

Part 5—Appendices

Appendix A—Classification of Laser System Performance

This appendix contains a description of the methods used to classify the performance of the lasers used in the infrared cavity ringdown (IR-CRD) spectrometer (described in Chapter 2). In general, our lasers should perform as well as listed for daily use. If the energy per pulse or energy fluctuations do not meet the listed specifications, the user should replace the flashlamps in the Nd:YAG and/or realign the laser system. If performance is still unacceptable, one or more lasers may require repair. A list of repairs made to the previous Nd:YAG laser (Quantel YG-661) can be found in Appendix B, though by no means is this an exhaustive list of fixes for a broken laser.

Introduction

As described in Chapter 2, the performance of a pulsed IR-CRD spectrometer is dependent on both the average energy per laser pulse, and the pulse-to-pulse energy fluctuations. The average energy per pulse will determine the ringdown amplitude, according to Equation A.1:

$$V_0 = \mathfrak{R} \times A \times \frac{(1-R)^2 c E_{IR}}{L_{opt}} (X), \quad (\text{A.1})$$

where V_0 is the ringdown amplitude, \mathfrak{R} is the photovoltaic responsivity of the photodiode (in A/W), A is the transimpedance amplification (in V/A), R is the cavity ringdown mirror reflectivity, L_{opt} is the cavity length, c is the speed of light, E_{IR} is the energy per pulse of the incident infrared light, and X is the fraction of light entering the cavity that couples to cavity modes. As E_{IR} becomes larger, the ringdown amplitude also becomes larger, allowing for a larger quantity of ringdown data to be collected before reaching the noise

limit of the detector. Additionally, increasing E_{IR} allows for higher reflectivity mirrors can be used, which increases the sensitivity of the instrument.

Cavity ringdown spectroscopy is theoretically insensitive to energy fluctuations; nonetheless, it is important to keep these fluctuations to a minimum because of data collection considerations. Ringdown data are sent to a 14-bit digital oscilloscope (Gage CompuScope CS1450), with a variable maximum detectable voltage ($\pm 0.1, 0.2, 0.5, 1, 2,$ or 5 V). In order to obtain high quality ringdown data, the oscilloscope's data range is set so that the ringdown amplitude is nearly equal to the maximum detectable voltage. If very large fluctuations in incident energy are present, successive pulses may either exceed the selected data range (causing clipping of the ringdown signal at short times), or have an amplitude well below the selected data range (leading to lower quality ringdown data). Both cases can lead to incorrectly fit ringdown traces, and thus noisy or incorrect spectra.

Average Energy Measurement Methods

The average pulse energy out of the YAG and dye lasers was measured using a volume absorbing power meter (Scientech AC2501). The power meter was calibrated at 1064 nm, and no corrections were made to the reported energies for other wavelengths of light. It was observed that this power meter had a slow response time before “settling into” the actual power reading. To account for this, laser light was allowed to strike the power meter for 15 seconds before recording the average power.

The average pulse energy of the NIR and MIR light (out of the Raman shifter and OPA respectively) were measured with a joulemeter (Newport 818E) connected to an

oscilloscope with 1 M Ω termination (see the next section for a discussion of impedance choice). When IR light strikes the joulemeter, a voltage is sent to the oscilloscope. This voltage can be converted to pulse energy using Equation A.2:

$$E_{IR} = V_{IR} \left(\frac{E}{V} \right)_{1064} \left(\frac{A_{1064}}{A_{IR}} \right), \quad (\text{A.2}),$$

where E_{IR} is the energy per pulse of the IR light, V_{IR} is the voltage reported by the oscilloscope, $(E/V)_{1064}$ is the conversion factor from voltage to energy for 1064 nm light, and A_{1064}/A_{IR} is the absorbance ratio of the joulemeter for 1064 nm light and the IR light of interest. For our joulemeter, $(E/V)_{1064} = 1 \text{ J} / 104.7 \text{ V}$. A typical value of A_{1064}/A_{IR} is 1.15 for 1370 nm light (central wavelength of the NIR range). A full chart is provided in the joulemeter manual for conversion to other wavelengths.

