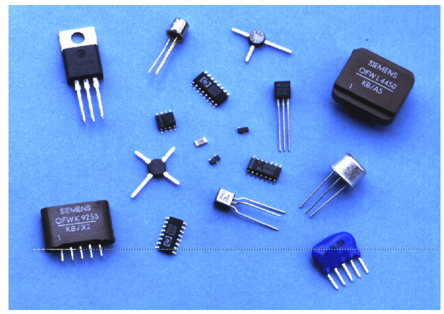
Slide #1

Accurate Measurement of Packaged RF Devices

RF and MW Device Test Seminar 1995

Slide #2

How to Measure These Devices



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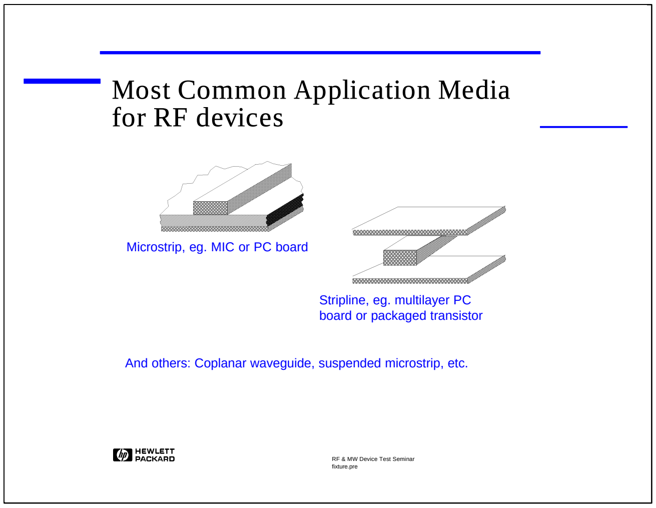
The previous modules of this seminar have discussed how to measure a variety of devices such as filters, mixers, and amplifiers. As technology develops, circuits and systems are shrinking, and traditional coaxial device packages are no longer practical in many cases. Some typical modern devices are shown in this photograph. The challenge is to apply coaxial instrumentation to non-coaxial measurement problems.

Slide #3



Today's RF devices are often designed for circuits that use microstrip or stripline as the transmission line medium. Microstrip consists of conductor traces that are deposited on a substrate, which sits on top of a ground plane. One example would be a single-layer PC board. Stripline is a multi-layer configuration with traces embedded between ground planes. This configuration is more complex than microstrip, but it offers better isolation and less dispersion.

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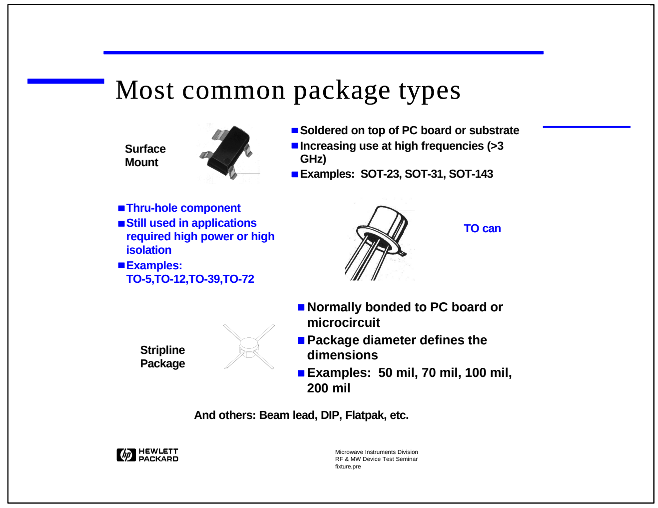

Many of the package types for RF devices can be grouped into 3 categories: surface mount, TO cans, and stripline. Surface mounts components can be easily soldered onto PC boards or substrates, and they are being used in RF applications to 3 GHz and higher frequencies. TO cans make use of older through-hole mounting techniques, but they still provide unique advantages for high power and high isolation applications. Stripline packages are also common and can be bonded onto PC boards or into microcircuits. The package diameter defines the dimension of the package.

Other frequently used packages include beam lead, flatpacks, and DIP.

