Introduction to the oscilloscope and digital data acquisition: Part 1

Eric D. Black California Institute of Technology v2.01

There are a certain number of essential tools that are so widely used that every aspiring scientists needs to know how to use them. In this lab we will cover the oscilloscope, particularly the digital, networked oscilloscope. Scientists and engineers of all stripes use oscilloscopes to "see" time-varying voltages over a wide range of scales, both in amplitude and duration, and the networked scope allows you to capture a record of these voltages and transfer that record to a computer, where you can graph and analyze it.

1 Introduction: what an oscilloscope does

An oscilloscope is a device for visualizing a voltage that is changing over time. It plots this voltage on a screen in exactly the way you'd expect, with the voltage on the vertical axis and time on the horizontal. You can change the range of either axis over several orders of magnitude by way of knobs on the front. The scope gets the voltage from an input on the front panel and the time from an internal clock. Some scopes have more than one input, or *channel*, so you can plot multiple voltages at once. Ours have two.

Oscilloscopes have a language all their own associated with them. Some terms you should know are,

1. *Scale:* The range of the vertical axis, usually expressed in units of volts per division. There are eight divisions on the screen, regardless of what



Figure 1: An oscilloscope. This is an example of one of the models you will be using in this lab, the TDS3012B, but they all work more or less the same way.

scale you set. If you set the scale to 100 mV/div, for example, the whole screen will have a range of 800 mV.

- 2. *Timebase:* The scale of the horizontal axis, usually expressed in time per division. Similar to the vertical scale, the total horizontal range is the time per division times the total number of divisions. On these scopes, there are ten horizontal divisions to a screen.
- 3. *Trigger:* How and when the scope starts the plot. This is just like pressing the button on a camera to take a picture, except that on an oscilloscope there are many ways to automate it. There is a button on the front panel of every oscilloscope that will allow you to manually trigger the display, but for fast-moving signals this is usually the least efficient way to do things. Instead, you can tell the scope to draw the screen as soon as certain conditions are met. This is one of the most important and subtle aspects of using an oscilloscope, and we will talk more about it later.
- 4. *Bandwidth:* The maximum frequency of a signal that the scope is capable of measuring. Anything moving faster than this will be missed by the scope, simply because it happens too fast. More on this later.
- 5. AC/DC: Strictly speaking, AC is shorthand for Alternating Current, and DC is short for Direct Current. More generally, however, we use DC to mean the static (or time-averaged) part of a voltage signal, and we use AC to refer to the time-changing part. For example, if a voltage signal is $V(x) = 2 + 0.1 \sin(\omega t)$, we might say that this signal has a 2volt DC part and a 0.1-volt AC part. The DC part is equal to the time average of V(x), and the AC part is the rest of the signal, $V(x) - V_{ave}$.
- 6. Coupling: You can use DC or AC coupling to input a signal into the oscilloscope. With DC coupling, the scope shows the whole signal V(t), both the DC and AC parts. With AC coupling, the signal is sent through a high-pass filter that removes the DC part while letting the AC part through. In other words, with DC coupling the oscilloscope plots V(t), while with AC coupling the scope plots $V(t) V_{ave}$. Using AC coupling allows you to zoom in on the small variations of a signal with a large DC part. Be warned, however, that AC coupling can sometimes distort the low-frequency components of a signal in addition to removing the DC part.

Coaxial Cable Construction



Figure 2: Coaxial transmission cable. (Image courtesy of The Fiber Optic Association.)

7. Impedance: The electrical impedance seen by the source when you plug it into the scope, sometimes referred to by its full title, input impledance. Most of the time, this will be high (1 M Ω) so that the circuit you are measuring is not disturbed. In some cases, however, you will need a 50 Ω input impedance to suppress reflections in the cable you are using to connect your circuit to your scope. More on this later.

