TDR 2006
Purdue University

A New Type of Test Signal for Improved TDR Resolution

Robert Flake, Isidro Lopez Jr. and Shi-jing Wang

Ref.: Flake, Robert, Lopez Jr., Isidro and Wang, Shi-jing, "A New Type of Test Signal for Improved TDR Resolution", Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID 34, 15 p., https://engineering.purdue.edu/TDR/Papers

A New Type of Test Signal for Improved TDR Resolution

Robert Flake[1], Isidro Lopez Jr[2]. and Shi-jing Wang[3]

[1]Professor of Electrical and Computer Engineering, The University of Texas at Austin, College of Engineering, Austin, TX 78712; PH (512) 471-1014; email: flake@ece.utexas.edu

[2]Graduate Student, The University of Texas at Austin, College of Engineering, Austin, TX 78712; PH (512) 471-0843; email: ilopez@mail.utexas.edu

[3]Graduate Student, The University of Texas at Austin, College of Engineering, Austin, TX 78712; PH (512) 471-0843; email: swang@ece.utexas.edu

Abstract

A new generation of high-resolution TDR instruments for testing cables will be discussed. The major advance in precision obtained with this new TDR is the result of the utilization of a TDR test signal, which does not undergo dispersion or change shape during transmission on lossy dispersive transmission lines.

Key Words Testing, Interconnects, Metal, Delay, Skew, High-Performance

Introduction

A new generation of high-resolution Time Domain Reflectometer (TDR) instruments for testing cables is being developed in our laboratory [1]. The major advance in precision obtained with this TDR is the result of the discovery and utilization of a non-sinusoidal signal that does not undergo dispersion or change of shape during transmission on lossy dispersive transmission lines [2-3]. This special signal is employed as the test pulse in this new type of TDR. This paper describes this signal and its remarkable behavior during propagation on long lossy metal cables.

This special waveform, in its simplest form is a pulse having a leading edge that is a positive exponential. The signal is referred to as "Speedy Delivery" (SD).

The time of flight (TOF) of the SD test signal traveling down and back from a cable fault is measured by obtaining equal voltage threshold crossing times of the input pulse and of the resulting reflected pulse propagating back from an impedance change at a fault in the cable. This process is repeated for a large number of threshold voltages and averaged to obtain the estimated TOF of the test signal to and from the location of the impedance change which caused the signal reflection.

Since the leading exponential edge of the test signal maintains its shape during transmission down the cable as well as after being reflected back to the input, all these (typically 100) TOF values obtained from 100 voltage threshold crossing times are essentially equal. These individual threshold TOF measurements are then averaged to obtain the estimated TOF of the SD test pulse. The result is a remarkable accuracy improvement in signal delay measurements obtained with this SD/TDR when compared with current state-of-the-art cable TDR technology.

The detailed description of the SD signal delay analysis is discussed next, followed by an example of measurements on a lossy dispersive 100m cable. These experimental measurements illustrate the shape preserving transmission nature of the SD pulse on cables and the remarkable SD/TDR resolution. Finally a preliminary study of the SD/TDR resolution vs. extended cable lengths (up to 400m) is presented.

Delay Analysis of the SD Waveform

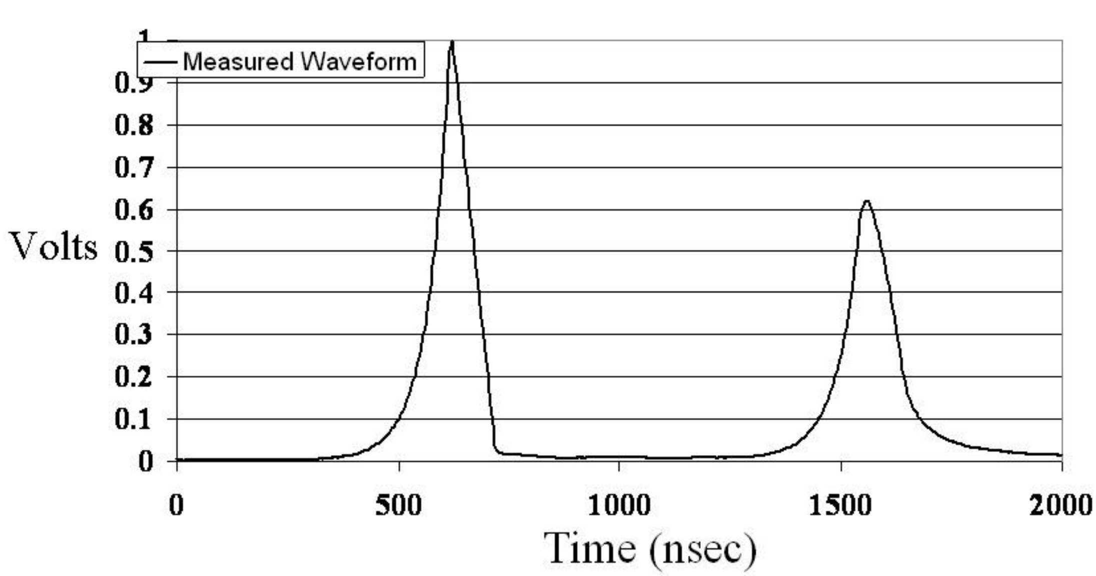

Figure 1: The Shape of the Leading Edge of the Reflected SD Waveform is unchanged after 200m Propagation on Coaxial Cable (SD/TDR Measurement)

Figure 1 shows the applied and reflected SD waveform on an unterminated 100m cable. The waveform on the right is the reflected pulse. The leading edge of this pulse keeps its shape as it propagates 200 meters (down and back) along the cable. Note the loss of signal amplitude of the reflected waveform and the dispersion of the tail of this pulse. However, the leading edge of this pulse keeps its shape. This is illustrated in figure 2, where the applied wave is translated in time so that the front edges of the two pulses coincide.

Figure 3 is a close-up of these overlapped pulses showing the precision of fit of the leading edges of the applied and reflected waves.

Measurement of SD Signal Delay

Figure 4 illustrates the method used to measure SD signal propagation delay. The time intervals between the crossing times of applied and reflected waves at equal threshold voltages are measured. 100 threshold voltage levels are selected inside a voltage interval, (e.g. 0.15 to 0.45 Volts). Since the shapes of the SD signal's leading edges are identical for the applied and reflected waves, the threshold crossing time intervals at each voltage level are theoretically equal. These measured time intervals are averaged to obtain the estimated delay or TOF of the propagating pulse.

