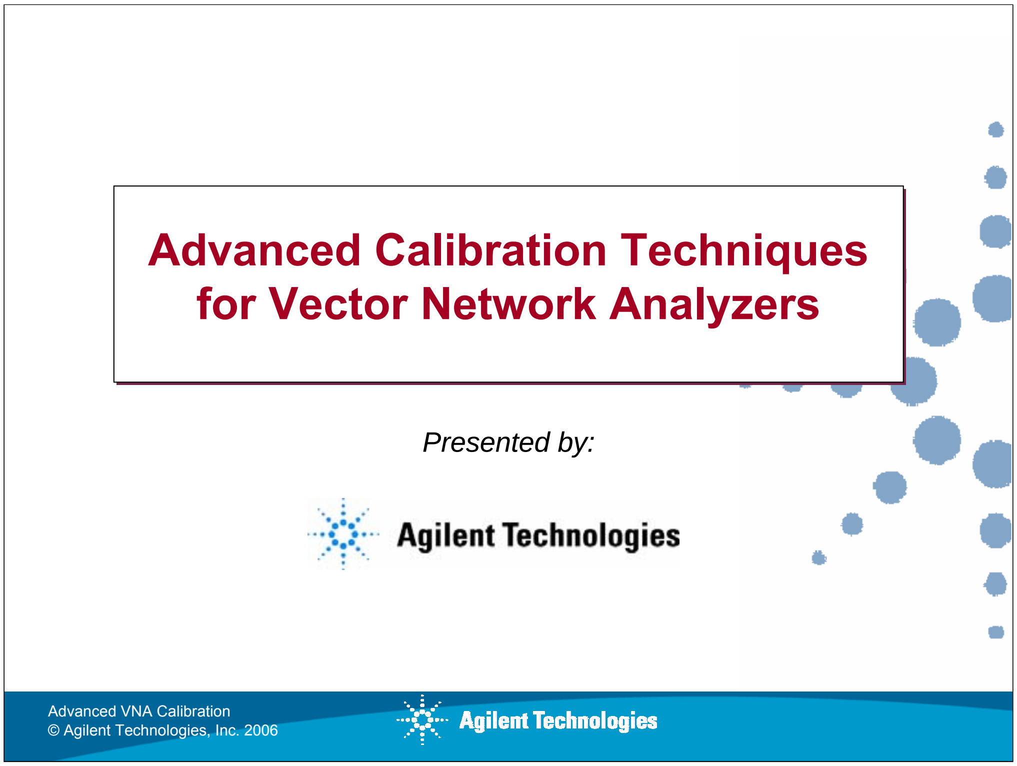
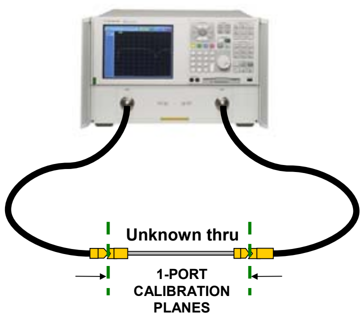
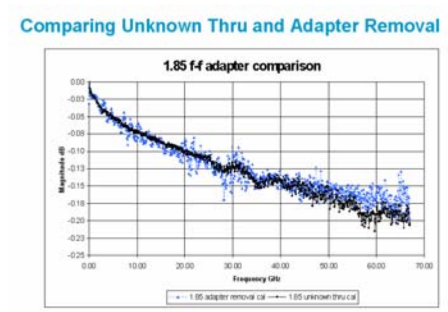



Welcome to “Advanced Calibration Techniques for Vector Network Analyzers.

# Objectives

- Provide insight into some of the latest **calibration techniques** that improve **accuracy** and make calibration **easier**
- Look at performance **improvements** using the advanced techniques compared to more traditional methods






The objective of this seminar is to provide insight into some of the latest calibration techniques that improve accuracy and make calibration easier. We will also look at performance improvements using the advanced techniques compared to more traditional methods.

## Agenda

- **Overview of Calibration**
- **Advanced Calibration Techniques**
  - "Unknown Thru" Calibration
  - Data-Based Calibration-Standard Definitions
  - Expanded (Weighted Least Squares) Calibration
- **Fixture And Probe Techniques**
  - Automatic Port Extensions
  - Embedding/De-embedding
  - Measuring Fixtures/Probes
- **Electronic Calibration**

Advanced VNA Calibration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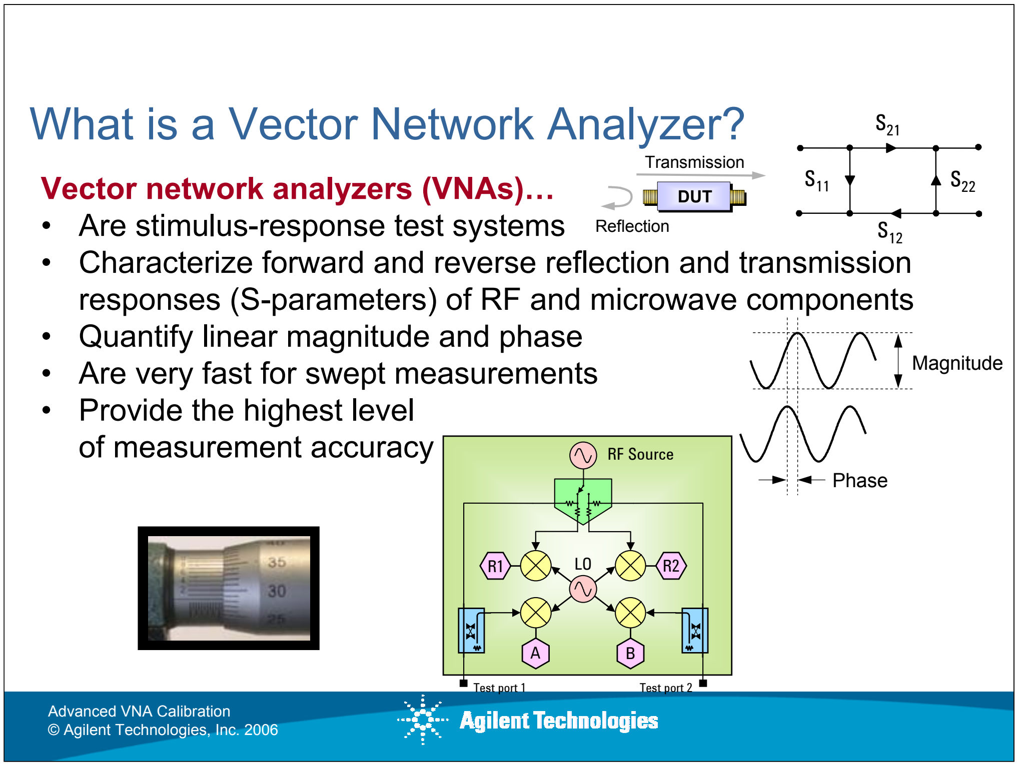
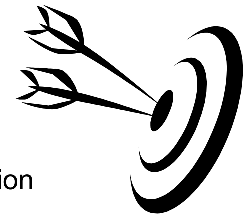
The first calibration technique we will cover is the "unknown thru" calibration.




A vector network analyzer (VNA) is a precision measuring tool that tests the electrical performance of high frequency components, in the radio frequency (RF), microwave, and millimeter-wave frequency bands (we will use the generic term RF to apply to all of these frequencies). A VNA is a stimulus-response test system, composed of an RF source and multiple measurement receivers. It is specifically designed to measure the forward and reverse reflection and transmission responses, or S-parameters, of RF components. S-parameters have both a magnitude and a phase component, and they characterize the linear performance of the DUT. While VNAs can also be used for characterizing some non-linear behavior like amplifier gain compression or intermodulation distortion, S-parameters are the primary measurement. The network analyzer hardware is optimized for speed, yielding swept measurements that are must faster than those obtained from the use of an individual source and an individual receiver like a spectrum analyzer. Through calibration, VNAs provide the highest level of accuracy for measuring RF components.

# The Need for Calibration



**How do we get accuracy?**

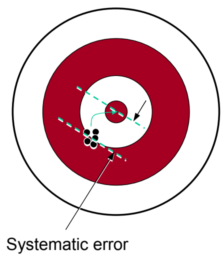
– With vector-error-corrected calibration
– Not the same as the yearly instrument calibration

**Why do we have to calibrate?**

– It is impossible to make perfect hardware
– It would be extremely difficult and expensive to make hardware good enough to entirely eliminate the need for error correction

**What does calibration do for us?**

– Removes the largest contributor to measurement uncertainty: systematic errors
– Provides best picture of true performance of DUT





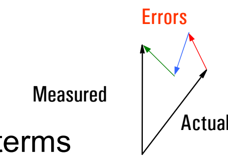


VNAs provide high measurement accuracy by calibrating the test system using a mathematical technique called vector error correction (this type of calibration is different than the yearly calibration done in a cal lab to ensure the instrument is functioning properly and meeting its published specifications for things like output power and receiver noise floor). Vector error correction accounts for measurement errors in the network analyzer itself, plus all of the test cables, adapters, fixtures, and/or probes that are between the analyzer and the DUT.

Why is calibration so important to network analysis? The reason is that it is impossible to make perfect test hardware, and too difficult and/or too expensive to make the network analyzer hardware so good that the need for error correction is entirely eliminated. Vector error correction is a cost effective way to improve the performance of test systems comprised of good but not perfect hardware. The right balance between hardware performance, cost, and system performance (including error correction) must be achieved. If the RF performance of the hardware is poor, then vector error correction will not be able to overcome all the deficiencies, and the overall system performance will suffer compared to that obtained from a system using better hardware.

Calibrating a VNA-based test system removes the largest contributor to measurement uncertainty, which are systematic errors. Systematic errors are repeatable, non-random errors that can be measured and removed mathematically. A vector-error-corrected VNA system provides the best picture of the true performance of the device under test (DUT). A network analyzer is really only as good as its calibration, so Agilent spends a great deal of effort to provide the most complete and highest-quality choices for calibration.

# What is Vector-Error Correction?




**Vector-error correction…**

- Is a process for characterizing systematic error terms
- Measures known electrical standards
- Removes effects of error terms from subsequent measurements

**Electrical standards…**

- Can be mechanical or electronic
- Are often an open, short, load, and thru, but can be arbitrary impedances as well



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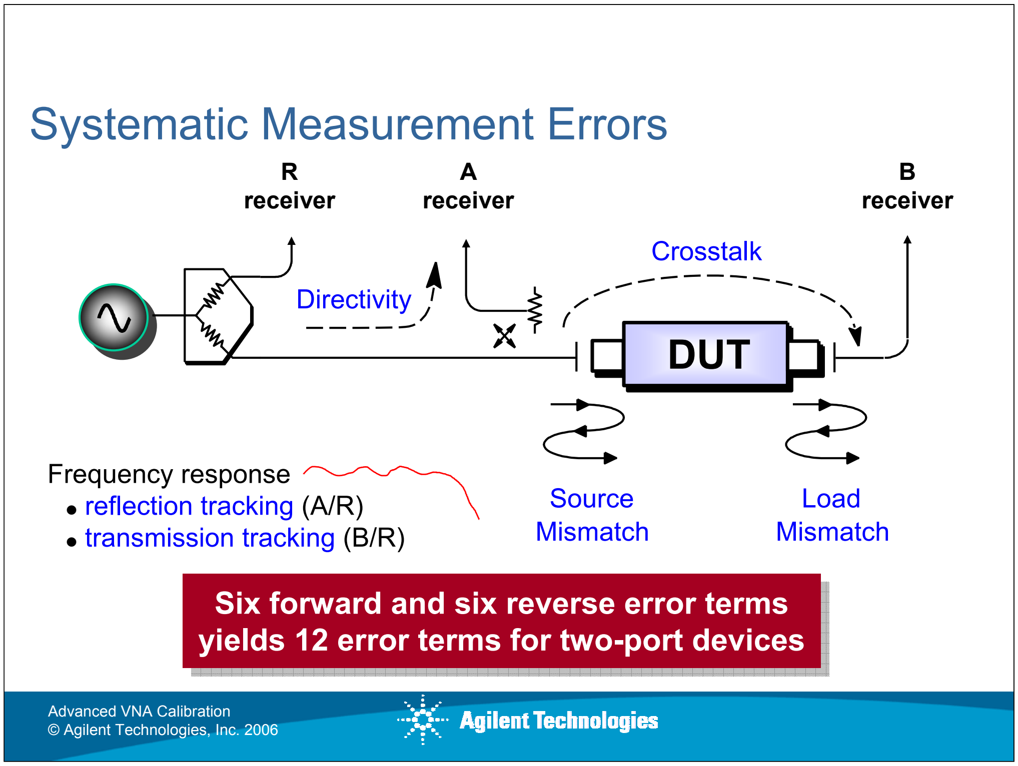
Vector-error correction is the process of characterizing systematic error terms by measuring known electrical calibration standards. Any deviation from the expected results is primarily due to systematic errors in the test system. Once these errors are quantified, their effects can be mathematically removed from subsequent measurements. The error terms can be expressed as vectors since they have a magnitude and phase component. Since any test system is affected by more than one cause of measurement error, the calibration process has to measure enough standards to sort out the magnitude and phase of the various errors.

The electrical standards used during the calibration process can be passive, mechanical devices, like the well-known short, open, load, and thru (SOLT) standards found in Agilent (and other) commercial calibration kits, or they can be arbitrary known impedances that are electronically switched, as is done with Agilent's ECal electronic calibration modules.




Shown here are the major systematic errors associated with network-analyzer measurements. The errors relating to signal leakage are directivity and crosstalk. Directivity limits dynamic range for reflection measurements, and crosstalk limits dynamic range for transmission measurements. The errors related to signal reflections are source and load mismatch. Source mismatch errors result from interactions between the test system's source match and the input match of the DUT. Load mismatch errors result from interactions between the test system's load match and the output match of the DUT. The final class of errors are related to frequency response of the receivers, and are called reflection and transmission tracking. The term "tracking" is used because S-parameter measurements are ratioed measurements between a test and a reference receiver. Therefore, the frequency response errors are due to imperfect tracking between the test and reference receivers.

The full two-port error model includes all six of these terms for the forward direction and the same six (with different data) in the reverse direction, for a total of twelve error terms. This is why two-port calibration is often referred to as twelve-term error correction. These same basic error terms are also used in error models for test systems with more than two test ports, where the total number of error terms is larger than 12.

## Performing the Calibration: SOLT

- Two most common types of calibration: SOLT and TRL
  - Both types remove all the systematic error terms
  - Type and definition of calibration standards are different
- SOLT
  - Basic form uses short, open, load, and known-thru standards
  - Advanced forms use multiple shorts and loads, unknown thru, arbitrary impedances (ECal)
  - Uses the 12-term error model
- Advantages:
  - Easy to perform
  - Applicable to a variety of environments (coaxial, fixture, waveguide…)
  - Provides a broadband calibration



There are two basic types of calibration used to correct for the systematic error terms that we discussed on the previous slide. The two types are SOLT (short, open, load, thru) and TRL (thru, reflect, line). The differences in the calibrations are related to the types of calibration standards they use and how the standards are defined. They each have their advantages, depending on frequency range and application. As its name implies, SOLT calibration is based on shorts, opens, loads, and thrus as calibration standards. In advanced forms, it can use multiple shorts and loads to cover a broader frequency range, and it can use undefined or unknown thrus, which we will cover in a later section. Electronic calibration is a form of SOLT calibration, where the shorts, opens and loads are replaced by known arbitrary impedances. We will discuss ECal in a later section as well.

SOLT cal is very easy to perform, and is used in a broad variety of environments. It is the most widely used choice for coaxial measurements, since there are many commercial coaxial calibration kits available to match most connector types. It can also be used with fixtures and probes. SOLT inherently provides a broadband calibration, essentially from DC to the upper frequency limit of the connector type being used.

## Performing the Calibration: TRL

- Basic form: thru, reflect, line standards
- Advanced forms: TRM, LRM, LRL, LRRL…
- Uses a 10-term error model

- Advantages
  - Uses standards that are easy to fabricate and have simpler definitions than SOLT
    - Only need transmission lines and high-reflect standards
    - Required to know impedance and approximate electrical length of line standards
    - Reflect standards can be any high-reflection standards like shorts or opens
    - Load not required; capacitance and inductance terms not required
  - Potential for most accurate calibration (depends on quality of transmission lines)
  - Commonly used for in-fixture and on-wafer environments



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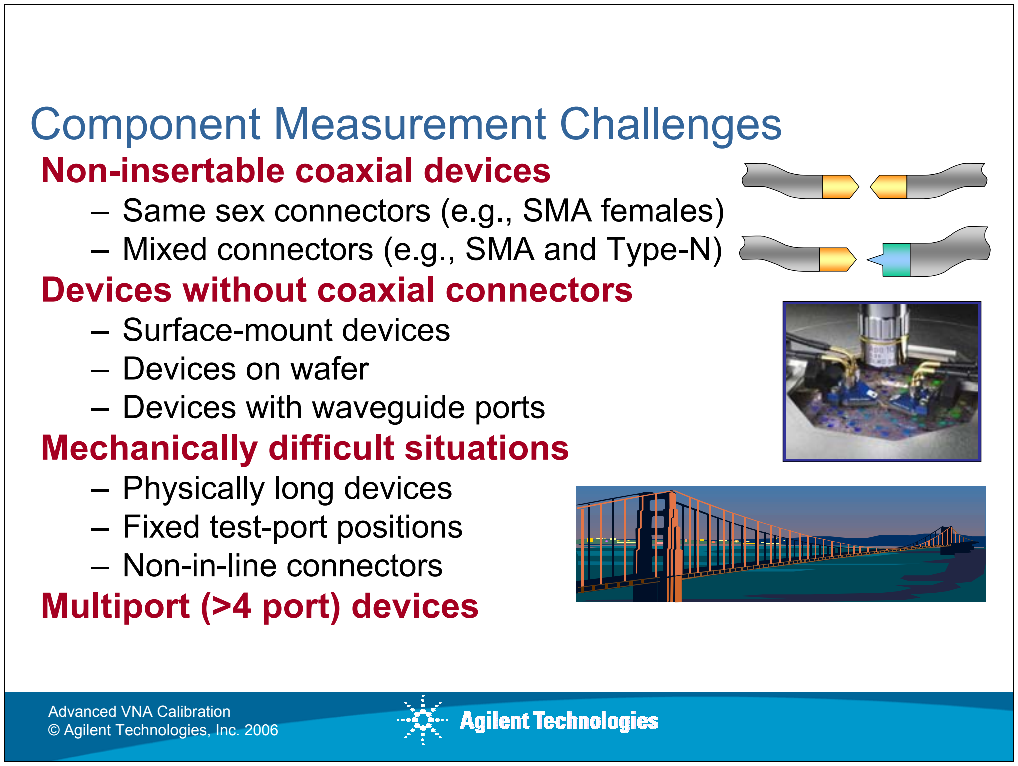
TRL calibration was developed for making accurate measurements of non-coaxial devices at microwave and millimeter-wave frequencies. It is commonly used for in-fixture and on-wafer environments. The basic form uses a zero-length thru, a longer thru (the “line”), and high-reflect standards like opens or shorts. There are many variations of TRL that substitute different standards (like lines for thrus, or loads for lines), but they all use the same error model and its associated assumptions. One of the biggest advantages of TRL is that the standards are generally easy to fabricate and they have simpler definitions than the standards used with SOLT. This means that for many non-coaxial applications, TRL can give superior accuracy. For TRL, it is only required to know the impedance and approximate electrical length of the line standards, and the reflect standards can be any high-reflection devices like shorts or opens. TRL does not require a load standard, which is desirable because it is difficult to make accurate high frequency, non-coaxial load standards. It is also not required to define the capacitance and inductance of the reflection standards.




Now that we know the basics of measuring the electrical performance of RF components, we can look at some of the measurement challenges that must be overcome to get accurate, repeatable measurements. The first challenge is for coaxial devices that are “non-insertable”. This means that the connectors on the DUT are such that the associated test-port cables of the test system cannot be connected directly together, without using some sort of RF adapter. During the thru portion of the calibration, the electrical characteristics of the adapter must be measured and removed from the calibration data. Common examples of non-insertable devices are those with the same connector sex on all ports (e.g., SMA female connectors), or those with mixed types of connectors (e.g., SMA on one port and Type-N on another port).

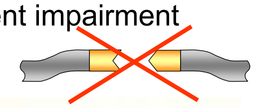
In today’s world of electronics, many RF devices don’t have coaxial connectors. For example, RF components found in mobile (cellular) handsets and wireless LAN circuitry are all implemented in surface-mount technology. Other examples of non-coaxial devices are those measured while still a part of the semiconductor wafer, or those with waveguide ports that are commonly found on very-high-power and/or very-high-frequency components.

Other situations that present measurement challenges are those that are mechanically difficult, such as physically long devices, fixed test-port positions, or devices with non in-line connectors.

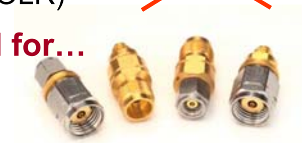
Finally, devices with more than four RF ports are a challenge since most modern commercial network analyzers come with up to only four integrated test ports. Test ports can be increased with external test sets, and calibration methodologies must be expanded to include these additional ports.

