Cost-Effective Traceability for Oscilloscope Calibration

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Abstract

The widespread adoption of ISO 9000 has brought an increased awareness of the need for traceable oscilloscope calibration. However, in-depth knowledge of the traceability requirements tended to lie mainly with the oscilloscope manufacturers, rather than calibration companies or instrument users.

The design of a new Fluke oscilloscope calibrator brought with it some interesting questions about the methods traditionally used for establishing traceability. In particular there appeared to be weak links in the traceability when compared to the more rigorous methods applied to DC and Low Frequency metrology. This paper examines these methods and explains the approach used by the Company to establish reliable traceability and make it easily available to the users of the product and those having to support it. European customer expectations dictated that we gain formal UK NAMAS Accreditation[1] of the automated system used for the calibration of the product.

Functional/Traceability Requirements

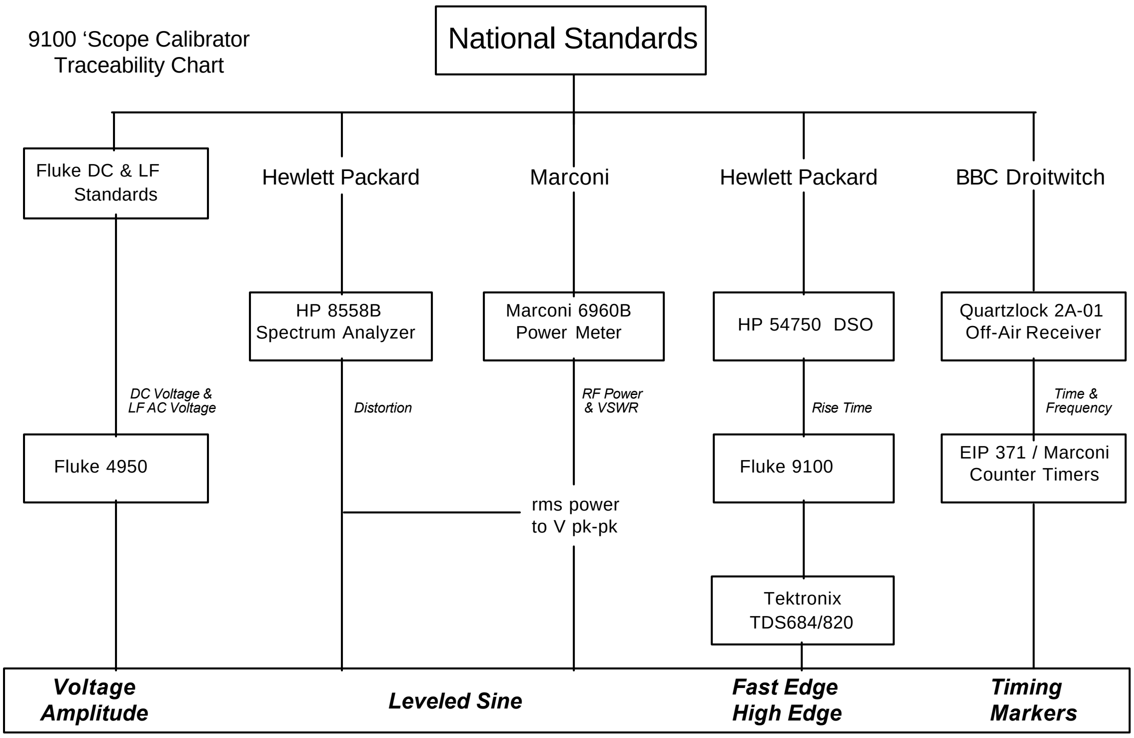
The basic traceability requirements for calibration of the Fluke 9100 are given below:-

