Comparison of Ultra-Fast Risetime Sampling Oscilloscopes (2011)

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INTRODUCTION

Starting in 1986, Picosecond Pulse Labs (PSPL) published an Application Note, AN-2, which was a comparison of all commercially available, broadband sampling oscilloscopes with risetimes faster than 35 ps. Since then oscilloscope manufacturers have introduced new models and discontinued old models. Revisions to AN-2 were published in 1989 as AN-2a, in 1994 as AN-2b, in 1998 as AN-2c, and in 2001 as AN-2d [1]. This newest, AN-2e, application note adds new samplers introduced in the last decade by Tektronix, Agilent, and LeCroy, including 70 and 100 GHz models. The results of the previous AN-2s are still valid, and they should be referred to for older model oscilloscopes. Earlier versions of AN-2 are still available from PSPL's web site: www.picosecond.com.

This latest oscilloscope comparison application note is a departure from the previous format. In older AN-2 application notes, the then current, fastest risetime pulse generator available was measured on each oscilloscope tested, with the observed waveforms shown as figures in the paper. Estimates were made of the respective risetimes. It was left up to the reader to interpret from the differences in displayed waveform perturbations which artifacts were due to the pulse generator and which were due to the oscilloscope's inherent step response.

This application note now displays the true, complete, step response waveform for each oscilloscope sampling head tested. The results are traceable to the international standards labs, PTB, NPL, and NIST.

INTERNATIONAL TRACEABILITY

There are three national standards labs that offer calibration services for pulse generators and oscilloscopes. They are the USA National Institute of Standards & Technology (NIST) [2], the UK National Physical Laboratory (NPL) [3], and the German Physikalisch-Technische Bundesanstalt (PTB) [4]. In 2010, PSPL sent one of its best sampling heads, a PSPL model 9043/SE70, to PTB for formal calibration of its step response. The complete modeling of this sampler using PTB, NPL, and NIST calibrations is documented in the PSPL application note, AN-26 [5]. The SE-70's step response, impulse response, and frequency response are shown in Figure 5.

DECONVOLUTION

A key mathematical tool used in the determination of the true step response of the oscilloscopes tested was "Deconvolution".

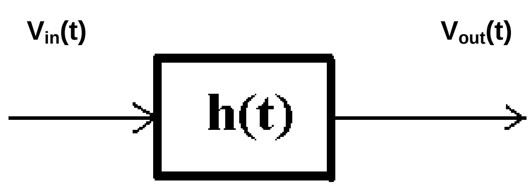

Fig. 1 Typical oscilloscope deconvolution problem. If we know $V_{out}(t)$ -- what is $V_{in}(t)$ or h(t) ?

When using oscilloscopes to measure pulse waveforms, our observable is always the displayed waveform, $V_{out}(t)$. What we really want to know is the actual input signal, $V_{in}(t)$. $V_{out}(t)$ is the convolution of $V_{in}(t)$ with the oscilloscope's impulse response h(t). To determine $V_{in}(t)$ from the observable $V_{out}(t)$, we thus need to 'deconvolve' out the oscilloscope's impulse response, h(t). The process to accomplish this is described in detail in PSPL's application note, AN-18 [6]. MatLab programs for performing deconvolution are available from PSPL's web site: www.picosecond.com.

The step response, impulse response, and frequency response are directly related. The step response is the integral of the impulse response. The frequency response of the oscilloscope is found by taking the Fast Fourier Transform (FFT) of the impulse response.

RISETIME TRANSFER STANDARD

To transfer the PTB calibration traceability from the SE-70 sampler to other oscilloscope samplers, we need to use a fast pulse generator as our transfer standard. The generator used was PSPL's fastest, model 4016, which produced a -5 V, 5 ps falltime, step pulse. The -5 V pulse was too large to apply directly to any sampling head. It was attenuated to the - 1/2 V level using a PSPL model 5510V-20dB attenuator. The -1/2 V, 4016 pulse was measured with the PTB calibrated 9043/SE-70, and the sampler's step/impulse response was deconvolved using the PSPL MatLab program, *GoldSE70decon.m* to obtain the true pulse waveform from the 4016. The deconvolved waveform is shown in Figures 2 and 3 and the spectral content in Figure 4.

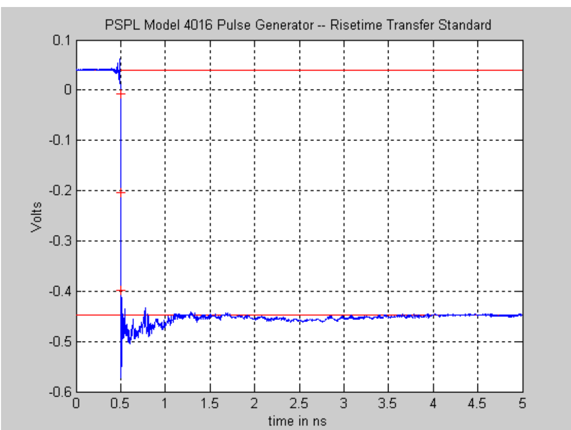

Fig. 2 PSPL model 4016 Pulse Generator, Risetime Transfer Standard, -1/2 V, 5 ps falltime, 500 ps/div, 5 ns time window

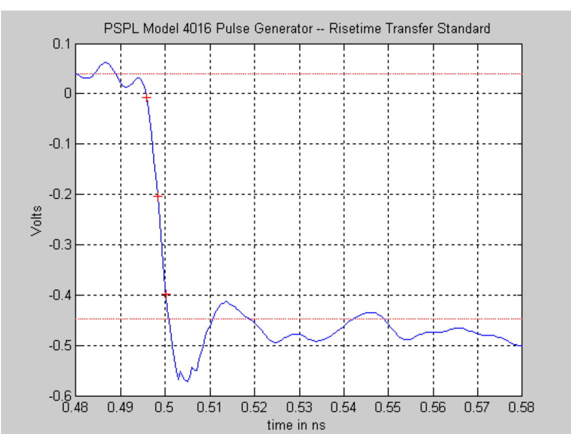

Fig. 3 PSPL model 4016 Pulse Generator, Risetime Transfer Standard, -1/2 V, 5 ps falltime, 10 ps/div, 100 ps time window