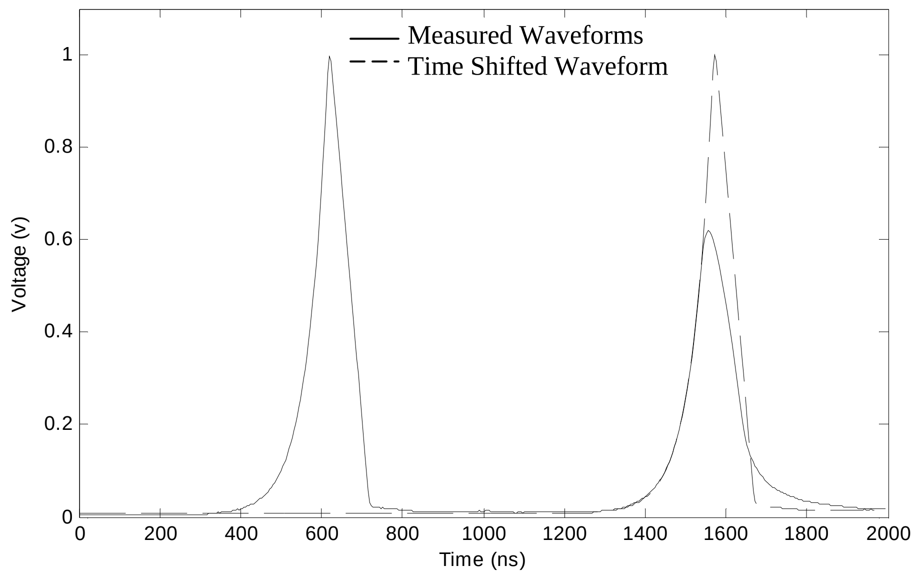

Figure 2: Reflected SD Waveform Preserves its Shape after 200m Propagation on Coaxial Cable (note applied input after translation)

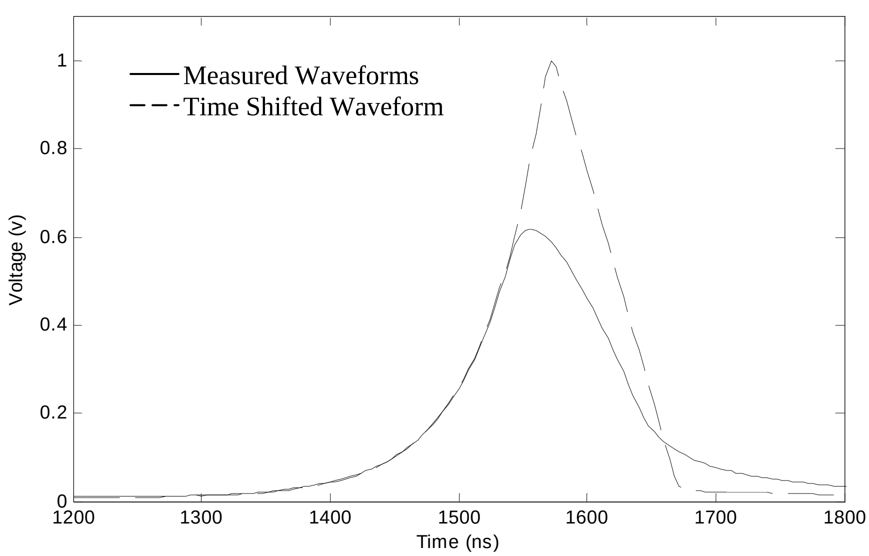

Figure 3: Reflected SD Waveform Preserves its Shape after 200m Propagation on Coaxial Cable (close up showing applied input after translation)

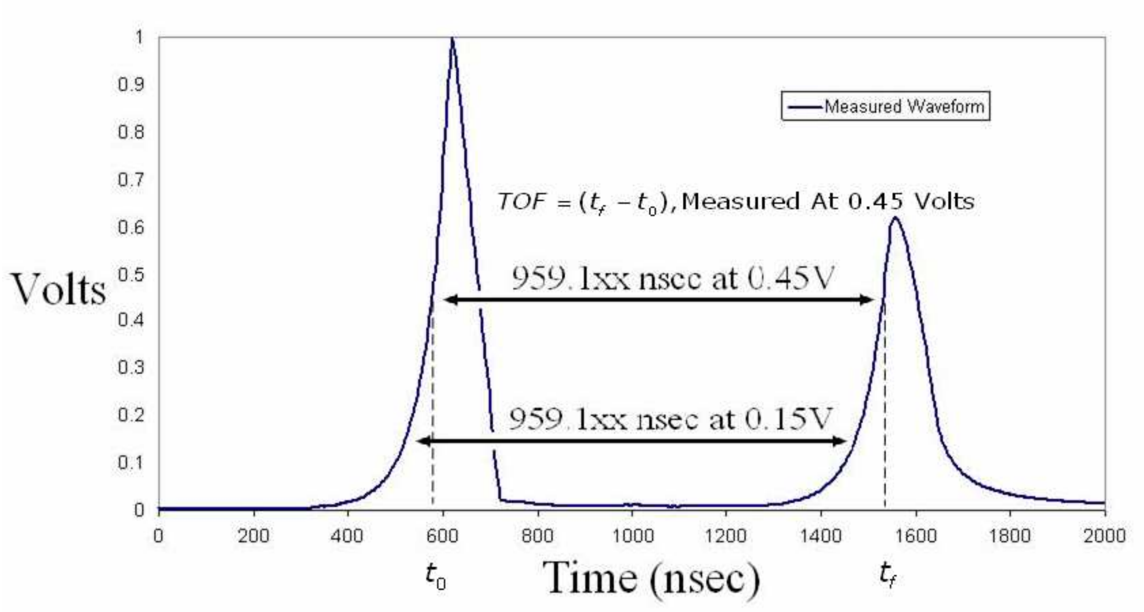

Figure 4: Measurement of SD Signal Propagation Delay

Figure 5 shows measurements of equal-voltage TOF intervals vs. threshold voltage plotted on the horizontal axis. The average of 100 constant voltage level TOF values was obtained between 0.15 volts and 0.45 volts. The histogram of these TOF measurements is shown in the Figure 5.

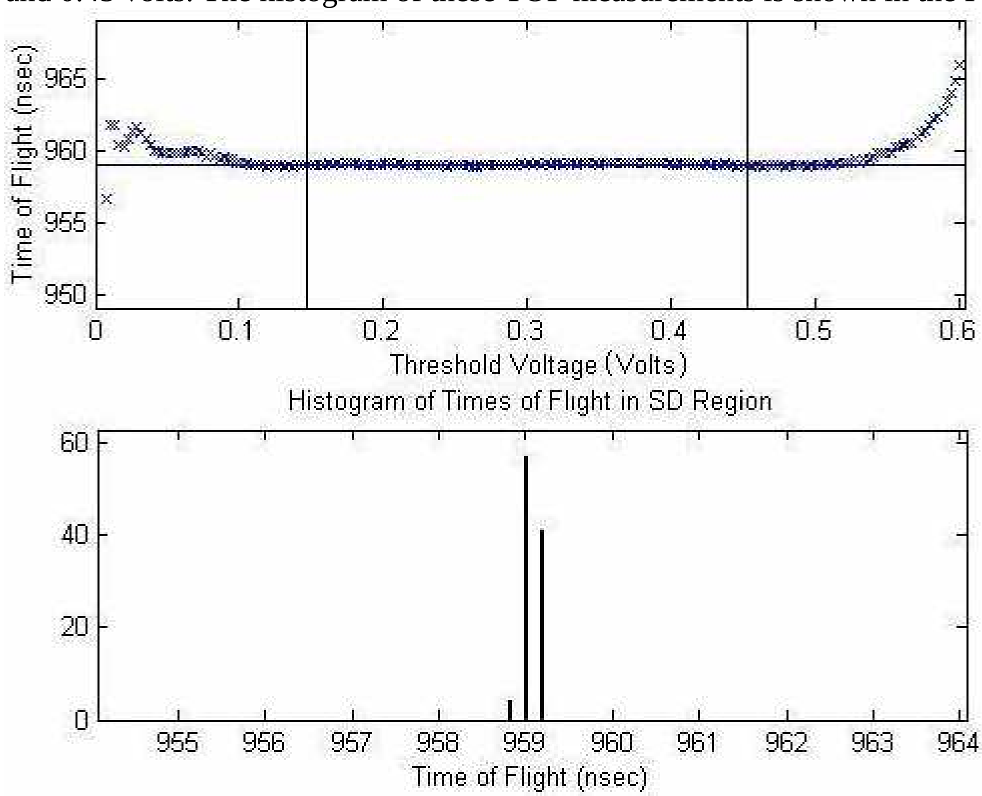

Figure 5: Measurement of SD Signal Propagation Delay

The three histogram buckets, in Figure 5, are 200 ps apart. 200 ps is the sample period of the 5 Giga Sample/ second digital oscilloscope used to measure these waveforms. This process of averaging a large number of equal threshold TOF measurements to obtain the TOF of the signal results in an enhanced accuracy for the basic TDR measurement, i.e. total propagation delay of the test signal.

