

Oscilloscopes and their Calibration

*David F. Martson
Quality Metrology Services™*



Abstract

Perhaps the most common piece of test equipment in the engineering and/or calibration laboratory is the ubiquitous oscilloscope. In the beginning, the oscilloscope's forebears, the oscillograph, were utilized primarily for waveform analysis and troubleshooting, due to their inability to make quantitative measurements, poor resolution, and quirkiness of use. With the introduction of the modern oscilloscope, calibration methods and equipment were simultaneously devised to support these instruments, though those early oscilloscopes were often relatively simple, low accuracy devices, by modern standards. Today's oscilloscopes offer performance that was unimaginable back in those early days, including bandwidths to 30 GHz or more, with sub-nanosecond timing becoming commonplace. Clearly, the calibration methods and equipment utilized to calibrate these current devices are anything but simple, yet they are still underestimated by many.

Introduction

Any discussion of oscilloscope calibration would be incomplete without a brief history of the modern (triggered sweep) oscilloscope's development. Following World War II, oscillographs (as they were then

called) were crude, rudimentary devices, unsuitable for quantitative measurements and used only for qualitative (visual) tasks, due to their free-running (untriggered) sweep, uncalibrated vertical deflection factor and horizontal sweep speeds. Simply stated, without the benefit of triggering, the input signal was, in the case of repetitive waveforms, an unstable signal moving across the screen, at best, and unusable for non-repetitive or one-shot events. When C. Howard Vollum, formerly a member of the U.S. Army Signal Corps team during the war that developed radar for the United States, designed and patented the first triggered sweep oscilloscope, the Tektronix®¹ Type 511, released in June 1947, everything changed. This was the beginning of the modern (analog) oscilloscope. For the first time, the sweep was triggered and vertical deflection and horizontal sweep speeds were calibrated, facilitating traceable, quantitative measurements. The device previously suitable only as a 'viewing screen' was now capable of measurement, as well as displaying electrical phenomena, including single-shot events, as never before, thanks to the triggered sweep design. While we take these capabilities for granted, they literally opened the door for uninhibited technological growth, previously unseen, that continues to this day, using oscilloscopes produced by many different manufacturers.

As is commonly the case with the introduction of any new technology, it was necessary for new methods and equipment for the calibration of the oscilloscope to be developed. With the introduction of the 511, Tektronix faced that necessity by developing the first calibration routines intended for a production environment. Equipment designed specifically for oscilloscope calibration did not exist, and the equipment available for use was inefficient at the task, requiring time-consuming and complex setups, impeding production. For example, verifying vertical deflection factors typically relied on the use of a DC power supply, monitored by an external voltmeter, while verifying bandwidth involved the use of a signal generator whose externally leveled output (typically using vacuum thermocouples, an extremely slow and tedious process) to ensure amplitude flatness over the desired frequency range.

Likely born out of their obvious need for specialized, dedicated-use equipment to support the manufacture of oscilloscopes, Tektronix became the first leader in the manufacturer of oscilloscope calibration equipment by default. Soon, the basic instrumentation for oscilloscope calibration was defined: the *standard amplitude calibrator* (vertical deflection factor), *fast-rise pulse generator* (vertical transient response), *high amplitude square wave generator* (vertical attenuator compensation), *constant amplitude signal generator* (vertical bandwidth and trigger sensitivity), and *time-mark generator* (horizontal sweep speeds). These types of instruments became commonplace, and came to be used universally to calibrate oscilloscopes. Though initially developed by Tektronix, these devices have subsequently been produced by other manufacturers in various configurations.

