Gold Standard, 4.8 ps, Sampling Oscilloscope Traceable to International Standards Labs

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INTRODUCTION

Picosecond Pulse Labs (PSPL) now has a 4.8 ps risetime sampling oscilloscope with a complete step and impulse response characterization traceable to international standards labs. It is the PSPL model 9043/SE-70 sampling head [1] (s/n 1117959). The SE-70, >70 GHz samplers were designed and built by PSPL and are sold by LeCroy. The oscilloscope main frame is the LeCroy Wave Expert model 100H. A composite step/impulse response was created utilizing intermeshed calibrations from PTB, NPL, and NIST. This application note documents the creation of this Gold Standard SE-70 step/impulse response. Examples are then given showing how the oscilloscope's impulse response can be deconvolved from real world picosecond pulse measurements.

PTB CALIBRATION

The Physikalisch Technische Bundesanstalt (PTB) is the national standards lab for Germany. PTB recently announced an improved calibration service for sampling oscilloscopes. In their paper in the April 2009 issue of the IEEE Transactions on Instrumentation & Measurement, they showed an example of their calibration process using a LeCroy SE-70 sampler [2].

PSPL has recently sent its "Gold Standard" SE-70 sampling head (s/n 1117959) to PTB for calibration. A PTB calibration is only supplied for a very limited time epoch of 100 ps. Figure 1 shows the PTB step and impulse response calibration data for the PSPL "Gold Standard" SE-70 sampler.

The PTB calibrated step response risetime for the 100 ps time epoch was 4.4 ps (±0.7 ps). The impulse response duration (fwhm) was 5.0 ps (±0.4 ps).

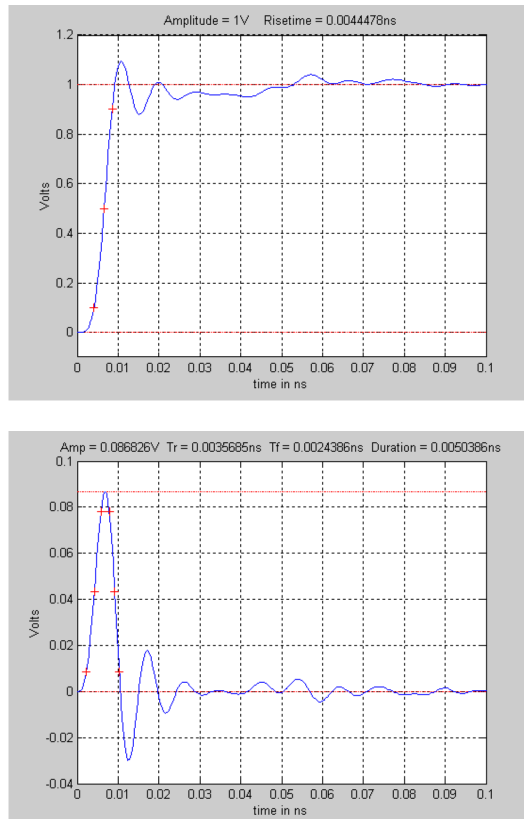


Fig. 1 PTB step response (top) and impulse response (bottom) calibration data for PSPL's Gold Std. SE-70 sampling head. Step T_{rise} = 4.4 ps & Impulse T_d = 5.0 ps.

BLOW-BY CHARACTERIZATION —- > 5 NS EPOCH

For complete characterization of the SE-70 sampler, the 100 ps epoch calibration data from PTB is insufficient. All samplers are plagued with a phenomena called "Blow-By". Blow-by causes low frequency, long-term signal distortion in the nanosecond domain. Blow-by is signal leakage around the sampling diodes that gets into the sampler's processing circuits and introduces waveform distortion. The leakage path is due to the capacitance of the sampling diodes and occurs when the sampling diodes are not being strobed. Blow-by compensation is a major headache for sampling head designers. Examples of "Blow-By" distortions can be seen in the comparisons of sampling oscilloscopes in PSPL's Application Notes AN-2 series [5].

While the PSPL SE-70 has good blow-by compensation, it is still not perfect. All PSPL samplers are aligned in final production test to minimize blow-by, using a National Institute of Standards & Technology (NIST) [6 & 7] calibrated PSPL model 6110, Reference Flat Pulse Generator. NIST is the USA national standards lab. The 6110 RFPG produces a 500 mV, negative going, step pulse that switches to the absolute voltage level of 0 V. It has a falltime of 425 ps. Its settling time is specified to be < 0.2% (3ns), < 0.1% (5ns), < 0.02% (10ns), and < 0.01% (100ns). The NIST calibration showed the actual performance to be even better, with settling to 0.02% for t > 5 ns, with the worst case being 0.15% overshoot at t = 3 ns. The NIST data was only valid for t > 3 ns.