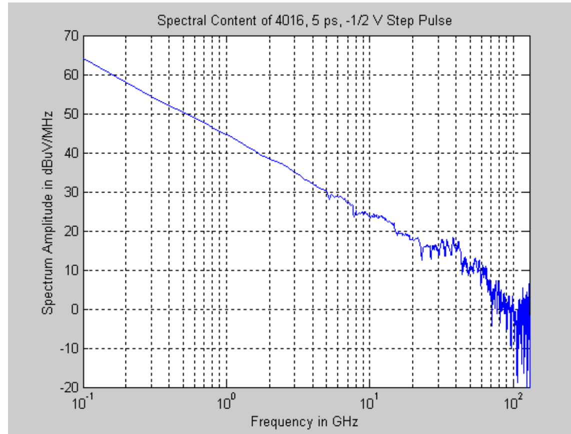

Fig. 4 Spectral Content of 4016 Step Pulse

This 4016 pulse generator was then used to measure and calibrate all of PSPL's numerous oscilloscope sampling heads from Tektronix, Hewlett-Packard, Agilent, and PSPL / LeCroy.

OSCILLOSCOPE MEASUREMENTS

Oscilloscope settings were standardized. Vertical settings were: 100 mV/div, 200 mV offset, and 128 signal averages were taken. Trigger controls were adjusted for minimum jitter. The timing jitter was measured and recorded. Delay was adjusted to position the leading edge of the 4016 pulse 500 ps in from the left side of the screen. Data were taken for a 5 ns time window with a sample spacing of 0.5 ps, 0.6, or 0.63 ps (depending upon the scope), and a total number of data points of 8,000 to 10,000. For the Tektronix, Hewlett-Packard, and Agilent oscilloscopes, they did not have sufficient memory depth, and multiple waveform acquisitions were required with smaller time windows, and then suitable increasing delays to fill out the desired 5 ns time window. The waveform data from the oscilloscope were downloaded and stored on an external computer for later data processing.

DATA PROCESSING

All measured waveforms were standardized using PSPL's MatLab program, *WaveModifyV4.m*, to a sample spacing of dt = 0.5 ps and total data points N = 10,000 for a total time window of Tw = 5 ns.

The next step was to remove the effects of jitter from the signal averaged waveforms. The presence of timing jitter distorts oscilloscope measurements. When signal averaging is used on a time jittered signal, it has the effect of introducing an additional low pass filter. For details, see the PSPL application note, AN-23 [7]. All measured waveforms were first processed with PSPL's MatLab program, *JitterDeconV12.m*, to remove the jitter.

The final step was to deconvolve the 4016 input waveform, $V_{in}(t)$, and the measured output waveform, $V_{out}(t)$, to determine h(t) and the step response. This was done using PSPL's MatLab program, *HdeconV33.m*. The Noise Floor Filter was used for deconvolution, with a cutoff frequency of 80 GHz to 130 GHz, depending upon the sampler under test. The step responses were all normalized to an amplitude of 1. The impulse response, h(t), was obtained as the derivative of the step response. The PSPL MatLab program, *PulseMeasV31.m*, was used to provide the waveform plots and to determine the various pulse parameters such as risetime, overshoot, impulse duration, etc. The PSPL MatLab program, *SpecAnalysisV22.m*, was used to determine the frequency response from h(t).

The figures on the following pages show for each of the tested sampling heads, the deconvolved Step Response (100 or 200 ps time window), Step Response Topline (5 ns time window), Impulse Response (100 or 200 ps time window), and Frequency Response. The frequency response plots were smoothed (except for Figure 5) to remove some of the noise introduced in the deconvolution process. The key performance parameters of step response risetime (10-90%), step response overshoot, impulse response duration (fwhm, 50%), bandwidth (-3 dB), and risetime * bandwidth product are listed with each figure.

OSCILLOSCOPES TESTED

The following oscilloscope sampling heads were tested:

Mfgr	Model #	Bandwidth Spec
PSPL/Lecroy	SE-100	100 GHz
PSPL/LeCroy	SE-70	70 GHz
PSPL/LeCroy	SE-50	50 GHz
PSPL/LeCroy	ST-20	20 GHz
Tektronix	80E06	70+ GHz
Tektronix	80E01	50 GHz
Agilent	86118A	70/50 GHz
Agilent	83484A	50/26.5 GHz
Agilent	86109A	40/18 GHz
Agilent	54754A	18/12.4 GHz

Note: PSPL designed and builds the LeCroy samplers on an OEM basis.

Detailed specs for these various samplers are available from the manufacturer's web sites: www.lecroy.com, www.tek.com, and www.agilent.com.

CONCLUSIONS

1. The fastest risetime was the PSPL SE-70 Gold Standard Sampling Head at 4.7 ps [5].
2. All samplers essentially meet their bandwidth specifications.
3. The highest bandwidth samplers were the PSPL/LeCroy SE-70 & SE-100 with > 100 GHz, -3 dB bandwidths.
4. The Tektronix samplers had the flattest step responses.
5. The PSPL/LeCroy and Agilent samplers had similar long term step response rollups in the 200 ps to 5 ns region.
6. The Tektronix 80E06, 70 GHz sampler had the most overshoot at 20%.
7. The Gaussian Risetime * Bandwidth = 0.35 relationship is valid for some samplers, but not all.

