Picosecond Pulse Labs

Application Note AN-2c

Comparison of Ultra-Fast Risetime, 18 to 50 GHz Digital Sampling Oscilloscopes

James R. Andrews, Ph.D., IEEE Fellow

Starting in 1986, 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 and in 1994 as AN-2b. This new AN-2c now updates AN-2b with additional data on the HP-54750 digital oscilloscopes introduced since 1994. The results of AN-2, AN-2a, and AN-2b are still valid, and they should still be referred to for older model oscilloscopes. Included in the tests performed and reported by PSPL are measurements of the risetimes, picosecond domain transient responses, and nanosecond domain settling time responses. Starting with AN-2b in 1994, a faster 12 ps pulse generator was used for risetime testing.

OSCILLOSCOPES TESTED FOR AN-2c

The high performance, >12 GHz bandwidth, digital sampling oscilloscope market is now dominated by Tektronix and Hewlett-Packard. Both companies offer bandwidths up to 50 GHz. TEK's oscilloscope is the model 11801B main frame with a wide selection of "SD" series, plug-in sampling heads. HP has discontinued their 54120 series of oscilloscopes that offered bandwidths from 12 to 50 GHz. They replaced the 54120 series with their 54750 series. HP also offers a wide selection of plug-in sampling heads. Both companies also offer another instrument called a Communications Signal Analyzer (TEK CSA-803A) or Digital Communications Analyzer (HP 83480A). These are really the same sampling oscilloscopes but configured with specialized firmware to appeal to the high speed digital communications market. This application note AN-2c only covers the TEK 11801B/CSA-803A, HP-54120A/B, and HP-54750A/83480A oscilloscopes. We only tested sampling heads with bandwidths of 18 GHz or higher.

PULSE GENERATORS

For consistency between the various AN-2 application notes, we have continued to test the various oscilloscopes with the same pulse generators. In the 1980s we used a 14 ps, 250 mV, HP-1106A tunnel diode pulser for risetime tests. PSPL's model TD-1107 is a direct replacement for the discontinued HP-1106. For AN-2b, we started testing with an even faster PSPL Model 4015B pulse generator with a 12 ps falltime. For the nanosecond domain, settling time transient response measurements, we used a PSPL Model 6110D Reference Flat Pulse Generator (RFPG), s/n 2. The PSPL 6110D is based upon an NBS (now NIST) RFPG design. It produces a mathematically predictable, very flat, clean, 500 mV step pulse with a falltime of 420 ps and settling times of 3 ns to 0.2% and 10 ns to 0.02%. PSPL has sent both the 4015B and 6110D used for these measurements to NIST for formal calibrations of risetime and settling time. More details regarding PSPL's NIST tracability are found in our Application Note, AN-6.

In 1991, PSPL introduced the Model 4015B ultra-fast, high-amplitude Pulse Generator. It produces a -9 V pulse with a typical falltime of 15 ps. For these tests a "premium" pulse head was used which produced an even faster 12 ps falltime. The -9 Volt pulse was attenuated using an HP-8490D, 50 GHz, 2.4 mm, 30 dB attenuator. The attenuator had a risetime of 5 ps. Thus, the resultant test pulse for the tests reported in this AN-2c was a -300 mV, 13.1 ps falltime step pulse. The tests reported here used the NIST-calibrated 4015B Pulse Generator prototype, s/n 2, with the 4015RPH pulse head, s/n 12. In 1994, PSPL introduced an improved version of the 4015. The 4015C provides a much cleaner, 15 ps step waveform suitable for calibrating oscilloscopes. Several standards labs are now using PSPL 4015s as their risetime calibration standards.