Table A.1 contains the performance data for the first laser setup used in this thesis (fully repaired Quantel YG-661 Nd:YAG laser, longitudinally pumped DCM dye laser), while Table A.2 contains the performance data for the second laser setup (Continuum Surelite III Nd:YAG laser, transversely pumped DCM dye laser). Both tables report the energy and energy fluctuations (1σ) for the Nd:YAG laser (oscillator, amplifier, and second harmonic generator), dye laser (at 640 nm, the center of DCM dye's range), and the Raman shifter (7283 cm^{-1}). To control the energy out of the Nd:YAG lasers, we adjusted either the flashlamp voltage (YG-661) or the q-switch delay time (Surelite III). The average energy and fluctuations were recorded on separate days. However, long term measurements of our laser data show that the data reported in Tables A.1 and A.2 are reproducible, and are thus representative of the overall laser system performance.

Table A.1. Laser Performance with Quantel YG-661 Nd:YAG laser^a

Flashlamps (kV)	1064 nm osc (mJ)	1064 nm amp (mJ)	532 nm (mJ)	Dye ^b 640 nm (mJ)	IR 7283 cm ⁻¹ 140 psi H ₂ (μ J)	IR 7283 cm ⁻¹ 200 psi H ₂ (μ J)
1.00	18.1 ($\pm 1.2\%$) ^c	111	14.4 ($\pm 6.4\%$)	0.1 ($\pm 18\%$)	—	—
1.05	38.2 ($\pm 0.8\%$)	205	49.4 ($\pm 3.5\%$)	2.3 ($\pm 8.0\%$)	—	—
1.10	60.1 ($\pm 0.7\%$)	290	94 ($\pm 2.4\%$)	6.3 ($\pm 5.5\%$)	—	—
1.15	84.1 ($\pm 0.6\%$)	371	146 ($\pm 1.5\%$)	10.8 ($\pm 4.5\%$)	—	—
1.20	111 ($\pm 0.5\%$)	450	192 ($\pm 1.3\%$)	15.0 ($\pm 4.7\%$)	—	—
1.25	137 ($\pm 0.5\%$)	523	234 ($\pm 1.2\%$)	18.2 ($\pm 5.0\%$)	24 ($\pm 23\%$)	35 ($\pm 29\%$)
1.30	169 ($\pm 0.5\%$)	—	285	20.2	41 ($\pm 13\%$)	51 ($\pm 16\%$)

a) Q-switch delay kept constant at 355 μ s

b) DCM dye, longitudinally pumped amplifier, no preamp installed. Oscillator 175 mg/L, amplifier 28 mg/L

c) Fluctuations are reported as 1σ

Table A.2. Laser Performance with Continuum Surelite III Nd:YAG laser^a

Q-sw delay (int, μ s)	1064 nm (mJ)	532 nm ^b (mJ)	Dye ^c 640 nm (mJ, w/preamp)	IR 7283 cm ⁻¹ 245 psi H ₂ (μ J)
160	140 ($\pm 2.5\%$) ^d	24 ($\pm 10.5\%$)	1.4	—
170	248 ($\pm 1.0\%$)	72 ($\pm 3.3\%$)	7.8	—
180	394 ($\pm 0.7\%$)	160 ($\pm 2.2\%$)	18.9	19 ($\pm 51\%$)
190	501	225	25.4	74 ($\pm 25\%$)
200	607 ($\pm 0.6\%$)	288 ($\pm 1.3\%$)	30.0	92 ($\pm 20\%$)
220	721 ($\pm 0.4\%$)	348	33.0	89 ($\pm 22\%$)
240	756 ($\pm 0.3\%$)	365 ($\pm 1.5\%$)	34.0	—

a) Flashlamp voltage kept constant at 1.39 kV

b) External second harmonic generation: Inrad 5-302 SHG (Type II) with temp controller

c) DCM dye, transversely pumped amplifier, preamp installed. Oscillator and preamp 270 mg/L, amplifier 90 mg/L.

