

Comparison of Ultra-Fast Risetime 18 to 50 GHz Digital Sampling Oscilloscopes (updated to include new instruments introduced in 2000)

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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 the 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, and in 1998 as AN-2c. In 2000, both Tektronix and Agilent introduced new 50 GHz, digital sampling oscilloscopes. This new AN-2d reviews the new TEK TDS-8000 and the Agilent 86100A oscilloscopes. The results of the previous AN-2s are still valid, and they should be referred to for older model oscilloscopes. The earlier versions of AN-2 are available from PSPL's Web site: www.picosecond.com. Tests performed on all oscilloscopes included risetimes, picosecond domain transient responses, and nanosecond domain settling time responses. This latest AN-2d now also includes 10 Gb/s eye diagram tests.

OSCILLOSCOPES TESTED FOR AN-2d

The high performance (>18 GHz bandwidth), digital sampling oscilloscope market is dominated by Tektronix and Agilent (formerly Hewlett-Packard). Both companies offer bandwidths up to 50 GHz. Both companies call their oscilloscopes also "communications signal analyzers".

Agilent's newest oscilloscope is their model 86100A main frame. This main frame can hold up to two, dual-channel, electrical or optical sampling plug-ins. Agilent did not redesign their electrical sampling plug-ins. The 86100A main frame still uses the plug-ins from their previous 54750 oscilloscope and 83480 communication signal analyzer. Agilent has renamed some of their previous plug-ins with new 861xx series numbers. The specific Agilent instrument tested by PSPL was the 86100A with electrical plug-ins, models 54753A (20/18/12 GHz, TDR) and 83484A (50/26 GHz).

Tektronix's newest oscilloscope is their model TDS-8000 (or CSA-8000) main frame. This main frame can accommodate up to four separate, dual-channel, electrical and two, single channel, optical plug-in sampling heads. Tektronix has totally redesigned their sampling heads. The

TDS-8000 does not support their earlier "SD" series plug-in sampling heads. Their new sampling heads now carry the model number designations of 80Exx and 80Cxx. The specific Tektronix instrument tested by PSPL was the model TDS-8000 with electrical plug-in module models 80E01 (50 GHz), 80E03 (20 GHz) and 80E04 (20 GHz TDR).

Both Tektronix's and Agilent's main frames are now basically personal computers that include a set of electrical and/or optical connectors for high-speed electrical or optical measurements. These new oscilloscope designs use much faster microprocessors and run under a Windows operating system. These new instruments now operate like a personal computer, with operator inputs from either a touch screen, mouse, or keyboard, in addition to a few conventional knobs. They support all normal computer features, including external monitors, laser printers, modems, network connections, etc.

PULSE GENERATORS

For consistency between the various AN-2 application notes, we have continued to test the various oscilloscopes with the same, or similar, pulse generators. For risetime and picosecond domain transient response tests, we have used 15 ps pulse generators. In the 1980s we used an HP-1106A tunnel diode pulser. PSPL's model TD1107 is a direct replacement for the discontinued HP-1106. Since 1994, we have used a PSPL model 4015 pulse generator. For nanosecond domain settling time tests, we have used a PSPL model 6110 reference flat pulse generator. Starting with this application note, we have included testing with a 10 Gb/s pulse pattern generator.

15 ps Pulser The PSPL model 4015C produces a -9 V, 15 ps falltime step pulse. For these tests the -9 V pulse was attenuated by 26 dB down to 450 mV, using PSPL model 5510K attenuators. The particular 4015C pulser and attenuators used for these tests were recently calibrated in the UK by the National Physical Lab (NPL). This was PSPL's primary, "gold", transfer standard, s/n 169. NPL reported the 10%-90% falltime of the attenuated pulse to be 15.3 ps, as measured in a 500 ps time

window (50 ps/div), Figure 1. NPL reported the pulse amplitude to be 457 mV, as measured in a 5 ns time window. The overshoot was 10%. Details regarding NPL's risetime calibration service are found in references [1-4]. The deconvolved pulse waveform from NPL, Figure 1, was the reference waveform used to compare the various oscilloscopes' risetimes and picosecond domain transient responses.

Reference Flat Pulse A PSPL model 6110D pulse generator was used to generate a known flat pulse for nanosecond domain, settling time measurements. The design of the model 6110D is based upon an NBS (now NIST) design [5]. It produces a mathematically predictable, very flat, clean, -500 mV step from +500 mV down to 0 V with a falltime of 427 ps and 0.2% overshoot. The pulse settles to 0 V in 3 ns to within <0.2%, and in 10 ns to 0.02%. The particular 6110D used for these tests was recently calibrated by NIST, and these numbers were confirmed. This was PSPL's primary, "gold", transfer standard, s/n 164.

10 Gb/s Pattern An Advantest model D-3186 was used as the test signal source to observe the 10 Gb/s eye pattern response of these oscilloscopes. The 2 V output pulse was attenuated using a PSPL model 5510K-10dB attenuator. This generator puts out very clean pulse waveforms, with 10%-90% risetimes of 27 ps and 90%-10% falltimes of 22 ps.