Function	Output
Voltage Amplitude:	DC Voltage, Square Wave at 1 kHz to 120 V pk-pk
Leveled Sine Wave:	10 Hz to 250 MHz, up to 5 V pk-pk into 50 Ω
Fast Edge:	1 ns Rise Time and Aberrations, 1 ms to 10 µs Period, up to 1 V pk-pk into 50 Ω
High Edge:	100 ns Rise Time, 1 ms to 10 µs Period, up to 60 V pk-pk into 1 M Ω
Timing Markers:	100 ns to 1 s, up to 1 V pk-pk into 50 Ω

Traceability Overview

The traceability for the calibration of the Fluke Oscilloscope Calibrator option is shown in figure 1. The chart shows the traceability paths for the oscilloscope parameters of Voltage Amplitude (DC/LF Vertical Gain Cal), Leveled Sinewave (Bandwidth Tests and -3dB Point), Fast/High Edge (Pulse Response and Rise Time) and Timing Markers (Horizontal Gain Calibration). The critical part of the traceability is the conversion from rms power (or Volts) to pk-pk voltage. This requires knowledge of the Power Meter VSWR and a very low distortion RF voltage source, such that the conversion from rms power to pk-pk volts can be easy. The spectrum analyzer is required to verify the source harmonic content.

Fig. 1



Detailed Description of Traceability and Methods

HF Sine Output Function

This is the leveled sine output that is used for bandwidth checking of oscilloscopes. Its main parameter is flatness over the range 50 kHz to 250 MHz.

Flatness traceability is via rms RF Power from Marconi using their Model 6960 with 6912 Power Sensor. It is calibrated by Marconi in terms of dBm (1mW into 50Ω). Conversion from rms power to pk-pk voltage requires knowledge of the impedances involved. The quality of the sensor impedance is specified in terms of VSWR and needs to be very low (<1.02) such that it does not introduce significant mismatch errors due to variations in impedance at different frequencies. Very low VSWRs are easily achieved at 1 MHz and above but VSWR of the sensor is known to be of the order of 1.30 at 50 kHz, due to the AC coupling employed in the input circuit. Because of this, the power meter is not used for traceable measurements below 1 MHz. In addition, there will also be an error if there is a mismatch between the source (9100 output impedance) and the power sensor impedance. The 9100 is calibrated with its output lead to reduce lead related mismatch errors.

Consideration of distortion is also important. For a pure sine wave the pk-pk voltage will be 2.828 times the rms value. However, if the crest factor deviates from 1.414:1 (due to distortion) there will be an error when calculating the pk-pk value. The source used (Fluke 9100) has a signal purity of <-35dBc for 2nd harmonic and <-40dBc for 3rd and higher order harmonics, thus ensuring that errors due to distortion are as low as possible.

At frequencies of 50 kHz and 1 MHz, the HF Sine output is measured using a Fluke 4950. The use of this instrument gives greater accuracy and together with a special Fluke low VSWR (<1.02) 50Ω termination, provides the necessary low frequency traceability for level. The termination contributes an uncertainty (due to mismatch) of ±0.03% to the measurements at 50 kHz and 1 MHz, assuming a source VSWR of <=1.03.

RF Voltage Uncertainty Considerations

The calibration uncertainty of the power meter is expressed in terms of power and since power = V^2/R, the uncertainty contribution has been divided by 2 to arrive at a contribution for derived voltage. The uncertainty of the Spectrum Analyzer used for the Distortion measurements was deemed to be insignificant in relation to the other uncertainty contributions and has therefore been ignored.

The uncertainty contributions can be simplified by “lumping” together similar contributions. For example, there is a limitation imposed on the measurement by the noise floor that is a combination of Power Meter noise and the noise of the 9100 HF Sine output. It is not practicable to isolate these as the instruments are always used together. Therefore, the noise contribution used is an overall one for measurements at a particular level. The contribution of the 4950 noise is not significant in relation to the noise and short term stability of the 9100 output and has therefore been ignored.

