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PSPL Calibrations and International Standards Traceability

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INTRODUCTION

Picosecond Pulse Labs' (PSPL) time domain and frequency domain calibrations are traceable to international standards. They are traceable to the USA National Institute of Standards & Technology (NIST), the UK National Physical Laboratory (NPL), and the German Physikalisch-Technische Bundesanstalt (PTB). PSPL has NIST-traceable transfer standards for DC voltage, DC resistance, DC current, frequency, time, attenuation, return loss, RF power, noise figure, and settling time. PSPL has an NPL calibrated 11 ps pulse generator for pulse risetime and waveform. PSPL has a PTB-calibrated 4.8 ps sampler for risetime and impulse/step response. The pulse parameters of "Risetime", "Settling Time" and "Amplitude" are directly traceable to PTB, NPL, and NIST [1-3], with PSPL pulse generator models 4015C and 6110D transfer standards calibrated by NPL and NIST and a PSPL 9043/SE-70 sampling head calibrated by PTB. All other parameters are indirectly traceable through various transfer standards that have been calibrated by secondary, NIST-traceable calibration labs.

The most important parameters of PSPL's products are their time domain and frequency domain responses. PSPL's highest performance, time domain pulse parameter calibrations are performed using a LeCroy model WE-100H digital sampling oscilloscope with a PTB calibrated PSPL model 9043/SE-70 sampling head [4]. Less critical measurements may also be made using PSPL SE-100, SE-50, and ST-20 samplers and Agilent and Tektronix digital sampling oscilloscopes. , PSPL's frequency domain calibrations are performed using various Anritsu, Agilent, and HP vector and scalar network analyzers, covering from 5 kHz to 65 GHz. All measurements are made using 50 Ω instruments.

The specification sheets for PSPL products are very detailed and include many specifications and typical data plots. All PSPL products, including pulse generators, samplers, and coaxial components, are 100% tested to verify that they meet all specifications. All PSPL products have individual serial numbers, with the sole exception being the model 5510, SMA attenuators. The construction, alignment, quality control, test, and calibration procedures for all PSPL products are completely documented. All of these procedures, etc., conform to ISO-9000 standards. All test data is recorded and kept in permanent files at PSPL. Several PSPL pulse generator models are supplied with a PTB/NPL/NIST-traceable calibration report that includes waveform plots. Calibration reports for PSPL coaxial components are only available as an extra cost option. Certificates of Conformance for all new products are supplied upon request at no charge. PSPL also offers a recalibration service for its pulse generators.

DC VOLTAGE, CURRENT, RESISTANCE, and ATTENUATION

The PSPL lab standard for these parameters are HP model 34401A digital multimeters. The accuracy specifications are: DC voltage 0.005%, DC current 0.05%, and DC resistance 0.02%. The calibrations of these DVMs are checked and certified bi-annually, using NIST-traceable standards, and by the secondary calibration lab, Tektronix Service Solutions (formerly Sypris T&M) mobile calibration van.

FREQUENCY and TIME

The PSPL lab standard for these parameters is an HP model 53131A frequency counter with high stability/ high accuracy time base and 3 GHz options. PSPL also uses a PSPL model 5650 divide by 8 trigger countdown to extend the frequency range of this counter to 16 GHz. The calibration of this counter is checked and certified bi-annually by Agilent, using NIST-traceable standards. This counter is then used by PSPL to calibrate all of its other frequency counters, signal generators, network analyzers, spectrum analyzers, and oscilloscope time bases.

RF POWER

PSPL's transfer standard for RF power from 10 MHz to 40 GHz is an Anritsu model ML2437A power meter with a model MA2444A power sensor head. The calibration of this instrument is checked and certified bi-annually by Anritsu, using NIST-traceable standards.

This instrument is then used by PSPL to calibrate the output power of network analyzers and frequency synthesizers, and also to calibrate spectrum analyzers.

NOISE FIGURE

PSPL's transfer standard for noise figure is an HP-8970A noise figure meter with an HP-346B noise head. The calibration of this instrument is checked and certified bi-annually by Agilent, using NIST-traceable standards.

INSERTION and RETURN LOSS

PSPL calibrates the insertion loss (attenuation) of coaxial attenuators at DC, using a well-regulated 5 Volt power supply, two wire wound, 7 watt, precision 50.0 Ω resistors, and the HP-34401A DVM. The attenuator under test is placed between these two resistors. The first resistor sets the source impedance to precisely 50 Ω, while the second resistor is the 50 Ω load. The DVM measures the voltage across the 50 Ω load. These calibrations are traceable to NIST through the HP-34401A DVM. PSPL assigns an uncertainty of ± 0.05 dB for the DC attenuation calibration of 50 Ω attenuators from 1 dB to 20 dB.

