Comparison of Ultra-Fast Rise Sampling Oscilloscopes

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The purpose of this application note is to compare the transient responses of all of the various broadband, sampling oscilloscopes. This study was limited to the fastest samplers with transition durations (10%-90% risetimes) of < 35 ps and corresponding bandwidths of > 10 GHz. It is very important for users of these instruments to realize that none of them will give the correct answer when measuring picosecond domain signals. The same pulse signal measured with different samplers will result in different pulse waveforms as displayed on the CRT screens. This application note is an updated revision of the previous PSPL AN-2 (1986) [1,2].

Nine samplers from five manufacturers were compared. They were: IWATSU, Tokyo, Japan; HEWLETT-PACKARD (HP), Colorado Springs, Colorado; TEKTRONIX (TEK), Beaverton, Oregon; HYPRES, Elmsford, New York and PICOSECOND PULSE LABS (PSPL), Boulder, Colorado.

In AN-2 (1986) the following samplers were compared: The HP samplers were the models 1430A and 1430C, used with both the 140 series (1411A and 1424A plug-ins) and 180 series (1811A plug-in) oscilloscopes. It should be noted that HP no longer manufactures these instruments. They are only available as used equipment. The TEK samplers were the S4 and S6 used with the 7000 series oscilloscopes and the 7S11/7T11 or 7S12 plug-ins. The S4 and S6 could also be used with the older 560 series scopes. The PSPL sampler was a model S-1430D. PSPL does not manufacture a sampling oscilloscope. The S-1430D sampler was designed to be used interchangeably with either the old HP (140 or 180 series) or old TEK (560 or 7000 series) sampling oscilloscopes. The PSPL S-1430D is now discontinued. The Iwatsu sampler was the SH-4B with their SAS-8130 digital sampling oscilloscope. It can also be used with their SAS-601B oscilloscope.

Since 1986 there has been a flurry of activity in new sampling oscilloscopes. HYPRES, IWATSU, HP and TEK have all introduced new digital sampling oscilloscopes. IWATSU's new scope is the improved SAS-8130A with the SH-4B sampling head. The TEK scope is the 11802 with the SD24 sampling head. The HP scope is the 54120A with the 54121A sampling head. The HYPRES model PSP-1000 is unique in that it uses Super-Conducting Josephson Junctions as a sampler. This application note includes these new scopes.

ps TRANSIENT STEP RESPONSES

For the picosecond domain, transient step response comparisons, we used the fastest tunnel diode pulse generator we could find. It was an old HP 1106A powered by a PSPL TD-1110B TD Pulse Driver. It produced a 0.26 V step. Based upon measurements on the HYPRES scope, we estimate that its transition duration was 14 ps. Figure 1a shows its waveform as measured on the 5 ps HYPRES scope.

It should be noted that HP no longer manufactures the 1106A. However, similar 25 ps risetime generators are available from IWATSU (SG-3102), TEK (S-52), and PSPL (TD-1107/TD-1110B). The S-52 is not a stand-alone unit but must be operated as a plug-in within a 7S12 TDR sampling plug-in. The IWATSU and PSPL TD Pulse Generators are stand-alone, line powered instruments. Some selected PSPL TD-1107s are available with less than 20 ps risetimes.

The collection of photographs and printer plots, Figures 1 and 2, show the picosecond domain, transient step responses of all of these samplers when driven by the same HP 1106A tunnel diode (s/n 732-00311). The common features in all photos and plots are the artifacts of the pulse generator's waveform. The differences from one plot to another are the perturbations introduced by the various samplers. From these waveforms, estimates were made of the transition durations of the various samplers. The results are listed in Table 1.