The Virtual Instrument SD/TDR Hardware

The SD signal is used as the test signal in the cable SD/TDR. The virtual instrument type of TDR constructed in our laboratory [1] is illustrated in the following figure. The hardware used to implement the SD/TDR consists of a laptop computer, a digital oscilloscope (500 MHz Bandwidth, 5GS/s) and an Arbitrary Waveform Generator (AWR) with 80 MHz Bandwidth. The applied waveform shown in Figure 4 generated by the AWG is applied to the cable.

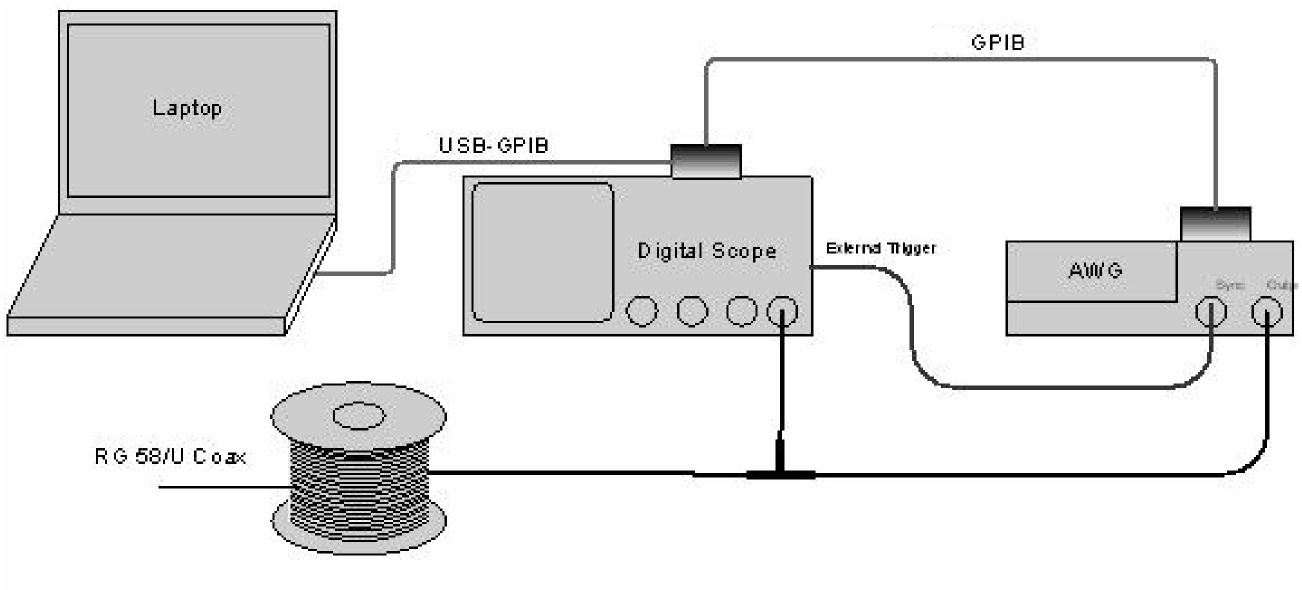

Figure 6: The Virtual Instrument SD/TDR Hardware

SD/TDR Resolution

Introduction to SD/TDR Software used to demonstrate the resolution of the SD/TDR

TDR measurements were made on a RG-58/U cable ("Coil 4": approximate 300ft (100m) long) using the "Speedy Delivery" signal as the test pulse. The average ("Mean 1" see Figure 7) of 30 SD signal delay measurements on the unterminated cable was obtained and then a short length of the cable was cut off. Then 30 more delay measurements were made on the slightly shortened cable to obtain a second average of 30 TOF values ("Mean 2" see Figure 7).

When the TDR instrument finished these measurements, the second SD signal delay mean (Mean2=968.662 ns), obtained from 30 TOF measurements after the cut was subtracted from the mean cable delay before the cut (Mean1=968.721 ns). The TOF difference (59.6ps) was divided by 2 (two-way signal travel on the cut piece of cable) and then divided by 131.3 ps/in. (our calibrated SD signal delay/ length for this cable). The result obtained was the predicted length of the cut fragment ("Equivalent distance": see Figure 7) of cable, 0.227in. (5.77mm), displayed on the SD/TDR computer monitor.