For frequency domain measurements from 10 MHz to 65 GHz of insertion loss/gain (S_{21}) and return loss (S_{11}), PSPL uses both scalar and vector network analyzers made by Anritsu. For low frequency measurements down to 5 kHz, PSPL uses an HP model 3577A vector network analyzer. The calibrations of these network analyzers are checked and certified bi-annually by the manufacturers, Anritsu and Agilent, using NIST-traceable standards.

In normal use, each network analyzer is calibrated frequently, using a calibration kit provided by the manufacturer. To verify the calibrated performance of each network analyzer, PSPL uses a set of attenuation and impedance standards from Anritsu. PSPL has two sets of Anritsu transfer standards. One set is for 2.9mm, K (40 GHz) connectors. The other set is for 1.85 mm, V (65 GHz) connectors.

The open circuit / short circuit standards are Anritsu models 22K50, 22KF50, 22V50, and 22VF50. Two sets of four precision, calibrated attenuators (3dB, 6dB, 10dB, and 20dB) with K (2.9mm) and V (1.85mm) connectors are used for insertion loss and high return loss (i.e., low vswr) standards. They are Anritsu models 41KC-S and 41V-S. The calibrations of these standards are checked and certified bi-annually by Anritsu, using NIST-traceable standards.

OSCILLOSCOPES

Because PSPL's products are mainly time domain oriented, the oscilloscope is PSPL's most important measurement instrument. PSPL uses oscilloscopes made by PSPL, LeCroy, Agilent, Hewlett-Packard, and Tektronix. Oscilloscopes include ultra-high bandwidth (up to 100 GHz) digital sampling oscilloscopes and more conventional, lower bandwidth, analog and digital oscilloscopes. The general performance parameters of all PSPL's various oscilloscopes are calibrated bi-annually by Tektronix Service Solutions (formerly Sypris T&M) mobile calibration van, using NIST-traceable standards. The LeCroy digital sampling oscilloscopes are calibrated biannually by the manufacturer, LeCroy. However, for the calibration of the high performance digital sampling oscilloscopes' risetimes, step responses, and settling times, PSPL does the calibrations ourselves, in-house, using transfer standards traceable to the international standards labs of PTB (DE), NPL (UK), and NIST (USA).

RISETIME STANDARD

The PSPL lab Gold Standard for risetime is a PSPL model 9043/SE-70, Sampling Head (s/n 1117959). PSPL has sent this transfer standard sampling head to PTB in Germany for calibration of its impulse response duration (fwhm = 5 ps), step response risetime (Tr = 4.8 ps), along with the complete waveforms for impulse and step responses for a 100 ps time epoch [1&5]. PSPL has created a complete MatLab [6] model for this PTB-calibrated 9043/SE-70 sampler that extends the calibrated step response beyond the 100 ps PTB data out to 100s of nanoseconds, using additional calibration data from measurements of an NPL-calibrated, 11.2 ps falltime, PSPL model 4015C pulse generator with an extra pulse sharpening pulse head and a NIST calibrated PSPL model 6110D reference flat pulse generator. Further details can be found in PSPL's application note, AN-26 [7]. For details on the PTB, NPL, and NIST calibration services, see references [1-3,5].

SETTLING TIME STANDARD

The PSPL lab standard for Settling Time is a PSPL model 6110D Reference Flat Pulse Generator head. The design of this generator is based upon a National Bureau of Standards (NBS, now NIST) design [8]. The pulse output of this generator, including the settling time response, is mathematically predictable. This generator has been sent to NIST for calibration of its settling time. The NIST calibration confirmed the validity of the math model. This generator has a settling time of 5 ns to < 0.1% and 10 ns to < 0.02%.

CALIBRATION vs. PRODUCTION and R&D OSCILLOSCOPES

Different levels of traceability and uncertainty are assigned to PSPL's various oscilloscopes depending upon their usage. For the most demanding, fastest risetime measurements for calibration reports for PSPL's < 20ps risetime step pulse generators, PSPL uses its LeCroy WE-100H digital sampling oscilloscope with the Gold Standard, PSPL 9043/SE-70 sampling head. This oscilloscope has had the most thorough characterization, modeling, and calibration with direct traceability to PTB, NPL, and NIST. Deconvolution is used on these measurements to remove the effects of timing jitter and the oscilloscope's step response and if used, the attenuator's step response. Further details are in a later section.

