Oscilloscopes demystified

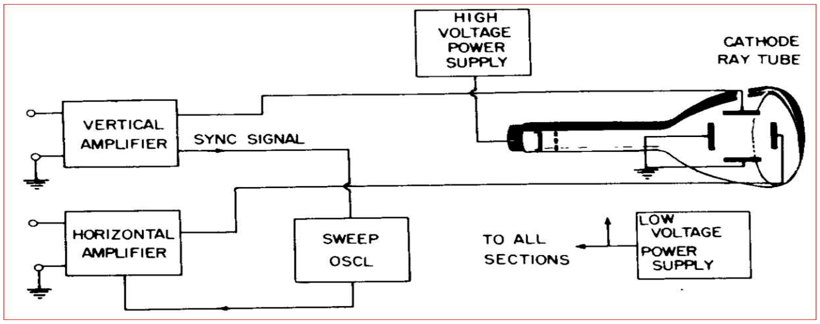
How they work, basic operation, do’s and don'ts.

Why an oscilloscope?

From the first time an inventor / engineer realized there was something strange going on with an electrical circuit, they wondered how they could analyze these events beyond the standard Volt and Amp meters.

The breakthrough came with the invention of the cathode ray tube. The cathode ray tube has an electron "gun" which fires a steady stream of electrons at a phosphor coated screen where it produces a visible dot. The electron stream can be bent in two basic ways; by an electrostatic, or a magnetic field. The cathode ray tube scope uses the electrostatic deflection method. By placing four plates around the electron stream at 0, 90, 180, and 270 degrees, a positive charge can bend this electron stream so as to reach every possible point on the front screen.

What’s inside?



There are a few basic functional blocks inside the scope, the two input amplifiers that take the probe signal, a sweep / trigger block, and the high and low Voltage power supplies.

The vertical amplifier is the one that connects to the external probe connection, while the horizontal amplifier normally connects to the sweep and trigger oscillators. The sweep oscillator generates a sawtooth signal that moves the dot across the screen from left to right at a steady speed. Once there, it briefly blanks the dot, and returns it very rapidly back to the start. The reason we see this moving dot as a line, is because of the glow persistence of the phosphor screen.
The vertical deflection is proportional to the probe input, and as such the variations of the input signal is in effect plotted against time. It is therefore said the oscilloscope displays the signal in the “time domain”. It is also possible to analyze a signal as a function of its frequency, its “frequency domain”. The latter is referred to as a spectrum analyzer, and outside of today’s presentation. The number of lines drawn on the screen is a function of the frequency of the signal to be analyzed, and made steady on the screen by the triggering circuit. We will talk about that more.

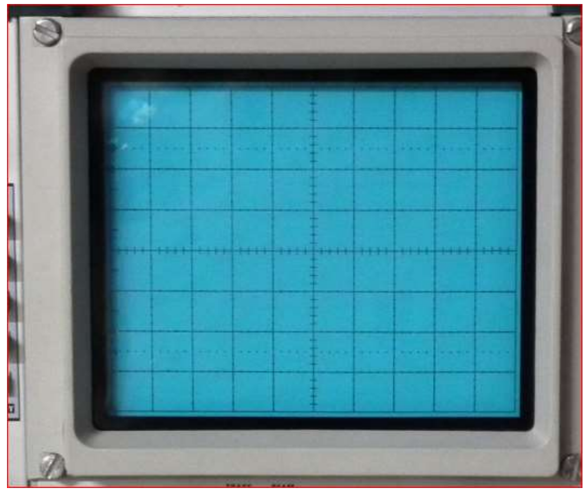
What’s outside?

Turning it on

Somewhere there is a power button. After warm-up, there should be a beam (dot or line) visible. If not, it may be adjusted off the screen, and the beam finder may help there. To make the beam clear, there are the following controls: Intensity (brightness) and focus. These can be adjusted to your liking. The astigmatism and trace rotation only need rare adjustment, and on many scopes are even hidden on the rear panel. We will look at the calibration terminals in a moment.