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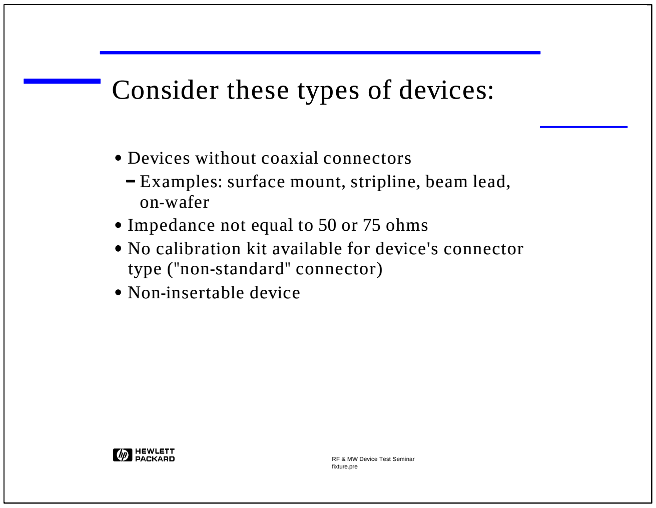

In addition to these non-coaxial packaged devices, other types of devices also present a measurement challenge for standard RF and microwave test equipment. Consider on-wafer devices, which require a special interface to the test system as well as different calibration methods. Also, most instruments have either 50 or 75 ohm impedance inputs and outputs. Connecting to devices with other impedances can cause mismatch problems.

Although network analyzers offer the capability to improve accuracy by performing a measurement calibration, this requires the use of a calibration kit in the appropriate connector type. If the device to be measured has a "non-standard" connector for which a cal kit is not available, some method is needed to account for the differences due to the non-standard connector.

One more category to consider is non-insertable devices. These present a problem because the device can't be inserted in the measurement system using the same configuration in which the measurement system alone was calibrated. The differences between the calibration and measurement configurations can cause errors in the measurement.

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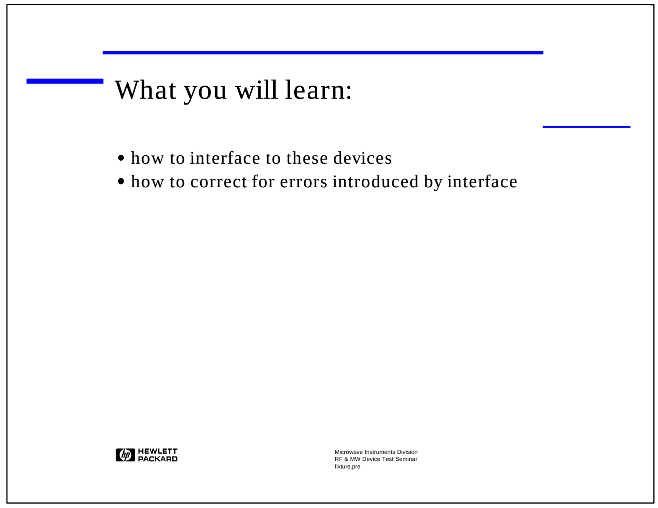

In this module, we will focus on two primary topics:

1. How to make the connection from 50 or 75 ohm coaxial test instruments to devices that are non-coaxial or have non-standard impedances or connector types

2. How to correct for measurement errors introduced by the connection interface

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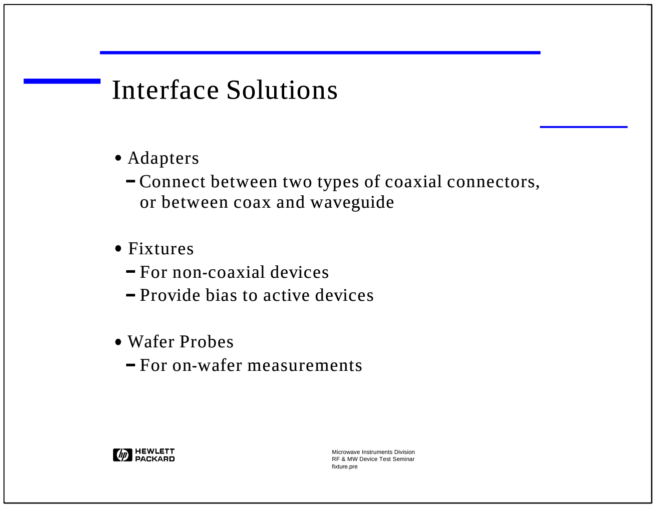
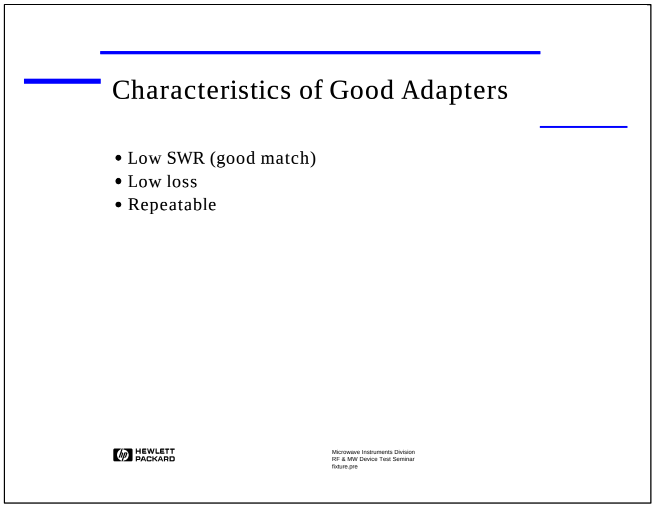