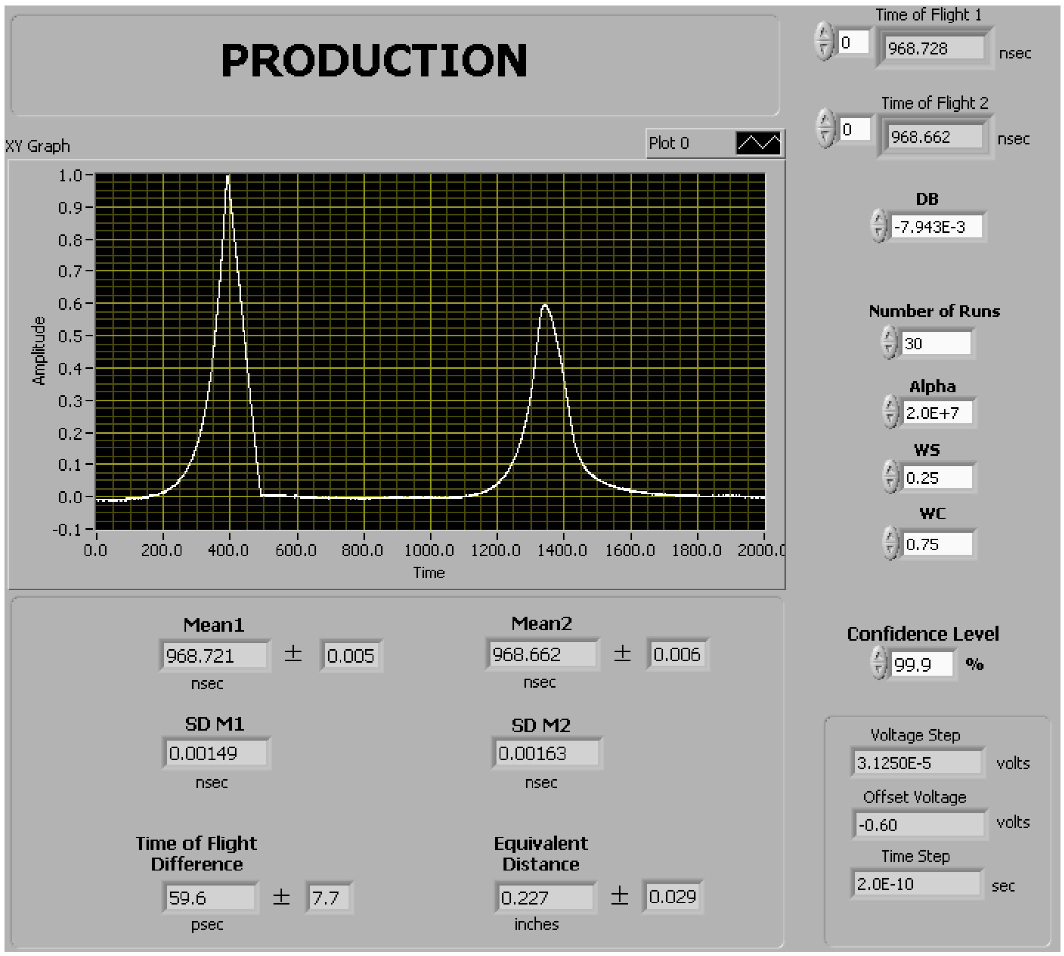

Figure7: SD/TDR Faceplate Computer Screen of the SD/TDR Production Software

Caliper measurements of the length of the cut off cable piece were also made by two observers of the experiment: 0.205in. (5.21mm) and 0.202in. (5.13mm). The differences between the SD/TDR estimated cut-off length and the two caliper measurements were .022in. (0.56mm) and .025in. (0.64mm) respectively, which when divided by 3600in. (300ft./100m) resulted in a 6.1ppm and 6.9ppm discrepancies or estimates of the SD/TDR relative spatial resolution. The corresponding experimental estimates of the absolute spatial resolution were 0.022in. (0.56mm) and 0.025in. (0.64mm).

Figure 7 also contains the reproduced digital oscilloscope display showing the transmitted and reflected pulse on the cable. In Figure 8, the measured waveform data is re-plotted by the demonstration software for both applied and reflected signals. The region in this demonstration chosen for the threshold voltages used to measure TOF data was between 25% and 75% of the peak voltage (VR) of the reflected wave. (Refer to Figure 1: $ws = 0.25$, $wc = 0.75$)

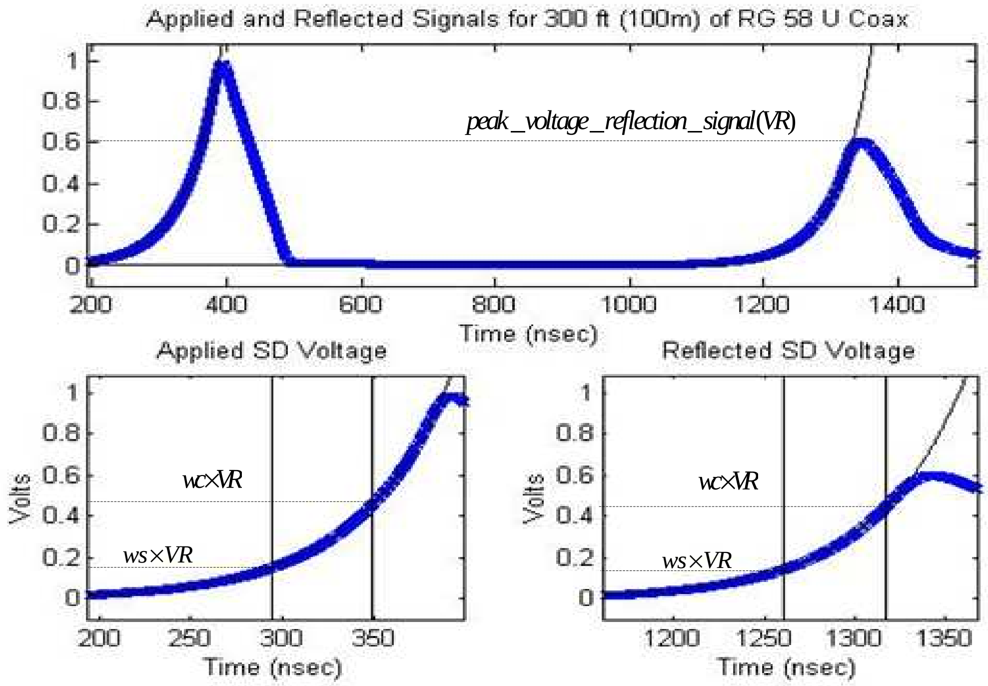

Figure 8: Applied and Reflected Signals along 300ft (100m) of unterminated RG-58 U Coax. (VR is the peak voltage of the reflected signal.)

The measured waveforms of both applied and reflected signals have the same SD wave shape ($V(t) = De^{\alpha t}$), which become linear ($\ln(D) + \alpha t$) in the natural log plots of the applied and reflected signals vs. time shown in figure 9.

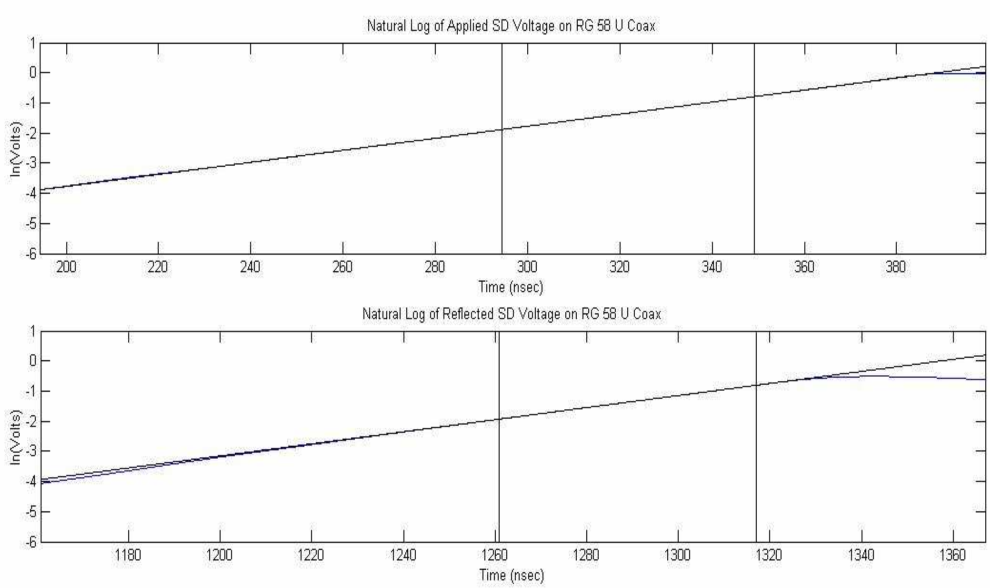

Figure 9: Natural Log of Applied and Reflected SD Voltages on the RG-58/U Coax

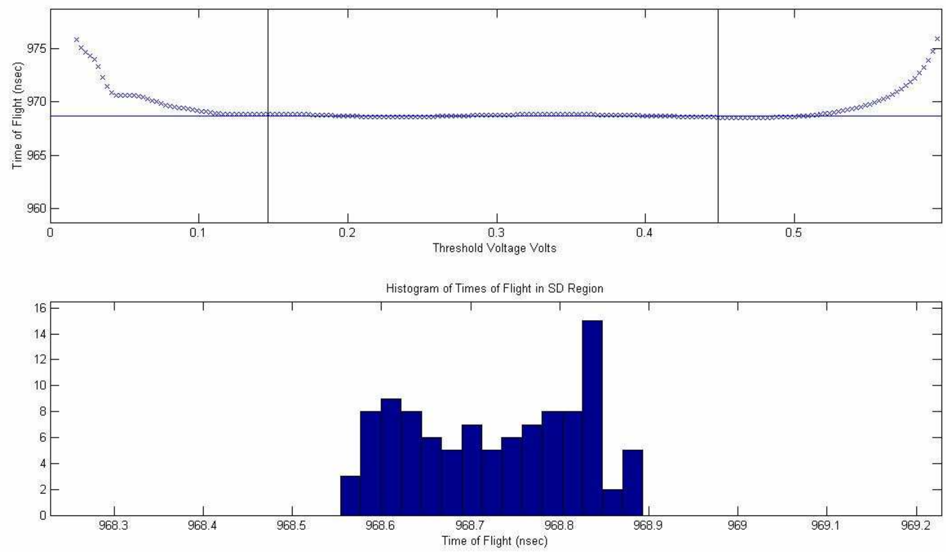

Figure 10: Histogram of Equal Voltage Times of Flight in SD Region Averaged for a Single TOF Measurement

