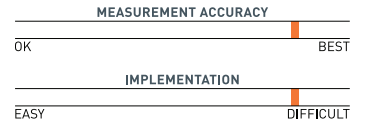


Advanced RF Calibration Techniques with Cascade Microtech's Pyramid Probe®

GENERAL-PURPOSE ISS CALIBRATION



Abstract

Cascade Microtech's Pyramid Probe enables customers to perform production-grade, on-wafer testing of RF structures and devices with high repeatability. When using the probes for device characterization or process monitoring, a higher degree of measurement resolution may be required. This application note reveals the steps required to perform the LRRM calibration technique in your characterization lab. With proactive planning and proper reference standards, this technique is suitable with Pyramid Probe for measurements in the 1-20+ GHz range.

Why Advanced Calibration?

Network-analyzer calibration involves characterizing the entire test fixture so subsequent measurements will pertain to the device under test (DUT) only. To characterize the transmission path of each port, numerous measurements of known standards are performed. An error matrix is computed so it can be applied to subsequent measurements.

When performing a calibration, there are tradeoffs between the type of standards measured and the mathematical algorithms used to compute the error model. For each technique, certain standards play a role in the overall characterization. Depending on the particular technique, some standards are known or fully characterized. For some methods, such as SOLR¹, characteristics of other standards (such as the thru path) are of little or no significance.

Although there are many calibration techniques to choose from, consider the following three techniques and how they differ:

Technique	Definition	Advantage	Ideal Standards	Relaxed Standards
SOLT	Short, Open, Load, Thru	Readily Available	Short, Open, Load, Thru	None
SOLR	Short, Open, Load, Reciprocal	Unknown Thru	Short, Open, Load	Thru
LRRM ²	Line, Reflect, Reflect, Match	Accuracy, Repeatability	Thru, Match Resistance	Open, Match Inductance

TABLE 1 Comparing Calibration Techniques

When establishing a calibration plan, you must consider what standards will be available within your test environment. For example, it may not be possible to probe a fully characterized, electrically clean, thru path. (In this case, you may wish to select SOLR, as the algorithm does not rely upon the thru for much of its calculations). Circumstances of this sort can quickly help determine which algorithm is optimal for your application.

This application note discusses calibration using the LRRM technique. LRRM (Line Reflect Reflect Match) provides a very high degree of repeatability in one-port and two-port measurements. Parasitic effects associated with the one port standards (Short, Open, Load) are characterized as part of the calibration. As a tradeoff, the characteristics of the thru path must not-only be known, but the path itself must be free of significant transmission anomalies.

This advanced-calibration algorithm is best suited for a well-designed probe environment, with proper pad placements on the device. It is advisable to consider the available calibration standards, when choosing a pad layout topology. When pad layout matches available standards, the best calibration can be achieved. When standards are not available, you may want to consider the tradeoffs of a simpler calibration technique.

The LRRM technique is an integral feature of Cascade Microtech's WinCal³ XE™ VNA calibration software. WinCal provides a unified calibration and measurement environment within one software application. After calibration, measurements may be taken from WinCal, or directly from the VNA. This application note assumes the LRRM calibration will be performed with WinCal.

Completing a calibration involves numerous steps, including design for calibration, selection of standards, characterization of standards, and finally, the calibration step. These are outlined in the flow chart of Figure 1, and are discussed in detail in this paper. Depending upon your situation, some steps may be skipped. For example, the characteristics of a known thru path may be available from a datasheet. In this case, steps leading up to thru-path characterization may be bypassed.

Design the DUT Interface for Calibration

In order to achieve a good calibration and ensure high repeatability of subsequent measurements, pad placement on the DUT must be considered. These are discussed in detail for Cascade Microtech's Infinity Probe® family⁴. Many of these rules are directly applicable to RF probing with Pyramid Probe technology. The following guidelines should be considered when designing a new device for RF probing:

- Select a basic pad footprint for ground-signal-ground (GSG), or signal-ground / ground-signal (SG/GS), to be consistent with input / output type, and packaging requirements. Choose a consistent pitch (the spacing between signal and ground) throughout the design. (This will minimize the number of standards required for calibration).
- Orient the pads such that an ideal transmission line path may be placed between the two ports. This is best achieved by placing the ports on opposing sides (West, East), with their respective signal and ground pads perfectly aligned. This path between the two ports must be free of additional signal traces, where an additional probe tip may interfere with the structure during calibration. If a straight thru path cannot be achieved, consider placing ports in-line and adjacent to one-another (configured as a GSGSG pattern).
- Minimize the distance between opposing ports. The LRRM calibration algorithm requires the distance of the thru path to be electrically short. For 20 GHz performance, it is best to keep the length of the thru path to less than 1mm in length. Best performance is achieved with a 100 – 400µm separation between the RF ports.
- The ground pads for each RF probe must be electrically connected together on the input and output. This is to provide a low-impedance common-ground node between ports during two-port RF measurements.
- Incorporate standards selection into the layout of your device. Choose a port-separation distance that best-matches an available transmission-line structure. (Addressed in the following section)

Select from Available Standards

Proper standards selection must be performed in conjunction with pad layout considerations. An Impedance Standard Substrate (ISS) consists of an alumina substrate with numerous Short, Open, Load and Thru structures to match a variety of probe configurations. A wide selection of ISS products is available⁵. Common products applicable to LRRM calibration on Pyramid Probe are presented in Table 2.