Figure 2 shows the SE-70's long-term, nanosecond domain blow-by. It is predominately characterized by a damped 120 MHz sine wave and a longer term exponential lasting 40 ns. The initial leading edge spike is an artifact of the RFPG and is mathematically predicted to be present by SPICE modeling.

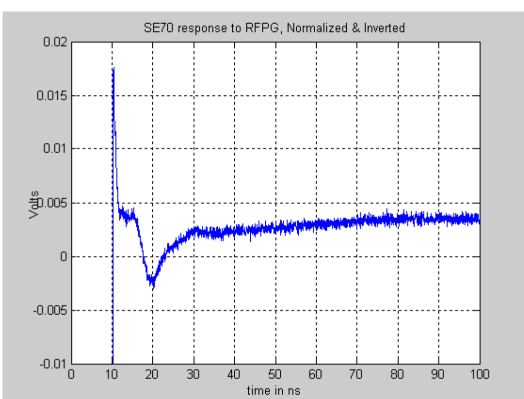


Fig. 2 SE-70 blow-by response to RFPG, expanded vertical = 0.5% /div, 100 ns time window.

REFINED MODEL — 100 PS TO 5 NS EPOCH

The PTB calibration data is excellent for the 0 to 100 ps epoch. The NIST data is excellent for the > 5 ns epoch. The 100 ps to 5 ns epoch still has considerable uncertainty. More measurements were needed to fill this gap. Two generators were used. They were the PSPL ST-20 and 4015C.

The PSPL/LeCroy ST-20 TDR sampling head includes an excellent TDR pulse generator with a very good settling time. The ST-20 uses the same pulse generation technique as the slower 6110 RFPG. This is the switched current technique, where the step's final value is 0 Volts [7]. The ST-20 TDR pulse is 250 mV in amplitude with a 9 ps risetime. Because it uses an SMA connector, the ST-20 pulse, when viewed on a 70 GHz sampler, shows overshoot and a lot of higher order mode ringing that is not seen when viewed on the ST-20's 20 GHz sampler. To minimize the ringing in the measurement, a 45 ps risetime filter was used on the output of the ST-20. Figure 3 shows the response of the SE70 to the 45 ps TDR pulse. The very fine structure seen in Figure 3 is considered to be a residual artifact of the low-pass filtered TDR pulse and not that of the SE-70 sampler. For the SE-70 blow-by math modeling, only the smoothed, slowly varying, general shape of the curve was used.

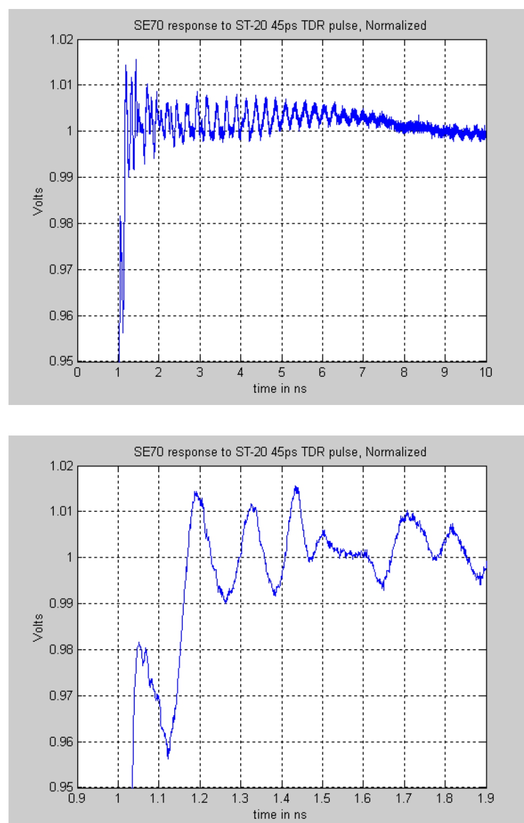


Fig. 3 SE-70's blow-by response to 45 ps TDR pulse. Settling time to 0 V topline expanded. 1%/div & 10 ns time window (top) & 1 ns (bottom). Ringing is generator artifact.

