Picosecond Pulse Labs

Application Note AN-3a

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Pulse Measurements in the Picosecond Domain

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The purpose of this application note is to discuss measurement problems with particular emphasis upon those that are unique to the picosecond domain. There are several excellent review papers **[1-4]** and a book **[5]** on this subject that are recommended reading. Several references appear in the January 1986 Proceedings of the IEEE special issue on Radio Measurement Methods and Standards.

For engineers and technicians that have spent their careers in the audio and video analog world and/or the TTL digital world, their first experiences in the picosecond world can be very frustrating. Crossing the < 1 ns frontier is the entry into the world of "Distributed Electronics" and microwave techniques. Recall that 1/1 ns = 1 GHz. Analysis at the microcircuit, IC chip level can still be handled as lumped circuits in the 100 ps to 1 ns domain. However, lumped element circuit measurement techniques are no longer valid. Even the simple wire bond from the IC chip to its carrier and on out into the real p.c. board world must be considered as a distributed transmission line. It is no longer possible to "probe" directly the circuit node of interest. All measurements must be considered to have been made at the end of a transmission line and the results interpreted with this in mind. The low frequency concept of "High" impedance of k Ohms or M Ohms no longer exists in distributed electronics. Free space impedance of 377 Ohms is "High" impedance in this domain. No measurement can be considered as "non-intrusive", but will extract power from the circuit under test and effect its performance.

"Accurate" measurements are quite difficult to make in the ps domain. Errors of 25% to 50% are not uncommon if care is not taken. To achieve results of 1% is extremely difficult even for the most experienced researcher. One must fully understand the transient performance of his measurement instrument, his test set-up, and the loading effects on the unit under test. All of the equipment must be in "calibration". To obtain accurate results, the "raw" measured data should be further processed to remove as many of the effects of the measuring instruments as possible. The best way to accomplish this is to digitize the data and use a computer to deconvolve **[6]** the measurement system transient response from the "observed - raw" data. The procedures used at the National Bureau of Standards (NBS) for their PS Pulse Calibration Service are a good example **[7]**.

OSCILLOSCOPES

The basic measurement instrument in the picosecond domain is still the familiar oscilloscope which gives the engineer or technician a visual presentation of the signal waveform versus time. For the measurement of single transient pulses, there are many manufacturers offering good scopes with bandwidths in the 100 to 500 MHz range. Above 500 MHz there is a very limited choice of real-time oscilloscopes. One scope is the TEK 7104 with a risetime of 350 ps and a bandwidth of 1GHz. Intertechnique in France produces the world's fastest, real-time, traveling-wave oscilloscope. It is their model IN7000 with 50 ps risetime and 7GHz bandwidth. It uses direct deflection with no amplifiers for a full scale deflection of 5 V. The IN7000 also includes a CRT screen digitizer, digital memory and IEEE-488 capabilities. It is marketed in the USA by Tektronix as the model 7250.

Oscilloscope risetimes down to as fast as 5 ps are now possible using sampling techniques. The major disadvantage of sampling oscilloscopes is that they require a repetitive waveform and cannot be used to measure single transients. Since 1986 several new, extremely fast (< 30 ps) sampling scopes have been introduced. They are: HYPRESS model 750, 5 ps rise, 70 GHz bandwidth; TEKTRONIX 11800/SD-26, 17.5 ps and 20 GHz; HEWLETT-PACKARD 54121A, 17.5 ps and 20 GHz; IWATSU SAS-8130A/SH-4B, < 30 ps and 12.4 GHz; and TEK 7854 with S4 (<25 ps) or S6 (< 30 ps). These are all completely programmable digitizing scopes.

In 1986, PSPL made a comparison test of all of the then available sampling scopes with risetimes less than 35 ps **[8]**. They included both analog and digital scopes from TEK, IWATSU, PSPL and HP. The same 17 ps risetime pulse generator was used to test all of the scopes. None of these oscilloscopes gave the same pulse waveform. The transient responses in the ps region were all significantly different. Also, the settling time performances in the ns and µs region were quite different. This demonstrated that significant differences in measurements will occur when different sampling oscilloscopes are used. Calibration methods are very necessary to establish transient response accuracy for oscilloscopes. PSPL hopes to publish in 1989 a new application note, AN-2a, using this same 17 ps generator to compare the new HYPRESS, IWATSU, TEK and HP scopes.