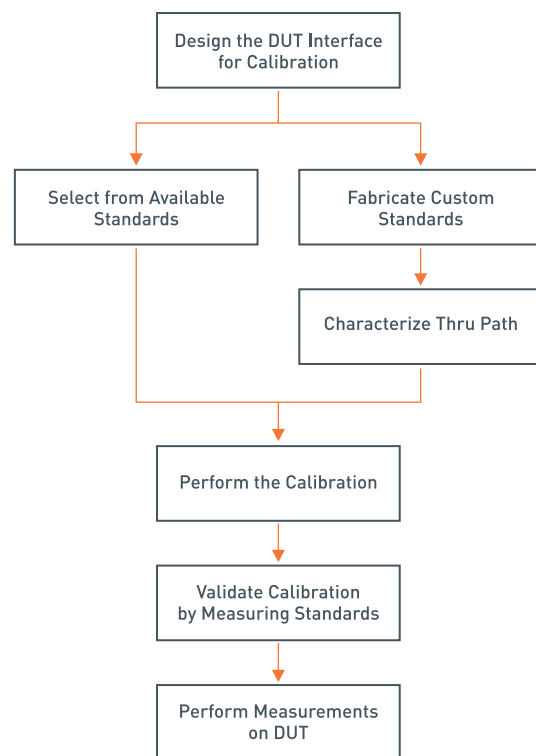


FIG. 1 Advanced Calibration Flow Chart

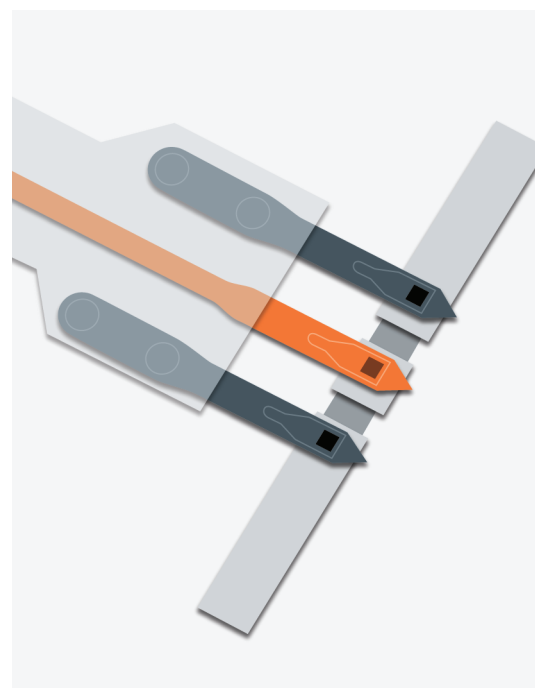


FIG. 2 Example Probe Configuration: GSG on a 101-190 50Ω Load



FIG. 3 Example Probe Configuration:
GSG on a 101-190C "Open" configuration

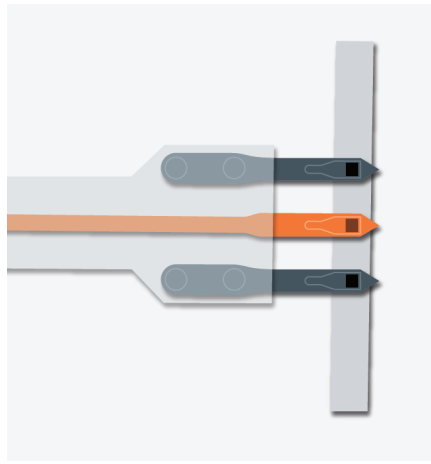


FIG. 4 Example Probe Configuration:
150µm pitch GSG, on a shorting structure

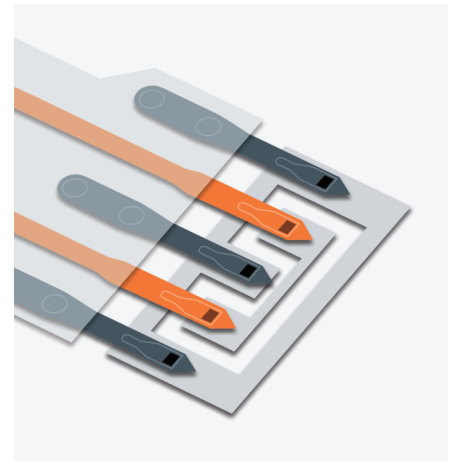


FIG. 5 Example Probe Configuration:
150µm pitch GSGSG on a 129-239
Loopback-Thru structure

101-190 (C)	LRM/LRRM	27 GSG	100-250	Excellent general-purpose ISS. "C" revision includes "Open" pads.
129-239	Dual/Differential	21 GSGSG, SGS, SGSG, GSGS	100-125	Inline GSG, GSGSG
129-246	Dual/ Differential	21 GSSG, SSG, GSS	100-150	Useful for G-S probe configurations.

TABLE 2 Common Impedance Standard Substrates for Pyramid Probe calibration

One of the most difficult requirements for LRRM calibration on Pyramid Probe is obtaining a proper thru path. With other technologies, such as Cascade Microtech's InfinityProbe, the spacing between probes may be adjusted during the calibration process. In the case of Pyramid Probe, the advantage of high positional accuracy comes with the tradeoff of not being able to reposition RF ports during calibration.

To complete an LRRM calibration, a high-quality thru path must be available between RF ports. In many cases, probes may be designed around a readily available thru path on a calibration substrate, as revealed in Figure 6. In some cases, an alternative solution is required.

There are three solutions to obtaining a thru path for your probe:

- **GOOD** Consider purchasing a custom Cal-Thru™ structure to match your probe. This is custom-fabricated using technology similar to the Pyramid Probe. Multiple thru paths built using the same membrane material as the Pyramid Probe are delivered on a small glass substrate. These may be mounted in place of an ISS. The Cal-Thru is best suited for applications up to 12 GHz. Although this is a cost-effective alternative to a full-custom ISS, it does require landing on multiple structures during calibration (probe an ISS for loads & shorts, probe the Cal-Thru structure for the thru path).
- **BETTER** Design a custom ISS to match your configuration. An ISS could be designed and fabricated to match the custom probe's configuration. This includes precision-trimmed 50Ω loads, shorting bars, verification standards, and custom-routed thru to match the device's pads. The advantage of this solution is that all standards required for advanced calibration are available on one substrate.
- **BEST** Design the probe to make use of a pre-existing thru path on an ISS. This provides the benefits of probing all standards on one substrate. A standard product is a more cost-effective approach to custom design, as well.

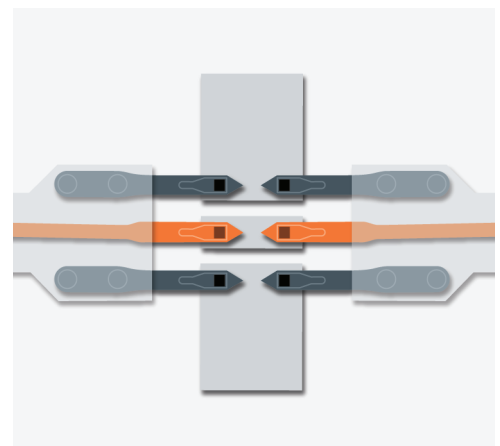


FIG. 6 Example Probe Configuration:
150µm pitch GSG, on a 101-190 220µm
transmission thru structure

Characterizing the Transmission (Thru) Path

Once a thru-path is obtained, it is critical for LRRM calibration that the characteristics of the transmission line be known. These include the electrical length between the probe tips and the path loss.

