Equipment usage note

Rigol DS2102E

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Rigol digital storage oscilloscope

Contents

Summary

The Rigol DS2102E digital storage oscilloscope is a device that is used to both display and measure time-varying voltages. Oscilloscopes are one of the most common and widely-applicable electronic test instruments, and knowing how to drive one, that is, how to correctly connect, configure, and measure electrical signals, is a cornerstone of experimental science and electronics.

Common pitfalls

Common issues encountered whilst using the device:

- **No signal appears on the oscilloscope**
  - Verify that a signal is expected from device under test
  - Ensure that the BNC cable is correctly connected to the oscilloscope
  - Verify that the channel into which the signal is plugged is active, indicated by green illumination behind the `CH1` and `CH2` buttons on the *VERTICAL* panel, or as highlighted on the bottom left of the screen
  - Verify that the oscilloscope is operating in `RUN` mode, as indicated by green illumination the `RUN/STOP` button
- **The signal is not stationary, appears to propagate, or the signal of interest is only shown some fraction of the time**
  - The triggering is not correctly configured, which is remedied through adjustment of the trigger `MODE` and trigger `LEVEL` on the `TRIGGER` panel

In all cases of troubleshooting, the recipe outlined below for configuring the oscilloscope should be followed in order to obtain a high-quality measurement.

The device

The modern oscilloscope can perform myriad tasks, but its primary function is the same as that for which is was developed: to view and ultimately measure time-varying voltages. One can never escape the history of oscilloscopes when discussing their purpose, as their function and development are intimately entwined. The production of cathode rays in 1869 led directly to the discovery of the electron, and with refinement led to the invention of the Cathode Ray Tube (CRT), and in turn the Cathode Ray Oscilloscope (CRO). The CRO provided a direct way to "see" voltage, something which provided unparalleled insight and utility. In the modern setting, one uses oscilloscopes for all manner of measurements, but their cash value is the same as it has always been: providing a way to directly visualise voltage.

How does it function?

Once again, understanding the device history can help to elucidate how the modern incarnation of a now antiquated device functions. A CRT consists of a hot cathode, usually barium oxide[1] heated by a tungsten filament, from which electrons are accelerated and directed to a phosphor-coated screen, producing light upon impact. The insight which spurred the development of the CRO was the realisation that by using electrodes to steer the beam, one constructs a relationship between the position of the electron beam on the screen and the voltage on the deflection electrodes. Ultimately, two deflector sets were installed, whereby horizonal deflection of the beam was done periodically at a fixed frequency and thus establishing a "time" axis and the vertical deflection was provided by the test voltage $V_{\text{test}}(t)$. Therefore, by measuring positions of the electron beam on the screen, provided the relationship between voltage and screen position was known, one could directly infer the signal $V_{\text{test}}(t)$. A schematic of a CRO is shown in figure 1.