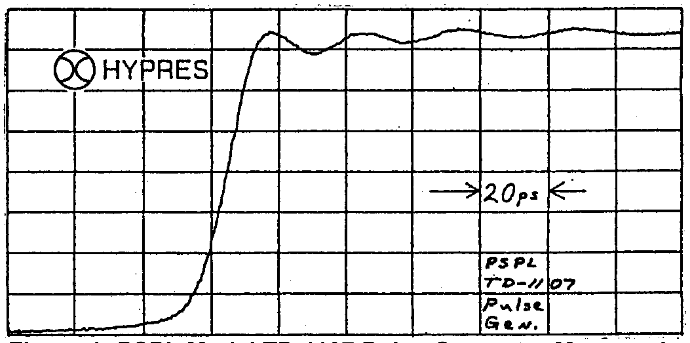

Figure 1: PSPL Model TD-1107 Pulse Generator Measured on HYPRESS Superconducting Sampling Oscilloscope

CALIBRATION STANDARDS

To make accurate measurements with any instrument, it is mandatory that it be calibrated against national standards. An oscilloscope makes two-dimensional measurements of voltage versus time. Thus, it must be calibrated with both voltage and time standards.

The transient response should be checked using very fast pulse generators. Sampling scopes have several internal adjustments which significantly affect their transient response. The bandwidth and risetime are directly proportional to the reverse bias and the strobe pulse applied to the sampling diode bridge. To check these adjustments an extremely fast pulse generator is required. Suitable 25 ps rise generators are the IWATSU SG-3102, TEK S-52 or PSPL TD-1107B (Figure 1). NBS offers a calibration service for these generators **[7,9]**. Fast samplers can also suffer from low frequency distortion called "blow- by". Improper adjustments of blow-by compensation can cause errors exceeding 100% in the 50 ns to several microsecond region. These circuits must be carefully adjusted using a square wave generator with a very flat pulse waveform. A suitable instrument is the PSPL 6110 Reference Flat Pulse Generator. It produces very flat 500 mV pulses with a 450 ps transition duration and is based upon a design concept first developed at NBS **[10]**.

For scope voltage calibration, DC voltage is the standard. For 50 Ohm scopes, it is best to use an accurate digital voltmeter (DVM) across the input connector to measure the actual DC voltage applied to the scope. To measure signal amplitudes which are larger than the dynamic range of the scope, it is necessary to use broadband, coaxial attenuators. To avoid distorting ps domain signals the attenuators should be rated at flat from DC to beyond the scope bandwidth. Figure 2 shows some examples of attenuators with "good" and "bad" pulse responses. The DC attenuation of each attenuator used should also be calibrated. Most broadband