## Unknown Thru Calibration

**The “Unknown Thru” technique is…**
- Used when a “flush” (zero-length or mate-able) thru cannot be used or when using a flush thru would cause measurement impairment
- A refinement of SOLT calibration
- Also called short-open-load-reciprocal-thru (SOLR)



**Unknown Thru technique eliminates need for…**
- Matched or characterized thru adapters
- Moving or bending test cables



**Works great for many component measurement challenges…**
- Non-insertable devices
- Mechanically difficult situations
- Multiport devices

Advanced VNA Calibration


Agilent Technologies

The unknown thru calibration technique is used when a “flush” (zero-length or mate-able) thru cannot be used or when using a flush thru would cause measurement impairment from cable movement. It is a refinement of SOLT calibration, and is also called short-open-load-reciprocal-thru (SOLR) calibration. The unknown thru technique eliminates the need for matched or characterized thru adapters, and largely eliminates the need to move or bend test cables. It works great for many component-measurement challenges such as non-insertable devices, mechanically difficult situations, and for multiport devices.

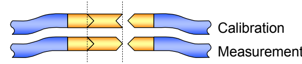
## Non-Insertable ECal Modules

ECal resolves many, but not all non-insertable

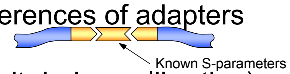



For non-insertable devices, Agilent's ECal modules can often be used. Some examples of same-sex or mixed-connector modules are shown here. However, some measurement applications cannot be solved using ECal alone, so it is desirable to have a general-purpose technique like the unknown-thru calibration which can be used in a variety of applications.

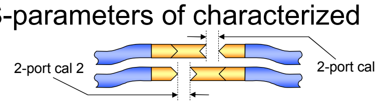
## Compromises of Traditional Non-Insertable Methods




- **Swap equal adapters**
  - Need phase matched adapters of different sexes (e.g., f-f, m-f)
  - Errors introduced from loss and mismatch differences of adapters



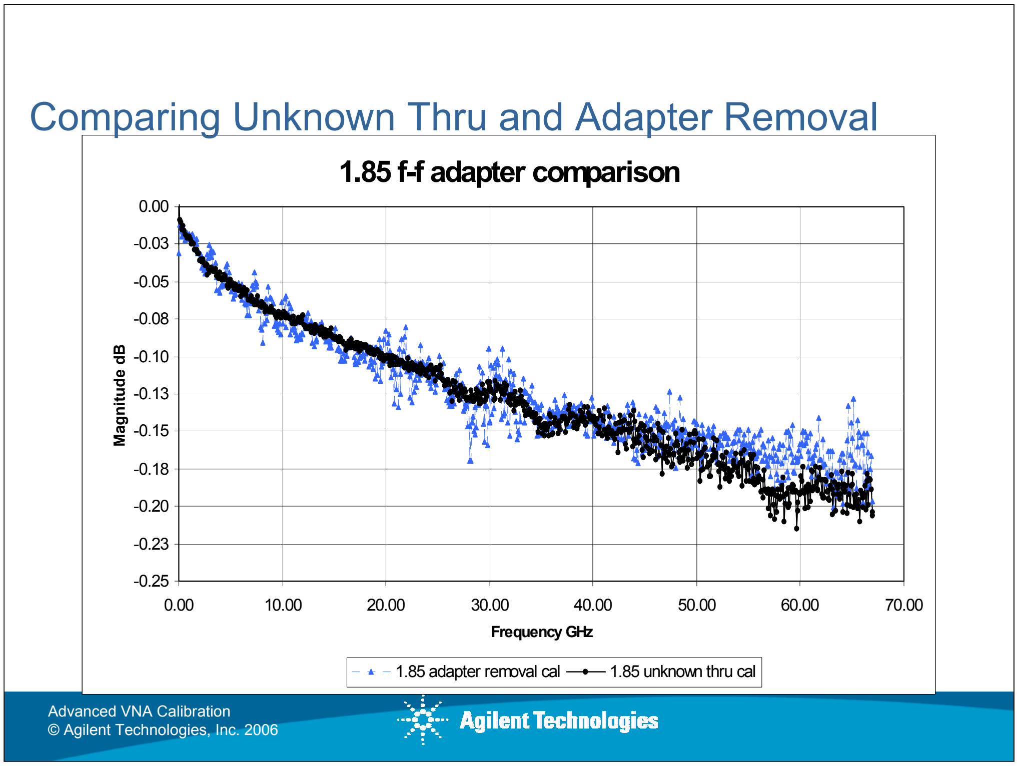

- **Use characterized thru**
  - Two-step process (characterize thru, then use it during calibration)
  - Need a non-insertable cal to measure S-parameters of characterized thru




- **Perform adapter removal cal**
  - Accurate but many steps in calibration (need to do two 2-port calibrations)
- **Add adapters after cal, then, during measurement…**
  - Use port extensions – doesn't remove adapter mismatch effects
  - De-embed adapters (S-parameters known) – similar to characterized thru



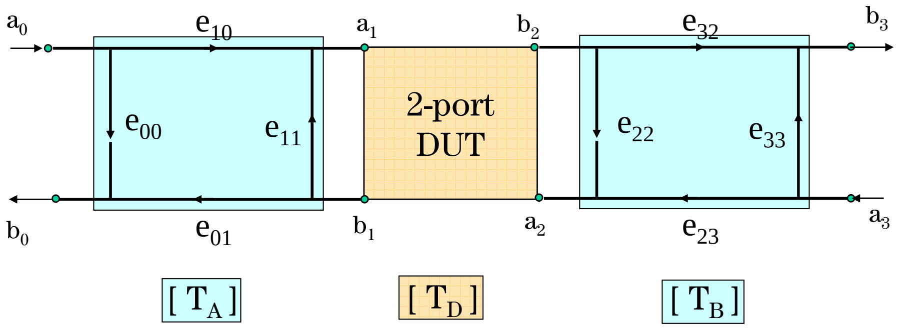

Traditional methods for measuring non-insertable devices all have compromises compared to the unknown thru technique. The swap-equal-adapter method works when phase-matched adapters are available. Many mechanical calibration kits for a specific connector type have these adapters, but they are difficult to obtain for mixed-connector-type situations. Also measurement error can result from the loss and mismatch differences between the adapters. Using a characterized thru is another method, but it is a two-step process as the user must first characterize the thru to obtain its S-parameters. This step often needs its own non-insertable calibration. An adapter-removal cal is a very accurate technique that is applicable to many non-insertable situations, but it is a lengthy process since it requires two two-port calibrations. Adding adapters after an insertable cal is often done, with mixed results. Using port extensions is a first-order correction, but it does not remove mismatch effects due to the addition of the adapter. The adapter can be de-embedded, but this also requires extra steps taken before the measurement to obtain the S-parameters of the adapter. All of these compromises are avoided with the unknown thru calibration.




In this slide, we compare the measurement of a 1.85 mm (67 GHz) female-to-female adapter using adapter removal calibration and unknown thru calibration. It is easily observed that the adapter removal calibration has considerably more variation in the data, indicating higher measurement uncertainty. This variation was primarily due to a combination of connector repeatability and cable movement.

## Unknown Thru Algorithm

Unknown thru algorithm uses same 8-term error model as TRL




$$[T_m] = \left(\frac{1}{e_{10}e_{32}}\right)\begin{bmatrix} e_{10}e_{01} - e_{00}e_{11} & e_{00} \\ -e_{11} & 1 \end{bmatrix}[T_D]\begin{bmatrix} e_{32}e_{23} - e_{22}e_{33} & e_{22} \\ -e_{33} & 1 \end{bmatrix}$$

Only 7 error terms need to be determined



Although the unknown thru calibration is a variant of SOLT calibration, the thru portion of the calibration is based on the thru-line-reflect (TRL) error model, which has 8 error terms instead of the 10 terms used in SOLT (we are ignoring the crosstalk terms here). Because of this, there are some constraints on the unknown thru technique.

## Unknown Thru Calibration Requirements

- Systematic errors of all test ports (directivity, source match, reflection tracking) can be completely characterized (6 terms)
- "Unknown thru" calibration standard (7th term):
  - Must be reciprocal (i.e., $S_{21} = S_{12}$)
  - Must know phase to within a quarter wavelength
- VNA signal-path switch errors can be quantified
  - Same restriction as TRL calibration
  - Requires dual reflectometers on all ports or equivalent (e.g., a 2-port 4-receiver VNA)

    OR
  - Requires characterization of switch correction terms via a two-tier calibration

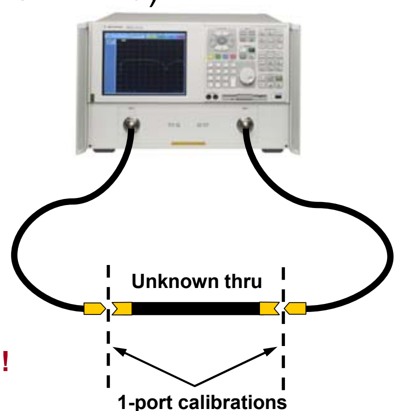
$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{b_{11}}{a_{11}} & \frac{b_{12}}{a_{22}} \\ \frac{b_{21}}{a_{11}} & \frac{b_{22}}{a_{22}} \end{bmatrix}}_{\text{Ideal S-parameters}} \bullet \underbrace{\begin{bmatrix} 1 & \frac{a_{12}}{a_{22}} \\ \frac{a_{21}}{a_{11}} & 1 \end{bmatrix}^{-1}}_{\text{Switch correction}}$$



The requirements for the unknown thru calibration are first, the normal reflection error terms (directivity, source match, and reflection tracking) can be acquired for each test port. This is accomplished by measuring shorts, opens, and loads, or by using ECal. The only constraint of the "unknown" thru standard is that it is reciprocal (i.e., S21=S12) and it's insertion phase must be known to within a quarter wavelength of the highest frequency of the measurement (i.e., the approximate group delay of the thru must be known). Other than that, the thru can have and arrangement of connectors, can be any length and shape, and can be very lossy (more on this later). One final constraint on the test system is that it must be capable of measuring the difference between the source match and load match on each test port, which is a normal TRL constraint. These differences in port match are due to the internal transfer switch within the analyzer, and they are used to calculate switch-correction terms that are a part of the TRL algorithm. The switch error terms can be directly measured with most two-port analyzers with two reference receivers, or by a two-tier calibration for analyzers with a single reference receiver (like the 4-port PNA-L) or for systems with external test sets. More discussion of this topic is in the section "TRL Calibration for Single-Reference Receiver VNAs".

## Two-Port Unknown Thru Calibration Sequence

1. Measure open, short, load on port 1 ($e_{00}$, $e_{11}$, $e_{10}e_{01}$)
2. Measure open, short, load on port 2 ($e_{22}$, $e_{33}$, $e_{32}e_{23}$)
3. Measure insertable adapter (unknown thru) between ports 1 and 2 ($e_{10}e_{32}$)
4. Confirm estimated electrical delay of unknown thru




**Unknown Thru calibration is as simple as performing a "flush thru" 2-port calibration!**



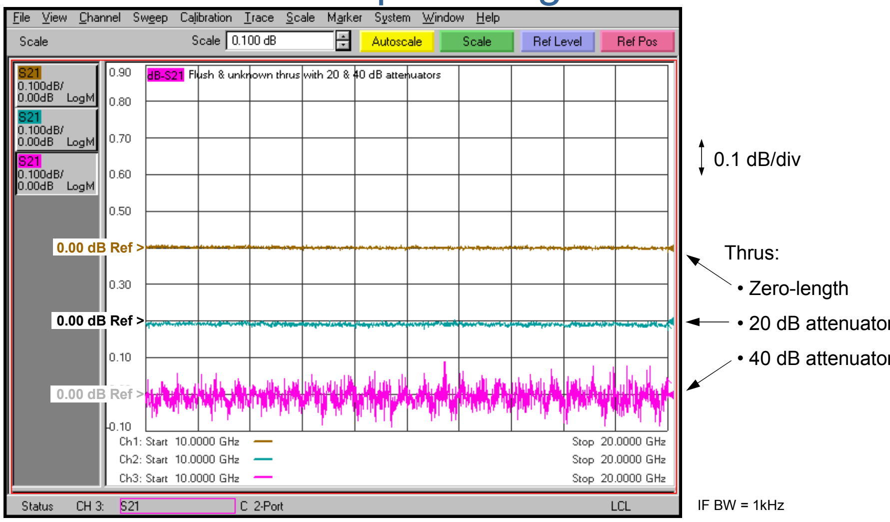

The sequence for performing an unknown thru calibration is essentially the same as that for a regular SOLT calibration, with the addition of an extra step where the operator must confirm the estimated delay of the thru adapter. The unknown thru algorithm makes a guess at the electrical delay of the thru, but the guess can be wrong if there are insufficient number of trace points for a given frequency span such that phase wrapping occurs between each trace point. For many adapters that are basically transmission lines, the electrical length can easily be estimated from the physical length of the thru and by knowing its velocity factor. The formula for calculating the time delay is time = distance/(speed of light x velocity factor). For example, an adapter that is 1 cm long and has a velocity factor of 0.7 (typical for Teflon dielectric material) would have a time delay of 1/(3x1010*0.7) or 47.6 ps.

# Unknown Thru Example Using a Bandpass Filter




Here is an example of measuring a zero-length thru with two different calibrations. In one case a zero-length or flush thru was used during the calibration (providing a reference trace for comparison) and in the other case, a bandpass filter was used for the unknown thru. The quality of the unknown thru calibration can be judged by looking at the trace noise on the measurement. We see that the trace noise remains very low for up to 20 dB of filter loss, and even at 40 dB loss (where the thru device was very reflective), the trace noise is only around 0.1 dB. This clearly demonstrates the robustness of Agilent's unknown thru algorithm.

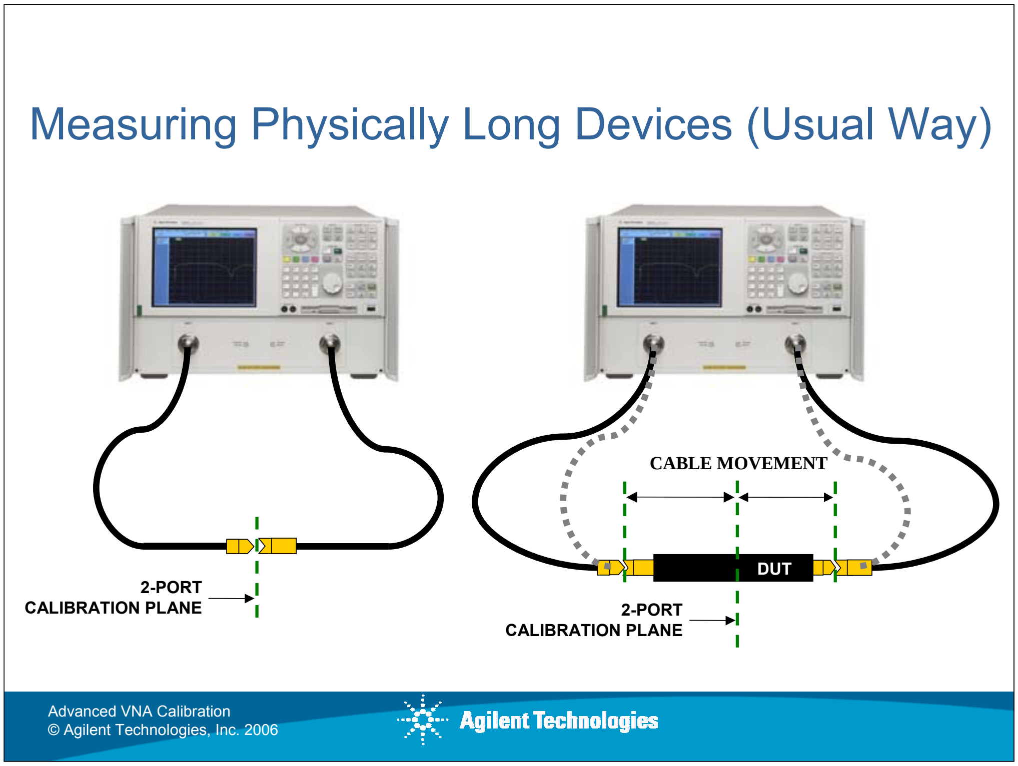
# Unknown Thru Example Using Attenuators



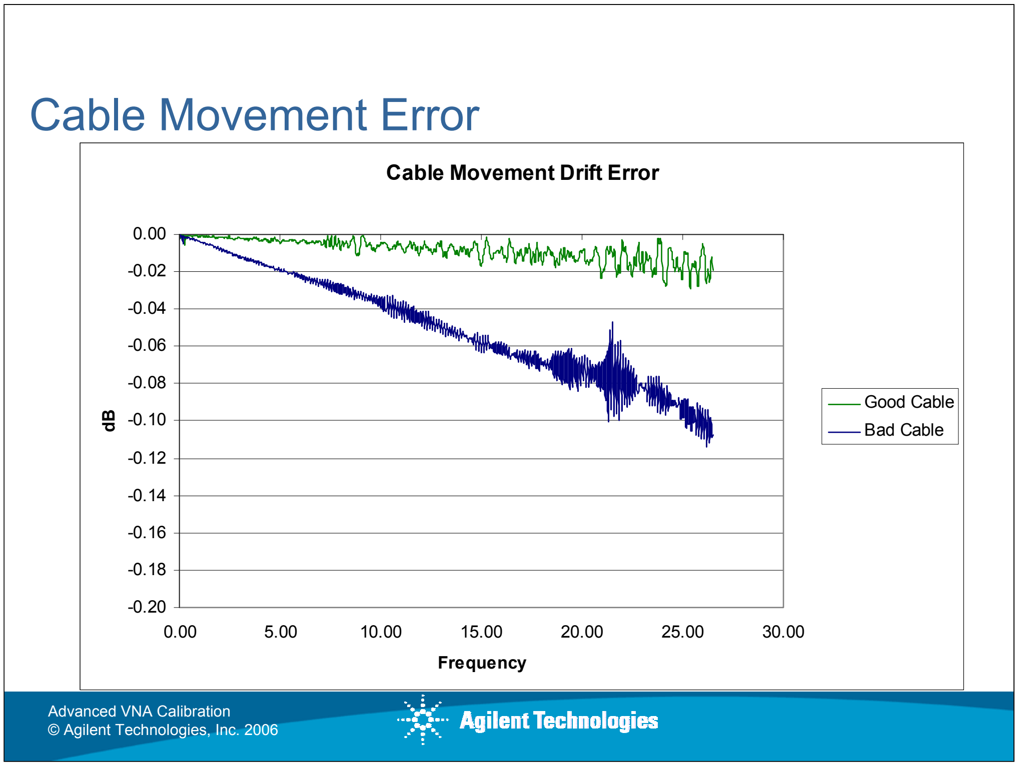

DUT is a zero-length thru



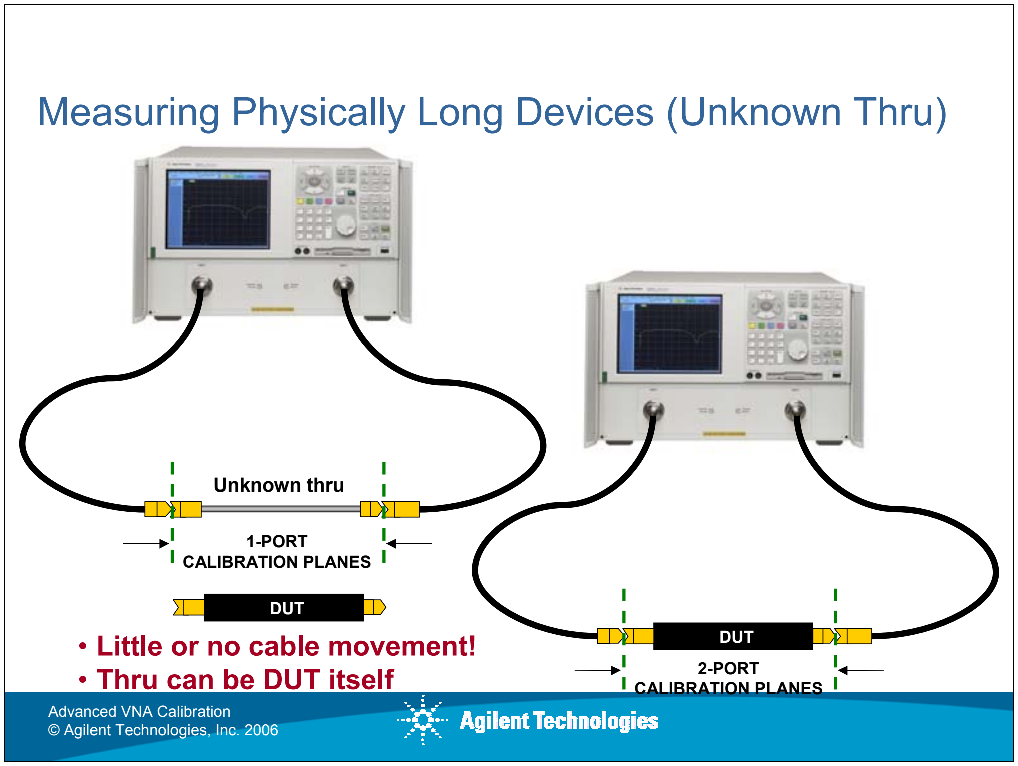
In this example, we again measure a zero-length thru, this time using three different calibrations (note that the scale per division is five times smaller than the previous example). For the upper trace, the thru for the calibration was also zero length. This is the best case and provides a reference trace for comparison. For the middle trace, a 20 dB attenuator was used during the calibration. We see that the trace noise is only slightly degraded. For the lower trace, a 40 dB attenuator was used during the calibration. We can clearly see the effects of reduced measurement dynamic range by the increased trace noise, but we also see a very flat response centered around a 0.0 dB reference value, as we would expect for a zero-length thru. Had we done these measurements with a narrower IF bandwidth (say 10 Hz instead of 1 kHz), the trace noise for the 40 dB case would have been significantly lower.