The top graph in Figure 10 shows the TOF measurements vs. threshold measurement voltage. The bottom graph in Figure 10 is the histogram of 100 Times of Flight values obtained from threshold voltages inside the signal voltage range (0.15v to 0.45v) defined by faceplate parameters *ws* and *wc* (see figure 7).

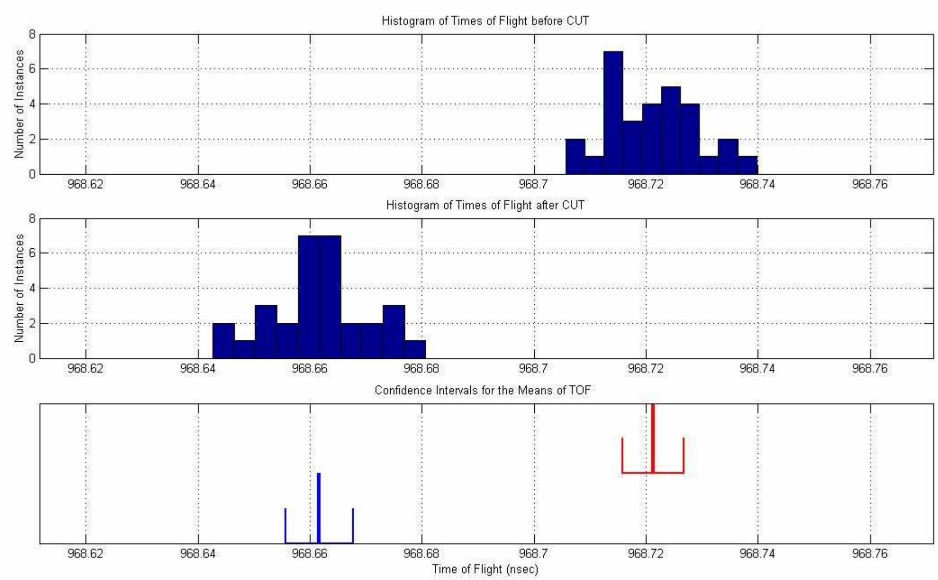

Figure 11: Histogram for 30 sample TOF measurements before and after CUT and the 99.9% confidence intervals of the two mean TOF (Mean 1 and Mean 2, see Figure 7) measurements.

The top graph of Figure 11 shows the histogram of the 30 SD signal delay measurements made before the cut (e.g. a small 5mm section was cut from the 100m cable length) that were averaged to obtain Mean1 (968.721 ns) shown in Figure 7. The middle graph of Figure 11 is the histogram of the 30 delay measurements made after the cable was trimmed. These measurements were averaged to obtain Mean2 (968.662 ns) shown in Figure 7. The bottom graph of Figure 11 shows Mean1 and Mean2 and a bar-diagram of their 99.9% t-distribution confidence intervals for the means of the 30 delay measurements.

Comparison with Spatial Resolution of Conventional TDR

In conventional TDR theory for high resolution units, the minimum spatial resolution is a function of the rise time of the applied TDR test pulse and the dielectric constant of the metal interconnect being measured. This minimum spatial resolution is:

$$l = \frac{t_r c}{2\sqrt{\varepsilon_r}},$$

Where: l is the length of the minimum spatial resolution, c is the speed of light in vacuum, t_r is the rise time of the applied test pulse, and ε_r is the relative dielectric constant of the interconnect.

Comparison of the SD/TDR Resolution with the Minimum Spatial Resolution of a Conventional TDR

The spatial resolution estimates obtained from the SD/TDR measurements on the cable were 0.022in (0.56mm) and 0.025in (0.64mm), the value of ε_r for the coaxial cable was 2.3. Conventional TDRs with these spatial resolutions would require test pulse rise times,

$$t_r = \frac{\ell * 2\sqrt{\varepsilon_r}}{c} = \frac{(0.56*10^{-3})*2\sqrt{2.3}}{3*10^{8}} = 5.66\,ps$$

and

$$t_r = \frac{\ell * 2\sqrt{\varepsilon_r}}{c} = \frac{(0.64*10^{-3})*2\sqrt{2.3}}{3*10^{8}} = 6.47\,ps$$

A test pulse with either of these rise times applied by a TDR would contain such high frequency energy that the leading edge of the propagating pulse used to estimate the signal TOF would be unresolvable by the TDR after traveling 200m on this RG-58/U coaxial cable.

Comparison of Equivalent Electrical Length (EEL) with Caliper Measurement

Statistical comparisons of the SD/TDR estimate (“Equivalent Distance” see Figure 7) of the cut cable fragment length compared with the measurements of this fragment length using a caliper are discussed below.

The Equivalent Electrical Length (EEL) of the caliper measurement of the cut cable fragment from a 300ft (100m) RG-58/U cable (Coil 4) is also compared graphically with the measured SD/TDR signal TOF before and after the cut in Figure 12.

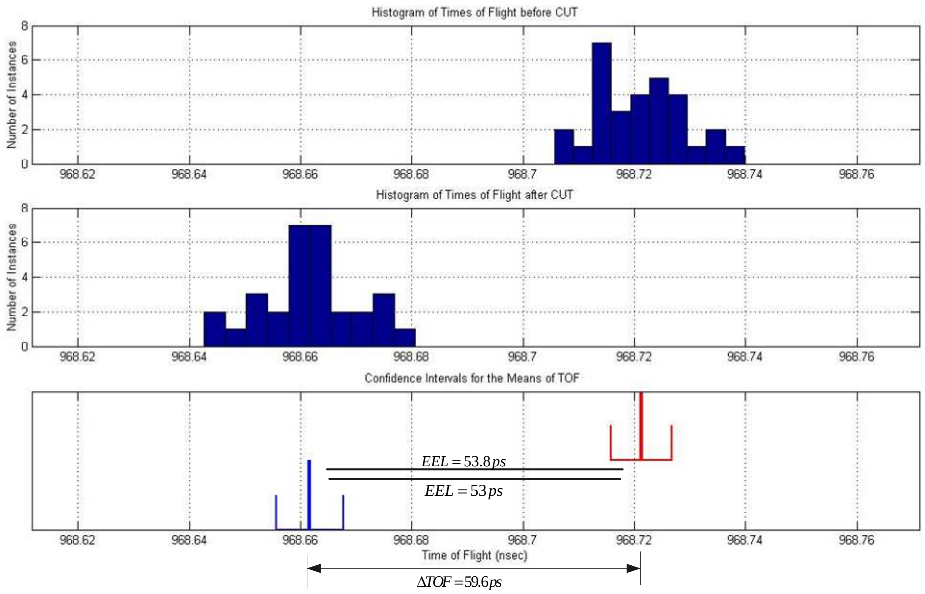

Figure 12: Equivalent two-way Electrical Length (EEL)
of two cut Fragment Caliper Measurements vs. ΔTOF for Coil 4 (100m)

