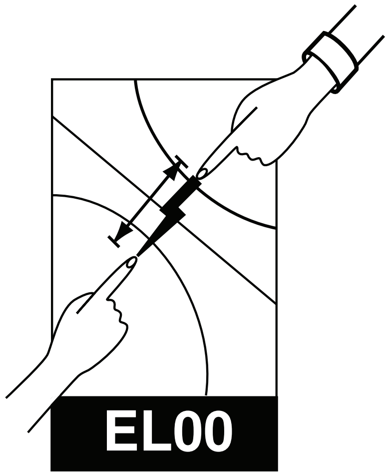
Oscillators, Multimeters, and Oscilloscopes



GDP, JAJ, updated RN October 2019

1 Objective

Our aim is to teach you enough about our function generators ("oscillators", or "arbitrary function generators" (AFGs)), digital multimeters (DMMs), and oscilloscopes ('scopes) for you to understand how to make basic measurements. These are common instruments in many laboratories. To help us to help you, you should, before coming to the laboratory, read through the descriptions of the three instruments in the "Instruments" chapter of your Electronics Manual [1] (hereafter referred to as "the Manual"). Remember to bring a practical notebook (logbook), pen, pencil (for sketches) and calculator with you whenever you come to the practical laboratories. It is safe to handle the circuits in this lab while they are operating.

⚠ Remember that you are responsible for your own safety when working in the laboratory. Always talk to a demonstrator or technician if you are concerned that anything may be unsafe.

2 Record keeping

You must keep a record of your work in the laboratory and this must be in a bound (not loose leaf) notebook. The question of what to record is simply answered. Your record and the practical script together must make it possible for the entire practical session to be reconstructed. Thus you should *write down everything that you do*, but there is no need to copy text from the script unless this is helpful. Tidiness is desirable in your logbook, but completeness is essential! Remember to put an error on every number - see AD26 — *Error Guide In First Year Electronics*[2] for more information.

> ▶ **When you see a text box like this you should write an answer to the question clearly in your lab notebook (logbook). You should check your answer with a demonstrator when convenient; do not wait until you have finished the lab to do so.**

[1] www-teaching.physics.ox.ac.uk/practical_course/ElectronicsManual.pdf

[2] www-teaching.physics.ox.ac.uk/practical_course/scripts/srv/local/rscripts/trunk/Admin/AD26/AD26.pdf

3 Connecting leads

Most of the leads we use for connecting instruments are made with *coaxial*[3] cable, cable in which an inner conductor is surrounded by insulation, then by a cylindrical outer conductor and finally by more insulation. The 'wires' are like a rod running down the centre of a tube, but made flexible. Our coaxial leads are fitted with coaxial plugs we refer to as "BNC connectors"[4]. The inner conductor in the cable goes to the central insulated pin in the plug, and the outer conductor goes to the plug body. To make a connection, offer up the plug to the socket and rotate the outer ring until the plug can be pushed home. Then turn the ring clockwise to lock the plug in place. Over time you will use leads with BNC connectors on both ends and leads with a BNC connector on one end and crocodile clips on the other. In the latter case the inner conductor in the lead goes to the clip with the red wire, and the outer conductor goes to the clip with the black wire. BNC connectors are very common; however, for low frequencies, such as for DMMs, input sockets are often designed to accept plain wires (red and black) not coaxial cable.

Figure 1: A coaxial cable showing the two conductors (left) and a BNC connector with cable (right).

You will also use "scope probes", which are designed to work with oscilloscopes and are the most common way to connect an oscilloscope to a circuit. These are also coaxial cables, with a connector on one end which will mate with the BNC input on the oscilloscope, and a "probe" on the other end. The probe has a short lead with a crocodile clip which is the outer conductor of the coaxial cable (and usually referred to as the "ground" or "common" connection). The inner conductor is connected to a small hook at the end of the probe, which you can expose by pushing back the spring loaded outer plastic cover. You can also remove the plastic outer by pulling it off and use the probe without the hook. The probe contains a small resistor-capacitor (RC) network which reduces the interference of the oscilloscope on the circuit it is attached to; it also reduces the voltage being measured at the oscilloscope by a factor of ten (for the probes in our labs).

Figure 2: From left: A scope probe; a blow-up showing the probe's tip hook; a probe with outer & hook removed.

[3]The inner and outer conductors have the same geometrical axis.