With the high frequency ringing on the ST-20 pulse, it was difficult to draw definitive conclusions regarding the sub-ns blow-by pattern. To fill this final gap, another PSPL pulse generator was used. This generator had been calibrated by the National Physical Laboratory (NPL) in the U.K. [8]. The generator was a specially modified PSPL model 4015C that used an extra PSPL 4006RPH, NLTL pulse head to speed up the pulse edge. This generator produced a 1/2 V negative going step pulse with an 11.2 ps (+1.8, -2.0 ps) falltime, Figure 4. This generator has been PSPL's risetime gold standard for traceability to international standards. The NPL data only covered a pulse topline epoch of 350 ps. This, however, was longer than the 100 ps epoch of the PTB data. Thus it was useful to help fill the final gap in arriving at a useful math model for the SE-70's step response.

Figure 4 shows the NPL calibration data for the 4015C, while Figure 5 shows the waveform as directly measured by the SE-70. There are definite, obvious differences. The SE-70 shows a slow 'roll-up' in the 90 to 100% region, even though the SE-70 has an extremely fast < 5 ps risetime per the PTB calibration. The NPL falltime, Figure 5, is 11.22 ps, while the SE-70 measured falltime, Figure 6, is much slower at 14.42 ps. This is a significant discrepancy of 2.2 ps, or almost 20 % error.

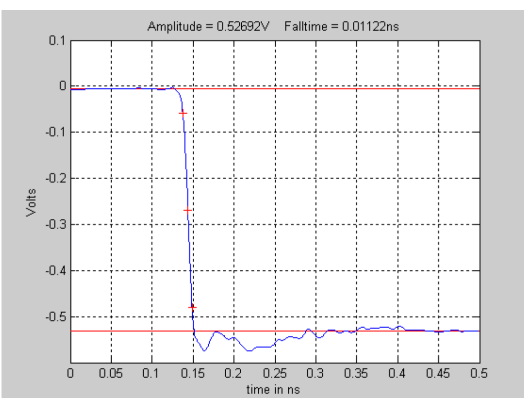


Fig. 4 NPL calibration data for PSPL's gold standard, model 4015C pulse generator. T_{fall} = 11.2 ps.

Figure 6 shows the normalized comparison of the NPL data with the waveform measured by the SE-70 sampler. The blue trace is the NPL data. The red trace is the SE-70 data. The green trace is the difference. It is obvious that the SE-70 sampler has some roll-up in its step response during the first 150 ps that needed to be accounted for in the blow-by model. It is in error by -6% at t = 50 ps and -3% at 100 ps.

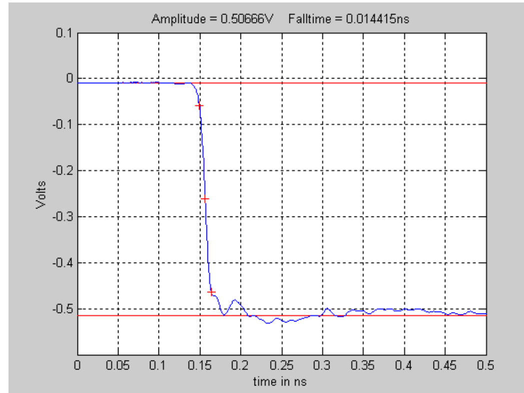


Fig. 5 SE-70 measurement of above NPL calibrated 4015C. T_{fall} = 14.2 ps.

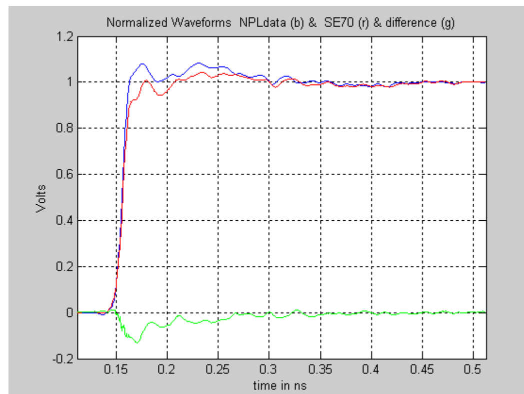


Fig. 6 Comparison of normalized NPL data blue) and the 4015C waveform measured by the SE-70 sampler (red). Difference (green).

