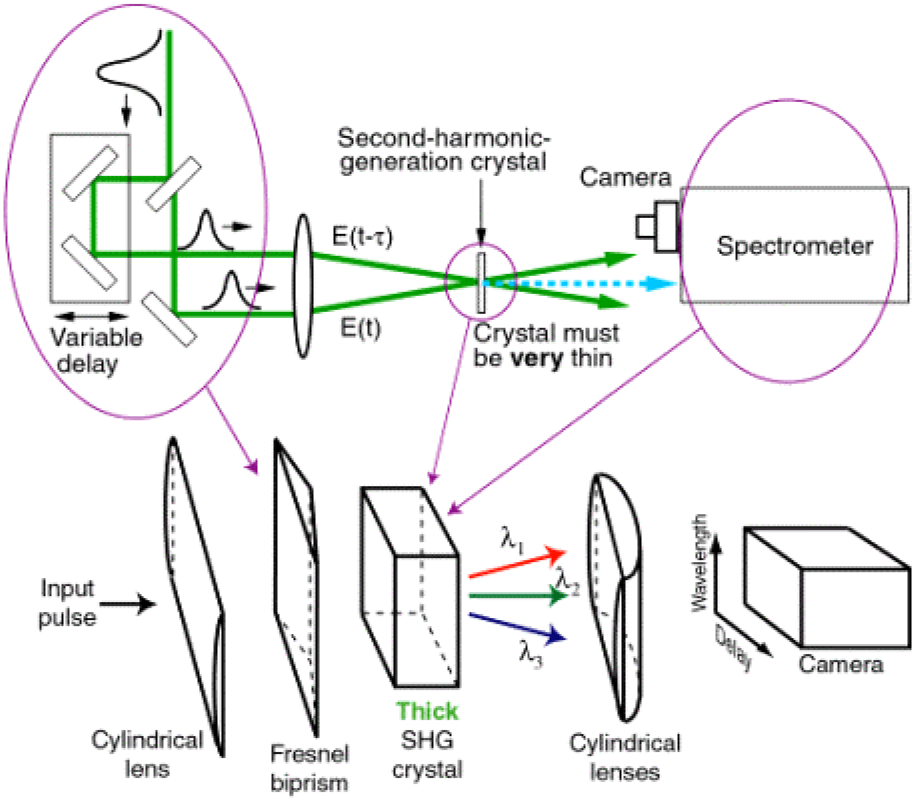


Figure E-1: Top: SHG FROG. While SHG FROG is the simplest intensity-and-phase ultrashort-pulse-measurement device, there are a few components of it that we'd like to eliminate to simplify it. Bottom: GRENOUILLE, which involves replacing the complex elements of SHG FROG with simpler ones. GRENOUILLE uses 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.

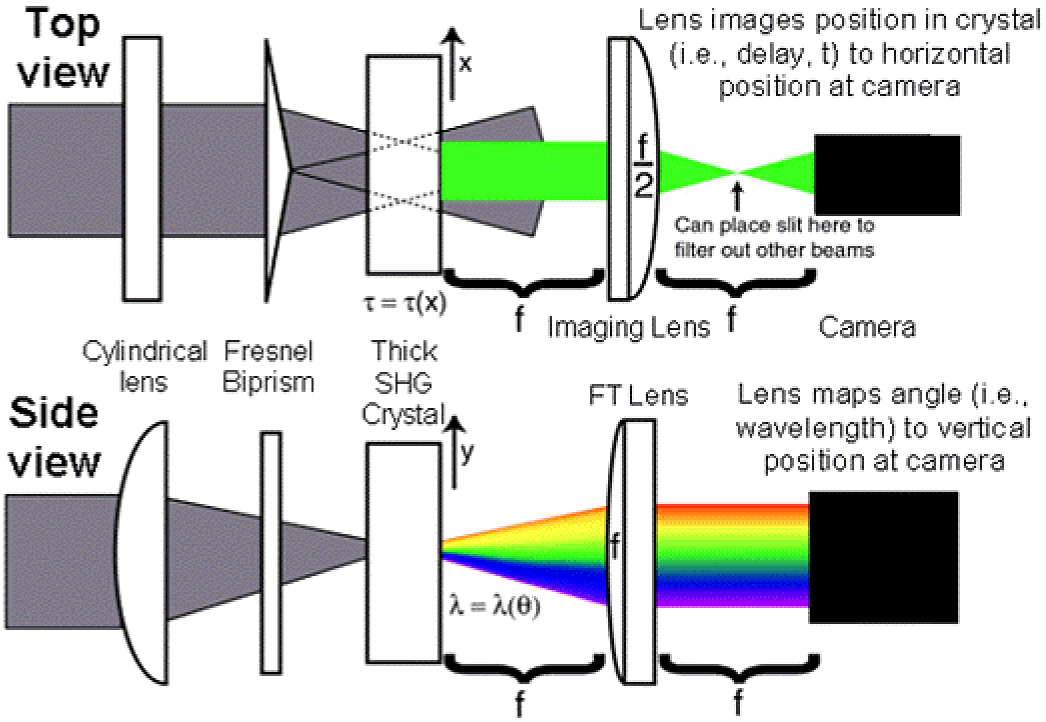


Figure E-2: Side and top views of the GRENOUILLE beam geometry of Figure E-1. Here, convenient focal lengths are shown for the two final cylindrical lenses (f and f/2).