Equipment Overview: Common Types and Applicability

Since the introduction of dedicated oscilloscope calibration equipment, there have also been many additional types of calibration fixtures used as well. For the purposes of this discussion, however, the focus is on the primary-use instruments utilized in calibration. Moreover, though several pieces of the

¹ *The author has no connection, professional or commercial, with Tektronix, other than a long association as a user of their products.*

equipment subsequently described may also be used for other testing, depending on unit under test (UUT) requirements, their usage is more commonly associated with a specific, primary purpose, e.g., vertical amplifier calibration. For the purposes of clarity, this discussion groups the calibration equipment discussion around the specific subsystems, e.g., vertical, triggering, and horizontal, and the calibration instrument(s) primarily used for each. In addition, it also uses the generic, descriptive names for the various instruments and/or functionality (many current oscilloscope calibration instruments are multifunction devices), rather than specific names subsequently used by the various manufacturers.

Vertical Subsystem

The primary characteristics requiring calibration in the oscilloscope's vertical subsystem are amplitude and frequency response, though as oscilloscope bandwidths have risen, the input impedance, a key contributor to measurement errors at high frequency, is often calibrated as well. To calibrate these functions, however, requires as many as five separate devices and/or functionality. Let's explore the requirements and instruments used to calibrate them.

The measurement of oscilloscope input impedance is straightforward, with oscilloscope calibrators from several manufacturers, both currently and in the past, having that functionality built in. Early on, however, that was not the case. Briefly, an 'L-C' meter was used to adjust the input capacitance (the resistive input values were typically fixed at 1 M Ω in those days) on the direct (non-attenuated) input range. Once set, the subsequent adjustment of the vertical attenuator compensation indirectly matches, via visual observation of the waveform fidelity, the impedance (capacitance) of the attenuator ranges with that of the previously measured direct input.

The *standard amplitude calibrator* is used to calibrate the vertical gain/attenuation of oscilloscopes. Initially, these instruments output a square wave signal (approx. 1 kHz), since in early, analog oscilloscopes, the CRT graticule was an overlay, rather than being etched on the glass. The use of a square wave helped to minimize parallax errors associated with amplitude measurement during calibration by simplifying viewing. Subsequently, largely due to the development of digital storage oscilloscopes (DSO, which typically include a digital readout for various parameters, including voltage), many oscilloscope manufacturers began using DC voltage to calibrate vertical deflection factor rather than a square wave. Later amplitude calibration instruments began including \pm DC volts, in addition to selectable frequency AC, and are capable of calibrating any of the various, applicable oscilloscope operating paradigms.

Though the calibration of vertical deflection factor is often accomplished using a single instrument and/or process, frequency response, however, is not always as straightforward. In older models of oscilloscopes, for example, the input attenuators often consisted of discrete, physical capacitor/resistor networks that required compensation (adjustment) in order to achieve a flat frequency response throughout the low and middle frequencies (similar to compensating a 10X probe for use with a particular oscilloscope). In order to accomplish this task, a *high amplitude square wave generator*, capable of producing approx. 100 Vpp, is used. The primary performance feature of this generator is to provide a square wave with very flat tops and bottoms in the lower to middle frequencies, with a large

enough amplitude range adequate to address the various attenuator ranges that commonly exist on oscilloscopes.

Another instrument used for the calibration of frequency response is the *fast-rise square wave generator*. Sometimes referred to as ‘fast edge generator,’ and unlike the high amplitude square wave generator, its fast-rise counterpart is commonly limited in its output capability to a few volts, and specified for rise-time and flatness, the latter generally for a specified time epoch following the transition. The characteristics of the fast-rise generator may be used directly for oscilloscope rise-time calibration (with or without adjustment), as well as for vertical amplifier frequency response, which some manufacturers prefer to use in lieu of the swept frequency method.

Perhaps the mostly commonly employed method of calibrating oscilloscope vertical frequency response is the swept frequency method using a *constant amplitude signal generator* (where an applicable device exists). By design, the constant amplitude generator sine wave output, typically ranging from several millivolts to a few volts, is internally leveled to maintain a *peak-detected*, flat output, in V_{pp} . This latter point is important to note in contrast to employing an *rms* levelling approach, which, unlike the peak responding device (oscilloscope) the generator’s output is designed to calibrate, instead also responds to distortion and noise products, inconsistent with the measurement.