The screen:

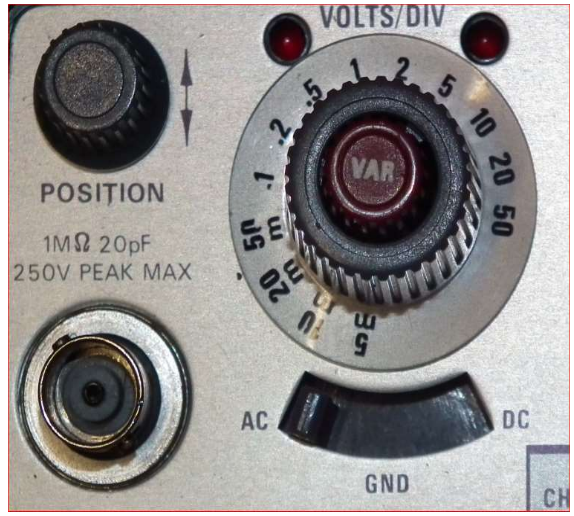
The screen on the scope is divided in squares called graticules, and each division on the vertical axis represents a Voltage step selected by the voltage selector for the active channel.



The horizontal axis represents the time scale; the values associated with each division is dependent on the switch settings.

About the controls

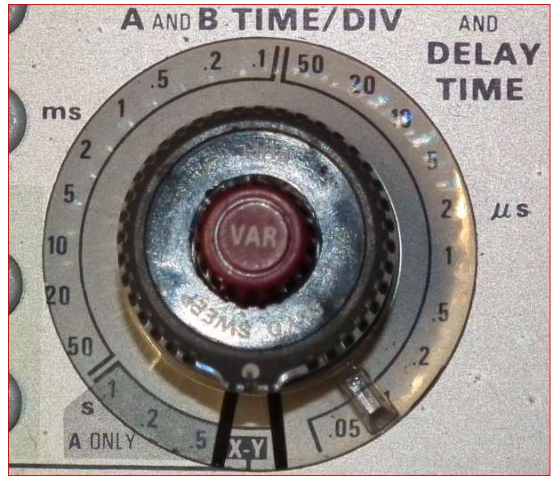
Note the two LEDs, one by the 0.5, and one by the 5. On this scope they represent the probe multiplier, when using a 1X probe the left LED is lit, and signifies the selected Volts/div, in this case 0.5V per screen division. If a 10X probe is used, the right-hand LED is lit, indicating each division on the graticule now represents 5V.



More about that later.
Below the switch is a slide switch to select the desired measurement, AC, or DC. The ground position simply returns the trace to the 0V position, at which time you can adjust the position button to set the trace on the zero line on the screen. It is a good practice to do that every time the voltage selector is moved. The VAR switch allows closer view of the signal, but Voltage is only calibrated in its OFF position.

Sweep controls….

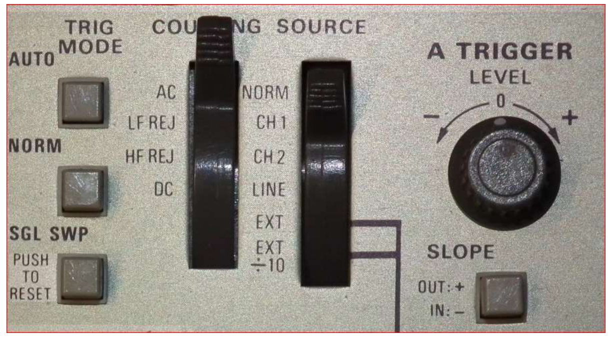
The pointer indicates the selected time per division on the graticule, so if the selector is set to 0.1ms, and it takes 5 squares to complete one cycle of the signal analyzed, the frequency of that signal is the inverse of the time, ex. 1s divided by 0.5ms, which is 2,000Hz, or 2 kHz. Pay close attention to the set time, if the switch was set at 0.5us, the frequency would be 2MHz!