The caliper measurements of the length of the cut off piece made by two observers were: 0.205 inch (0.64mm) and 0.202inch (0.56mm). Their equivalent Electrical Lengths (in ps) are computed as shown below:

$$\text{Two Way Equivalent Electrical Length 1 or EEL 1 (ps)} = 0.205(\text{inch}) \times 131.3(\frac{\text{ps}}{\text{inch}}) \times 2 = 53.8ps$$

$$\text{Two Way Equivalent Electrical Length 2 or EEL2 (ps)} = 0.202(\text{inch}) \times 131.3(\frac{\text{ps}}{\text{inch}}) \times 2 = 53ps$$

These Equivalent Electrical Lengths are added to figure 11 and shown as Figure 12 above. Note the close comparison of the EEL of the cut cable fragment corresponding to the length measured by a caliper with the equivalent difference in mean SD/TDR TOF cable measurements before and after the cut.

Various combination circuits containing four similar length RG-58/U cable coils (“Coil2”, “Coil3”, “Coil4” and “Coil5”) were used in a series of SD/TDR resolution studies by repeating the series of measurements previously discussed on the single coil (“Coil4”). The following figures (analogous to Figure 12 for Cable 4) summarize these measurements for various combinations of circuits formed from the series connection of the four cables.

Summary Study of SD/TDR Resolution Results Obtained Over a Range of Extended Cable Lengths from 100m to 400m

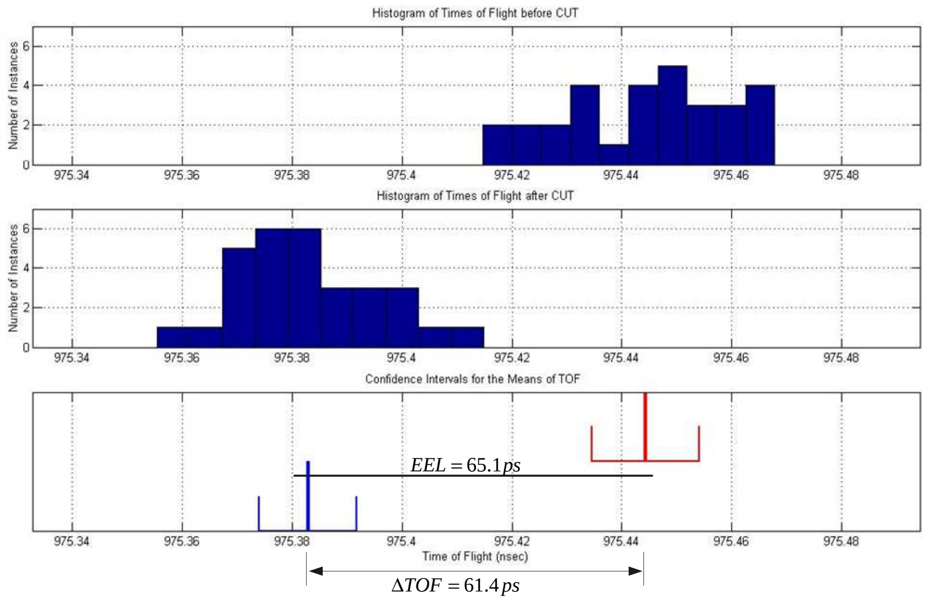

Figure 13: Equivalent two-way Electrical Length (EEL)
of a cut Fragment Caliper Measurement vs. ΔTOF for Coil 2 (100m)

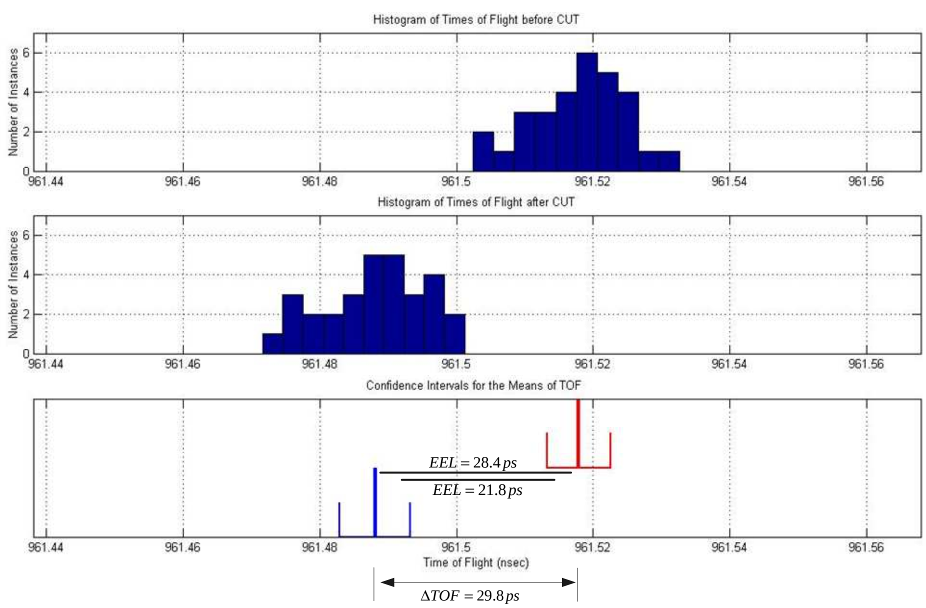

Figure 14: Equivalent two-way Electrical Length (EEL)
of a cut Fragment Caliper Measurement vs. ΔTOF for Coil 3 (100m)

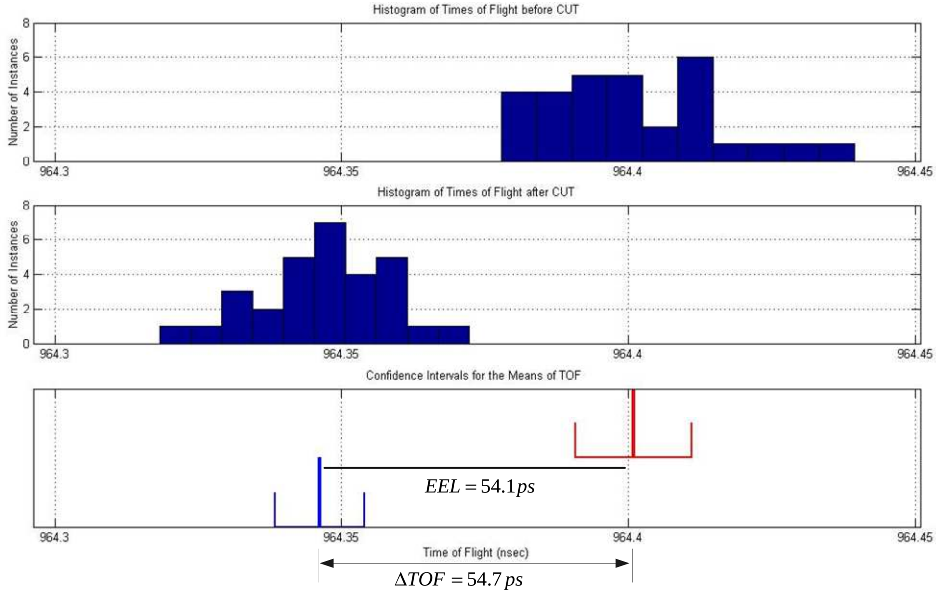

Figure 15: Equivalent two-way Electrical Length (EEL) of a cut Fragment Caliper Measurement vs. ΔTOF for Coil 5 (100m)