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").

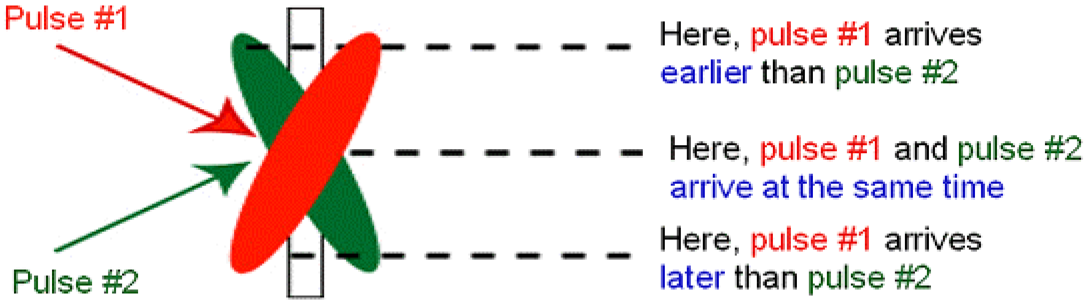


Figure E-3a: Crossing beams at an angle maps delay onto transverse position.

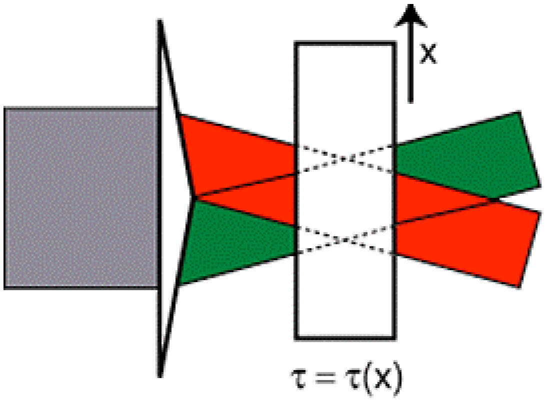


Figure E-3b: Crossing beams at an angle using a Fresnel briprism (different colors are used to distinguish the beams). Note that the beams are automatically aligned in space and time.

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*.

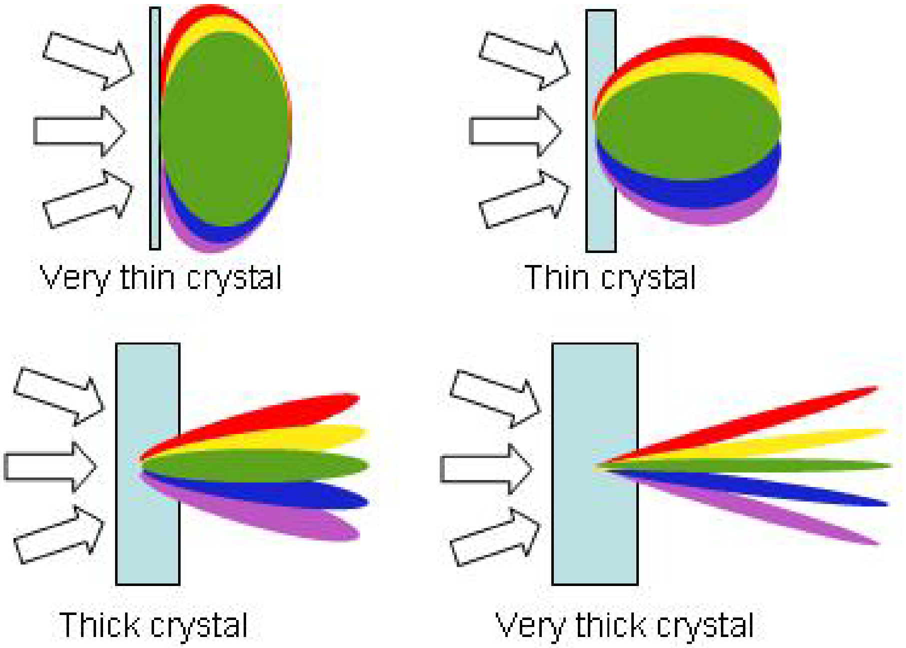


Figure E-4: Thin and thick SHG crystals illuminated by converging broadband light and polar plots of the generated colors vs. crystal exit angle. Note that the very thin crystal (ordinarily required in pulse-measurement techniques) generates the second harmonic of all colors in the forward direction. 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: $\mathrm{GVM} \bullet L << \tau_p$.

