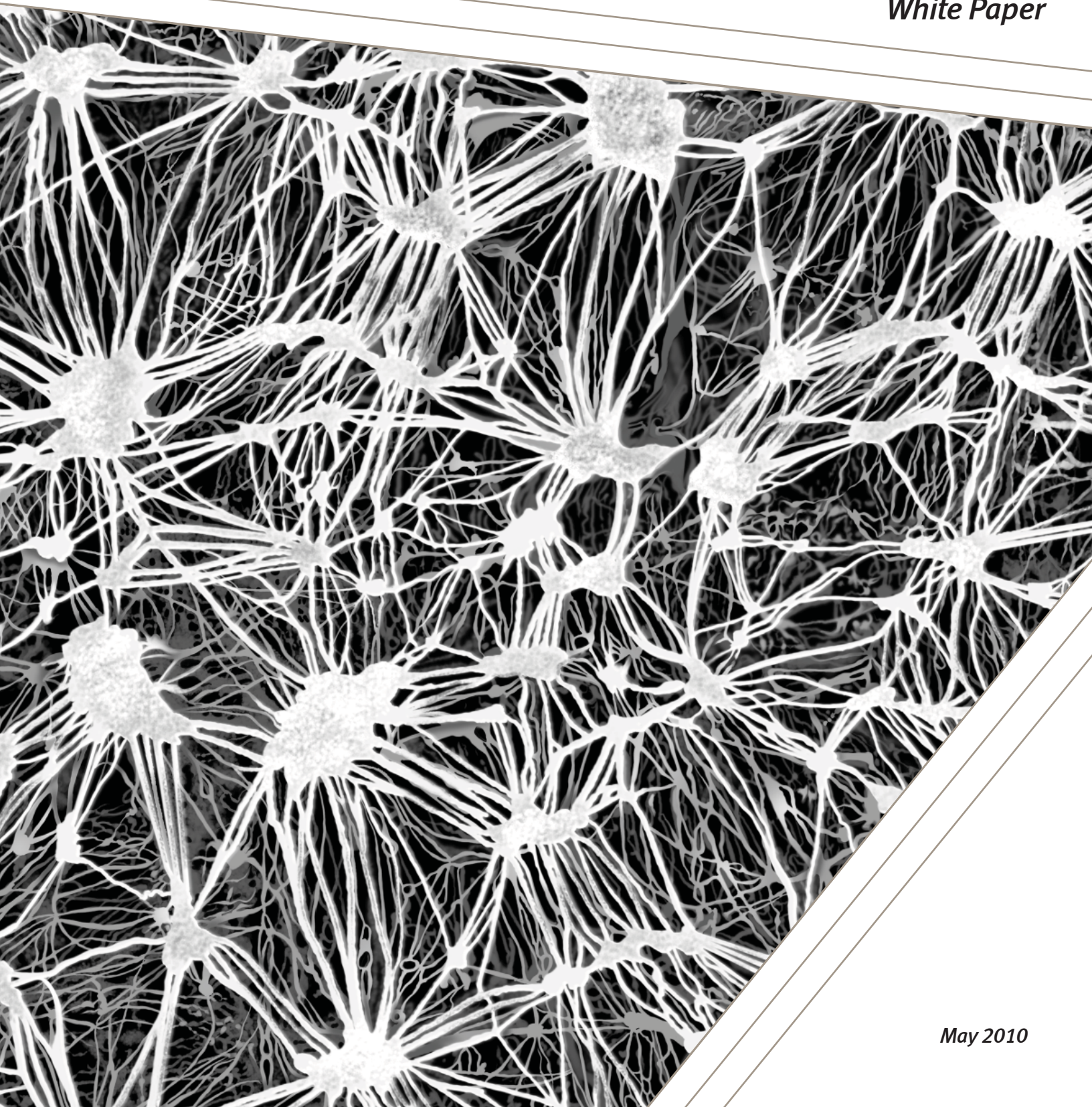
A Comparison of Measurement Uncertainty in Vector Network Analyzers and Time Domain Reflectometers

White Paper



May 2010

Abstract:
Measurement uncertainty has a direct impact on the reliability of test instruments. To determine if there is a quantifiable difference in measurement uncertainty between the TDR and VNA, W. L. Gore & Associates performed a series of experiments, initially testing six cable assemblies in controlled conditions on each instrument. The instruments' measurement uncertain under best-case scenario was evaulated using the highest-performing assembly. To ensure TDR/VNA test parity, the VNA's performance was evaluated using a s11 one-port reflection method as well as the more traditional s21 two-port transmission method.

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A Comparison of Measurement Uncertainty in Vector Network Analyzers and Time Domain Reflectometers

In the test and measurement industry, two distinct camps exist: those who favor vector network analyzers (VNA) and those who favor time domain reflectometers (TDR). Each camp relies heavily upon its instrument of choice for a variety of test and measurement and analytical tasks. The TDR's strong suit is temporal analysis — characterizing impedance or reflection coefficient with respect to time. Its quick setup, intuitive controls, and results-oriented operation appeal to a broad range of users. The VNA excels in frequency domain analysis — characterizing amplitude and phase with respect to frequency. Learning to operate the VNA can be intimidating, but in return it offers an extremely stable, precise, and versatile measurement platform. Interestingly, both instruments have the ability to perform time or frequency domain analysis through built-in Fast Fourier Transform (FFT) algorithms or ancillary software.

Individuals working in digital applications tend to prefer the TDR, while those involved in traditional RF applications consider the VNA to be a laboratory staple. The push for ever-faster data rates has fueled an analytical rethink of high-speed digital signaling. Contemporary wisdom views high-speed digital systems as high-frequency applications; therefore, more traditional, physics-based microwave analysis techniques can be applied. Once this concept is embraced, users follow a tendency to exploit the strengths of the TDR and the VNA, combining time and frequency domain analysis to accelerate design and development cycles. Both instruments can measure impedance, time delay, phase delay, and reflection coefficient, so they are often thought of as equals. This begs the question: Is there a quantifiable difference in measurement uncertainty between the TDR and VNA?