It should be noted that at this point of their development, oscilloscopes have effective vertical bandwidths in excess of 30 GHz and, at this writing, there are no dedicated constant amplitude generators available beyond 6.4 GHz. Currently, when verifying UUT frequency response at frequencies in excess of that (or when such a generator is unavailable), the most common method is to use a high performance (low distortion and noise) *HF signal generator* in conjunction with a power meter and sensor and power splitter to externally level the measurement at the input to the UUT.

Triggering Subsystem

The oscilloscope’s triggering subsystem may consist of many operating modes and sources. For example, common choices for trigger sources are INT, EXT, LINE, etc. Common trigger modes are AC, DC, AC HF REJ, though in modern oscilloscopes, few, if any, of these modes are explicitly verified during calibration. Though some modern oscilloscope manufacturers have added additional functionality to this subsystem, the intent of this paper is to address the most common, mainstream characteristics and the instruments used to calibrate them.

The main functional parameters of the triggering subsystem requiring calibration are trigger sensitivity, typically internal and external, and trigger bandwidth (frequency response). Generally, these traits are both calibrated using a *constant amplitude signal generator* (or power meter/sensor). As mentioned at the outset, however, oscilloscopes with bandwidths of 30 GHz or more exist at this writing, with 10 GHz bandwidths becoming increasingly common. Similar to vertical frequency response calibration, above, trigger bandwidth verification may require a signal source beyond the capability of a dedicated oscilloscope calibration instrument, i.e., an *HF generator*.

Horizontal Subsystem

The oscilloscope's horizontal subsystem, sometimes referred to as the horizontal timebase, sets the UUT displayed time scale (time/div), which, in the case of one current model of DSO, ranges from 20 s/div to 1 ps/div in real time! The calibration of the horizontal subsystem is accomplished entirely (in most cases) using a *time mark generator*. The time mark generator is designed to output time pulses (some models may utilize (or offer selectable) sine or spike waveforms, in lieu of, or in addition to pulses) at intervals matching those available on the oscilloscope. Additionally, some oscilloscopes offer external horizontal inputs with specified sensitivities and bandwidths; those models may require a *standard amplitude calibrator*, or other calibrated voltage source to address the former, a *constant amplitude signal generator* for the latter.

Manual Methods: Theory and Practice

With the development of the modern oscilloscope, it was also necessary to *simultaneously* devise the methods to calibrate them!

Oscilloscope calibration requires a repetitive testing regimen and address more test points than many other instruments, exceeded only, perhaps, by spectrum analyzers. With that in mind, any metrologically sound means to streamline the process, minimizing the tedium and, therefore, the possibility of errors occurring, are welcome! Though anecdotally attributed to Tektronix, a process has evolved over the years that virtually all major oscilloscope manufacturers use/specify in their respective calibration documentation. Briefly, the main subsystems of the oscilloscope (vertical, triggering, and horizontal) are each calibrated respectively, using the just calibrated (referred to in some circles as characterization) functional parameter as a basis for subsequent calibration of another parameter, function, or subsystem. The details of this process, by subsystem, are examined below.

Vertical Subsystem

Prior to beginning the actual calibration process, it may be necessary to perform routine operators or other preliminary adjustments. One such adjustment, for example, is the check/adjustment of the DC Step Attenuator Balance. Since this is typically an operator adjustment, it is independent of the calibrated parameters of vertical deflection factor, bandwidth, and other calibrated parameters associated with the vertical subsystem. Simply stated, proper DC Step Atten Bal (as it is sometimes abbreviated) occurs when no vertical shift in the trace as the input attenuator (Volts/Div) is switched throughout its range. While common on many older models of oscilloscopes, adjustment of the DC Step Atten Bal has all but disappeared in modern designs.

Following any necessary preliminary adjustments, the input impedance is measured. As mentioned previously, this is accomplished in a straightforward manner, with the oscilloscope calibrator having built-in functionality specifically designed for this purpose.