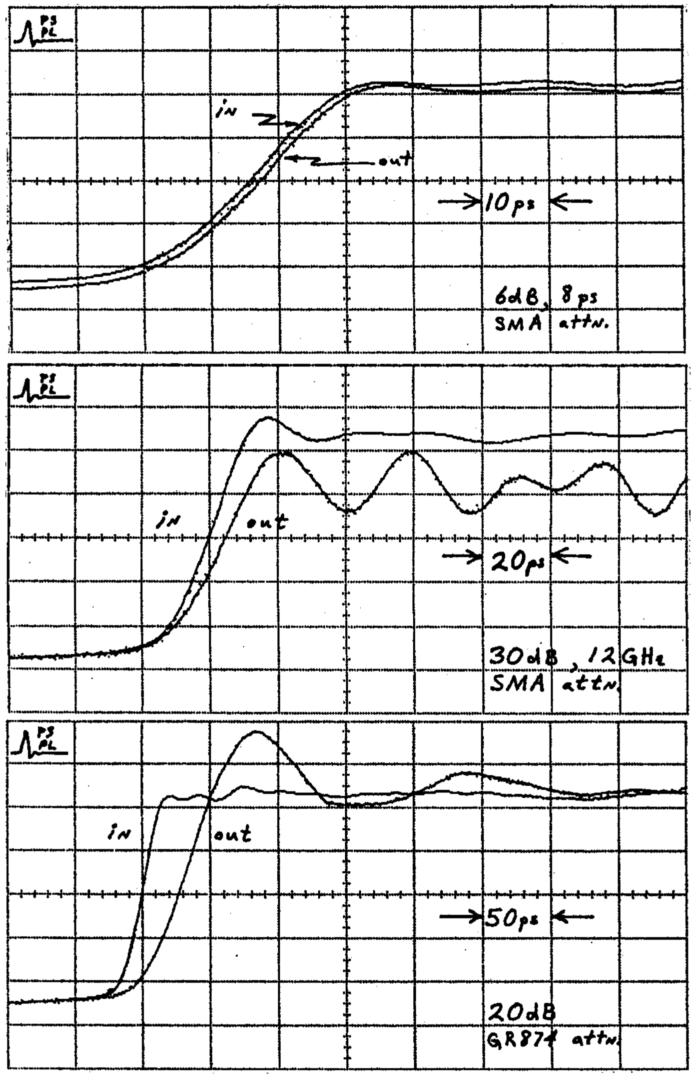

Figure 2: Examples of "Good" and "Bad" Attenuator Transient Response

attenuators have rather loose specs. A spec. of ±0.5 dB means a potential error of ±6%.

For 50 Ohm input impedance scopes, it is also important to know the actual DC input resistance. Most scope manufacturers simply say in their specs., "nominally 50 Ohms" with no % spec. For feed-thru sampling heads such as the Iwatsu SH-4B, TEK S-6 or HP-1430, the DC impedance is determined by the termination attached to the output connector by the user. A typical broadband 50 Ohm termination will have a VSWR spec. of < 1.05. This means that the resistance could be from 47.6 to 52.5 Ohms. When measuring the output from a signal source with a source impedance of 50.0 Ohms, a scope VSWR of 1.05 means that voltage measurements could be in error by as much as 2.5%. When attenuators are used, one also needs to know their impedance. Many broadband attenuators have a typical spec. of VSWR < 1.2. This means a resistance range of 41.7 to 60 Ohms and voltage measurement errors up to 9%. Input impedance mismatch also causes reflections back into the system under test. If the system is not matched, then these reflections will be re-reflected and appear later in time as distortions of the waveform.

To calibrate an oscilloscope time base, accurately known frequencies are used. Several companies produce instruments called time mark generators. Examples are the Tektronix TG501 and the Heath/Zenith IG4244. These produce pulses with repetition rates derived from a stable crystal oscillator. Digital IC dividers are used to obtain lower rep. rates in a 1-2-5 sequence. The typical upper rep. rate for this technique is 100 MHz, i.e. 10 ns time interval markers. For shorter time intervals, sine waves are typically used. Either synthesized generators or frequency counters are used to determine the actual frequency.

For time marks less than 1 ns, it becomes difficult to use sine wave generators directly. The problem lies in the poor trigger synchronization performance of most scopes for frequencies above 1GHz. The trigger circuits must provide a countdown ratio of about 100,000:1. They work fair in the short term but occasionally tend to slip phase by a cycle. This phase slip is deadly to acquiring data with signal averaging on a digital scope. There are three other techniques which avoid this problem. One is to use a synthesized, microwave signal generator and trigger the scope from the generator's 10 MHz reference output. Caution: some synthesized generators have been found to have excessive phase noise and are not suitable. The NBS technique **[11]** is to shock excite a 5 GHz transmission cavity wavemeter with a low rep. rate (100 kHz), fast 100 ps impulse. The cavity has a very high Q and thus rings at 5 GHz (1/f=200 ps) for >100 ns. The low rep. rate impulse gen. also triggers the scope reliably.

