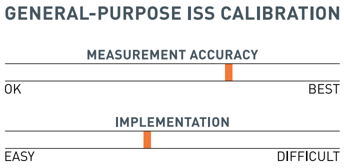
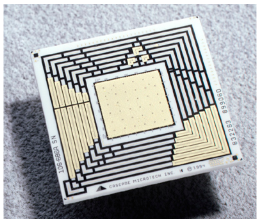
Cascade Microtech, Inc.

APPLICATION NOTE

RF Calibration Using the General-Purpose ISS for Pyramid Probe® Applications





Abstract

Cascade Microtech's Pyramid Probe® enables customers to perform production-grade, on-die measurements of RF and RF-parametric structures, with high repeatability and long probe life. As RF frequencies continue to increase, the need for proper Vector Network Analyzer (VNA) calibration becomes increasingly important. This application note reveals one of the most straightforward methods of performing a calibration, using a general-purpose Impedance Standard Substrate (ISS) and the SOLR technique. This is suitable for Pyramid Probe applications in the 1-12 GHz range.

Why Calibration?

VNA calibration is different from the traditional calibration of most lab instruments. With many instruments, it becomes necessary to send the unit to a service facility, in order to align and calibrate signal levels, frequency standards, etc. This is usually performed annually, or semi-annually. In addition to instrument alignment, measurement calibration is necessary. With a VNA, there are three reasons to perform calibration at the time of measurement:

- **Set the reference plane at the Device Under Test (DUT).** Establishing a reference plane means that the instrument will not be a part of the measurement. Reflected power (magnitude and phase) will be the result of the device, not the probe card.
- **The setup has changed.** The calibration reference plane is usually at the end of the test cables, or at the probe tips. The path from the VNA to the reference plane may have changed, due to wear or positioning of the cables, replacement of the probe, etc.
- **The VNA is subject to aging and environmental conditions.** Many components, with even the best VNA, may drift slightly, due to temperature, humidity, the age of key components within the unit, etc. These variations need to be characterized and mathematically removed.

To calibrate a VNA, we are setting the reference plane at some point between the VNA's front panel, and the device to be tested. For on-die testing with Pyramid Probes, it is ideal for most applications to set the reference plane at the probe tip itself. After calibration, measurements on-screen will reflect the S-parameters at the device.

Calibration involves presenting a set of known standards to the VNA, and then training it to those standards through measurement. Typically, an Open, a Short, and a 50Ω Load are presented on each port. A transmission line connecting two ports ("thru") is typically required for calibration as well. These measured standards are used to compute error terms, which derive a mathematical model of the errors between the VNA and the reference plane. Once these error terms are known, they may be stored into the VNA itself while measurements are being taken.

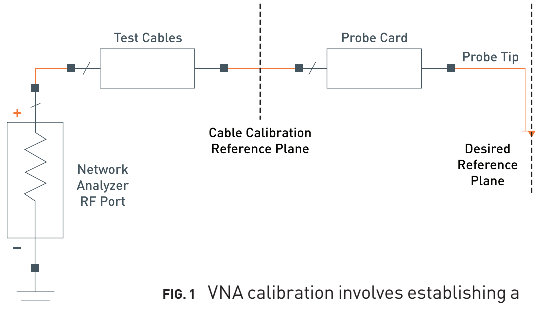


FIG. 1 VNA calibration involves establishing a reference plane. Errors are characterized and removed from subsequent measurements.

For consumer RF applications involving frequencies in the 1-12 GHz range, routine calibration every few days is more than adequate. For higher-frequency applications, the calibration interval should be shortened. Any time the path between the VNA and the probe tip has changed (such as when a cable or probe core is replaced, or when the VNA sweep range has been altered), the instrument should be re-calibrated.

S-Parameters

The S-parameter (or Scattering Parameter), is a measurement which reveals the reflection coefficient, Γ_{ij} (or S_{ij}), at one port when excited by another port. The scattering parameter S_{ij} is the measured (reflected) signal at port j, when stimulated by a signal at port i. S_{ij} is a complex number.