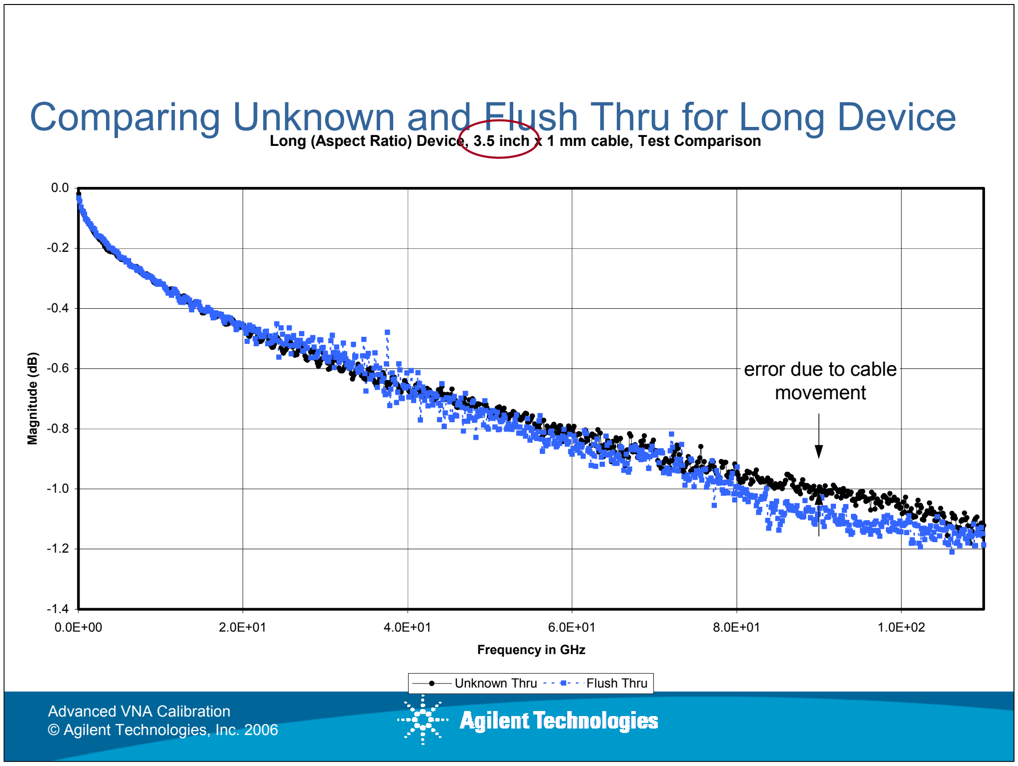

Let's take a look at measuring a physically long device (in this case, an insertable device) using flexible test cables. The calibration is straight-forward, but to measure the device, we must move the cables from where they were doing the calibration. This physical movement can introduce significant measurement error, especially as measurement frequencies increase. The lower the quality of the test cables, the more error introduced.



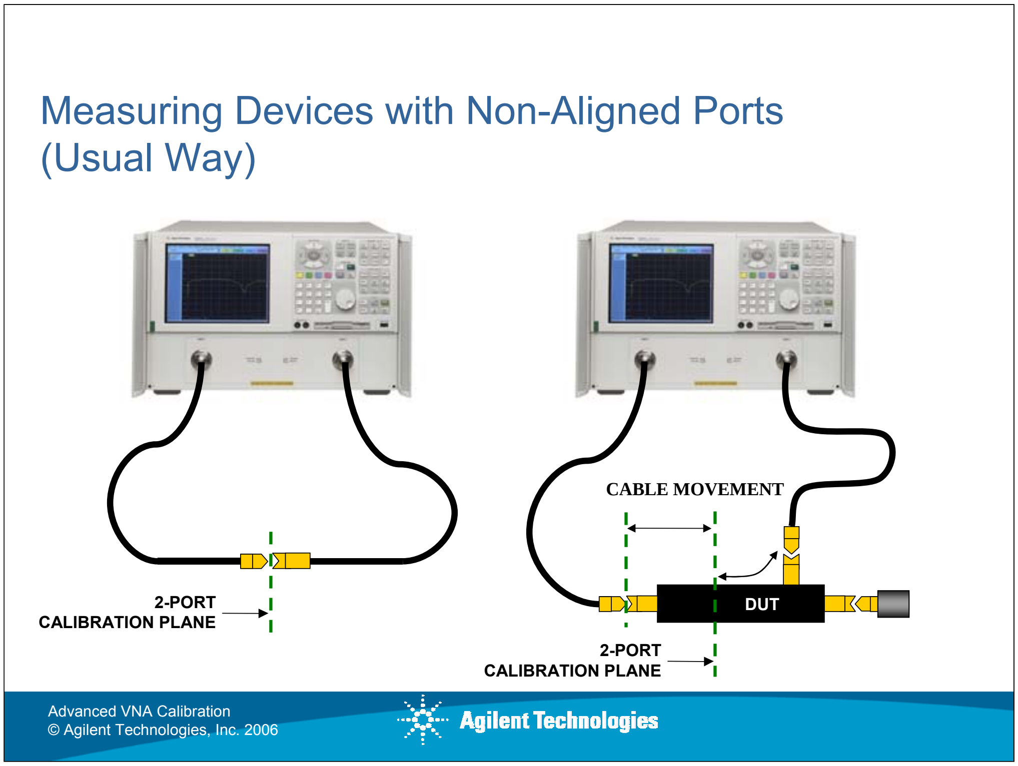

Here we see examples of the error introduced by cable movement, using two different cables. The so-called "bad" cable was actually the same cable type as the "good" cable, but it was much older and had been used much more. At 26.5 GHz, the bad cable had an error of -0.1 dB, compared to about -0.02 dB error of the good cable. While 0.1 dB may not seem like a lot of error, it is a significant amount for many low-loss devices that themselves only have a few tenths of dB or less of loss. For these low-loss devices, this amount of error could easily cause a good device to appear bad, or vice versa.



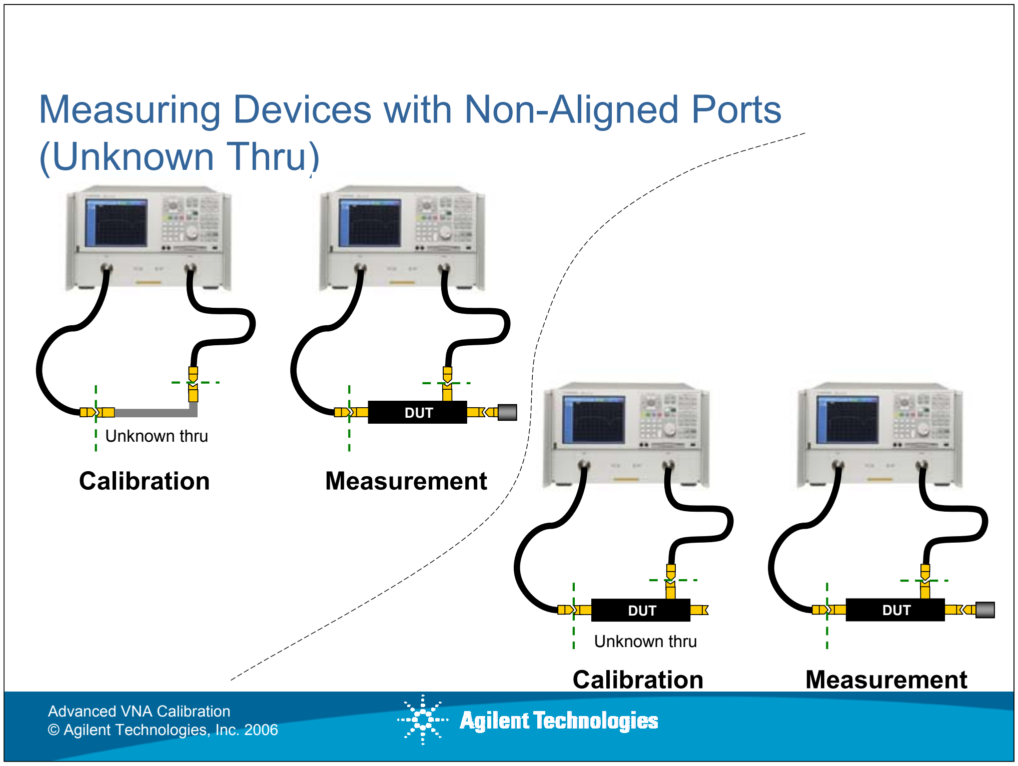

Here is how we can measure a physically long device using the unknown thru technique. During the through step, a thru that is the same length as the DUT can be used, or, if the DUT is reciprocal and has less than 40 dB of loss, the DUT itself can be used as the thru. If a thru is used that is the same length as the DUT, very little cable movement occurs when the DUT is inserted, as the cables only need to move the slight amount it takes to unattach and reattach the test cables. If the DUT is used as the unknown thru, then there is zero cable movement, since the measurement of the DUT can occur immediately after the calibration, without detaching and reattaching the test cables.




Here is an example of measuring a 3.5 inch transmission line, using a normal insertable SOLT cal and an unknown thru cal. In this example, we are measuring up to 110 GHz. We can see that cable movement causes significant measurement error around 35 GHz, and around 90 GHz.

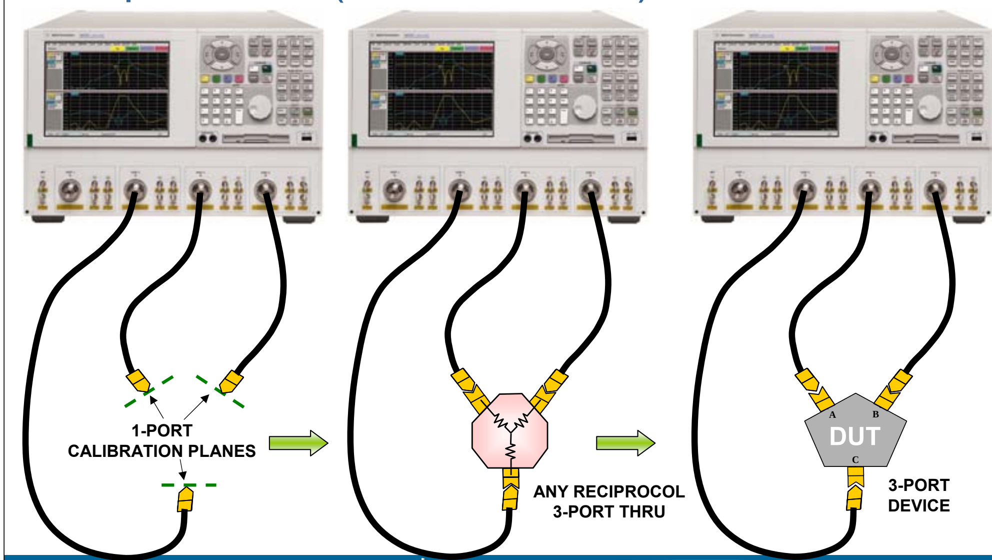



Here is the traditional way of measuring a device that is physically long and has non-aligned connectors. Again, there is lots of cable movement between the calibration and the measurement of any of the port pairs of the DUT.




Cable movement is very small or zero by using an unknown thru that matches the geometry of the DUT, or by using the DUT itself as the thru.

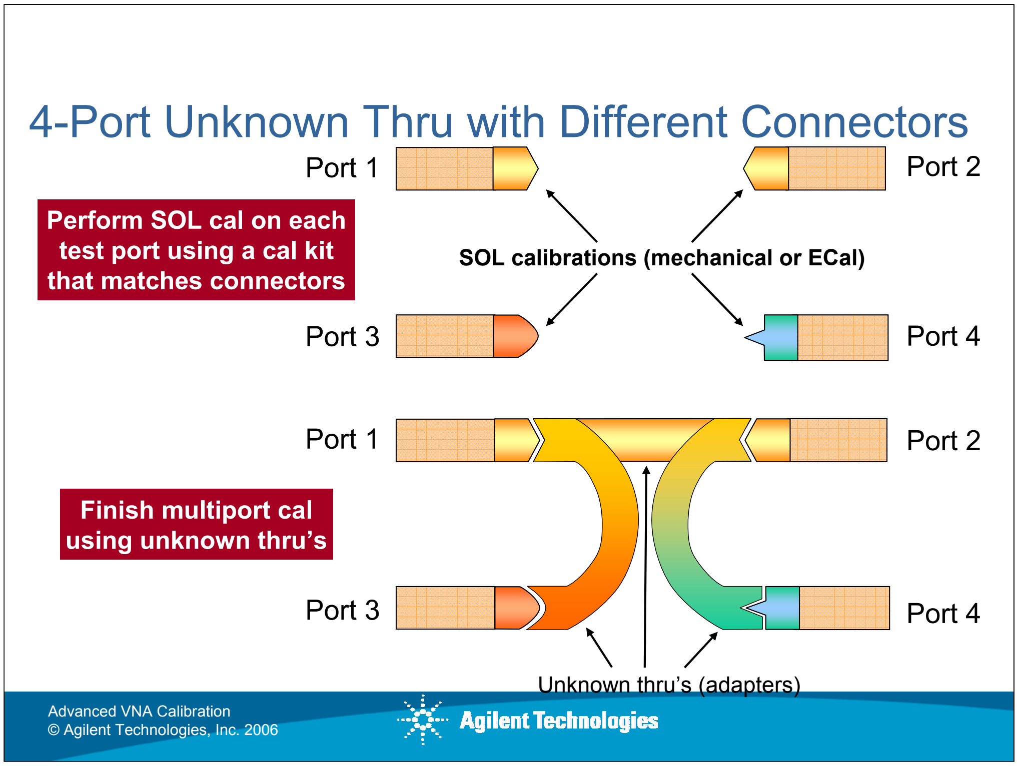
# Multiport Case (Unknown Thru)





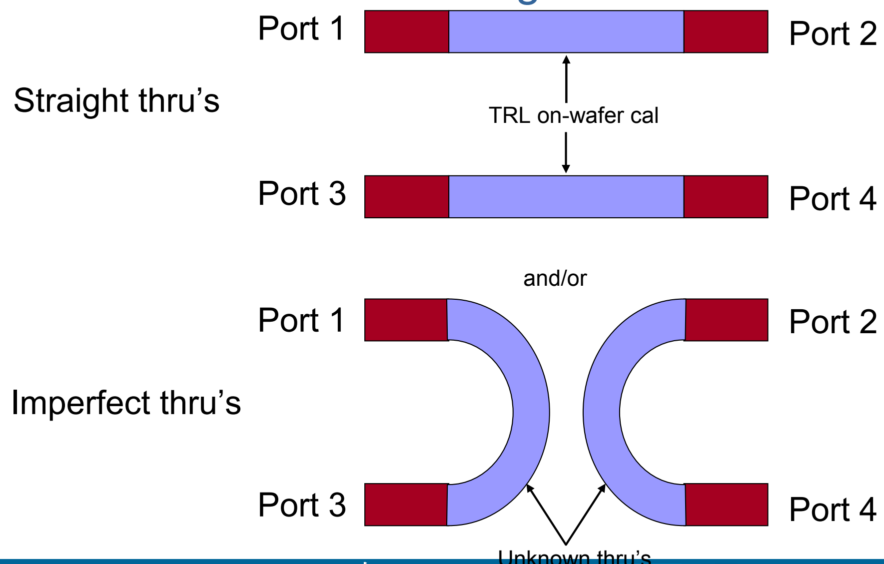



Here is an example of measuring all ports of a three-port device. In this example, the thru device used during calibration was a three-resistor power splitter (a reciprocal device) that matched the geometry of the DUT. If the DUT had been the power splitter, it could have also been used for the thru calibrations.




Here is an example of using the unknown thru on a four-port test system with four-port error correction, where multiple connector types are used. The unknown thru calibration requires a short, open, and load for each test port, using standards that match the port's connector type. For the thru calibrations, only three thru adapters are needed, and they can be any length and shape, as long as their connector types match those on the port pairs used for the thru calibrations. With Agilent's reduced-thru technique, only three thru standards are needed for a full four-port calibration.

## On-Wafer Calibrations Using Unknown Thru's

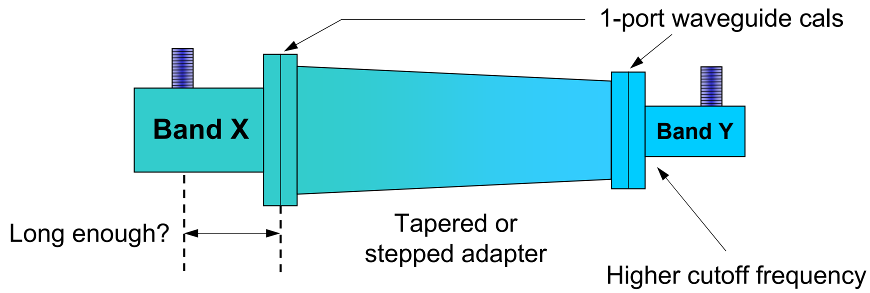





This concept of using the unknown thru calibration for four-port calibrations also works well for on-wafer measurements. In this example, we can perform TRL calibrations between port pairs 1-2 and 3-4, where the quality of the thrus is quite high since they are straight transmission lines. For the thru connection between port pairs 1-3 and 2-4 where a curved thru must be used (which would not make a good TRL thru), unknown thru calibrations can be done. Note that we do not have to repeat the reflection measurements on the four test ports for the unknown thru calibrations, since we already know the three reflection error terms for each test port from the two TRL calibrations performed first. It is sufficient to just measure the two additional curved thrus, as there is then enough information to perform unknown thru calibrations for those corresponding port pairs.

## Unknown Thru for Different Waveguide Bands

- Calibrate each waveguide adapter with appropriate waveguide cal kit
- Watch out for these potential problems:
  - Non-overlapping waveguide bands
  - Attenuation near cutoff may be too high for thru calibration
  - Undesired higher-order modes
    (longer adapters provide better attenuation for higher-order modes)



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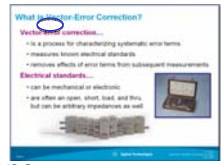
In this final example of using the unknown thru calibration, we show that the concept of an unknown reciprocal thru can also be applied to the case of DUTs with two different waveguide types. For example, the DUT might have circular waveguide on one end and rectangular waveguide on the other end. If the two waveguide types have non-overlapping frequency ranges, then measurements (and calibrations) must be done in the region where the two bands overlap. Care should be taken to stay away from the cutoff frequencies of the adapters, where the transmission attenuation gets quite high. Also, watch out for undesired higher-order modes that can cause measurement errors. In general, the longer the adapter, the more attenuation provided for unwanted higher-order modes.

## Defining Calibration Standards



- VNA calibration requires a known electrical standard
- Several approaches for "knowing" electrical performance
  - **Nominal models** based on nominal physical dimensions
  - **Characterized models** based on individually measured physical dimensions
  - **Characterized models or data** based on individually measured electrical quantities
- Models can be polynomial based or data based
  - Polynomial example: $C_0$, $C_1$, $C_2$, $C_3$ for capacitance of open
  - Data-based example: CITIFILE with magnitude and phase data versus frequency

Polynomial definition

Data-based definition



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Calibrating a VNA-based test system requires calibration standards with known electrical performance. There are several approaches to figuring out what the electrical performance actually is for a given standard. The most common approach, which is used is most calibration kits below 67 GHz, is to derive nominal models based on nominal physical dimensions. Physical dimensions can be measured very precisely, and since the calibration standards are simple mechanical structures, their electrical performance can be easily modeled based on their dimensions. Any variations in the physical dimensions of a given type of standard from cal kit to cal kit leaves a small amount of residual error. With high quality, repeatable standards, this error is small enough for most commercial applications. However, for the utmost in accuracy, the residual error can be decreased even further by individually measuring each calibration standard. For high quality standards, this generally yields the highest measurement accuracy. For example, in metrology laboratories, individually measured precision-machined airlines are used with thru-reflect-line (TRL) calibration to yield the highest accuracy possible. If the process of making the mechanical standards is not precisely controlled, then the individually characterized approach can be used to get similar residual errors as the nominal approach to precision standards.

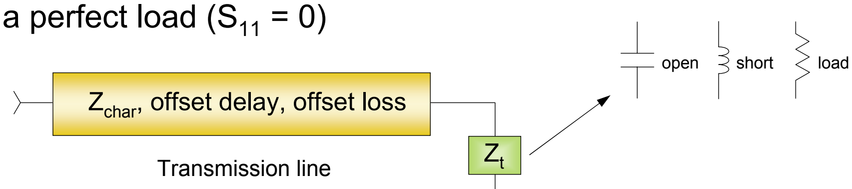
Another approach to defining the electrical performance of a calibration standard is to actually measure its electrical quantities instead of its physical dimensions. This approach works especially well when the calibration standard is not based on a simple transmission-line structure, so predicting its electrical performance from its physical dimensions would be difficult. An example of this are calibration standards used in a test fixture. The measured-electrical-quantities approach initially requires a calibrated test system to derive the models of the standards – the better we calibrate this test system, the better our models will be for the calibration standards.

The models that are used to describe the electrical performance of the calibration standards can be one of two types: polynomial or data-based. Polynomial models use a polynomial expression to approximate the performance versus frequency of the standard.