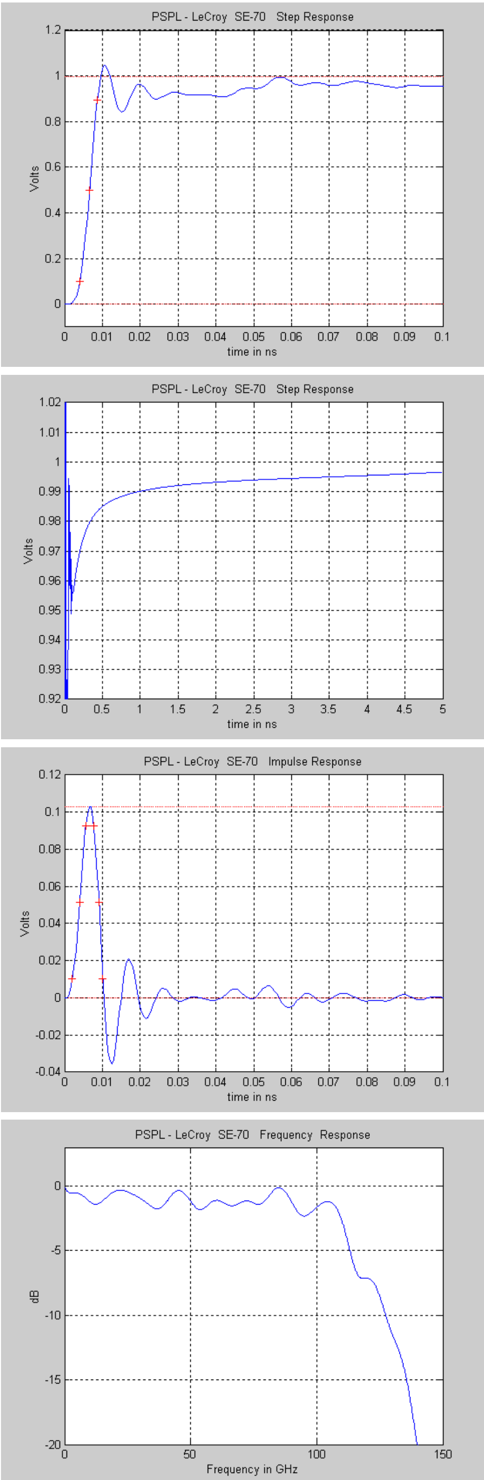

Fig. 5 PSPL - LeCroy SE-70 Sampler
(from PTB calibration, see AN-26 [5])
Trise = 4.7 ps, OS = 5%, fwhm = 5.1 ps
BW(-3dB) = 110 GHz, Tr*BW = 0.51

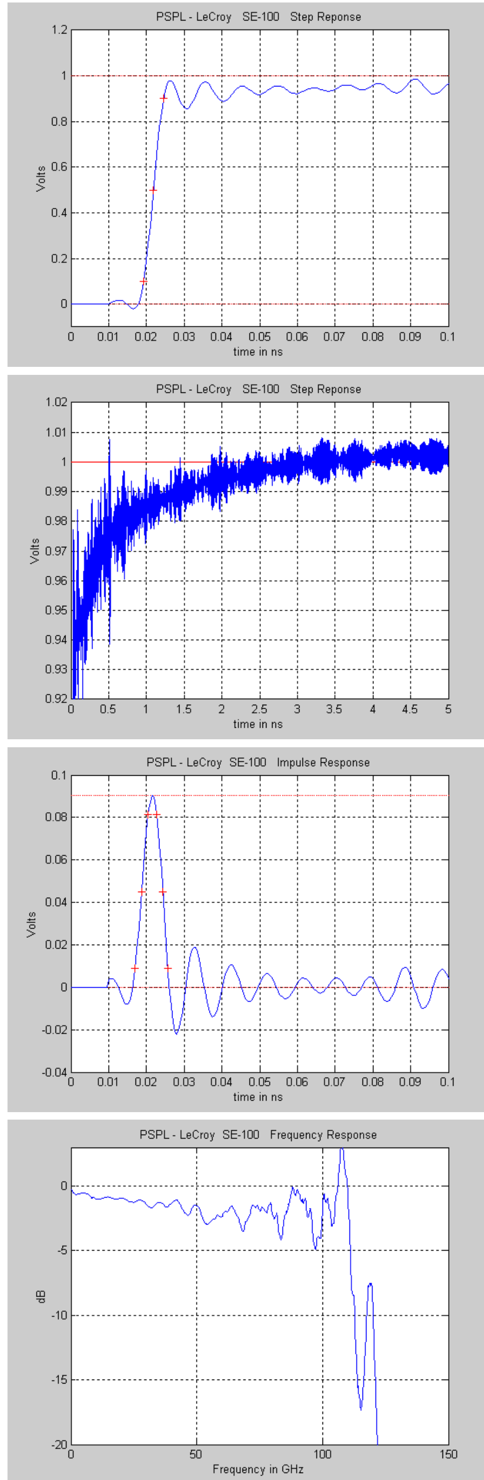

Fig. 6 PSPL - LeCroy SE-100 Sampler
Trise = 5.3 ps, OS = none, fwhm = 5.6 ps
BW(-3dB) = 110 GHz, Tr*BW = 0.53