Measuring S_{ii} (such as S_{11}) at a port reveals the impedance looking into that port. Measuring power at one port while stimulating another (such as S_{21}) will reveal the insertion loss, or cross-coupling between two different structures. For passive networks, the magnitude of S never exceeds 1.

S-parameters are typically measured at every combination of ports on a VNA. For a 2-port network analyzer, this implies four measurements: S_{11}, S_{21}, S_{12} and S_{22}. For passive networks, S_{21} and S_{12} will reveal the same result. For a 4-port VNA, 16 measurements will be taken. Due to the nature of the devices under measurement, some measurements such as S_{41} may return meaningless information.

A network analyzer usually acquires S-parameters in a sweep, as a function of frequency. If the VNA is set up to sweep 401 points across a given frequency range, 401 unique calibration points need to be computed. The embedded computing resources within the VNA will keep this organized automatically.

A thru measurement, such as S_{21}, is often referred to as the "insertion loss." In other words, if this network were inserted into the transmission path, the signal loss would be revealed by this measurement. Reflected power measured at the same port on which it was stimulated is referred to as the "reflection coefficient." This also reveals the impedance looking into the network from that port.

There are two popular ways of plotting S-parameters vs. frequency. These are magnitude power, and the Smith chart. For magnitude power, the insertion loss (S_{21}), or reflection coefficient (S_{11} or S_{22}), may be represented by:

$$|dB| = 20\text{Log}_{10}\left(\sqrt{S^2_{re_{ij}} + S^2_{im_{ij}}}\right)$$

An example of magnitude power is seen in Figure 2.

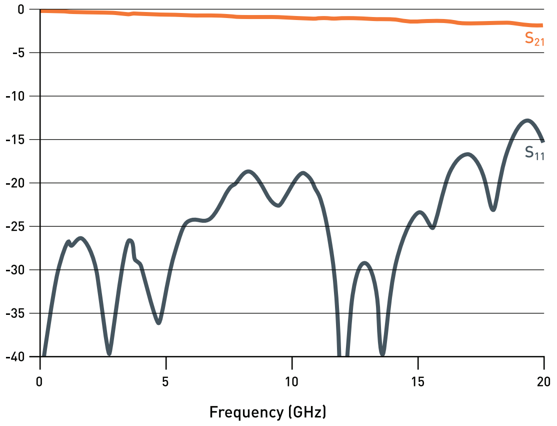


FIG. 2 Passive network S-parameter example. Insertion loss, near the top of the graph, is nearly 0 across the operating frequency range. The reflection coefficient S_{11} is better than -18dB, indicating a reasonable match to 50Ω.

The Smith chart is a polar plot of the reflection coefficient. The peculiar lines of the Smith chart allow impedance to be directly measured from the chart. Constant resistance circles and constant reactance lines form the axes of the chart. Conversion of reflection coefficient (or S-parameter) to normalized impedance is accomplished by:

$$Z_L = Z_o \frac{1+\Gamma}{1-\Gamma} \quad \text{and} \quad \Gamma_{ij} = S_{ij} = \frac{Z_L - Z_o}{Z_L + Z_o}$$

where Z_0 is the characteristic impedance of the systems, typically 50Ω.

As an example, in a 50Ω environment, a reflection coefficient of 0.69∠ – 145° reveals an impedance of 10 – j15Ω.

Although the Smith chart displays a normalized reflection coefficient, it is customary to refer to these impedances by the characteristic impedance of the system (such as 50Ω). A reflection coefficient of 0 translates to a normalized impedance of 1, depicted by a single dot at the center of the Smith chart.

The example shown in Figure 3 reveals the reflection coefficient (near 0), or impedance (hovering about 50Ω resistive), looking into port 1 of the example network. If the magnitude of the reflection coefficient were plotted in dB, we would see a return loss for S_{11} on the order of -20 to -30dB, as shown in Figure 2 above. As the reflection coefficient continues to decrease, the return loss will be an even greater number (moving lower on the magnitude dB graph). On the Smith chart, this will form an even tighter "dot" near the center of the chart.