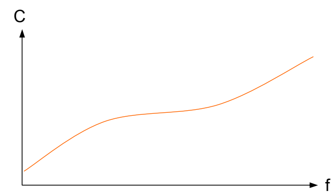
**(Continued on page M6-33)**

## Traditional Polynomial-Based Models

- Lossy transmission line terminated with either…
  - a frequency-dependant impedance for opens and shorts
  - a perfect load ($S_{11}$ = 0)




- Third-order polynomial models for $Z_t$:
  - Open capacitance:
    $C(f) = C_0 + C_1{*}f + C_2{*}f^2 + C_3{*}f^3$
  - Short inductance:
    $L(f) = L_0 + L_1{*}f + L_2{*}f^2 + L_3{*}f^3$






Let's take a closer look at traditional polynomial-based models. The most widely used model is a lossy transmission line terminated with a frequency-dependent impedance (for open and short standards), or a perfect load (S11 = 0). The lossy transmission line is described by a characteristic impedance and offset delay and offset loss values. The frequency-dependent impedance models are third-order polynomial expressions of capacitance versus frequency for open standards, and inductance versus frequency for short standards. Opens look capacitive due to fringing fields within the open, and shorts look inductive due to a finite length of the short itself. With this polynomial model, the VNA creates S-parameter data versus frequency for the standards as part of the calibration process.

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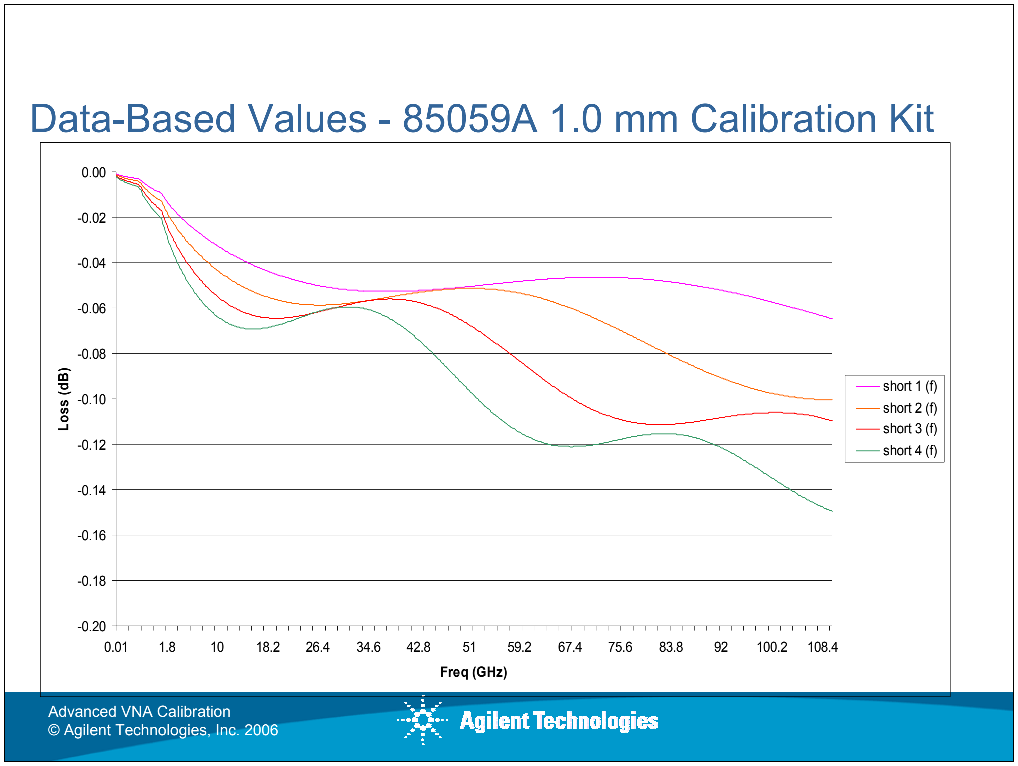
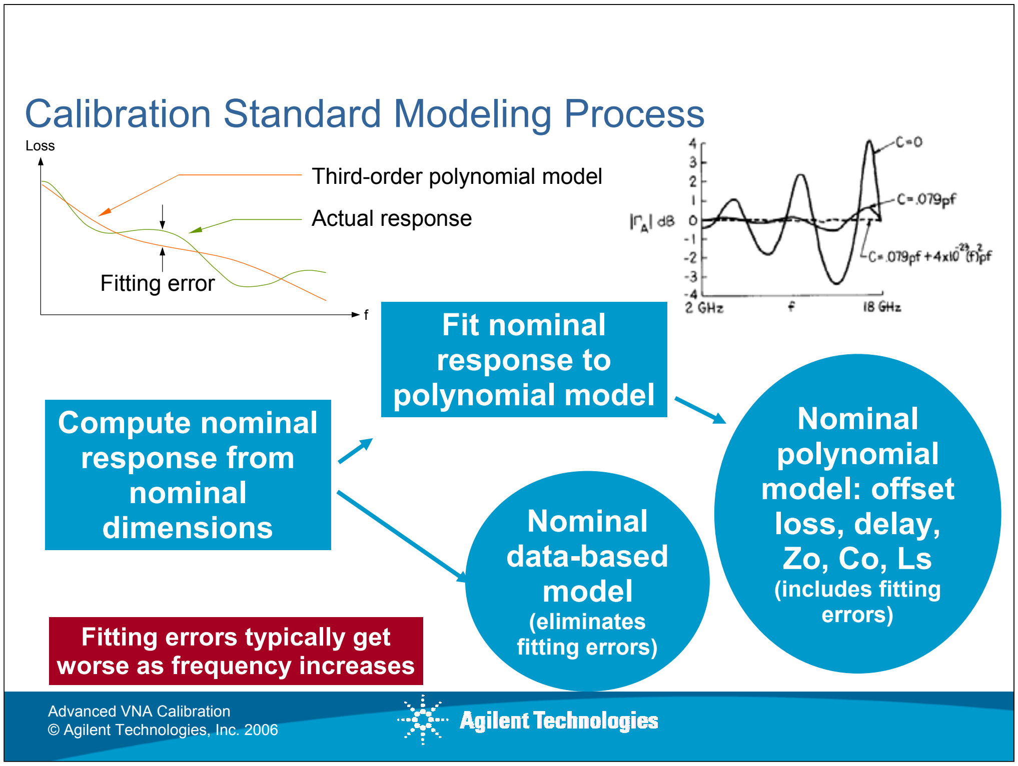
**(continued from page M6-32)**

Typically, a third-order polynomial expression is used. This approach is simple, but accuracy degrades as frequency increases. The second approach is to specify the electrical performance in a data file that contains magnitude and phase data versus frequency, covering the entire band of operation. In most cases, this data is generated from a physical and electrical model of the standard, just like ADS generates S-parameters from a circuit model. This approach can yield a more accurate description of electrical performance than that which can be obtained using a polynomial expression of limited order. Note that even when we are measuring the electrical performance of a standard, we can use the data for either a polynomial or data-based model. If we measure the capacitance of an open or the inductance of a short, we can use this data to derive a polynomial model. If we measure S-parameter data, we can directly use it as a data-based model.




Data-based models that depend on measurements of physical dimensions also use the model of a lossy transmission line terminated with a frequency-dependant impedance. However, instead of using a polynomial expression to model the characteristics of the open and short standards, a set of S-parameters is directly calculated based on this model. This gives more a more accurate description of the performance of each standard versus frequency, as the data is not limited to a third-order polynomial response.

Here is an example of a data-based model for describing the electrical performance of the short standards used in Agilent's 1.0 mm 110 GHz coaxial calibration kit. The loss of the loads versus frequency is shown, and we can see that describing the electrical performance of these standards up to 110 GHz would require a polynomial expression of substantially higher order than three.

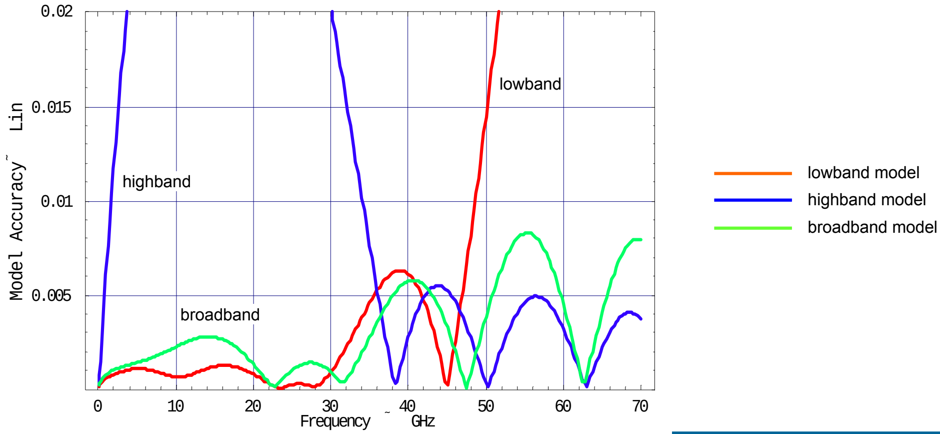



Seeing the actual frequency data of calibration standards (shown on the previous slide) makes it clear that using a polynomial model is always an approximation of actual performance. Fitting a third-order response to the actual response will yield fitting errors that generally get worse as frequency increases. The example in the upper right of the slide helps illustrate this as well by showing the simulated reflection response of an open with increasingly higher order capacitive polynomials (from zero to second order). Using data-based models eliminates the fitting errors.

## Fitting Errors

- A given standard can have more than one polynomial model
- Optimized, multi-band models often used to improve accuracy at high frequencies

**Comparison of polynomial models for 1.85 mm short 1 (5.4 mm offset)**

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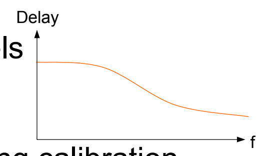
For high frequency calibration kits, each standard typically has more than one polynomial model. This allows performance to be optimized for different frequency bands, to yield high accuracy across the full frequency range of the calibration kit. The slide shows three different models for a short. Each model would be used in the error-correction calculations only over its corresponding frequency range.

## Benefits of Data-Based Standards

- Increased accuracy of calibration compared to using polynomial models, especially for frequencies > 50 GHz
- Eliminates the necessity of fitting the calibration standard's response to a limited set of low-order models
  - Not restricted to "coax" or "waveguide" models
  - Account for any type of dispersion
  - Great for on-wafer, microstrip, coplanar, etc.

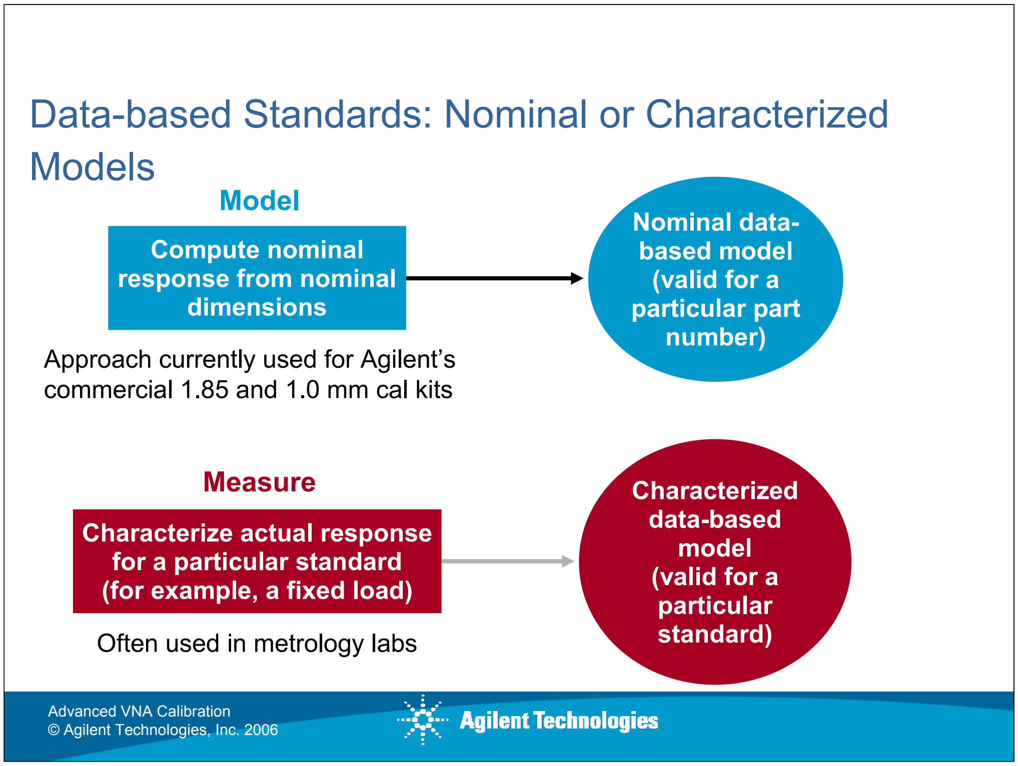



- Makes it easy to use characterized devices during calibration
  - No longer need to assume perfect standards (like a broadband load)
  - Use of a characterized load retains ease-of-use of a broadband-load SOLT calibration while significantly improving accuracy
- Can include accuracy data for expanded math



As an alternative to polynomial-based models, data-based models can provide increased measurement accuracy, especially for frequencies above 50 GHz. This is accomplished by eliminating the necessity of fitting the calibration standard's response to a limited set of low-order models. Agilent uses data-based models for the 85058B/E 1.85 mm 67 GHz and the 85059A 1.0 mm 110 GHz calibration kits for improved accuracy.

Data-based models are not restricted to coax or waveguide models, and they can account for any type of group delay dispersion. This makes them ideal for non-coaxial environments like on-wafer, microstrip, co-planar, etc. Data-based standards also provide a mechanism to use characterized devices for many different types of calibration. For example, SOLT calibration could use a characterized broadband (non-sliding) load standard instead of assuming that the load is perfect. This retains the ease-of-use of a broadband-load SOLT calibration while significantly improving accuracy. Another advantage that we will discuss in more detail in the next section is that the data files that contain the standard's electrical performance can also contain accuracy data versus frequency. This additional data helps the expanded calibration mathematics decide how to weight overlapping standards.




Just like with polynomial models, data-based models can use nominal data or individual data. With the approach to data-based standards that Agilent uses for its commercial 1.85 mm (67 GHz) and 1.0 mm (110 GHz) cal kits, the data-based models are derived from nominal dimensions. This means that the models are valid for a particular part number. For example, all of the SHORT1 standards in all of the 1.0 mm cal kits would use the same data-based model. Any particular standard can also be individually characterized, which would give a data-based model that was valid for that individual standard. An example would be characterizing the electrical response of a particular fixed-load standard.

## Data-Based Standard File

```
CITIFILE A.01.01
#PNA Rev A.01.00
#PNA STDTYPE DATABASED
COMMENT MODEL: 85058-60101
COMMENT SERIAL NUMBER: NOMINAL
#PNA STDREV Rev A.01.00
#PNA STDLABEL "SHORT 1 -M-"
#PNA STDDESC "1.85 mm male [SHORT 1]"
#PNA STDFRQMIN 0
#PNA STDFRQMAX 70000000000
#PNA STDNUMPORTS 1
COMMENT "1.85 mm" known so #PNA DEFINECONNECTOR statement non needed
COMMENT #PNA DEFINECONNECTOR "1.85 mm" 0 70000000000 COAX
#PNA CONNECTOR 1 "1.85 mm" MALE
COMMENT PINDEPTH is optional, only applies to coax devices
#PNA PINDEPTH 1 0.007 0.007

NAME DATA
COMMENT This section describes the s parameter data and weighting
COMMENT factor for the calibration standard
COMMENT COVERAGEFACTOR is used to scale the weighting factor
COMMENT S[i,j] is sij for the standard. Supported formats: RI
COMMENT U[i,j] is the weighting factor for sij.
COMMENT Supported U[i,j] formats: RI, MAG
#PNA COVERAGEFACTOR 2
```

```
COMMENT note number of points is 509 below
VAR Freq MAG 509
DATA S[1,1] RI
DATA U[1,1] MAG
VAR_LIST_BEGIN
0
10000000
15000000
...
70000000000
VAR_LIST_END
BEGIN
-1,0
-0.99976354927,0.00249289367
-0.99970950119,0.00367766097
...
0.9772034982,-0.14575300423
END
BEGIN
0.00028
0.00028
0.00028
...
0.005
END
```

**Ignored when not used with expanded calibration**

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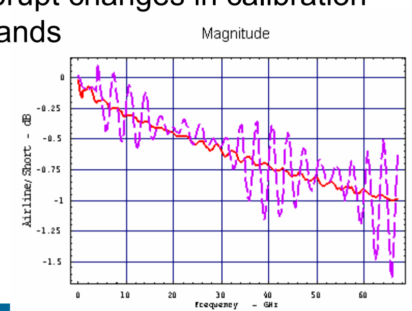
Here is an example of the file format of a data-based file. It contains S-parameter data as well as optional accuracy data. The accuracy data is used with expanded calibration, which will be covered in the next section.

## What is Expanded (Weighted-Least-Squares) Cal?

- Measures multiple (>3) standards at each frequency to provide over-determined solution to reflection error terms of SOL cal
- Uses weighted-least-squares fit to calculate error coefficients
- Weighting factor is a function of frequency and is a combination of calibration-standard accuracy and proximity to other standards
- Eliminates discontinuities due to abrupt changes in calibration standards for different frequency bands




**Result: higher accuracy!**



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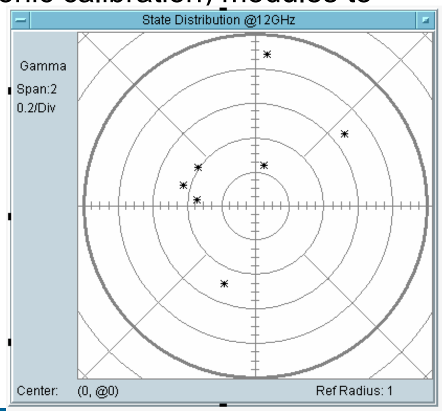
Expanded calibration is another method that can be used to increase measurement accuracy, especially for high frequencies. Expanded cals measure more than the minimum of three reflection standards to provide an over-determined solution to computing the three reflection error terms for each test port. It can be used for SOL-type calibrations. The data from the measured calibration standards is combined in a weighted-least-squares algorithm to calculate the error coefficients. The weighting factor for each standard is a function of frequency, and is derived from a combination of a calibration-standard-accuracy estimate, and the electrical proximity of that standard to the other standards. One of the biggest benefits of expanded calibration is it eliminates the measurement error discontinuities that occur when the definition of a standard abruptly changes from one frequency band to the next. This can be clearly seen later on in this section when we show actual measurement data for different types of calibration.

# Advantage of Measuring More Than 3 Standards

- Similar to trace averaging – the more data, the better the results
- Reduces residual errors after calibration
- Used in Agilent's ECal (electronic calibration) modules to improve accuracy







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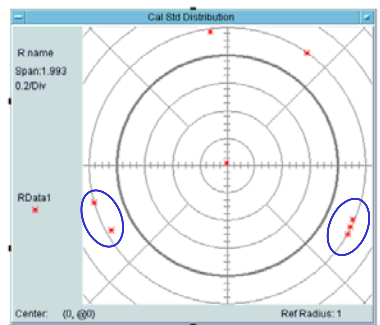
Measuring more than three standards or impedances at each frequency provides more data that can be processed to improve accuracy, similar to using trace averaging to reduce noise and improve measurement accuracy. A difference, however, is that expanded cals work with repeatable, systematic errors, while trace averaging lowers random, noise errors from trace to trace. Expanded math is also used in Agilent's ECal modules to increase accuracy, where between 4 and 7 impedances are measured at each frequency point.

## Why “Weighted” Least Squares?

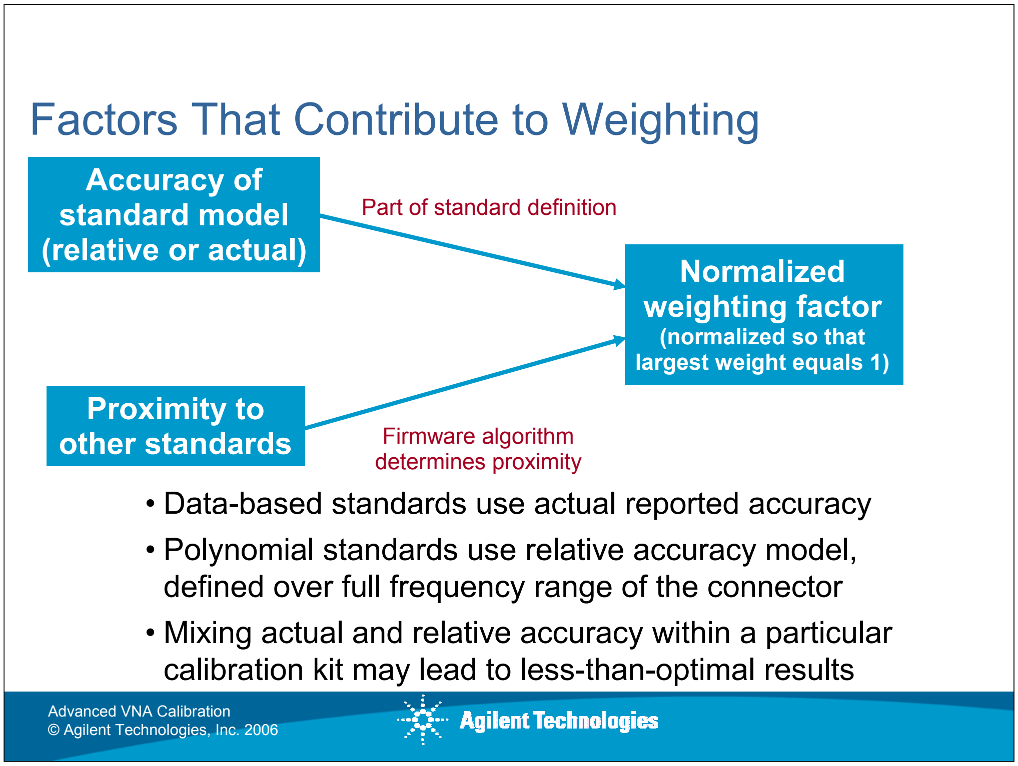
- Weighted least squares (WLS) beneficial when calibration standards are known with different levels of accuracy
  - Fixed loads are more accurate at low frequencies
  - Sliding loads are generally more accurate at higher frequencies
  - Shorts are more accurate than opens
- Less weighting is assigned to calibration standards that are bunched together (proximity effect)


**Patented WLS algorithm**






Agilent’s patented weighted-least-squares algorithm determines which standard should dominate when the various calibration standards for a particular frequency have different levels of accuracy. For example, at low frequencies, fixed loads are generally more accurate than sliding loads. However, at high frequencies, sliding loads are more accurate than fixed loads. Shorts tend to be more accurate than opens, since the inductive effect of a finite length of the short standard is easier to model than the capacitive effect of fringing fields in an open standard. Another part of the algorithm determines how close together the impedances of the various standards are at each frequency. Less weighting is assigned to calibration standards that are bunched together. In the example on the slide, the two lower, bunched groups of standards will have a lower relative weighting than the two impedances that are in the top half of the polar plot.