STEP RESPONSE MODEL

The MatLab model developed by the author for the SE-70 sampler is a composite of the 100 ps epoch PTB data, the 350 ps epoch NPL data, and the 200 ns epoch NIST data. All of this data was carefully analyzed, and a table of correction data points was created. A math model was then created for the Gold Std. SE-70 sampler. The model used the actual, normalized PTB data for the first 100 ps. A math function composed of several damped sinusoids and exponentials was created to closely model the overall blow-by effects. This blow-by math model was then multiplied with the normalized PTB step response data. Figure 7 shows the resultant math model Blow-By correction curve.

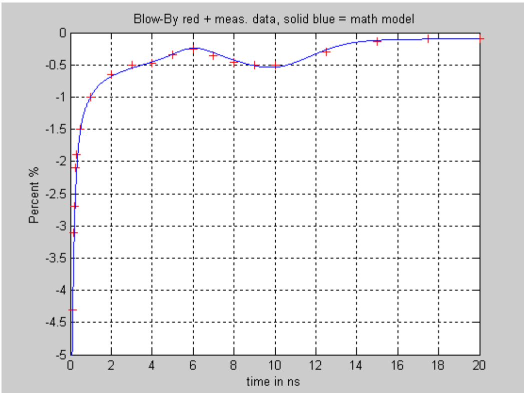


Fig. 7 Blow-By correction math model for Gold Std. SE-70 sampler. Blue trace is math model. Red crosses are measured blow-by data. 20 ns time window.

Figure 8 shows PSPL's best estimate for the actual step response of our Gold Std. SE-70 sampler. This includes the 100 ps time epoch PTB calibration data along with our math model for the longer time Blow-by effects. The slow roll-up in the 90% to 100% region causes a slowing in the actual risetime. Whereas the PTB calibrated risetime for the first 100 ps epoch was 4.4 ps, we feel that the actual risetime of the instrument is actually 4.75 ps.

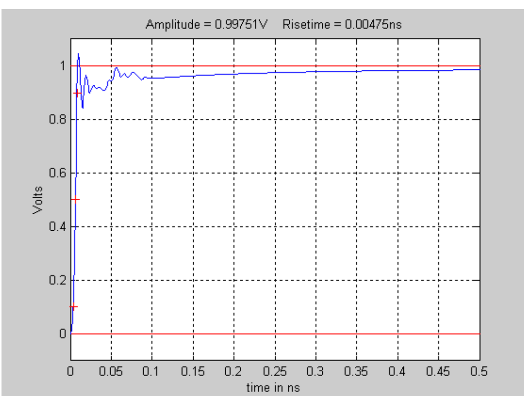


Fig. 8 Gold Std. SE-70 step response including PTB calibration data and modeled Blow-by effects. 500 ps time window. T_{rise} = 4.75 ps.

To demonstrate the effectiveness of this refined blow-by model, the SE-70 sampler's step response, Figure 8, was deconvolved from the raw, measured 4015C data of Figure 5. The result is shown in Figure 9 and was then compared again to the NPL calibration data and is shown in Figure 10. Excellent agreement was obtained with < ±5% difference in the 30-50ps region and < ±1% beyond 50 ps.

The deconvolved falltime was 11.8 ps, which compared favorably with the NPL value of 11.2 ps and was well within the NPL quoted uncertainty limits of +1.8 ps, -2.0 ps.

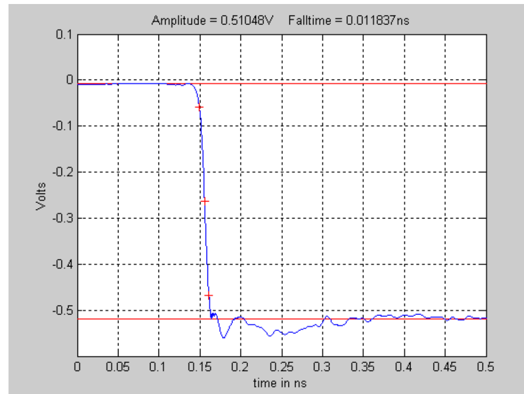


Fig. 9 Deconvolved 4015 waveform. T_{fall} = 11.8 ps.

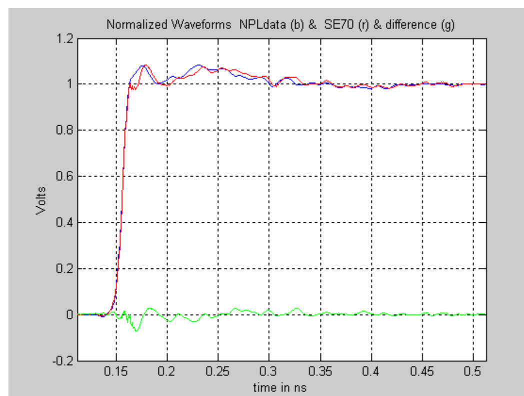


Fig. 10 4015C waveforms. Comparison of normalized NPL data (blue) and deconvolved SE-70 measurement (red). Difference (green).