[4]"BNC" stands for "**B**ayonet **N**eill-**C**oncelman", i.e., the type of locking mechanism and the names of the engineers by whom it was designed.

4 A simple setup

A good way to learn about the instruments is to connect them together so that the output of your function generator is fed both to your DMM and to your scope. To set this up you need two coaxial leads with BNC plugs on one end and crocodile clips on the other, and a twin wire lead with red and black plugs on one end and crocodile clips on the other. Plug one of the coaxial leads into the left hand (yellow, **Out1**) output socket of your function generator and the other into the left input channel (yellow) of your scope. Plug the twin wire lead into the DMM with the red wire going to the socket labelled V-Ω-Hz and the black wire to the socket labelled **COM** (common). Finally clip the three black leads together and the three red leads together. (To keep the red and black leads apart so they can't touch you could connect the clips to the two large loops on one side of the circuit board provided. If you do, connect the black leads to the large loop attached to the copper track on the circuit board and the red leads to the other large loop.)

5 Setting details

We advocate strongly that you read the scripts carefully before getting to the laboratory. Pictures of the instruments are included in Appendix B, however in this section it will be hard to make complete sense of the settings lists without the instruments in front of you. Nevertheless the function of the settings is worth understanding in advance of the lab.

Turn on your instruments; the ON/OFF switch for the scope is on the top of the case on the left-hand side. The settings we would like you to make are listed below. Ask a demonstrator (raise your hand to attract attention) if you get stuck.

5.1 DMM settings

Volts, AC, 20 V *range.* The DMM displays the root mean square (rms) value of a voltage.

5.2 AFG settings

Sinewave, 1 kHz*, use* ***Out1***. Like many modern instruments, the AFG has buttons (five, grey, to the immediate right of the screen) which drive a soft menu on the screen. Also like much of modern hardware, 'playing' is the best way to understand how it works in detail. In this case, make sure channel one is selected using the Ch1/2 button. Select "sinewave" using the leftmost button below the screen. Ensure that "frequency" is selected using the top button from the default soft menu (and not "period"). The frequency is then set to 1 kHz by pressing the "1" and then the "kilohertz" soft buttons. The frequency can be tuned by rotating the large knob (LK). The digit in the frequency display that is altered by the LK can be selected using the buttons below the knob on the front panel. Play with these controls to get familiar with what they do. Now set the maximum and minimum amplitudes to ± 5 V using the third and fourth soft buttons and using the LK. Ensure that the offset is zero. Finally turn on the output from the AFG using the On/Off button located immediately above the output. Like all real sources of voltage (formally, an "electromotive force") the AFG has an internal resistance (50 Ω).

5.3 Oscilloscope settings

Setting up the oscilloscope can be a bit trickier than some instruments. With the modern digital 'scopes you will use in the labs, there is one button, labelled "autoset", located towards the top right of the front panel, which when pressed will work out sensible settings and implement them so that a signal can be seen. However, it is invariably the case that these default settings are not optimal, so it is essential to know how to control the oscilloscope manually. In the majority of cases a soft menu is made visible by pushing a menu button. Selection of an item in the menu is made by highlighting it by rotating the

"Multipurpose knob" (MPK), the large knob at the top of the front panel and then pressing the MPK inwards to enter the selection. Here are the settings we would like you to enter:-

- Find the HORIZONTAL area of the front panel and set the scale to 250 μs per (large horizontal) division (about 1.5 cm). The time per division is displayed at the bottom of the screen to the right of the capital letter "M". In the same area of the front panel, press the "Acquire" button and select "sample" with the top soft button. Next use the "Horizontal Position" knob to ensure that the orange "T-arrow" at the top of the screen is lined up with the central vertical graticule; this is the trigger location.
- Press the yellow 1 button to bring up the Channel 1 (**CH1**) input menu;
- Set the **CH1** coupling to DC;
- Set the **CH1** bandwidth limit to On;
- Set the probe factor to $X1$
- Set the Volts/division to 5 V per (large vertical) division (about 1 cm) (note: you can use the "Coarse" and "Fine" settings for this — try it);
- Set **CH1** invert to off.

There is a yellow "1" pointer on the left-hand side of the screen; this should be set onto the central horizontal graticule line using the **CH1** vertical position control knob.