Next, the vertical gain/attenuation ratios are calibrated using the standard amplitude calibrator. As mentioned above, older, primarily analog models using cathode-ray tubes (CRTs) for displays utilized a

square wave signal for vertical gain calibration. Most modern models using solid-state displays, e.g., liquid crystal displays (LCDs), are typically calibrated using a DC stimulus, with some models utilizing the consecutive application of a zero-centered, \pm DC signal for gain calibration, where others prefer a zero-starting +DC signal alone. Generally speaking, calibration of vertical gain begins with the highest sensitivity available on the UUT (Unit Under Test), incrementing up through the range of available attenuation ratios (i.e., Volts/Div settings) until the upper limit of the UUT is reached. The steps are repeated on any additional available vertical inputs. This process may be a throwback to earlier designs, where the lowest range commonly bypassed the vertical attenuator networks, delivering the signal directly to the vertical amplifier with minimal signal conditioning (excluding input coupling) but, ultimately, it varies from manufacturer, model, and design. Once calibrated, the UUT display can be subsequently used to set required amplitude levels, such as those required for triggering calibration, alleviating the need for an external piece of equipment to set those levels, reducing time and increasing throughput. It should be noted that with some legacy designs, the Tektronix 7000 series of oscilloscope mainframes, for example, accommodated many models of vertical preamplifiers or 'plug-ins,' and must use either a calibrated mainframe or first have the mainframe gain calibrated prior to calibration of the UUT vertical plug-in, in order to support plug-in interchangeability while retaining accuracy².

At this point, the calibration of the UUT low and middle frequency response is completed, in the case of those models using discrete, and sometimes, electronic adjustment of the attenuator compensation in models that offer that capability. For those that do support discrete calibration of this parameter, it is normally accomplished using the high amplitude square wave generator. Some models, like many recent products produced by Tektronix, have built-in self-calibration or operator adjustment routines referred to as "Signal Path Compensation" (SPC) that performs these compensation adjustments automatically, without any external equipment required. In either case, the adjustment of the aforementioned attenuator networks to achieve smooth, flat amplitude vs. frequency response in the UUT is achieved. Though many newer oscilloscopes no longer require discrete compensation adjustments, the calibration laboratory workload may consist of many units that do.

The final step in calibrating the vertical subsystem is the verification of its frequency response. As mentioned above, the swept frequency method using a constant amplitude signal generator is most commonly employed for verification, though a fast-rise square wave generator is typically used for adjustment. Briefly recalling electrical theory, a square wave is harmonically rich, and the application of an adequately fast (its transient response corresponds to the UUT bandwidth) square wave, whose post-transition response is flat within a specific time epoch (window), facilitates proper adjustment of the UUT, ensuring a flat bandpass throughout the frequency range while rolling off smoothly at its upper bandwidth (-3 dB) limit.

Though the swept frequency method using a constant amplitude signal generator directly connected to the UUT is most commonly used for frequency response calibration, in today's market of higher and

² *Oscilloscope mainframes capable of accepting interchangeable vertical preamplifiers are equipped with an integral voltage calibrator, facilitating the adjustment of the preamplifier gain to match that of the mainframe. During calibration, the mainframe calibrator, which may source either AC, DC, or both, is also verified.*

higher bandwidth oscilloscopes, the use of a signal generator in conjunction with a power meter, power sensor, and power splitter is becoming increasingly more common. A typical connection for such testing is shown in Figure 1 below.

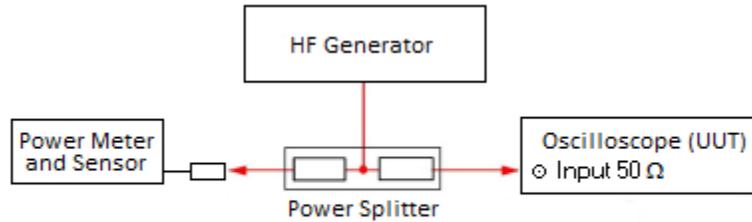


Fig. 1. Frequency response test configuration using an externally leveled signal source

When using the above setup for frequency response testing, some additional areas of uncertainty are important to consider:

- HF Generator distortion and noise
- Power Splitter tracking error (output arm matching)
- Mismatch between the Power Splitter and the UUT
- Mismatch between the Power Sensor and Power Splitter

Fortunately, the impact the above has on the measurement process may be minimized through careful selection of instrumentation and its magnitude calculated and accounted for as part of the overall uncertainty. For example, if using an HF Generator whose harmonic distortion is -30 dBc, the additional uncertainty contribution is approx. 3%. Using a generator with a lower distortion level will lower the uncertainty associated with it. Similarly, using a power splitter with a low tracking error, as well as having a lower output VSWR improves the match at the UUT, as does utilizing a power sensor with a lower VSWR.

When calibrating oscilloscope frequency response using the swept frequency method (described above), it may be necessary to address UUT input impedances of both 1 M Ω (an upper bandwidth limit of 250 MHz is typical for UUTs equipped with a 1 M Ω input impedance), as well as 50 Ω . Since the various models of constant amplitude signal generators manufactured for this purpose over the years have characteristic output impedances of 50 Ω , when calibrating devices with a 1 M Ω input impedance, an external 50 Ω , feedthrough termination is employed at the generator output for impedance matching with the UUT input³. Depending on the shunt capacitance of the UUT and the VSWR of the termination used, an allowance may be necessary for the mismatch incurred at higher frequencies.

³ It should be noted that some models of oscilloscope calibrators have switchable, internal 50 Ω terminations, rather than necessitating the physical insertion of an external termination.

Triggering Subsystem

Following calibration of the vertical subsystem and its associated parameters, the calibration of the triggering subsystem typically follows, trigger sensitivity and trigger bandwidth. Trigger sensitivity, on most oscilloscopes, is calibrated for both internal and external sources. Generally speaking, internal trigger sensitivity is specified in terms of either UUT vertical divisions or fractions thereof (e.g., ≤ 0.7 div from DC to 50 MHz), or in terms of full-scale or fractions thereof (e.g., $\leq 50\%FS$ at 11 GHz), and is often specified in combination with a limiting frequency. External trigger sensitivity is typically specified in terms of rms voltage required at the trigger input to effect stable triggering. Trigger bandwidth, the point at which stable triggering is unachievable or, in DSOs, the inability to display the input waveform due to undersampling, may be limited by the vertical frequency response of the UUT.

Trigger bandwidth specifications may exceed the vertical bandwidth of the oscilloscope, in some cases, to extend the functional characteristics of the unit, even though quantitative measurements of vertical parameters are not possible. During trigger bandwidth calibration, even when using a constant amplitude signal generator, it is generally necessary, due to the UUTs vertical frequency response, to readjust the generator output signal level in order to maintain the specified conditions. For example, in the above specifications ($\leq 50\%FS$ at 11 GHz), as applied to an oscilloscope with a 10 GHz bandwidth, would require increasing the output of the generator some 3 dB (30%) at 11 GHz in order to maintain the same display (amplitude) indication as when measured midband.

If calibration of the UUT trigger bandwidth requires a signal source beyond the capability of a dedicated oscilloscope calibration instrument, an HF Generator is connected via a power splitter to both the vertical and external trigger inputs. The applied signal level is measured using the UUTs just calibrated vertical input⁴. A typical configuration is shown in Fig. 2.

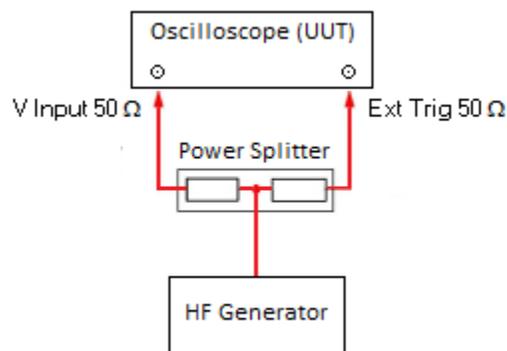


Fig. 2. Typical external trigger bandwidth test configuration using an external HF signal source