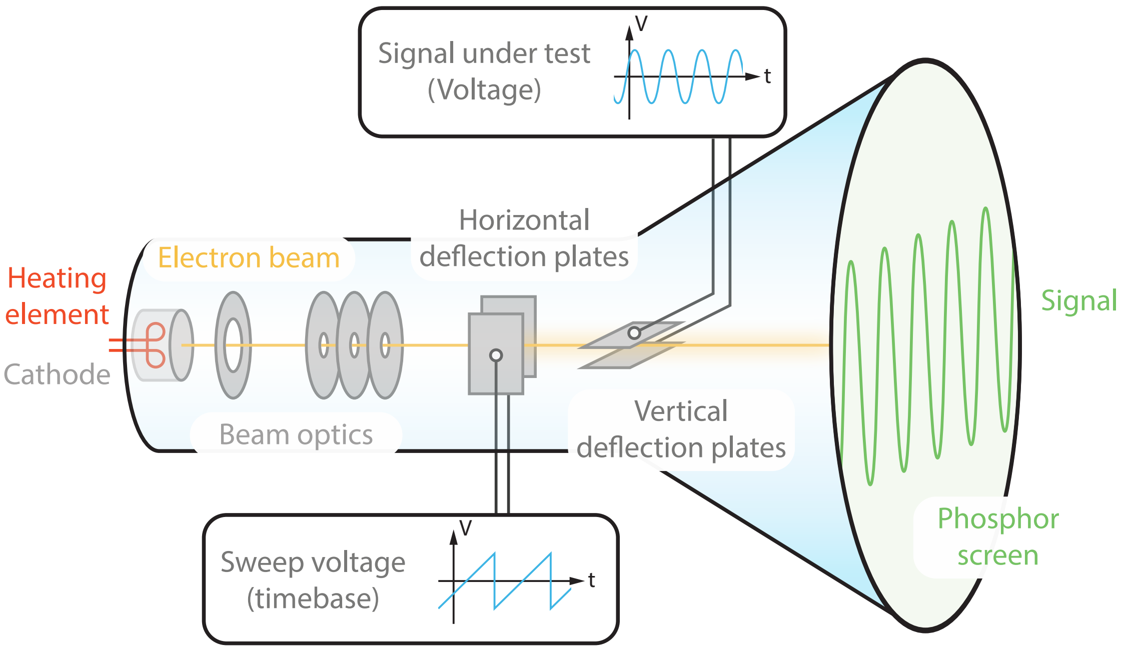

Figure 1: A schematic of a Cathode Ray Oscilloscope (CRO)

Modern oscilloscopes, usually termed Digital Storage Oscilloscopes (DSOs) accurately reproduce the function of CROs, but confer the benefits of modern electronics. The key difference between a CRO and a DSO is that whilst the signal as measured on a CRO is a real-time sampling of the signal under test, a DSO performs an acquisition of the signal under test for some duration, and then displays the signal as it was recorded. In order to do this, a DSO must discretely sample the voltage under test in both voltage and time in a process

[1]chosen because its low work function

known as digitisation, which is carried out by an analogue-to-digital converter. Details of analogue-to-digital converters and conversion considerations are detailed elsewhere, but it is important to understand that if one wishes to accurately measure a given signal, it is critical that the resolution for both the time and voltage be set appropriately.

How does one drive it - part I: taming the device

Like many modern instruments, oscilloscopes are extremely capable devices; however, they are not capable of autonomous functioning and must be configured with care. Any knowledge of the signal under test will aid in correctly configuring an oscilloscope, but it is not strictly necessary, as one can use the oscilloscope as a tool for assessing and converging on the optimum settings.

What am I looking at?

Oscilloscopes are typically comprised of a screen upon which the voltage of one or more signals as a function of time are displayed, along with a collection of controls to configure the display and acquisition of the signal. Before getting into the weeds on the specifics of using a DSO, the anatomy of the display and DSO controls is presented.