2 Acquiring and viewing a signal

2.1 Coaxial cables and connectors

At your station you should have an oscilloscope, a signal generator (sometimes also called a *function generator*), and some coaxial cables with BNC connectors on each end. Coaxial cable, or coax for short, is widely used for signal transmission in many fields, and you may already have seen it in other labs or audio-visual applications. A diagram of a coaxial cable is shown in Figure 2. The inner conductor carries the signal voltage and is surrounded by a dielectric, a conducting shield which is held at ground (zero volts), and then another dielectric jacket. This configuration both shields the conductor from outside electrical interference and helps contain the signal inside the coax, minimizing the interference it contributes to the outside world. At either end of the cables are connectors known as BNC, which is short for *Bayonet Neill-Concelman* (or *Berkeley Nucleonics Corporation*, depending on who you ask). Bayonet refers to the way it locks in place when you plug it in, and Neill-Concelman refer to Paul Neill and Carl Concelman, of Bell Labs and Amphenol, respectively, the two guys who are generally credited with inventing it.

2.2 Viewing a signal, triggering

2.2.1 Viewing

- 1. Turn the oscilloscope and signal generator on, and connect the output of the signal generator to the input of Channel 1 of this oscilloscope. The Rigol DG1022 function generators you will use in this lab have two signal outputs. Channel 1 is the bottom of the two front-panel outputs and you have to push the button next to the output to turn it on. This button lights up when the channel is on.
- 2. On the signal generator, select a sine-wave with an amplitude of one volt and a frequency of one kilohertz.
- 3. Using the SCALE or VOLTS/DIV knob under the VERTICAL section of the scope's front panel, set the vertical scale so that the amplitude of the signal fits in a vertical division. Note that there aren't markings around the knob. You will have to look on the screen to see what the scale is.
- 4. Calculate the period of a one kilohertz signal (you should be able to do this in your head), and set the timebase of the scope so that one period fits into one horizontal division. This is done with the front-panel knob labelled either SCALE or SEC/DIV under the HORIZONTAL section.
- 5. Use the knob labelled LEVEL in the TRIGGER section to set the level to zero volts. There is both a number on the screen and a small arrow on the left edge that shows you what the level is.

2.2.2 Triggering

At this point you may see a stable signal on the screen, or you may not, depending on what the other trigger settings are. Far too many people stop at this stage or press buttons at random until they get a stable signal. As a consequence, triggering is a black art to them, or worse, they blame the scope when they don't get what they want. You can do better. From here, I want you to explore some other trigger settings so that you become master of the scope, and not the other way around.

As mentioned above, the "trigger" on the oscilloscope is what causes the scope to start plotting your signal. For example, you may tell the scope to wait until the voltage moves through one volt in the positive direction; that is, the voltage goes from just below one volt to just above one volt. When this happens, the scope commences plotting your signal to the screen. When it gets to the end of the screen, the scope waits until the trigger conditions are again met, and then its plots the signal again. And it repeats this loop indefinitely.

Most trigger options are accessed from "soft" or "contextual" menus that you pull up on the screen. Under the TRIGGER section of the front panel of the oscilloscope, there is a button labeled MENU. Push this, and it will bring up a set of soft menus. You can select these menus and their options with the buttons along the bottom and right side of the screen.

Key trigger options you need to understand are,

- 1. Acquire: Run vs. Stop. There is a very important button at the top, right-hand corner of the front panel labelled RUN/STOP. Press it, and see what it does. Press it again. It should toggle between running and stopping. (No big surprises here, but this button is not obvious if you don't know to look for it, and it is frightfully important.) Look for the words "Run" or "Stop" on the screen to tell you which mode you are in. You will often use Stop mode to freeze a signal on the screen so that you can examine it more closely, print it, or save it. More on the last two options later.
- 2. Trigger Source: What voltage the scope looks at for the trigger. This can be Channel 1, Channel 2, an "external" (EXT) source, 60 Hz power line signal, and sometimes other options. You can play around with this if you want, but at this point it is optional. Right now all you need to do is set it to the channel your signal is going into.
- 3. Trigger Mode: Normal vs. Auto (Untriggerred Roll). Under Normal trigger mode, the scope will wait as long as is necessary for the trigger conditions to be met. If those conditions are never met, the scope does

not trigger. Under Auto, the scope has a "finite attention span" and will only wait so long. After that, it triggers on its own and draws on the screen whatever voltage just happens to be on the input when its patience runs out. Set the mode to Normal, then move the trigger level until it is above the highest part of the signal. What happens? Move the trigger level in and out of the signal and observe the response of the scope. Now set the mode to Auto and repeat this experiment. Do you see the difference? Record your observations in your lab notebook.