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

$$\mathrm{GVM}\ L >> \tau_p \tag{1}$$

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:

$$\mathrm{GVD}\ L << \tau_c \tag{2}$$

where $\mathrm{GVD} \equiv 1/v_g(\lambda_0 - \delta\lambda/2) - 1/v_g(\lambda_0 + \delta\lambda/2)$, $\delta\lambda$ 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:

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

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

$$\mathrm{GVM} / \mathrm{GVD} >> \mathrm{TBP} \tag{4}$$

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 E-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.

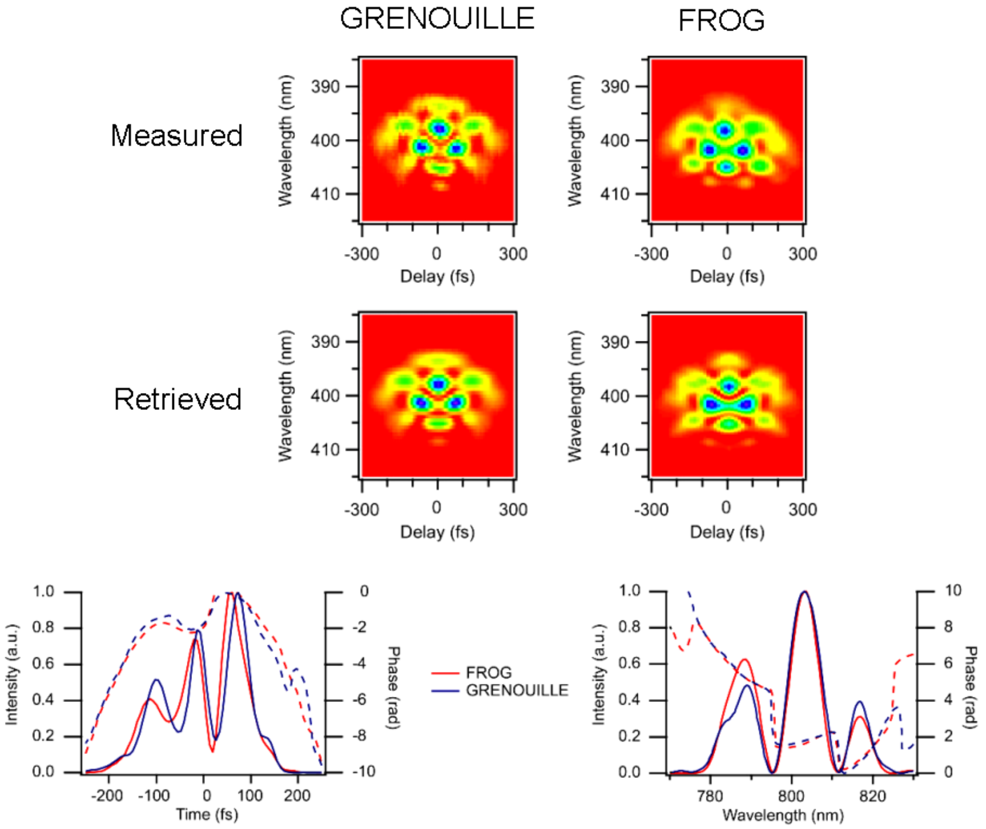


Figure E-5: Comparison between GRENOUILLE and FROG measurements of a complex test pulse.

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).

Appendix F: About Swamp Optics

Founded in 2001, Swamp Optics offers recently invented innovative and cost-effective devices for measuring ultrashort laser pulses.

We specialize in frequency-resolved-optical-gating (FROG), the most robust and reliable method for measuring the time-depended intensity and phase of an ultrashort pulse. FROG is rigorous, general, and relatively simple to implement, and it has become a very successful technique with many accomplishments.

Swamp Optics' founder is Rick Trebino, a specialist in ultrashort-laser-pulse measurement, and the Georgia Research Alliance-Eminent Scholar Chair of Ultrafast Optical Physics at the Georgia Institute of Technology.

Rick Trebino

Appendix G: Legal stuff

GRENOUILLE is a pretty safe device. Not much can go wrong with it and hurt you. But if you’re really tired or careless, you could inadvertently reflect a beam from your laser off one of the beam-steering mirrors needed to send the beam into it, or off the GRENOUILLE itself and hurt an eye. And who knows what else could happen? Please take the same care in using GRENOUILLE as you would with any other device that operates with lasers, and everyone will be safe and happy.

GRENOUILLE has been produced patented under licenses from Sandia National Labs and Georgia Tech.

Finally, if you’re still reading at this point, you really should get into the lab and get some work done!

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