d) Fluctuations are reported as 1σ

Pulse-to-Pulse Energy Fluctuation Measurement Methods

It is impossible to use the volume absorbing power meter to measure pulse-to-pulse fluctuations of the YAG or dye lasers due to its slow response time (15 seconds) compared to the time between pulses (0.1 seconds). Instead, a Si photodiode (ThorLabs DET210) was used to collect scattered laser light. NIR and MIR light was still collected with a joulemeter (Newport 818E). 255 consecutive pulses were sent to the CompuScope 1450 card (50 MS/s sampling rate, 20 ns period between samples), and saved to disk using GageScope 3.0 software (see the next section for a caveat on saving the pulses to disk). The height and timing of these pulses were analyzed to determine the standard deviation for shot-to-shot energy.

The Si photodiode and joulemeter are both designed to be 50 Ω terminated. However, using the correct termination cause problems when the laser pulse being observed is as short as or shorter than the period between consecutive samples (20 ns). Artificial changes in amplitude will be observed due to the timing jitter, resulting in an apparent energy fluctuation that is larger than the actual distribution.

The above point can be proven very easily. A function generator was used to generate a sine wave (269 ns period, 3.84 MHz frequency, 245 mV peak-to-peak amplitude). The sine wave was sent to the CompuScope card, and the signal was recorded for sampling rates of 50, 25, 10, and 5 MS/s. Figure A.1 shows the recorded waveforms.