Normally this timescale is the same for both channels, since that is the most common requirement. The VAR button is similar in function as on the Voltage scale, but MUST be in the detent position to do a measurement.
Time delay delays the trigger (explained next slide) and effectively shifts the pattern on the graticule, but does not affect frequency. This is handy when measuring frequency, it allows you to shift the start of the pattern to the graticule, making it easier to measure. The X-Y position disables the time base, and plots the 2nd channel on the horizontal axis. More about that later.

Triggering

When a signal is presented to the probe for display, it would run freely, and it would be near impossible to analyze a single period.

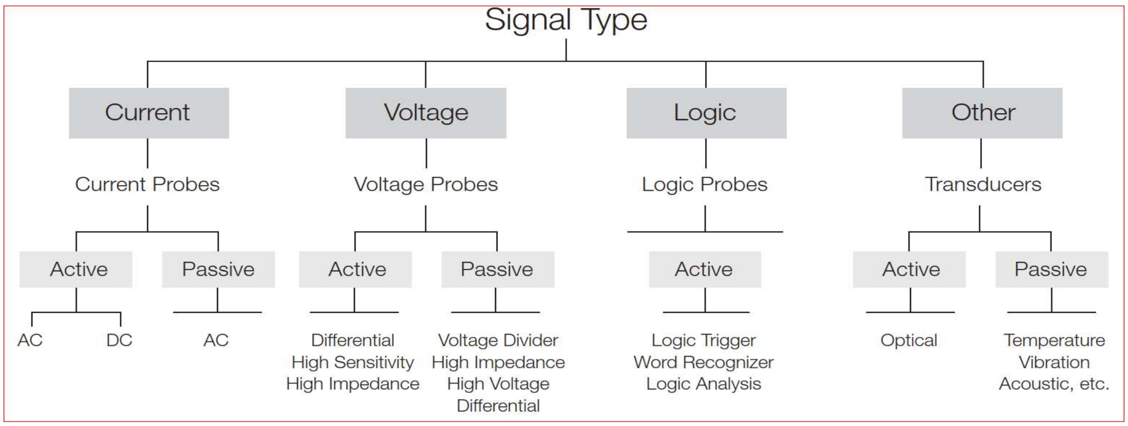


So, the scope has a trigger circuit that effectively tells the scope when to start drawing the signal. This function ensures that every sweep starts at, or near the start of the closed next cycle of the signal, and providing a stable picture.

Triggering is a very complex subject, so I will discuss the basics only. The trigger level sets the Voltage the trigger circuit will interpret as the start of the signal. You can adjust the trigger level knob until you have a good picture, but does not affect any measurement, and therefore does not have any numbers etc. assigned. Setting the trigger mode to “Auto” is recommended for normal use until you learn advanced triggers. Coupling is important, especially AC/DC. In case of a complex, or dirty signal, and you have difficulty getting a stable trigger, you can try the LF or HF rejection setting.
The source switch is a bit more intuitive, including the external trigger option which I will not get into either.

It's all about the probes!

The chart below shows the different types of common probes:

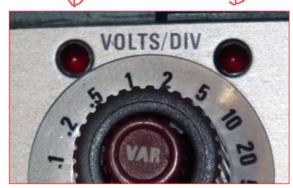


Unfortunately, most new oscilloscope owners spend way too much time on the scope itself, and not enough on the probe. If you have the wrong probe, or use it incorrectly, your measurements may not be correct.