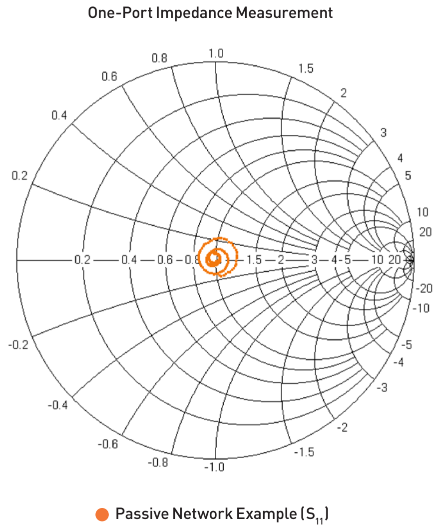


FIG. 3 Impedance vs. frequency example.

It is important to set the right expectations when examining results from the VNA. If the goal is to see 50Ω on a Smith chart, a return loss better than -10dB may be sufficient to say that condition has been satisfied. A measurement variation on the order of 0.2dB on this type of measurement is relatively meaningless. For insertion loss measurements, as is the case with S_{21} from Figure 2, a measurement variance of 0.2dB may or may not be more significant. This all depends upon the application at hand, and the expectations of the accuracy, etc.

Performing a Calibration

For many probe-tip configurations, Pyramid Probes may be calibrated using a general-purpose ISS. Cascade Microtech's general-purpose ISS 106-686 includes a large ground area, with 36-50Ω loads peppered across the surface. This provides the ability to touchdown on a short and a load, for most probe configurations. The open is accomplished by leaving the probe tips in air.

For frequencies of interest in the 1-12 GHz range, the SOLR[1] calibration technique is recommended. SOLR stands for "Short, Open, Load, Reciprocal." (This is also referred to as the "unknown thru" calibration). The advantage of this technique is that the port-to-port thru-path does not need to be perfect. Many thru paths, including 90° angle thru paths, are available on the periphery of the general-purpose ISS.

The calibration technique involves a final step of computing the error terms, or Calibration Coefficients. The SOLR calibration can be performed from the front panel of many VNAs. (Select SOLT and then check "unknown thru" when specifying the thru length). The SOLR technique may be performed with Cascade Microtech's WinCal XE™ software, as well.

An example for performing a 2-port calibration is discussed here. The Pyramid Probe configuration is a pair of GSG probes with 150μm pitch between signal and ground. The distance between the two ports is 200μm.

Creating a Cal Kit

When using a VNA, a calibration kit must be derived. This consists of entering characteristics of the standards used for calibration. This is similar to the standards used to define a mechanical cal kit, such as coaxial standards. The method of entry will vary for every VNA model available. Fortunately, this can be set up once for the VNA and then referenced for future calibrations.

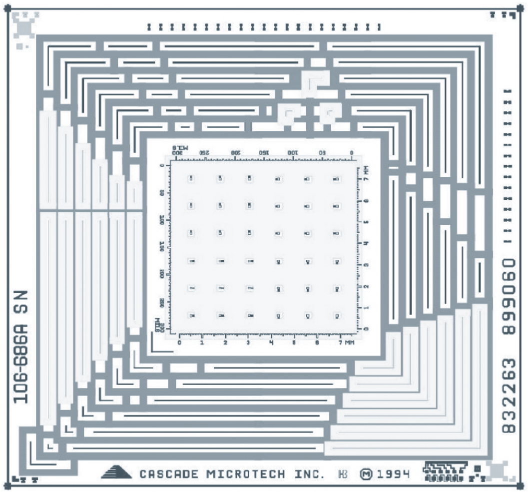


FIG. 4 General-purpose ISS, for challenging probe configurations.

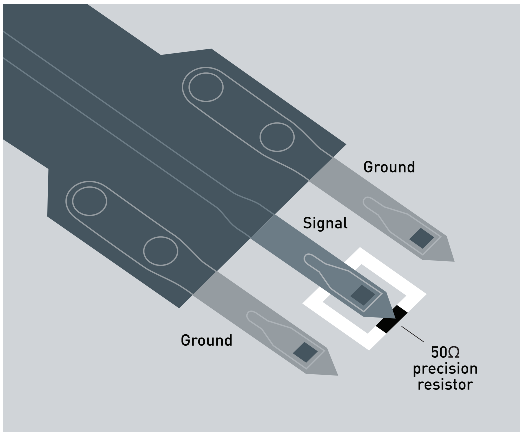


FIG. 5 Landing a G-S-G probe from the left onto a resistor load using the general-purpose ISS.