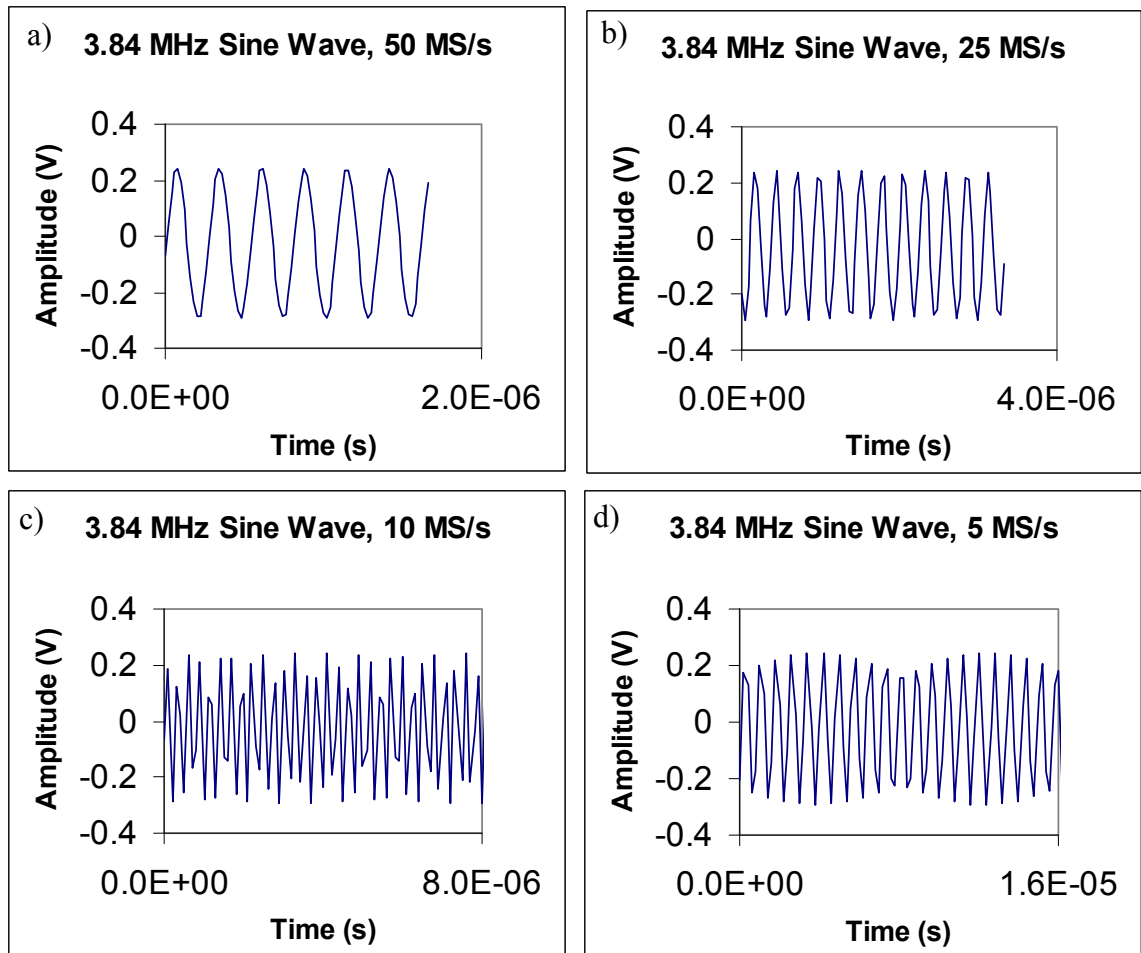


Figure A.1. Waveforms collected for a sine wave input (3.84 MHz frequency) to our PC oscilloscope card (GaGe CompuScope CS1450) set to sampling rates of 50 MS/s (a), 25 MS/s (b), 10 MS/s (c), and 5 MS/s (d).

At 50 and 25 MS/s, the constant amplitude out of the function generator is reproduced reasonably well. At 10 and 5 MS/s, the peak amplitude appears to be fluctuating, despite not adjusting the function generator. This is not surprising: since the sine frequency and the scope sampling rate do not match (and also are not multiples of each other), the CompuScope card samples different parts of the sine wave during each period. The result is that the sine wave's amplitude appears to be fluctuating.

Based on this analysis, it should be clear that the same sampling issue will occur when measuring peak heights of our laser pulses on the oscilloscope. The FWHM of our laser pulses is less than 10 ns, as confirmed on an oscilloscope with a very high sampling rate (2.5 GS/s, 0.4 ns period between samples). Because the CompuScope can only sample every 20 ns, we expect that the limited sampling rate of the CompuScope will make the apparent peak fluctuation larger than the actual fluctuation.

Our solution to this problem is to “spread out” the peak over a time period greater than 20 ns. We can do this by changing the impedance of the oscilloscope to 1 M Ω , rather than the expected 50 Ω . When light strikes the photodiode, the voltage produced will charge the BNC cable due to impedance mismatching. This has the effect of creating a “signal plateau,” as shown in Figure A.2. It can be shown that the average height of this plateau (after subtracting out the nonzero baseline) is proportional to the average energy measured with our power meter. This indicates that the plateau height is a measure of shot energy, and can be used as a substitute for peak height in our energy fluctuation analysis.

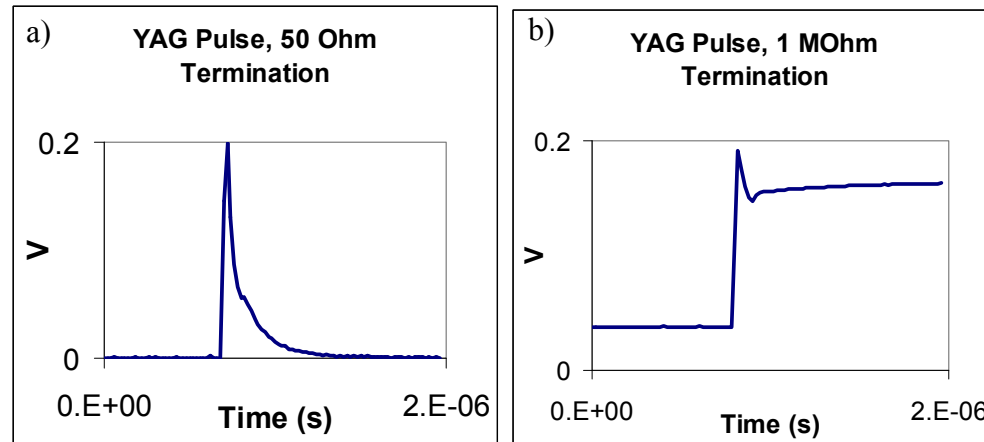


Figure A.2. Comparison of measurements of 532 nm light scattered to a Si photodiode, with CompuScope termination of 50 Ω (a) and 1 M Ω (b). After subtracting out the baseline, the average plateau height is proportional to the average power measured with a power meter, indicating that plateau height is a measure of shot-to-shot energy.

