Before You Buy an Oscilloscope …

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Contents

1 Overview

For anyone doing electronics - as a job, studies or a hobby - the oscilloscope is an indispensable tool. You'll spend a lot of time with your scope, so it's important to get something that does what you need. In this paper, we discuss oscilloscope features and specifications, things that are useful to know before buying an oscilloscope.

The *Summary* section of the paper, page 10, lists and summarizes some points to be aware of.

2 Analogue and Digital Oscilloscopes

The first oscilloscopes were *analog* in nature. Figure 1 shows an example. The input voltage is amplified and applied to the vertical deflection plates of a cathode-ray tube. This deflects the electron beam vertically. At the same time, a ramp voltage is applied to the horizontal deflection plates. The overall effect is to trace out a voltage-time waveform.

Figure 1: The Classic Tek454 Oscilloscope, the first portable oscilloscope with a 150MHz bandwidth

Analogue oscilloscopes are still available and they are useful, general purpose instruments.

More recently, based on developments in the computer field, *digital* oscilloscopes have become available. Figure 2 shows an example of digital scope hardware – the Syscomp DSO-101 scope in a measurement setup with the WGM-101 waveform generator. Figure 3 shows the graphical user interface for the scope. In the case of the DSO-101, the display appears on an attached computer. The input signal is sampled at some rate and converted into a stream of values, each value proportional to the input voltage at some instant. A computer of some sort then plots these values on a display screen as a graph of voltage vs time.

Each type of scope has advantages. Here's a comparison:

- **Cost**

  For a set of features and bandwidth, a digital scope will be less expensive than an analog oscilloscope. There are several cost centres in an analog oscilloscope: the mechanical switches on the front panel, the circuits of the vertical amplifier, and the power supplies.

  A digital oscilloscope is inherently a lower-cost device than an analog scope. Switches and potentiometers can be electronic rather than mechanical. This lowers the cost and size *and* provides opportunities for automatic operation.

  All analog oscilloscopes include a display. Some digital oscilloscopes include a display, others (like the DSO-101) use a computer, so that must be taken into account for a fair comparison of cost. For example, if you need a portable oscilloscope on your travels, and you already have to take a laptop computer, then something like the DSO-101 adds very little to the size, weight and cost.

- **Printing and Storage of Waveforms**

  To store an analog scope waveform you have to photograph it. Historically, this was done with a special-purpose Polaroid film camera. These days, an inexpensive digital camera will work, but the quality is marginal.

Figure 2: The Syscomp DSO-101 digital oscilloscope hardware with waveform generator WGM-101 in a typical measurement setup

The digital scope has a significant advantage. The waveform data is a stream of numbers that can be stored, printed, manipulated and displayed as a computer file. Or the waveform data can be inhaled into a spreadsheet for further processing. This is especially important in an university or college laboratory, where students need to manipulate, record and annotate waveforms for lab reports.

- **Display Triggering**
  The analog and digital oscilloscope have similar triggering capabilities in most respects.

  Analogue oscilloscopes often have a *delay line* in the vertical channel so that the waveform can be viewed at the point of the trigger. However, it is difficult to view a waveform much in advance of the trigger - especially if the trigger is a non-repeditive event.

  The digital scope has a significant advantage in this respect: it can capture and display a waveform *before* the trigger point. This can be invaluable in diagnosing what caused a trigger event to occur[1].

- **Display Storage**
  It can be very useful to be able to capture and store a random event. Set the trigger mode to single shot, ensure that the trigger level is correct, reset the trigger, and then wait. When the event occurs, it will be shown on the display.

  An oscilloscope that can do this is known as a *storage oscilloscope*. There are analog storage oscilloscopes. These require a special cathode-ray tube and, at least in some cases, they are tricky to set up and use successfully. Analog storage oscilloscopes are now obsolescent.

[1] To do this, the scope captures samples continuously and then freezes when the trigger event occurs. The time in advance of the trigger event depends on the sample rate and the size of the waveform memory. The DSO-101 has a sliding cursor that defines the trigger point. For a pre-trigger display, it can be moved over to the right edge of the display area.