Three primary categories of interface solutions will be discussed: adapters, fixtures, and wafer probes. Adapters provide connections between two types of coaxial connectors, such as 3.5 mm to type-N, or between coaxial and waveguide connectors. Fixtures are used to connect to non-coaxial devices such as surface mount or other packaged devices. They can also have the capability to provide DC bias to active devices. Finally, wafer probes convert signals from coaxial to the coplanar on-wafer environment.

Slide #8



First, let's consider adapters. In order to minimize the error introduced by adding an adapter to a measurement system, the adapter needs to have low SWR or mismatch, low loss, and high repeatability.

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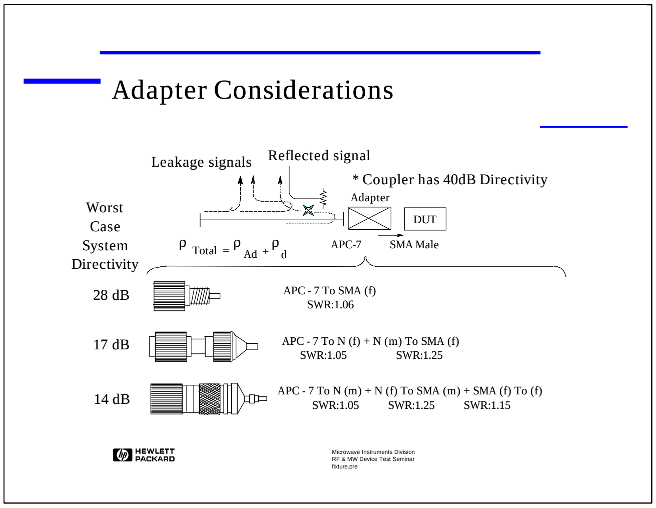

Here is an example to demonstrate why low SWR or mismatch is important. As you may know, in a reflection measurement, the directivity of a system is a measure of the error introduced by an imperfect signal separation device. It typically includes any signal which is detected at the coupled port which has not been reflected by the DUT. This directivity error will add with the true reflected signal from the device, causing an error in the measured data. Overall directivity is the limit to which a DUT's return loss or reflection can be measured, so it is important to have good directivity to measure low reflection devices.

In this example, the coupler has a 7 mm connector and 40 dB directivity, which is equivalent to a reflection coefficient of $\rho = 0.01$ (directivity in dB = $-20 \log \rho$). Suppose we want to connect to a DUT with an SMA male connector. We need to adapt from 7 mm to SMA.

If we choose a precision 7 mm to SMA adapter with a SWR of 1.06, which has $\rho = 0.03$, the overall directivity becomes $\rho = 0.04$ or 28 dB. However, if we use 2 adapters to do the same job, the reflection from each adapter adds up to degrade the directivity to 17 dB, and the last example using 3 adapters shows an even worse directivity of 14 dB. It is clear that a low SWR is desirable to avoid degrading the directivity of the system.

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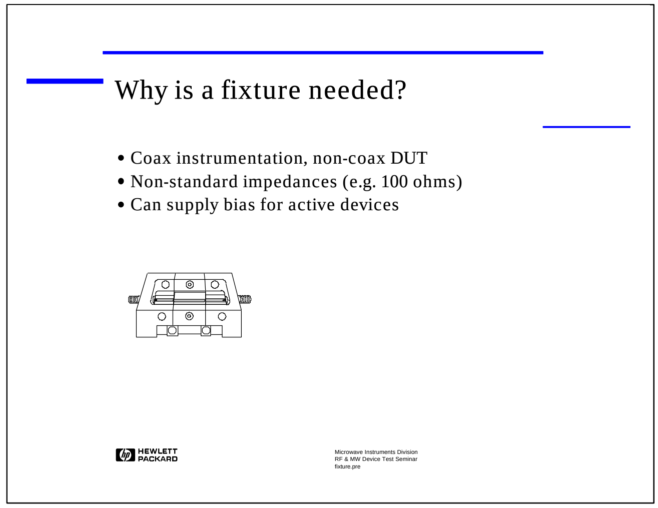

Next, let's consider fixtures. Fixtures are needed to interface non-coaxial devices to coaxial test instruments. It may also be necessary to transform the characteristic impedance from standard 50 or 75 ohm instruments to a non-standard impedance and to apply bias if an active device is being measured.