Common probes:

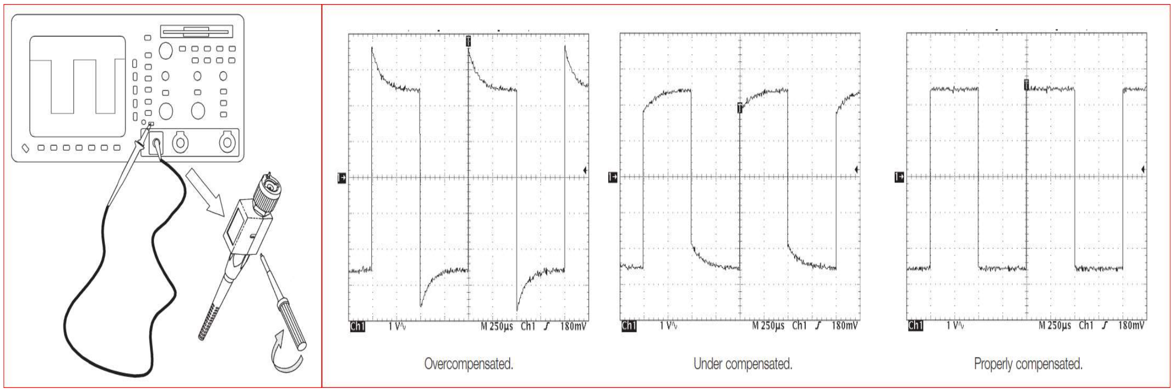
“Smart” probes

Advanced probes will tell the scope what they are.



The left and right probes are dedicated (no X1 – X10 switch) X10 probes. When connected to the port, the pin tells the scope it is an X10, and the scope adjusts its measurement display accordingly. On some older non-microprocessor units (such as the Tek 455) it controls a LED that will remind you of the proper multiplier to be used. The more “professional” line of probes rarely have a multiplier switch, the switch function often requires compromises in the design which are not acceptable in the professional field. Some advanced probes such as differential probes have an amplifier built in which can get its supply power from one of the other contacts around the BNC connector.

Probe compensation



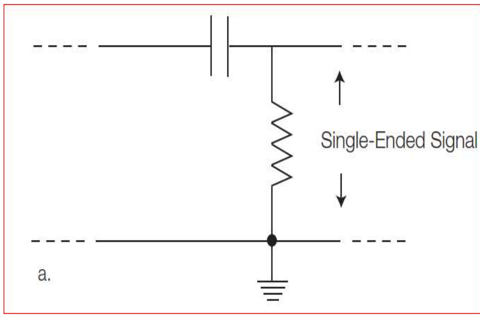
Overcompensated. Under compensated. Properly compensated.

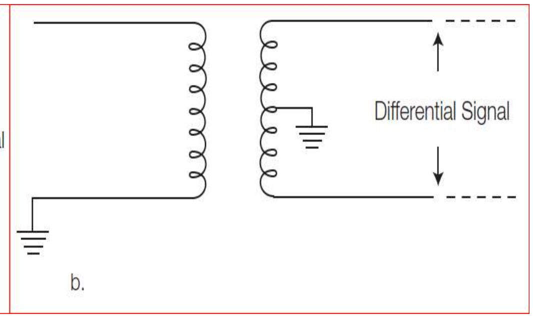
Every scope has a probe compensation port, usually 5V, 1kH square wave. Its purpose is to provide an accurate signal for probe compensation. Once a probe is calibrated on that scope, it should be OK for all of its input ports. If the probe is later used on a different scope, it may need to be calibrated again since there may be slight differences.

Single ended and differential probes

Most standard probes are of the single ended type:

The differential probe looks like this:





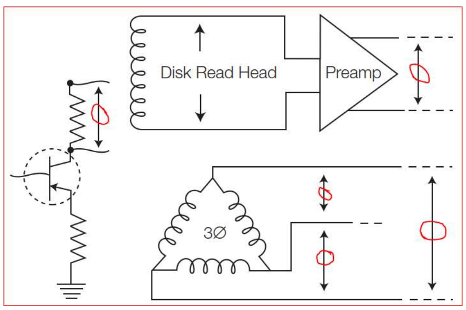
It is VERY important to know what kind of probe you have, most likely it is a single ended probe. The critical thing with a single ended probe is that ALL measurements MUST be made in relation to the ground!! If you are working on a radio without power transformer, there is a good possibility the chassis is not at ground level. If you clip the ground lead of your scope to a hot chassis, the most likely result will be the total destruction of your scope!