Table 1: 10%-90% Transition Duration of Samplers

Mfr.	Model	Mfr. Spec (risetime)	Measured by PSPL
HYPRES	PSP-1000	5 ps	----
TEK	SD-24	17.5 ps	17-18 ps
HP	54121A	17.5 ps	17-18 ps
IWATSU	SH-4B	< 30 ps	33 ps
TEK	S-6	< 30 ps	28 ps
TEK	S-4	< 25 ps	20 ps
HP	1430C	20 ps	22 ps
HP	1430A	28 ps	29 ps
PSPL	S-1430D	28 ps	26 ps

To obtain a transition duration (10-90% risetime) measurement, it was first necessary to accurately establish the 0% and 100% amplitude levels [3]. The newer digital sampling scopes automatically measure risetime. This feature was used along with personal observation of the 0% and 100% levels selected by the scope to ensure

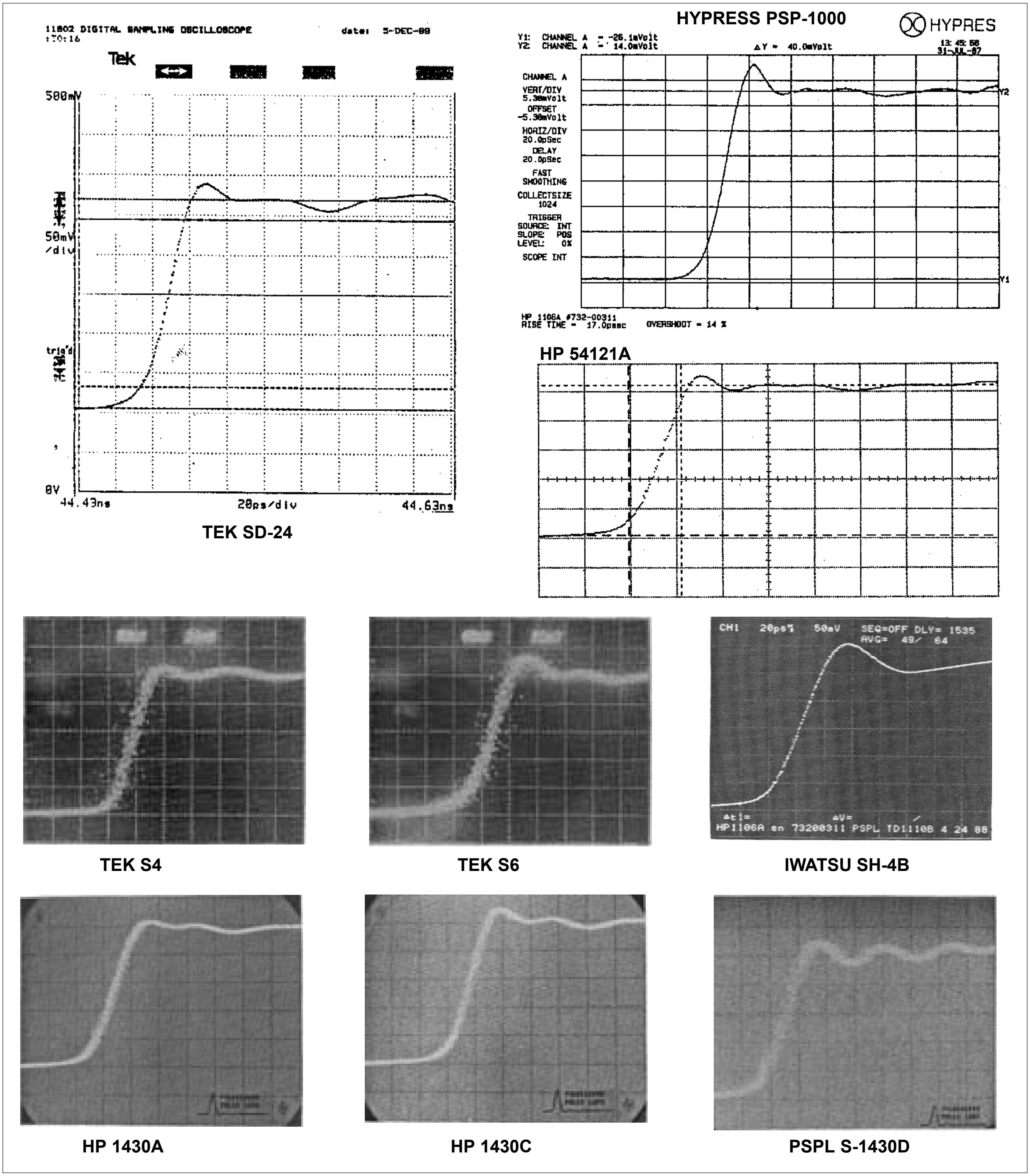

Figure 1: Picosecond Domain Transient Step Responses of 9 Sampling Heads
Input step from HP-1106A TD pulser. 50 mV/div and 20 ps/div.