Although characterizing the thru path may appear to be a difficult task, it only needs to be performed once. The loss may be directly measured after performing a SOLR calibration. The SOLR does not rely upon the path loss during calibration. Although an estimated length is required for proper SOLR calibration, the value entered may be a gross estimate. (As an alternative to path characterization, phase velocity and loss estimates of two known materials are provided in Table 3).

Here are the steps to obtain the electrical length of the transmission thru, along with the loss:

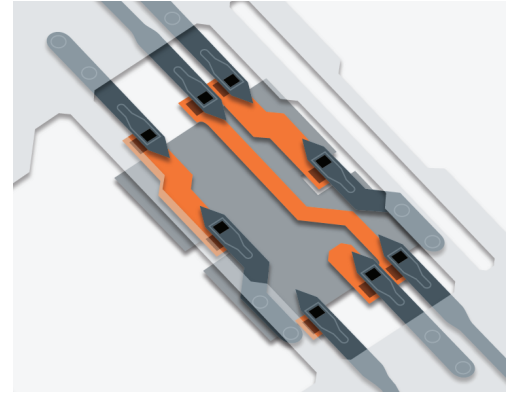


FIG. 7 Example custom Cal-Thru path of a 3-port RF structure

- **Estimate the delay between ports** (see Table 3). Following the path of the thru, calculate the length in microns:

$$\text{delay (ps)} = \frac{l(\mu\text{m})}{v_p \left(\frac{\mu\text{m}}{\text{ps}} \right)}$$

For example, a 500 μm thru-path distance on a Cal-Thru (167 $\mu\text{m}/\text{ps}$) equates to a 3ps delay.

- **Perform a 2-port SOLR VNA calibration**⁶. Measure Short, Open and Load standards for both ports. For these standards, use the default correction coefficients ($L_{\text{short}}, C_{\text{open}}, L_{\text{term}}$) for the pitch of the probe and the selected ISS.
- **Enter the estimated delay into the calibration software**. Measure the thru standard. (Note that some VNAs will calculate this value for you during the probing process. When using a VNA, be sure to select “unknown-thru” with the SOLT algorithm).
- **Compute the correction coefficients**. Store them into the VNA for subsequent measurement. Your network analyzer is now calibrated.
- **Verify the calibration was performed correctly**. Before performing any real measurement, re-measure an open and a short. Confirm S_{11} on the Smith chart reveals a reflection coefficient of +1 and -1, respectively. Remember, the stray parasitic effects ($C_{\text{open}}, L_{\text{short}}$) will cause the “dots” to appear as small tails.
- **Obtain the path loss by measurement**. Probe the thru standard between the calibrated ports. Measure S_{21} on a log-magnitude plot. This is the loss of the transmission thru path. In WinCal terms, record the loss in dB at the highest frequency you will use with the structure. Remember that this loss was measured for the length of the thru structure (which means the “Ref-Delay” length will equate to the delay of your thru path).

Material	ϵ_e	Phase Velocity	Ref-Loss	Ref-Delay	Ref-Freq
Alumina (Cascade ISS), Coplanar Waveguide	5.33	130 $\mu\text{m}/\text{ps}$	0.55 dB	27ps	40 GHz
Thin-Film (Cascade Cal-Thru), Microstrip	3.23	167 $\mu\text{m}/\text{ps}$	0.43 dB	30ps	10 GHz

TABLE 3 Delay & Loss Characteristics for Cascade thru-paths⁷

The thru-path characteristics may be estimated from previous measurements. For the transmission path chosen, the phase velocity & reference loss will be unique. Table 2 reveals these constants for the two thru-path options discussed in this paper. (The loss values for the ISS are already entered within WinCal). The only calculation required is to enter the delay for the probe’s actual spacing, as described earlier.

Once the loss characteristics of the unique thru-path are known, the LRRM calibration may be performed.

Performing the Calibration

The LRRM calibration is accomplished with WinCal XE calibration software. Once the calibration has been performed, the calibration (error correction matrix) may be stored in the VNA. This way, you can still perform LRRM-calibrated measurements directly from the VNA.

For each standard, it is important to enter the appropriate characteristics of the standard into WinCal. For LRRM, the critical elements include the resistance of the Load, and the characteristics of the thru path.