For accurate measurements, the fixture must introduce minimum change to the test signal. without destroying the DUT, and provide a repeatable connection to the device.

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Fixtures Available From HP

Package Type	Fixture
70, 100 mil stripline	HP 85041A
200 mil stripline	HP 11608A

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Hewlett-Packard offers two fixtures for stripline devices. The HP 85041A and 11608A are designed for stripline transistors.

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Other Fixtures

- Fixtures from Inter-continental Microwave (ICM)
  - chips
  - surface mount
  - thin film
  - beam lead
  - stripline
  - TO-5, 8, 8B, 39, and 12
  - DIP (14 pin VTD, 24 pin AT-540)
- See ICM catalog for details (HP lit. no. 5091-4254E)

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fixture.pre

In addition to HP's products, a company called Inter-Continental Microwave has developed many modern test fixtures for a variety of RF and high speed packaged devices. ICM offers fixtures for chips, surface mount packages (including SMT, SOT, and SOIC), thin film and microstrip circuits, beam lead, TO cans, and DIP packages. For more details about ICM's products, ask your local HP office for a copy of ICM's catalog, HP literature number 5091-4254E.

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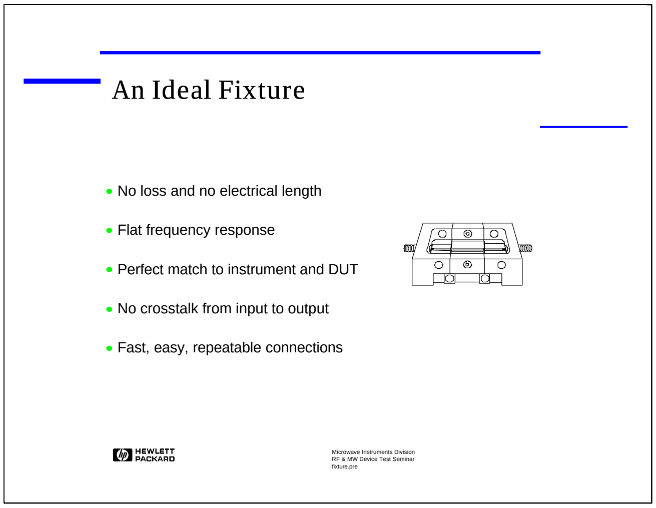

Many customers choose to design their own fixtures, so let's consider what is required for a good test fixture. Ideally, a fixture should provide a transparent connection between the test instrument and the device under test. This means it should have no loss or electrical length and a flat frequency response, to prevent distortion of the actual signal. A perfect match to both the instrument and the DUT eliminates reflected test signals. The signal should be effectively coupled into the test device, rather than leaking around the device and resulting in crosstalk from input to output. Repeatable connections are necessary to ensure consistent data.

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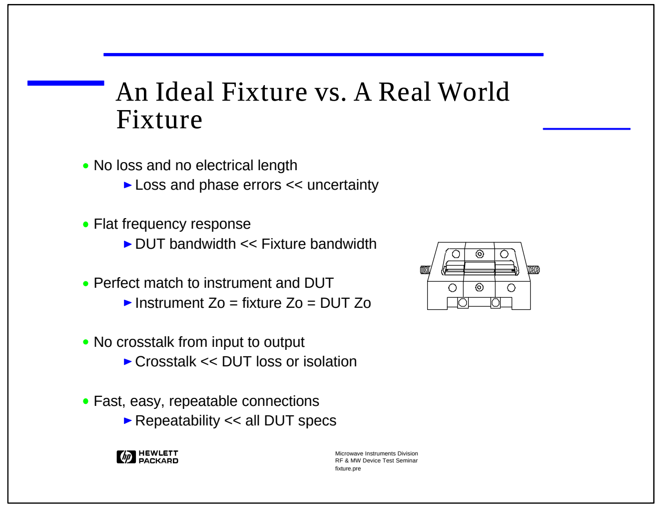

In the real world, it's impossible to build an ideal fixture, especially at high frequencies. However, it is possible to optimize the performance of the test fixture relative to the performance of the test device. If the fixture's effects on the test signal are relatively small compared to the device's parameters, then the fixture's effects can be assumed to be negligible.