RISETIMES

Figure 2 shows the 4015C pulse as measured by the Agilent and Tektronix oscilloscopes, using the various plug-in sampling heads. This figure shows the picosecond domain transient response out to 350 ps (50 ps/div). The fine structure in the waveform after the transition was expanded by 5X to allow closer examination. All waveforms were recorded under identical conditions, with signal averaging turned on. To measure the falltimes, we used the automatic pulse parameter measurement features found on both the Tektronix and Agilent scopes. The 0% and 100% levels were determined automatically, using histograms. To provide traceability to NPL's calibration, we measured the falltimes at 50 ps/div, with the waveforms positioned precisely at the same position used by NPL and as shown in Figure 1 (i.e., the transition edge was placed 150 ps in from the left side of the screen). The results are tabulated in Table I. The calculated 10% - 90% risetimes in Table I are from the root-difference-of-squares equation:

$$T_r(\text{calc}) = [T_f^2(\text{meas}) - 15.3 \text{ ps}^2(\text{gen}) - (2.57 * \sigma_{\text{jitter}})^2]^{1/2}$$

The 15.3 ps term is the NPL calibrated falltime of the 4015C pulse generator. The last term accounts for the effects of using signal averaging on a time jittering transition. Signal averaging of jitter is equivalent to adding an additional low-pass filter with a bandwidth of $\text{BW}_{\text{jitter}} = 0.132 / \sigma_{\text{jitter}}$, where σ_{jitter} is the standard deviation of the timing jitter [6].

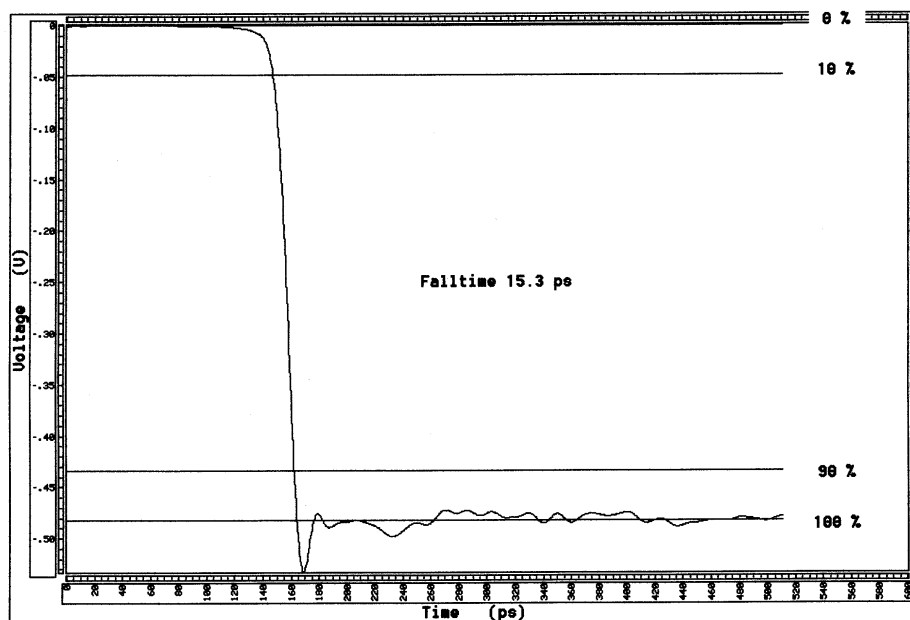


Figure 1

PSPL Model 4015C pulse as calibrated by NPL. The time window is 500 ps.

Table I — Results of Risetime Tests run at PSPL

Mfgr	Sampler Plug-In	Bandwidth Setting	Falltime (meas)	Risetime (calc)
Agilent	83484A	50 GHz	17.9 ps	8.6 ps
		26 GHz	19.0 ps	10.7 ps
Agilent	54753A Ch 2	20 GHz	21.8 ps	15.1 ps
		12 GHz	26.7 ps	21.6 ps
Agilent	54753A Ch 1	18 GHz (TDR)	24.7 ps	19.1 ps
		12 GHz (TDR)	29.1 ps	24.5 ps
TEK	80E01	50 GHz	17.1 ps	6.7 ps
TEK	80E03	20 GHz	22.2 ps	15.7 ps
TEK	80E04	20 GHz (TDR)	22.8 ps	16.5 ps

The Agilent oscilloscope allows a choice of two bandwidth settings. This is accomplished by changing the DC bias applied to the sampling diodes. This feature is not available in the Tektronix oscilloscope. Lowering the bandwidth slows down the risetime and also reduces the sampler vertical noise. Waveforms are not shown for the lower bandwidth settings on the Agilent scope. The waveforms were identical to the high bandwidth settings, except for slower risetimes.

SETTLING TIME

The settling time response of the various samplers was measured using the PSPL model 6110D Reference Flat Pulse Generator. Figure 3 shows the results. The reference pulse was a negative transition from 500 mV to 0 Volts with a 0.2 % overshoot and then settles to 0 V within 0.2% in 2 ns and 0.02% in 4 ns. Figure 3 only shows the greatly expanded oscilloscope settling waveforms to the 0 V level at a vertical scale of 0.5% / div and a horizontal scale of 5 ns/div. All three of the TEK samplers settle to within $\pm 0.1\%$ within < 5 ns. All three of the Agilent samplers have a similar settling characteristic. Their response is typically about 1% too low and then takes an additional 40 ns to monotonically settle to within $\pm 0.1\%$.

PS to NS DOMAIN TRANSIENT RESPONSES

The NPL risetime calibration covered the time epoch for the first 350 ps. The NIST settling time calibration covered the time epoch for times greater than 2 ns. To bridge the gap between 350 ps and 2 ns, an additional set of tests was performed on these various samplers, using a 100 MHz square wave from the Advantest D3186 pattern generator. Figure 4 shows the results taken at a time scale of 500 ps/div over a time window of 5 ns. This test bridges the gap from the picosecond domain to the short nanosecond domain. The topline was expanded 10X to allow closer examination of the fine structure. The TEK samplers all show overshoot, while the Agilent samplers all show a slow roll-up.