Find the trigger area of the front panel and press the menu button; make the following trigger settings:-

- Set the trigger source to **CH1**;
- Set the trigger type to "edge;
- Set the trigger slope to "rising";
- Set the trigger level to 0 V using the knob labelled 'Level'; when you rotate the knob a (yellow) line will appear on the screen showing where the trigger level is; it needs to line up with the yellow "1" arrow which defines the zero of voltage for **CH1**;
- Set the trigger mode to "Normal";
- Set the trigger coupling to DC;
- Set the trigger holdoff to 500 ns;

It should be clear what most of these settings do but several need further explanation. The yellow "1" pointer on the left-hand side of the screen indicates the vertical position corresponding to zero volts input on the **CH1** display. The **CH1** coupling setting determines how the voltage at the input is connected to the electronics in the oscilloscope: On "GND" the input is disconnected from the scope internally; on "DC" it is connected; and on "AC" a large capacitor is added internally in series with the channel input.

Setting the **CH1** bandwidth limit to "On" reduces the frequency at which the vertical sensitivity starts to fall from a default of 20 MHz down to 6 MHz. This reduces fluctuations in the display caused by unwanted pick-up of stray signals in the lab. Probe $X1$ means that a scope probe is not being used; probes, as described earlier, have resistors and capacitors in them which reduce the voltage. If a probe is connected, this setting should be $X10$.

The oscilloscope will record the voltage as a function of time, and display what it has recorded. It will keep repeating this process, so the image is updated to show the latest voltages present. The data are re-recorded and the screen is re-drawn approximately twice per second. The rate is variable, it depends on the settings and can be much less frequent than this when the time per division is long.

The ”trigger” on the oscilloscope is the device which tells the scope where in the signal pattern to start drawing on the screen. With the settings chosen, “triggering” occurs when the voltage in **CH1** is rising and crosses 0 V (the trigger level that you set previously). The trigger level is shown either by the line across the screen when the knob is rotated, or by the little arrow on the *right*-hand side of the screen (*not* the ”1 arrow” on the left!) If the input signal is changed so that it does not cross the trigger level, no triggering will occur and the last triggered trace will be displayed. Setting the trigger mode to ”Auto” triggers the trace at a low frequency even when the trigger voltage is not crossed, so that you can see something of the new input - but it won’t be stationary because the frequency of the triggering will not be related to the frequency of the input signal. ”Trigger holdoff” is the time after a trigger event for which further triggering is suppressed. You will seldom need to change this setting from the 500 ns specified above.

Having made these settings you should see on the oscilloscope a stationary yellow sine wave trace with a peak-to-peak amplitude of about 10 V. Note that the trace starts when the rising voltage crosses 0 V, as expected from the trigger settings (in practice there is a slight offset which is probably due to the oscilloscopes’ firmware).

6 Getting to know the instruments

Spend some time changing various settings and observing the effects on the scope. Talk to a demonstrator if something happens that you weren’t expecting. Return your settings to those above when you have finished exploring.

7 Recording readings and errors

When recording instrumental readings it is vital to remember that most readings come in two parts: a raw reading (such as a number on a scale or the size of some feature on an oscilloscope trace) and the instrumental settings (such as the time base setting of the oscilloscope). You should generally record these two parts *separately*, rather than conflating them into a single number. Each part of a reading also gives rise to a corresponding uncertainty, traditionally called an *error*. The error from the setting (the *calibration error*) can be looked up in the Manual, while the error from reading the scale (the *reading error*) usually has to be found using common sense to estimate the smallest difference that could be reliably distinguished. You should write down estimates of errors in your readings whenever you make measurements, as *measurements without errors are essentially meaningless*. Appendix A gives an expanded description of this topic and how to estimate errors.

8 Combining errors

Errors in parts of a reading, or in two different readings, have to be combined to estimate the total error in a measured number. This process, called *error propagation* can be quite complex to do properly but in simple cases it is straightforward; see the box at the start of AD26 — *Error Guide In First Year Electronics*[5] as a minimum for this lab. If you have time, read AD26 and AD02 — *Estimating Experimental Errors*[6]. Note that you need to be constantly aware that when combining measurements the calibration errors will behave differently to the reading errors; in a ratio, for example, calibration errors can cancel out completely leaving just the combination of reading errors.