For example, if the fixture's loss is much less than the acceptable measurement uncertainty at the test frequency, then it can be ignored.

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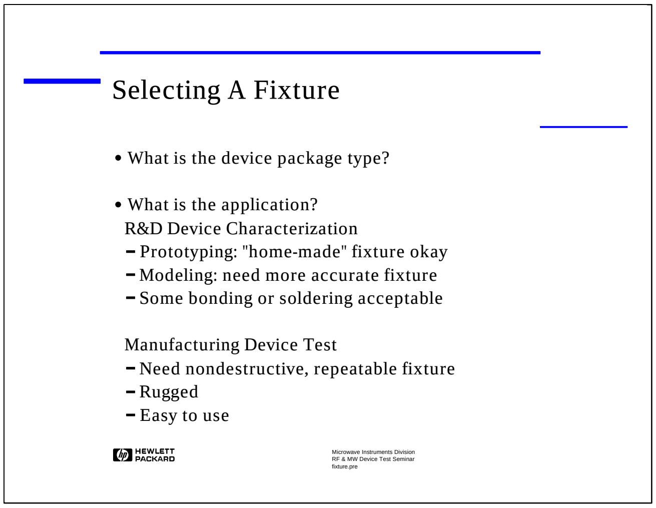

So how can you decide what type of fixture to use?

The first criteria is the device package type. That will determine which fixtures are appropriate to your device. There is a summary at the end of this section which lists common device packages and appropriate fixtures that are available from HP or third party vendors.

The second consideration is what is the application? For an R&D engineer who wants to check a device's performance, a "home-made" fixture may work quite well. In fact, he may be able to fabricate a fixture that allows him to test the device in the same environment in which it will be used, for example, mounted on a PC board. On the other hand, if an engineer needs to characterize a device so that it can be used in modeling, he will need a fixture that allows good error correction techniques and high accuracy. For R&D, nondestructive testing is not always a requirement, and it's often not a problem if the fixture requires some bonding or soldering.

For production testing of RF devices, obviously you would want nondestructive test. Also, repeatability, ease of use (getting the device in and out of the fixture), ruggedness, and simple (preferably infrequent) calibration techniques are important.

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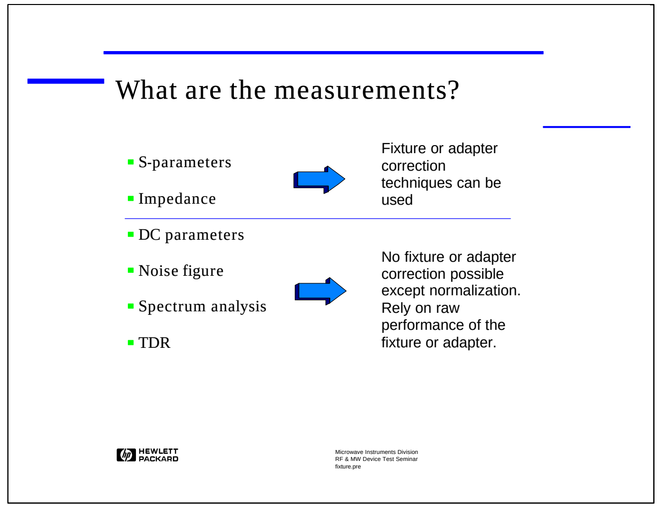

From this point on, we will consider adapters and fixtures as a single category, since they are just different ways of interfacing test equipment to various devices.

The degree to which we can compensate for the errors caused by adapters or fixtures depends on the type of measurements that are desired. Test instruments such as network analyzers and impedance analyzers provide a means for mathematically compensating for a fixture's errors. However, when fixtures are used with other instruments such as spectrum analyzers or TDR's, there is little that can be done to compensate for fixture error. Therefore, for these applications, it is necessary to select a high quality fixture whose effects on the test signal are negligible when compared to the test device's effects. Important RF parameters to consider when selecting such a fixture include SWR, insertion loss, and bandwidth.

For the remainder of this session, we will focus on techniques that can be used with network analyzers to improve the accuracy of s-parameter measurements.