SAMPLER FREQUENCY RESPONSE

The impulse response, h(t), is the derivative of the step response. From h(t), the frequency response, H(f), can be obtained using a Fourier Transform. Figure 11 shows the computed frequency response of the SE-70 sampler. The -3 dB bandwidth is seen to be approximately 110 GHz. Beyond this the response drops very rapidly. The response is not Gaussian, and thus the commonly used risetime-bandwidth equation, Tr * BW = 0.35 is not valid for this oscilloscope. For this oscilloscope, Tr * BW = 0.53.

Fig. 11 Frequency response of Gold Std. SE-70 sampling head.

DECONVOLUTION

Deconvolution is the mathematical process used to determine an input waveform, $v_{in}(t)$, when one has an output waveform, $v_{out}(t)$ and also the impulse response, h(t), of the network the input waveform passed through. Several MatLab deconvolution programs have been written by the author. To learn more about deconvolution, the reader is referred to PSPL's application note AN-18 [8]. Several of these programs are available from PSPL's web site: www.picosecond.com.

Conceptually, deconvolution seems to be a very straight-forward process. It can be expressed by the formulas:

$$V_{in}(f) = FFT[v_{out}(t)] / FFT[h(t)] \qquad (1)$$

$$v_{in}(t) = invFFT[\, V_{in}(f)\,] \qquad (2)$$

where FFT[h(t)] is H(f), the oscilloscope's frequency response transfer function (Figure 11). The real problems arise when $V_{out}(f)$ and/or H(f) have dropped into the noise. Dividing noise by noise in equation. 1 leads to indeterminate results, with the net effect causing the resultant deconvolution solution for $v_{in}(t)$ to blow up. Many researchers have struggled for many years to master this problem. The PSPL MatLab deconvolution programs incorporate a selection of various deconvolution filters that can be selected by the user. These are discussed in detail in AN-18.

NOISE FLOOR FILTER

The author has recently come up with a new deconvolution filter technique that seems to work extremely well. It is called the Noise Floor Filter. The most current version of PSPL's MatLab deconvolution programs incorporate this filter. The concept is simple. First, one must realize that, once the signal has dropped into the noise, it can not be recovered, no matter how exotic a deconvolution filter is used.

In the MatLab program, the spectrum of $V_{out}(f)$ is automatically examined in the upper portions just below the Nyquist frequency to determine the noise floor. The mean noise floor in dB is determined along with the worst case, highest noise level. Then $V_{out}(f)$ is examined, starting at the lowest frequencies and working upwards to find the first frequency at which $V_{out}(f)$ has dropped down to the level of the worst case noise in the noise floor. This frequency is labeled as f_{co}. The MatLab program then performs the division of equation (1) from DC up to f_{co}, as normal. However, above f_{co}, $V_{in}(f)$ is then set to be equal to $V_{out}(f)$. Thus, when the inverse FFT operation of equation (2) is performed, the resultant $v_{in}(t)$ solution is stable.

JITTER DECONVOLUTION

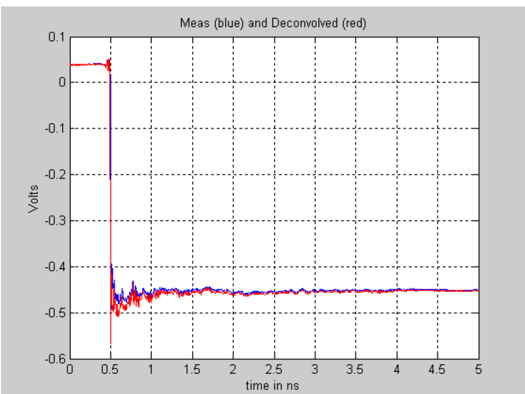
Usually when precision measurements are made with sampling oscilloscopes, signal averaging is done to enhance the signal to noise (s/n) ratio. Averaging works great for removing vertical noise. However, when jitter, i.e., horizontal or timing noise, is present, signal averaging has the effect of introducing an additional Gaussian low pass filter into the measurement. This slows down fast edges and smears pulse waveforms. The effect of signal averaged jitter can also be removed using deconvolution. For details, see the PSPL jitter application note, AN-23 [9].