Similar methodology can be applied to the mismatch uncertainty contribution. This is as a result of matching the characteristic impedances of the 9100 source output, the connecting cable and the Power Sensor input termination. The final lumped contribution considers the measured VSWR of the 9100 output, the length and properties of the connecting lead and adapters, and the measured VSWR of the Power Sensor. For reasons of practicality, the analysis of the mismatch error has been made on $\mathbf{Z_0}$ (no phase information) basis, from measurements of the source and Power Meter Sensor VSWR. If the phase were known, it would be possible to apply a correction for the mismatch error.

The 4950 MTS traceability up to 1 MHz has already been established and accredited by NAMAS. However, there is an additional small contribution of ±0.03% due to the 50Ω termination used with the 4950. The 4950 uncertainties quoted for 9100 LF Level/HF Sine outputs include this allowance for the 50Ω termination's matching at 50 kHz and 1 MHz.

Measurements were made of the 9100 HF Sine output distortion using a spectrum analyzer. The results showed that the source harmonic distortion was >-40dB below the fundamental and so allowed the simple conversion from rms power to pk-pk volts. It can be demonstrated that at very low distortion levels(>30 dBc), the effects of 2nd harmonic are greatly reduced and that 3rd harmonic effects dominate.

Automated measurements were made of the worst case combined noise of the Fluke 9100 and Marconi 6960 Power Meter at the nominal levels required. The measurements were made at 10 MHz (DDS generated) and 12 MHz (VCO generated). The noise contributions used were worst case noise recorded for either frequency and based on the sample standard deviation multiplied by the Student's *t* factor to give the appropriate confidence level.

The 6960 has a 4½ digit resolution and displays its readings in Watts. Its LSD resolution is an uncertainty contribution and is divided by 2 (to give a ½ digit). A conversion is made in software from rms Watts to pk-pk Volts. The resolution component is combined as an RSS with a fixed linearity component of 0.5% (from the 6960 Operating Manual) to give the linearity and resolution uncertainty contributions for each level.

Fast Edge Function

Risetime is defined as the time taken for a transition from 10% to 90% of the pk-pk amplitude of the pulse. The Fast Edge function is used to determine the Risetime of oscilloscopes at reduced amplitudes and requires the measurement of the Fluke 9100's Fast Edge output at 1ns into a 50Ω load. The measurements are made using a Tektronix TDS 820 DSO. The TDS 820 with Option 1D (no delay lines) is specified with a bandwidth of 8 GHz and a risetime of 43.8 ps. The TDS 820 is periodically compared to an HP 54750A High Bandwidth (20 GHz) DSO using a 9100 as the transfer standard. Note that the comparison is of a functional nature to ensure that the risetime is less than a particular figure rather than a calibration from which a correction can be applied. The HP 54750 is calibrated by Agilent for Risetime and has a risetime response error that is insignificant compared to that of the 9100's 1 ns output. A secondary parameter for risetime traceability is the consideration of aberrations. The calibration of the HP 54750 also includes a statement about the aberration content in terms of a percentage of the amplitude of the applied repetitive pulse. The Fast Edge output of the 9100 has an output impedance of 50Ω and therefore is dependent upon correct termination at the end of its output cable. The 9100 is calibrated with its own individual output lead. A purpose built 1ns transfer standard has also been used. This device uses similar pulse generation circuitry to that used in the 9100, but is much smaller and therefore better suited for transportation. The device has been calibrated by NIST for risetime and aberrations and has proved a useful tool for verifying the aberration content of the HP 54750 and TDS820.

High Edge Function

High Edge is used to determine the Risetime of oscilloscope range attenuators at higher amplitudes up to a maximum of 55 Volts pk-pk and requires the measurement of the Fluke 9100's High Edge output at 100ns into a 1 MΩ load. The measurements are made using the same equipment as for Fast Edge with the addition of a special high bandwidth attenuator. The attenuator reduces the level applied to the TDS 820 whilst not significantly degrading the shape of the pulse. The attenuator is part of the 9100 automatic calibration system and is remotely controlled. Note that the High Edge output of the 9100 is generated from a zero impedance source, rather than 50Ω.