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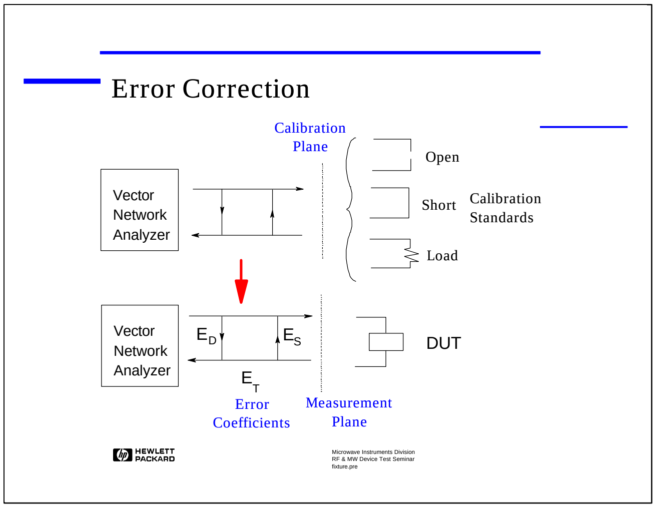

The next section of this seminar covers the recommended procedures for reducing the error introduced by a test fixture or adapter in the measurement of s-parameters.

Network analyzers have an error-correction capability that can compensate for errors in a test system. This is done by performing a measurement calibration. During this procedure, several known devices are connected to the test port and measured. The network analyzer uses this data to compute the frequency response and mismatch of the interconnecting hardware. It creates a set of error coefficients that are used to mathematically remove the errors from the measured data. The devices used for calibration, called standards, have RF characteristics that are precisely known and defined. HP supplies calibration kits for a variety of coaxial and waveguide connector types.

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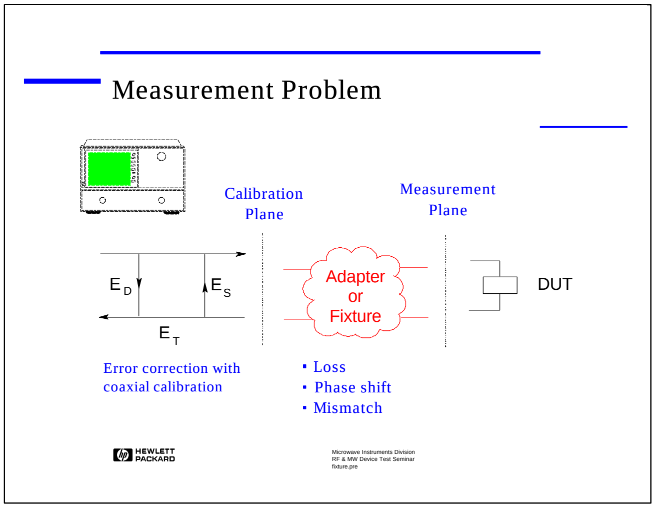

The problem occurs when cal standards are not available in the same connector type as the device. In that case, it is possible to perform a calibration in a "standard" or "known" connector type at the test port to correct for errors up to that point (referred to as the "calibration plane"). However. adding the adapter or fixture introduces additional loss, phase shift, and mismatch that can add error to the measurement of the DUT.

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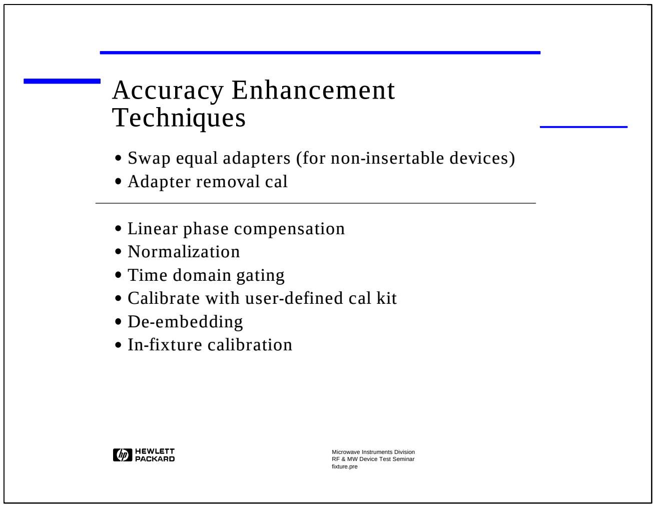

These are the most common methods for removing the effects of fixtures or adapters. The first two are aimed towards measuring non-insertable devices, and apply mostly to adapters. The remaining techniques are more focused towards fixtures. We will look at an example measurement problem to help demonstrate these techniques.

Not all of these techniques are available on every HP network analyzer, but a table at the end of this module summarizes which techniques are compatible with which network analyzers.