Issue with Saving “MultiRec” ASCII Waveforms

As described above, in order to measure pulse-to-pulse fluctuations, 255 consecutive pulses were collected, saved to disk using GageScope 3.0 software (Build 494), and analyzed. Consecutive pulses can be recorded using the “MultiRec” function of the GageScope software. However, a bug in the software prevents saving all 255 pulses to a single file in ASCII format. If the MultiRec feature is used, the user must save each pulse as a separate file.

In order to illustrate this bug, 255 consecutive near IR pulses were collected by a PDA400 InGaAs detector, and recorded by our CompuScope CS1450 board. The signals from these 255 pulses were displayed in GageScope, and the signal was saved to disk in the GageScope native file format (SIG), as well as to ASCII format (ASC). When saving a multirecord file, the user is given the option to save all of the records appended to one large file, or to split into many single-record files.

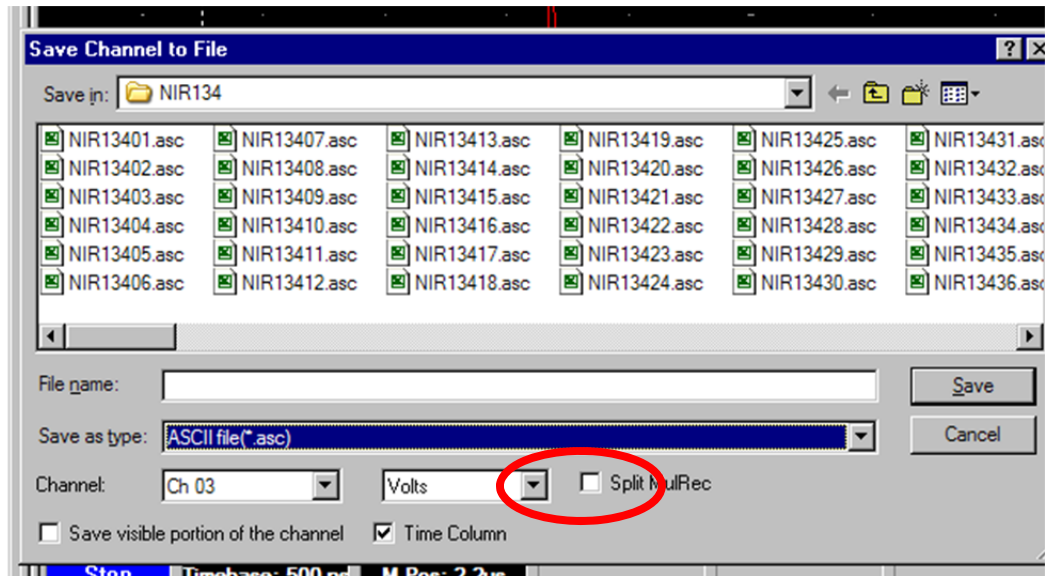


Figure A.3. The “Split MulRec” checkbox (circled) in the GageScope program determines whether or not multiple oscilloscope traces are saved as one large file (unchecked), or split into individual files (checked).

There are no issues saving multiple pulses to one SIG file, and consequently only one SIG file is needed to store the 255 pulses. However, there are issues saving ASC files. Consider the first four records in the set of 255 pulses, saved as a SIG file and displayed in GageScope (Figure A.4). We notice that although the amplitude of the ringdown varies (due to laser fluctuations), the program is able to record each pulse properly.