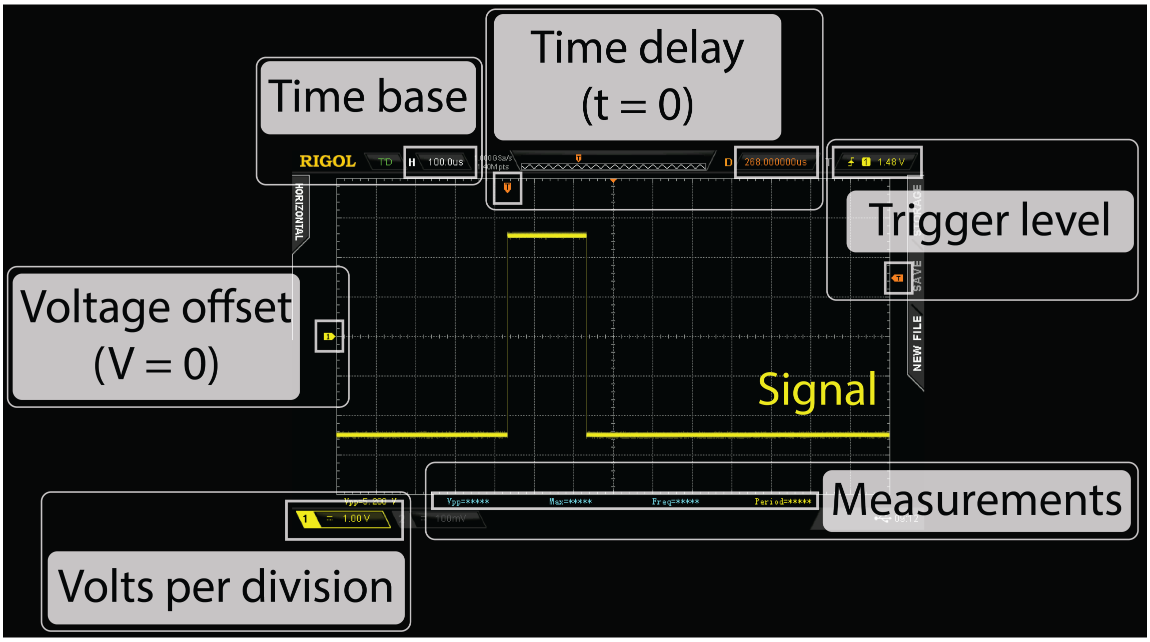

Figure 2: A screenshot of an DSO signal with annotations highlighting important features

Shown in figure 4 is an annotated screenshot from the DSO, recorded whilst a square pulse signal was connected the oscilloscope. The display shows a trace of the signal voltage versus time, with a signal connected into channel one (`CH1`) appearing in yellow. To interpret the signal, we begin by looking at the signal amplitude. Shown in the bottom left is the *volts per division*, which in this case is 1 V per division. The signal pulse rises five divisions from *low* to *high*, thus the amplitude of the signal is 5 V. The voltage offset marker indicates the point of $V = 0$ V, which in this case corresponds to the axis, and thus the signal is best characterised as a ± 2.5 V pulse, with *low* and *high* state voltages of -2.5 V and 2.5 V respectively. To determine the duration of the *high* pulse, one must look at the *time base*, which indicates the time per horizonal division, which in this case is 100 μs.

Exercise 1

What is the duration of the *high* state of the pulse? Given the signal was produced using a waveform generator set to produce a uniform square wave of frequency $f = 1\,\text{kHz}$, what must have been the duty cycle of the signal generator?

The time delay allows one to move the position of the trace on the display, and is indicated by the marker indicating the time $t = 0$, which in this case is set to $268\,\mu\text{s}$. The idea of a $t = 0$ leads to what is the most complex aspect of an oscilloscope: triggering. To understand what triggering is, let us consider the measured of a square wave an unknown frequency on an oscilloscope. An oscilloscope has two relevant time-domain parameters: the time base (for how long one measures) and the refresh rate (how often one measures). Whilst the time base is somewhat intuitive, the refresh rate is somewhat more subtle: how often should an oscilloscope refresh? And should this be a fixed parameter or should it be variable?

The answer can be teased out by considering our unknown signal being measured at a fixed frequency, for example at $f = 50\,\text{Hz}$, the line frequency of the mains power - something the DSO can do. If the signal under test is anything other than an integer multiple of the line frequency, if one were to take snapshots and overlay them, they could not be stacked in any meaningful way. In this explicit example where a periodic function is being sampled at a fixed frequency, the resulting phenomenon of aliasing is akin to beats in the context of interference, and the situation is displayed in figure 3. With a single instance of a trace, that is, the signal sampled over some interval of time, there is no real sense that it is important that the signal be "aligned". But with more traces, if they are just collected and refreshed on the screen, it is very unlikely that subsequent traces will neatly overlap, or put another way, they will not be aligned. Therefore, if a large number of traces are collected and are overlaid, as is the case for normal DSO operation, one will simply observe a mess on the display: either something unintelligible, or a signal which appears to be propagating. As an aside, note that this is this phenomenon is commonly observed, especially when filming: bizarre rotational motion of car wheels, strange "banding" across displays, slow-motion oscillations of guitar strings, or even stationary helicopter rotors, all are manifestations of periodic observation of oscillations.