Characterizing the time delay of a passive device, such as a coaxial cable assembly, is a common use for the TDR and VNA. It is therefore an ideal vehicle for a performance comparison. How do the two compare under ideal test conditions and the less-than-ideal environment of production testing? Do both instruments possess similar levels of measurement precision?

W. L. Gore & Associates addressed these questions by examining the measurement uncertainty and repeatability of the TDR and VNA. These tests did not, however, address the absolute measurement accuracy of either instrument. In the first series of experiments, Gore tested six cable assemblies (also referred to as the device under test, DUT) on both a TDR and a VNA. Gore then ran another series of experiments using the best-performing cable assembly from the first series to evaluate the best-case scenario. Finally, to ensure TDR/VNA test parity, VNA measurements of the best-performing cable assembly were made using one-port s11 reflection techniques in addition to the more traditional two-port s21 transmission method.

Description of Multiple-Assembly Experiment

Objective: In a manner consistent with commonly used production test practices, measure the time delay of the cable assemblies with both a TDR and a VNA, and to compare the resulting measurement uncertainty of the two instruments under these conditions.

To understand the capabilities of any measurement system, it is important to test the system's response to a variety of input. Data based upon a single type of input can lead to erroneous conclusions. Therefore, Gore designed the experiment using different cable assembly types with a range of insertion loss and voltage standing wave ratio (VSWR) characteristics made by various manufacturers. Six new cable assemblies were used, each equipped with SubMiniature version A (SMA) pin connectors. Electrical data was acquired through VNA analysis (Table 1).

Table 1: Electrical/physical characteristics of sample cable assemblies

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
length	39.4-in	96.0-in	30.0-in	36.0-in	120.0-in	8.0-in
max. loss @ 18 GHz	1.13 dB	5.02 dB	2.66 dB	1.32 dB	4.26 dB	0.46 dB
max. VSWR thru 18 GHz	3.13:1	1.27:1	1.13:1	1.13:1	1.28:1	1.10:1

The experiment consisted of two rounds of testing. Within a round, each sample was connected to the TDR or VNA and measured five consecutive times without being disconnected or disturbed — repeat testing. After five measurements, the sample was removed from the instrument and not reconnected until the next round of testing — round testing. Sample assemblies were labeled 1 through 6, and their test order within each round was randomized to reduce test bias. The same operator was used throughout the entire experiment. Tests were conducted over a two-day period: TDR testing on the first day VNA testing on the second day.

In total, there were 60 measurements: six samples x five repeat tests x two rounds. Repeat testing was intended to capture the instrument's test repeatability or instrument uncertainty. The round-to-round testing was designed to reveal measurement reproducibility, but also indirectly captured connect/disconnect, test fixture, and to some extent, operator influences. In summary, round testing of a sample reflects instrument uncertainty, while round-to-round testing reflects test uncertainty.

Test Configurations

During the TDR portion of testing (Figure 1), the sample assemblies were connected directly to the TDR sampling head, while the opposite end was terminated with a 3.5mm precision open standard. This was done to ensure a well-defined and controlled termination. Once an assembly was disconnected from the TDR, the precision open was removed as well, and it was connected to the next sample ready for testing.

In the VNA portion of testing, the sample assemblies were connected between ports 1 and 2 (Figure 2).

In both TDR and VNA testing, the samples were well-supported. Standard RF cable assembly care and handling practices were exercised, e.g., cleaning connectors with alcohol, drying with a moisture-free air source, tightening connectors to proper torque, and careful handling of the cable itself.

Figure 1: TDR setup

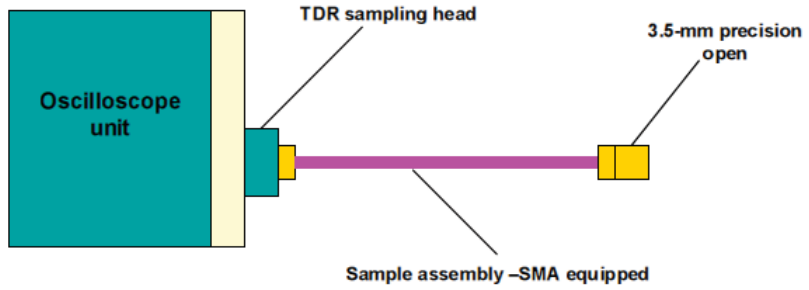
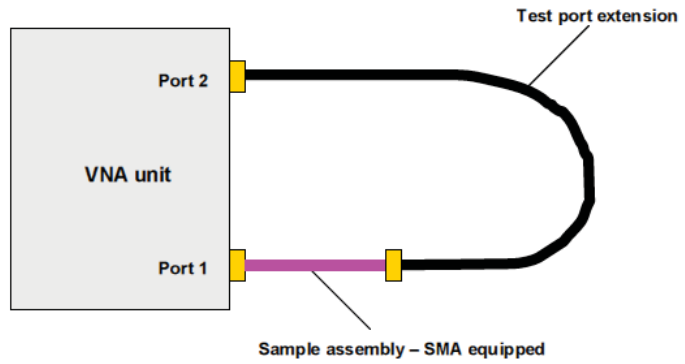


Figure 2: VNA setup



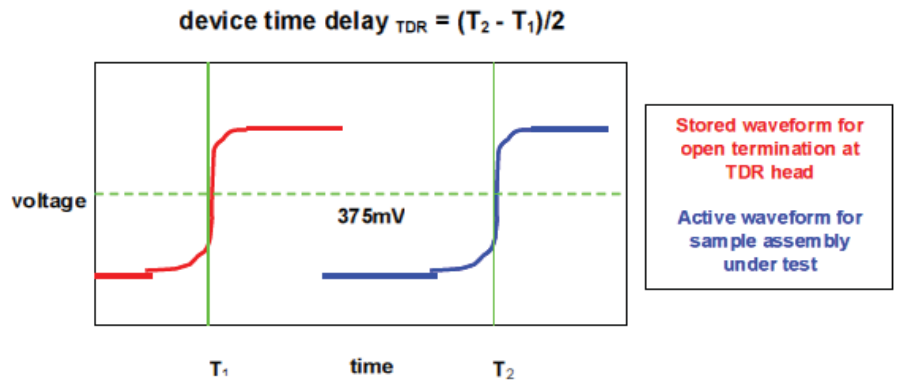
Equipment and Test Conditions

Laboratory conditions were controlled to an ambient temperature of 22° C and relative humidity of 30 percent.