A third alternative for scope time base calibration in the ps region is to use known lengths of transmission line. For a uniform coaxial cable of known length and dielectric constant, the time delay is given by:

$$TD = 1 / v_p \qquad v_p = c / \sqrt{\varepsilon}$$

A very fast pulse could be displayed on the CRT and then the known length of coax inserted between the generator and scope and the shift in the pulse position noted. In practice this is difficult to do accurately and repeatably. The reason is that most oscilloscopes are plagued by long-term drifts of several tens of picoseconds. To get around this drift problem, we recommend instead that a different scheme be used. A coaxial tee is inserted between the pulse generator and the scope input. Various offset short circuited coax stub lines of known lengths are attached to the tee. With a fast step input, the descending staircase waveform shown in Figure 3 results. Even if time base drift is present, the leading edge is always used as the reference edge to measure the relative time shift as the various offset shorts are connected. PSPL produces a set of these Time Base Calibration Standards. It is the Model 5900A with standards for 95 ps, 191 ps, 260 ps, 500 ps, 1 ns, 2 ns, and 5 ns.

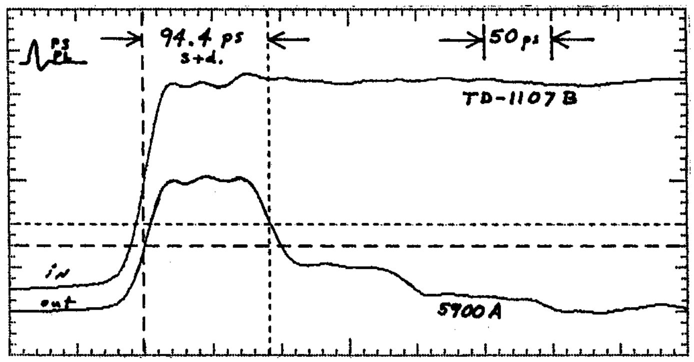

Figure 3: Time Base Calibration Using Short Circuit Stubs

COAXIAL CABLES

Having a calibrated oscilloscope is not enough to make ps measurements. The scope must still be connected to the circuit or instrument under test. In the ps domain this is always done using coaxial cable of typically 50 Ohm impedance. It comes as a shock to most newcomers in this field to discover that simple coax cable can severely distort a pulse waveform. An ideal cable would not distort a pulse. However if any ohmic loss is present in either the conductors or dielectric, then waveform distortion will occur. Another cause of waveform distortion can be phase distortion due to nonuniformities in the cable. Figure 4 shows the result of transmitting a 25 ps rise step pulse through a long length of ordinary RG-58C/U coax. This waveform is the typical response of a coax cable in which the primary loss mechanism is due to skin effect in the conductors. Wigington and Nahman's classical paper **[12]** on this subject has shown that this curve is closely approximated by the complimentary error function whose argument is inversely proportional to the square-root of time. The Cerf function has a rapid rate of rise up to the 50% level and then rolls over and takes an extremely long time to move up toward the 100% level.

The example of Figure 4 is an extreme example for ps measurements. However, even very short lengths of coax can still cause errors in the ps domain. Cable runs of 1 ft. to 3 ft. are not uncommon in ordinary test set-ups. Figure 5(a) shows the effect of passing a fast TD-1107B pulse through 25 to 200 cm of RG-58C/U. The leading edge is slowed down and the amplitude is decreased. On slower time scales the slow Cerf function dribble-up is very apparent. Even short lengths of RG-58C/U cause severe distortion of ps pulses. Better quality cable is required for ps measurements. The coax cable usually used is CT-141- 50 with SMA connectors. It is 0.141" dia., semi- rigid coax built with a solid silver-plated copper or copper-weld center conductor. The outer conductor is solid copper and the dielectric is Teflon. The 50 Ohm impedance is very uniform and can be held to less than ±0.5 Ohms. Figure 5(b) shows the effect of passing the TD-1107B pulse through 15 to 200 cm of CT-141-50. There are also some special, expensive, microwave test set, flexible cables made with expanded Teflon and larger diameter center conductors. They have even lower losses than the CT- 141-50 semi-rigid. These special cables are built by Gore-Tex, Adams-Russell, Sealectro, Suhner and others. Figure 5(c) shows the response of some Gore cables. Do not use for pulse measurements any coax cables that use spline or tube dielectrics or have corrogated conductors. These cables have low attenuation, but poor phase responses. Phase distortion in these cables causes Bessel function ringing in the step response. Figure 5(d) shows this effect in a microwave test set cable.