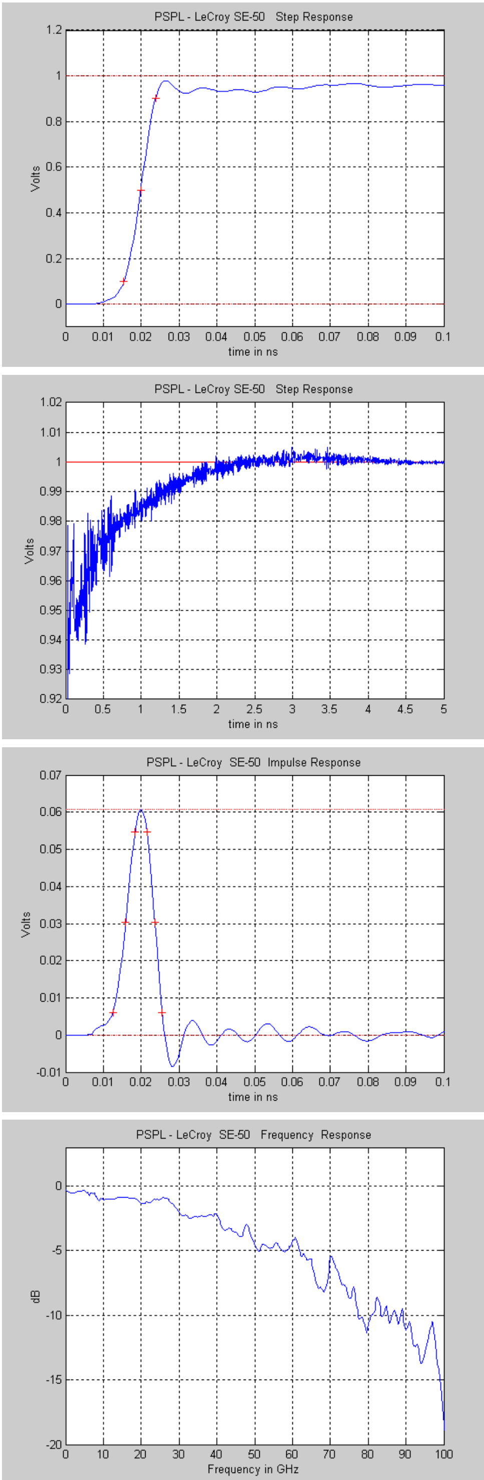

Fig. 7 PSPL - LeCroy SE-50 Sampler
Trise = 8.4 ps, OS = none, fwhm = 7.8 ps
BW(-3dB) = 45 GHz, Tr*BW = 0.38

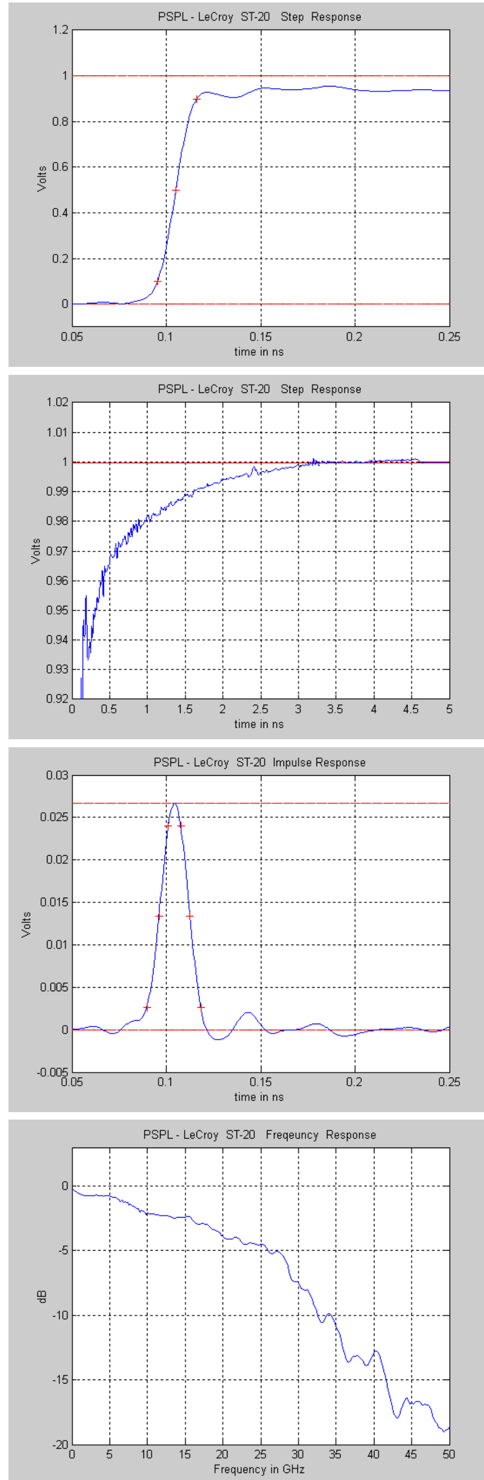

Fig. 8 PSPL - LeCroy ST-20 Sampler
Trise = 20.7 ps, OS = none, fwhm = 16.5 ps
BW(-3dB) = 18 GHz, Tr*BW = 0.37

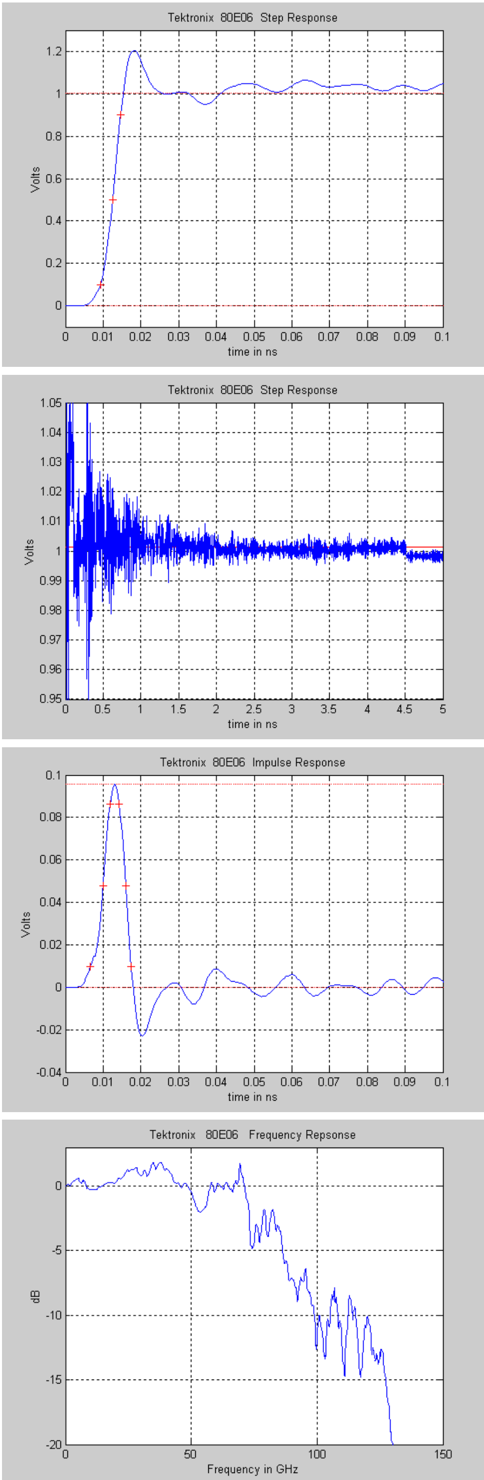

Fig. 9 TEK 80E06 - 70 GHz Sampler
Trise = 5.4 ps, OS = 20.4%, fwhm = 6.1 ps
BW(-3 dB) = 72 GHz, Tr*BW = 0.39