10 Gb/s EYE DIAGRAMS

A very common use today of these sampling oscilloscopes is to measure 10 Gb/s telecommunication system signals. The most common measurement is the eye diagram. Figure 5 shows the eye diagrams of these samplers when tested with a 10 Gb/s, $2^{11} - 1$, PRBS signal. Identical test conditions were used. Color graded, infinite displays were selected. Data was acquired for 30 seconds. For best viewing of Figure 5 in color, we suggest you view it from PSPL's Web site: www.picosecond.com.

SAMPLER CONCLUSIONS

In general, the main observation is that the Agilent samplers all have a 1% to 1.2% slow rollup in their step responses and take 40 ns to reach their correct, final value. The TEK samplers all have 4% overshoot but settle rapidly within 2 ns to their correct, final value. The risetimes reported here in Table I compare favorably with the risetimes claimed by the manufacturers. Due to risetime/bandwidth limitations, none of the samplers were able to reproduce the 4015 pulser's 10% overshoot (Figure 1).

TEK 80E01 (50 GHz) This sampler has a 7 ps risetime. Its ps domain ($t < 300$ ps) transient response tracked very close to the NPL calibration. For times less than 500 ps, it has an excessive overshoot of 4 %, but it then has a settling time to $< 0.2\%$ in 2 ns. In the long term (5 ns - 400 ns), it has a $\pm 0.15\%$ settling time ripple.

Agilent 83484A (50 GHz) This sampler has a 9 ps risetime. This is very close to the 9.4 ps reported in ref [7] for the HP-54124A, 50 GHz sampler, which was calibrated by HP using the "nose-to-nose" technique. Like the TEK 80E01, this sampler's ps domain ($t < 300$ ps) transient response tracked very close to the NPL calibration. This sampler's major error is a slow rollup settling time. For times in the ps domain and few ns, its response is -1% too low. It takes 40 ns to settle to within $< \pm 0.1\%$

TEK 80E03 (20 GHz) This sampler has a 16 ps risetime. For times less than 100 ps, its response seems to be 4% high. At 500 ps, it has an overshoot of 1.2%, but it then has a settling time to $< 0.2\%$ in 2 ns. After 2 ns, it shows $< \pm 0.1\%$ ripple.

Agilent 54753A (20 GHz) This is the sampling channel without the TDR pulser. It had a risetime of 15 ps. Except for the slower risetime, its settling response is essentially identical to the Agilent 50 GHz sampler discussed above. The leading edge step response (see Figure 5 @ 20 ps/div) is different than seen on other samplers. It is quite fast in the center region, but the foot

on the leading edge rises slowly, and likewise there is then a slow roll-up toward the 100% level. This causes the 10 Gb/s eye diagram to have an almost circular appearance.

TEK 80E04 (TDR 20 GHz) This sampler has a 17 ps risetime. This sampler had the most noticeable defect in its ps domain response of all the samplers tested. This was a large +6.5% bump located 80 ps after the leading edge of the pulse. It is surmised that this bump is due to an internal reflection between the sampler and the TDR pulser circuitry. The 10 Gb/s eye diagram of this sampler was deemed unacceptable due to this reflection. This sampler would be acceptable for eye diagram testing at 2.5 Gb/s and lower, but not at 10 Gb/s. With the exception of the +6.5% bump, the transient and settling time responses of this sampler were identical to the 80E03.
Note: After observing the unacceptable 10 Gb/s eye diagram, PSPL has been in correspondence with Tektronix's sampler design engineers to call their attention to the problem. The Tektronix engineers have since informed PSPL that they are working on a solution to remedy this defect. Thus, this defect may not be present in future production 80E04 TDR samplers.

Agilent 54753A (TDR 18 GHz) This sampler includes a built-in TDR pulser. It has a 19 ps risetime. Except for the slower risetime, its response is identical to the Agilent 20 GHz sampler discussed above.

OTHER TESTS

PSPL also performed several other tests on these oscilloscopes. They included checking the time base calibration, trigger jitter, input impedance, vertical noise, DC voltage calibration, and low frequency square wave response. In most cases the scopes performed far better than specified by the manufacturers. The digital time bases in both of these scopes were extremely accurate for all times from ps to ms. Even on the very fast 10 ps/div sweep, errors were typically less than 1 ps in 100 ps. For ns and μ s sweeps, the accuracies were found to be better than 0.2%. Both scopes include two trigger circuits: a direct DC-coupled trigger and a pre-scaler. Agilent's trigger is rated for operation from DC to 2.5 GHz direct and to 12 GHz with the pre-scaler. Tektronix's trigger is rated for operation from DC to 3 GHz direct and to 10 GHz with the pre-scaler. Table II lists the measured jitters under several test conditions. For the particular scopes tested, the Agilent triggered up to 2.5 GHz direct and 15 GHz with the prescaler, while the TEK triggered up to 5 GHz direct and 13 GHz with the prescaler. Tektronix's prescaler caused some "kick-out" from its input connector, which caused some distortion onto the signal under test. This "kick-out" was not observed on the Agilent scope.

TABLE II — Timing Jitter Performance

Trigger Signal Test Conditions	Trigger Mode	Agilent 86100A	Tektronix TDS-8000
-400mV pulse 100ps fall 100 kHz	Direct	1.03 ps rms	1.11 ps rms
2 GHz sine wave, 300 mVptp	Direct	0.94 ps rms	1.00 ps rms
10 GHz sine wave, 300 mVptp	Pre-Scaler	0.85 ps rms	1.00 ps rms

Table III lists the measured vertical noise for each sampler tested. They all had input resistances very close to 50 Ω , within $\pm 0.5 \Omega$. These new scopes are extremely accurate DC voltmeters, especially for ΔV measurements. The major error source in both scopes is a thermally sensitive, vertical DC offset. Performing the "Vertical Calibration" menu operation virtually eliminates this DC offset error. The square wave response was also tested from 5 MHz to 100 Hz. The Agilent scope had a perfect square wave response when it was operated in the signal averaged "best flatness" mode. If it was operated in the "live" no signal averaging mode or the signal average "best throughput" mode, then errors as large as 2% occurred. They were particularly noticeable for 100 kHz square waves. The Tektronix scope had a perfect square wave response operating in either the "live" mode or signal averaged mode. The Tektronix scope, however, was found to have a unique problem for sweep speeds slower than 10 μ s/div. The data display rate on the screen very dramatically slowed down for slower speed sweeps and was deemed unusable. This effect was not noted on the Agilent scope.