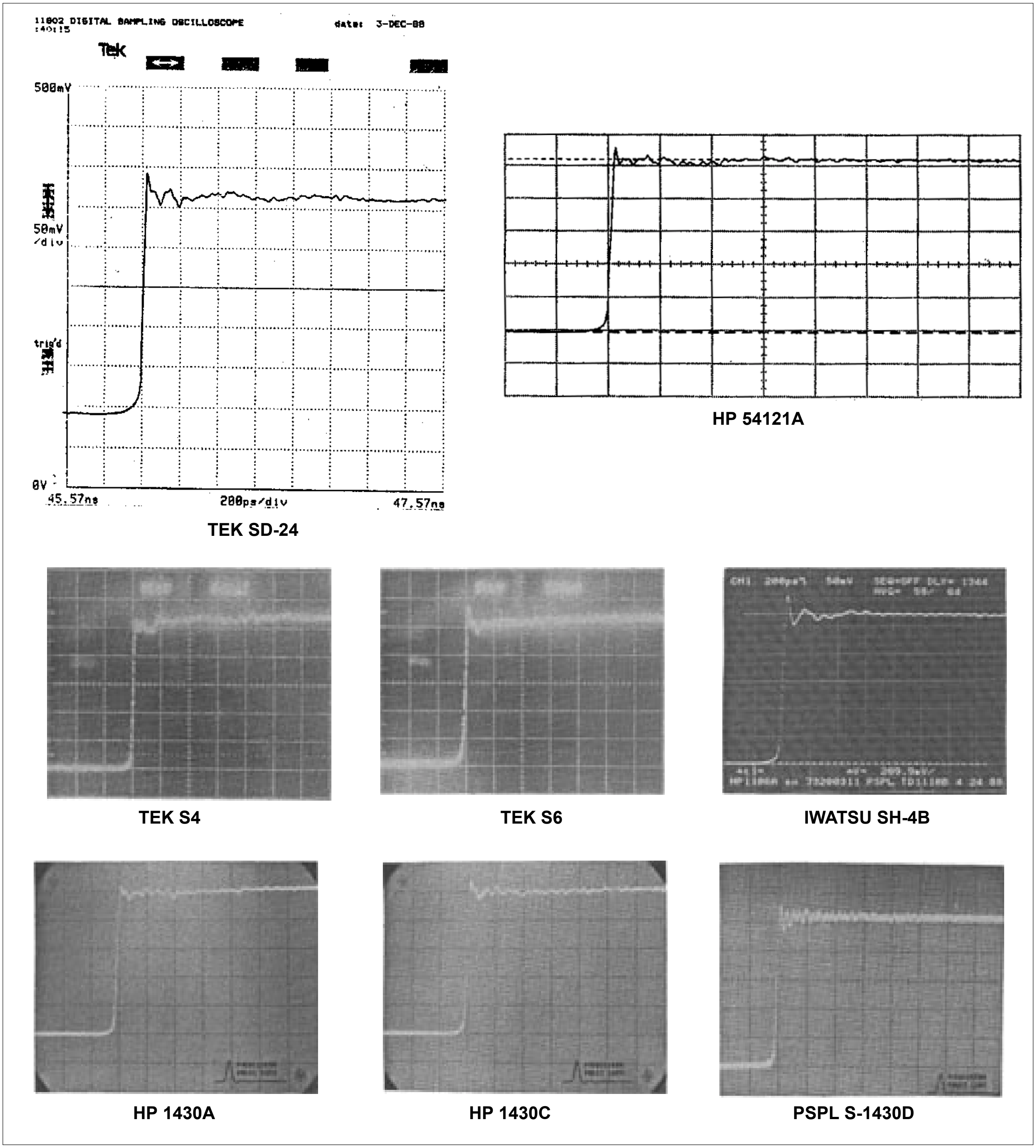

Figure 2 Picosecond Domain Transient Step Responses of 8 Sampling Heads
Input step from HP-1106A TD pulser. 50 mV/div and 200 ps/div.

consistency. For the older analog scopes, data was taken directly from the scope photos.