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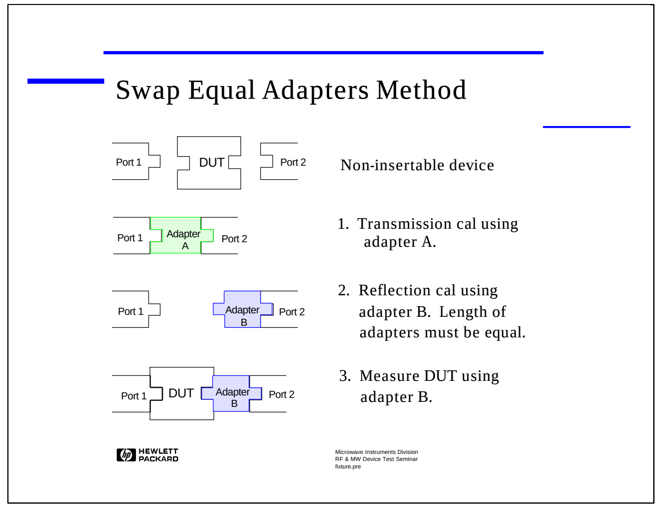

The first technique, "Swap equal adapters," applies to the problem of how to calibrate when you want to measure a non-insertable device. A common example is a device that has the same sex connector on both the input and output.

This method requires the use of two precision matched adapters which are "equal." To be equal, the adapters need to have the same match, Zo, insertion loss, and electrical delay. The first step in the procedure is to perform a transmission calibration using the first adapter. Then, adapter A is removed, and adapter B is placed on port 2. Adapter B becomes the effective test port. The reflection cal is performed. Then the DUT is measured with adapter B in place.

The errors remaining after calibration with this method are equal to the differences between the two adapters that are used.

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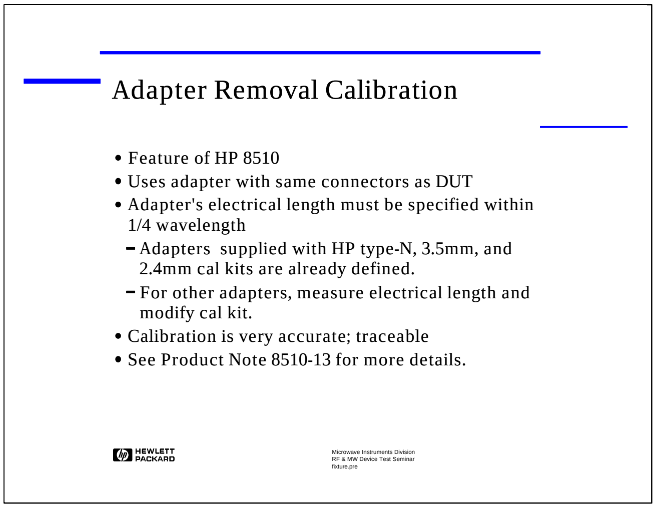

Adapter removal calibration provides the most complete and accurate calibration procedure for non-insertable devices. It is a feature available on the HP 8510 network analyzer. This method uses an adapter that has the same connectors as the non-insertable DUT. The electrical length of the adapter must be specified within 1/4 wavelength at each frequency. HP's type-N, 3.5 mm, and 2.4 mm cal kits for the HP 8510 contain adapters that have been specified for this purpose.

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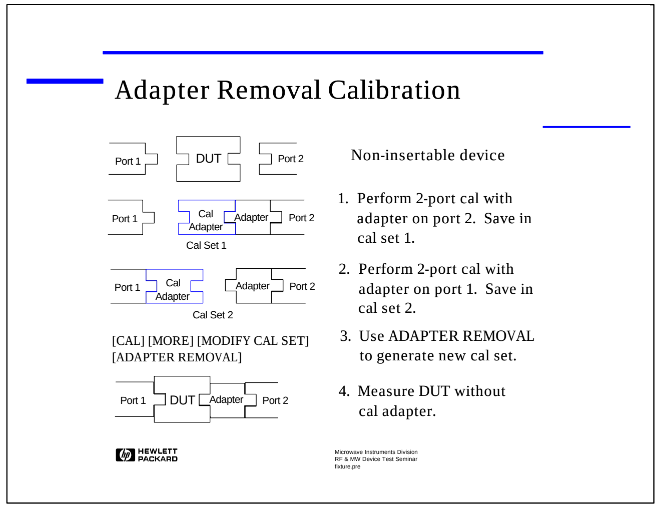

Two full 2-port calibrations are needed for adapter removal calibration. The first calibration is performed with the precision adapter on port 2, and the data is saved into a cal set. Next, the second calibration is performed with the precision adapter on port 1, and the data is saved into a second cal set. Then, press the following keys: [CAL] [MORE] [MODIFY CAL SET] [ADAPTER REMOVAL]. Specify the locations of the two cal sets, the cal kit containing the adapter's definition, and then press [MODIFY & SAVE]. The HP 8510 will generate a new set of error coefficients that remove the effects of the adapter. This adapter can then be removed so that the DUT can be measured in its place.