TABLE III — Sampler Vertical Noise

Tektronix Samplers	Noise (rms)	Agilent Samplers	Noise (rms)
80E01 (50 GHz)	2.0 mV	83484A (50 GHz)	1.2 mV
80E03 (20 GHz)	620 μ V	(26 GHz)	600 μ V
80E04 (TDR)	560 μ V	54753A (20 GHz)	580 μ V
		(12 GHz)	250 μ V

AGILENT 86100A

This is Agilent's replacement for the 54750 and 83480 series of scopes. It still uses the same sampler plug-ins. Thus, the risetimes and settling performances did not change in the new main frame. The major changes were increased microprocessor speed and a Windows operating system. One key capability found in the Agilent scopes that is not in the Tektronix scopes is the ability to do normalization (i.e., deconvolution) of TDR and TDT measurements. The built-in TDR pulser in the Agilent 54753A and 54754A TDR plug-ins has a relatively slow 33 ps risetime. However, by using their normalization software, the effective TDR/TDT risetimes can be enhanced down to 20 ps. If the PSPL 4015C, 15 ps pulse

generator is used with this scope, then normalized TDR and TDT risetimes down to 10 ps can be obtained. Details are found in PSPL's application note, AN-5c [8 & 9]. An objection to Agilent's present TDR software (version A.02.01) is that it does not allow the use of the automated pulse parameter measurements when in the TDR/TDT mode, except for rise/falltime.

TEKTRONIX TDS-8000

This is Tektronix's replacement for the 11,800 series oscilloscopes. Like the Agilent 86100A, the TDS-8000 uses a faster microprocessor and Windows operating system. Both companies' oscilloscopes are similar and include a large array of firmware features. A major advantage that Tektronix has historically had over HP (now Agilent) is the very small size of their sampling heads. For measuring ultra-fast risetime electrical pulses, this is a very distinct advantage. It allows the user to move the TEK sampler on an extender cable to the pulse source. When one is forced to carry a fast pulse from a remote location to an oscilloscope main frame, a coax cable must be used. Picosecond pulses are distorted and slowed down whenever they are transported over even the shortest possible coax cables. For examples, see PSPL AN-3a [10]. Locating the samplers within the oscilloscope's mainframe is not an issue when measuring optical pulse signals. The bandwidth limitations of single mode optical fiber is not a consideration for the short distances encountered in a lab bench test setup. A major shortcoming in the Tektronix scope is the lack of TDR/TDT normalization capability. Tektronix's built-in TDR pulser is faster than Agilent's. It has a risetime of 27 ps.