All tunnel diode pulse generators suffer from a baseline distortion that makes determination of a “true” 0% level difficult. This appears as a relatively slow rising ramp just prior to the very fast switching transition of the TD. This is feed-thru of the TD triggering pulse. It is quite apparent in Figure 2. Thus, to obtain a better measure of the ”true” sampler response, we chose the 0% level as the left edge of the screen on the 20 ps/div. scale.

The 100% level is considerably more difficult to determine due to the overshoots, ringing, fast perturbations and slow ramps present in the various samplers’ responses. We used the 20 ps/div. plots to determine the 100% level. For the SH-4B sampler which still showed significant perturbations at the end of the 20 ps/div. plot, we used a 50 ps/div. sweep. For the older analog scopes, we used an “eyeball” histogram of the waveform to determine 100%.

The root sum of squares equation was used to obtain an estimate of the actual step response transition durations (10%-90% risetimes).

$$Tr(sampler) = [Tr^2(obs) - Tr^2(pulser) - Tr^2(jitter)]^{1/2}$$

where Tr(pulser) = 14 ps. See the later section on “Noise and Jitter” for an explanation of Tr(jitter). Strictly speaking, this equation only holds for purely Gaussian signals and systems with no overshoot. The test pulse from the HP-1106A definitely violates the “no overshoot” condition. More accurate results could be obtained if mathematical models of the samplers were known and numerical deconvolution was used. NBS uses this technique for their fast picosecond domain, pulse calibration service [4].

For the nanosecond-domain, settling-time comparisons, a PSPL model 6110 Reference Flat Pulse Generator (RFPG) was used. The PSPL 6110 is based upon an NBS RFPG design [5]. PSPICE computer modeling of the 6110 was used to predict its RFPG waveform into 50 Ohms [6]. It produces a very flat, clean step from 500 mV to 0 V, with a 420 ps transition duration (falltime). The overshoot is 1.5%. It has a settling time of less than 2 ns to within +0.4% and -0.6%, less than 3 ns to within ±0.2%, and less than 5 ns to within ±0.1% of 0 V.

Figures 3 and 4 show the settling time transient performance of the various samplers tested. The old TEK S-4 sampler had the worst settling time performance. It showed a gradual rise in 4 ns to a max. overshoot of 5.5% and then an exponential decay back to the 100% level requiring an additional 25 ns. In contrast, the new TEK SD-24 had the best settling time performance. It very closely followed the mathematically predicted RFPG waveform. In the long term, it settled to within ±0.1%.

NOISE AND JITTER

Two other parameters that are important in characterizing sampling scopes are their noise and jitter. Noise is vertical or voltage uncertainty, while jitter is horizontal or timing uncertainty. Noise is primarily determined by sampling head design. Jitter is usually determined by the quality of the trigger and time base circuits and not the sampling head. Table 2 lists the measured vertical noise and timing jitter for the various sampling oscilloscopes.

Table 2: Noise and Jitter Performance

Mfr.	Sampler Model	Scope Model	Vertical Noise (rms)	Timing Jitter (rms)
TEK	SD-24	11802	1.2 mV	2.5 ps
HP	54121A	54120A	1.2 mV	1.6 ps
IWATSU	SH-4B	SAS8130A	2.5 mV	2.5 ps
TEK	S-6	7S12/S53	2.3 mV	3.3 ps
TEK	S-4	7S11/7T11	1.3 mV	2.7 ps
HP	1430C	1411A/1424A	1.3 mV	2.0 ps
HP	1430A	1411A/1424A	1.0 mV	2.0 ps
PSPL	S-1430D	1811A	3.3 mV	2.7 ps

Visual measurements of vertical noise and timing jitter are very subjective to human interpretation. Most of these noise processes have Gaussian distributions. Most human observers, when asked to visually estimate the “width” of a randomly occurring Gaussian process, usually give an answer that is equal to 3 Sigma, (i.e. +1.5 and -1.5 Sigma). A “width” of 3 Sigma includes 87% of the total noise events. The “RMS” value of a Gaussian distribution is 1 Sigma. The new HP 54120A digital scope includes the capability of doing voltage and time “Histograms” to determine noise and jitter distributions.