RISETIMES

Figure 1 shows the leading edge of the 4015B Pulse Generator pulse as measured by seven different HP and TEK oscilloscopes. To measure the falltimes, we used the automatic pulse parameter measurement features found on both the TEK and HP scopes. The 0% and 100% levels were determined automatically using histograms. The falltimes were measured on the waveforms shown in Figure 1. The results are tabulated in Table 1. The calculated 10% - 90% risetimes in Table 1 are from the root-difference-of-squares equation:

$$Tr\ (calc) = [\ Tf(meas)^2\ -\ 13.1\ ps^2\ (gen)\ ]^{1/2}$$

Table 1: Results of Tests Run at PSPL on High Performance Digital Sampling Oscilloscopes

Mfgr	**Main Frame**	**Sampler Plug-In**	**Falltime** (meas)	**Risetime** (calc)	**Settling Error** at t = 5 ns	**Vertical Noise** (rms)	**Timing Jitter** (rms)
HP	54120A	54121A	20.8 ps	16.2 ps	-1 %	0.9 mV	1.6 ps
HP	54120B	54123A	17.2 ps	11.2 ps	-0.7 %	0.9 mV	1.0 ps
HP	54120B	54124A	16.1 ps	9.4 ps	-0.7 %	1.3 mV	1.0 ps
TEK	11801B	SD-24	22.1 ps	17.8 ps	0 %	0.6 mV	1.4 ps
TEK	11801B	SD-32	15.8 ps	8.8 ps	+0.1%	1.9 mV	1.4 ps
HP	83480A	54754A	20.6 ps	15.9 ps	-1.4 %	0.5 mV	0.85 ps
HP	83480A	54742A	15.9 ps	9.0 ps	-0.8 %	0.7 mV	0.85 ps

PS RESPONSES

Figures 1 and 2 show the 4015B waveform as measured by these various scopes at sweep speeds of 10 ps/div. and 50 ps/div. A close, careful inspection of these waveforms shows similarities between these seven different samplers. The common features in all of the plots are the artifacts of the pulse generator's non-perfect waveform. In particular, the overshoot and damped 10 GHz ring is from the pulse generator. What is more important to consider are the differences from one plot to another. These are the perturbations introduced by the various samplers. The higher bandwidth (34 GHz and 50 GHz) samplers definitely resolve more fine structure on the pulse. The 50 GHz HP-54752A and 54124A responses are essentially identical. The Tek SD-32 50 GHz sampler shows a bit more overshoot compared to the other samplers. The HP-54754A, 18 GHz, TDR sampler shows the most differences compared to all of the other samplers. The foot on the leading edge of its step response rises slower, and then there is a slow roll-up of its step response after the leading edge.

SETTLING TIME TRANSIENT RESPONSES

Figure 3 shows the settling time transient responses for these various scopes. The input pulse was from the PSPL Model 6110D RFPG. The reference pulse switches from a high state of 500 mV to a 0 Volt baseline in 420 ps. The actual settling time waveform of this generator has been mathematically modeled by PSPL using PSPICE. This generator has been calibrated by NIST and the modeled response confirmed. The generator has a 1.5 % overshoot below 0 Volts and then rapidly settles back up to the 0 Volt baseline. The settling is to within 0.2% in 3 ns, 0.1 % in 5 ns, 0.02 % in 10 ns and 0.01% in 100 ns. Figure 3 does not show the complete pulse waveform. It only shows a greatly expanded vertical scale (0.4 %/div.) to show the settling behavior near the 0 Volt baseline. The 0 Volt DC reference is shown for all figures. Some DC offset error is noted for all samplers. The three HP 54120 series samplers show almost identical responses. Likewise, the two HP 54750 series samplers show nearly identical responses, but different from the earlier 54120 series. They settle to within 0.2 % in 40 ns, whereas the 54120 series took a much longer 400 ns. The settling error of the 18 GHz HP-54754A was almost twice as large as the 50 GHz HP-54752A. The TEK samplers have better settling time responses than the HP samplers. The TEK SD-32 seems to have too much short term peaking. In the 1 ns to 5 ns interval the SD-32 most closely follows the predicted 6110D RFPG waveform. The TEK SD-24 has the best overall settling time performance, and its waveform most closely follows the predicted 6110D RFPG waveform.

OTHER TESTS

PSPL also performed several other tests on these oscilloscopes. They included checking the input resistance, vertical noise, DC voltage calibration, time base calibration, and trigger performance, including timing jitter. In most cases the scopes performed far better than specified by the manufacturers. They all had input resistances very close to 50 Ohms. In comparison to the earlier generation sampling scopes, these new digital scopes are extremely accurate instruments. They are very accurate DC voltmeters. The sole exceptions were the 54124A with -1.6% gain error and the 54754A with a disappointing -2.5% gain error. The vertical noise results are listed in Table 1.