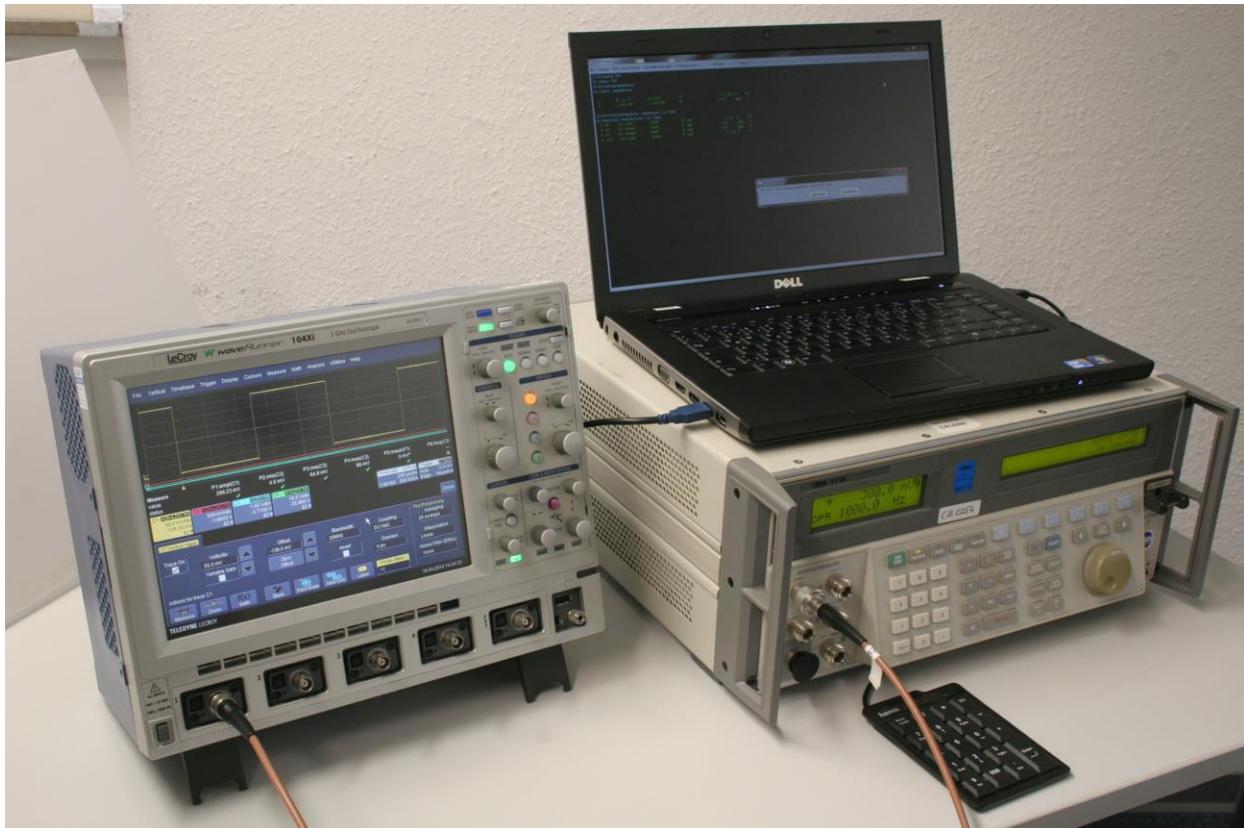
⁴ Trigger bandwidth is a single-sided specification, i.e., Pass/Fail, with only a minimum specified signal level required for stable triggering, e.g., 200 mV at 1.8 GHz. As a result, it is typically specified with an allowance for the vertical performance and calibration requirements accounted for during design.

