The DC Motor Extravaganza

Pre-Lab: MacGyver and Sampling Rates

A Bit of History

You might be expecting a history of motors here. Maybe something about the clever contraptions that Michael Faraday created in the 1820s or the first useful motors that were devised in the decades that followed? Well, that's not exactly the angle that we're going to take here. Instead, let's talk about a man who never existed and his inventions that never truly were (and possibly never truly could be). That man is Angus MacGyver, although no one ever really uses his first name. He's just MacGyver.

In the unfortunate case that you are unfamiliar, *MacGyver* is an action-adventure television series that ran from 1985 through 1992. Watching it now is a little bit like opening a time capsule. The series starred actor Richard Dean Anderson, a clean-cut gentleman with a well-groomed mullet that could make a hockey player weep. The instrumentation of the theme song (all synthesizer) evokes the excitement of the early days of personal computers. The basic storyline, on the other hand, is timeless (or trite, if you prefer). According to Netflix, MacGyver is "a former special ops agent [who] brings down corrupt dictators and other bad guys." In his own words, MacGyver gets a phone call "when somebody's in trouble and needs some rescuin'."

However, those descriptions don't truly capture the essence of MacGyver, that which separates this immortal series from the pretenders. The show and the character are legendary not so much because of the storylines. It's the way in which MacGyver navigates the otherwise hackneyed narratives that sets him apart. MacGyver never uses a gun; rather, he is famous for creating gadgets and solving problems using mundane materials like paperclips, coins, bubble gum, and roll after roll of duct tape.

Here are a few examples of typical MacGyver moments:

- When the battery on his pocket radio dies, he sticks two types of wire into a cactus to bring the radio back to life.
- When bad guys are chasing him up a mountain, he fills a crack in a rock with water and freezes it with a fire extinguisher, breaking off a boulder that smashes the villains' car.
- When a circuit is broken by a bad fuse, he uses a bubble gum wrapper to complete the circuit. He offers the stick of gum to his friend.
- When he discovers a crack in his car's radiator, he runs to a chicken coop, takes an egg, and cracks it onto the radiator, cooking it and sealing the fissure. (The Mythbusters even showed that this works!)

In addition, MacGyver creates and defuses more bombs than you can possibly imagine using just the materials he finds around him.

Despite being off the air for two decades now, MacGyver's unmatched resourcefulness has earned him what looks to be permanent place in pop culture. A search of "MacGyver" on nasa.gov returns three pages of articles about NASA engineers nicknamed MacGyver and situations where NASA scientists had to "put on their MacGyver hats" to save the day. Perhaps an even better barometer than NASA, the popular website urbandictionary.com has literally dozens of entries for "MacGyver" used as a noun, verb, and adjective. (Be aware that not all of these definitions would be rated G.)

What's a Motor?

Generally speaking, a motor is a device that converts electrical energy into mechanical energy. In most cases, electromagnetic forces are employed to spin a rotor. The spinning rotor can then turn a wheel or fan blade or anything else an engineer can envision. Motors can run on AC or DC power, though most motors only run on one or the other. This lab will treat only DC motors.

Some vocabulary will be useful as we move forward. The *rotor* is the part of a motor that spins. The *stator* is the part of a motor that does not spin (or is static). A *brush* creates an electrical connection between the rotor and the stator. In most DC motors, the rotor spins due to the interaction between permanent magnets and a coil (or set of coils) of wire that act as an electromagnet. The most common design for small DC motors has the permanent magnets as part of the stator while the coil is part of the rotor. The motor that you will build in lab is a little backwards: the permanent magnet will spin while the electromagnet remains static. From a physics standpoint, there is not much of a difference between the two designs (so sayeth the Principle of Relativity). However, this design is much less common. That being said, it is not unheard of. For example, there's a small water pump for aquariums and fountains in the lab storeroom that utilizes our somewhat unorthodox design. A final vital component of a DC motor is the *commutator*. The commutator acts to change the direction of current flow within a DC motor. The importance of the commutator should become clear when you build your motor in lab.