Risetime Uncertainty Considerations

The treatment of the uncertainties for pulse measurements is different to that used for other parameters. In particular, the uncertainty contributions for risetime traceability are very small compared to the required capability of 1 ns. The measurement of aberration content in terms of percentage of the pk-pk level are usually dependent upon the properties of the oscilloscope input circuit dynamics. As an example, to examine the aberration content, it is necessary to "zoom-in" on a particular part of the waveform in order to obtain sufficient resolution of the aberration component. This can lead to overdriving the input circuit of some oscilloscopes and result in distortion and the generation of additional aberrations. This has been tested for both oscilloscopes by observing the percentage and shape of the aberrations for different sensitivities of the input amplifiers.

In terms of the 1 ns measurement requirement, the effects of the HP 54750's risetime are considered to be insignificant due to its 20 GHz bandwidth. This corresponds to a theoretical risetime (t_{rise})of 17.5 ps, using the relationship:- $t_{rise} = 0.35/Bandwidth$, where *Bandwidth* corresponds to the specified -3dB point of the

HP 54750. This is 57 times (in terms of risetime) better than the 1ns requirement of the 9100 and so has negligible degradation of the waveform. In order to maintain traceability, our intention is to periodically return the oscilloscope to Agilent for calibration. Depending on the development of other projects, the HP 54750 may possibly be sent to the National Physical Laboratory for verification against their Optically Generated Pulse Standard.

The Tektronix TDS 820 with option 1D (delay lines removed) has a specified bandwidth of 8 GHz. This corresponds to a theoretical risetime (t_{rise}) of 43.8 ps. This is nearly 23 times (in terms of risetime) better than the 1ns of the fastest output of the 9100 and so has negligible degradation of the waveform.

The built-in cursors of the oscilloscope(s) can be used to improve the ease of use and accuracy of determining both risetime and aberrations. In this case it is important that the vertical resolution is adequate. For the TDS 820, the resolution is 14 bits. This corresponds to a resolution of 1 part in 16,384 or 0.006%, assuming that the whole display height is used. In practice, 80% of the display height will normally be used therefore the available resolution will reduce to 1 in 13,106 or 0.008%.

For the HP 54750, the vertical resolution is 12 bits. This corresponds to a resolution of 1 part in 4096 or 0.024%. As with the TDS 820, 80% of the available display height will normally be used, therefore the available resolution will reduce to 1 in 3,276 or 0.031%. For both oscilloscopes, vertical resolution is a very small uncertainty contribution, provided that the setups are such that 80% of the available height of the display is always used. In the case of the TDS 820, where the setup is automatically downloaded via the IEE-488 interface, the user need not be concerned about resolution. Because of the 1ns risetime of the waveform, there is no problem with horizontal resolution in terms of accurately determining the slope of the rising (or falling) edge of the applied pulse by using the HP 54750's cursors.

Mismatch measurements of the 9100 source output are difficult due to the automatic leveling loop used. However, the measurements we have made show that reflections are at least 24dB down (a VSWR of 1.13) on the signal when used in conjunction with the standard 1 metre connecting lead terminated with the HP 54750. In resistive terms, the 9100 output is within ±2% of 50Ω, which in simple terms, corresponds to a VSWR of 1.20. The reactive component at HF is primarily due to the output capacitance of the 9100 pulse generator and the input capacitance of the oscilloscope. The 9100 output circuit is designed to compensate for typical capacitive loads at the end of the standard connecting lead (by maintaining a low VSWR such that the load reflections are absorbed). When considering the pulse speed and the length and properties of the cable, reflections are unlikely to effect the risetime, or aberrations within the first 10ns of the pulse edge. The input reflection of the HP 54750 has been measured by Agilent and is reported on their NAMAS certificate for the instrument. This is specified in terms of

+ and - inputs for channels 2 and 4 as 1.19% (+) and -2.55% (-), which corresponds to VSWRs of 1.25 (+) and 1.39 (-). This corresponds to mismatch errors of 1.34% (+) and 1.96% (-) and assumes a source VSWR of 1.13. The TDS 820 VSWR is specified at <1.1 from DC to 6 GHz and <1.3 from 6 GHz to 8 GHz.