All sampling oscilloscope manufacturers include some circuitry to reduce the apparent effects of noise and jitter. On the older analog scopes this was called “smoothing”, “filtered”, or “high-resolution”. In each case, they simply reduced the forward gain in the sampling postamplifier. This reduced the sampling efficiency far below its normal 100% value. This does reduce the apparent noise and jitter; however, it also can drastically distort the waveform. If the sampling efficiency is precisely 100%, then each sample is the correct value and is not a function of previous values. However, when the sampling efficiency is not 100%, many samples are required to converge on the correct value after an abrupt change in the waveform. We recommend that “smoothing” never be used.

The newer digital sampling oscilloscopes include digital averaging capabilities. With this, the samplers can be operated at the normal 100% sampling efficiency. Digital signal averaging removes the random vertical noise effects correctly without distorting the waveform. Note that the waveform plots shown in Figures 1 and 2 for the PSP-1000, SD-24, 54121A, and SH-4B are all digital averaged plots.

Vertical signal averaging on a horizontally, time jittering waveform will give a clean-appearing, but distorted waveform. The averaged waveform will have slower transitions than the original waveform. Gans [4] has shown that this is equivalent to adding a low-pass filter into the measurement.The effective bandwidth of this filter is:

BW(-3 dB) = 0.132 x (1/Sigma).

For example, vertical averaging of a 3.3 ps jitter is equivalent to a 40 GHz low-pass filter with an 8.8 ps risetime. In [4], Gans showed how this low-pass filter effect can be removed by measuring the jitter sigma and using digital deconvolution.

OBSERVATIONS ON INDIVIDUAL SAMPLING SCOPES

HP-1430C: The HP 1430A, B, and C samplers were essentially identical in construction. The "A", 28 ps, version was designed by Wayne Grove and introduced in 1966 [7]. In 1972, the "B", APC-7, and the "C", type N connector, 20 ps samplers were introduced as improved versions of the "A". The major improvement seems to have been made with better Schottky sampling diodes. The "A" and "C" ps and ns responses are essentially identical with the exception that the "C" has a bit faster transition duration, more overshoot, and more vertical noise. The 1430A shown in Figure 1 has a transition duration of 29 ps and an overshoot of 4% while the 1430C has a transition duration of 22 ps and an overshoot of 8%. In the slower ns region, Figure 3, both the 1430A and 1430C samplers' settling time characteristic consists of a slow 3% roll-up with a 5 ns time constant.

These samplers are a feed-thru design. This means that the signal passes thru the sampler and comes back out of a coaxial output connector. Thus the signal can be reused elsewhere. This is a particularly convenient arrangement for Time Domain Reflectometer (TDR) measurements [8]. For normal measurements, the output connector is terminated by a 50 Ohm termination which must have a very low VSWR. Slight impedance discontinuites in the output connector and the resistive termination can be easily noticed in the transient responses starting 800 ps after the transition. At t = 350 ps another discontinuity is noted. This is due to the "blow-by" pickoff resistor for the low frequency compensation circuit. Riad [9] has done a complete computer modeling and simulation for the HP1430 sampler response. His model is used in the NBS pulse calibration service [4].

TEK S-4: The S-4 was designed by George Frye [10] and introduced in 1968. It is a member of the TEK "S" series of sampling heads which includes the S1 (50 Ohm, 350 ps), S2 (50 Ohm, 75 ps), S3A (100 kOhm, 350 ps), S5 (1 MOhm, 1 ns), and S6 (50 Ohms, 30 ps). All of the "S" series heads are interchangeable with identical mechanical dimensions and electrical interfaces. Several sampling plug-in and mainframe scope combinations including the 7854 digital mainframe are available.

The S4 uses a unique traveling wave, 6-diode sampling bridge. Most sampler designs use either a 2 or 4-diode bridge with very narrow triangular strobe pulses [11]. The traveling wave strobe of the S4 is instead a 200 ps rectangular pulse with an extremely fast trailing edge. The diode bridge is actually on for 200 ps. The < 25 ps sampler risetime is actually obtained by a 25 ps charge trap between sampling diodes. We found the 200 ps wide strobe caused a unique problem for the S4. When a tunnel diode pulser was mounted directly on the input connector of the S4, the leakage of the 200 ps strobe was sufficient to cause false triggering of the TD. The falsely triggered TD pulse would then enter the S4's diode bridge during the 200 ps "on" time. The resultant CRT waveform was quite unstable and very strange with sometimes a negative risetime display. The simple cure for this was to introduce a delay line between the pulse generator and the sampler. The delay must be greater than the strobe pulse duration. Thus for the S-4 waveform in Figure 1, a 500 ps, 7 mm air line was used.