Picking a Sampling Rate

In this lab, you will have to create your own experiment in which you are measuring a periodic quantity. That means choosing an appropriate sampling rate is absolutely vital. Read Appendix A concerning sampling rates and answer the following questions.

> PL1. Dogs can hear sounds with frequencies of up to 60,000 Hz. If you were recording music that you were going to sell to dogs (humor us here), what is the minimum sampling rate would you use? Give your response in Hz.
>
> PL2. If you set the sampling rate on the Vernier microphone to 5000 samples/s what is the maximum recording length that you can use in Logger Pro?
>
> **Read This:** Questions PL3 and PL4 relate to this paragraph. According to Wikipedia, at most beaches, the time between consecutive high tides is 12 hours and 25 minutes. Since you are always a little skeptical of Wikipedia, you devise a simple experiment to test this statement.

Your plan is to go to a beach and measure the ocean level at some regular interval over the course of several days. Then you will plot your data.

PL3. What is the longest time that you could wait between samples if you wanted to test Wikipedia's claim?

PL4. What might you conclude about tides if you measure the ocean level once a day, always at noon?

MacGyver

In the unlikely event that you haven't already scoured the internet for videos illustrating the awesomeness of MacGyver, take a look at the video whose link is on the Pre-Lab Links page of the lab website. Then answer the following questions.

PL5. What two substances does MacGyver combine to make the thermite?

PL6. Where do these two substances come from?

PL7. What does MacGyver use to light the thermite torch?

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Read This: The closest thing to MacGyver in the Wash U physics department is Professor Jonathan Katz, who has published papers on using corn starch to plug underwater oil spills and on spraying aerosols into the atmosphere to slow climate change. See the lab website for links to details.

End of Pre-Lab

Part I: Building a Battery-Powered Fan

The Story

Feeling a bit warm, and inspired by your longtime or newfound love of MacGyver, you decide to build an electric fan using materials that you can likely find in your kitchen, basement, or garage. That is, it's time to put on your MacGyver hat.

Equipment

- Contents of Foam Cup
    - Foam cup
    - Lid
    - Enameled wire
      (6-meter & 8-inch segments)
    - Pre-fabricated rotor
      (two nails, two magnets, glue)
    - Putty
- Contents of Box 1
    - Duct Tape
    - Craft knife
    - Sandpaper
    - Power Supply at 3 V (replaces the battery)
    - White out
    - 2 Alligator clips
    - Multimeter
- A coin

1a. Constructing a Fan

Do This: Find the DC Motor Slideshow on the In-Lab Links of the lab website and follow the directions to create your very own powered fan.

S1

Synthesis Question 1 (15 Points): Perform an experiment to determine which side of your magnet is the north pole. Your response must include:

- A clear description of <u>your experiment's procedure.</u> The procedure of how you built the motor should be only one sentence - a reference to the slideshow.
- A diagram that shows at the very least: your magnet with labeled poles, a current, and some magnetic field lines produced by that current. (Recall that dots can indicate that something is directed out of the page and *x*'s can indicate that something is directed into the page.)
- An explanation of how you determined the direction of the current and how you know the direction of the magnetic field lines created by that current.

1b. How does the motor work?

Do This: Go back to the slideshow and finish constructing the motor.

Read This: The motor is yours to take at home. If you do not plan to keep it, you do not need to cut the cup lid to create the blade. If you want to create the blade, please ask your lab assistant for a pair of scissors. Do not use the knife to cut the lid. It is not safe.

Do This: After making sure that the motor works, observe the role of each part of the motor. You might want to connect and disconnect each part to see what they do.

S2

Synthesis Question 2 (25 points): Describe in your own words how your uncommon DC Motor works. Include:

- A circuit diagram of the motor (not a copy of the diagram on the slideshow).
- the role of each element of your motor:
  - wire
  - magnet
  - coin
  - brush.

Part II: How Fast is the Rotor Spinning?