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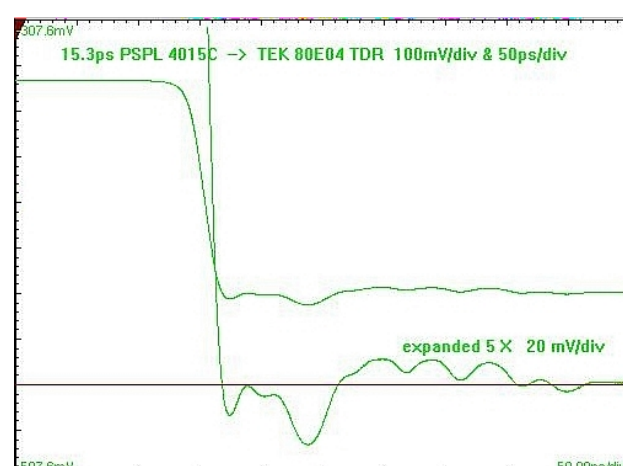
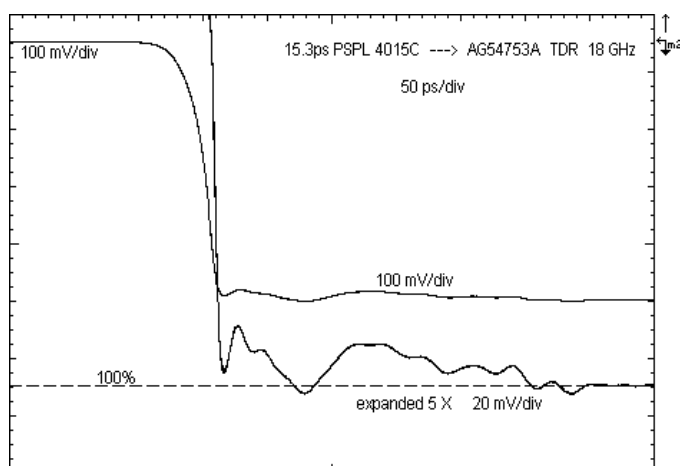
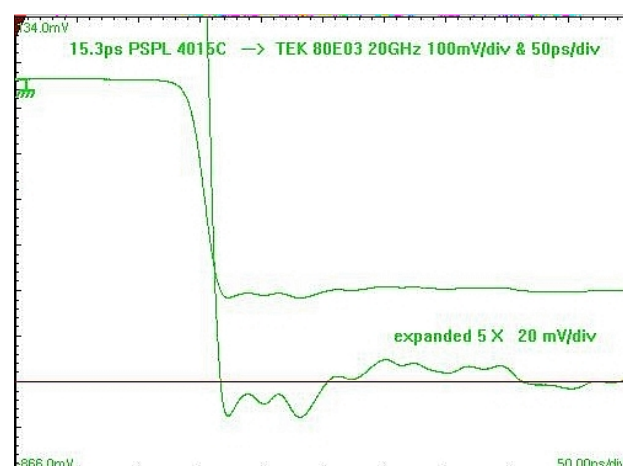
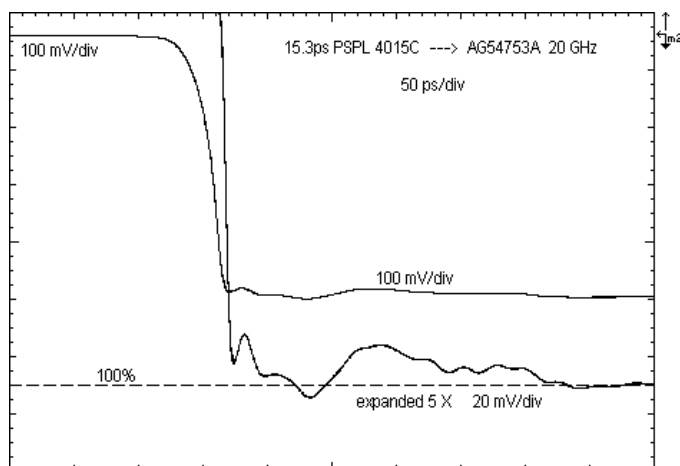
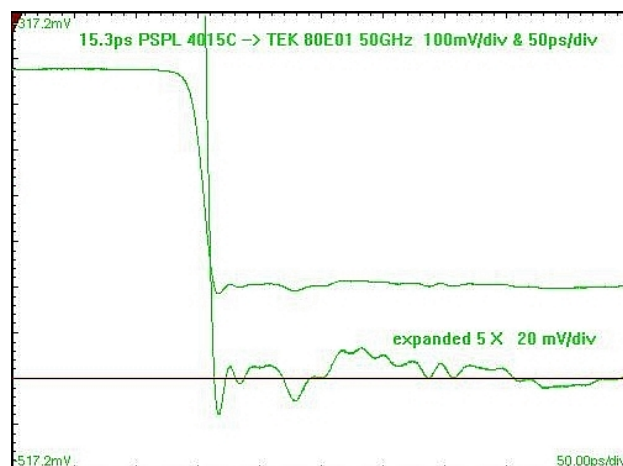
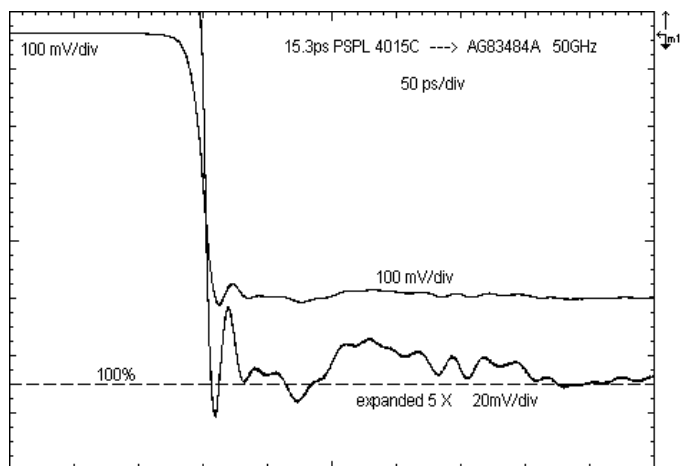


Figure 2

Risetime and ps transient responses of various Agilent and Tektronix samplers when driven by the PSPL Model 4015C, 15.3 ps falltime, pulse generator. 500 ps time window @ 50 ps/div. Vertical scales are 100 mV/div and expanded 5X to 20 mV/div.