[5] `www-teaching.physics.ox.ac.uk/practical_course/scripts/srv/local/rscripts/trunk/Admin/AD26/AD26.pdf`
[6] `www-teaching.physics.ox.ac.uk/practical_course/Admin/AD02.pdf`

9 Comparing and combining measured values

In many experiments in the electronics lab you will measure the same number in two or more different ways, and two obvious questions arise. Firstly, are the two values *consistent* after allowing for errors? To be consistent the measurements do not necessarily have to agree within errors, but should be close to agreement (see AD26). If the values are not consistent, it suggests that either you have made a mistake, or the theory you are using to model your experiment is wrong. Secondly, if two measurements are consistent, then how should these be combined to get a best estimate of the true value? The ideal procedure for doing this can be quite complicated, but if one measurement is much better than the others then it is simplest just to use this measurement as a best estimate.

10 Comparing measurements on the scope and the DMM

10.1 Period

Check that the period of the displayed sine wave is consistent with the AFG frequency setting. The period is measured as follows:-

- Press the cursor button to bring up the cursor menu and select cursor type ”Time”;
- Select cursor 1 and position it on a zero-crossing of the waveform using the MPK;
- Select cursor 2 and position it on another zero-crossing of the waveform;
- Record the Δt shown;
- Derive the period.

The AFG frequency is within 0.002% of the value set and the accuracy of the time measurement on the scope is 0.01%. The resolution of the cursors can be seen as a cursor position is slowly changed. Are the two values consistent?

10.2 Amplitude

Next check that the peak-to-peak amplitude of the sine wave agrees with the root mean square (rms) value shown on your DMM. The peak-to-peak value of a sine wave is $2\sqrt{2}$ times its rms value. Set the cursor type to ”Amplitude” then place one cursor on the positive peaks of the sine wave and the other on the negative peaks. Record the displayed voltage difference (the peak-to-peak value). The calibration error in the volts per division on the scope is $\pm 3\%$ and the calibration error of the DMM for volts AC is $\pm 1\%$. Again consider the resolution of the cursors.

▶ Are your measurements consistent? Give your best estimate of the actual frequency and voltage (and their uncertainties).

11 Putting a load on the oscillator

The circuit board includes two resistors in series. Use the coloured bands to deduce their nominal resistances and tolerances (the Manual describes how to do this, and there are also multicoloured guides on many benches). Deduce the nominal resistance and tolerance of the combination. Disconnect the DMM, set it to measure resistance, and measure the two resistances separately and the total resistance.

Change the circuit back to the way it is described in section 4 (all blacks together and all reds together) and record the voltage (not resistance) reading on the DMM, i.e., record the readings without the board connected. Now rearrange the connections by moving all three red clips so that the two resistors in series are connected across the AFG output. Record the new reading on the DMM.

Disconnect the **CH1** scope input cable and reconnect it with its outer (black) lead on the red terminal of the AFG, and its inner (red) lead on the black terminal.

▶ **Explain what you see in each case. Hints: consider internal resistances, examine the front panel of your AFG, and remember that all things connected to earth are connected to each other.**

12 Measuring phase difference in an RC circuit

When using the DMM and/or capacitance meter to measure resistance and capacitance, *it is very important that the AFG is DISCONNECTED*. It is possible to cause damage to the instruments if this is not the case.

Record the nominal values and tolerances of the resistor and capacitor connected in series on your board — the capacitor is difficult to read but have a go! Measure their values using your DMM (Ohms setting, 20 kΩ scale) and capacitance meter (left-hand-side inputs, blue button pressed in, 200 nF scale). It is important to ensure that the AFG and scope are not attached when you make these measurements — why is this?

Here you will be using both channels of your scope so turn on **CH2** (with the blue "2" button). Connect the scope leads as shown in figure 3, **CH1** to display the voltage at the AFG terminals and **CH2** to display the voltage across the capacitor. Leave the trigger settings as before, triggering off the **CH1** voltage. Both traces will start when the **CH1** voltage crosses the trigger level, and so corresponding times on the two traces are vertically above each other.