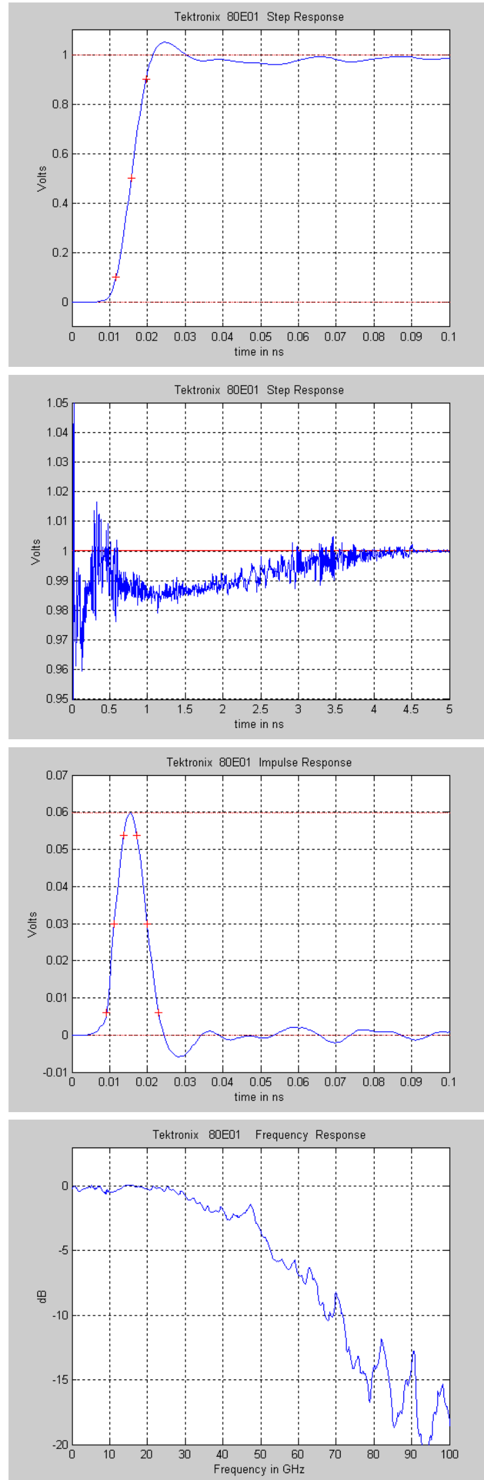

Fig. 10 TEK 80E01 - 50 GHz Sampler
Trise = 7.9 ps, OS = 5.1%, fwhm = 8.8 ps
BW(-3 dB) = 49 GHz, Tr*BW = 0.39

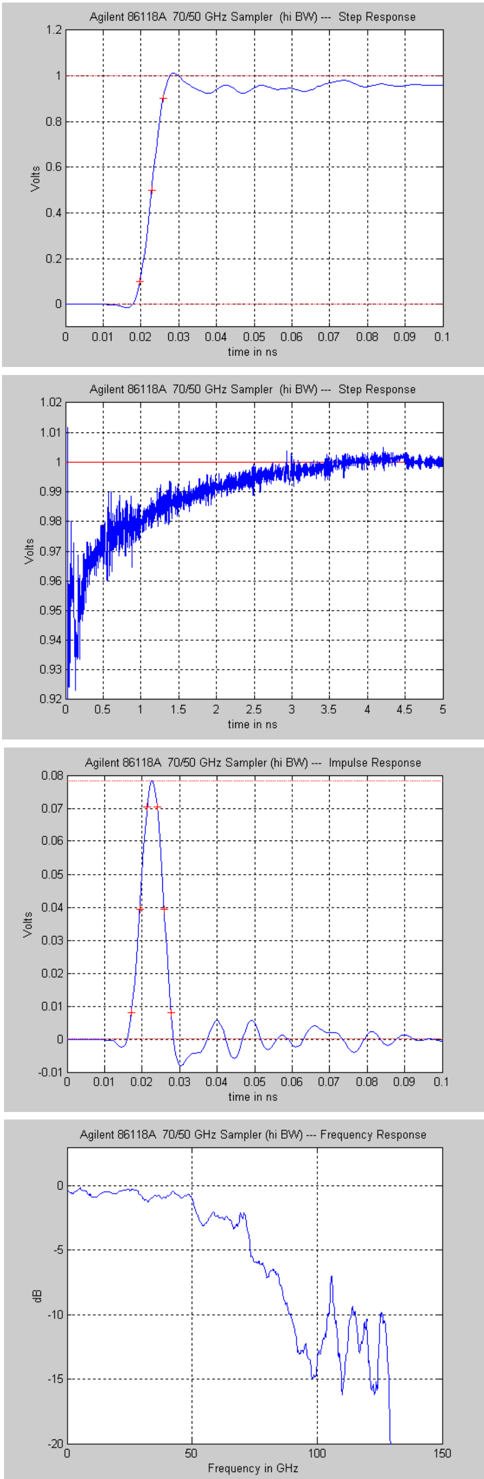

Fig. 11 Agilent 86118A - 70/50 GHz Sampler
high bandwidth setting
Trise = 6.1 ps, OS = 1%, fwhm = 6.5 ps
BW(-3dB) = 70 GHz, Tr*BW = 0.43