TDR testing: Gore used the Tektronix CSA8000 and CSA8200 equipped with an 80E04 TDR sampling head. This equipment uses a launched signal with time domain step, with a rise time of approximately 17.5 ps (measured between 10 and 90 percent amplitude levels). The oscilloscope and sampling head were calibrated and compensated per the manufacturer's instructions before the start of testing. The sample cable assemblies were terminated with the 3.5mm precision open (socket) from the Agilent 85052B standard mechanical calibration kit.

TDR time delay measurement method (Figure 3): The TDR was configured for 250 averages per measurement. The final time delay value was recorded at 2,000 acquisitions. Waveform for an open circuit (no termination) at sampling head was stored in trace memory and used as measurement reference (T_1). Fitted with precision open termination, the sample assembly was connected to the TDR, and the round-trip time delay value was recorded using the instrument's built-in time delay measurement algorithm. Round-trip time delay was taken as difference in time between the active waveform (T_2), representing the precision open circuit at the end of the sample assembly and the stored waveform, representing the open circuit at the TDR head. Time delay was recorded at 375mV level. The actual sample assembly time delay is one-half of the measured round-trip time delay.

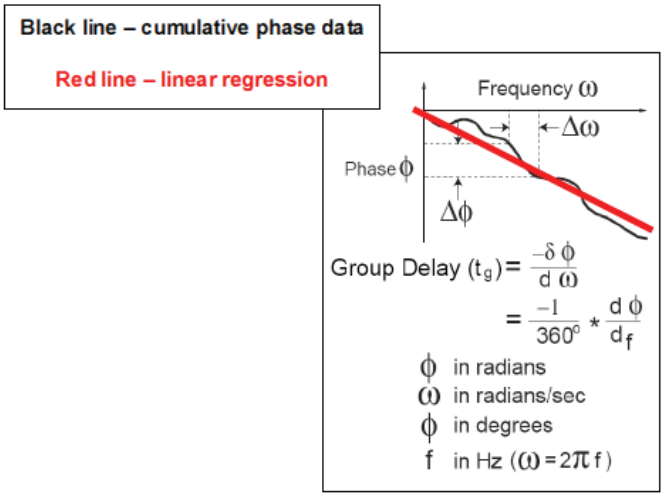
Figure 3: TDR waveform display for time delay measurement, showing both stored and active waveforms and measurement graticules



VNA testing: Gore selected the Agilent Technologies 50 GHz PNA, model E8364B, configured for two-port calibration, 0.045 GHz to 18.045 GHz, and 801 point sweep. No smoothing or averaging was applied, and IF Bandwidth was set to 100 Hz. A 38-inch GORE® VNA assembly, model FB0HA0HB038.0, was connected to port two as a port extension. The instrument calibration was current per the ANSI/NCSL Z540 standard, done with the 3.5mm precision open (socket) from the Agilent 85052B standard mechanical calibration kit. One-port measurements were made using identical settings and calibration kit, and no port extension required.

VNA time delay measurement method (Figure 4): The sample assembly was connected to VNA ports one and two and stimulated through swept frequency range; s-parameter data was collected. Gore's proprietary software was used to extract the cumulative phase information over swept frequency range from the s21 s-parameter data. Time delay was calculated by performing a least-squares curve fit, linear regression of the cumulative phase. The slope of the linear regression represents the change in phase with respect to the change in frequency or the group delay (t_g). The group delay value returned from this process was taken as the device time delay.

Figure 4: Group delay calculation as applied to s-parameter data — Agilent Technologies

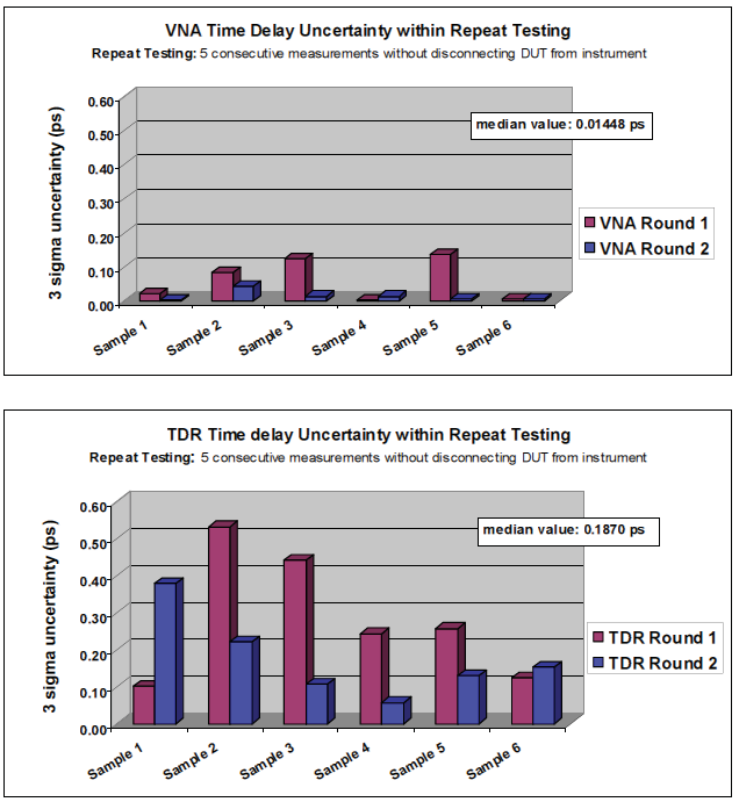


Multiple Assemblies Experiment Results

The ±3 sigma measurement uncertainty by sample for TDR and VNA were examined together for rounds one and two (Figure 5). At the outset, two important observations were made:

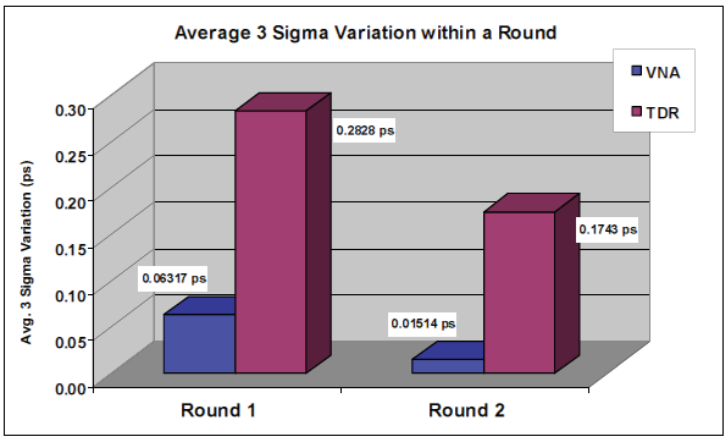
- measurement uncertainty for both instruments is clearly device-under-test dependent
- the median uncertainty across rounds are separated by approximately an order of magnitude; overall the values for the VNA are significantly lower than that of the TDR

Figure 5: Repeat testing for both instruments, ±3 sigma uncertainty by test sample, scaled identically



On average, the difference between the two instruments (Figure 6) was consistently an order of magnitude (approximate).

Figure 6: Average 3 sigma variation in measurement uncertainty within a testing round

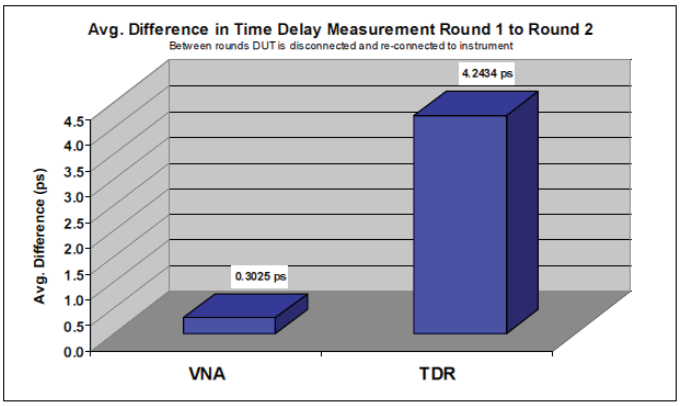


These results illustrated instrument repeatability, i.e., the variability associated with measuring the same DUT repeatedly without disturbing it or the measurement system. They gave a window into the uncertainty of the instrument itself under the prevailing test conditions, based on the assumption that the DUT and any related fixtures were stable.

Rounds one and two were intended to capture measurement system variability stemming from connect/disconnect cycling of the DUT, referred to as measurement reproducibility. Connectors can affect measurement reproducibility; however, when SMA connectors are new and in good condition, they possess sufficient repeatability such that a significant influence on reproducibility was not anticipated. All six sample assemblies were equipped with SMA pin connectors; during the experiment each was thoroughly cleaned before every round and tightened to the appropriate torque value.

In a production test scenario, it is often necessary to re-measure a device for re¬classification. Between the two rounds, the measured time delay of a sample differed, on average by 0.3 ps for the VNA and 4.2 ps for the TDR (Figure 7). These values included operator handling and connect/disconnect effects. These real-world effects are inevitable under production test conditions. Extreme measures could be employed to control these effects during the experiments; however, such efforts proved impractical and could have yielded results inconsistent with typical product usage or performance.

Figure 7: Average difference in measured time delay from round one to round two across six test samples



Best-Case Performance Experiments

A review of the initial experimental results indicated that one sample consistently performed better than the others in both TDR and VNA testing. This assembly, sample 6, was identified as a best-case scenario for both instruments and selected to undergo additional analysis. A second experiment was created to gather information on measurement uncertainty under best-case conditions. The instruments, conditions, and configuration were identical to those used in the initial experiments on multiple assemblies. The details of the experiment were as follows:

- Repeat testing of 22 consecutive measurements without disconnecting/disturbing the DUT and test system
- Reproducibility testing of 22 connect/disconnect cycles of the DUT, with measurements taken at each connect/disconnect cycle

The number of measurements (22) was determined through a confidence interval calculation. This number assured a 98 percent confidence that the sample mean in the experiment would be within ±0.08 ps of the actual population mean, based upon an estimated standard deviation of 0.16 ps.

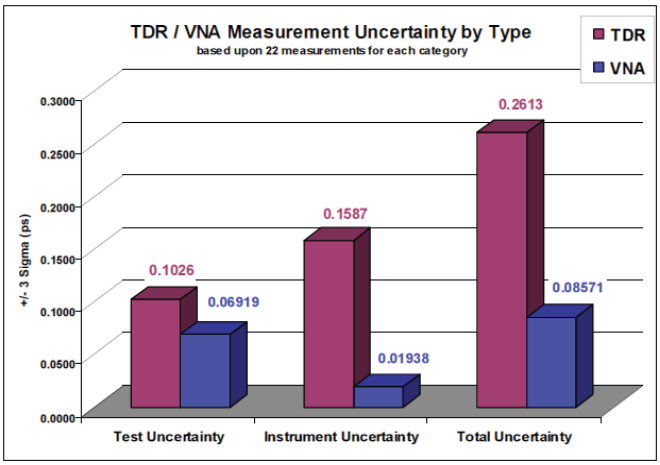
The objective was to observe measurement uncertainty under more closely controlled conditions. Towards that end, during TDR testing the 3.5mm precision open was left in place during all 22 connect/disconnect measurements; the sample assembly connection was cycled at the TDR sampling head only. Likewise during VNA testing, the sample assembly connection was cycled at port one only. This strategy, although not representative of production testing, introduced a disturbance into the test system such that the outcome could be observed.