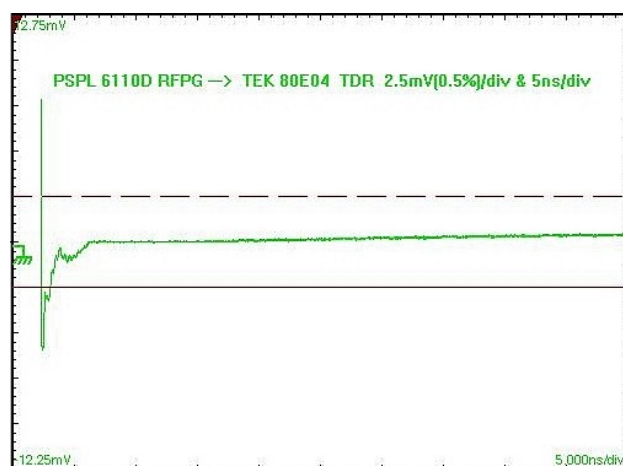
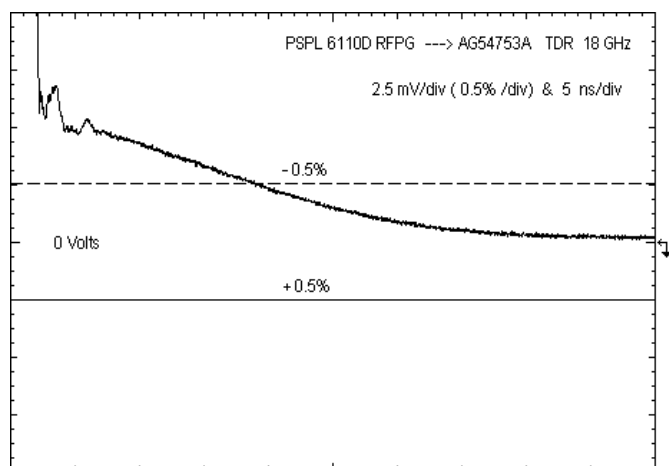
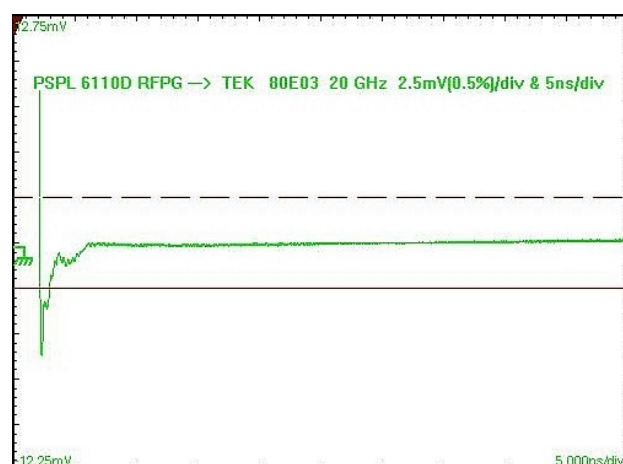
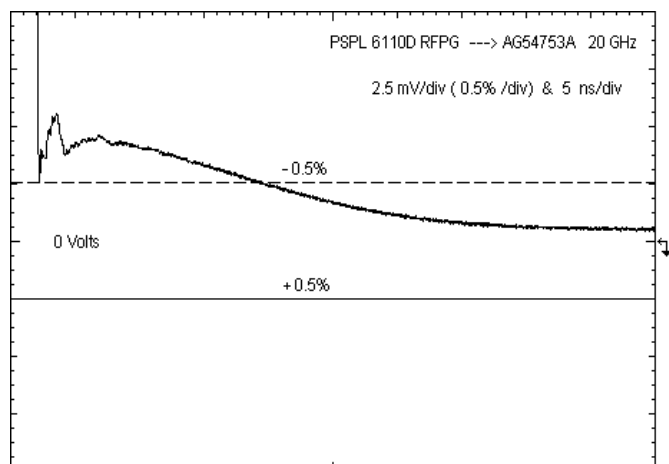
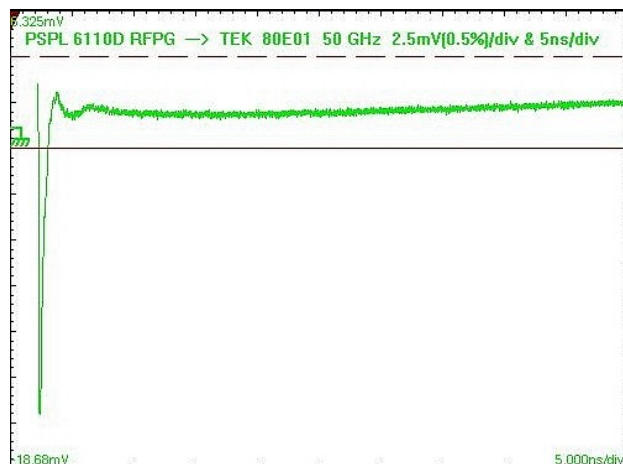
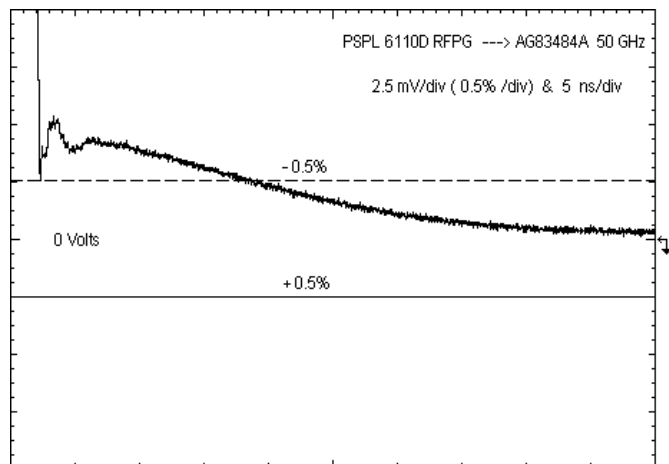


Figure 3

Settling time responses of various Agilent and Tektronix samplers.
Reference flat pulse from PSPL Model 6110D pulse generator. Vertical scale is 0.5%/div.
Horizontal scale is 5 ns/div. The horizontal cursers are at -0.5% and +0.5% levels.