The Story

MacGyver, being a curious man, would certainly wonder how quickly your rotor is spinning. A *tachometer* is a device that measures the rate at which a rotor turns. We don't have tachometers in the lab. Of course, that would never discourage our hero MacGyver. As he once said, "maybe we can whip up something with what [we] got around here." Being in an intro physics lab, we have lots of instruments for LabPro.

Equipment

- Your motor
- Power Supply (at 3 V)
- Vernier current sensor (in Box 2)
- Vernier microphone (in Box 2)
- Vernier light sensor (in Box 2)
- Various little items (in Box 2)

2. Your Tachometer

In this experiment, you must use one of the three sensors listed in the equipment section: the current sensor, the microphone, or the light sensor. It will be very helpful to review Appendix A (About Sampling Rates) before taking any data. Also, this is probably best to do ***without the fan blade*** since that will allow your rotor to spin faster. Most motors end up spinning at a rate of about 20 Hz. See the lab website for the all-time records.

Be creative! There are lots of correct ways to complete this experiment. As an incentive to think outside the box, if you measure the rotor's frequency using two independent methods simultaneously, you can earn five points of **extra credit** on this report! Appendix A explains a little about each instrument. Appendix B gives important information about using multiple instruments at once.

S3

Synthesis Question 3 (60 Points): Devise and perform an experiment to determine the rate at which your rotor is spinning. You can change the sampling rate in Logger Pro by clicking the clock icon: . A complete response will contain the following:

- A diagram showing your experimental setup
- The sampling rate that you choose with a justification for why you have chosen it
- The recording length that you choose with a justification for why you have chosen it
- A well-labeled plot showing several periods of some periodic data. An appropriate zoom level should be chosen such that the periodic nature of the data is apparent.
- A clear explanation of how you used the plot to determine the rate at which the rotor is spinning. That is, connect the shape of the plot to the motion of the rotor.
- The frequency with which the rotor is spinning in Hz and RPM's.

Time to Clean Up!

Please clean up your station according to the Cleanup! Slideshow found on the lab website.

Appendix A: About Sampling Rates

The Rule of Thumb for Sampling Rates

Any time that you are measuring a quantity that is periodic, the rate at which you take measurements (called the *sampling rate*) is very important. Let's just cut to the chase.

Rule of Thumb

If you want to measure a waveform with a frequency f you must use a sampling rate of at least $2f$.

However, if you have the data storage capacity, there is no harm in sampling as fast as possible given the particular equipment you are dealing with. Note that the waveform does not necessarily have to be sinusoidal. The rule of thumb holds for any periodic waveform.

Two Examples

As a first example to motivate this rule, let's say you wanted to make a plot of the intensity of the sunlight hitting your roof as a function of time. A plot of sunlight hitting your roof will be more or less periodic, increasing during the day and decreasing at night. The period of the waveform would be 24 hours, or 1 day, making the frequency 1 day^{-1}. Let's say you just take one measurement at 3 PM each day. Your plot will end up looking pretty flat. Your data will not show the day/night variation that we know exists. That's because you aren't taking data often enough. Put another way, your sampling rate is too low. If you start taking an additional measurement each day at 3 AM, then you will be able to see the expected periodicity of the sunlight on your roof. Notice that we have increased the sampling rate to 2 day^{-1} which is exactly what the Rule of Thumb says we must do in order to see the waveform. Sampling at higher rates would make the periodic nature even easier to see.

As an additional example, the highest frequency of sound that a typical person can hear is about 20 kHz. That means if you are recording a sound, it would be nice to capture all frequencies up to 20 kHz. According to the Rule of Thumb, in order to measure sound with a frequency of 20 kHz, a microphone must sample with a rate of at least 40 kHz (because 20 kHz x 2 = 40 kHz). Sure enough, *WAV* files are typically recorded at 44.1 kHz.