Horizontal Subsystem

Prior to the advent of the DSO (digital storage oscilloscope), the timebase in analog models consisted of a sweep circuit whose rates were determined by discrete components, usually based on RC time constants. As a result, each sweep speed (horizontal sweep rate) required calibration, due to component drift or other effects that affected the accuracy. To accomplish that, it was necessary for calibration personnel to increment through each available sweep speed (including those of the delayed/delaying sweep, if present) on the UUT while simultaneously setting the time mark generator output to match the indicated speed. For every sweep speed, the operator would check for coincidence, within the UUTs stated tolerance, with the display graticule, typically specified over the center eight horizontal divisions (2nd to 9th vertical graticule lines), though some models were specified over the entire 10 division sweep. The sweep magnifier (5x or 10x were common), if equipped, is verified in the same fashion.

In DSO models, the sweep speed determining components are often locked to a master timebase, usually a quartz crystal type, by frequency dividers and phase locked loops (PLLs), and except for failure, virtually never requiring verification of each individual sweep speed. Instead, differing approaches are used, the most common involving direct measurement of the time base using a frequency counter at a designated output (e.g., Frequency Reference Out).

Automated Methods: Trends and Guidelines



Some years ago, when the US Air Force Metrology and Calibration Program (AFMETCAL) began to prepare for the implementation and use of their 'NextGen' automation software in their calibration labs, they first conducted a study to see which type of instrument(s) would enjoy the greatest benefit (reduction in calibration time) the most from automation. Though the spectrum analyzer topped the list, oscilloscopes rated quite high, largely due to the number of repetitive tests that are performed over several input channels, a task for which automation excels. Make no mistake; the gains from automation for a laboratory that has a high volume of oscilloscope workload are immense, in both throughput and quality.

There are several different options, when it comes to automating the calibration of oscilloscopes (or any other item). The first choice, perhaps, is the language or platform that best suits the laboratory's needs. Beyond the expected, 'How much does it cost?' Other questions, such as,

- Does the manufacturer support it?
- Is it compatible with the operating system(s) of my lab computers?
- What hardware interface(s) does it support?
- Are existing (software) calibration procedures available and how much do they cost?
- Can the procedures be edited locally or do they require the manufacturer to make changes?
- Are the procedures warranted and do they support measurement uncertainty?

are typical, and must be answered individually by each facility.

Perhaps the best advice is to first talk with other users (not the product sales staff) about the software they use, its advantages and disadvantages. Does the manufacturer adequately support it and the needs of the lab? Are they happy with it? In addition, any other questions pertinent to their facility and its needs.

Oftentimes, personal computers (PCs) used in calibration laboratories are not at the cutting edge of that technology. It is very important that any software choice not only supports the current operating system(s) of the lab's existing PCs, but also is forward compatible, actively upgraded to take advantage of new operating systems as they are implemented.

The GPIB (General Purpose Interface Bus) has and continues to be, especially in the case of calibration instrumentation, the primary interface used for remote control. When it comes to the oscilloscope workload, however, the remote options are many and varied, e.g., RS-232, USB, and Firewire, to name a few. A review of the remote interfaces supported by the software vs. those installed on the workload is imperative, in order to gain the most benefit from any software.

Several vendors supply calibration software platforms and/or software calibration procedures in various forms. In the case of 'canned' procedures, be especially vigilant of their quality and implementation. In my own experience, I have seen too many procedures sold as a black box. That is, the details of the tests, including the setup of the UUT and the calibration instruments, are invisible to the operators, and it must be taken on faith that the procedure writer knew what they were doing when it was developed. Unfortunately, many lack the same metrological rigor and overall quality that a skilled metrology

technician would apply during a manual calibration setting, delivering substandard results, in the author's opinion. If in doubt, ask to see the validation results and/or the measurement uncertainties associated with the use of the program, prior to purchase. *Remember, it is the responsibility of the laboratory to validate all software procedures used for calibration; a poor choice in the beginning becomes more costly to maintain than the benefits it provides.*

Calibration Uncertainty: Guidelines and Examples

As with any calibration process, the contributors to the uncertainty of measurement and the determination of their magnitude on the calibration process must be defined in accordance with accepted policies and practices, recognized through the world of metrology. Specifically, the Guide to the Uncertainty of Measurement, often referred to as the GUM. For oscilloscopes, the primary uncertainty sources are:

- Uncertainty associated with the reference standards, resolution and harmonics
- Uncertainty associated with impedance mismatch between the reference standard and the UUT
- Uncertainty associated with the UUT itself, including reading uncertainty, noise and switch repeatability
- In the case of DSO calibration, internal algorithms (e.g., averaging and interpolation) and their implementation into the UUT firmware may affect the results of the calibration and the uncertainties associated with it

Below is an example of the measurement uncertainty computation for oscilloscope vertical deflection.