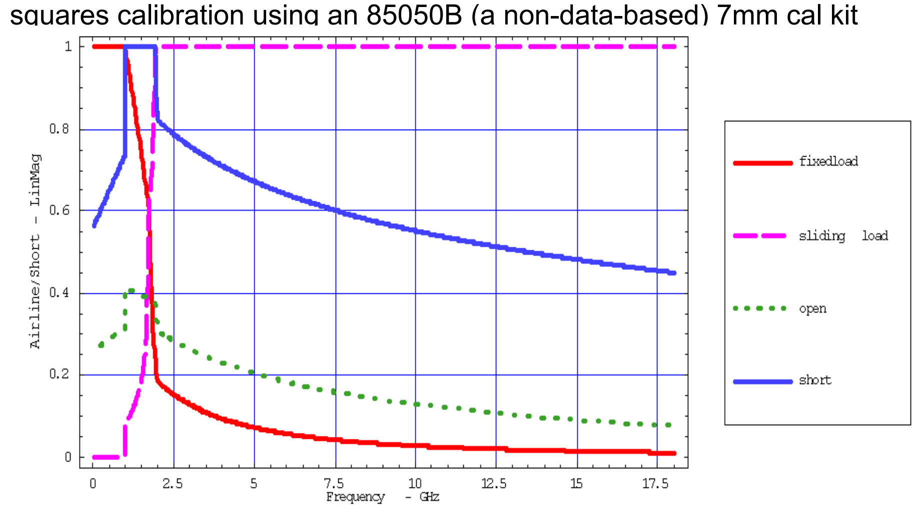



The accuracy data for standards can be expressed in relative or actual terms. This data is part of the definition of the standard. Data-based standards use actual reported accuracy data contained in the data file associated with the cal kit. Polynomial models use a relative accuracy model, where the standards are relative to each other, and their accuracy is defined over the full frequency range of the connector type they use.

As long as any given cal kit uses one method or the other for all of the standards, the expanded calibration math assigns the correct weighting to the standards, and the resulting calibration gives good results. However, mixing actual and relative accuracy data within a particular calibration kit may lead to less-than-optimal results. This is because the polynomial electrical models are often fitted and used only over a narrow frequency range, but the accuracy data, which is defined over the full frequency range of the standard, can incorrectly influence the expanded math over the un-used, non-fitted range of frequencies.

# Example of Relative (Normalized) Weighting

Weights for each standard versus frequency for a weighted-least squares calibration using an 85050B (a non-data-based) 7mm cal kit

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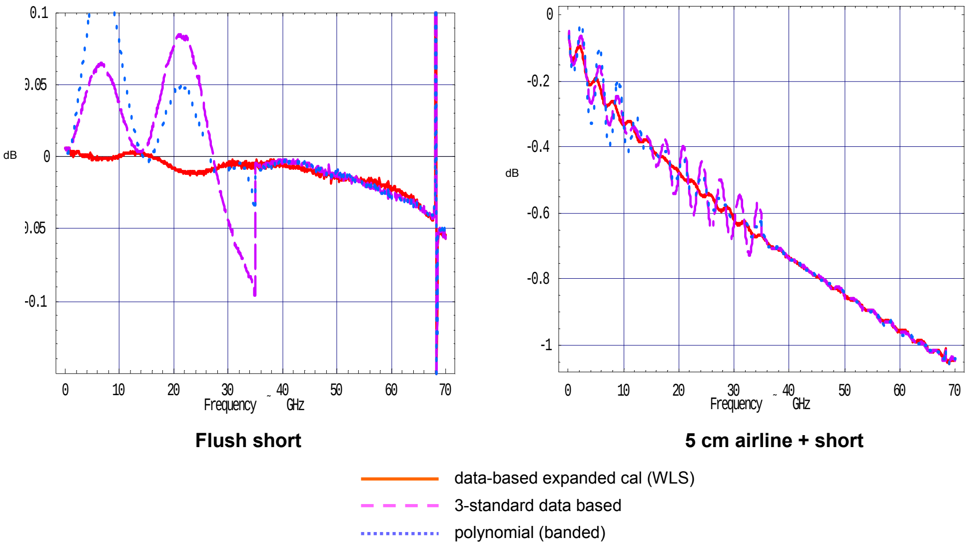
Here is an example of the relative accuracies assigned to a non-data-based cal kit (an 85050B, 7 mm, 18 GHz cal kit). Notice that the accuracy data has been normalized to the most accurate standards at any given frequency, which have been assigned a value of 1. We can also see that the fixed load has high relative accuracy up to about 2.4 GHz, and the sliding load has high relative accuracy above 2.4 GHz. During this crossover region of the loads, the short's accuracy is high. We also can see that the short has a higher relative accuracy than the open across the entire frequency range of the cal kit.

## Measurements Comparing Three Calibrations

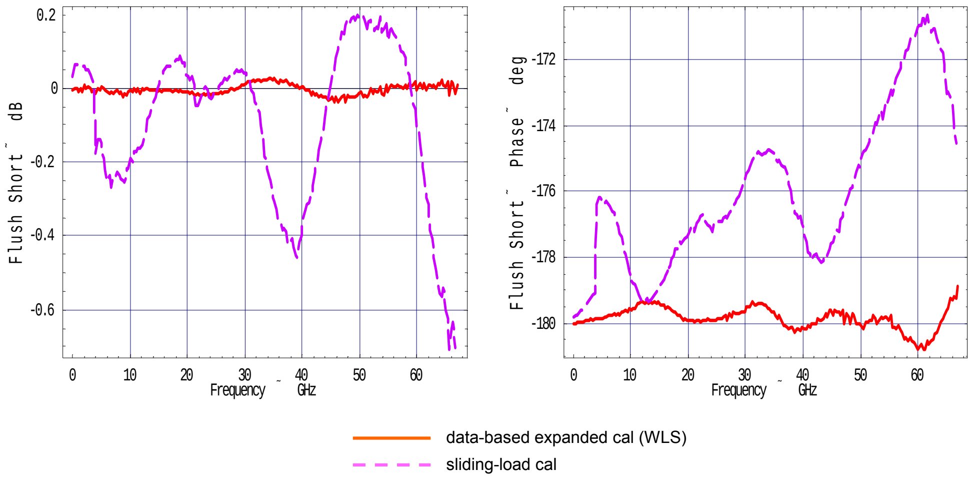







Here is a measurement comparison of two DUTs measured with three different types of calibration. For measurements of the flush short, both the traditional banded-polynomial model and a 3-standard data-based model yield much higher error (and with sharp discontinuities) compared to the data-based expanded calibration using the weighted-least-squares math. The right plot shows a short measured at the end of a 5 cm airline, which is a common DUT to test the quality of a calibration. Here we see that the expanded cal gives the best results again, with substantially lower ripple than the other two calibration types.

## WLS and Sliding-Load* Calibration Comparison – Flush Short




* Commercially available (non-Agilent) sliding-load cal kit

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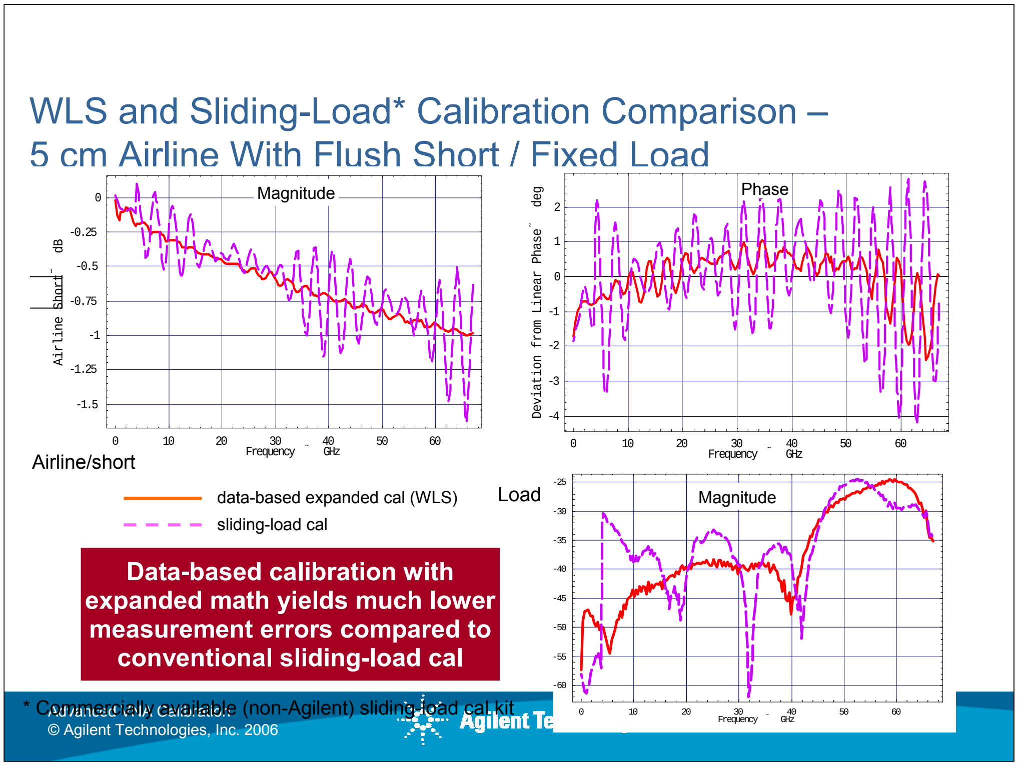
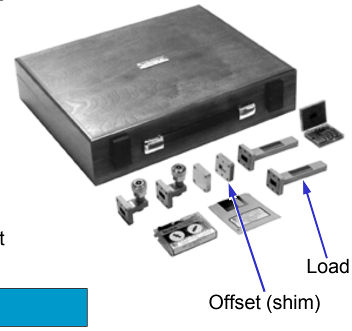
Here is another measurement example of a flush short, with both magnitude and phase data. In this example, we compare the accuracy between a data-based expanded calibration, and a sliding-load calibration done with a commercial, but non-Agilent calibration kit. Again, we see the accuracy improvement of the expanded calibration.




In these examples, we again compare a data-based expanded cal with a sliding-load cal. Both DUTs contain a 5 cm airline. For the airline/short combination, the sliding-load calibration shows considerably higher ripple in both the magnitude and phase responses. The measurement of the airline/load shows the improvement of the data-based expanded cal (bigger negative numbers are better), especially below about 40 GHz.

## Offset Load Calibration Overview

- Offset-load calibration originated with 8510
- Offset load is a compound standard – load is connected multiple times with different offsets
- In simplest and most common form, there are just two connections: the load by itself, and the load with an offset
- Similar to a sliding load standard, except offsets are set by a known, precise transmission line (e.g., a waveguide section)
- Not the same as a load standard with defined delay, which is a single standard

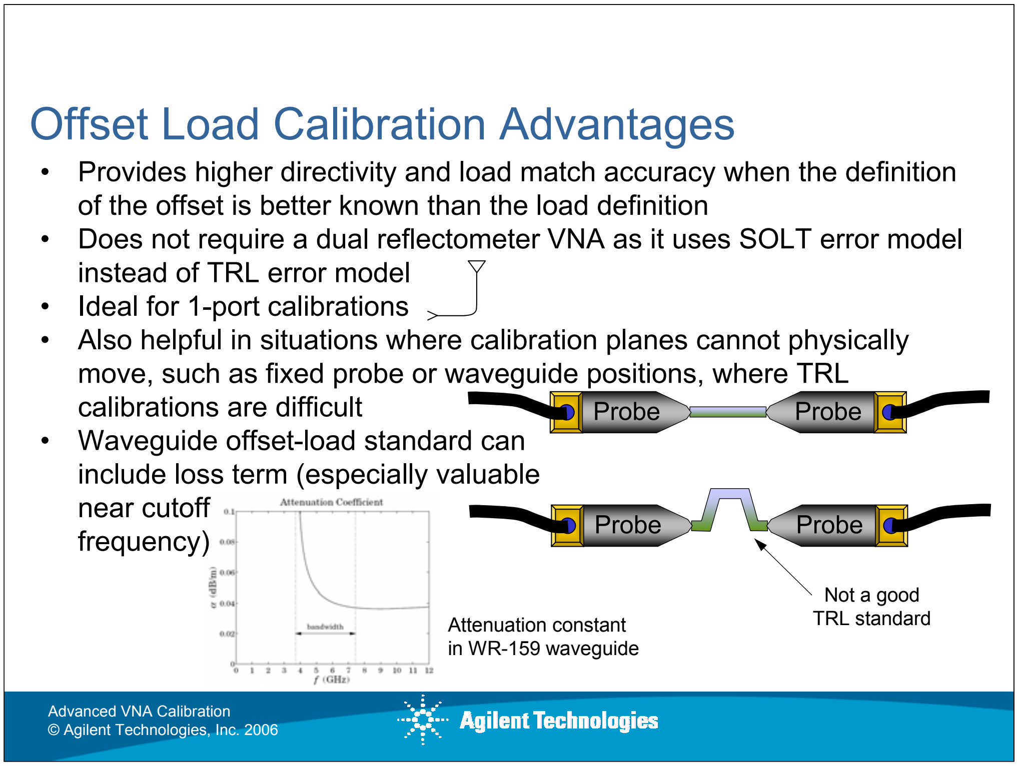




**1. Measure load by itself** **2. Measure load plus offset**



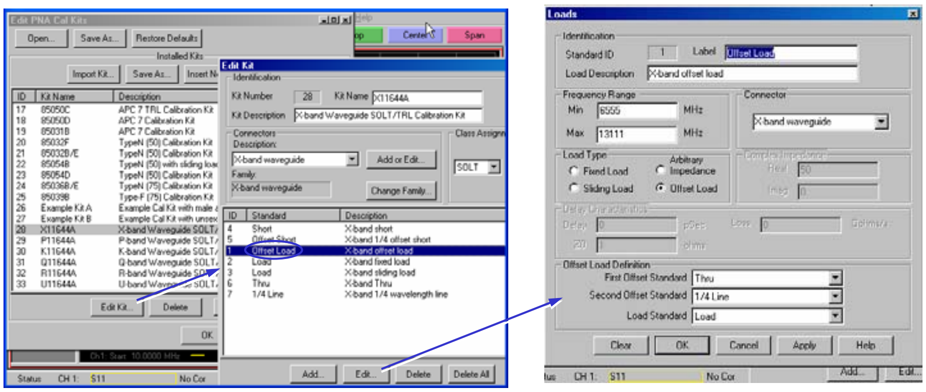
The offset-load calibration technique originated with HP 8510. It is an SOLT technique most commonly used in waveguide environments. Instead of using a fixed load standard, the load is connected multiple times with different offsets, so that the load becomes a compound standard. In its simplest and most common form, there are just two connections: the load by itself, and the load with a phase offset added to it. The offset can be a coaxial transmission line or a short piece of waveguide section. The technique is similar to a sliding-load standard, except the offsets are set by a precise, known phase offset, whereas the offsets are not precisely known in a sliding load. Instead, the sliding load provides enough phase offsets so that a circle can be accurately fitted to the data. Although the term “offset” is often used with calibration standards to indicate a single standard with some finite delay (an offset short for example), in this case the term “offset” is used with a compound standard.




Offset-load calibration offers several advantages than a standard SOLT cal. It can provide better corrected directivity and load match when the definition of the offset is better known than that of the load, which is generally assumed to be perfect even when it is not. Compared to TRL, it does not require a dual reflectometer or a two-tier calibration since it uses the SOLT error model. It is often used for one-port calibrations such as at the end of a waveguide antenna feed. It is also helpful in situations where the calibration planes cannot physically move and where TRL calibrations are difficult, such as with fixed probe or waveguide positions. Finally, a waveguide offset-load standard can include a loss term that can improve accuracy near the cutoff frequency of the waveguide. This is an improvement from the 8510 version.

# Offset Load Definition

- Only available in PNA guided calibration (SmartCal)
- Math is enhanced over what 8510 did
- Offset load definitions are included in Agilent waveguide cal kits

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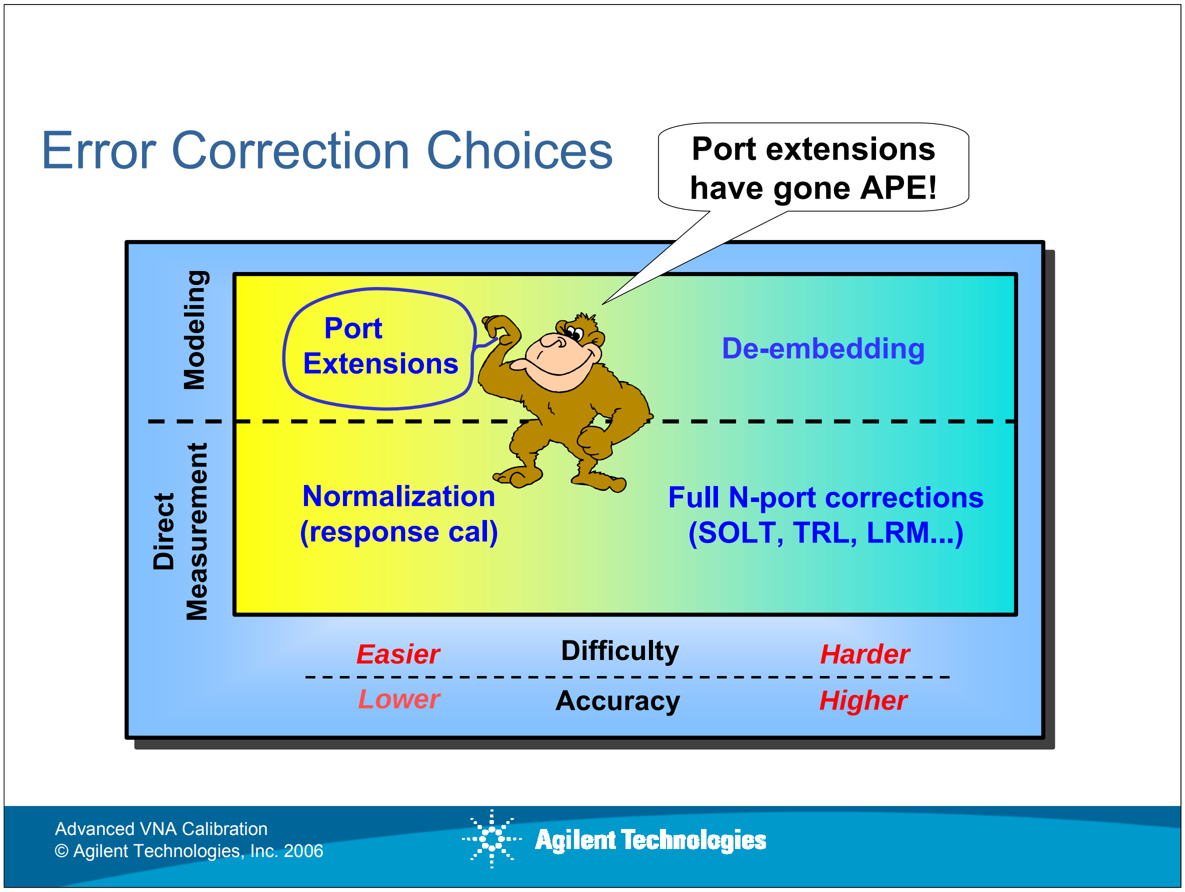
The offset-load calibration is only available in the PNA/PNA-L family as part of the guided calibration (SmartCal). The math used in the cal is enhanced compared to what was done in the 8510, primarily due to a better loss definition. Agilent's waveguide cal kits include offset-load definitions based on the standards provided in the kit.



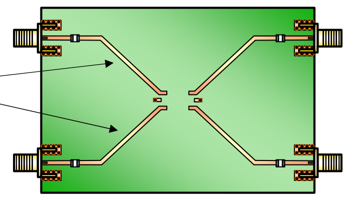

There are two fundamental error-correction techniques: modeling and direct measurement. Each has relatively simple versions and more complicated versions that require greater work, but yield more accurate measurements. Calibration based on modeling uses mathematical corrections derived from a model of the fixture. Often, the fixture is measured as part of the process of deriving an accurate model. Direct measurement usually involves measuring physical calibration standards and calculating error terms. This method provides accuracy that is primarily based on how precisely we know the characteristics of our calibration standards.