Because the standards used will be at the probe tip, an electrical length of 0 may be used for the Short, Open and Load.

Each standard requires slight correction coefficients to be entered. These coefficients account for the open-circuit parallel capacitance and short-circuit series inductance of the probes. Since Pyramid Probes share similar technology to the Cascade's Infinity Probe® family, it is useful to obtain these parameters from the Infinity Probe tables.

Pitch	C-Open (fF) Calkit Open C_0	L-Short (pH) Calkit Short L_0	L-Term(pH) Calkit Load L_{Term}
100μm	-6.5	3.3	-0.4
125μm	-6.6	5.7	1.6
150μm	-6.7	8.2	3.7
200μm	-6.8	13.2	7.9
250μm	-7.0	18.2	12.1

For this example, the pitch between Ground and Signal, Signal and Ground, is 150μm. The coefficients would be -6.7fF for C_{Open}, 8.2pH for L_{Short} and 3.7pH for L_{Term}. When entering cal-kit parameters into a VNA[2], these values pertain to C_0, L_0 and L_t, for the Open, Short and Load, respectively. (Polynomial terms for L_1, L_2, C_1, C_2, etc., may be set to 0).

The correction coefficients will not exactly match that of a custom probe configuration, as Pyramid Probes involve custom layout to match your die. However, the variation in these coefficients will be of little significance at frequencies below 12 GHz. As an example, 1pH of error in L_{Term} at 2.4 GHz results in only a 15mΩ error in reactance. This error is tolerable for most lower-frequency measurements.

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 recommended. Any change in the frequency sweep, number of data points, resolution bandwidth, etc., will typically imply the unit should be re-calibrated against the new configuration.

Start the calibration procedure, either from WinCal or from the VNA front panel. Measure the reflect standards for each separate port on the probe:

- **OPEN** Lift the probe off of any DUT or ISS. By probing in air, we are very close to probing on an Open standard. Collect the Open standard measurement for both ports.
- **SHORT** Position each probe over the conductive surface in the center of the ISS. Collect the Short standard measurement.
- **LOAD** Position each probe (individually) over a resistor in the center area of the ISS. Be sure to find a resistor that is oriented away from the direction of the probe, as shown in Figure 5. (The probe's transmission line should not overlap the resistor itself). Collect the Load standard measurement.

To complete the measurement process, position the two probes over a transmission line path on the periphery of the 106-686 ISS. Land the probe such that the two signal paths connect. Make certain that the four return path (ground) probe tips are electrically connected on the ISS as well. Collect the Thru standard measurement.

Your standards have now been collected. At this point, the SOLR algorithm has enough information to compute the correction coefficients. If you are using WinCal, be sure to transfer the correct coefficients to the VNA prior to taking any measurements.

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 thru should reveal an insertion loss near 0 dB.

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 field 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.