- **Enter the load resistance:** With a precision 50Ω load, verify the location on the standard has been certified to 50.0Ω. The inductance of the load will be determined by WinCal. Verify the “Automatically calculate load inductance” box has been checked.
- **Enter the thru path characteristics:** This includes the transmission line impedance (typically 50Ω), the electrical delay of the path, and the expected loss of the transmission line.

Steps to Calibrate

Remember to set up the full VNA frequency sweep prior to performing the calibration. A narrow IF bandwidth, such as 300 Hz, is essential to obtaining a good calibration. Any change in these parameters will invalidate the calibration.

Start the calibration procedure from WinCal and select 2-port LRRM. Measure the reflect standards for each separate port on the probe:

- **OPEN REFLECT** If open standards are available, position each probe on the open pads and make contact. This is shown in Figure 3. Collect the Open Reflect standard measurement for both ports. If the open standard is not available, leave the probe tips in air. (It is important to probe both ports identically—land on the same geometric topology with each pad).
- **SHORT REFLECT** Position each probe on the shorting surface and make electrical contact. An example is shown in Figure 4. Collect the Short Reflect measurement for both ports.
- **MATCH (LOAD)** Position one probe on a resistor load, as shown in Figure 2. Collect the Match measurement for this port. Remember to confirm the resistance of the standard is properly entered into the calibration software. (Note that only one match measurement is required for this calibration technique).

To complete the calibration process, position the two probes on the transmission thru path. An example is shown in Figure 6. Verify that the delay and loss characteristics have been entered into the calibration software properly. Verify that all of the return path (ground) probe tips are electrically connected to the thru structure as well. Collect the Thru standard measurement.

Your standards have now been collected. At this point, the LRRM algorithm has enough information to compute the correction coefficients. Be sure to transfer the correct coefficients to the VNA prior to taking any measurements.

Validate the Calibration by Measuring Standards

It is helpful to probe a few known standards, to confirm the calibration worked. Use the ISS to measure S_{11} and verify the load is at the center of the Smith chart. The open and short will be represented as dots on the right and left side of the Smith chart, respectively. Measuring S_{21} on the matching thru structure should reveal an electrical length and insertion loss which matches the characteristics entered while performing the calibration.

When verifying the calibration, remember that you will not see a “perfect short,” or a “perfect open” from the standards. Any standard you use will reveal its own anomalies. For example, the shorting bar contains a small amount of inductance between signal and ground pads. This inductance will be revealed in the measurement after calibration. Thru-path loss measured between two probes will be real, not an error in the calibration.

Other standards to consider include a capacitor, an inductor, or a transmission line stub. An open transmission line will appear as an open at low frequency and follow the outer-radius of the Smith chart clockwise (much like a capacitor). Be aware of the placement of such standards with respect to other probe tips. The most obvious example is when another RF port comes into contact with the transmission line. The probed standard will now appear as a thru, rather than an open stub.

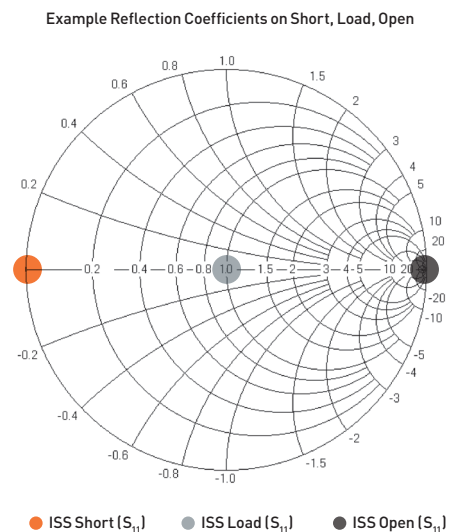


FIG. 8 Re-measuring Short, Load and Open standards after calibration.