- 4. Trigger Mode: Single Sequence. Use this when you want the scope to trigger once and then stop, freezing the screen and ignoring any subsequent triggers so you can see what you caught.
- 5. Trigger Level: The voltage required to start the trigger.
- 6. Trigger Slope: Whether the scope triggers as the input voltage hits the trigger level while rising or falling. Note the little icon at the base of the screen that tells you whether you are set to trigger on a rising signal or a falling one. Toggle between these two options, and see what results.
- 7. Trigger Coupling: DC, AC, high-frequency reject, noise reject, among other options. These are dead useful features, especially the noise-reject options, but they are optional for you to explore at this point. Play with them if you want to and have the time, and then leave this setting on DC for the rest of the lab.

2.2.3 Printing

You can capture what is on your screen, and most of the settings, with a single button on most modern scopes. On the TDS3012B, look for a button just outside the bottom, left-hand corner of the screen with a little printer icon on it. Press it, and a printout of your screen will go to the laser printer in the lab. (All the TDS3012B scopes are networked and share a single printer in this lab.)

With your one-volt, one-kilohertz signal going into Channel 1, set your trigger options to the following,

1. Mode: RUN

- 2. Trigger Source: Channel 1
- 3. Trigger Mode: NORMAL
- 4. Trigger Level: 0 V
- 5. Trigger Slope: Rising
- 6. Trigger Coupling: DC

Set the options for Channel 1 to the following,

- 1. Coupling: DC
- 2. Impedance: 1 M Ω

Print a screenshot, and tape it into your lab notebook. Now, increase your timebase to 100 ms/div, and lower the frequency of your signal to 10 Hz. Switch between NORMAL and AUTO trigger modes, and observe the difference. Can you explain this behavior?

2.2.4 Horizontal zoom

Set the frequency of your signal back to 1 kHz signal and your scope's timebase back to 1 ms.

At the bottom of the HORIZONTAL section of the front panel is a button with an icon that looks like a magnifying glass on it. Push it. You should see a split screen that allows you to zoom in on certain areas of the screen. You can control this feature using the horizontal position and scale knobs.

Laboratory exercise: If you've done the first part of this lab correctly, you should have ten periods on the screen. Use the zoom function to zoom in on one of them. Print a screenshot of your results, and tape it into your lab notebook.

2.2.5 External triggering

Remember that SYNC output I told you to about earlier? Well, now is the time to see what it does. Now that you know how to look at a signal, examine what comes out of the SYNC port by sending it into Channel 1 of the oscilloscope. On the Rigols you will use in this lab, it is on the back of the instrument and normally turned off. You will have to turn it on from the front panel on these models.

Once you have your SYNC signal displayed, adjust the frequency and amplitude of the function generator, and see how that affects the SYNC signal. It should be independent of the amplitude you set, but it should respond to the frequency. The SYNC (TTL) signal is a pulse train at the same frequency as the main signal and in phase with it, and it is often used for triggering when the main signal won't work.

Connect the SYNC output to the oscilloscope's EXT TRIG input, and change the trigger source from Ch 1 to EXT. Now connect the main output back to Channel 1 using a second cable, and look at what you see on the screen. Adjust the amplitude and frequency, and note the response. You should be able to reduce the amplitude well below the nominal trigger level (as it would be if you were triggering off Channel 1) and still see a stable signal with a clean trigger. That's what external triggering is for.

3 Measurements

3.1 Automated measurements

Locate the button labeled MEASURE on the front panel. Press it, and examine the soft-menu options it brings up on the screen. Have the scope measure the amplitude and frequency of your sine wave, and write the results down in your lab notebook.

3.2 Cursors

Sometimes the automated measurement functions are inadequate for what you need to do. Cursors are also available to allow you to perform measurements by hand or to set baseline markers. Press the CURSOR button, and bring up a set of vertical cursors. Use the SELECT button on the TDS3012B to toggle between them, and the general-purpose knob to move the selected cursor. Note that there are two numbers displayed at the top of the screen, the distance between the cursors, and the absolute location of the selected cursor. Toggle back and forth between the available units, and see what is available. Try the same thing with horizontal cursors.