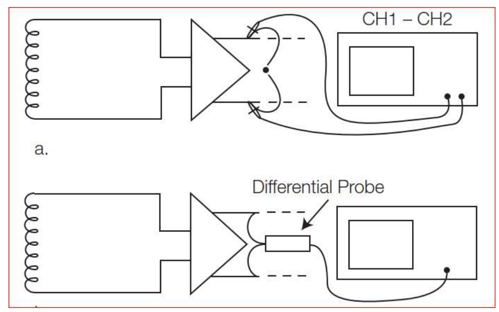
Use an isolation transformer to isolate the ground from your project!

Differential measurement:

Below is a couple of examples (red circles) of what is meant by a differential measurement.

A differential measurement may be possible on a two-channel scope with basic math abilities.

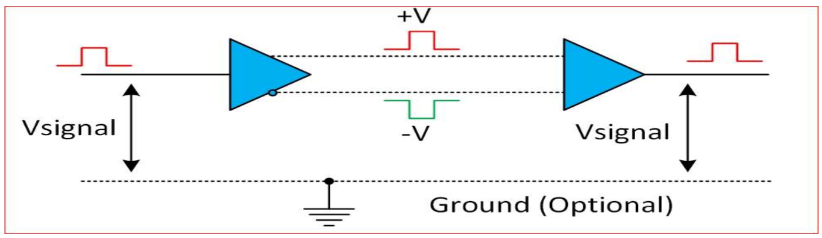




It clearly shows that a standard single ended probe is not able to make these measurements without running into grounding problems. Any error here can destroy your scope, possibly even cause injury if you work on high energy equipment.
Using bot channels, one is set to invert, and then both channels are added. In this case the grounds on the probes are NOT used, and both probes can now together make a differential measurement, shown below. The second picture shows the use of a designated differential probe.

Differential measurement with a standard dual trace oscilloscope

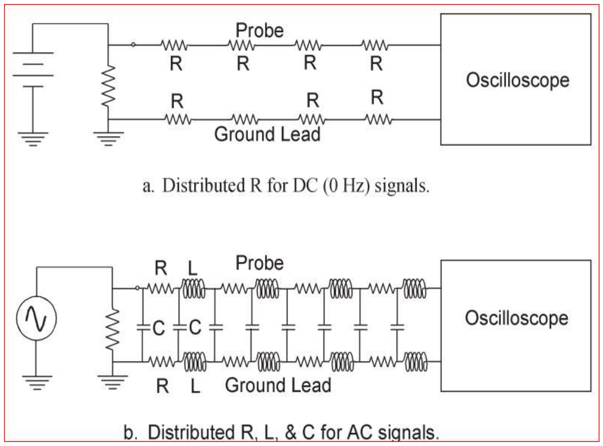
Differential measurements are often useful if we want to analyze a signal over a single component. When you don't have a differential probe, it can be simulated by using the ADD function together with the INVERT on one of the two inputs.



The two ground clips should be clipped together and protected so they will not accidently touch anything.
Time base and Volts/division should be set the same on both channels.
The disadvantage of this method is that the input wire length has doubled, and on higher frequencies can result in some distortion.

What is inside a probe?

An oscilloscope probe is not like the probe on a multimeter; that is essentially a piece of wire with a pointy end.



The oscilloscope probe is a very complex part designed to be electrically as invisible as possible under all conditions with thin the frequencies it is designed for. The bandwidth of the probe therefore must match the bandwidth of the scope.

1 to1 probes and attenuator probes

The input of a scope is typically in the range of 50mV to 50V. A 1 to 1 probe will reflect a measured voltage of that range correctly on the screen, and is referred to as a 1X probe. It presents a 1MOhm and (brand specific) something like 100pF load to the device probed.