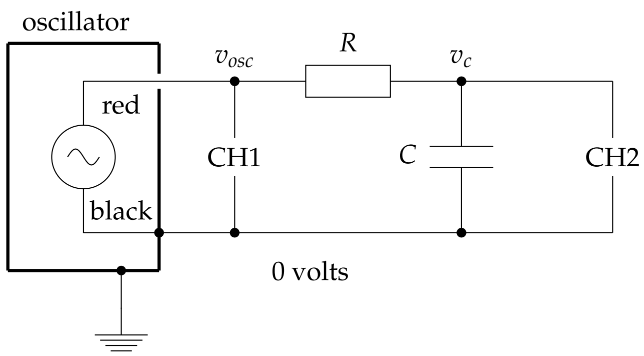


Figure 3: Circuit for phase difference measurements

We define the black lead of the oscillator (which is connected to earth) as 0 V. The voltage difference across the capacitor, $V_c = v_c - 0 = v_c$, has the form $V_c = V_{c0}\sin(\omega t + \phi_c)$ where V_{c0} is the amplitude (peak value) and ϕ_c is the phase. The voltage difference across the AFG terminals is similarly $V_{osc} = V_{osc0}\sin(\omega t + \phi_{osc})$. If the phase difference $\phi_c - \phi_{osc}$ is positive then V_c is said to lead V_{osc}; we could also say that V_{osc} lags V_c.

Set your oscillator to sine wave, 500 Hz, and measure the ratio V_{c0}/V_{osc0}. Is V_c lagging or leading? Measure the time difference between zero crossings on the two traces, and use this to determine the phase shift in radians. Theoretically the ratio of amplitudes is given by

$$\frac{V_{c0}}{V_{osc0}} = \frac{1}{\sqrt{1+\omega^2C^2R^2}}$$

and the phase difference $\phi_c - \phi_{osc}$ by

$$\tan(\phi_c - \phi_{osc}) = -\omega CR$$

where C and R are your capacitance and resistance of your components respectively. (You will derive these two expressions in EL02 — *Circuits Excited by Harmonic Voltages* and in your circuit theory tutorials.)

▶ **Use these two expressions to predict the amplitude ratio and phase difference, and compare the results with your measured values.**

Record what happens (just the general pattern; don't try to make measurements) to the amplitude ratio and phase difference (i) as the frequency is reduced, and (ii) as the frequency is increased. Determine the limiting values (that is, the behaviour at very high and very low frequency) of the amplitude ratio and the phase shift.

▶ **Try using a scope probe for channel 2 for the measurement. Do you detect any difference in your result ? Comment.**

To do this properly you first need to ensure the scope probe is calibrated properly. This is done by connecting the probe to one channel on the scope, then using it to measure the square wave output voltage from the **scope**, which appears on the small metal pin to the lower right of the scope control panel. There is a small adjustment screw in the side of the scope probe body **at the oscilloscope end** which you can rotate using a small plastic screwdriver (why does it need to be plastic?).

13 Extra topics

If you have time left then well done! Now try some of these extra experiments.

1. **Square waves:** Return to the settings in section 10. Switch the AfG output to square wave and record the voltage measurements again. This time the DMM should disagree with the oscilloscope (it should disagree for any waveform other than a sine wave, and for a square wave should read about 11 % too high). Can you explain this discrepancy? Note that most modern DMMs do not suffer from this effect, but you need to check when using an unfamiliar instrument.

2. **Other trigger sources:** You have been using the signal on **CH1** to trigger the time base, but other signals (e.g. **CH2**, **EXT**ernal, or **LINE**) can be selected. When the trigger source is set to **LINE** triggering occurs at mains frequency causing any signal at mains frequency to become stationary on the screen. This is useful for identifying interference coming from the mains. Unclip the **CH1** lead and leave it lying on the bench without the clips touching. You should pick up a signal from the mains cables around the bench. Notice that this signal becomes larger if you touch the clip on the red lead with your finger, but touching the black lead has little effect.

3. **Frequency response:** The sensitivity of the DMM used as an AC voltmeter falls off above 1 kHz whereas the scope sensitivity is maintained (with bandwidth limit off) around 50 MHz. Simultaneously use the scope and the DMM to measure the output voltage of the AFG. For the scope select

the 'measure' menu and then turn on the "RMS" measurement. Leave the AFG output amplitude as ± 5 V, and record the DMM and scope readings at these frequencies: 20, 30, 40, 50, 100, 200 and 600 Hz, and 1, 2, 4, 10 and 20 kHz. Plot the results using a logarithmic frequency scale. (Use your laptop if you have one; graph paper is available if not).