The digital time bases in all of these scopes were extremely accurate for all times from ps to ms. Even on the fastest 10 ps/div sweep, errors were typically less than 1 ps in 100 ps. For slower sweeps, performance was even better. There is a word of caution, however. Potentially serious errors can occur at particular integer-related time positions for either the HP or TEK scopes. This is due to the architecture of their time bases. For example, in the HP scopes this occurs every 4 ns. The HP time base counts cycles of a very stable 250 MHz oscillator for its coarse delay and sweep. It then has a 4 ns ramp generator running between clock cycles as the vernier. If the ramp crossover and 250 MHz oscillator are not perfectly aligned, then "glitches" in the waveform can occur every 4 ns. This can be disastrous if a fast ps risetime edge happens to land at the N*4ns crossover point. All of these scopes had excellent trigger circuits with very low timing jitter. We measured jitters ranging from 0.85 ps rms to 1.4 ps rms.

HP-54120 SCOPE

As noted previously, HP has discontinued this scope. We have retained it in this report because of the large numbers of these scopes that are still being used today and also to provide a tie backwards to our previous AN-2 application notes. These scopes all included a built-in 35 ps risetime TDR pulse generator in one of the channels. The 54120 series had a unique feature which enhanced its TDR capability. It included built-in software to do deconvolution (HP called it "normalization") and digital filtering of TDR and TDT waveforms. This allowed one to have a very clean test signal with either a faster or slower risetime pulse. Risetimes as fast as 20 ps were possible normalizing the built-in 35 ps TDR pulse. If the 15 ps PSPL 4015 pulse generator is used instead as the 35 ps TDR pulse, then TDR and TDT measurements with risetimes down to 10 ps are possible. For further details, see PSPL's AN-5a. HP made a major contribution to improving pulse measurement standards by a very careful analysis, modeling, and measurement of the complete transient impulse and step response of the 54124A, 50 GHz sampler. This work was reported in the Sept. 1990 issue of the IEEE Spectrum.

HP-54750/83480 SCOPES

This is HP's replacement for the 54120 series. The key critical hardware elements of the samplers, trigger, and digital time base were retained from the 54120 series. The picosecond domain responses are similar to those of the 54120 series. The sampling "blow-by" circuits apparently were redesigned because the settling time responses are different from the 54120 series. The major improvements were in the microprocessor speed and enhanced firmware. It compares favorably to the data acquisition speed and firmware capabilities of the Tek scopes. One key capability found in the HP scope not found in the Tek scopes is the ability to do normalization of TDR and TDT measurements. The built-in TDR pulser in the HP scope has a relatively slow 45 ps risetime. However, by using their normalization firmware, the effective TDR/TDT risetimes can be enhanced down to 20 ps. If the PSPL 4015, 15 ps pulse generator is used with this scope, then TDT risetimes down to 10 ps can be obtained. The 54750 TDR/TDT software does however contain a serious "Bug" which prevents it from doing 10 ps TDR measurements with the 4015 pulse generator.

TEK 11801B/CSA-803A SCOPES

In our 1994 AN-2b, we reported that the TEK scope had a very objectionable defect in the SD-24 TDR pulse. We reported that the TDR pulse hopped back and forth by 3 ps at a 1 Hz rate. Since then Tektronix has contacted PSPL and informed us that they have now modified the firmware to allow the user to disable the blinking front panel TDR LED that was causing the 1 Hz, 3 ps "hop". The TEK scope does not have TDR "normalization" to decrease risetime, but it does have digital filtering to slow down risetimes. TEK's TDR pulse risetime was measured to be 23 ps.