One arrives at the solution by designing a way to "align" traces, which can be done via a number of methods, but the most common is to find a defining feature of the trace as the point to use as $t = 0$. For example, in the case of the square pulse shown in figure 4, one could locate the rising edge of the pulse and locate this at the time $t = 0$. Indeed, this is what is happening: as indicated by the *trigger* level on the right, every time a pulse is measured having a rising edge which passes the voltage of $V = 1.48\,\text{V}$ (this value is arbitrary) the DSO is "triggered" to update, displaying the triggering event at $t = 0$. In the case of a periodic signal, this has the effect of removing aliasing and ensuring that the signal does not appear to propagate. Animations showing a periodic signal being refreshed at a rate of 50 Hz illustrate a DSO displaying a signal with aliasing and triggering.

The final element of the display of which it is worth being familiar is the *measurement* panel, which exists underneath the trace and will display any values that you have configured the DSO to measure.

Shown in figure 4 is an annotated image of the DSO. The display has been discussed in detail above, but the purpose of this image is to illustrate that although there are many buttons and knobs on an oscilloscope, they are neatly grouped and one needn't have full command over the entire interface, rather it is important to have good command over the controls which maximise functionality. Notably, there are two key sections of which to be aware, which themselves are grouped on the panel, which are the `VERTICAL` and `HORIZONTAL` controls, which adjust the voltage and time scales respectively. On the right is the `TRIGGER` panel, which as explained above is critical to making a meaningful measurement. As a general, you will adjust the `VERTICAL` and `HORIZONTAL` settings regularly to investigate the quantities of interest, whereas adjustment of the `TRIGGER` is typically only required when the input signal is changed.

When changing the configuration, it is sometimes necessary to navigate on-screen menus, and this can be mostly done using the multifunctional *selection knob*.

How do I set it up?