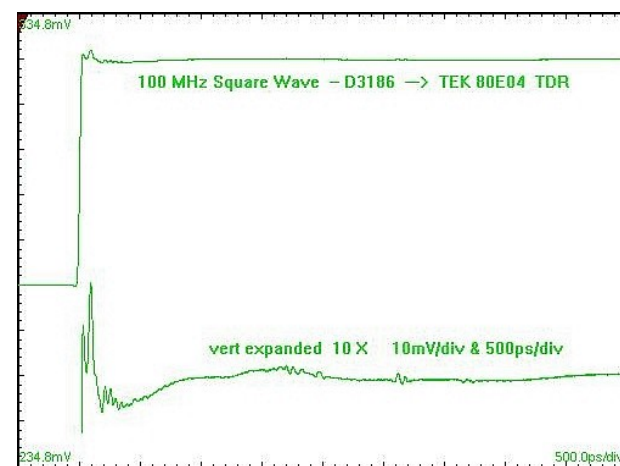
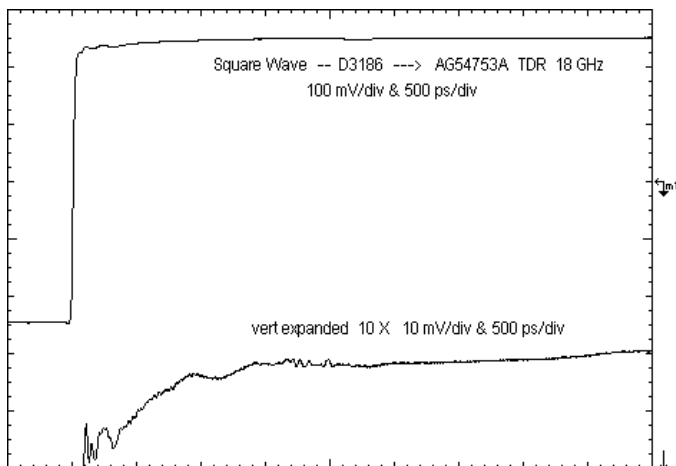
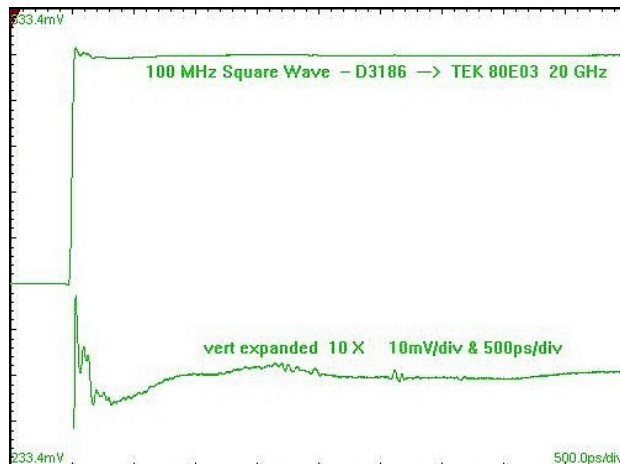
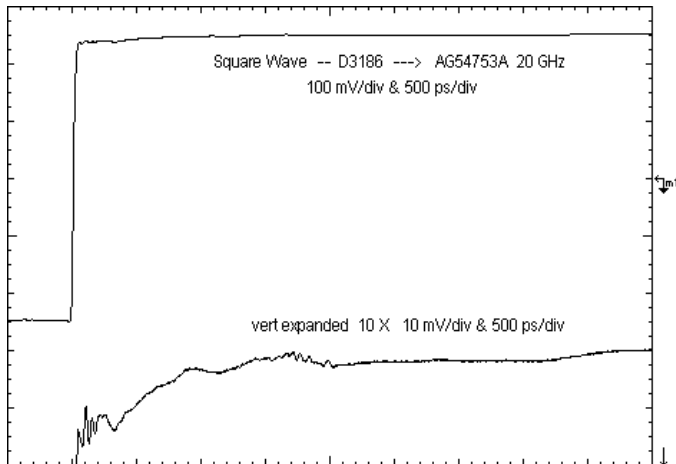
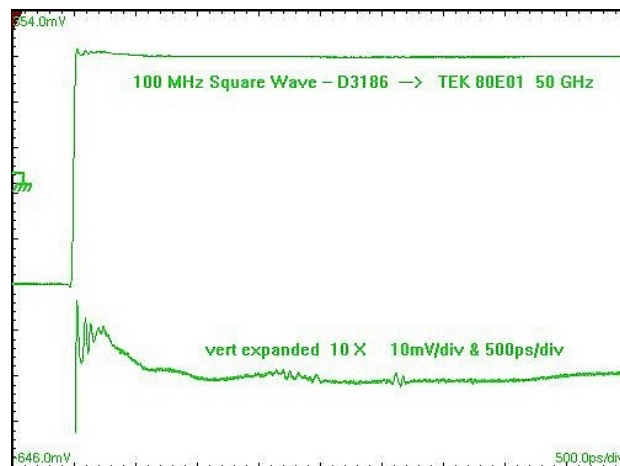
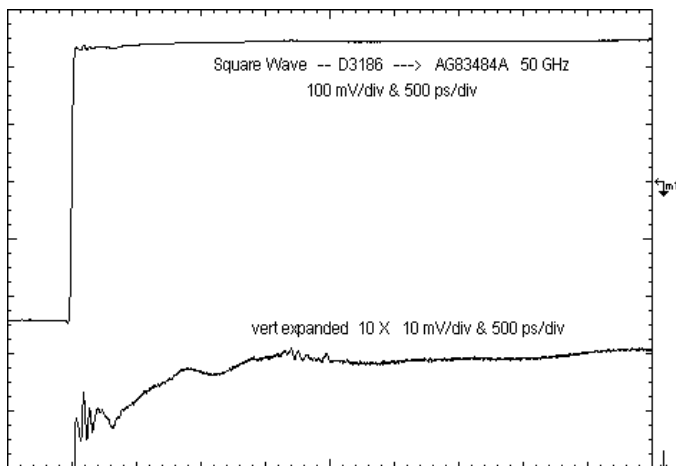


Figure 4

Pulse response of various Agilent and Tektronix samplers
when driven by a 100 MHz square wave from an Advantest model D-3186 pattern generator. 500 ps/div.
Vertical scales are 100 mV/div and expanded 10X to 10 mV/div.