For less demanding calibrations of other products, production testing, and general R&D work, either LeCroy or Agilent or Tek digital sampling oscilloscopes are used, but without using deconvolution. For these measurements, the waveforms as displayed on the oscilloscopes are used directly. The sole exception is for risetime measurements. The simple root-sum-of-squares equation is used to remove the effects of the oscilloscope risetime.

Every oscilloscope and sampling head owned by PSPL has been individually calibrated for risetime. A calibration sticker with the risetime is attached to each instrument. The PSPL internal risetime transfer standard used to calibrate all other samplers is PSPL's calibration lab standard, model 4016 pulse generator with a falltime of 5 ps [7]. This generator is traceable to PTB through the PTB calibrated 9043/SE-70 sampling head.

TIME DOMAIN CALIBRATION of PULSE GENERATORS

The LeCroy, Agilent, and HP oscilloscopes used by PSPL for calibrations include built-in pulse parameter measurement firmware. Many measurements made by PSPL use this "Auto Measure" feature. These oscilloscopes follow the IEEE Standard 194-1977, IEEE Standard Pulse Terms & Definitions". This standard specifies that the histogram method is to be used to first determine the baseline (0% level) and topline (100% level). These levels are determined in a long time window epoch that includes all features of the pulse waveform. The Pulse Amplitude is the difference between the pulse baseline and topline. The Transition Durations (10%-90% Risetime and 90%-10% Falltime) are then measured in much shorter transition epoch time windows at a faster time base sweep speed, using the 0%, 10%, 90%, and 100% levels determined previously in the long time epoch window. For PSPL's highest accuracy measurements, waveform data files are off-loaded from the digital oscilloscope to a separate computer for further data processing in MatLab. For pulse parameter measurements on these off-loaded files, PSPL uses its own custom MatLab program called *PulseMeasV31.m* This program adheres to the IEEE standard.

PSPL's various sampling oscilloscopes have bandwidths ranging from 12 GHz to 100 GHz and corresponding risetimes from 30 ps to < 5 ps. For risetimes slower than 200 ps, they are reported as directly measured by the oscilloscope. For pulse generators with risetimes faster than 200 ps, the risetime reported is calculated from the root-sum-of-squares RSS equation, which removes, to a first order correction, the risetime of the oscilloscope.

$$Tr(gen) = [Tr(meas)^2 - Tr(scope)^2]^{1/2}$$

For pulses with amplitudes larger than 500 mV (for Agilent or Tek oscilloscopes) or 1.2 V (for PSPL samplers), precision, calibrated attenuators are placed between the pulse generator and the oscilloscope. PSPL uses PSPL model 5510-K, 2.9mm, 40 GHz attenuators or model 5510-V, 1.85mm, 65 GHz attenuators These attenuators are all calibrated for their DC attenuation and risetime. They have typical risetimes of the order of 5 ps. When an attenuator is used in a measurement, its effect on the measurement is also removed using the RSS equation:

Most measurements are made using signal averaging to enhance the signal-to-noise ratio in the measurement. However, when timing jitter is present, signal averaging has the effect of introducing an additional low pass filter into the measurement. For details, see PSPL application note AN-23 [9]. When signal averaging is used, an additional measurement is also made of the unaveraged timing jitter standard deviation, σ. The effective risetime of the signal averaging low-pass filter is Tr(jitter) = 2.56 * σ. Thus for most measurements, the following RSS equation is used to calculate the pulse generator's risetime (falltime).

$$Tr(gen) = [Tr(meas)^2 - Tr(scope)^2 - Tr(atten)^2 - (2.56*\sigma_{jitter})^2]^{1/2}$$

For most pulse generators, PSPL does not attempt to remove the settling time errors in the measurement oscilloscope. Instead, their effects are accounted for in PSPL's amplitude uncertainties. For PSPL's precision, reference flat pulse generators, models 6110D and 10,300B, PSPL does do additional data processing to remove settling time errors. The NIST-calibrated, settling time transfer standard, model 6110D, is attached directly to the oscilloscope. The oscilloscope's settling time response is stored in the oscilloscope's memory. Next, the generator under test is attached to the oscilloscope. The amplitude and delay of the generator's waveform display are adjusted to overlay the previously stored 6110D reference flat pulse waveform. The oscilloscope's waveform math function is then used to compute and display the difference between the two waveforms. This difference is the measured flatness of the generator under test.