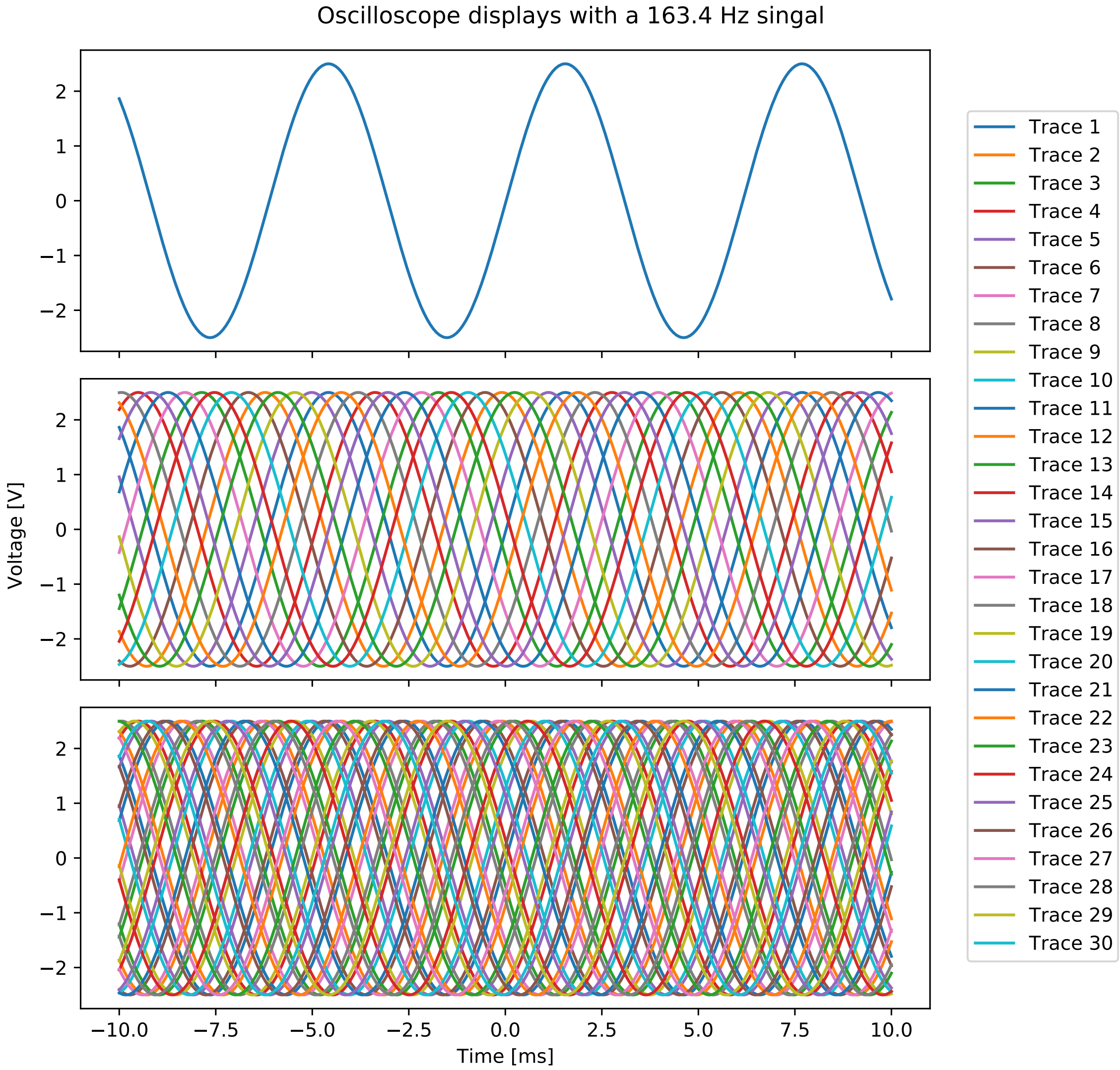

Figure 3: A collection of simulated oscilloscope traces with a periodic input signal. The oscilloscope collects traces at a fixed frequency of 50 Hz and thus when an input signal of a different frequency is sampled at 50 Hz, there is a phases mismatch between subsequent traces, which when overlaid makes it difficult to meaningfully observe the signal of interest.

> Oscilloscopes are often equipped with an *autoset* feature: a single-press auto-configuration button (in the case, the `Auto` button) which tries to figure out the optimal settings for given input signals, which routinely fails to function well. The purpose of this guide is to convince you that the usage of such a feature is significantly less robust, and once fluent in DSO usage, slower, than manual DSO configuration.

As with the configuration of most devices, it is worthwhile to really understand what the device is doing/trying to do in order to correctly configure the device. This information is outline in the above text, so ensure that this is properly digested. As a recap: the DSO will display the voltage from a measured source as a function of time, and works best with pulsed or periodic signals. To make a useful measurement, the oscilloscope must be told how to overlay subsequent measurements such that we can meaningfully interpret the displayed signal. From this point, the required measurement(s) can be performed and if required, the signal exported and analysed. Below is a recipe for configuring an oscilloscope:

1. The DSO should be powered on and the signal under test connected using a cable with a

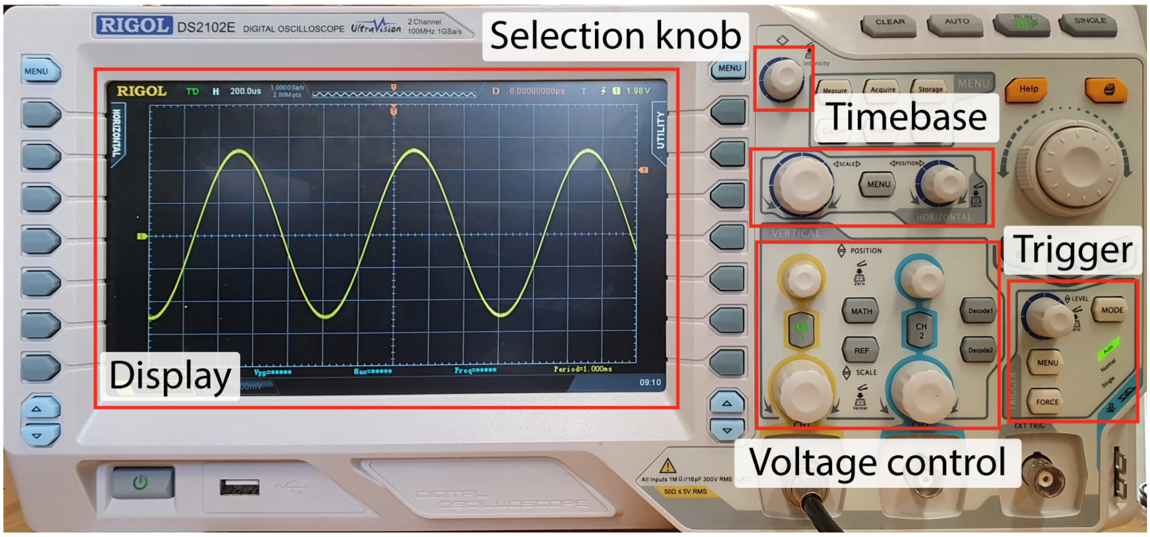

Figure 4: An annotated image of the DSO interface

BNC connector into either input channel 1 or 2, labelled `CH1` and `CH2` respectively. Take care to ensure the cable is correctly connected: a notch on the DSO connector should mate with the connector on the cable, and be rotated clockwise to secure the connection.

2. The DSO must be instructed to acquire data, which is done by pressing the `RUN/STOP` button. When it is *running*, a green LED backlight should be illuminated, and when it is *stopped*, a red LED backlight will be illuminated. Ensure the DSO is *running*.

3. The first task is to correctly set voltage and time scales. The order of these operations is not important, but depending on the exact signal to be measured it may be preferable to do one before the other. In any case, any *a priori* information you have about the signal will help you estimate the appropriate voltage and/or time scale(s). If the signal is connected to `CH1`, the signal and associated settings are highlighted in yellow, and if the signal is connected to `CH2`, the signal and settings are highlighted in blue. We must first ensure that the signal is being collected, which is toggled by the `CH 1` (or `CH 2`) button within the `VERTICAL` panel (see figure 4). Pressing the `CH 1` button will enable/disable measurement, as indicated by the LED backlight, in addition to showing a channel configuration menu on the right-hand side of the screen. These settings will need not be altered unless one is attempting a non-trivial measurement.

   - Setting the voltage scale: with the channel of interest activated, one can use the two knobs associated with that channel within the `VERTICAL` panel to *position* the signal (move it up and down) and *scale* the signal (zoom in and out). The value listed in the bottom left-hand corner of the screen indicates how many volts are represented per vertical screen division, ranging from 500 μV through to 10 V. If a signal is visible on the screen, adjust the `SCALE` knob such that the signal occupies most, but not all, of the vertical range.
   - Setting the timebase: the two knobs within the `HORIZONTAL` panel can be used to *position* the signal (move it left and right) and *scale* the signal (zoom in and out). The timebase (the time per division) is indicated on the top left of the display, and the appropriate value will be determined by the timescale over which the signal of interest varies. In general, for a periodic signal, one would want to display a number of signal cycles in order to collect an accurate measurement of the frequency, whereas for pulsed signal, one is typically only concerned with the shape and duration of the pulse.

   If one cannot achieve a meaningful signal on the oscilloscope, be it a propagating signal or simply a jumbled mess, it may be necessary to set the triggering and then return to the voltage and time settings.

4. Setting the trigger: to set the trigger, one must decide upon which feature the DSO should

identify and overlap traces. By default this is a rising edge, but it could equally be a falling edge, a pulse of a given width, or a host of other features. To trigger to a rising edge, press the `MENU` button on the `TRIGGER` panel, which will display the *TRIGGER* menu. Using the buttons located next to the screen:

- Ensure that the `Type` is set to `Edge`, this will indicate that we want to trigger on an edge
- Set the `Source` to `CH1` (or `CH2`) to indicate from which channel the oscilloscope will trigger
- The `Slope` should be set to $\uparrow$ in order to trigger on the rising edge
- The `Sweep` should be set to `Normal`; by default it is set to `Auto`. **NOTE: adjusting this setting may cause the signal to vanish from the display**. This is because when the `Sweep` is set to `Auto`, the DSO will look for a trigger, and if it does not find one, it will then force itself to trigger from the signal used to power the DSO, in this case the main power. When set to `Normal`, the display will not update unless a specified trigger event is found, and thus if the trigger level is not correctly set, it will not update.