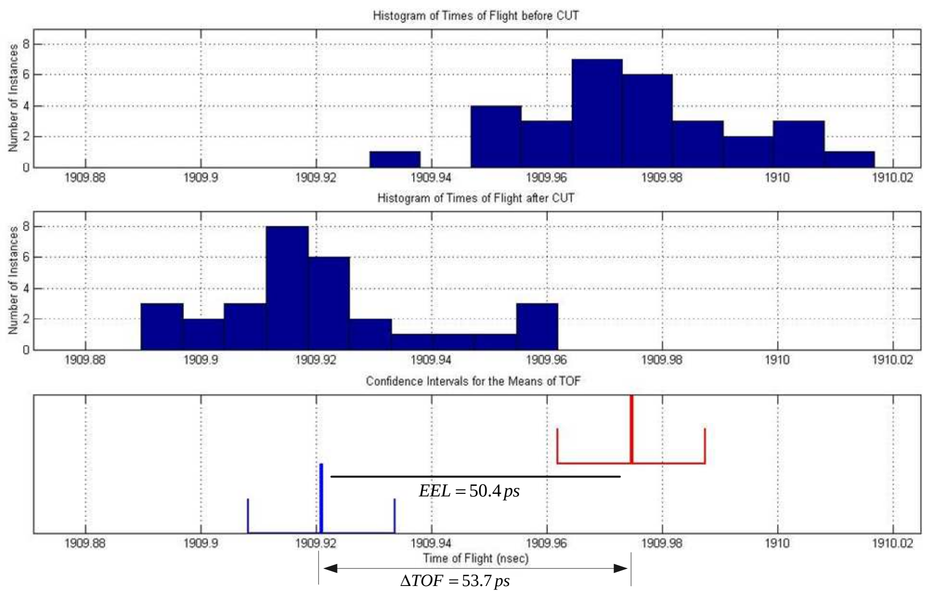

Figure 16: Equivalent two-way Electrical Length (EEL) of a cut Fragment Caliper Measurement vs. ΔTOF for Coil 2 and Coil 3 Connected in Series (200m)

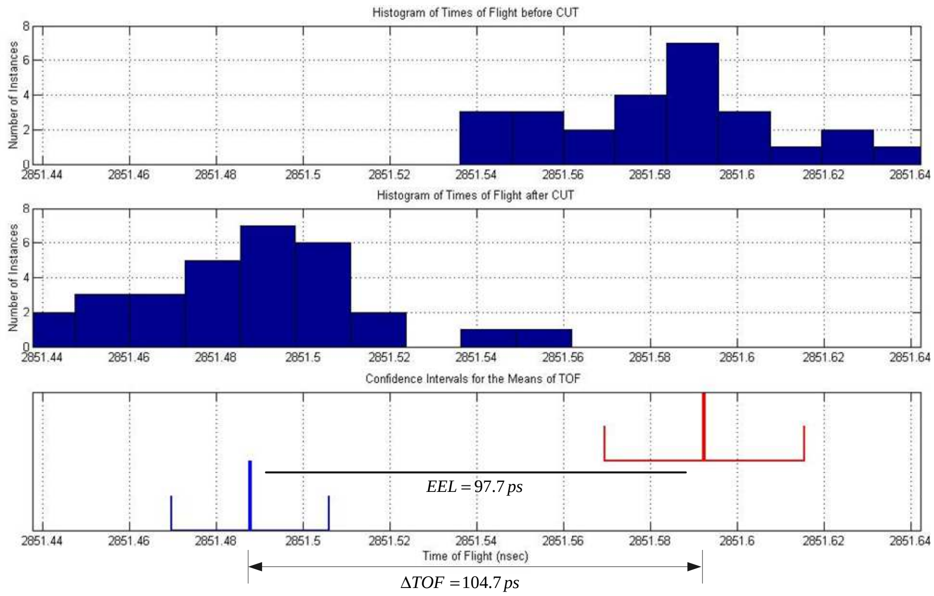

Figure 17: Equivalent two-way Electrical Length (EEL) of a cut Fragment Caliper Measurement vs. ΔTOF for Coil 2, Coil 3 and Coil 4 Connected in Series (300m)

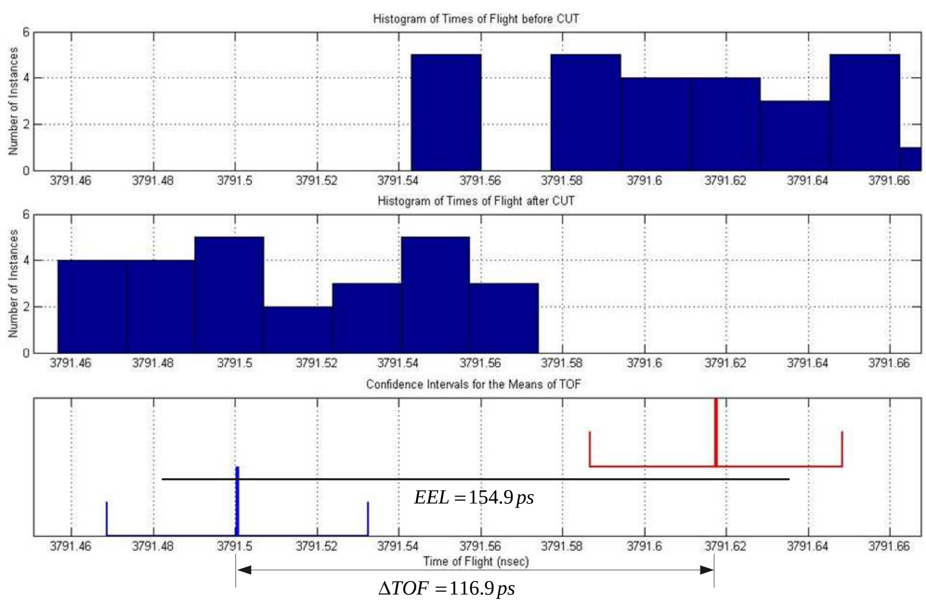

Figure 18: Equivalent two-way Electrical Length (EEL) of a cut Fragment Caliper Measurement vs. ΔTOF for Coil 2, Coil 3, Coil 4 and Coil 5 Connected in Series (400m)

The summary of these SD/TDR resolution measurements is collected in Table 1 below.