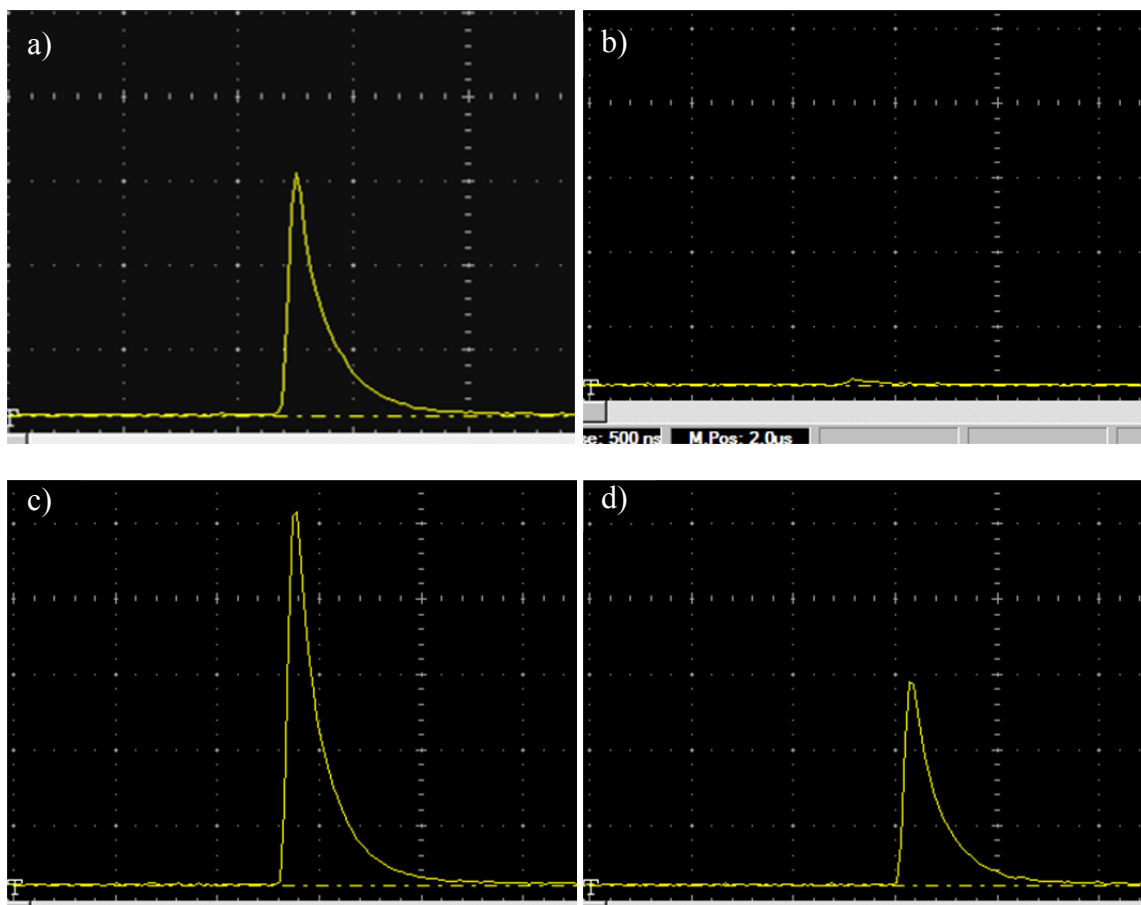


Figure A.4. Records 1 (a), 2 (b), 3 (c), and 4 (d) of the 255 consecutive NIR pulses collected, displayed in GageScope 3.0. The records were saved in GageScope’s native SIG file format. The width of each window is roughly 3 μ s.

Now consider the same records when saved into ASC files. The waveforms can be plotted in Excel. If we check the “Split MulRec” button, then we obtain 255 files with one waveform stored in each. The first four records obtained this way are presented in Figure A.5. Note that when saving the waveforms in ASC format and enabling “Split MulRec,” the ASC waveforms match the SIG waveforms. This indicates that GageScope is saving the individual records properly.