Risetime Response at 10 ps/div

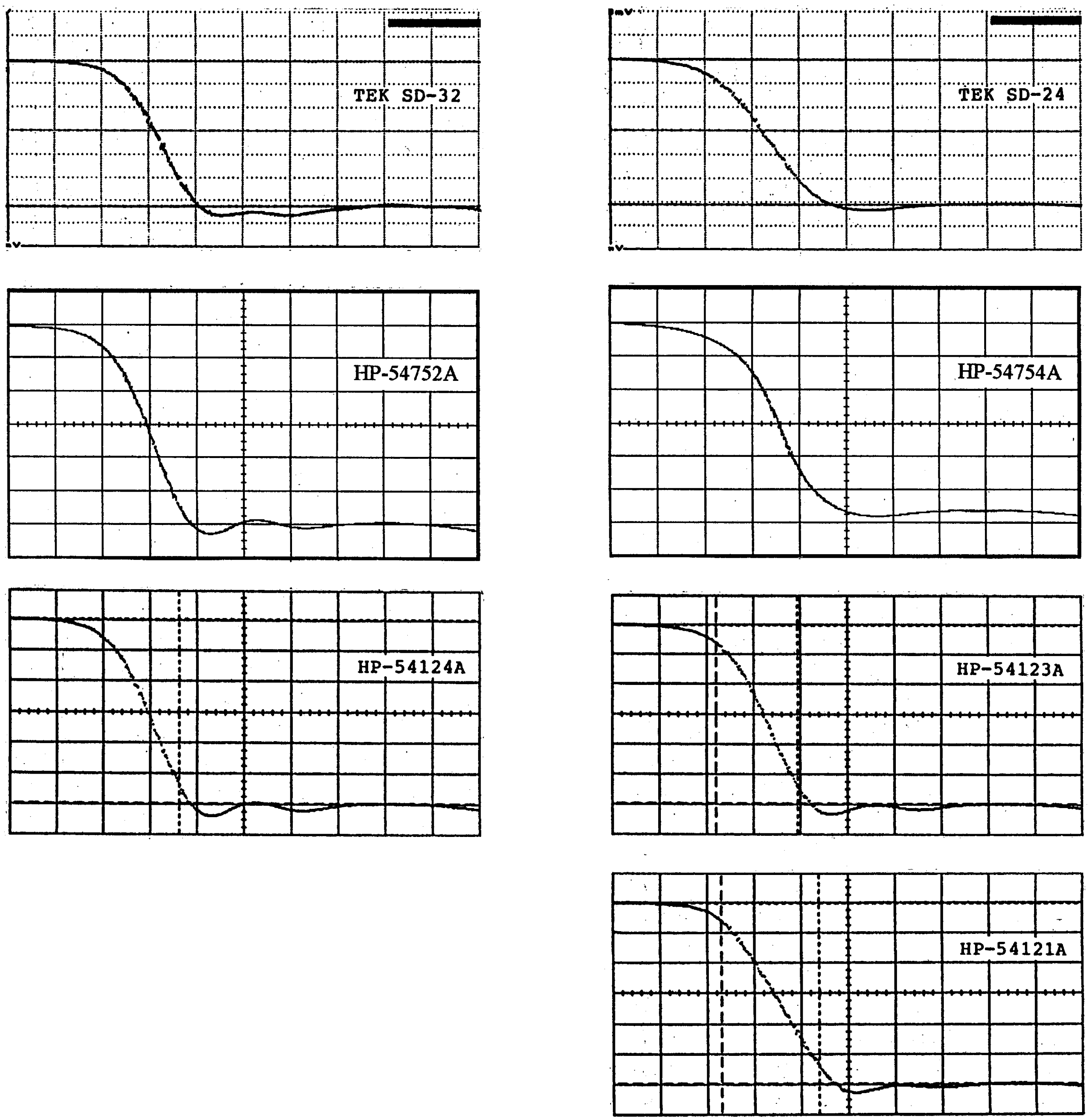

Figure 1: Risetime Performance of Various HP and TEK Digital Sampling Oscilloscopes
Input was -300 mV, 13.1 ps Falltime Pulse from PSPL 4015B Pulse Generator. Vertical = 50 mV/div.
Horizontal = 10 ps/div.