Port extensions are the simplest tool in our RF-measurements tool box. They eliminate the need for building precise, in-fixture calibration standards, which are difficult to do (especially the load standard), and which take a lot of time and effort. Traditionally, port extensions have only accounted for additional electrical phase and group delay caused by an adapter or test fixture that is between the coaxial calibration plane and the DUT. In this next section, we will see how Agilent's new Automatic Port Extensions (APE) feature improves upon traditional port extensions, and how it is a simple technique that yields medium-accuracy measurements.

## APE = Automatic Port Extensions

- First solution to apply both electrical delay and insertion loss to enhance port extensions
- First approach to give reasonable alternative to building in-fixture calibration standards or de-embedding fixture
- Recommended procedure: perform a two-step calibration
  - Step 1: Perform a full two-port coaxial calibration (includes network analyzer, test cables, and adapters)
  - Step 2: Perform a response calibration of test fixture

**APE accounts for loss and phase of fixture transmission lines**





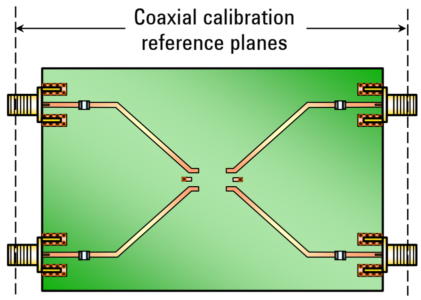

As was pointed out earlier, many of today's RF devices do not have coaxial connectors, and are often tested in a test fixture of some sort. Printed-circuit-board (PCB) fixtures are especially common in R&D since they are relatively inexpensive and easy to make. However, the loss of PCBs cannot be ignored as test frequencies go beyond about 3 GHz. Many of the devices used in today's wireless appliances have to be tested up to 13 GHz. So, when measuring devices on fixtures, it is necessary to reduce or eliminate both the loss and delay of the fixture, allowing you to measure the true characteristics of the DUT. One common practice is to use port extensions. On a PCB fixture, you can think of the traces on the fixture as extensions of the coaxial test cables that are between the network analyzer and the DUT. By performing port extension, we can extend the coaxial test ports so that our calibration plane is right at the terminals of the DUT, and not at the connectors of the fixture.

Agilent's Automatic Port Extensions (APE) feature is comprised of two pieces. The first piece is that it corrects for both loss and delay of text fixtures. The second piece is that the VNA provides a convenient, automated way to calculate the loss and delay terms by a simple measurement of an open or short circuit, which is easy to do in a test fixture.

The recommended procedure to using APE is to do a two-step calibration. The first step, while not strictly necessary, is to do a two-port or four-port coaxial calibration. This step removes the errors of the VNA, test cables and any coaxial adapters used, and gives excellent effective source matches at all of the fixtures connectors. This step is especially important for well-designed test fixtures that have good connector match (around 30 dB or better). **(Continued on page M6-79)**

# Automatic Port Extensions – Step 1

- First, perform coaxial calibration at fixture connectors to remove errors due to VNA and test cables
- At this point, only the fixture loss, delay and fixture mismatch remain as sources of error.







After step one, the only sources of measurement error that remain are the fixture loss, delay, and fixture mismatch.

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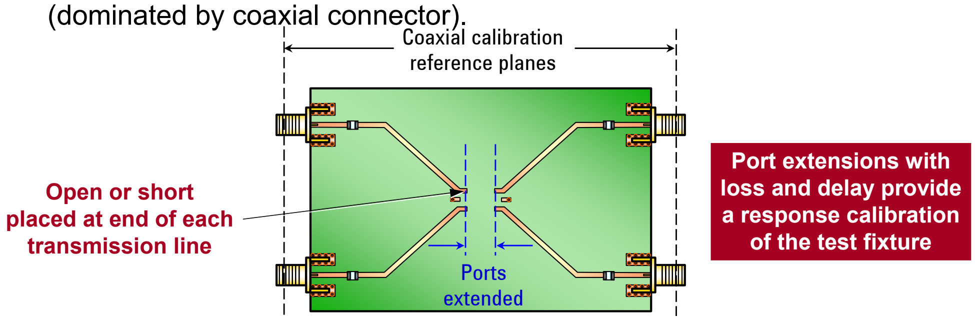
**(Continued from page M6-78)**

The second step is to perform a response calibration of the test fixture. This is the step where loss and delay is removed. For a really quick measurement of the DUT, step 1 can be skipped, and the response calibration can be used to correct the entire test system. This may be adequate for transmission measurements, but reflection measurements are likely to have a lot of error with this approach.

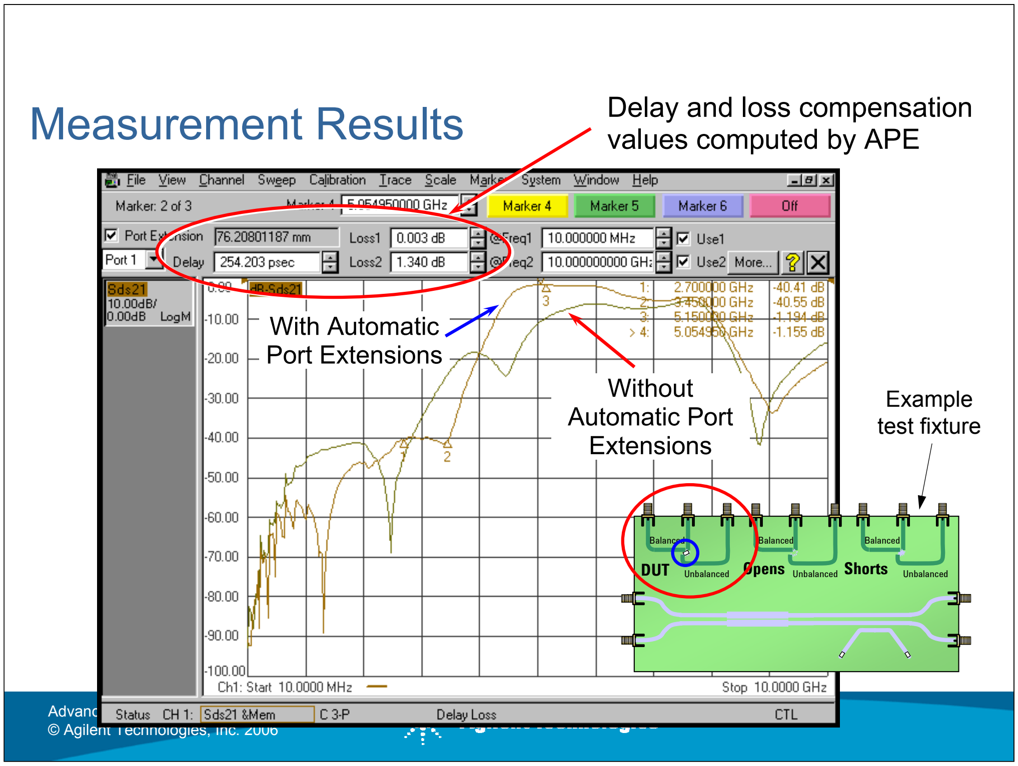
## Automatic Port Extensions – Step 2

- After coaxial calibration, connect an open or short to the portion of fixture being measured (will be repeated for all ports of text fixture)
- Perform APE: algorithm measures each portion of fixture and computes insertion loss and electrical delay
- Values calculated by APE are entered into port extension feature
- Now, only fixture mismatch remains as source of error (dominated by coaxial connector).






After the coaxial calibration done in step 1, we now need to measure an open or short circuit (or sometimes both, which will be discussed later). The APE algorithm measures the open or short, and computes the insertion loss and electrical delay of that portion of the test fixture. This step is repeated for each portion of the test fixture. After this step, only the fixture mismatch remains as a source of error. The main source of mismatch error is the transition from coax to microstrip that occurs at the connector of each of the fixture’s ports. Measurement accuracy is increased by minimizing the reflection at this transition by using good quality, edge-mounted connectors, and having good 50-ohm transmission lines on the test fixture. The port-extension technique gives good results with medium-level accuracy. While not as accurate as using high-quality in-fixture calibration standards, it is by far an easier method for testing fixtured components, and is adequate for many applications.



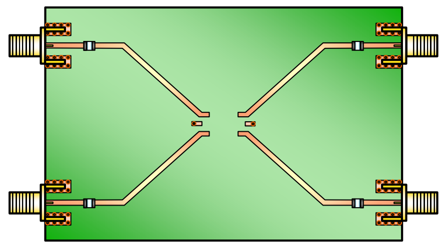

Here is a measurement example of a balanced-to-unbalanced 5.5 GHz WLAN filter, tested up to 10 GHz. We can see the APE toolbar on the PNA, which shows the delay and loss terms for port one of the test fixture used for the measurement. The values were calculated automatically by the APE feature. The two traces on the PNA show measurements of the DUT with and without port extensions.

Without using port extensions, you are measuring the fixture plus the DUT. The distorted response is due to not compensating for phase (especially important for a balanced port), and not compensating for the loss of the transmission lines on the PCB. With the port extensions on, we have removed the significant errors due to the test fixture, giving us a good picture of the performance of our device.

## Automatic Port Extensions – Implementation

- Measures $S_{ii}$ (reflection) of each port
- Uses ideal open or short models
- Computes electrical delay using best-fit straight-line model
- Computes insertion loss using a best-fit coaxial (one frequency point) or dielectric (two frequency points) loss model
- Computed delay and loss values are automatically displayed via a port-extension tool bar
- Values saved as part of instrument state

Measure reflection of each test port with open or short

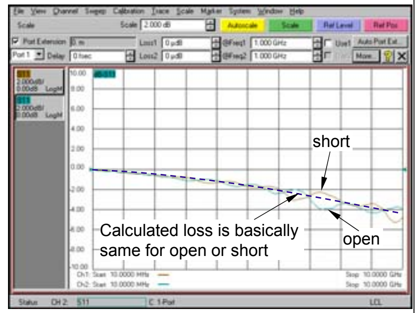





The automatic-port extension feature measures the reflection coefficient of each port of the test fixture, using an open or short standard with ideal models (no inductance or capacitance). Electrical delay is calculated using a best-fit straight-line model. The loss term is calculated in one of two ways, depending on the media used for the transmission line. The loss model is assumed to be either coaxial or dielectric. The dielectric model is used when the fixture is built on a PCB. Both the coaxial and dielectric models give a variable loss versus frequency that is not simple a straight line.

# Which Standards Should I Use?

- For broadband applications, shorts or opens work equally well
- Choose the most convenient standard (often an open) – this is a key benefit of Automatic Port Extensions
- Will using both an open and a short improve accuracy?
  - Using two standards makes little difference for broadband measurements, as many ripples occur and calculated loss is the same for open or short
  - Using two standards improves accuracy for narrowband measurements, where a full ripple cycle does not occur

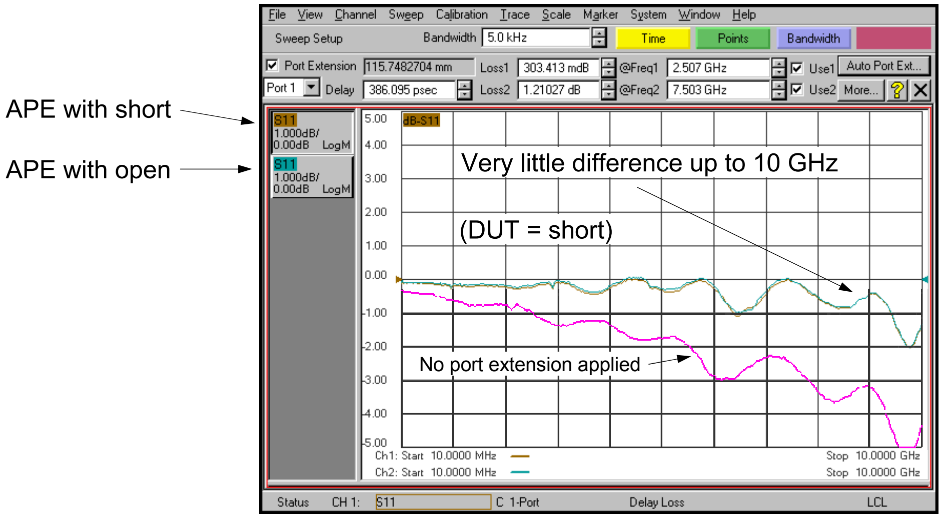



Broadband



In most cases, only one high-reflection standard is needed to accurately calculate the loss and delay terms. The condition that needs to be met for this to occur is that the frequency span of the measurement must be large enough so that the ripple in the reflection measurement goes thru a full cycle or so. In this case, the most convenient standard can be used, which is often an open. Using two standards makes little difference for broadband measurements, as many ripples occur and the calculated loss is the same for using an open or short. Using two standards improves accuracy for narrowband measurements, where a full ripple cycle does not occur.

# Broadband APE Example



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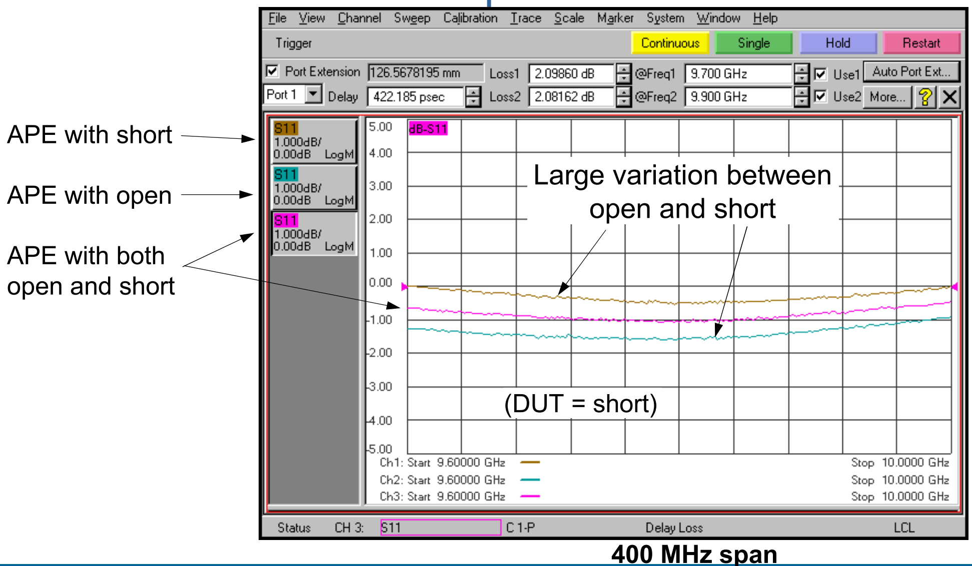
Here is an example of a broadband reflection measurement done on a short standard. As can easily be seen, the loss term is essentially identical whether an open or a short standard is used for the automatic port-extension calculation.

# Narrowband APE Example




Advanced VNA Calibration
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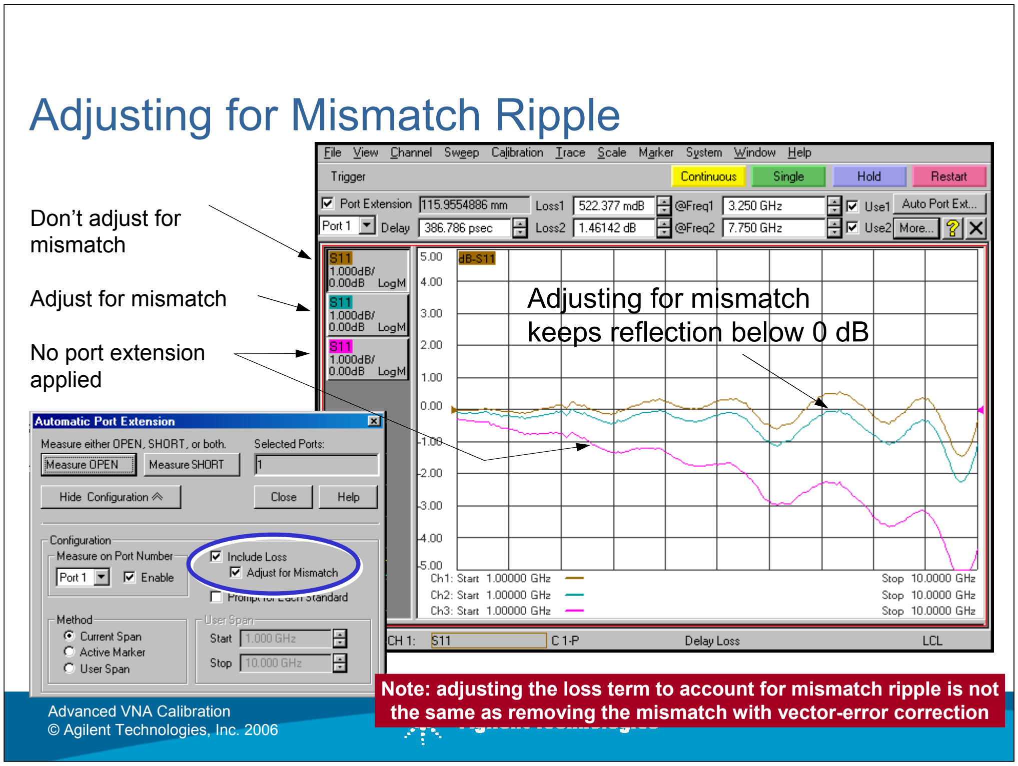
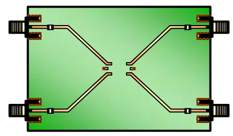
Here is a narrowband example where we see a large difference in the loss term, depending on whether an open or shot standard is used. This is because the frequency span of the measurement is smaller than a complete cycle of the ripple.

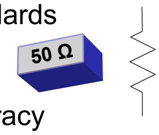



The APE feature has a refinement for adjusting the loss term. Normally, the best mathematical approach to fitting the loss data is to center the error on either side of 0 dB. However, this will cause the reflection coefficient of an open or short to go above zero for some frequencies, which some users might find objectionable, since a passive device can never truly have reflection gain. As an option, a user can select a check box called “adjust for mismatch”. This box causes a little more loss to be added to the loss values so that the reflection measurement of the open or short never goes above zero. So, instead of having a measurement with error of +/- dx (dx = error due to ripple), the “adjust for mismatch” feature changes the error to -2dx. Note that adjusting the loss term to account for mismatch ripple is not the same as removing the mismatch with vector-error correction, as would be done with an in-fixture two-port calibration.

# Summary of Automatic Port Extensions




- Especially useful for in-fixture applications where complete calibration standards are not available
- Eliminates the need to design and build difficult load standards
- Applicable to a wide range of fixture designs
- Works with probes too
- Easy to use and provides quick results with medium accuracy





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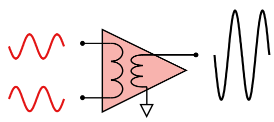
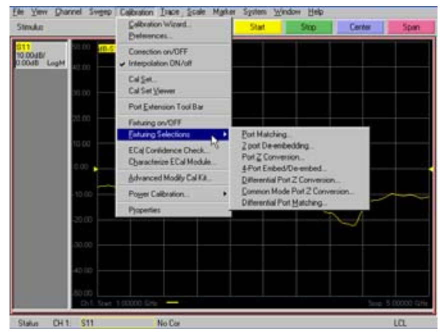
Here is a summary of the Automatic Port Extensions feature.

## Virtual Fixturing Using Software Tools in VNA

- Software-fixture tools recalculate single-ended S-parameter data to…
  - Change test port impedances
  - De-embed test fixtures, probes, adapters, cables, etc.
  - Embed matching circuits
  - Calculate mixed-mode (differential / common mode) S-parameters
- Fixturing features are common to PNA and ENA families and Physical Layer Test Software (PLTS)
- Especially useful for single-ended-to-balanced or fully balanced devices





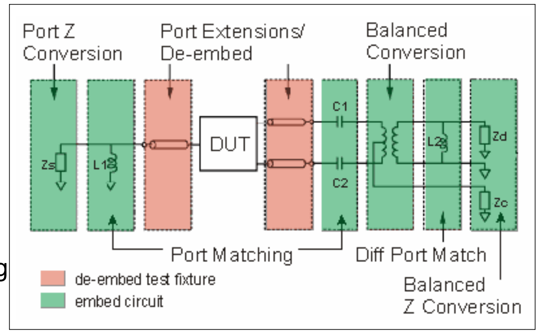


While VNAs doe a great job of measuring accurate S-parameters, sometimes further processing of the data is required for specific applications such as measuring non-50-ohm devices, or measuring devices with a balanced port. Many of these software-fixture tools are built into the analyzer. For non-50-ohm devices, it is possible to restate the S-parameter data so that it looks like the DUT was measured in an impedance other than 50 ohms. It is also possible to embed virtual matching circuits, which is often needed for devices like SAW filters, without having to actually add inductors and capacitors to the text fixture. Undesirable pieces of the test system can be mathematically removed by de-embedding their S-parameters. And finally, for devices with at least one balanced port, mixed-mode (differential and common-mode) S-parameters can be calculated.

These fixturing features are common to the PNA and ENA families of network analyzers, and Agilent's Physical Layer Test Software (PLTS). They are especially useful for single-ended-to-balanced or fully balanced devices.