Simulated Data or Lots of Plots

We will not prove the Rule of Thumb here, but we will give you some additional confidence in its validity through a series of plots that begin on the next page. All of the plots will show some number of discrete points along a 22-Hz cosine wave. In all of the plots, we will be looking at a quarter-second segment of the waveform.

We begin with 100 points, equivalent to a sampling rate of 400 Hz (100 points / 0.25 s = 400 Hz) shown in Figure 1.

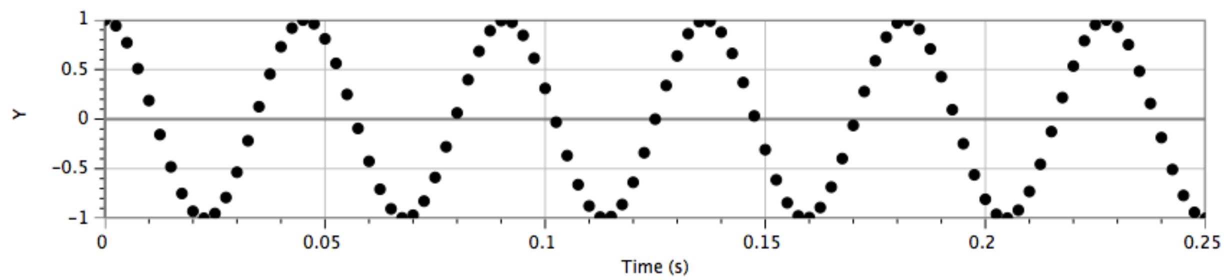

Figure 1: 22 Hz wave sampled at 400 Hz.

It should be very obvious that the plotted points fall on a cosine curve. We can cut the number of points in half and still be confident that we are looking at a 22-Hz cosine wave (Figure 2).

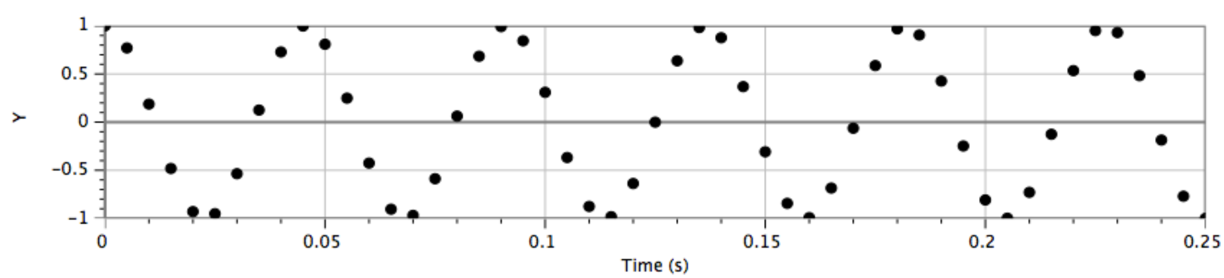

Figure 2: 22-Hz wave sampled at 200 Hz.

At this point, we are sampling at nearly 10 times the frequency of the wave, which is well above the rate we need according to the Rule of Thumb. If we cut the points in half again (sampling at 100 Hz), it becomes more difficult, but not impossible, to see the 22-Hz wave (Figure 3).

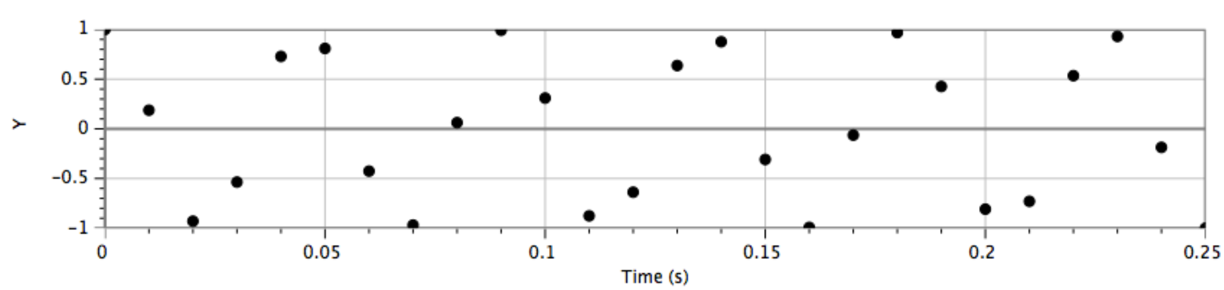

Figure 3: 22-Hz wave sampled at 100 Hz.