Probe	Attenuation	R	C
P6101B	1X	1 MΩ	100 pF
P6109B	10X	10 MΩ	13 pF
P6139A	10X	10 MΩ	8 pF
P6243	10X	1 MΩ	≤1 pF

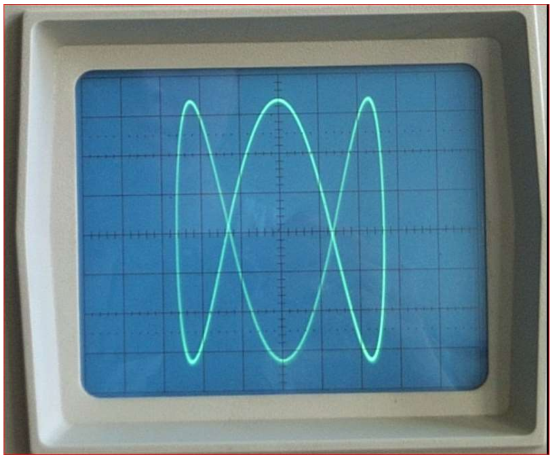
Many of the cheaper probes have a small selector switch on the probe to select 1X or 10X. With these probes you must remember that what you see on the screen is actually 10 times greater than what the screen indicates when on the 10X setting. Frequency is not affected. High Voltage measurements can be made with 50X or even 100X probes. Probes with an attenuation of more than 1X are therefore called attenuator probes. This may, or may not be a problem. Regardless, a 10X probe is more common, and the chart below shows an example of that. The max. input voltage is now between 500mV and 500V, while circuit load is greatly reduced.

WARNING:

Do NOT connect your probe ground to anything you are not 100% sure of it is also at ground level, or floating!!!

Use an isolation transformer if not sure!

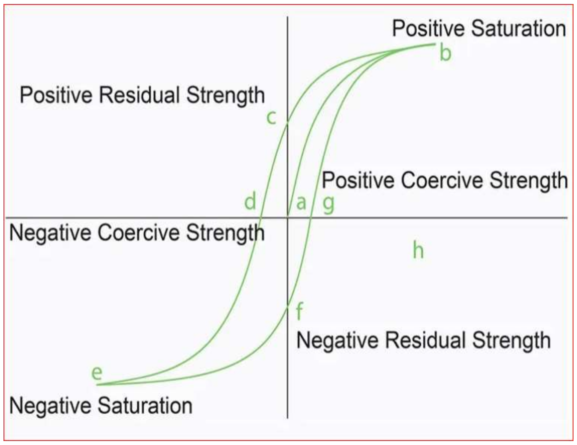
X-Y measurements – Lissajous figure



The Lissajous pattern is probably one of the most interesting and well-known patterns. In order to produce one, the scope must be set in the X-Y mode.

Two wave sources are required, two signal generators is best, but a small transformer can be used to provide one 60Hz signal, and the second signal from a low frequency signal generator.
This pattern shows frequency relations between the two signals, two equal sinodial frequencies will result in a perfect circle. If one signal is twice the frequency of the other, the circle twists, and shows one crossing point. Making the signal half of the first will turn the pattern 90 degrees. If one signal is 3 times the first, two crossings will be observed, 4 times three crossings, etc.