The S4 is internally terminated in 50 Ohms. Thus, its low frequency, nanosecond response is not dependent upon the quality of termination connected by the user. With the internal termination, the signal is not available for reuse. Thus, the S4 is not suitable for TDR. The major defect of the S4 for precision measurements is its poor nanosecond domain settling time response, Figure 3. Close inspection shows that the S4 response has a very fast risetime, with a flat response for 200 ps. At 200 ps it has an abrupt +7% step. Then the waveform continued to climb slowly up to the 105.5% level in about 4 ns. It then slowly recovered back to the 100% level after 25 ns. The TEK spec. is <=10% and some units used by the author in the past have been as bad as 10%.

TEK S-6: The S-6 sampling head was introduced in 1971. It is a 50 Ohm feed-thru sampler. It is a bit slower than the S4 but overall has a better transient response. The particular unit tested had a 28 ps risetime. The nanosecond settling time response, Figure 3, is considerably better than the S-4, with a 1% roll-up and a time constant of about 10 ns.

PSPL S-1430D: The PSPL S-1430D sampler was designed in 1983 by Gordon DeWitte, EG&G - Los Alamos, and Jim Andrews, PSPL [12]. It was built on contract to the D.O.E. as a replacement for the discontinued HP1430 samplers. It was a 50 Ohm feed-thru design. A dual-channel version has also been built. The major ps domain response features are a 26 ps rise with a 20 GHz damped oscillation following the leading edge. The ringing is about ±6% and damped within 200 ps. In the nanosecond domain the settling time response is relatively flat. The major ns discontinuities are the “blow-by” pick-off resistor at 3.2 ns and the output termination at 3.7 ns.

IWATSU SH-4B: Iwatsu has several sampling oscilloscopes with transition durations from 350 ps to < 30 ps. Their design engineers are Kensuke Kobayashi and Nobuyuki Kunito. Iwatsu builds two sampling heads that are interchangeable mechanically and electrically. They are the SH-1B (50 Ohm, 100 ps) and the SH-4B (50 Ohms, < 30 ps) which we tested. The SH-4B is a 50 Ohm feed-thru design and thus suitable for TDR. The dominant ps domain transient response, Figures 1 and 2, characteristic of the SH-4B sampler is a 33 ps rise and then a large 12% overshoot followed by two cycles of a damped 10 GHz sine wave. A minor reflection due to the output connector and termination appear at 500 ps. After that the step response is relatively flat. In the nanosecond domain, the settling time response (Figure 4) was flat within 0.8%.

The IWATSU main frame SAS-8130A is a completely redesigned instrument that was introduced in 1987 [13]. It is a two-channel digital sampling scope. It is IEEE-488 programmable. The new “A” version dramatically improved the jitter performance from the original 8130 scope. The new time base design of N. Kunito has reduced the jitter down to 2.5 ps rms.

HP-54120/5412IA: This scope was introduced in July 1988. The chief HP engineer was Ken Rush. The 54121A sampler uses a 2-diode (GaAs) sampling bridge. It is based upon microwave mixer technology that was developed for HP’s frequency counters and the 8510 network analyzer. The 54120A is IEEE-488 programmable.

The HP54121A sampler is internally terminated in 50 Ohms. The risetime is 17.5 ps as specified. The picosecond domain transient performance was found to track very closely with waveforms measured on the HYPRES scope. Its major defect occurs in the nanosecond domain in its settling time performance (Figure 4). The initial response is about 1% low. The settling transient appears as a damped 3 MHz sine wave. The 54121A sampler includes four sampling channels, one TDR pulser, and the trigger and time base circuits. The time base accuracy was found to be excellent. The timing jitter was found to be excellent at 1.6 ps rms. This was the lowest jitter found in all of the scopes tested.