Picosecond Domain Response at 50 ps/div

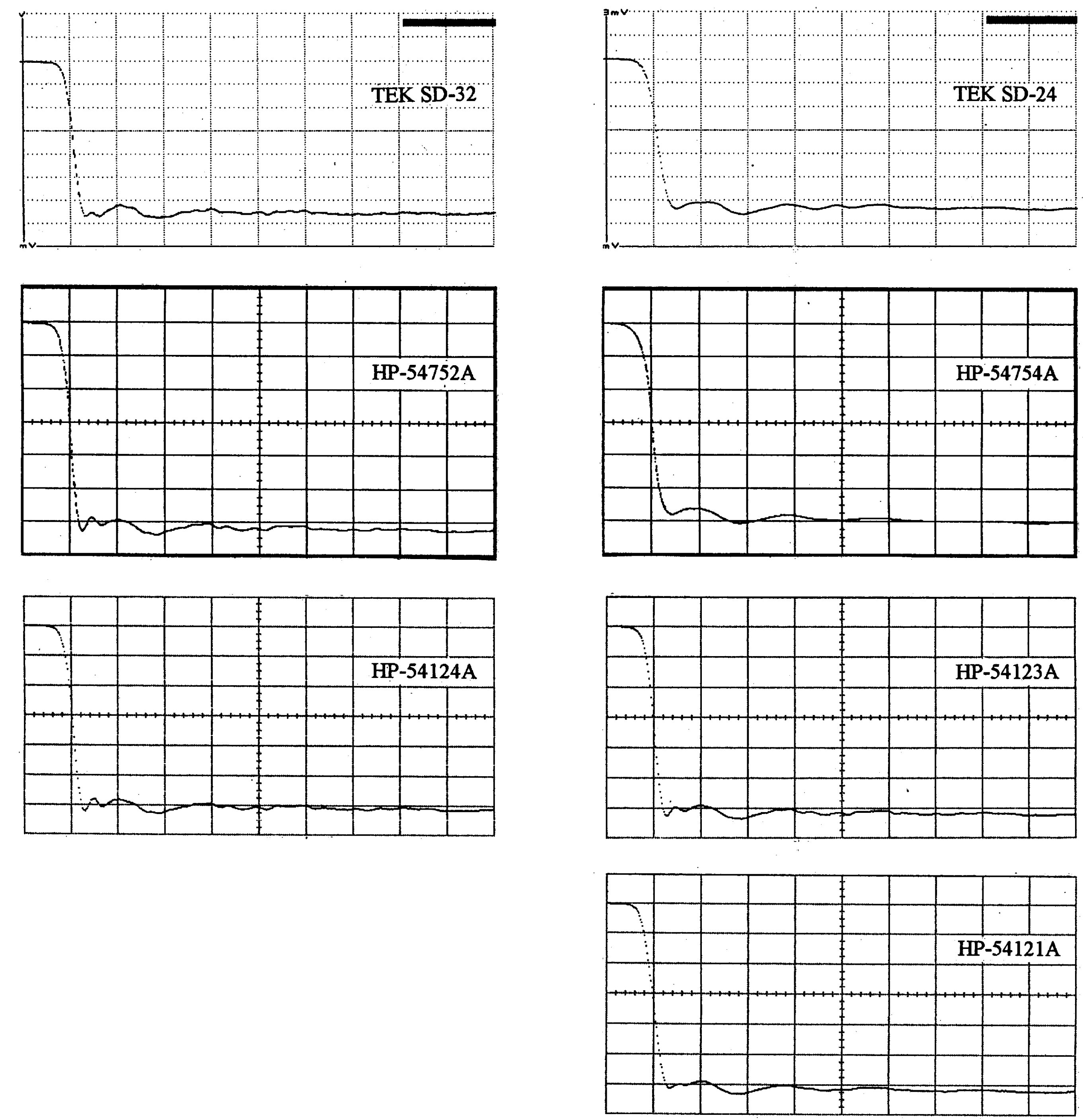

Figure 2: Measurements of PSPL Model 4015B, -300 mV, 13 ps Step Pulse by Various TEK and HP Digital Sampling Oscilloscopes
Vertical = 50 mV/div. Horizontal = 50 ps/div.