The trigger level is the voltage at which the rising edge must pass in order to trigger. For a signal that oscillates between some voltage $V = \pm V_0$, like that seen in figure 4, it makes sense that the trigger level be set to $V = 0\,\mathrm{V}$ as this corresponds to the steepest point of the curve and thus be more accurately located. In the case of a sharp pulse like that shown in figure 4, setting the trigger level anywhere within the jump for the *low* state to the *high* state would be largely equivalent. To adjust the trigger level, use the `LEVEL` control within the `TRIGGER` panel, and observe that the level is indicated on the display in the top right-hand corner of the display, in addition to a thin, orange, dashed line of constant voltage being displayed during, and shortly after, level adjustment. If the level is off the screen, you can push the `LEVEL` knob to set the level to 0 V. With the trigger level appropriately set, the DSO should be recording and displaying the signal; the voltage scale and timebase settings can be tweaked to achieve the optimal viewing of the signal.

How does one drive it - part II: maximising utility

Depending on what task one is trying to accomplish, the achievement of signal observation may be the end point of the DSO usage journey, but it may also be only the beginning. Listed below are descriptions of common DSO utilities, but the list is by no means exhaustive. Moreover, the device is relatively user friendly, so you are encouraged to explore the features of the device.

Measurement

In addition to manual measurement of quantities of interest (amplitude, period, rise time, etc.), the DSO is capable of measuring these quantities in real time. This functionality is activated using the menu on the left of the display. By pressing the `MENU` button, a list of measurable quantities will be displayed, sorted into `VERTIAL` and `HORIZONTAL` measurements, for voltage and time respectively. Pressing the `CH1` and `CH2` buttons will allow the measurements to be calculated from the signals on channels one and two respectively, with colour coding used to indicate the channel used for the measurement. Active measurements will be displayed in the area below the traces, and can be removed by pressing the `Measure` button as located on the `MENU` panel and selecting `Clear`. Other functionality is presented in the `MEASURE` menu, including a display of all measurements and the inclusion of measurement statistics.

Cursors

Cursors allow for flexible measurements and signal signposting, but require a degree of wrangling. To activate the cursor functionality, press the `Cursor` button as located on the `MENU` panel and select the desired mode: `Manual` for unconstrained cursor placement, or `Track` for 1-demensional control of cursor placement, with the other dimension tracking the selected trace. To get a feeling for the functionality, it is suggested that the `Mode` be set to `Manual` and the `DisplayMode` be set to `X-Y`. By setting the `SelectCursor` to either `X` or `Y`, one is able to move the cursors to perform time or voltage measurements respectively. The multifunctional knob is used to position the cursor and can be pressed to alternate between the two cursors of a given dimension. The likely measurements of interest, such as ΔX, $1/\Delta X$ and ΔY, are computer and displayed in the top left of the trace area.

Mathematical operations

In addition to signal measurement and the extraction of basic quantities, the DSO can perform a range of mathematical operations. To activate this functionality, press the `MATH` button on the `VERTICAL` panel, and then use the menu to select the operation (`VERTICAL`) and relevant source(s). Beyond simple arithmetic operations, it is possible to implement powerful signal processing operations such as digital filters, the Fourier transform, and in the extreme case define arbitrary operations; however, the computational power of the DSO is limited and more sophisticated operations are best done on a dedicated machine.

Recording/exporting data

Getting a signal from the DSO to another device, be it for further analysis or documentation is a common task. In most cases, the simplest way to transfer data will be using a USB flash drive, which can be connected on the front panel. In order to maximise the likelihood that the trace(s) that you want to export is saved, one should stop the DSO acquiring data. Then, on the `MENU` panel, press the `Storage` button which will open the *Storage* menu. Modify the `Storage` item at the top of the list to select the information to be recorded: in most cases, recording the data of the entire waveform(s) will be the most appropriate action (select `CSV`), but sometimes recording a screengrab is also useful (select `Picture`). Select the `Save` item, which will open a file browser-like popup, and one can navigate the desired save location, which in most cases will be a USB flash drive which will be displayed in the DSO root directory with the USB logo. From here one can create a directory to store the file(s) (select `New Folder`) or save the file (select `New File`).

Additional resources

- The manufacturer's website, including download links for software, drivers, and firmware
- The instruction manual
- POLUS is a resource for all things related to experimental physics at UTAS