As a result of these considerations, the main uncertainty contributions are the basic accuracy of the oscilloscopes, the effects of mismatch of either oscilloscope and the 9100 source, cables and connectors. Where High Edge measurements are made, the effects of the pulse response of the special attenuator must also be considered. Where the effects of risetime of the instruments are combined, the assumption has been made that overshoot and other aberrations are small (<5%) and that the transient edge (10% to 90%) can be considered guassian in form. In this case, the cumulative risetime and risetime uncertainty can be calculated as a root-sum-of squares of the individual components.

Voltage Amplitude Function

The Voltage Amplitude function is used to determine the basic sensitivity of oscilloscopes and requires the measurement of two of the Fluke 9100's output parameters: DC Voltage and AC Voltage (1 kHz squarewave). This is done using the DCV and ACV functions of the Fluke 4950 MTS respectively.

There are no particular problems with the DC measurement (other than consideration of the tolerance of the 50Ω termination), as the range of voltages are within the normal measurement capability of the 4950. However for AC measurements, there are several potential problems due the nature of the UUT's output. These are explained below.

The 4950's AC converter is completely DC coupled and would be susceptible to any DC offsets present. To eliminate this potential source of error, an external capacitor is connected in series with the signal Hi to provide DC blocking. The capacitor is switched in automatically by the automated system as required. The value of the capacitor is 10µF. It will introduce a small error due to its reactance (15.9 Ω at 1 kHz) in series with the input impedance of the 4950 (nominally 116k Ω/163pF to 404k Ω/152pF at 1 kHz depending on range).

There will be some attenuation caused by the capacitive reactance of the blocking capacitor in series with the input impedance of the 4950. In addition to this, there will also be small reduction in the output of the 9100 due to additional loading of its output resistance. Using the above figures and assuming a 50Ω source and termination, the error will be in the region of -30ppm and is corrected in the measurement system software for each 4950 range.
The 9100's AC Amplitude output is a squarewave and requires the response of the 4950's AC converter to non-sinusoidal waveforms to be verified. This is made easier by the low crest factor (nominally 1:1) and the fact that the "edges" of the

9100 squarewave output are deliberately slowed down to remove HF harmonics. This done to ensure that the 9100 is easy to use where the UUT oscilloscope has a cursor facility that may be used to automatically display pk-pk values of the applied waveform. Without slew-rate limiting, the fast edge of the squarewave could cause saturation and ringing in the amplifier circuits resulting in erroneous measurement of the LF pk-pk amplitude where automatic cursor measurements are made.

The 4950 measures and reports in terms of rms values. The pk-pk values are calculated from the rms measurements assuming a nominal crest factor of 1 (pk-pk = 2 x $\sqrt{2}$). However, because of the slew-limiting, the crest factor is greater than unity. This introduces an error and must be corrected.

Markers and Frequency

The Timing Markers function is used to determine the Timebase accuracy of oscilloscopes and requires the measurement of the 9100's Timing Marker output in terms of frequency. The average periodic time of the timing markers is calculated from measurements of the marker frequency. These measurements have been made using existing equipment i.e. EIP Source Locking Microwave Counter to 250 MHz and a Marconi 2437 Universal Counter/Timer for frequencies up to 100 MHz. However, for routine calibrations, the integral frequency counter of the Fluke 9000/9100 Capacitance Calibration System Programmable Current/Timing Source is used for measurements up to 10 MHz. These instruments are traceably calibrated to the Quartzlock 2A-01 Off-Air Frequency Standard.