For this portion of the analysis, TDR and VNA measurement uncertainty was divided in three categories:

- Instrument uncertainty — uncertainty associated with the instrument platform itself, measured through repeat testing, i.e., 22 consecutive measurements without disconnecting the DUT from the instrument
- Total uncertainty — uncertainty resulting from the cumulative effects of instrument characteristics, test fixture, test conditions, and operator influences; measured through connect/disconnect cycling; includes instrument uncertainty
- Test uncertainty — resulting from operator error, test fixture influences and prevailing environmental conditions at time of test; measured indirectly

Because of the best-case uncertainty for sample 6 (Figure 8), test uncertainty values were expected to be similar in the TDR and VNA due to similarities in test configurations.

Figure 8: ±3 sigma uncertainty analysis of sample 6 measurements



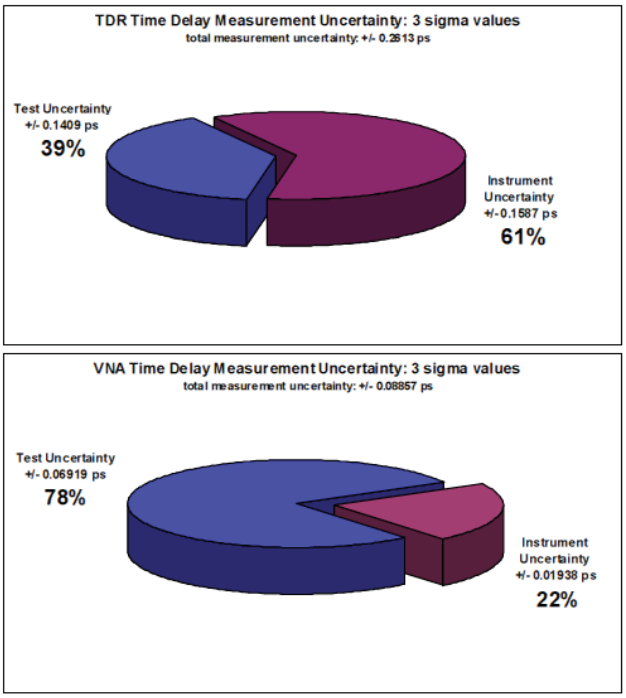
Test uncertainty was measured indirectly. Based upon the previous definitions, test uncertainty was derived was derived in the following way:

Total uncertainty = Test uncertainty + Instrument uncertainty
therefore:
Test uncertainty = Total uncertainty – Instrument uncertainty

Best-Case Performance Results

With this information, the best-case uncertainty associated with each instrument platform could be assessed. 22 percent of the total measurement uncertainty for the VNA was associated with the instrument itself, as compared to 61 percent for the TDR (Figure 9). This was a repeating theme throughout the experiment. This significant difference was determined to mean that even under ideal test conditions, i.e., minimal test fixture, operator, and environmental influences, the gap in TDR/VNA measurement uncertainty remained, as it was inherent to instrument performance.

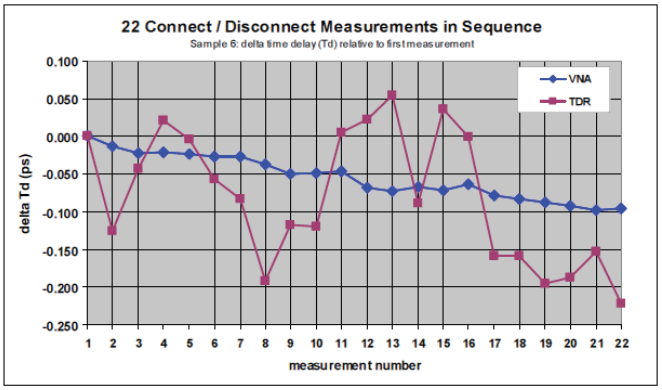
Figure 9: Total measurement uncertainty broken down by test and instrument uncertainty



The reader may have concerns around the external processing of the s-parameter data (see VNA Time Delay Measurement Method), thinking this aided in the VNA's reduced instrument uncertainty. In practice, a time delay value delivered directly from the VNA is calculated by applying a smoothing aperture, essentially a variable length, moving average filter. The aperture was adjustable to encompass the entire swept frequency range or a small portion of it. Comparisons of the VNA manufacturer's standard method with Gore's method used for this experiment indicated similar instrument uncertainty results. Gore's post-processing method was used primarily for reasons of convenience in data collection.

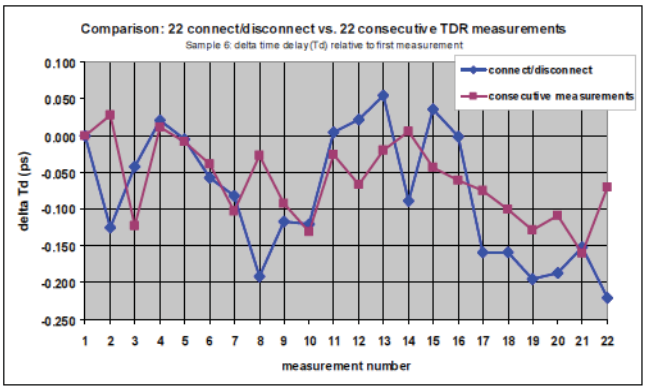
The 22 connect/disconnect measurements of sample 6 (Figure 10) showed that the VNA measurements had a range spanning 0.0983 ps as compared to the TDR's range of 0.275 ps. Both data sets clearly trended downward, i.e., a progressively shorter device delay.