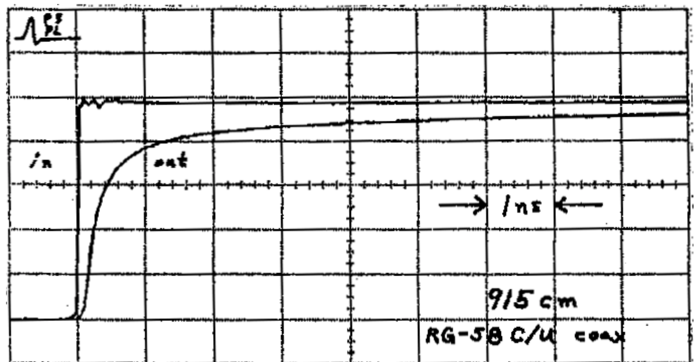

Figure 4: Step Response of a Long Coaxial Cable Showing the Classical Skin-effect "Dribble-up"

It is also instructive to see what happens to an impulse after it has been passed through short lengths of coax. cable. Figure 6 below shows the effect of passing a 64 ps wide (FWHM) impulse through 25 to 200 cm of RG-58C/U. The output impulse is smeared out and has lost amplitude.

COAX CONNECTORS

Connectors are required to attach coax cables to various circuits and instruments. The choice of connectors is also very important to maintain the pulse waveform fidelity in the ps domain. The connector must have the same characteristic impedance as the coax cable and not introduce any impedance discontinuities. The BNC connector which is very widely used throughout the electronics industry is not suitable