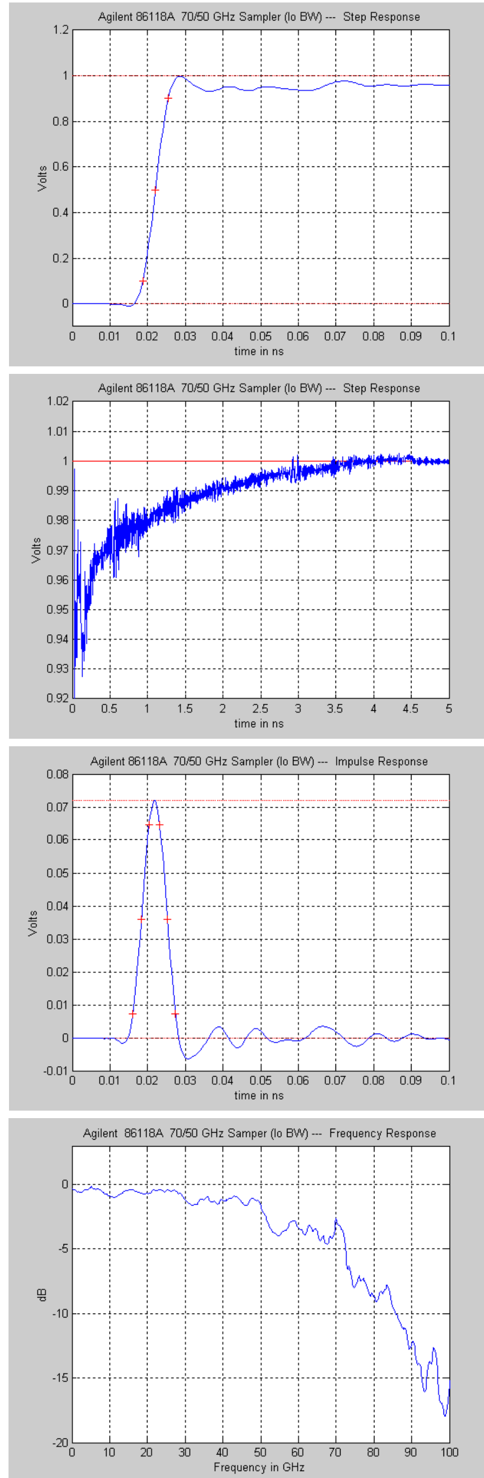

Fig. 12 Agilent 86118A - 70/50 GHz Sampler
low bandwidth setting
Trise = 6.7 ps, OS = none, fwhm = 7.0 ps
BW(-3dB) = 52 GHz, Tr*BW = 0.35

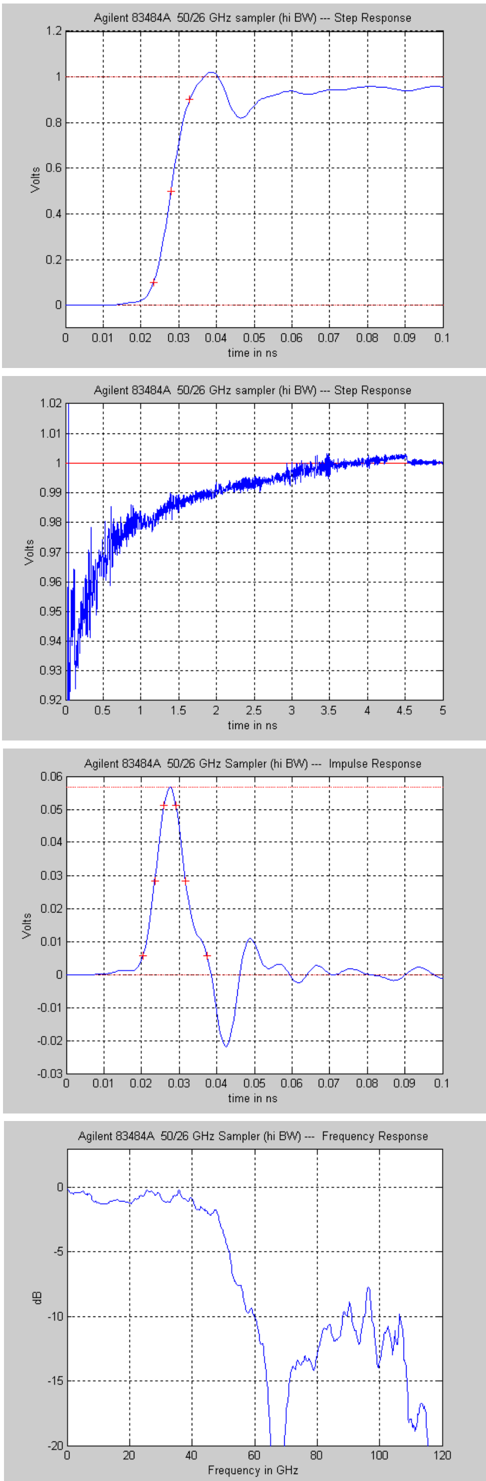

Fig. 13 Agilent 83484A - 50/26 GHz Sampler
high bandwidth setting
Trise = 9.5 ps, OS = 2.1%, fwhm = 8.2 ps
BW(-3dB) = 49 GHz, Tr*BW = 0.47