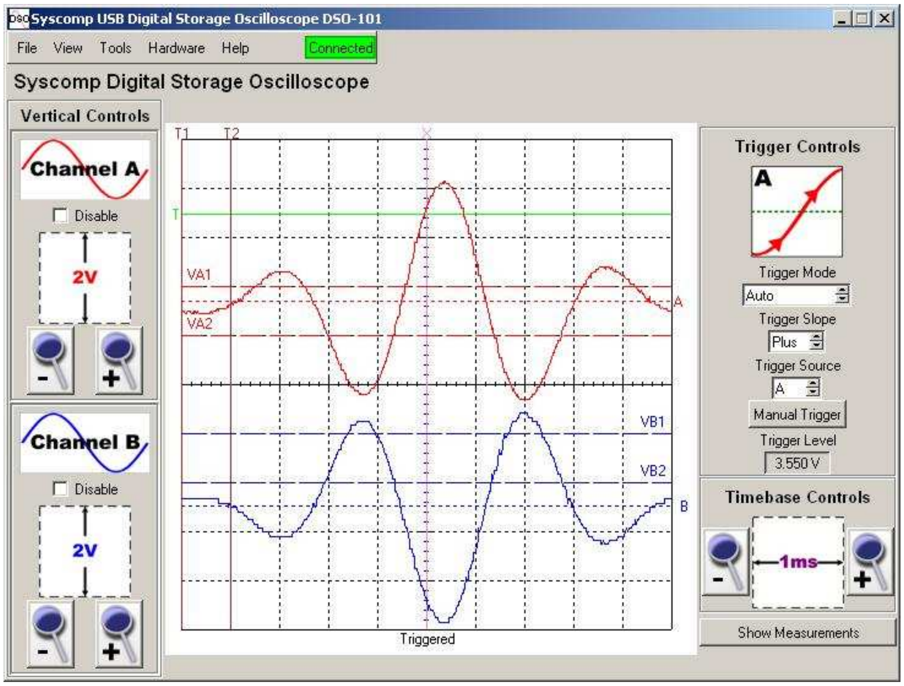

Figure 3: A Digital scope graphical user interface

A digital oscilloscope is inherently a storage oscilloscope. The paper *Single-Shot Capture Using the DSO-101 Oscilloscope: Measurements on a Relay*, a Syscomp Application Note, shows the DSO-101 oscilloscope capturing the switching transient of a relay contact.

As in the case of repetitive waveforms, this single-shot waveform can be saved as a data file for further analysis or as an image file for documentation.

- **Weight, Size and Portability**
  Analog oscilloscopes are invariably bigger, heavier and more delicate than their digital counterparts. The analog scope uses a cathode ray tube, a device that require filament power to light it up and high voltage supplies to accelerate its electrons. This inevitably confers a significant size and weight penalty.

  A digital scope, even one that includes its own display, will be smaller, lighter and more rugged than an analog oscilloscope. While battery powered analog scopes do exist[2], portability is a much more practical proposition for a digital oscilloscope.

- **Reliability**
  Some analog oscilloscopes are works of engineering art and operate flawlessly for decades. However, the electromechanical devices - switches and potentiometers - eventually become noisy and intermittent.

  A digital oscilloscope has fewer electromechanical parts. For example, the Syscomp DSO-101 scope contains two electromechanical relays. All other controls are electronic. These scopes and others like them are brand new, so their reliability has yet to be proven. However, eliminating switches and potentiometers is a step in the right direction.

[2] A charming example of a battery-powered analog oscilloscope is shown in reference [1]. The CRT is 1 1/2 inches in diameter, and the batteries (one of them 45 volts!) occupy half the total volume.

- **Automation**
  Generally speaking, an analog oscilloscope is configured by operating various manual controls and switches. On the other hand, the DSO-101 is configured by *electronic* controls and switches that are actuated from the host PC. A script of some sort can run on the host PC to automate the measurement task. In the case of the DSO-101 (and Syscomp WGM-101 waveform generator) the USB port has been configured to appear as a high-speed serial port. The automation script issues commands to the scope (and generator) hardware via this *pseudo-serial* port. Any programming language that can talk to a serial port can be used to automate the instruments.

  For example, figure 2 shows the Syscomp WGM-101 waveform generator and DSO-101 oscilloscope operating under control of a network analyser program [2].

3 The Effect of Oscilloscope Bandwidth on Measurements

An oscilloscope is a device that plots a waveform of voltage vs time. The voltage may be derived from some sensor that produces a voltage in response to another variable such as acceleration. So the oscilloscope is really a general purpose device for showing the variation of some quantity with time.