GoldSE70decon.m

The author has written a MatLab function program that automatically performs complete deconvolution of PSPL'S Gold Std., SE-70 sampler measurements. It incorporates the composite, calibrated, PTB/NPL/NIST step response model (Figure 8), signal averaged jitter deconvolution, and h(t) deconvolution. It uses the Noise Floor Filter method. It works automatically for any selected time window, T_w, and sample spacing, dt. The inputs are the $v_{out}(t)$ data file, dt, and the sigma (σ) of the timing jitter. It returns a $v_{in}(t)$ data file. The program contains in excess of 600 lines of code. This program was used for the previous NPL-4015C deconvolution, Figures 9 and 10, and the following example.

PSPL 4016 PULSER DECONVOLUTION

Measurements were made using the Gold Std. SE-70 sampler on PSPL's fastest pulse generator, a model 4016. It puts out a -5 V, negative step waveform. To reduce its output to a safe level for the sampler, a PSPL 5510V-20dB (V connector, >60 GHz, < 5 ps) attenuator was placed between the 4016 pulse head and the SE-70. The -1/2 V output from the 20 dB attenuator was measured with the SE-70 signal averaged, and a data file was stored in the computer. It is shown in Figure 12 as the blue trace. The falltime was 7.3 ps with an undershoot of 9.2%. The timing jitter sigma was measured to be 1.75 ps. The sample spacing was 0.6 ps. This waveform was then deconvolved, using the MatLab program *GoldSE70decon.m.* The program removed first the effects of the signal averaged jitter and then the oscilloscope's step response. The deconvolution noise filter cutoff was set to 120 GHz. The resultant deconvolved waveform is shown in Figure 12 in red.



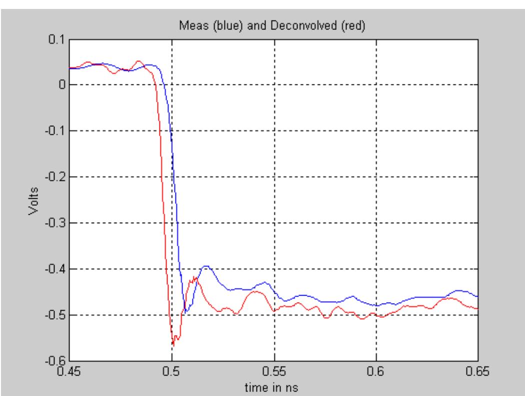


Fig. 12 Deconvolution (red) of PSPL 4016 pulser. Measured waveform (blue), Deconvolved waveform (red), 5 ns (top), and 200 ps (bottom) time windows.

After deconvolution, the true falltime was found to be 5.2 ps with an undershoot of 23.5%. This was a significant improvement in falltime of over 2 ps, or 40%. It should be noted that the V attenuator's step response could also be deconvolved, and the true falltime of the 4016 would be found to be even faster.

CONCLUSION

Having PTB step response calibration data for ultra-fast risetime samplers, along with blow-by modeling and mathematical deconvolution, leads to a significant enhancement in fast pulse measurement capability.

REFERENCES

[1] 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.

[2] Mark Bieler, Meinhard Spitzer, Klaus Pierz & Uwe Sieger, "Improved Optoelectronic Technique for the Time-Domain Characterization of Sampling Oscilloscopes", IEEE Trans. I&M, vol. 58, no. 4, April, 2009, pp. 1065-1071. For additional info — www.ptb.de.

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[4] MATLAB, Math Works, Natick, MA, www.mathworks.com.

[5] J.R. Andrews, "Comparison of Ultra-Fast Risetime Sampling Oscilloscopes", AN-2a thru AN-2d, 1989 thru 2001.

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[8] National Physical Lab, UK. See www.npl.co.uk, click on "Ultrafast Measurements & Calibrations".

[9] J.R. Andrews, "Deconvolution of System Impulse Responses & Time Domain Waveforms", Application Note AN-18, Picosecond Pulse Labs, Boulder, CO, Oct. 2004.

[10] J.R .Andrews, "Removing Jitter From Picosecond Pulse Measurements", Application Note AN-23, Picosecond Pulse Labs, Boulder, CO, Sept. 2009.

Note: PSPL Application Notes referred to here may be obtained from the PSPL web site: www.picosecond.com.