Model Equation:

$$\Delta y = \frac{N_{ind} \times S_{osc} \times S_w}{2\sqrt{2} \times T \times (V_{cal,ind} \times R_{cal} + \delta O_{cal}) + \delta V_{osc,noise}}$$

With $T = 1$ and $R_{cal} \approx 1$, the above equation reduces approximately to:

$$\Delta y \approx \frac{N_{ind} \times S_{osc} \times S_w}{2\sqrt{2} \times V_{cal,ind} \times R_{cal} \times T \times \left(1 + \frac{\delta O_{cal}}{V_{cal,ind}}\right) \left(1 + \frac{\delta V_{osc,noise}}{2\sqrt{2} \times V_{cal,ind}}\right)}$$

where:

Δ_y	Vertical axis relative deviation
N_{ind}	Number of divisions indicated in oscilloscope display
S_{osc}	Sensitivity setting (range) of the oscilloscope
S_w	Switch repeatability of the oscilloscope
T	Transmission factor (loading effect) at calibrator output
$V_{cal, ind}$	Calibrator output voltage indication
R_{cal}	Calibrator readout factor
δO_{cal}	Calibrator offset voltage

$\partial V_{osc, noise}$ Oscilloscope noise (voltage), referred to the input

Using the above model, calculating the uncertainty budget for calibrating the 500 mV/div range utilizing a 6 division signal coverage:

Symbol X_i	Estimate X_i	Relative Standard Uncertainty $W(X_i)$	Probability Distribution	Sensitivity Coefficient $ c_i $	Relative Uncertainty Contribution $W_i(y)$
Δ_y	0.0033	0.12%	Gaussian	1	0.12%
N_{ind}	6 div	-	rectangular	-	-
S_{osc}	0.5 V/div	0.021%	rectangular	1	0.021%
S_W	1	0.058%	rectangular	1	0.058%
T	1	0.0029%	rectangular	1	0.0029%
$V_{cal, ind}$	1.0572 V	0.087%	rectangular	1	0.087%
R_{cal}	1	0.00058%	rectangular	1	0.0006%
$1 + \frac{\delta O_{cal}}{V_{cal, ind}}$	1	0.012%	rectangular	1	0.012%
$1 + \frac{\delta V_{osc, noise}}{2\sqrt{2} \times V_{cal, ind}}$	1	0.034%	rectangular	1	0.034%
Δ_y	1.0033				0.165%

In the above example, the relative uncertainty $W(y)$ of the measurement result (measurand) is calculated using the root sum square (rss) method. Because, in this case, the sensitivity coefficients equal 1, there is no impact on this measurement. The expanded uncertainty, therefore, expressed using a coverage factor of $k = 2$ (approximately 95%) is 0.33%

Acknowledgements

The author wishes to express his appreciation to Mr. Karl-Peter Lallmann at [1A CAL GmbH](#), for manuscript and technical review, as well as for the photographs used herein.

The Author



David Martson's personal experience with oscilloscope calibration goes back to the Tektronix 515, the second model of oscilloscope commercially produced by Tektronix, and continues to the modern day. His background in calibration and metrology includes DC-LF and RF/ μ W disciplines with over 40 years of experience, as well as having more than 20 years experience in laboratory automation. Mr. Martson served on the NCSLi (National Conference of Standards Laboratories, International) 141 Automatic Test and Measurement advisory committee. Mr. Martson has previously authored technical papers relating to calibration, metrology, and calibration automation.