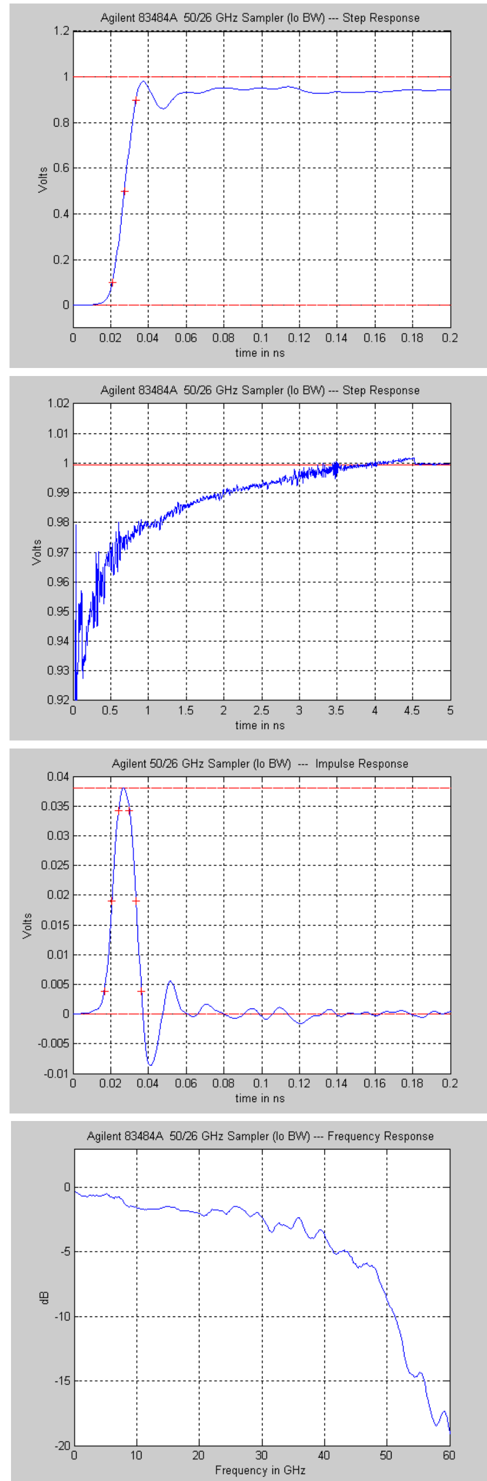

Fig. 14 Agilent 83484A - 50/26 GHz Sampler
low bandwidth setting
Trise = 12.5 ps, OS = none, fwhm = 12.9 ps
BW(-3dB) = 31 GHz, Tr*BW = 0.39

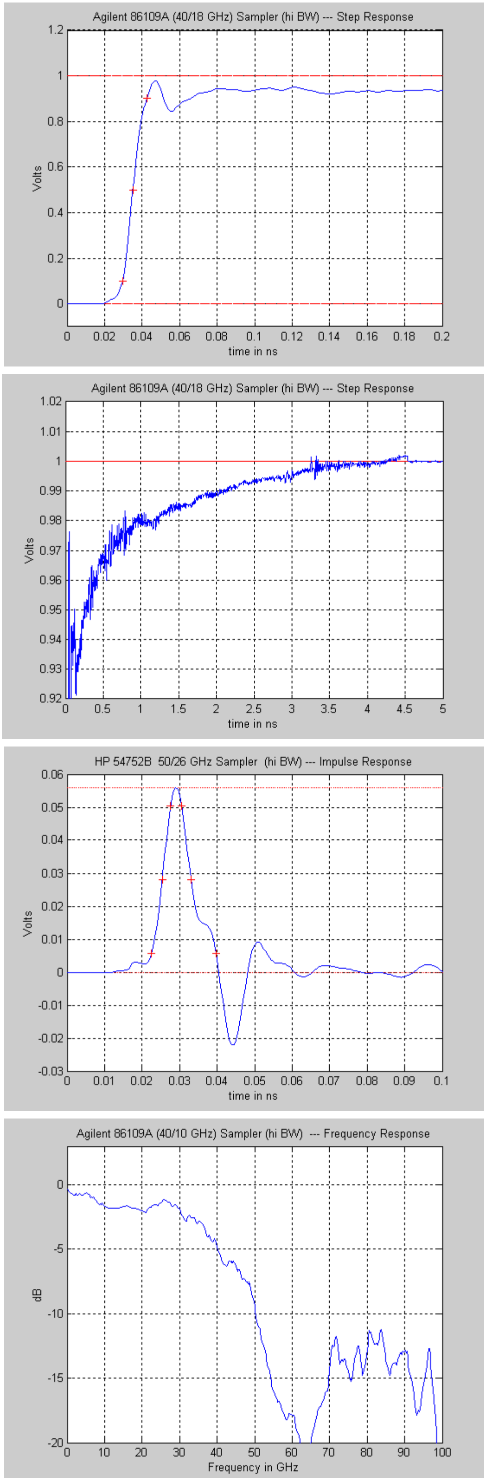

Fig. 15 Agilent 86109A - 40/18 GHz Sampler
high bandwidth setting
Trise = 13 ps, OS = none, fwhm = 9.7 ps
BW(-3dB) = 37 GHz, Tr*BW = 0.48

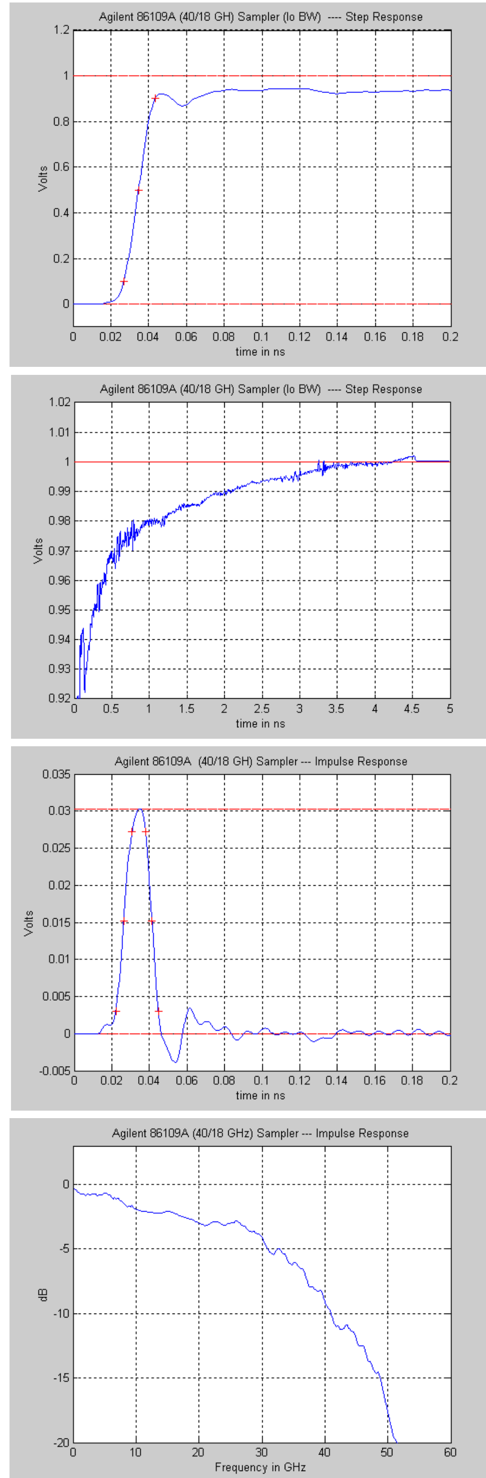

Fig. 16 Agilent 86109A - 40/18 GHz Sampler
low bandwidth setting
Trise = 16.6 ps, OS = none, fwhm = 15.1 ps
BW(-3dB) = 27 GHz, Tr*BW = 0.45