## Order of Fixturing Operations

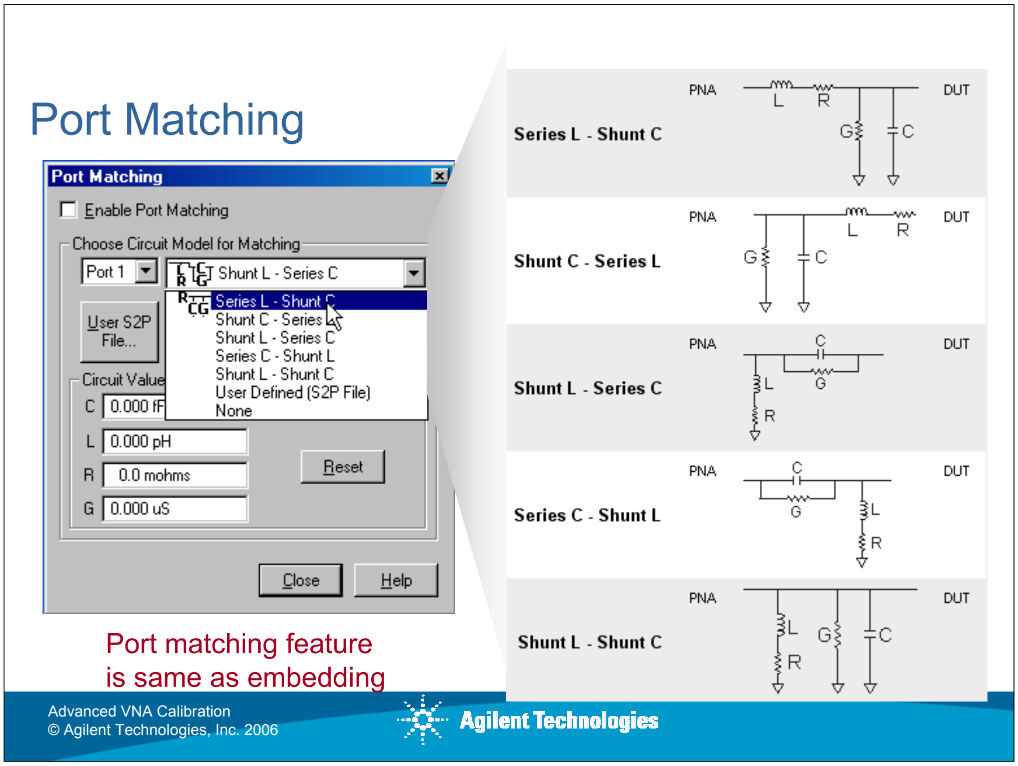
- **First, single-ended functions are processed in this order:**
  - Port extensions
  - 2-port de-embedding
  - Port Z (impedance) conversion
  - Port matching / circuit embedding
  - 4-port network embed/de-embed
- **Then, balanced functions are processed in this order:**
  - Balanced conversion
  - Differential- / common-mode port Z conversion
  - Differential matching / circuit embedding



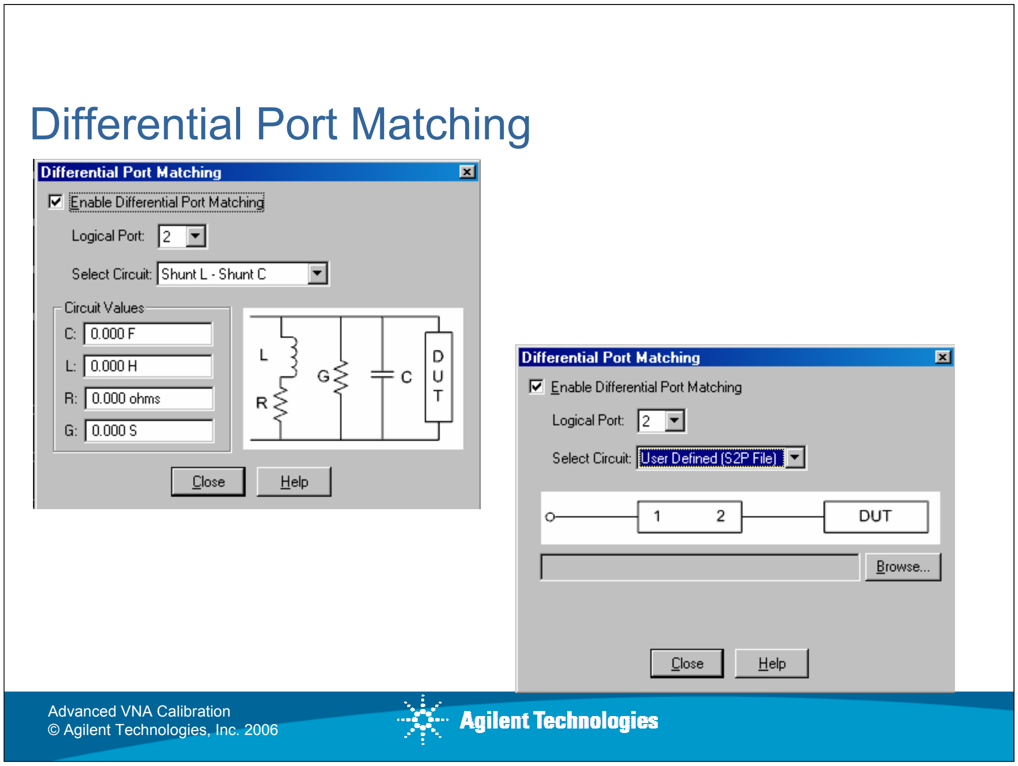

**Example circuit simulation**



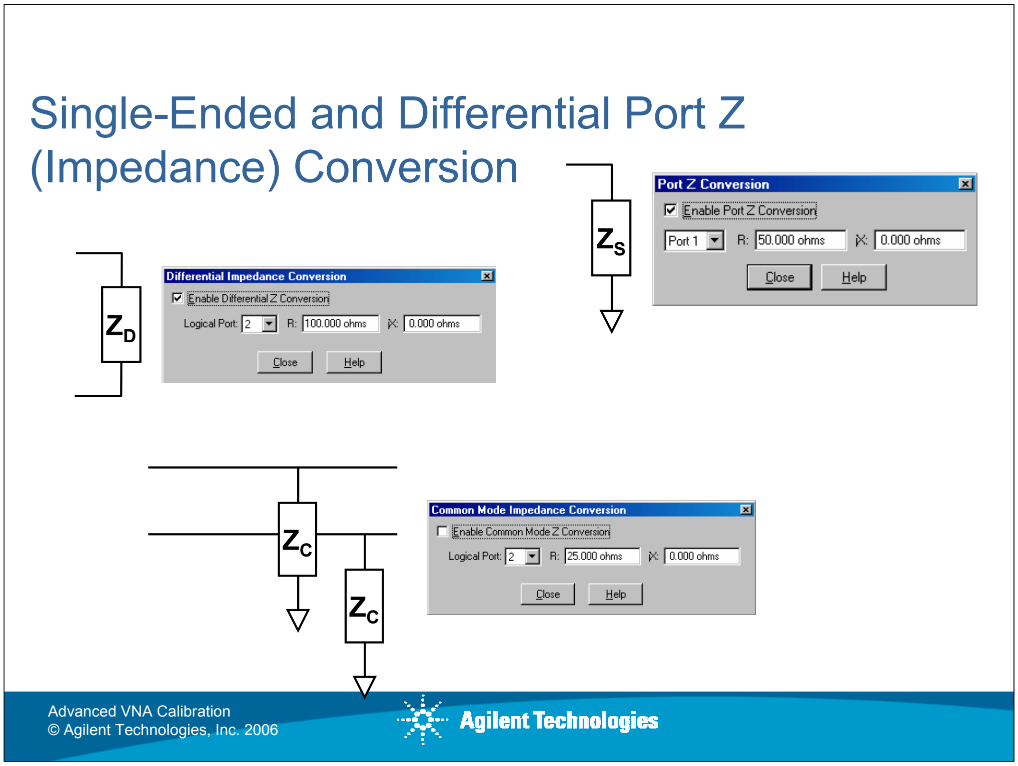
This slides shows the order that the various fixturing operations are applied to the measured S-parameters.




The port-matching feature allows the user to select virtual matching circuits with various circuit topologies, as shown on the slide. If one of the predefined circuits cannot be used, then an s2p file can be embedded into the measurements.

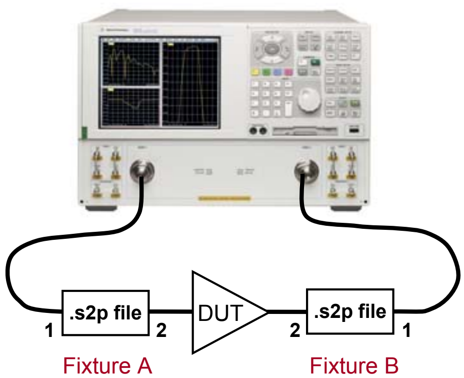


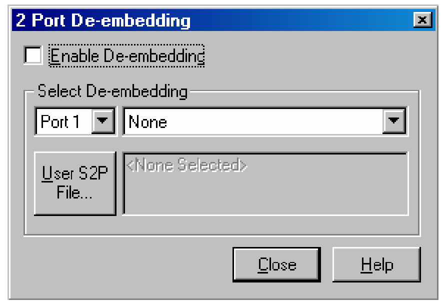

Port matching can also be applied to differential circuits.




For non-50-ohm devices, the test-port impedances can be recalculated in terms of single-ended, differential-mode, or common-mode topologies.

# Two-Port De-Embedding




**PNA uses this file definition for ports:**
- **Port 1 of the fixture is connected to the PNA**
- **Port 2 of the fixture is connected to the DUT**



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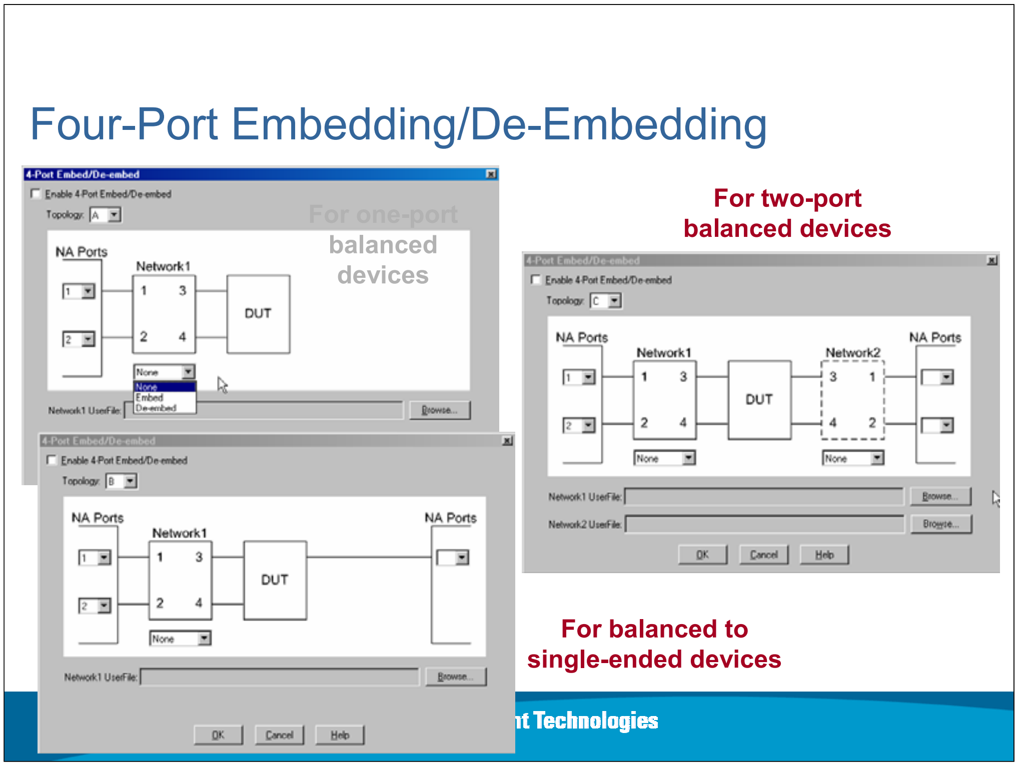
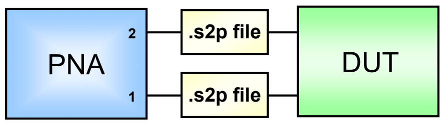
De-embedding is used to remove the undesired effects of fixtures, adapters, probes, or whatever. To use this feature, the user must know the S-parameters of the circuit that will be removed. The S-parameters are placed in a file with a specific format known as “s2p”. The slide shows the convention for numbering the ports of the two-port fixtures that will be de-embedded.



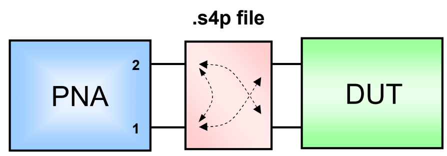

In addition to two-port de-embedding, four-port circuits can also be de-embedded.

# Two Versus Four Port Embedding / De-Embedding

- Question: On a balanced port, what is the difference between:
  - Two .s2p embedding/de-embedding files?
  - One .s4p embedding/de-embedding files?
- Answer: Crosstalk terms!




**Cannot simulate fixture crosstalk between PNA ports 1 and 2**




**Can use full “leaky” model to simulate fixture crosstalk**

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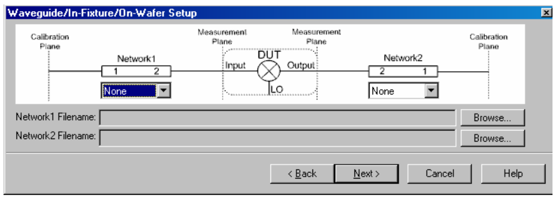
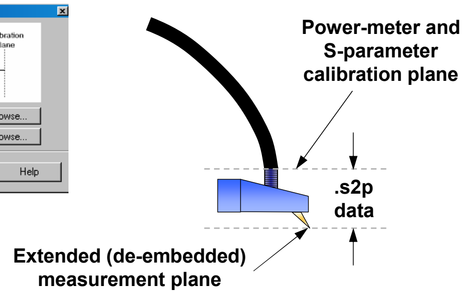
For devices with balanced ports, four-port de-embedding allows simulation of crosstalk between the test ports. Although crosstalk is insignificant when using coaxial cables, it may be significant when fixtures or probes are used.

# On-Wafer Mixer Measurements Using FCA

- Previous versions of the Frequency Converter Application (FCA) did not allow on-wafer measurements using Scalar- or Vector-Mixer Cals
- A.06.0x allows embedding of probe data files during FCA calibration
- Perform S-parameter, power-meter, & cal-mixer calibrations in coax
- After coax calibrations, reference plane is at probe tip



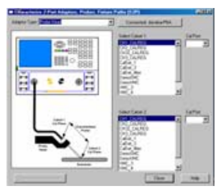


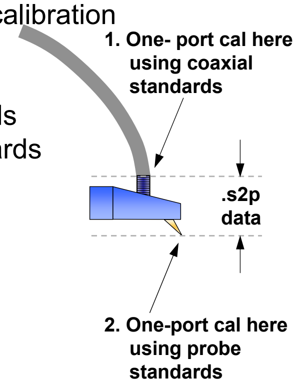


De-embedding allows the use of Agilent's scalar-mixer calibrations (SMC) and vector-mixer calibrations (VMC) for measuring mixers and converters on-wafer. Previous versions of the Frequency Converter Application (FCA) did not allow on-wafer measurements using SMC or VMC. The latest firmware revision now allows embedding of probe data files during the FCA calibration. For subsequent measurements, the probe data is then de-embedded. All of the calibration steps (S-parameter, power-meter, & calibration-mixer calibrations) are done at the end of the coaxial cables. After the coax calibrations, the reference plane is at the probe tip, due to the embedded probe s2p files.

# How Do I Get My Probe De-Embedding Data?

- Three techniques to measure S-parameter data of probes…
  - Easiest: use PNA or ENA macro that performs two one-port calibrations
  - Measure a thru and then do an adapter-removal calibration
  - Measure a thru and then do an unknown thru calibration
- Using two one-port calibrations…
  - Assumes probe is reciprocal (S21 = S12)
  - First one-port calibration uses coaxial standards
  - Second one-port calibration uses probe standards
  - Macro extracts .s2p data of probe using the two one-port calibrations





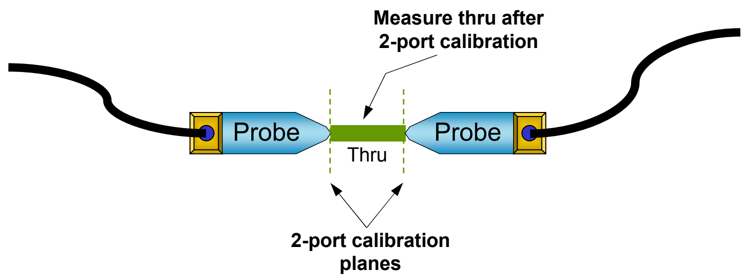



There are three ways to get S-parameter data of probes. The easiest way is to perform two one-port calibrations. This technique assumes the probe is reciprocal (i.e., S21 = S12), which is always the case. The first one-port calibration is done at the end of the coaxial connector, using coaxial standards. The second one-port calibration is done at the end of the probe tip, using on-wafer standards. ENA and PNA analyzers provide a macro that then extracts the s2p data of the probe using the two one-port calibrations. Note that this technique can also be done for fixtures, where the second one-port calibration is done with in-fixture instead of on-wafer standards.

## Measuring Probes Using Adapter Removal or Unknown Thru Calibration

In either case, start by measuring a thru standard:

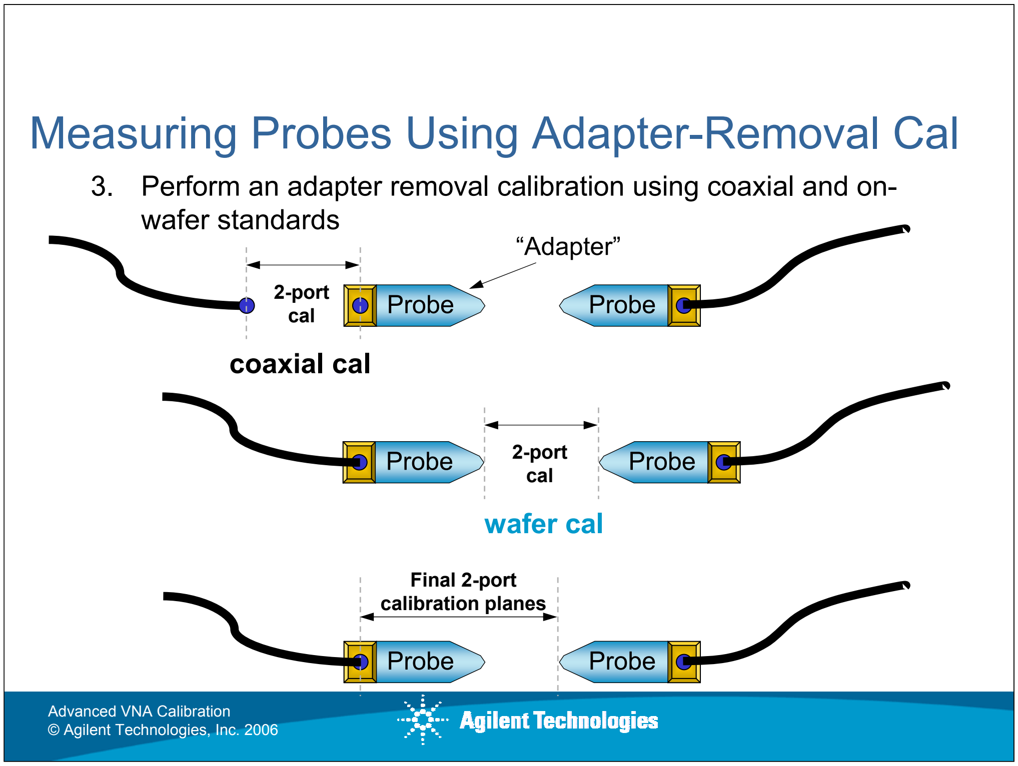
1. Perform an SOLT or TRL cal using wafer probes
2. Measure thru device and save data in .s2p file for de-embedding in a later step







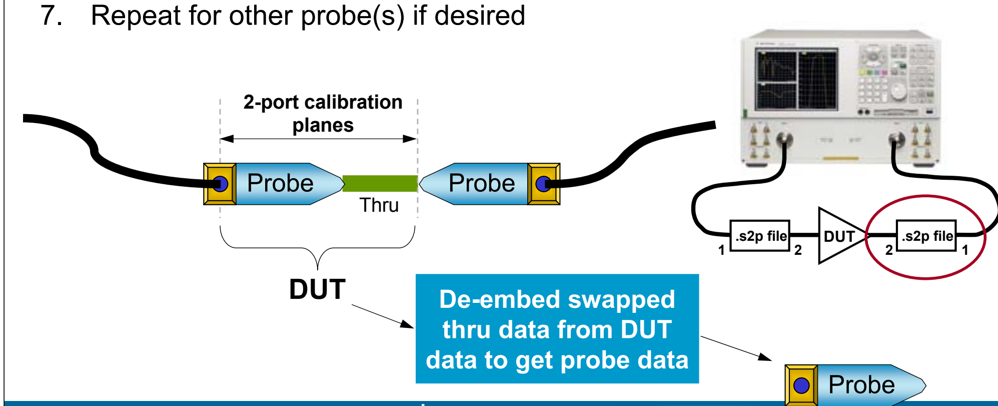
Adapter removal or unknown thru calibration can be used to get the S-parameters of probes. The first step in both cases is to perform an on-wafer calibration using either SOLT or TRL standards. Then, a thru device is measured and its S-parameter data is saved in an s2p file for de-embedding in a later step.




This slide shows how adapter removal is used as part of a procedure to get the S-parameters of a probe. After the thru is measured, a new calibration is done with the adapter-removal technique, using a combination of coaxial and on-wafer standards. The final 2-port calibration planes are shown on the slide.