Frequency Uncertainty Considerations

Frequency traceability was already well established through the use of an Off-Air receiver and the BBC's Droitwich 198 kHz transmitter. The accuracy of the 198 kHz carrier has been improved in recent years. Originally, it was specified as having an accuracy of ±5 parts in 10^8 . Discussions with the BBC's engineering department confirm that this has now been improved to ±2 parts in 10^{11} with day to day variations of ±1 part in 10^{11}. The NPL's Time and Frequency Service provides monthly data on how well the Droitwich transmitter's carrier frequency has performed.

Discussions with the manufacturer of the Off-Air standard confirms that the PLL of the receiver does not contribute significant systematic errors and that the dominant contribution is in terms of noise and jitter. However, provided that the standard has been given a minimum of 1 minute to acquire and lock to the carrier, and that measurements made against the standard are averaged over a minimum of 10 seconds, the random contribution will be of the order of ±2 parts in 10^9.

The Fluke Frequency Reference Source is used to provide a 1 MHz clock for the Fluke "Capcal" counter. The source provides one 10 MHz output and four buffered 1 MHz outputs for up to four Fluke "Capcal" counters. The source uses a high stability crystal oscillator that is specified in terms of stability at ±0.05ppm per year and ±0.1ppm from 0°C to 60°C (±0.002 ppm/°C). Additionally, the aging rate of the crystal is specified ±1 part in 10^9 per day under continuous operation. The reference source is periodically compared to the Off-Air standard to determine its error and drift rate.

The Fluke "Capcal" counter is an integral frequency counter module in the programmable Current and Timing Source of the 9000/9100 capacitance calibration system. This counter uses either an internal reference oscillator (specified at ±0.2ppm/year) or the 1MHz output of the Fluke Frequency Reference Source. The Off-Air standard may also be used to improve accuracy. The counter has pre-set trigger sensitivity and is designed to work at a nominal signal level of 1V pk-pk, although it can also reliably handle TTL levels. The range of frequencies measured by the counter are in decades from 10 kHz to 10 MHz with selectable gate times of 10s (0.1 Hz resolution) or 100s (0.01 Hz resolution). Note that the 0.01 Hz resolution is not available at 10 MHz. Readings from the counter are available via the IEEE-488 interface only, there being no integral display. The software used to control the counter has a facility for applying corrections for known errors in the frequency reference. These are applied automatically from correction data held in a system correction file.

The EIP counter is only used for special "type test" measurements above 10 MHz and is not required for routine calibration of the 9100. It is capable of measuring up to 18 GHz, but is normally used in the 10 MHz-300 MHz range where measurements of the 9100's Option 250 HF Sine output frequency are required. In this mode, the maximum resolution is ±10Hz. The EIP counter has an IEEE-488 interface and may be used for automated measurements if required.

The Marconi 2437 may be used in place of the Fluke "Capcal" counter and is capable of measuring up to 100 MHz with a maximum resolution of 0.01 Hz (at 1 MHz). The uncertainties obtained by the 2437 and "Capcal" counter are basically same at the levels and frequencies of interest.

When external references are used (the normal mode of operation), and when the counters are used at the levels and frequencies given above, there are only three uncertainty contributions:- that of the external reference (either the 1 MHz/10 MHz Frequency Reference Source or Off-Air Standard), the resolution of the counter, and combined noise and jitter. The trigger modes, gate times and signal levels used ensure that the noise is always maintained at less than the least significant digit of the counter. Therefore a contribution of ±1 LSD for noise and resolution is used. If the internal reference of the counter is used, an additional allowance for the stability of that reference with time and temperature must be allowed for the specified calibration interval.

Summary

The methods described have been successfully applied and have resulted in the measurement systems receiving NAMAS Accreditation[1] for the automated calibration of the Fluke 9100 oscilloscope calibrator. Provision has been made in the methods and traceability to allow it to be easily extended to cover future products with extended performance.

References

1. UK NAMAS Accreditation number 0183, granted on the 3rd August 1995.