However, even if it may be difficult for us to see the 22-Hz wave, Logger Pro has no problem finding it if asked to fit a curve to the data (Figure 4).

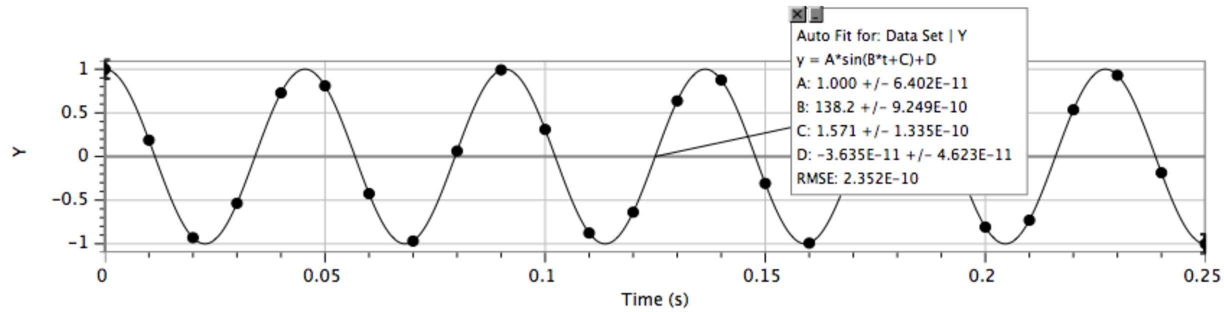

Figure 4: 22-Hz wave sampled at 100 Hz with curve fit.

Notice that the angular frequency of the fit (B) is 138.2 rad/s, which is equivalent to 22 Hz. Now let's see what the plot looks like if we sample at 44 Hz, the lowest effective sampling rate according to the Rule of Thumb (Figure 5).

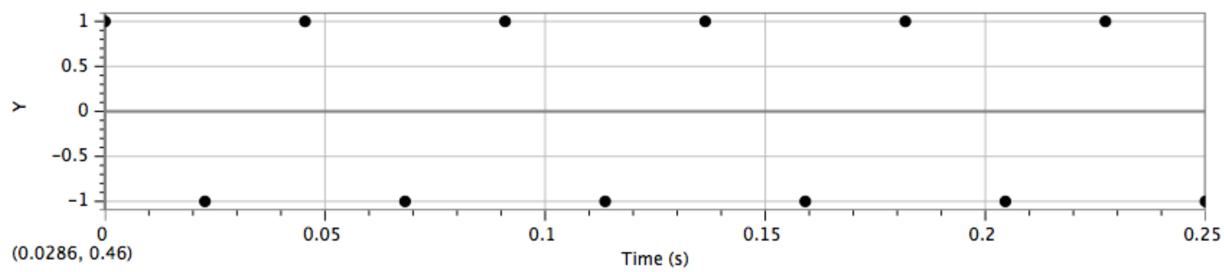

Figure 5: 22-Hz wave sampled at 44 Hz, the lowest rate allowed by the rule of thumb.

You can likely still see the 22-Hz wave, and Logger Pro has no problem, as shown in Figure 6.