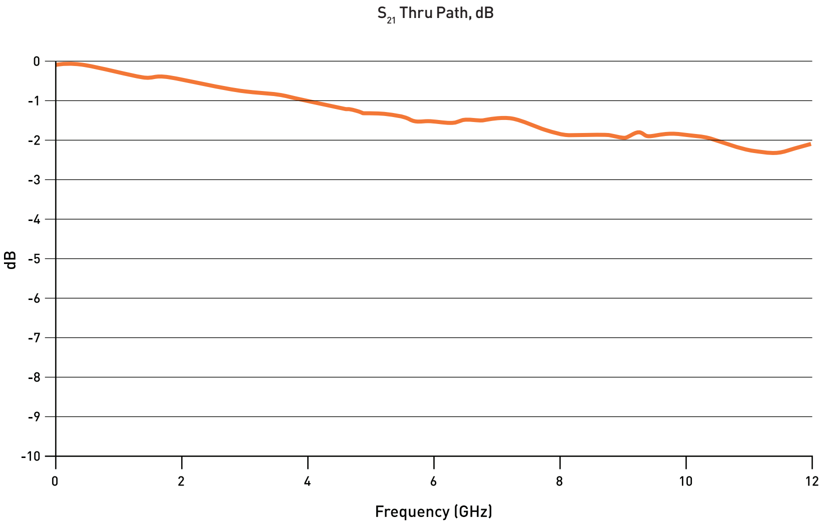


FIG. 6 Measuring a Thru path after calibration. Slight losses are revealed at higher frequencies. This is a normal occurrence, as these losses are to be expected with any transmission path.

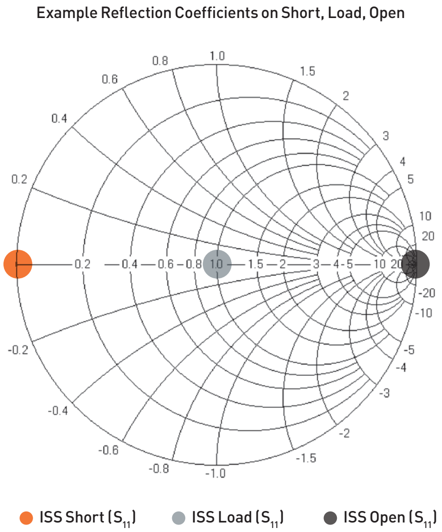


FIG. 7 Re-measuring Short, Load and Open standards after calibration.

Probe Calibration Challenges

This paper discussed an easy scenario, with tight-pitched probes placed immediately across from one another, with a relatively low frequency range. Many designs do not offer such ideal situations. Here are a few suggestions to overcome the more challenging probe-tip orientations:

- **Use SOLR calibration for sub-10 GHz applications.** The SOLR calibration technique does not require the thru to be perfect. In fact, nothing but an estimated length of the thru needs to be known. Any transmission line may be used to connect between the two paths.

- **Consider building a custom Cal-Thru structure to match your probe.** As an alternative to a custom ISS, a membrane-based thru path may be fabricated to match your probe's configurations. The final assembly will mount like a second ISS, providing the thru-path between your ports. Automated calibration on your probe station will need to know how to position on both the ISS (for loads and shorts), as well as the thru paths on the custom thru structure.

- **Design for calibration.** A few minor design considerations prior to product tape-out will greatly improve your success when probing for known-good-die:

  Maintain a tight 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.

  Consider placing RF ports in a direct line with one another. In the case of a multi-port device, place respective RF ports at 90° angles from one another. This will allow general purpose structures to be used for thru-path calibration.

  Investigate Cascade Microtech's wide selection of industry-standard substrates. Confirm every RF port will have a load, short and thru for calibration. For Pyramid Probes, 106-686 (general-purpose) and 101-190 (GSG 100-250µm) are recommended as a place to start the selection process.

---

[1] "An SOLR Calibration for Accurate Measurement of Orthogonal On-Wafer DUTs," IEEE MTT-S International Microwave Symposium, Denver, CO, June 1997.

[2] "Specifying Calibration Standards and Kits for Agilent Vector Network Analyzers," Application Note 1287-11, Agilent Technologies.
http://cp.literature.agilent.com/litweb/pdf/5989-4840EN.pdf

Cascade Microtech, Inc.
toll free: +1-800-550-3279
phone: +1-503-601-1000
email: cmi_sales@cmicro.com

Cascade Microtech GmbH
phone: +49-811-60005-0
email: cmg_sales@cmicro.com

Cascade Microtech Japan
phone: +81-3-5615-5150
email: cmj_sales@cmicro.com

Cascade Microtech Shanghai
phone: +86-21-3330-3188
email: cmc_sales@cmicro.com

Cascade Microtech Singapore
phone: +65-6873-7482
email: cms_sales@cmicro.com

Cascade Microtech Taiwan
phone: +886-3-5722810
email: cmt_sales@cmicro.com