The *bandwidth* of an oscilloscope is the frequency range over which the vertical dimension of the display is accurate. Early oscilloscopes were AC coupled, so the bandwidth was the frequency range between the lowest useable frequency and the highest useable frequency of operation.

Modern oscilloscopes have the option of operating down to zero frequency - they are said to be *dc coupled*. So the bandwidth is simply the maximum useable frequency of operation.

As frequency increases, the gain of the vertical channel eventually decreases, making the display less accurate. The maximum useable frequency is traditionally taken as the frequency at which this gain has fallen by 3db (70.7%) compared to its low-frequency or mid-frequency values. This is a significant decrease, a 30% error in amplitude measurement.

When one is observing a waveform with higher order harmonics, then these harmonics will extend to a much higher frequency than the fundamental. For example, a square wave has components at 1, 3, 5, 7,... times the fundamental frequency. These components become smaller at higher frequency and at some point, sufficiently small to be neglected. So a 1kHz square wave will contain components at 1kHz, 3kHz, 5kHz and so on. A sufficient number of these harmonics must be present to accurately represent this square wave.

A useful rule of thumb is that the oscilloscope bandwidth should be 5 times the highest frequency in the signal. For example, the Syscomp DSO-101 has a 2MHz bandwidth. Then the highest frequency of operation should be in the order of 400kHz. A 400kHz square wave would be displayed with the first three components intact, which is sufficient for many applications.

Notice that the *shape* of a sine wave continues to be intact right up to the maximum operating frequency of the oscilloscope. So a measurement to simply to check that a waveform is present and to determine the frequency of the waveform – without an accurate amplitude measurement – can be done up to the maximum bandwidth of the instrument.

4 How Much Bandwidth Do You Need?

Oscilloscope bandwidth is a bit like car horsepower. In a car, it's nice to have the power on tap when you need it, but it comes with a cost. A higher-power car generally consumes more fuel and - for a given payload - weighs more. A car that is optimized for city driving may have lower operating costs and be easier to manoeuvre in traffic. It depends on the application.

Similarly, oscilloscope bandwidth has a cost. All other things being equal, a higher-bandwidth oscilloscope is more expensive, requires line power or a large battery and is larger and heavier than a low-bandwidth scope. A moderatebandwidth scope like the DSO-101 is inexpensive, operates from USB power, and will fit into a jacket pocket or laptop case.

Applications for a low-bandwidth oscilloscope include:

- Audio
- Power-line related signals
- Control systems
- Mechatronics and Robotics
- General purpose op-amp applications

Applications for a high-bandwidth oscilloscope add these applications:

- Measurement of radio frequency signals
- Observing medium and high frequency digital pulse waveforms
- Video

5 How much Bandwidth Do You Get?

This area is a bit tricky, and it's important to understand the oscilloscope specification.

With an analog scope, the bandwidth is a cut-and-dried proposition. The vertical amplifier response is down 3db at some frequency.

With a digital scope, it's more complicated. The maximum useable frequency depends on the bandwidth of the vertical amplifier *and* the sampling rate.

The usual situation is *sampling rate higher than bandwidth*. For example, in the DSO-101, the sampling rate is 20MSamples/sec. The bandwidth is 2MHz. This configuration is based on a very simple idea: you need at least 10 data points to define a waveform with sufficient precision. Consequently, this oscilloscope is not useable at much above 2MHz, and there is no point in providing more vertical bandwidth than 2MHz.

Notice that a 20MSample/sec is not necessarily a 20MHz bandwidth oscilloscope. The two are often confused - sometimes deliberately.

Example
The sound card in a personal computer can be used as an oscilloscope. The bandwidth and sampling rate specifications for one sound card are [6]: sampling rate: 44.1KS/sec, bandwidth: 100Hz to 4KHz Over what frequency range is this oscilloscope useful?
Answer
Using the '10 samples miniimum' rule, the maximum useful frequency is 44.1KS/sec$/10 = 4.4$KS/sec. This is a reasonable fit to the upper bandwidth frequency, 4kHz.

Notice that the lower bandwidth limit of this scope is 100Hz, so it cannot display the DC (zero frequency) component of a waveform. Some audio frequencies would be visible - most speach is in the 3kHz region, for example – but viewing the entire audio band requires response to 20kHz.