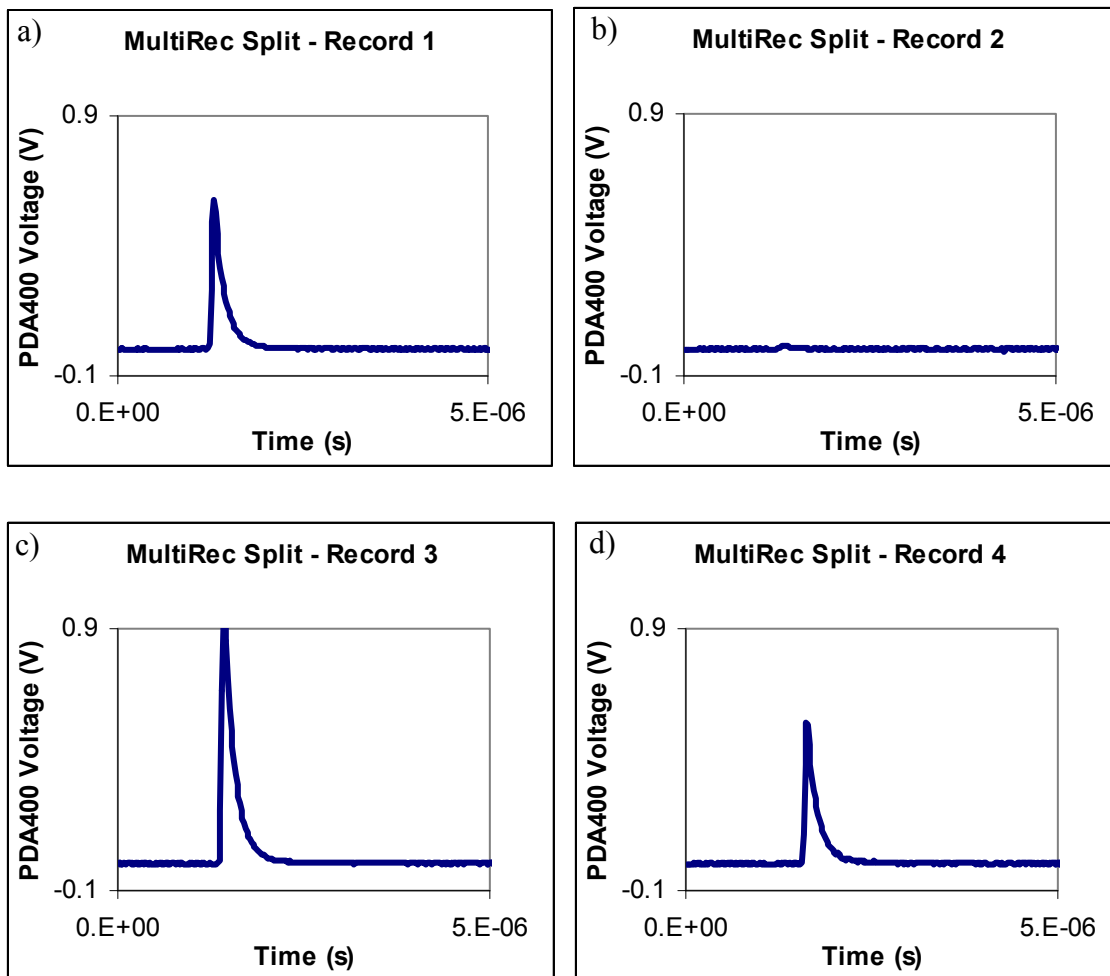


Figure A.5. Pulse records 1 (a), 2 (b), 3 (c), and 4 (d) in ASC format, using the “Split MulRec” option. The shapes of these records match the shapes in Figure A.4.

On the other hand, if we save the waveforms to ASC format without using “Split MulRec,” then we obtain the plots in Figure A.6. Note that only the first record is recorded properly in Figure A.6. All further records in the single file are corrupted, and do not show the measured pulse. This issue persists regardless of voltage range, time scale, or most other settings on the CompuScope board. However, the bug disappears when the CompuScope is set to certain sampling rates (50 MS/s, 100 kS/s). It is possible that this bug has been corrected in later versions or builds of the GageScope software.