4. **Aliasing:** A digital oscilloscope effectively works by repeatedly sampling the incoming voltage. It measures the voltage at a given time and records the value in a memory. It then measures it again a (very) short time later and stores the new voltage in a different memory. It may repeat this process (effectively) 10^9 times per second. The recorded values are then manipulated by a small computer in the instrument and displayed on the screen. Set your AFG to generate a 300 kHz signal. Set your oscilloscope time base to 1 s per division. What is the frequency of the signal visible on the scope? Work it out from the trace, not by trying to use the oscilloscope's frequency measurement option. Explain what you see.
5. **Coaxial cable:** The cable used in the lab is referred to as "50 Ω" cable. Measure the resistance between the centre conductor and the outer conductor using a DMM. If you don't know why it's called 50 Ω, or don't know why coax is used at all, then ask a demonstrator to explain it.
6. **XY display:** Connect the scope and AFG to measure the phase shift as in section 12, and set the AFG frequency to 500 Hz. Press the utility menu button, select the display submenu and then select "XY". It is possible to get the phase shift from this display, as described in the Manual; if you are interested take a look at how it should be done. Return the scope to YT display.

14 Summary

▶ **Write a brief summary (no more than a quarter of a page) in your lab book describing what you think are the key elements to have learned from this practical. Ask a demonstrator to check this and sign off your book. They might then sign you off on the computer system, or might send you to another demonstrator to do this. *It is your responsibility to ensure that you are signed off on the computer system.***

15 Recapitulation

If you have completed everything, splendid. If not, try to think about how you could have worked more efficiently. For the future, try to remember that

1. If one of an instrument's leads is permanently connected to earth, then there are restrictions on the ways it can be connected to circuits or other instruments which also have connections to earth (the important point being that all earth leads are effectively connected *together*, not that they are connected to earth).
2. You need to be aware of the internal output resistances of AFGs and other sources, and the input resistances of meters and 'scopes. If you did the optional parts you will know that care needs to be taken when using DMMs to measure voltages which are not sine waves and when measuring at very high or very low frequencies.
3. It is essential to record instrument settings whenever a measurement is made and to estimate the errors in any measured quantity.
4. Instruments need to be used thoughtfully to avoid confusion; for example, if you did the optional section you will have seen an artefact caused by sampling: aliasing.

Find out which experiment you will be doing in week 3 and obtain a copy of the script; read this *before* going to the laboratory.

A Appendix A: Observations, Errors, Measurements, and Results

Experimental data consists of *observations* which are made up of four parts, (i) a reading, (ii) the error in the reading (the *reading*, *statistical*, or *random* error), (iii) the range, (iv) the error in the range (the *calibration* or *systematic* error).

For example, an observation of the position above the bottom graticule line on an oscilloscope of the positive peaks of a sine wave might be recorded as 6.3 divisions, reading error 0.05 divisions, range 2 volts per division, calibration error 5%. An observation of the position of the negative peaks might be 2.2 divisions, reading error 0.05 divisions, range 2 volts per division, calibration error 5%.

These are normally abbreviated by multiplying the reading by the range, but keeping the two errors, so

$$12.6\,\text{V} \pm 0.1\,\text{V (stat)} \pm 5\%\ \text{(sys) and } 4.4\,\text{V} \pm 0.1\,\text{V (stat)} \pm 5\%\ \text{(sys)},$$

where (stat) is short for "statistical" and means the reading error in this case, and (sys) is short for "systematic" and means calibration in this case. However, this should not be done if different scales are to be used for different readings which will then be used together. In the above case, both readings used the 2 V scale on the same instrument (or channel of the instrument). This means that they both share the same systematic error. If the scale was not the same, or two different channels were used, then it is important to note that fact, or to record the reading and the scale setting separately, as described in the script above. The reason for this is explained in AD26 and AD02.

A.1 Reading errors — analogue instruments

For analogue instruments the reading error is the smallest change in position of the "pointer", or movement of a line on a screen, that can be discerned. It is almost always much smaller than the finest divisions on the scale.

A.2 Reading errors — digital readouts

On digital instruments the reading error is the *truncation error* or *resolution* which is $\pm\frac{1}{\sqrt{12}}$ in the least significant digit, e.g. if a four-digit display shows 5.432 the reading lies between 5.4315 and 5.4325 and the error is taken as ± 0.0003 (see AD26 or AD02 for an explanation of this).