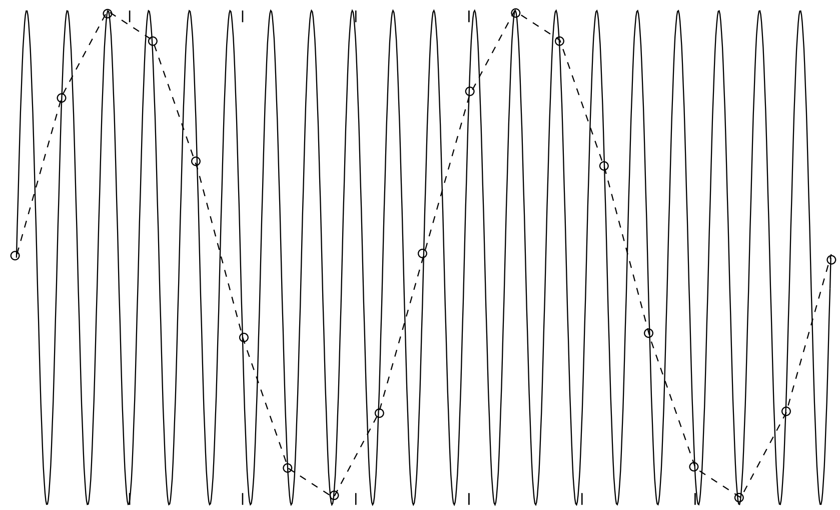

Figure 4: Downsampled Sine Wave

6 Downsampling

There are circumstances where a digital oscilloscope can *downsample* an input waveform [4]. The principle is illustrated in figure 4.

The solid trace is the high frequency input signal. The dotted trace is the downsampled version. Circles mark each sample point.

The samples of the input waveform are obtained in such a way that each sample is located slightly later in the incoming waveform. The effect is to display the shape of the incoming waveform, but at a much lower frequency. In this way, the oscilloscope can display a waveform that is much higher than the sampling frequency.

This is exactly the same principle used in the *stroboscope* [5], which is a device for slowing down the motion of a mechanical device.

In figure 4 the samples are taken at each cycle of the input waveform. In practice, several cycles of the input may elapse between each sample, in which case the division ratio between input and display is larger. As well, figure 4 shows the input as a sine wave, but any waveshape can be treated this way.

The requirements for this to work are as follows:

- The signal must be repetitive, that is, it cannot change shape – amplitude or timing – while being sampled. Consequently, this technique does not work on transient waveforms.
- The vertical amplifier bandwidth must be sufficient for the input signal. In other words, the vertical bandwidth must be *larger* than the sampling rate.
- The A/D converter bandwidth must be larger than the sample frequency. Some, but not all, A/D converters will work in this mode.
- Any jitter in the sampling interval is magnified as noise in the displayed waveform. Consequently, the sampling interval must be very stable.

Some care must be taken to work backwards from the displayed waveform to determine the actual frequency of the input waveform.

In general, then, it is much more convenient to observe high frequency waveforms directly. Sampling oscilloscopes are still in use to view very high frequencies, but where possible they are being replaced by 'real time' oscilloscopes.

7 Dynamic Range in Digital Oscilloscopes

The *dynamic range* of the oscilloscope is the range of amplitudes that the oscilloscope can display.

Many digital oscilloscopes – including the Syscomp DSO-101 – use an 8 bit A/D converter. An 8 bit converter can output a maximum digital value of $2^8 = 256$. The smallest useful value in peak-peak volts is defined by the number of vertical points we'd like to see in our waveform display. A reasonable choice is 100 points: more than that are difficult to detect visually.

Then for any single setting of the vertical gain control, the range of largest possible signal amplitude to smallest allowable signal amplitude is $256/100 \approx 2.5 : 1$. This is very limiting.

Consider an oscilloscope where the largest allowable signal into the input jack is 50 volts p-p (peak-peak) and it has only one vertical setting. Then the minimum signal, to ensure that we see 100 vertical points, is $50/2.5 = 20$ volts p-p. There is nothing to say that you can't apply, say, a 1 volt peak-peak signal to this oscilloscope. However, the vertical display will be $1/50 \times 256 \approx 5$ vertical points, ie, extremely blocky. Of course, this 5 step blocky display could be adjusted in software to be any size we liked[3], but that wouldn't improve the resolution.

By itself, then, a fixed input voltage range is not all that useful. What can be done in order that the oscilloscope can measure a wider range of inputs? There are two possibilities: (1) put a variable gain amplifier in front of the A/D converter, and (2) increase the resolution (number of bits) of the A/D converter.