However, the current software used in 17 Noyes suffers from this bug. In order to do correct analyses of multiple record files, we must split the file first, and then use a LabVIEW program to recompile the data.

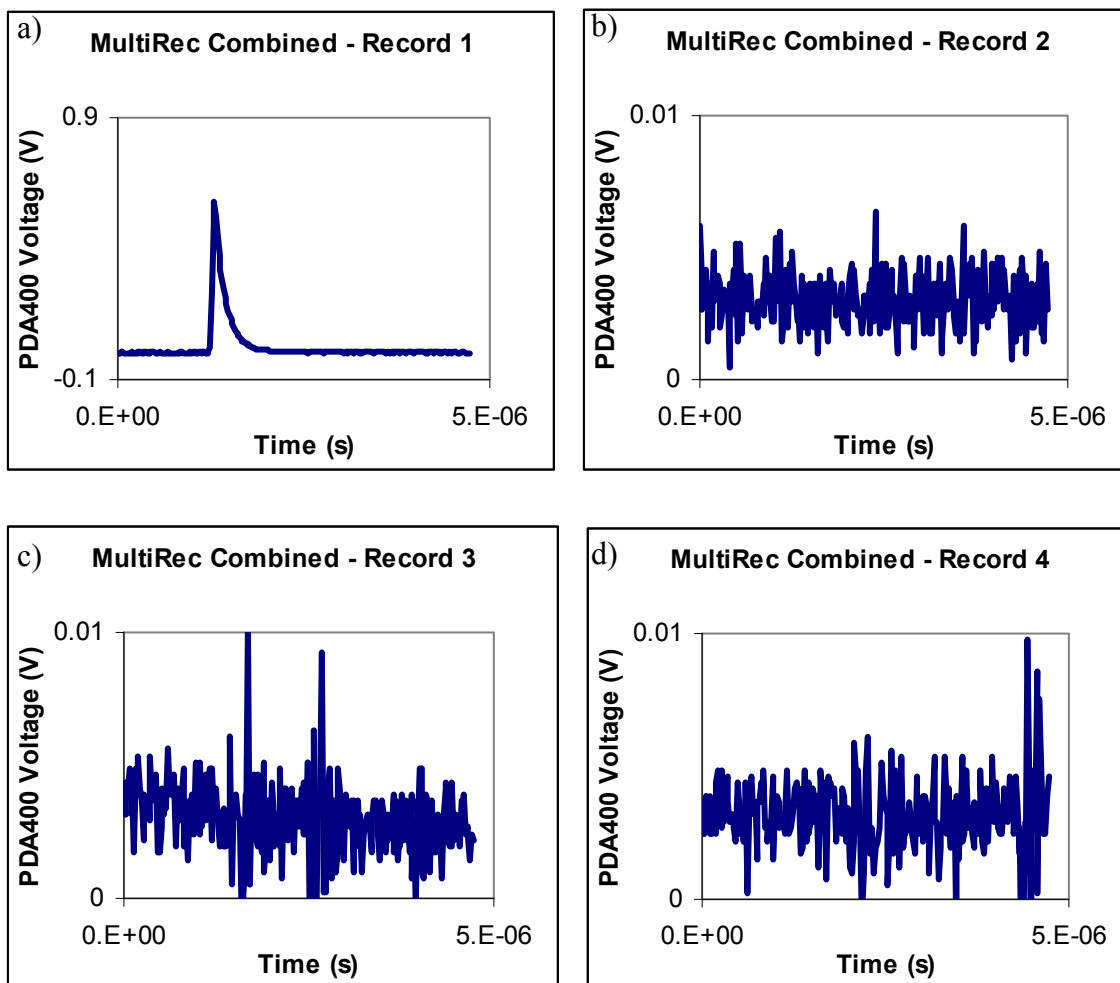


Figure A.6. Pulse records 1 (a), 2 (b), 3 (c), and 4 (d) in ASC format, saved to one single file. The shapes do not match the records in Figure A.4, indicating an error when saving all data to one ASC file.