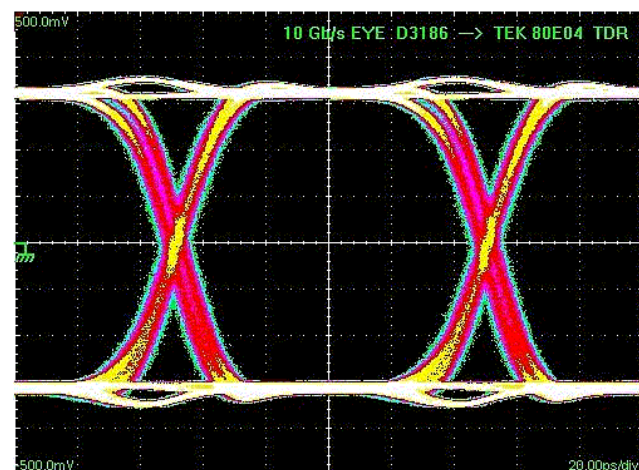
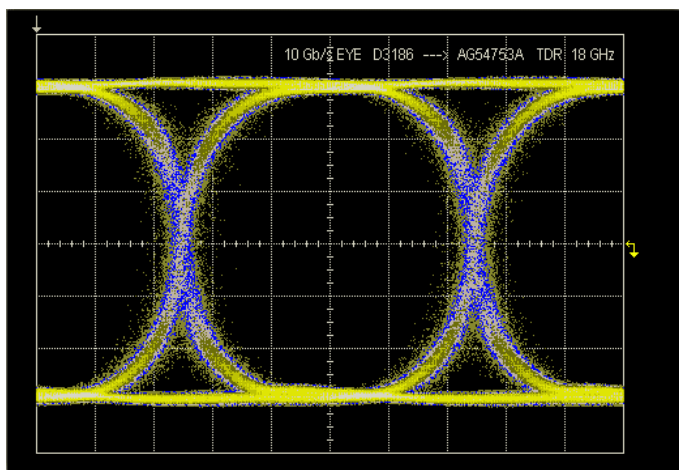
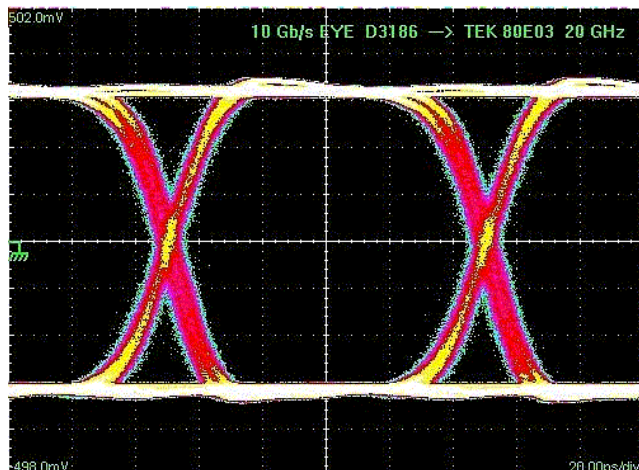
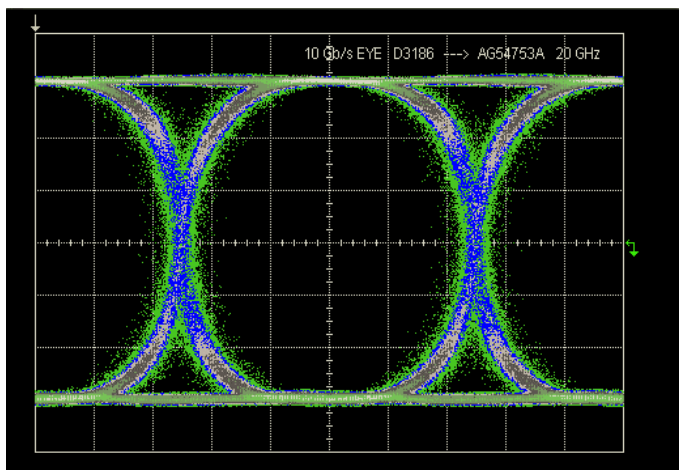
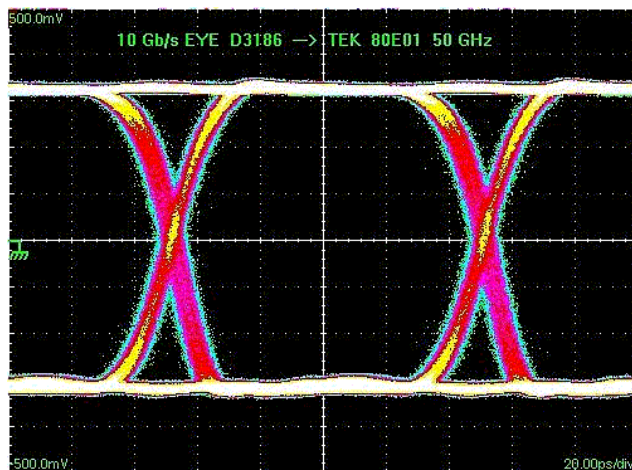
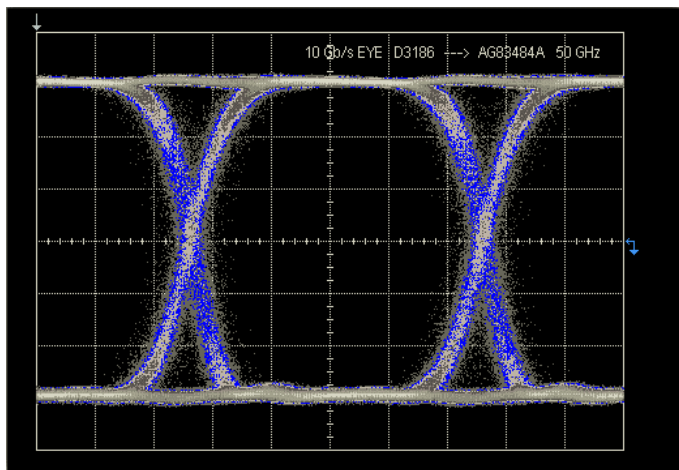


Figure 5

10 Gb/s eye diagrams of various Agilent and Tektronix samplers.
100 mV/div and 20 ps/div. Color-graded displays.