7.1 Variable Gain Preamp

A *variable gain preamplifier* moves this $2.5 : 1$ dynamic range so that it can accomodate a variety of input levels. Each vertical gain setting permits a different maximum input level. In this way the $2.5 : 1$ dynamic range is increased to a much larger overall dynamic range. The DSO-101 uses this approach. It has 7 preamplifier settings, in the traditional oscilloscope 1:2:5 sequence[4]. The screen is 10 divisions in height.

In the case of the DSO-101, the maximum allowable signal and minimum signal to display 100 vertical points, at the various gain settings are:

Scope setting	Maximum Signal, Vp-p	Minimum Signal, Vp-p
5 volts/div	50	20
2 volts/div	20	8
1 volt/div	10	4
0.5 volts/div	5	2
0.2 volts/div	2	0.8
0.1 volts/div	1	0.4
0.05 volts/div	0.5	0.2

Consequently, the DSO-101 can display signals between 50 volts p-p and 0.2 volts p-p, a dynamic range of 250:1, with a minimum vertical resolution of 100 points.

(Mathematically, the dynamic range is approximately equal to $R^{(N-1)}$ where R is the dynamic range of any given stage and N is the number of gain settings. In the case of the DSO-101, $R = 2.5$ and $N = 7$).

[3] This is sometimes referred to as *software magnification* or *digital zoom*.

[4] Analog oscilloscopes had to deal with this problem too. The lower limit on signal amplitude was defined by what was comfortable to view on the display screen, and the noise level of the circuitry. Much of the cost and complexity in an analog scope is associated with this variable gain requirement.

7.2 High Resolution A/D Converter

For the oscilloscope manufacturer, an 8 bit A/D converter is attractive because speedy 8 bit units are available at very modest cost[5].

Given the fact that the variable gain vertical preamplifier is complicated, can this same dynamic range be provided by increasing the number of bits on the A/D converter? For a given sampling speed, the price of the A/D converter increases with number of bits, but there are cost savings to be had in eliminating the preamplifier.

For the A/D converter to provide, say, a 250:1 dynamic range, with a minimum resolution of 100 vertical points, then the maximum A/D output value would be $250 \times 100 = 25000$. This would require a 15 bit A/D converter. High speed 16 bit A/D converters do exist, but they are currently extremely expensive. For the time being, the most practical approach is a variable gain preamplifier.

There is one situation where a high-resolution A/D converter is important. When calculating the spectrum of the waveform *when there are large amplitude and small amplitude signal components present at the same time*, the dynamic range of the display – between the largest and smallest simultaneously viewable signals – is established by the number of bits in the A/D converter. As a rough rule of thumb, each A/D bit adds 6 db of resolution, so an 8 bit converter can view spectral components that are about 48 db below the maximum signal. It may be necessary to have a larger dynamic range in audio work where viewing small levels of harmonic distortion in the presence of a much larger signal.

Scopes with high-resolution A/D converters are available, but they are more expensive and/or have lower bandwidth than scopes with 8 bit A/D converters.

7.3 Input Impedance

The input impedance of the oscilloscope is important because it determines the *loading effect* on the circuit being measured. Ideally, the input to the oscilloscope would appear as an open circuit, but that's not the case.

The input of an oscilloscope is specified as something like 1MΩ resistance in parallel with 20pF capacitance. This is allows the oscilloscope to be used with x10 probes.

Some inexpensive scopes do not have this input impedance so they cannot be used with a x10 probe. (For more on oscilloscope probes, see the Syscomp application note *Oscilloscope Probes: Theory and Practice*.)

At low frequencies, the capacitive reactance of the 20pF is negligible compared to the resistance, and the effective input impedance is about 1MΩ. So as long as the internal resistance of the circuit being measured is much less than 1MΩ, the scope will have little effect on the circuit. So far so good.

At high frequencies, however, the input impedance decreases. Suppose the analog bandwidth of the oscilloscope is given as 100MHz. If the circuit delivered 1 volt peak-peak at 100MHz to the input, it would see a capacitive input impedance of 80 ohms and be required to drive 12.5mA peak. This is over the current limit of many op-amps.

To reduce the effect of the scope input capacitance on the circuit, the most common solution is to use a $\times 10$ scope probe to connect to the circuit. The $\times 10$ probe attenuates the signal amplitude by a factor of ten, increases the input resistance by a factor of ten, and decreases the input capacitance by a factor of ten. This may or may not be an acceptable capacitive load to connect into the circuit.