X-Y measurements – Hysteresis curve

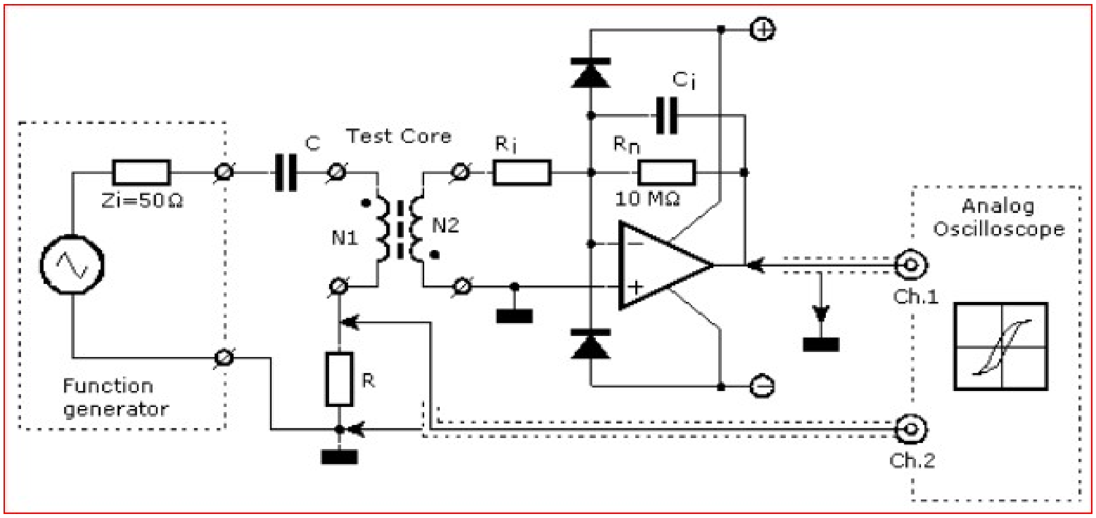


This curve represents the magnetic properties of a ferro magnetic object, most usual an inductor core. It is known as the B-H curve, and is a bit more complicated to produce.

Example: a small transformer.

On the horizontal channel we put the input Voltage to the transformer. The vertical signal is taken from a secondary winding of the transformer, but here is a twist. The vertical channel must represent the slope of the curve, and is mathematically referred to as the first derivative of the signal curve.

X-Y measurements – Hysteresis curve (cont.)



The diagram shows the setup for this measurement. There is the transformer hooked up to a sine wave source, and on the secondary side is an operational amplifier (OPAMP) configured as an integrator.

What scope should I consider purchasing?

As with any purchase, you have to have some idea what you want to do with it. I am going to approach that in the context of the OVRC mandate; the restoration of vintage radio, audio, and TV equipment.
Is a scope essential or needed for this work? Well, mostly, no, not really. Radios and audio equipment rarely require an oscilloscope to repair. TV's a bit more often.
So, in the following slides I will present a few scopes from my personal collection with some comments.

In general, the modern digital scopes are designed for the digital nature of all stuff produced in the last couple of decades or so. Even the coffee pot has a microprocessor in it nowadays.

As a generalized statement the old analog stuff is therefore better served with analog tools. Makes sense eh?

RCA model TE-601-A

This scope is a part of our illustrious and fearless leader's collection, Gord Rabjohn. It is a cool machine, but not much for making measurements. If the price was right, I would buy it, but as a collectors item only.

Heathkit IO 4105 single channel 5MHz analog

Not much to say here, obviously also very limited in capability and usefulness. If you are considering purchasing one, put your hand on your wallet, and walk away. Unless you are buying it for pure nostalgic reasons.

(I’m actually planning to make a clock with this one)

Heathkit analog 20MHz dual channel

For most radio and TV work a scope like this is very useful. Scopes in this class are easy to find, affordable, and simple to use. Disadvantage is that they tend to be big and heavy. The A and B time base is locked for both channels, but that is fine for most input / output comparison.

Tektronix 455 Dual channel 50MHz analog

A scope like this is absolutely perfect for radio and tv repair.

Units similar to this can be found for around $80 or sometimes less, documentation is usually easy to find, and they are often easily repaired. I was gifted two of these, one as donor, one to fix. Turned out both were easily repaired, so now I have two.