Table 1: Summary of Results of Extended SD/TDR Resolution vs. Cable Lengths

TDR Resolution vs Distance								
Est. Cable Length	Coil	Mean TOF before Cut ("Mean1")	Mean TOF after Cut ("Mean2")	"TOF Difference"	Estimated Length of Cut ("Equivalent Distance")	Caliper Measure-ment	Resolution	Relative Resolution (Relative Error)
m		nsec	nsec	psec	in. (mm)	in. (mm)	in. (mm)	ppm
100	Coil 2	975.444	975.383	61.4	0.234 (5.94)	0.248 (6.30)	0.014 (0.36)	3.9
100	Coil 3	961.518	961.488	29.8	0.114 (2.90)	0.108 (2.74)	0.006 (0.15)	1.7
						0.083 (2.11)	0.031 (0.79)	8.6
100	Coil 4	968.721	968.662	59.6	0.227 (5.77)	0.205 (5.21)	0.022 (0.56)	6.1
						0.202 (5.13)	0.025 (0.64)	6.9
100	Coil 5	964.401	964.346	54.7	0.208 (5.28)	0.206 (5.23)	0.002 (0.05)	0.6
200	Coil2 and Coil3 in Series	1909.975	1909.92	53.7	0.205 (5.21)	0.192 (4.88)	0.013 (0.33)	1.8
300	Coil 2, Coil3 and Coil4 in Series	2851.592	2851.49	104.7	0.399 (10.13)	0.372 (9.45)	0.027 (0.69)	2.5
400	Coil2, Coil3, Coil4 and Coil5 in Series	3791.617	3791.5	116.9	0.445 (11.30)	0.59 (14.99)	0.145 (3.68)	10.1

The SD/TDR Resolution vs. Cable Length and SD/TDR Relative Resolution vs. Cable Length results obtained in these experiments are plotted in Figure 19 and Figure 20 below. This demonstrates that the SD/TDR has a much higher resolution than conventional cable TDRs.

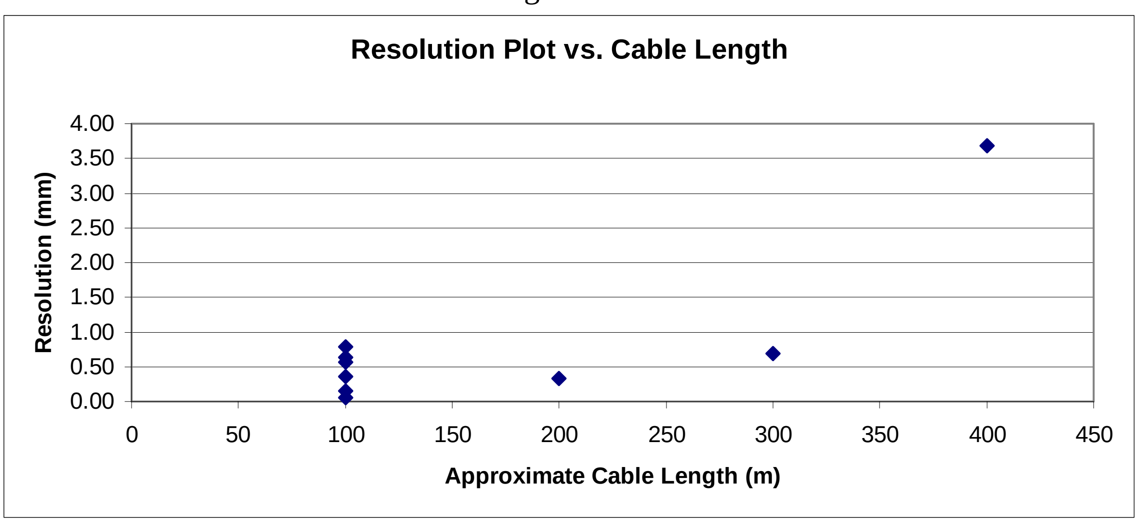

Figure 19: Summary of TDR Resolution Results vs Cable Lengths

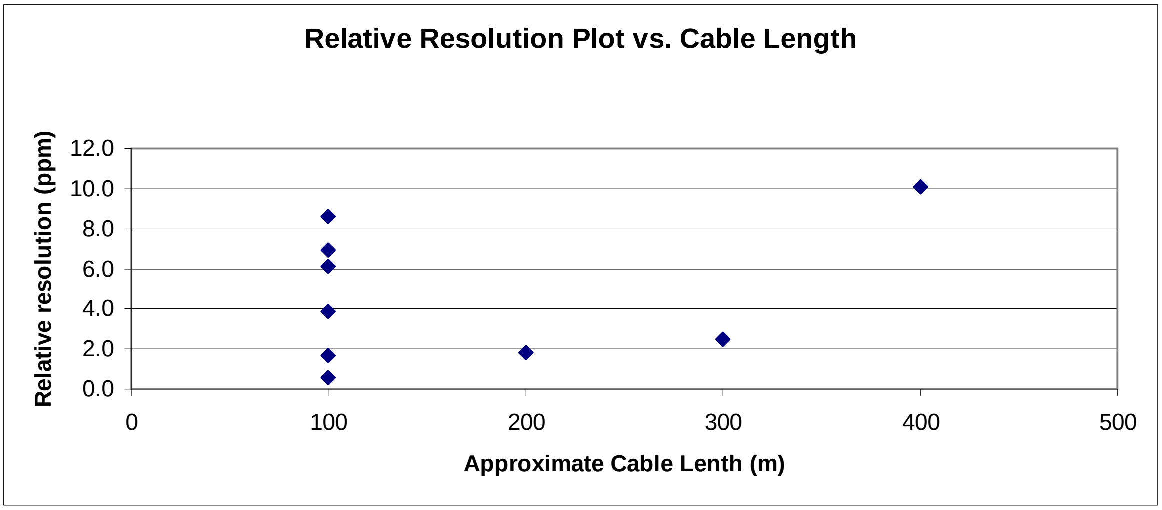

Figure 20: Summary of SD/TDR Relative Resolution vs. Cable Lengths

Conclusions

The application of the SD signal in a virtual instrument version of a TDR (SD/TDR) was discussed. Experimental results obtained with the instrument measuring electrical lengths of coaxial cables were presented. Remarkable spatial resolution (~10 ppm) of electrical length measurements (Signal Delay) was obtained with the SD/TDR pulses on cables ranging from 100 m to 400 m in length. The practical application of this result is that we can measure total signal delay on cables with an accuracy far surpassing current commercial cable TDRs.

References

[1] R. H. Flake, S. Liao, S.J. Wang, "Advances in Test Technology for High-Speed System Interconnects", Proceedings of the 12th International Conference on Mixed Design of Integrated Circuits and Systems (MIXDES 2005), June 22-25, 2005, Krakow, Poland

[2] R. H. Flake and J. F. Biskup, "Signal propagation without distortion in dispersive lossy media", 11th IEEE International Conference on Electronics, Circuits and System Proceedings, pp. 407-410, Dec 2004, Tel-Aviv, Israel. ISBN 0-7803-8715-5.

[3] Robert H. Flake and John Biskup, "Part II (Experiments) Signal Propagation without Distortion on Lossy Transmission Lines Having Frequency Dependent Parameters", 9th IEEE workshop on signal propagation on interconnects, pp. 51-54, May 2005, Garmish-Partenkirchen, Germany. ISBN 0-7803-9054-7.

Biographical Information

Robert Flake obtained his B.S. degree in engineering physics, M.A. degree in physics and D.Sc. degree in electrical engineering at Washington University in St. Louis, Missouri. He currently is a professor of electrical and computer engineering at The University of Texas at Austin.

Isidro Lopez Jr. received his B.S. degree in electrical engineering from The University of Texas-Pan American in Edinburg, Texas. He is currently a MSEE candidate at The University of Texas at Austin.

Shi-jing Wang received his B.S. degree in electrical engineering from Zhejiang University in Hangzhou, China. He is currently a MSEE degree candidate at The University of Texas at Austin.