If high input impedance at high frequency is important, then you can use an *active probe* to buffer the signal. An active probe [7], [8] can present the circuit under test with a capacitance that is a fraction of a picofarad. However, the amplitude range is typically limited to a few volts.

[5] The author once did a video-wall design which used 48, 8 bit A/D converters. At the time, they were $40 each, and that was considered a bargain. The current price of similar units is about $2.

8 Summary

- A used analog scope can be a viable option, but be aware of its shortcomings in features, size, weight and reliability.
- Digital scopes are replacing analog units in the marketplace, so if you want features like portability, coloured-coded traces, single-shot capture (storage scope function), printing waveforms or pre-trigger view, you need a digital scope.
- Buy the scope that you need for the type of measurements you'll be doing. Bandwidth costs money and increases the size and weight.
- It is challenging for the scope manufacturer to design a variable gain wideband oscilloscope preamplifier. However, it's critically important for viewing a range of signals from large to small. When shopping for a digital scope, read the specifications carefully to determine how many vertical gain steps are provided.
- Check that the scope has an input resistance of 1MΩ in parallel with a small capacitance, typically 15 to 30pF. Then the scope can be used with a x10 probe.
- Check the software. At a minimum, it should provide a well documented API (applications programming interface). Syscomp provides the instrument API *and* source code, so it's possible to modify and add features.
- Check the computer platform requirements. Syscomp instrument code runs under Windows, Linux, Unix and Mac[6] operating systems.
- If the scope has a built-in screen, check the resolution. To see waveform detail, you need something in the order of 250 pixels in each dimension.
- Be aware of the effect of the oscilloscope input capacitance on the circuit that is being measured. At high frequency, it is the input capacitance that determines the load on the circuit.

The following table summarizes the features of three different types of oscilloscopes: a fully analog oscilloscope, an inexpensive digital oscilloscope with an integral display, and the DSO-101 USB oscilloscope. There are advantages and disadvantages to each type of instrument, as the table indicates. (The *Analog Scope* and *Digital Scope with Integral Display* entries are representative of low-cost oscilloscopes of this type, but specifications vary. Check the datasheet for a specific oscilloscope to see if these features are available.)

[6] Some restrictions apply. Check with us for supported operating systems and harware.

Function	Analog Scope	Digital Scope, Integral Display	Digital Scope USB (DSO-101)	
Capture Display Image	No	Yes	Yes	
Data Capture to CSV file	No	Yes	Yes	
Programmable Operation	No	Yes	Yes	
Amplitude, Time Cursors	No	Yes	Yes	[1]
Pretrigger View	No	Yes	Yes	
Waveform Zoom	Maybe [2]	No	Yes	
Single Shot Storage	Usually No	Yes	Yes	[3]
Colour Traces	No	Option, extra cost	Yes	
Portability	Poor	Good	Excellent	
Battery Power	No	No	Yes	[4]
Electronic Controls	No	Yes	Yes	[5]
Spectrum Analysis	No	Yes	Yes [6]	
Waveform Math	No	No	Yes	
Custom Displays	No	No	Yes [7]	
Save/Restore Setups	No	Yes	Yes	
Source Code Available	N/A	No	Yes	
Analog Bandwidth	20 to 150MHz	20MHz typical	2MHz	

Notes

1. Cursor readouts make it much easier to measure waveform parameters such as frequency.
2. Analog scope waveform zoom is known as *delayed sweep*. It is available only on high-end analog oscilloscopes.
3. Analog storage is obsolete but available on some surplus oscilloscopes. It requires a special display tube, and is difficult to use.
4. Uses the host computer power, eg, battery-powered laptop.
5. Mechanical controls eventually deteriorate and cannot be remote controlled. A digital oscilloscope with integral display will have some simple mechanical controls, probably of higher reliability than the complex mechanical switches and potentiometers of the analog oscilloscope design. The DSO-101 USB oscilloscope has one mechanical relay, otherwise is all-electronic control.
6. The DSO-101 displays the conventional trace display **and** spectrum analysis, simultaneously.
7. The DSO-101 can display a histogram of waveform statistics, useful in analysis of noise-like signals. This is representative of real-time displays that may be created for special applications.

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Revision History

28 June 2006: First release
1 April 2007: Minor correction re automation, added Mac support
5 July 2008: Added comparison table under *Summary*