One way to measure the frequency of a signal is to place one vertical

cursor on a peak near the left-had side of the screen, then place the other on a peak several periods down. The display will tell you the distance between the two, and you then divide (if your units are in seconds) or multiply (if your units are 1/s) to get the period or frequency of an individual oscillation. Do this, and verify that you get the same answer as you did in the last section.

4 Special considerations of data acquisition with digital electronics: aliasing and the Nyquist theorem

The oscilloscope you are working with is *digital*. This is the case for most modern scopes and, in fact, almost every way we take data. What this means is that the voltages you measure are not recorded continuously, but are *sampled*, *i.e.* individual points are recorded, and the continuous signal they were sampled from is then inferred. If your sampling rate is high, that is you take a lot of points closely spaced from a slowly-varying signal, then all is well, and your collection of points will accurately represent the signal. If, however, you sample too slowly, you can never be sure from your data points alone what the actual frequency of the original signal was. A typical case is shown in Figure 3. Given the set of points in red, there are actually *multiple* sine waves that could both fit the data. So which is it? Which is the original signal the data was sampled from? Without additional information, you have no way of knowing. Fortunately there is a theorem that tells you what additional information you need.

4.0.1 The Nyquist-Shannon sampling theorem

Any continuous function f(t) is only uniquely determined by a set of discretelysampled points if the sampling rate R is greater than twice the highestfrequency component of f(t).

4.0.2 Laboratory exercise:

- 1. Set the timebase of the scope to 2.0 ms per division.
- 2. The manual states that the record of a TDS3012B oscilloscope trace contains 10^4 points over the whole screen. This corresponds to 10^3



Figure 3: Aliasing, or undersampling, can sometimes cause a very high-frequency signal to be misinterpreted as a lower-frequency one. (Image courtesy of industrial-needs.com.)

points per division. Calculate the sampling rate R of your scope at this timebase. What is the highest-frequency signal you can accurately sample at this rate? This is known as the *Nyquist frequency*.

- 3. Set the frequency of your function generator to this frequency, and observe what you see on the screen. You may have to fine-tune your signal-generator's frequency to get close enough to the Nyquist frequency to see visible aliasing. Also, triggering may act weird. This is normal and the result of phase jitter in an undersampled signal. Make a screenshot, and tape it into your lab notebook.
- 4. Lower the sampling rate by increasing the timebase from 2.0 ms/div to 4, then 10, then 20. As the sampling rate gets farther and farther below the Nyquist frequency, you should notice the aliasing getting more and more pronounced. Take a screenshot of the trace you like best, and tape it into your lab notebook. Is there an obvious relationship between the apparent frequency of the aliased signal and the difference between the sampling rate and the Nyquist frequency?
- 5. Now increase the sampling rate by changing the timebase from 20 ms/div to 10, then 4, then 2, and observe what the reconstructed signal looks like at each setting.
- 6. Keep going, and bring your timebase down to 20 μ s, then 10, then 4, then 2. Now you are sampling at a much higher rate than the actual

frequency of the signal, and you should see an accurate representation of your signal on the screen. Take a screenshot of this, and tape it into your lab notebook.

7. Set the scope to measure the frequency of Channel 1, and look at the result as a function of the timebase. Can you predict at what timebase this measurement will break down? Is your observation consistent with your prediction?

4.0.3 Application of the sampling theorem: anti-aliasing filters

In an ideal world, if we wanted to digitize a signal we would analyze it, determine its highest frequency component, and then sample at a rate twice that frequency. Most of the time, however, our sampling rate R is a property of our electronics and not something we can easily change, so in the real world we usually do the opposite. We construct electronics with a sampling rate that we think is reasonably high, then filter all incoming signals so as to remove any frequency components greater than R/2. Such a filter is called an *anti-aliasing filter*, because the confusion of mistaking a high-frequency signal for a low-frequency one is called *aliasing*. Strictly speaking, this is *temporal* aliasing, because it occurs as you sample a signal in time. There is also *spatial* aliasing that occurs in image processing, and the basic idea is the same.