For PSPL's fastest (Trise < 20ps) step pulse generators, a different, more precise calibration procedure is followed. This includes the PSPL models 4005, 4015, 4016, 4020, and 4022. For these models, the LeCroy WE-100H digital sampling oscilloscope is used along with the PSPL, Gold Std., model 9043/SE-70 sampling head. This SE-70 sampler has been completely characterized and modeled with direct traceability to PTB, NPL, and NIST. For details see PSPL application note AN-26 [7]. The complete step pulse waveform is measured in a 5 ns time window (500 ps/div), with a sample spacing of 0.5ps. The measured waveform data array is transferred to a separate computer for further data processing. A custom, PSPL MatLab program, *GoldSE70decon.m*, is then used to deconvolve out the risetime limiting effects of the signal averaged timing jitter, the SE-70 sampler's step response, and if used, the attenuator's risetime. The custom program contains a complete model of the sampler, including the early 100 ps epoch PTB calibration data, the mid-term calibration from the NPL calibrated 4015C pulse generator, and the long term calibration data from the NIST-calibrated 6110D RFPG. For further details on deconvolution, see PSPL's application note, AN-18 [10]. The PSPL MatLab program *PulseMeasV31.m* is then used to measure the various pulse parameters.

Tables 1 and 2 list PSPL's claimed uncertainties for risetime and amplitude calibrations of ultra-fast step pulse generators, using the PTB/NPL/NIST-calibrated Gold Standard. 9043/SE-70 sampler, and deconvolution. For these calibrations, PSPL furnishes, along with the formal calibration report, a CD data disc with the deconvolved, 5 ns time window waveform.

For second tier calibrations that do not include deconvolution, Tables 3 and 4 list PSPL's claimed risetime and amplitude uncertainties for pulse generator calibrations.

PSPL calibration reports also often include other pulse parameters such as precursor, overshoot, perturbations, flatness, and jitter. No uncertainties are claimed for these parameters. These tables are only valid for amplitudes up to 50 Volts. These tables assume that the measured pulse is "clean". If there are a lot of perturbations on the pulse, then the accuracy is degraded beyond that listed in these tables.

Table 1:
Pulse Generator Risetime Calibration Accuracy
(deconvolution method, no attenuators, < 1 ps jitter σ)

Risetime	Uncertainty	Risetime	Uncertainty
5 ps	± 2 ps	12 ps	± 1.5ps
6 ps	+1.9ps -2 ps	15 ps	+1.4ps -1.5ps
8 ps	+1.7ps -2ps	20 ps	± 1.3ps
10 ps	+1.6 ps -1.8 ps	30 ps	± 1.2ps

(deconvolution method, 1 attenuator, <1.5 ps jitter σ)

Risetime	Uncertainty	Risetime	Uncertainty
5 ps	+2.6 ps -3 ps	12 ps	+1.7 ps -2 ps
6 ps	+2.4 ps -3 ps	15 ps	+1.5 ps -1.7 ps
8 ps	+2 ps -2.8 ps	20 ps	+1.4 ps -1.5 ps
10 ps	+1.8 ps -2.3 ps	30 ps	± 1.3 ps

Table 2:
Pulse Generator Amplitude Calibration Accuracy
(deconvolution method, 5 ns time window)
(Note: If an attenuator is used, add 0.6%)

Time Epoch	Uncertainty
t < 100 ps	+1.1%, -2.3%
100ps < t < 500ps	+1.1%, -1.5%
500ps < t < 2 ns	+1.1%, -1.2%
t > 2ns	± 1.1%

Table 3:
Pulse Generator Risetime Calibration Accuracy
(simple RSS method)

Risetime	Uncertainty	Risetime	Uncertainty
15ps	+2.8ps, -2.2ps	500 ps	1.6%
15ps *	+3.3ps, -2.7ps	1 ns	1.3%
20ps	+2.5ps, -2.1ps	2 ns	0.7%
20ps *	+2.9ps, -2.4ps	5 ns	0.8%
30ps	± 5%	10 ns	1.4%
30ps *	± 7%	20 ns	1.5%
50ps	± 3%	50 ns	0.5%
50ps *	3.6%	100 ns	0.3%
100ps	2.5%	200 ns	0.2%
100ps **	3%	>500 ns	0.1%
200ps	1.9%		
200ps **	2%		

(* up to 5 V with one attenuator)
(** up to 50 V with two attenuators)
(This table is valid for amplitudes from 200 mV to 50 V. Above 500 ps, the uncertainty is not dependent upon the amplitude.)