TEK 11802/SD-24: TEK introduced this new scope in the fall of 1989. It is a completely new design and is not interchangeable with any of the previous “S” series TEK sampling scopes. The TEK design team included: Stan Kaveckis, Augoston Augoston, John Carlson, John Rettig, Jon Lucker and Roy Lewallen. The 11802 is a completely digital mainframe. It can support two SD-24 dual-channel samplers. It is IEEE- 488 programmable. The time base accuracy was excellent. The trigger jitter was 2.5 ps rms.

The SD-24 sampler uses a six-diode sampling bridge similar in concept to the “trapped charge”, traveling wave S-4 sampler. The SD-24 is a dual-channel sampler which includes a built-in TDR pulser. The SD-24 sampler is internally terminated in 50 Ohms. The risetime is 17.5 ps as specified. The picosecond domain transient performance was found to track well with waveforms measured on the HYPRES scope. It did show a few extra small (4%) perturbations in the 200 ps to 500 ps region that were not seen on the HYPRES or HP-54121A samplers. After 1 ns, the settling time transient performance was excellent. It was far better than any of the other samplers tested.

HYPRES PSP-1000: HYPRES is a new start-up company founded by Sadeg Faris with the objective of commercializing Super-Conducting Josephson Junction Technology [14]. Their first product is the PSP-1000 Digital Sampling Oscilloscope and TDR which was introduced in 1986. The chief engineer was Eric Hanson. It is the front-runner in this field with a claimed risetime of 5 ps.

Unfortunately, we have a very limited set of data and no operating experience with this instrument. Our only test was in July, 1987, when HYPRES brought a “demo” PSP-1000 to Boulder, CO. The “demo” unit was definitely much faster than any other sampling scope. We were able to see smaller, faster artifacts on pulses that we had not seen before. The “demo” unit did have several problems. The most troubling was a severe non-linearity in the time base. HYPRES has since informed us that this has been corrected. Until we have an opportunity to perform an exhaustive evaluation of the HYPRES scope, we will withhold any further comments.

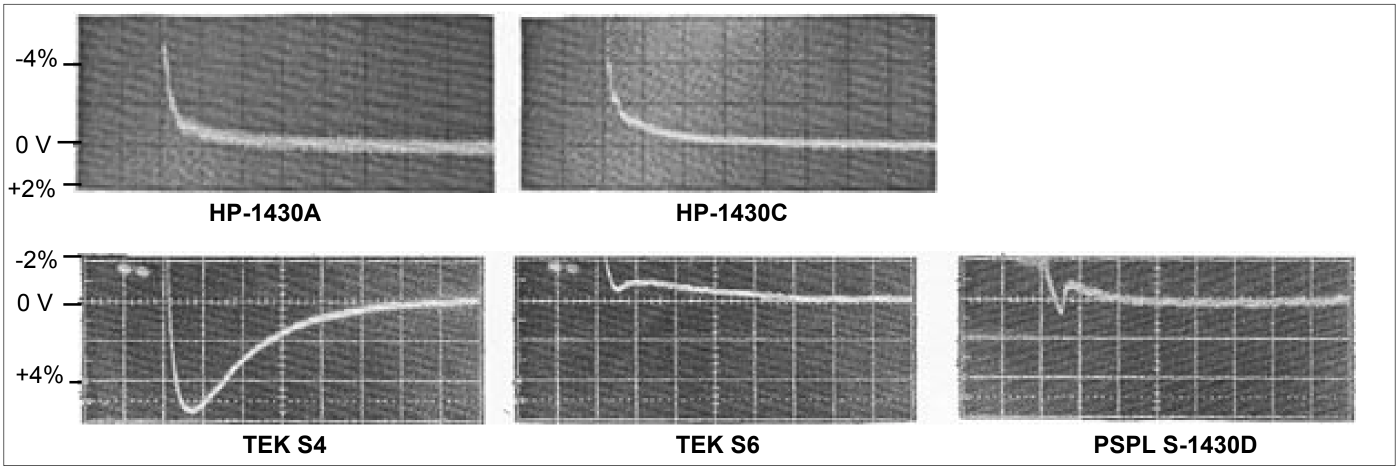

Figure 3: Settling Time Performance of Older Samplers at 10 mV/div (2%/div) and 5 ns/div
Input from PSPL 6100 RFPG. AN-2, 8/86 data.