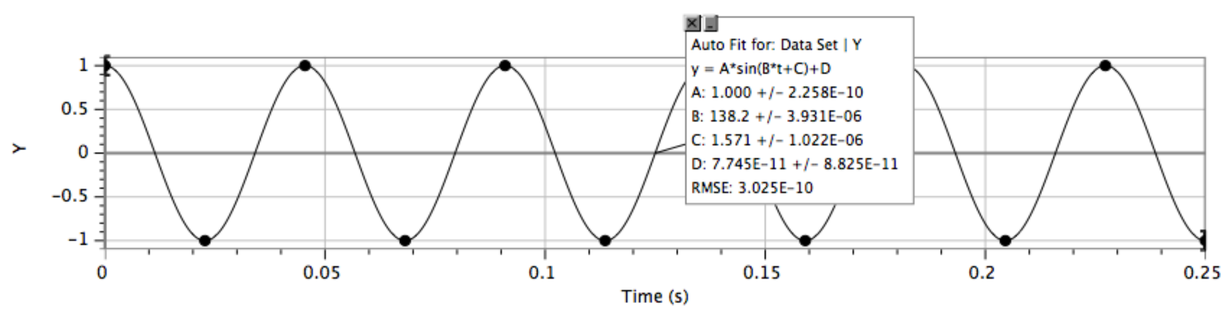

Figure 6: 22-Hz wave sampled at 44 Hz with curve fit.

Once again, the angular frequency of the fit (B) is equivalent to 22 Hz.

However, if we drop the sampling rate just a tiny bit down to 40 Hz, we can no longer tell that we started with a 22-Hz wave (Figures 7 and 8).

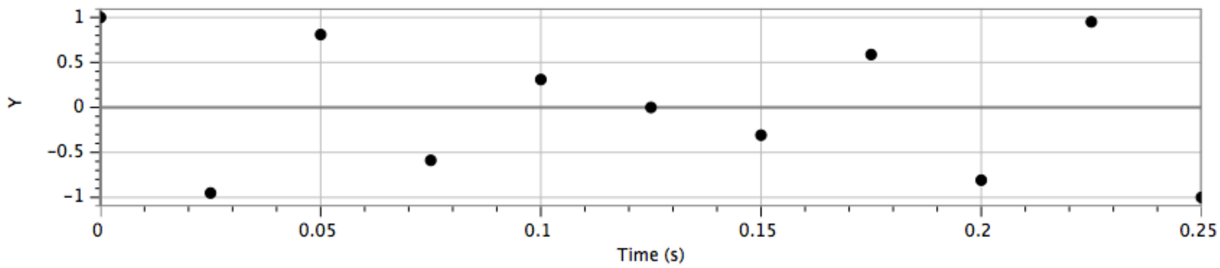

Figure 7: 22-Hz wave sampled at 40 Hz, just below the necessary sampling rate according to the Rule of Thumb.

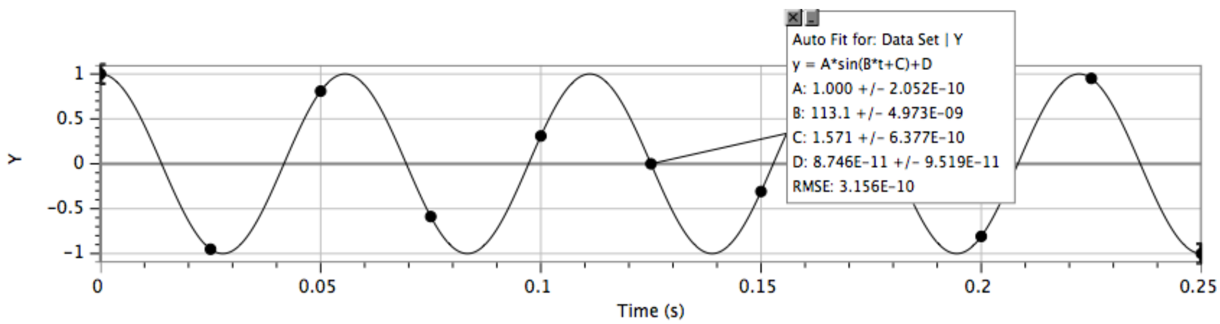

Figure 8: 22-Hz wave sampled at 40 Hz with (incorrect) curve fit**.**

Notice that the angular frequency of the fit (B) is no longer equivalent to 22 Hz. Once the sampling rate drops below 44 Hz, we can't see the 22-Hz wave anymore. Things just get worse as the sampling rate decreases further. In fact, if we sample at 22 Hz (Figure 9), the wave disappears completely!