Figure 10: Connect/diconnect measurements in sequence, illustrating the change in time delay with respect to the first measurement



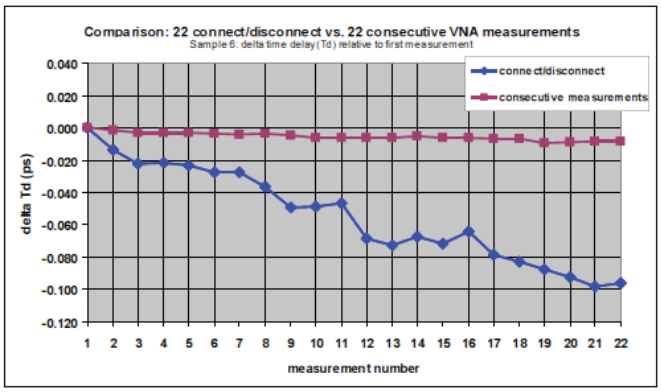
The TDR data indicated a potential repeatability issue with the 3.5mm connector on the TDR sampling head (Figure 11); this variability was associated with the instrument itself, not with the connector.

Figure 11: TDR repeatability: connect/disconnect vs. consecutive measurements with un disturbed DUT



The data showed instrument variability influencing the connect/disconnect TDR measurements. An identical test was conducted using a second TDR, similarly equipped and from the same manufacturer. The outcome was comparable to the initial findings. As a point of comparison, VNA data is shown in Figure 12.

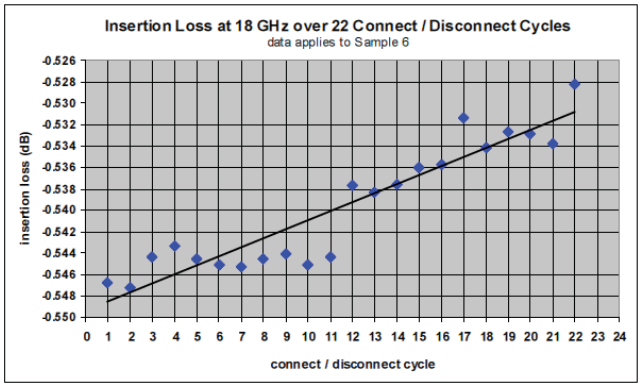
Figure 12: VNA repeatability: connect/disconnect vs. consecutive measurements with undisturbed DUT



The downward-trending behavior may be attributed to burnishing of SMA/3.5mm mated interfaces. Recalling the VNA test configuration, a 3.5mm connector was used as the calibrated reference plane to which the test sample's SMA was mated.

Insertion loss for sample 6 decreased over a series of 22 connect/disconnect cycles (Figure 13). Connecting and disconnecting the SMA interface in succession (without cleaning between cycles, as was done in the experiment) had the potential to burnish the mated connector interface components. It was theorized that over the course of 22 test cycles, the mated interfaces were sufficiently abraded to experience improved electrical contact, as evidenced by a reduction in insertion loss and electrical length.

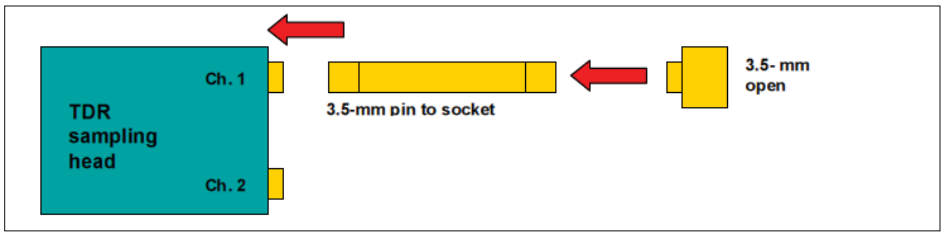
Figure 13: Sample 6 insertion loss over 22 connect/disconnect cycles, indicated reduction in loss



It is of some interest to compare the absolute time delay values for sample 6 as measured by the TDR and VNA. An examination of repeat testing (22 consecutive measurements made without disturbing the DUT) produced an average time delay of 0.817364 ns for the VNA and 0.849754 ns for the TDR; a difference of 32.5 ps. This discrepancy was unexpected and an attempt was made to obtain closer agreement between the two instruments.

The average time delay value of 0.849754 ns was referenced to an open circuit at the TDR sampling head, meaning the connection at the head was not terminated. The reflection from the resulting open circuit was stored as a reference waveform. Measurements of sample 6 were taken with respect to this reference. To improve agreement between TDR and VNA measurements, the sampling head was fitted with a 3.5mm pin to 3.5mm socket precision adapter (connector saver) from a VNA calibration kit (Figure 14). The adapter provided a precise reference plane and sufficient electrical length to establish a new reference plane well away from the sampling head's 3.5mm panel connector.

Figure 14: TDR Sampling head design with 3.5mm socket precision adapter



To define a new reference plane, a 3.5mm (pin) precision open from a VNA calibration kit was used. The open was connected to the sampling head, and the resulting waveform was stored as the new reference. TDR measurements of sample 6 were conducted. The reference plane calibration was applied to the primary TDR used in this experiment as well as a second TDR of the same manufacturer (Table 2).

Table 2: Comparison of averaage time delay values for Sample 6. Average based upon 22 consecutive measurements without disturbing DUT

	"No termination" calibration at ref. plane	"Precision open" calibration at ref. plane	VNA measured time delay (avg.)
TDR #1 time delay (avg.)	0.849754 ns	0.818797 ns	0.817364 ns
TDR #2 time delay (avg.)	0.84735 ns	0.817649 ns	

TDA / VNA Test Parity

Previously, all VNA measurements were made via (s21) transmission techniques. To ensure TDR/VNA test parity, VNA measurements of sample 6 were made using one-port s11 reflection techniques in addition to the more traditional two-port s21 transmission method. For one-port measurements, the VNA was configured as previously described (see Test Configurations). A one-port short, open, load calibration was conducted using the same calibration kit employed for the earlier two-port measurements. No test port extension was required. DUT time delay was extracted using the linear curve fit method described (see Equipment and Test Conditions). The curve fit was applied to s11 data.