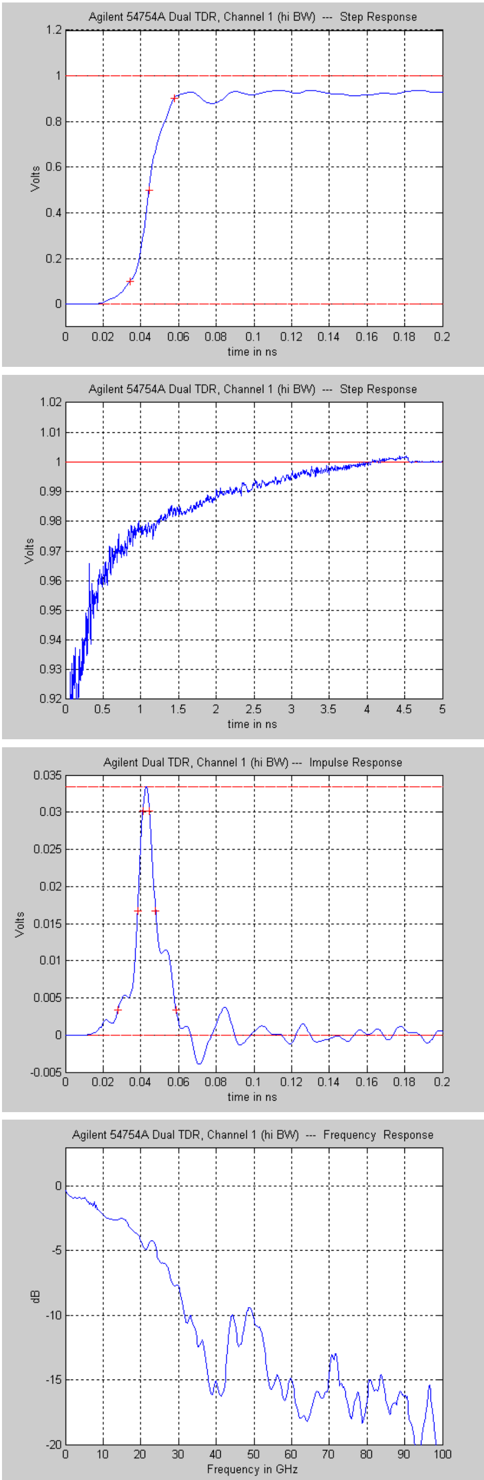

Fig. 17 Agilent 54754A - 18/12 GHz Sampler
high bandwidth setting
Trise = 23.4 ps, OS = none, fwhm = 9.5 ps
BW(-3dB) = 17.5 GHz, Tr*BW = 0.41

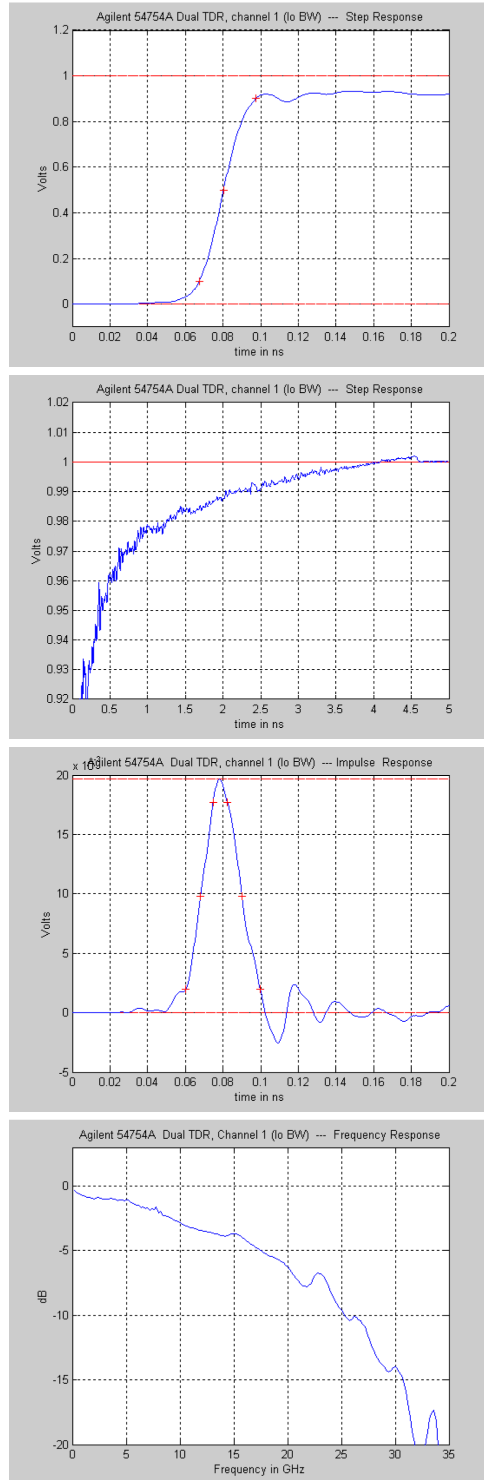

Fig. 18 Agilent 54754A - 18/12 GHz Sampler
low bandwidth setting
Trise = 30.1 ps, OS = none, fwhm = 21.8 ps
BW(-3dB) = 11 GHz, Tr*BW = 0.33

REFERENCES

[1] J.R. Andrews, "Comparison of Ultra-Fast Risetime Sampling Oscilloscopes", Application Notes AN-2a, AN-2b, AN-2c & AN-2d, 1989 thru 2001, Picosecond Pulse Labs, Boulder, CO

[2] National Institute of Standards & Technology (NIST), Calibration service # 65250S for "Repetitive Pulse Waveform Measurements -- Including Settling Parameters" See www.nist.gov

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

[4] 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

[5] J.R. Andrews, "Gold Standard, 4.8 ps, Sampling Oscilloscope Traceable to International Standards Labs", Application Note AN-26, Picosecond Pulse Labs, Boulder, CO, Dec. 2010

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

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

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