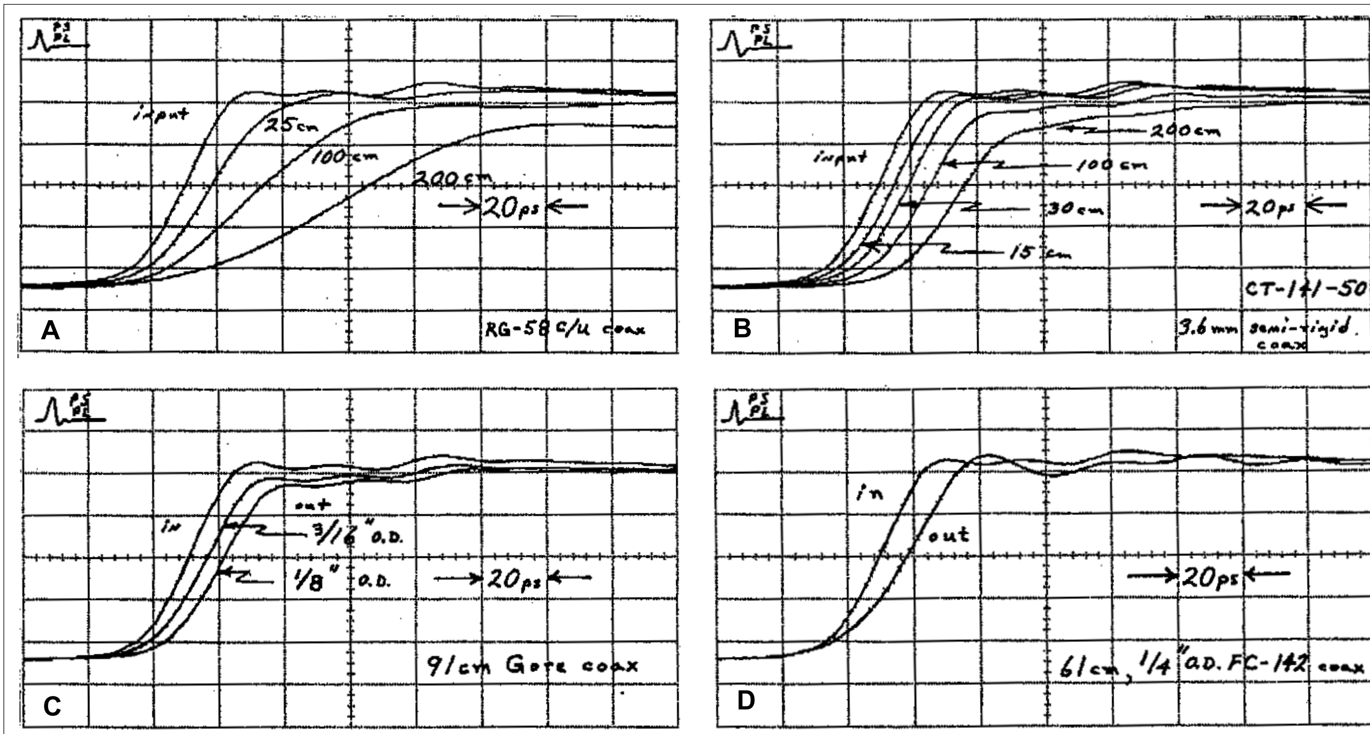

Figure 5: Transient Responses of Short Coaxial Cables

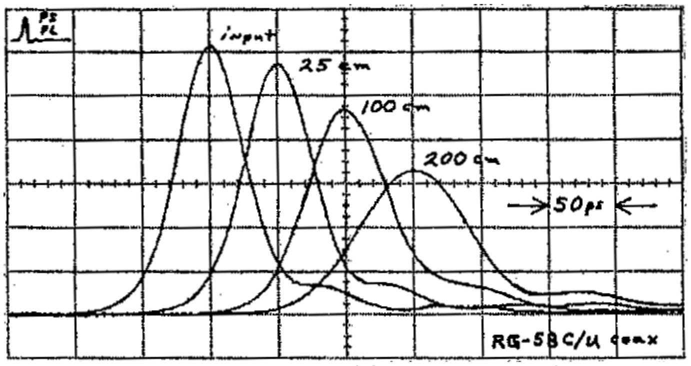

Figure 6: Impulse Response of Short Lengths of RG-58C/U

for pulses faster than 1/3 ns. Figure 7(a) shows the result of passing the TD-1107B pulse through a BNC plug/jack connector pair. Another consideration is the physical size of connectors or coax. If the connector diameter is too large, then the presence of nonuniformities and the high frequency spectrum of fast rising pulses will excite higher-order waveguide modes in the connector. Figure 7(b) shows the higher-order mode ringing in a 14mm dia. GR874 connector pair when passing the TD-1107B pulse. The industry standard connector for frequencies to 18 GHz and pulses of > 20 ps is the SMA. The SMA was designed for the 0.141" semi-rigid coax. Precision type N and APC-7 connectors can also be used to 18 GHz or 20 ps. For even faster

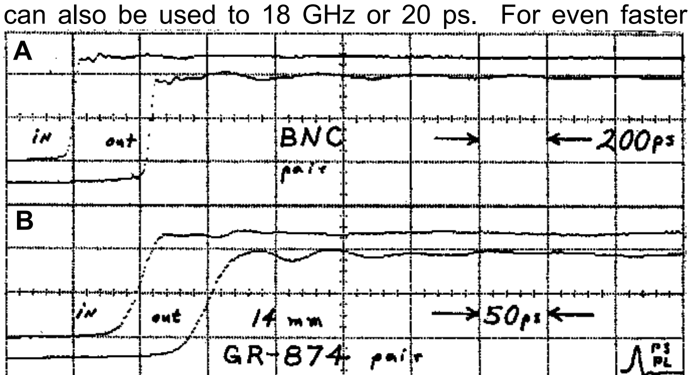

Figure 7: Step Response of BNC (top) and 14 mm, GR-874 (bottom) Connector Pairs

risetimes (< 20 ps) the industry is moving to the even smaller, higher frequency coax connectors such as the APC-3.5, K, and OSM-50. Having the right connector is still not enough if it is not installed or used properly. Considerable pulse distortion and ringing can occur when a connector is not tightened properly.