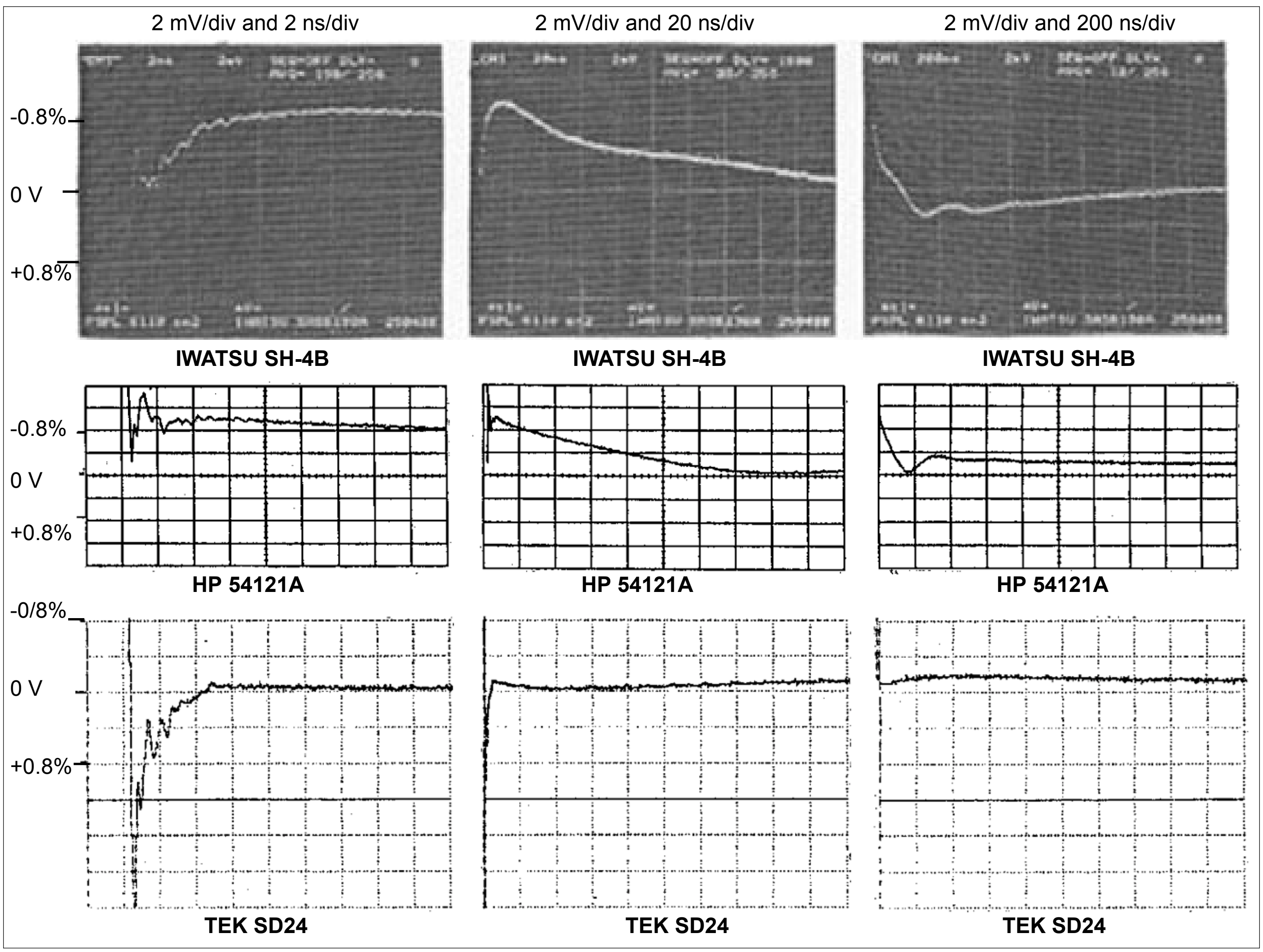

Figure 4: Settling Time Performance of New Digital Sampling Oscilloscopes: 2 mV/div (0.4%/div)
Input from PSPL 6110 NBS type Ref. Flat Pulse Generator with 500 mV to 0 V pulse, 420 ps falltime, 1.5% overshoot and settling time to within +0.4%, -0.6% in < 2 ns, to +-0.2% in < 3 ns, and to +-0.1% in < 5 ns.

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