A.3 Reading errors — scope cursors

For cursors on a scope it is necessary to distinguish between the error and the resolution. The error is *NOT* simply the truncation error in the readout of the cursor's location. It is often possible to estimate a reading to a better accuracy than the truncation error; for example, it is sometimes possible to see that a signal crosses a graticule line between two possible cursor locations. In such cases the error is smaller than the truncation error by a factor equal to the estimated improvement over the resolution.

A.4 Calibration errors

The calibration errors of analogue and digital instruments are determined by the quality of their design and construction and are defined by the manufacturers in the instrument specifications. The calibration errors of our instruments can be found in chapter 7 of the Manual.

A.5 Combining errors — results

Almost always it is the difference between two observations which is of interest. We will call such differences *measurements*. Examples of measurements are those of the period and magnitude of a sine wave voltage made on an oscilloscope. Another example is that of a voltage measured on an analogue or digital meter where the observations are made both when the voltage is present and when it is known not to be present. Both observations must be made in order to remove assumptions about, or reliance on, the zero setting of the meter. (In fact most of our instruments do, or can be set to, read zero for zero input, within the reading error, but this does not take away from the principle).

See the box at the start of AD26 to see how to combine errors in the electronics labs.

B Appendix B: Instrument Pictures

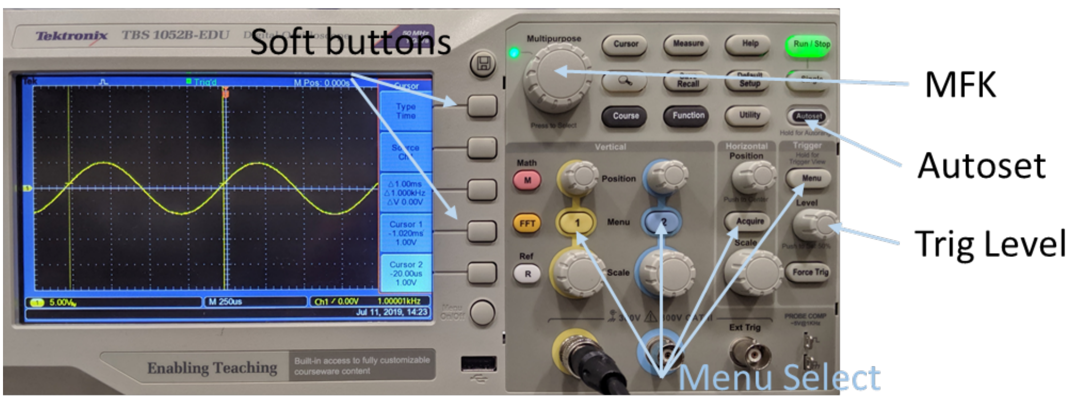


Figure 4: The oscilloscope screen and controls.

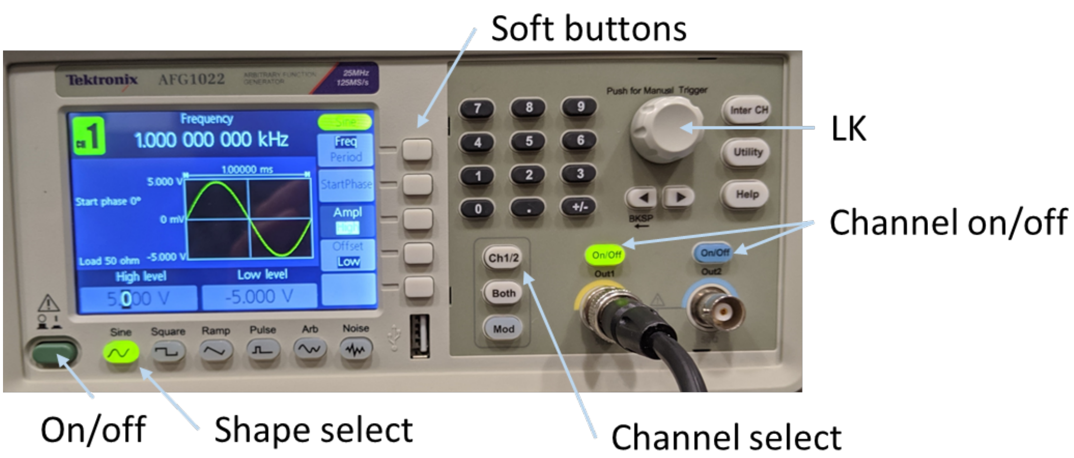


Figure 5: The arbitrary function generator (AFG) screen and controls.