Table 4:
Pulse Generator Amplitude Calibration Accuracy
(simple RSS method)

Time Epoch	300 mV	5 V	50 V
1 ns	+3.5% -2.5%	+4.7% -3.7%	+5.3%, -4.3%
10 ns	+2.5% -1.5%	+3.7% -2.7%	+4.3% -3.3
100 ns	+1.8% -0.8%	+3.0% -2.0%	+3.6% -2.6%
100 ns*	± 0.5%	± 1.7%	± 2.3%
1 µs	± 0.8%	± 2.0%	± 2.6%
1 µs*	± 0.5%	± 1.7%	± 2.3%
>1 µs	± 0.5%	± 1.7%	± 2.3%

(* special calib. procedure used to remove scope settling time error.
Only used for 10300B pulse generator)

TIME DOMAIN CALIBRATION of COAXIAL COMPONENTS

PSPL measures the time domain step response of most of its broadband coaxial components. These measurements are PTB/NPL/NIST-traceable. Both Time Domain Transmission (TDT) and Time Domain Reflectometry (TDR) measurements are made. Agilent and HP digital sampling oscilloscopes are used for these measurements. These oscilloscopes all include built-in firmware to do deconvolution of TDT and TDR network measurements. It should be noted that Agilent (HP) calls this process “normalization” rather than deconvolution. This allows the user to remove the effects of using imperfect pulse generators and oscilloscopes. The result is as if one were testing with a perfectly flat step function with a controlled, Gaussian shaped risetime. Normalization is the equivalent of performing a system calibration on a vector network analyzer (VNA). Similar TRL standards are used for TDT/TDR calibration as are used for the VNA. They include an open, short, and 50 Ω terminations, plus a through line. The HP/Agilent digital sampling oscilloscopes include a built-in TDR pulser with a 200 mV amplitude and 35 ps risetime. PSPL uses this 35 ps TDR pulse for testing components with risetimes > 25 ps. For testing components with risetimes less than 25 ps, a much faster pulse source is required. PSPL uses its own model 4015C, 15 ps pulse generator or model 4020 or 4022, < 10ps, TDR/TDT Source Enhancement pulse generators.

To initially calibrate the oscilloscope, the TDR/TDT source waveforms are measured under different conditions and stored in the oscilloscope's memories. For TDT (S21), the two calibration waveforms are an "Open" (i.e., no connection between the generator and oscilloscope), 0 Volt baseline, and a "Thru" connection of the generator directly into the oscilloscope. For TDR (S11), they are a "Short" (i.e., the reflection from a short circuit, ρ = -1) and a 50 Ω termination (ρ = 0). The Device Under Test (DUT) is next connected to the oscilloscope, and its TDT and TDR response waveforms are measured. The oscilloscope's 'normalization' firmware then performs mathematical deconvolution of the calibration and response waveforms to remove the generator and oscilloscope system defects.

Deconvolution is done by transforming time domain waveforms to the frequency domain, dividing $V_{out}(f)$ by $V_{in}(f)$ and then inverse transforming back to the time domain. This process results in very clean, Gaussian rise input test pulses and also removes long term settling time errors. HP/Agilent has also included in their 'normalization' firmware a user selectable, low pass, digital Gaussian filter. With this filter, the user can select an equivalent input test pulse risetime that is either slower or faster than the actual test pulse. In practice one is able to enhance the effective risetime at most by about 50% of the actual measurement system risetime. The lower limit when using the 15 ps pulse from the PSPL 4015 with a 50 GHz sampler is about 10 ps. PSPL's application note AN-5c [11] gives more details. Table 5 lists PSPL's uncertainty limits for risetime calibrations of broadband coaxial components when using the HP/Agilent oscilloscope TDT/TDR normalization.

Table 5:
Broadband Coaxial Component Risetime Accuracy
(using HP/Agilent TDT/TDR normalization)

Risetime	Uncertainty	Risetime	Uncertainty
10 ps	+1.5ps -2ps	1 ns	± 1%
20 ps	+1 ps -2 ps	2 ns	± 0.6%
30 ps	± 3.5%	5 ns	± 0.3%
50 ps	± 2.5%	10 ns	± 0.25%
100 ps	± 2%	20 ns	± 0.2%
200 ps	± 1.5%	>200 ns	± 0.15%
500 ps	± 1.2%		

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[3] National Institute of Standards & Technology, USA, Calibration service # 65250S for "Repetitive Pulse Waveform Measurements — Including Settling Parameters"; see www.nist.gov.

[4] LeCroy web site: www.lecroy.com.
WaveExpert model 100H oscilloscope.

Note: *PSPL designed and builds the LeCroy SE, ST & SO series sampling heads on an OEM basis.*

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