Nanosecond Settling Time Response

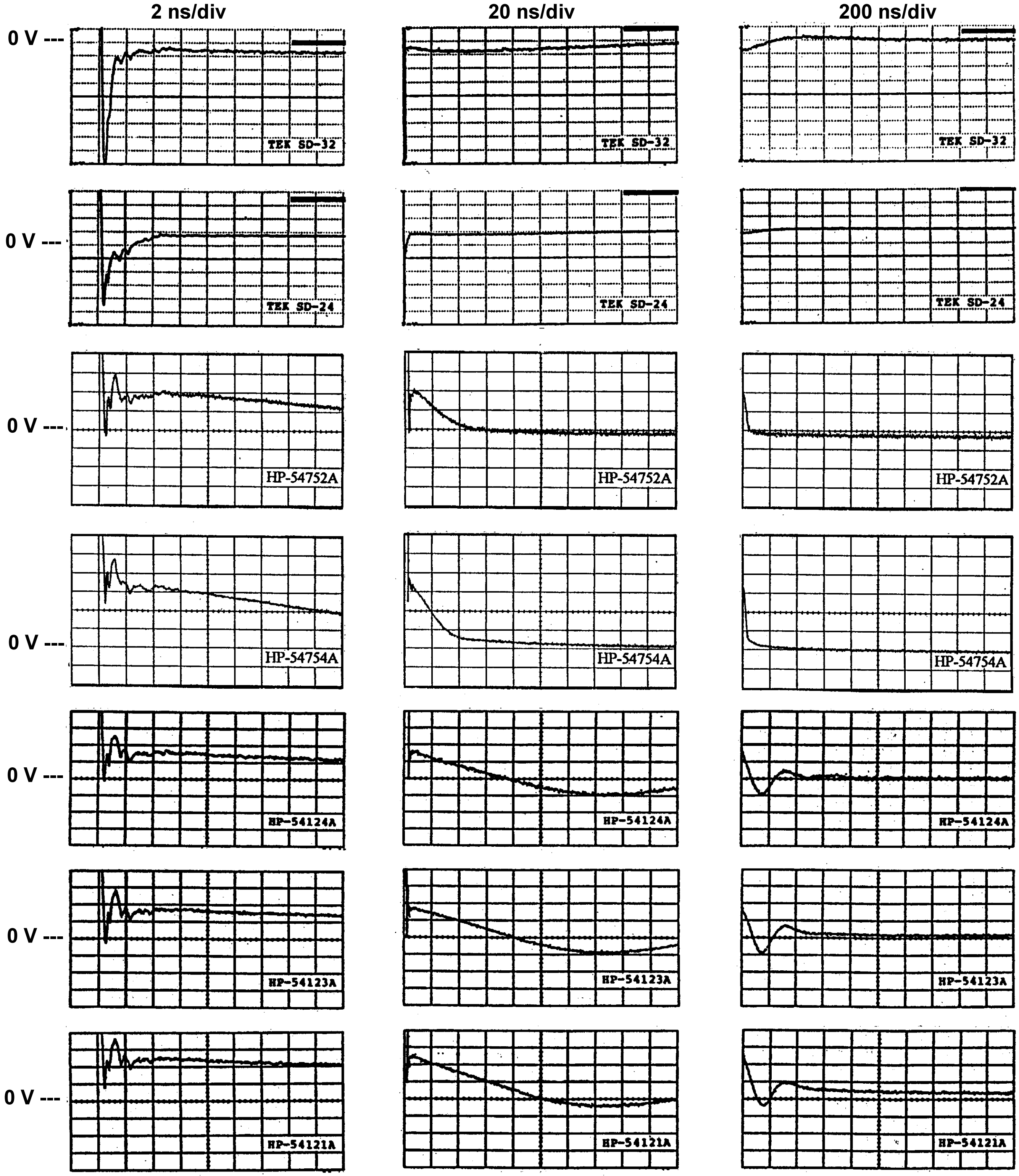

Figure 3: Nanosecond Domain Settling Time Response of Various HP and TEK Digital Sampling Oscilloscopes
Input was 420 ps falltime step pulse from 500 mV to 0 Volts from PSPL 6110D Reference Flat Pulse Generator. The reference pulse settles flat to 0 Volts baseline to within 0.1% in less than 5 ns. Vertical = 0.4%/div (2 mV/div). Horizontal scales are 2 ns/div, 20 ns/div and 200 ns/div.