PROBES

Coax cables are always the preferred means to connect to circuits for ps measurements. However there are some situations where this is not practical and the experimenter would prefer to use a high impedance, hand held probe. Conventional 10 X, 10 M Ohm probes are not useful below 1ns (350 MHz). TEK and Phillips do build active probes which incorporate a FET within the probe. They are useful down to 350 ps (1 GHz). IWATSU, TEK and HP build 10 X, 500 Ohm resistive divider probes with faster risetimes. These 10 X probes consist of a 450 Ohm resistor in the probe tip which provides a 10:1 resistive divider into the 50 Ohm probe output coax cable which then is terminated into the 50 Ohm scope input. Figure 8 shows the results of tests PSPL run on the HP and TEK probes. The probe was inserted into an aperature in a 3 mm coax line to measure the TD-1107B pulse. The bottom plot dramatically shows the effect of not using a very short ground connection. The added inductance of a short 10 cm ground wire causes ringing which extends well into the ns region.

There are times when it is desirable to monitor a signal in a coax line without loading it. An example might be to monitor the input and output signals of a GaAs digital IC. Hand held

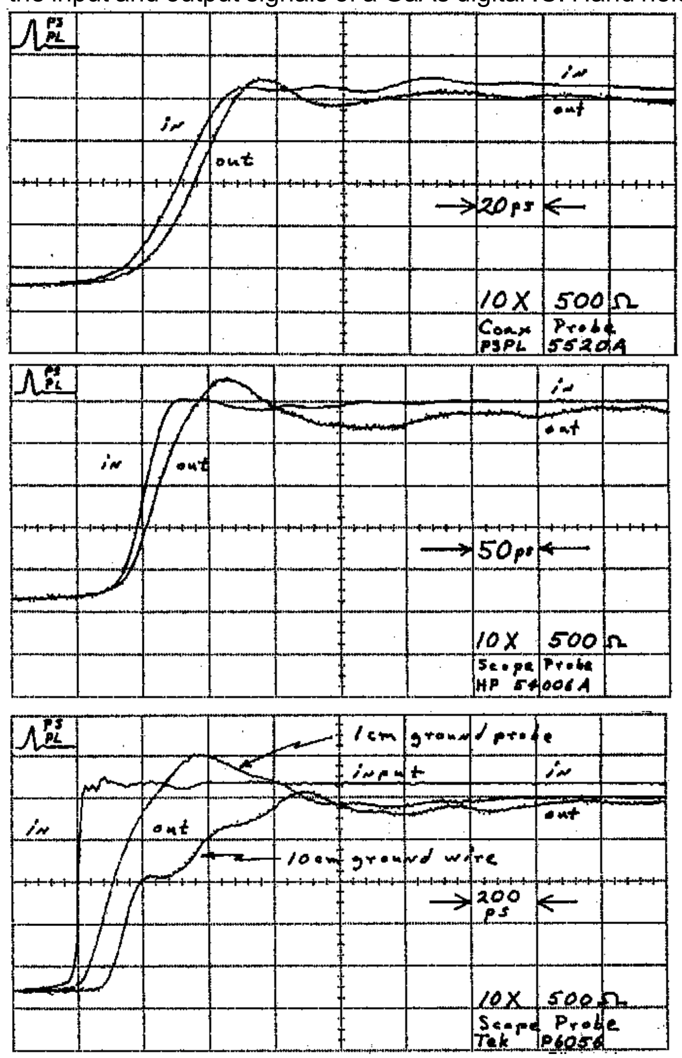

Figure 8: Step Responses of 10 X, 500 Ohm Signal Probes

probes are not suitable. Instead a 10 X, 500 Ohm probe built into a coaxial line structure should be used. The PSPL Model 5520A is an excellent choice. It has a transition duration of < 20 ps and passes a pulse waveform with minimal distortion. Figure 8 shows the 5520A's 10X output when monitoring the 25 ps TD-1107B pulse.

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