Instrument uncertainty was virtually unchanged between reflection (s11) and transmission (s21) methods (Figure 15). There was a 0.1ps discrepancy between reflection and transmission methods when performing connect/disconnect cycling of the DUT (Figure 16). The downward trending time delay effect was present in the one-port data as well, albeit very subtle and not to the extent visible in the two-port s21 data. A portion of 0.1ps discrepancy may be attributed to the flexible test port extension used during s21 transmission measurements.

The effects of test port extensions on VNA measurements are well understood. Even the most stable, high-quality flexible port extension introduces some level of test system error when disturbed, as was the case during connect/disconnect cycling of the sample 6 DUT. Within the flexible port extension, 0.1 ps represented a physical change on the order of 0.001 inches (0.025mm); the amount of physical distortion associated with a change of this magnitude was small indeed.

Figure 15: VNA repeatability via s11 and s21 methods with 22 consecutive measurements without disturbing DUT

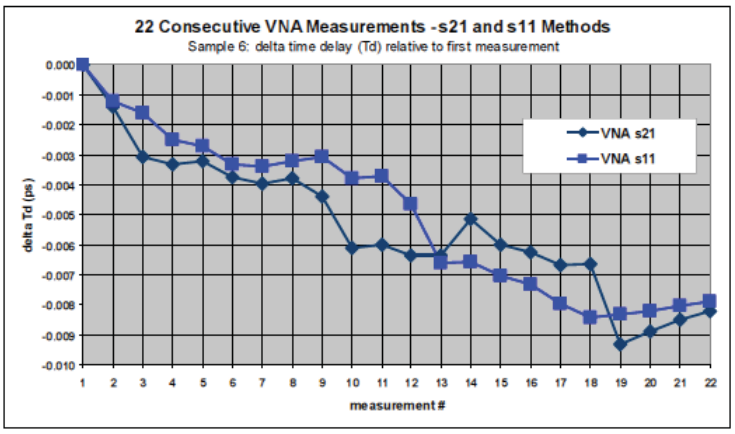
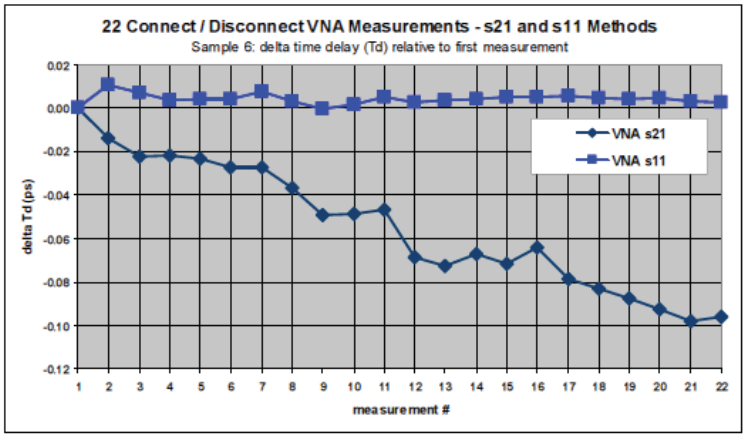
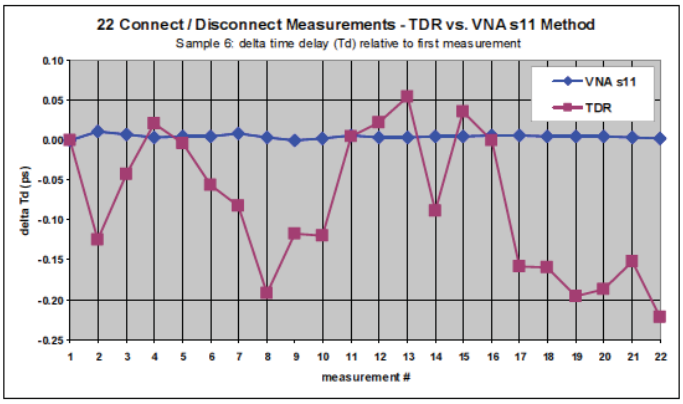


Figure 16: VNA repeatability via s11 and s21 methods with 22 connect/disconnect measurements without distrurbing DUT



A comparison of the 22 connect/disconnect performance of the TDR with that of the VNA when using s11 reflection measurement techniques indicated that the VNA's uncertainty was approximately an order of magnitude below that of the TDR under similar measurement conditions (Figure 17).

Figure 17: VNA s11 vs. TDA connect/disconnect measurements in sequence for sample 6

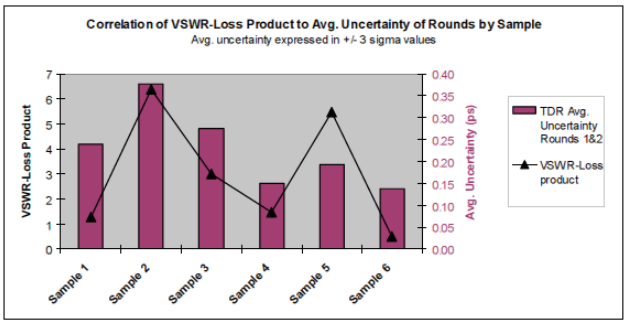


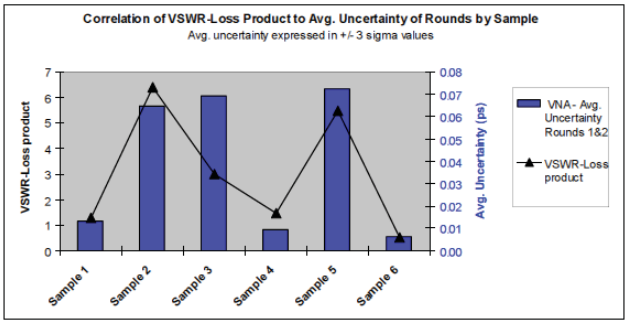
The Voltage Standing Wave Ratio (VSWR)–Loss Product

The experiments produced an unexpected finding: a relationship between DUT performance and measurement uncertainty. The results demonstrated measurement uncertainty of the TDR and VNA as having a device-under-test dependency (Figure 5).