Verifying Known Standards after Calibration

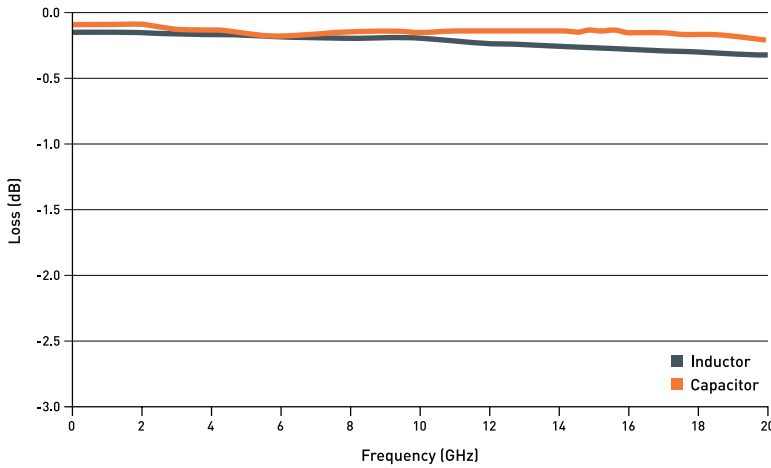


FIG. 9 Magnitude dB plot of two passive components after calibration. The inductor and capacitor reveal very slight loss at higher frequencies. The devices are behaving as expected.

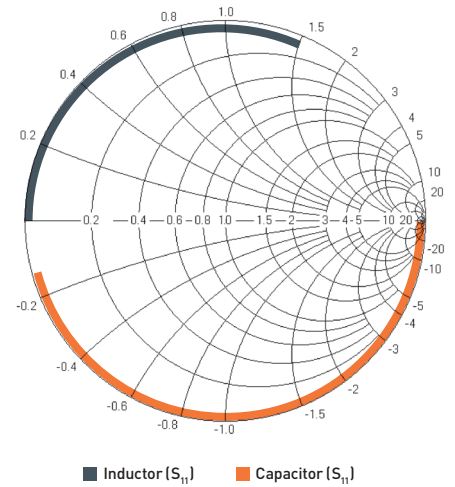


FIG. 10 Reflection Coefficient (S_{11}) of two passive components after calibration. The inductor appears as a short at lowest frequency. The capacitor appears as an open at lowest frequency.

Probe Calibration Challenges

This application note discusses a calibration technique designed to reveal high-accuracy and high-repeatability for RF measurements across a very wide frequency range. For Pyramid Probe, this technique is only recommended for applications requiring high-frequency measurements above 12 GHz. For lower frequency applications, consider the SOLR two-port calibration technique.

It is critical to incorporate best-known methods into the design of the device and the probe card to ensure high accuracy can be achieved. Design considerations prior to product tape-out will greatly improve your success when probing for known-good-die:

- **Maintain a uniform GSG pitch whenever possible.** Since the RF field exists in the region “between” the wires, the return path for RF is just as critical as the driven line. Even for 2 GHz designs, it is best to land return paths next to the driven line. An example is 100-150 μ m G-S-G pitch.
- **Place RF ports in a direct line with one-another.** In the case of a multi-port device, place respective RF ports at 90-degree angles from one-another. This can allow general-purpose structures to be used for thru-path calibration.
- **Consider purchasing a custom Cal-Thru structure to match all RF port-to-port paths.** As discussed previously, a clean thru path is an essential requirement of the LRRM calibration technique. The custom Cal-Thru also provides a second standard (other than your DUT) to use for measurement system verification.
- **Investigate Cascade Microtech’s wide selection of Industry Standard Substrates.** Confirm every RF port will have a load, short and thru available for calibration. Cascade Microtech recommends the 101-190 (GSG 100-250 μ m) as a good product to consider starting with.

¹ S. Basu and L. Hayden, “An SOLR Calibration for Accurate Measurement of Orthogonal On-Wafer DUTs,” IEEE MTT-S International Microwave Symposium, Denver, CO, June 1997.
² A. Davidson, K. Jones, and E. Strid, “LRM and LRRM calibrations with automatic determination of load inductance,” 36th ARFTG Conf. Dig., Monterey, CA, Fall 1990, pp. 57-63.
³ More information on WinCal may be found online at <http://www.cmicro.com/wincal>.
⁴ “Mechanical Layout Rules for Infinity Probes[®],” Cascade Microtech Application Note, 2006.
⁵ “ISS Series of Impedance Standard Substrates,” Cascade Microtech Datasheet. See <http://www.cmicro.com>.
⁶ The SOLR calibration technique is discussed in the Pyramid Probe Application Note “RF Calibration Using the General-Purpose ISS for Pyramid Probe Applications”.
⁷ All values are based upon actual measurements. Relative dielectric constants are based upon the measured phase velocity of the stated transmission line within an air-substrate medium.

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