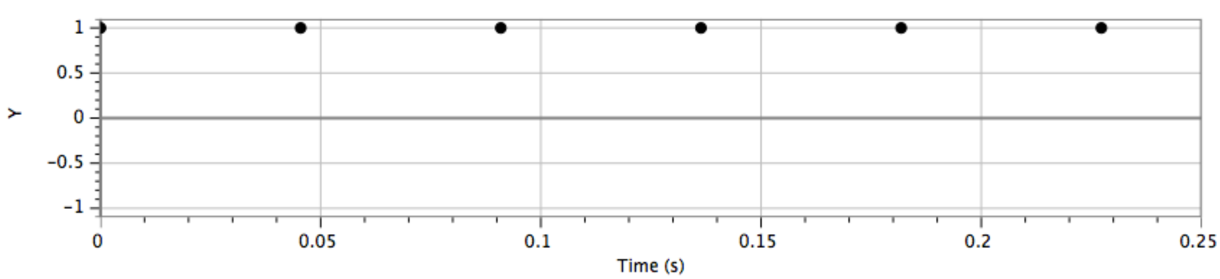

Figure 9: 22-Hz wave sampled at 22 Hz. Where's the wave?

Sampling with Vernier

Here are some useful specs on the Vernier instruments that you can use today.

- The Vernier light sensor can sample at up to **1000 Hz**. The light sensor plots the brightness of the light that is incident on it as a function of time.
- The Vernier current sensor can sample at up to **100,000 Hz**. The current sensor is simply an ammeter that plots current vs. time.
- The Vernier microphone can sample at up to **100,000 Hz**. The microphone shows you the shape of the sound wave that it records.

Length of Recording in Vernier

This appendix has focused on the sampling rate necessary for measuring a periodic quantity, but the *length* of the recording must also be considered. The length of the recording must be several periods long in order to see the oscillation. The LabQuest interface is not designed to take more than 35,000 measurements in a single run. That means that if you are sampling at 100,000 Hz, you can't record for longer than 0.35 seconds. If you are recording at 1000 Hz, you can record for up to 35 seconds. ***So if you increase the sampling rate you may have to shorten the recording length*.**

VERITAS and Sampling Really Fast

An appropriate sampling rate is important when gathering data on any value that changes with time. We have looked at periodic values here, but careful selection of a sampling rate is important for recording pulses as well.

CURRENT Washington University in St. Louis RESEARCH

Professor Buckley and his group are involved in a research project involving a quartet of telescopes called VERITAS. These telescopes are looking to detect and study pulses of light that last roughly 4 to 10 nanoseconds. Those are extremely fast pulses. In order to correctly see the shape of these pulses, the telescopes must sample really fast. VERITAS can, in fact, sample extremely quickly, at a rate of 500 MHz, or once every 2 ns. That means that on a 10-ns pulse, VERITAS gathers five data points and thus gets a good look at the shape of the pulse.

The downside of sampling so fast is that VERITAS produces an incredible amount of data. In order to prevent its hard drives from filling up extremely quickly, there is special software that detects pulses and saves the associated data while throwing away the data that don't contain a pulse. See the lab website for links to more details.

Appendix B: Using Multiple Vernier Sensors Simultaneously

There's a Catch or Two

When using two sensors at the same time, you have to be extra careful about the sampling rate and the recording time.

Each instrument will record at the sampling rate that you enter. That means the total data points collected will be the sampling rate times the recording length times the number of instruments. The total data points collected should not exceed 35,000 points.

Moreover, when multiple instruments are attached, the sampling rate gets capped at 10,000 Hz. And you should be careful that the sampling rate does not exceed the maximum sampling rate of either instrument. This is important if the maximum sampling rate of each instrument is different.