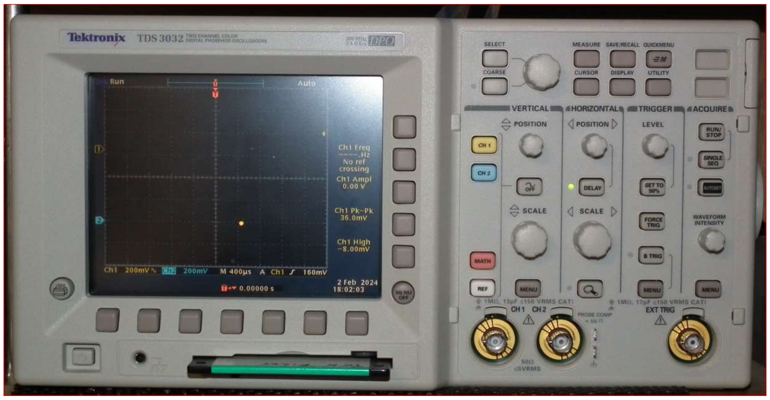
Tektronix TAS 475 four channel 100MHz analog microprocessor scope

Very nice unit, but overkill for radio work. It may be useful for some TV work, but then you are way out of my wheelhouse.

Some of the benefits of a microprocessor scope is on-screen measurements, auto set function, and storage of setting parameters. Obvious disadvantage is the higher learning curve of some of the advanced features. Four channels is nice if you need that, but rarely useful in radio and tv repair.
Repair is significantly more complicated, and several proprietary parts are difficult, or even impossible to find. This particular unit has an issue with astigmatism, I have not been able to get to that yet. Not high on the list for vintage radio and tv repair.

Tektronix TDS3032 dual channel 300MHz digital storage scope

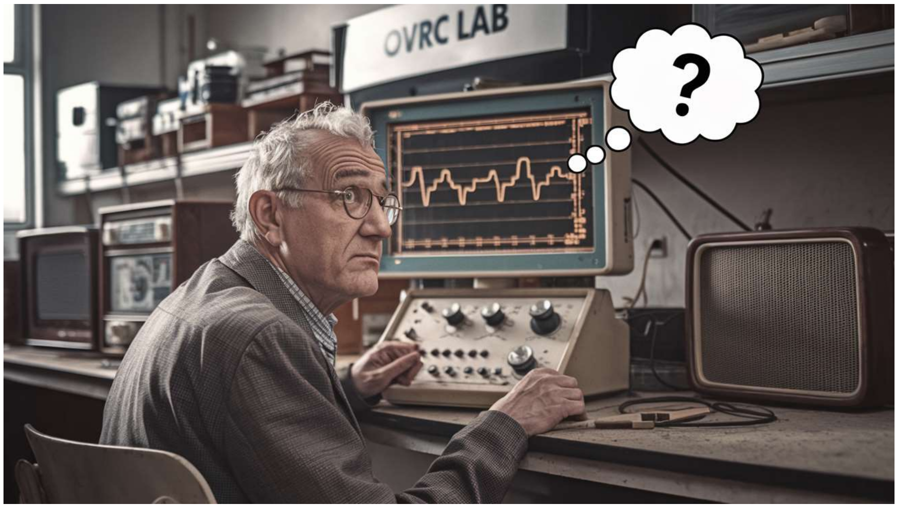
An awesome scope if you need it.



It is easy to get lost in the settings and equally difficult to undo what you did not intended to do. Not recommended at all for vintage radio and tv work.

Frame capture, on screen measurements, printing, advanced math functions including Fourier transform functions. It can capture transient and intermittent signals, and store them for later analysis using the advanced trigger functions. The unit is light, small, and portable. It has a significant learning curve due to the many advanced capabilities. This scope is optimized for working on digital circuits, and not very nice for low frequency radio and tv work. Proper probes are expensive.

Questions?



Credits

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Presented to the January general meeting of the Ottawa Vintage Radio Club (OVRC) in room 148 in the Fisher Park Community Center on 250 Holland Av. Ottawa on Jan. 8, 2025.