But what was it about this particular test sample that caused it to have an influence on the measurement system? Two obvious areas of investigation are the VSWR and insertion loss characteristics of the test samples. VSWR and insertion loss, when analyzed separately, produced a weak correlation to measurement uncertainty. However, when the product of an individual test sample's VSWR and insertion loss (at maximum frequency) were taken, the correlation was quite strong and evident in both TDR and VNA data (Figure 18).

Table 18: VSWR–Loss product for TDR (top) and VNA (bottom) — note scale differences in right axes





The correlation between the VSWR–Loss product and measurement uncertainty was especially prominent in the VNA data. The VSWR–Loss product indicated that as loss or VSWR increased, measurement uncertainty increased. This relationship accounted for the device-under-test influence on measurement uncertainty. Although these findings are interesting, they are not surprising. It is customary for VNA manufacturers to formally state instrument uncertainty in terms of DUT VSWR and loss. Examination showed the VNA to be less sensitive to the effects of the VSWR–Loss product by an order of magnitude.

The VSWR–Loss product showed that a measurement system's performance was linked, in part, to what it was measuring. Therefore, a thorough understanding of DUT/measurement system interaction is necessary to capture accurate DUT performance. To ignore this imperative is to ignore the fundamental reason for making measurements. We measure in an effort to seek the truth under a given set of conditions. If the conditions are not clearly defined, there is no point of reference and thus, no reliable means of comparison.

Conclusion

W. L. Gore & Associates addressed the question of measurement uncertainty and repeatability of the TDR and VNA, with the following findings:

- Measurement Uncertainty — In both the TDR and VNA, instrument-related measurement uncertainty was found to be dependent upon the device under test's VSWR and insertion loss. The median measurement uncertainty for the VNA was found to be an order of magnitude below that of the TDR: 0.01448 ps versus 0.1870 ps, based upon 3 sigma values.

- Measurement Reproducibility — The TDR exhibited a 4.2 ps (on average) difference between time delay measurements separated by one connect/disconnect cycle. The VNA exhibited a 0.3 ps (on average) difference under the same conditions.

- Best-Case Performance Analysis — Total measurement uncertainty was broken down into two components: test uncertainty (attributed to test fixtures, test method, and operator) and instrument uncertainty (attributed to the instrument itself). TDR instrument-related uncertainty accounted for 61 percent of the total measurement uncertainty. VNA instrument-related uncertainty made up 22 percent of the total uncertainty.

- Measurement Repeatability in Best-Case Performance — Best-case performance testing examined measurement repeatability over 22 connect/disconnect cycles, indicating a downward trend in the test sample's measured time delay over 22 test cycles. Both the TDR and VNA recorded this trend, but with a significant difference: VNA measurements returned a range spanning 0.0983 ps as compared to the TDR's range of 0.275 ps.

- TDR/VNA One-Port Measurement Parity — The VNA was reconfigured from a two-port to a one-port calibration and best-case performance testing was repeated. DUT time delay data was extracted from the resulting s11 reflection data. Findings indicated virtually no change in VNA instrument uncertainty as compared to two-port s21 data, and measurement uncertainty associated with connect/disconnect DUT testing decreased.

- VSWR–Loss Product — A correlation existed between instrument measurement uncertainty and the DUT's VSWR and insertion loss. It appeared to follow the product of the DUT's VSWR and insertion loss. The VSWR–Loss product was a strong indicator of changes in measurement uncertainty across a variety of DUTs.

The topic of measurement is a popular one and fundamental to the test and measurement industry. Measurement uncertainty, however, is an often-ignored part of the measurement discussion. When we measure, we attempt to go from the unknown to the known. Addressing measurement uncertainty adds yet another dimension of unknown to our efforts, and this can be inconvenient. Once our trusted instrument of choice has produced a number,

it is frequently taken as truthful, accurate, and good enough. In some cases, this may be sufficient, but when precision is required, knowledge of an instrument's or test system's capabilities is crucial. Without this information, the output of testing may be rendered useless or worse yet, create more questions than it answers.

Example: A specification calls for a passive device to have a time delay of 6.0 ps, ±0.5 ps. Therefore, the device in question can have a time delay between 6.5 ps and 5.5 ps and still be within specification. If we agree beforehand that a measurement must be reproducible within limits to be considered legitimate, then the need to understand the measurement system's uncertainty becomes clear. Any measurement system used to characterize this device must have an uncertainty of better than ±0.5 ps to resolve the data adequately. A traditional rule of thumb states measurement system precision should be approximately ten times greater than the tolerance it is being compared against. In many instances this is neither practical nor possible, so concessions must be made to bound claims of measurement precision properly, calling yet again for an understanding of uncertainty associated with the measurement system. In a production test scenario, specification compliance, especially during qualification, is often determined through a series of measurements over a period of time, as opposed to a single occurrence. If the measurement is not reproducible, compliance is unlikely. If the DUT has the stability and repeatability to deliver performance at a fraction of the stated ±0.5 ps tolerance, measuring it with a system possessing an uncertainty of ±1.0 ps will likely result in values ranging ±1.0 ps about a nominal value.

The findings of Gore's experiments suggested that before making critical production measurements with either a TDR or VNA, it is necessary to understand the interaction of the DUT and measurement system. No claims describing either instrument platform as superior to the other have been made. Each has its strengths and weaknesses, but in the hands of a properly trained and experienced user, both are formidable tools. Data has been presented indicating one instrument platform operates with a significantly lower level of measurement uncertainty under specific conditions. It is left to the reader to decide which best suits his or her needs given the application requirements.

A Comparison of Measurement Uncertainty in Vector Network Analyzers and Time Domain Reflectometers

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