## Measuring Probes Using Adapter-Removal Cal (cont)

4. Measure thru plus probe
5. De-embed *swapped* thru data to obtain probe data
6. Save probe data in .s2p file for later use in measuring DUTs
7. Repeat for other probe(s) if desired

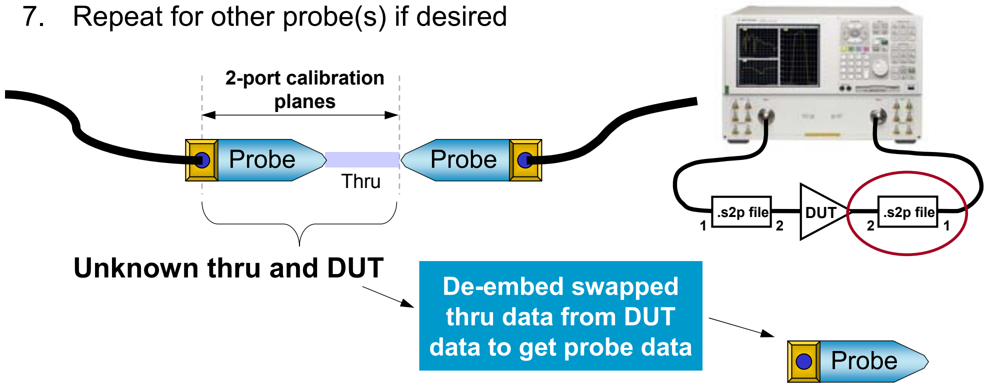





The last step is to measure the probe and thru from step 2 as a combined DUT. Since we previously measured the thru, we can de-embed its S-parameters from the measurement, which then leaves only the S-parameters of the probe. Note that we have to swap the data of the s2p file since the thru is between the probe (our intended DUT) and port two of the test system. Swapping the data means that the S11 and S22 columns are swapped and optionally, the S21 and S12 columns can be swapped (theoretically, S21 = S12 for a passive, reciprocal device, so this step can be omitted if desired). The measurement of the probe (with the thru de-embedded) should be saved in a s2p file for later use where it will be de-embedded from the measurements of some actual DUT.

## Measuring Probes Using Unknown Thru Cal

3. Perform unknown thru cal in coax and with probe
4. Measure thru plus probe
5. De-embed *swapped* thru data to obtain probe data
6. Save probe data in .s2p file for later use in measuring DUTs
7. Repeat for other probe(s) if desired





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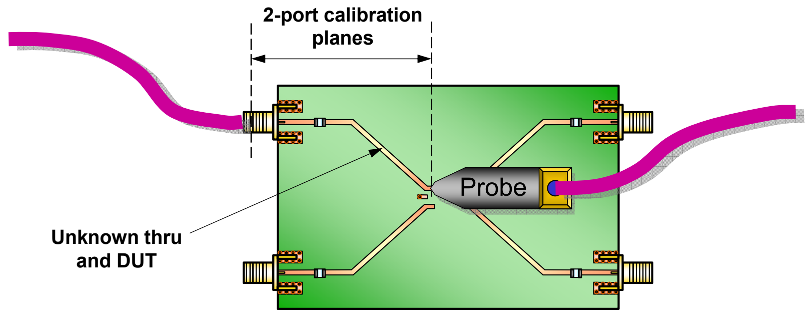
A similar technique for measuring the S-parameters of a probe can be done using the unknown-thru technique. This method starts with an unknown-thru calibration using coaxial and on-wafer standards, and by using the probe and thru together as an unknown thru. The same procedure as described on the previous slide can be used to de-embed the thru data, leaving only the S-parameters of the probe.

## How Do I Get My Fixture De-Embedding Data?

1. Perform an unknown thru cal using coax on one side, a probe on the other side, and the fixture itself for the unknown thru
2. Measure the fixture section and save data as .s2p file
3. Repeat for each section of fixture





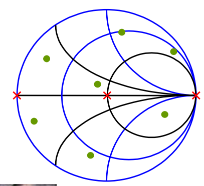


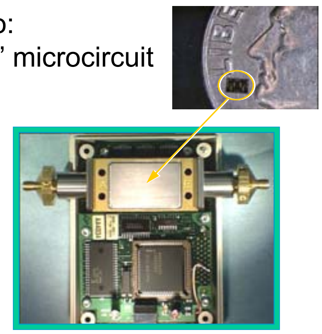

The easiest way to measure a fixture is if a probe is available that can probe the DUT end of the transmission lines in the fixture. In this case, the user performs an unknown thru calibration using coaxial standards on one side, and a probe ISS for the other side. The fixture's transmission line is the unknown thru. After the calibration is done, then the fixture is simply measured, without moving the probe or coaxial cable. The measurement procedure is repeated for each section of the fixture, using the same calibration as was done for the first arm. In order for the probe to measure the end of the transmission line, ground pads must be placed on the fixture with the correct spacing to match the pitch of the probe.

An alternative to probing the fixture is to use the two one-port calibration technique. This method has the disadvantage that in-fixture calibration standards must be fabricated and characterized in order to do a one-port in-fixture calibration.

## What is Electronic Calibration?

- Calibration using standards that are electronically switched known impedances, instead of shorts, opens and loads
- Impedance standards are spread out on the Smith chart
- Impedances known by measurements at factory using individually characterized coaxial airlines and TRL cals
- Impedances are very repeatable due to:
  – Hermetically sealed “ECal on a chip” microcircuit
  – Internal electric heater
  – Low thermal mass of microcircuit
  – Low thermal conductivity between microcircuit and outside world
  – Mechanically rugged connectors





Advanced VNA Calibration
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Electronic calibration is a powerful technique that is fast, easy to use, and accurate. Instead of using shorts, opens and loads as is done with mechanical calibration kits, the standards within the ECal modules are electronically switched known impedances. The arbitrary impedances are spread out on the Smith chart, and are known by precise electrical measurements at the factory using a test system that was calibrated with individually characterized coaxial airlines and a TRL calibration. This TRL calibration is directly traceable to national standards labs via physical measurements of the airlines, and the characterized ECal module then becomes a transfer standard. The impedances used in the ECal module are very repeatable due to several things:

A hermetically sealed “ECal on a chip” microcircuit using transistor switches with excellent high-frequency performance

An internal electric heater to stabilize the temperature of the microcircuit for a broad outside-ambient-temperature range

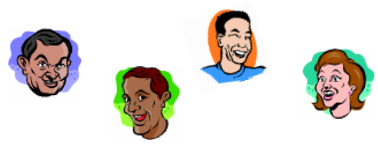
Low thermal mass of the microcircuit to optimize the closed-loop thermal-feedback bandwidth of the heater

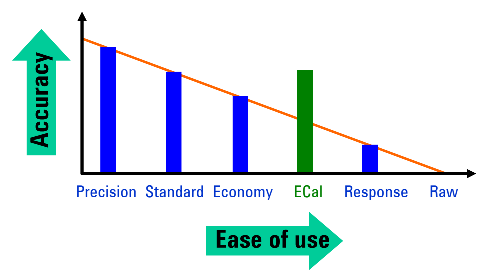
Low thermal conductivity between the microcircuit and the outside world, to minimize open-loop temperature variations

Mechanically rugged connectors for repeatable electrical connections

# Benefits of Electronic Calibration

- Provides fast AND accurate calibration
  - Typical calibration takes **20 to 60 seconds** with ECal versus several to many minutes when using mechanical standards
  - Accuracy equivalent to a **short-open-sliding-load** calibration
- No risk of connecting the wrong mechanical standard
- Lowers wear and tear on connectors and standards
- Lowers chances of repetitive-motion injuries of users, especially for test systems with a large number of test ports





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ECal provides fast AND accurate calibrations. A typical ECal calibration takes between 20 and 60 seconds, compared to several to many minutes when using mechanical standards. The accuracy of an ECal calibration is approximately equivalent to a short-open-sliding-load-thru calibration, which provides a very accurate level of calibration. There are other benefits of using ECal, such as eliminating the risk of connecting the wrong mechanical standard during the calibration (e.g., connecting a short instead of an open), which can dramatically increase the time it takes to successfully calibrate the test system. ECal also lowers wear and tear on connectors and standards since there are less connections, and it lowers the chance of repetitive-motion injuries of users, especially for test systems with a large number of test ports.

# Agilent's "ECal" Line of Electronic Calibration

- Frequency coverage from 300 kHz to 67 GHz in many connector types (7/16, Type F, N, and 7, 3.5, 2.4, 2.92, 1.85 mm)
- Two and four port modules, with mixed connector sexes and types
- User characterization of modules lets you add adapters, use different connectors, de-embed fixtures and probes, and do yearly re-certification
- Easy connection with USB



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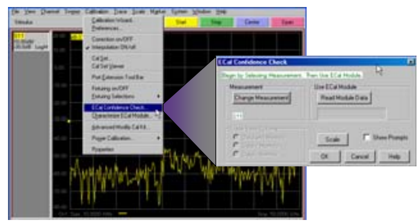
Agilent's ECal line of electronic calibration modules covers the frequency range of 300 kHz to 67 GHz with many models in many different connector types, as indicated on the slide. Both two and four port modules are available, with the same connectors or with mixed connector sexes or connector types. The modules are connected to the network analyzer with a USB connection. A powerful feature known as user characterization lets you add adapters, use different connector types, de-embed fixtures and probes, and do yearly cal re-certifications.

## Details of User Characterization

- Add up to 5 user-measured data sets to flash memory of module
- Easy to perform:
  - Define frequency range and number of points
  - Calibrate network analyzer with mechanical standards (quality of user characterization depends on this calibration)
  - Follow calibration wizard to characterize each port of ECal module
- User-characterized ECal is used just like a standard factory-characterized ECal
- Confidence check tells you when to characterize again





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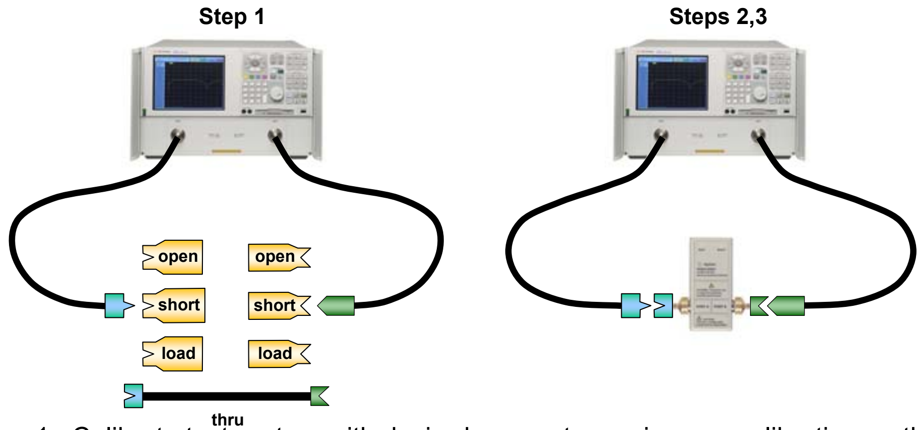
User characterization allows users to add adapters and then characterize the module with the adapters in place, extending the benefits of speed and ease of use to connector combinations or types that are not available from Agilent. An example would be waveguide on one side and coax on the other side of the module. A user can save up to five user-measured data sets to the flash memory of any ECal module. The procedure is easy to perform. The first step is to set up the analyzer with the desired frequency range and number of points. Next, the network analyzer must be calibrated with mechanical standards that match the connectors on the ECal module. The better this calibration is, the more accurate the user characterization will be. After calibrating the test system, a calibration wizard provides a guide to characterize each port of the ECal with its associated adapters. After the module has been characterized, it can be used just like a standard ECal module. There is even a confidence check that helps you decide if a re-characterization is needed or not. User characterization allows companies to do their own yearly (or sooner as required) re-certifications, so they only have to send their modules back to Agilent when a repair is required.

## User Characterization: Using Adapters




Step 1: Calibrate test system with desired connectors using any calibration method (SOLT, SOLR, TRL)

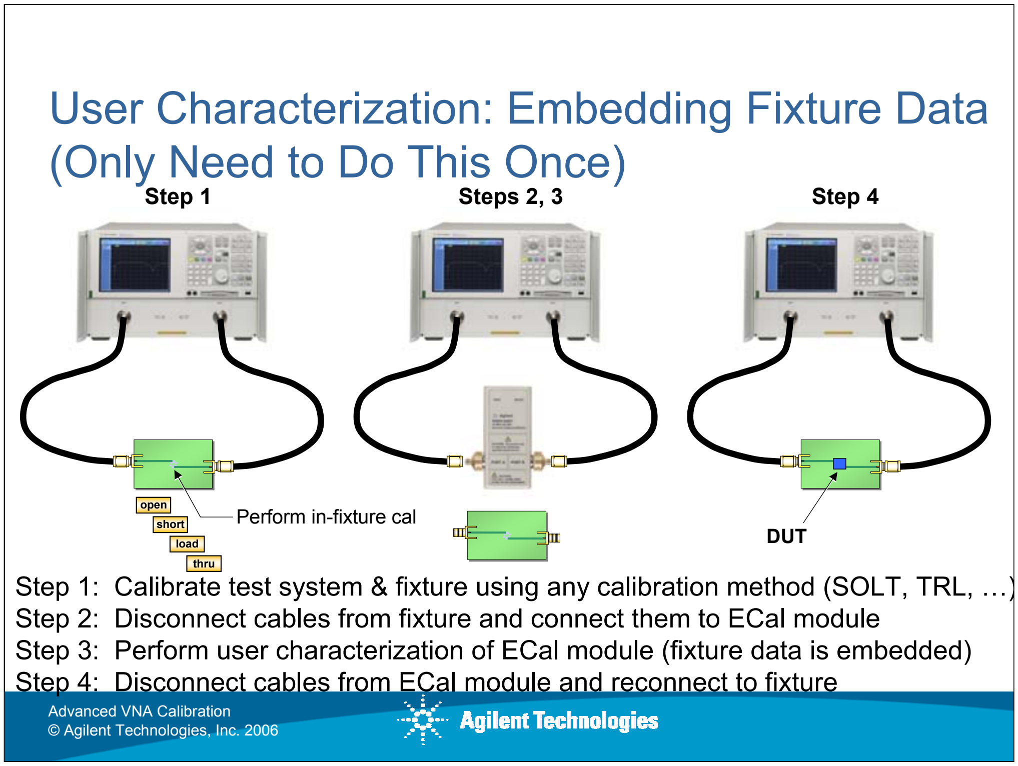
Step 2: Connect ECal module with adapters to analyzer

Step 3: Perform user characterization of ECal module using calibrated test system



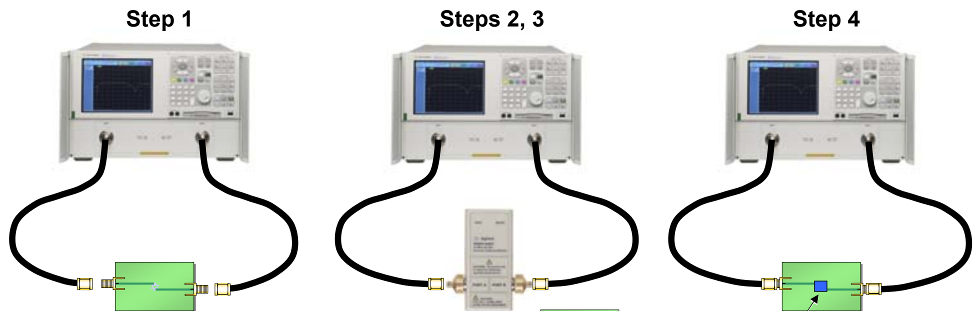
Here is the procedure to characterize an ECal module on a PNA. The first step is to calibrate the test system with the desired connectors that will mate with the adapters on the ECal module. Any calibration method can be used that yields a two-port calibration (for a two-port ECal) or a four-port calibration (for a four-port ECal). This calibration should be performed carefully, as the accuracy of this calibration is transferred into the module.

Next, the ECal module with adapters is connected, and the characterization process is started. The ECal's internal impedance states are measured, and their associated S-parameters are written to the memory in the ECal.




The user-characterization feature can also be used with fixtures and probes. Using the procedure shown on the slide, we can embed the S-parameters of the fixture (shown) or probe in the user-characterization data, and then subsequent calibrations using the ECal module will de-embed the fixture or probes. The first step, which only has to be done once, is to calibrate the test system with in-fixture standards (or with an ISS when using probes). Then, the fixture or probes are removed, and the ECal module is characterized. The fixture is reattached for measurements of the DUT.

## User Characterization: Applying Fixture Cal (Simple! Does Not Require In-Fixture Cal)




Step 1: Disconnect cables from fixture
Step 2: Connect cables to ECal module
Step 3: Perform "User-Defined ECal Calibration" of test system
Step 4: Disconnect cables from ECal module and re-connect them to fixture with DUT
Step 5: Start measuring! (Fixture data is de-embedded from the measurement)

Advanced VNA Calibration

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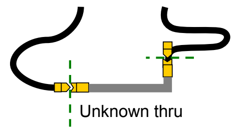
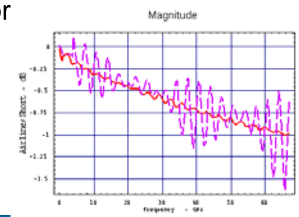
Whenever we wish to recalibrate our system, we simply disconnect the fixture (or probes), connect the ECal with the embedded data, and recalibrate our system, without having to perform an in-fixture calibration. The assumption we're making is that any errors in the test system are due to drift in the network analyzer or cables, and that the electrical performance of the fixture (or probes) has not changed. After the calibration is done, we reconnect the fixture (or probes) and measure our DUTs. At any time, we can easily recalibrate the system with ECal, and we don't have to repeat the slower in-fixture or on-wafer calibrations.

# Summary

- **Calibration** is a key part of accurate measurements using vector network analyzers
- Many **new techniques** increase accuracy or make calibration easier to perform, especially for fixtured or on-wafer measurements
- The **"Unknown Thru" calibration** eliminates cable movement and simplifies non-insertable calibrations




- **Data-based-standard definitions** and **expanded calibration** using weighted-least-squares math greatly impr 67 GHz and 110 GHz measurements
- Testing multiport devices is easier and more accurate than ever due to **N-port calibration** and **reduced-standard calibrations**



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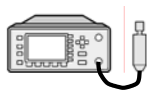
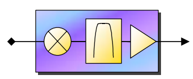
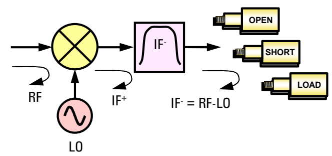
## Summary (continued)

- **Two-tier TRL calibration** allows single-receiver VNAs like Agilent's 4-port PNA-L take advantage of TRL, LRM, LRL cals for fixtures & probes

- **Offset-load calibration** increases accuracy for one-port waveguide cals with compound load standard and accurate waveguide loss model
- Advanced **mixer/converter calibrations** yield the highest accuracy for measuring conversion loss and absolute group delay

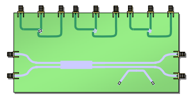




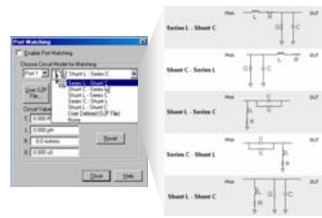


## Summary (continued)

- **Automatic-port extensions** are simple to perform for medium-accuracy measurements of fixtured components



- **Software fixture tools** allow port-impedance conversions, embedding, de-embedding, and mixed-mode S-parameter measurements of single-ended and balanced devices



- **Electronic calibration** is a simple, fast and accurate way to calibrate network analyzers in a variety of applications

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# Additional Resources

- **Application note** 1287-11 “Specifying Calibration Standards and Kits for Agilent Vector Network Analyzers”, 5989-4840EN
- **Magazine article** *“Latest Advances in VNA Accuracy Enhancements”*, Dave Blackham, Ken Wong, Microwave Journal, July, 2005
- **Agilent Web links**:
  - –Network analyzer calibration: www.agilent.com/find/nacal
  - –PNA network analyzers: www.agilent.com/find/pna
  - –PNA-L network analyzers: www.agilent.com/find/pnal
  - –ECal electronic cal modules: www.agilent.com/find/ecal
  - –PNA Help Online: na.tm.agilent.com/pna/help/PNAWebHelp/help.htm
  - –Cal kit definitions: na.tm.agilent.com/pna/caldefs/stddefs.html




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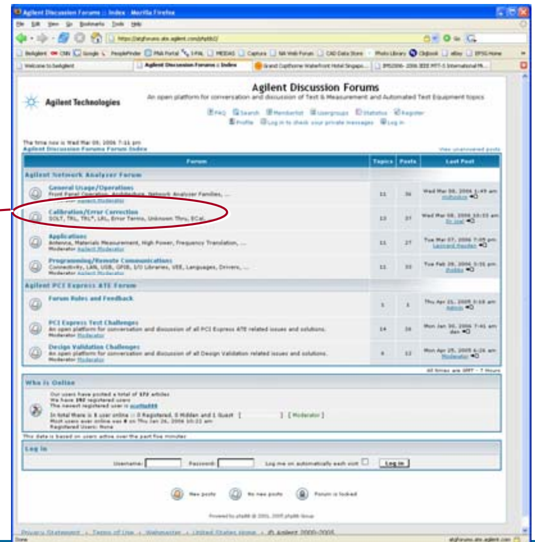
# Network Analyzer Forum

www.agilent.com/find/agilent_naforum

- Learn more about calibration, applications, general usage, and remote operation
- Get answers from the factory
- Have peer-to-peer discussions




Dedicated section for calibration and error correction issues

Advanced VNA Calibration
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