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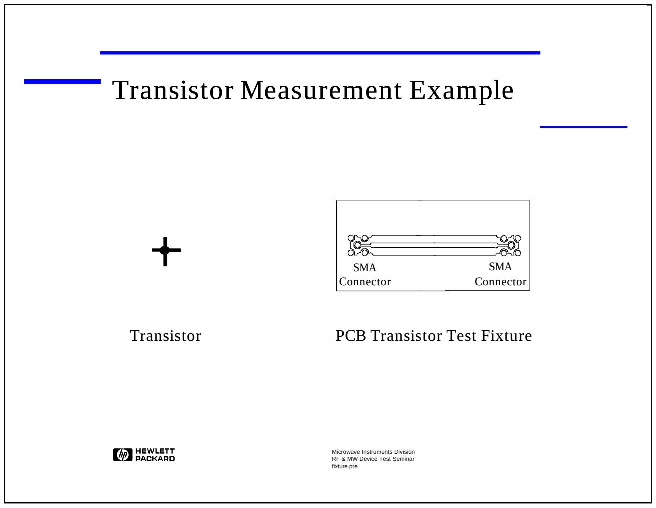

Before we discuss the other accuracy enhancement techniques, let's consider a measurement problem where these techniques might be useful. The goal is to measure a transistor that is typically used with microstrip circuits. The drawings show a "fixture" that can be used to measure this device in an environment similar to the one where it will be used. This fixture basically consists of a microstrip (PC) board with SMA connectors.

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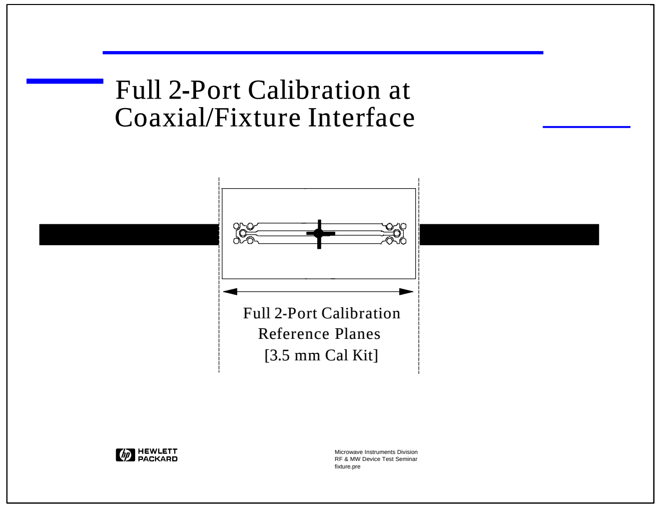

The first step is to perform a full 2-port calibration in 3.5 mm at the coaxial/fixture interface to establish a known reference plane outside the fixture. This coaxial calibration does not account for any effects due to the fixture or adapters.

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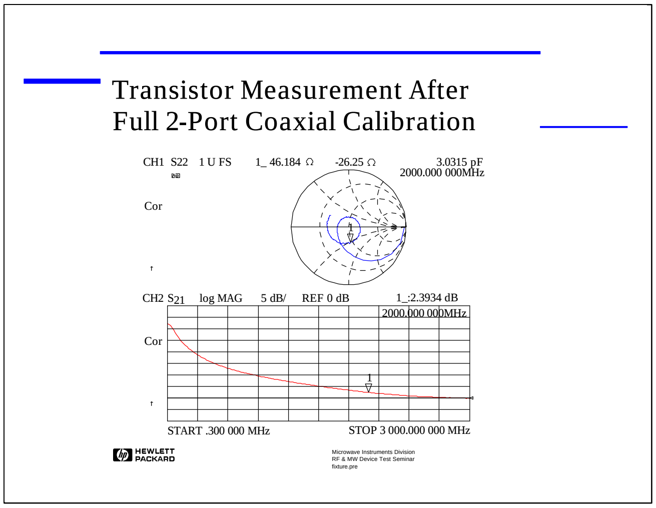

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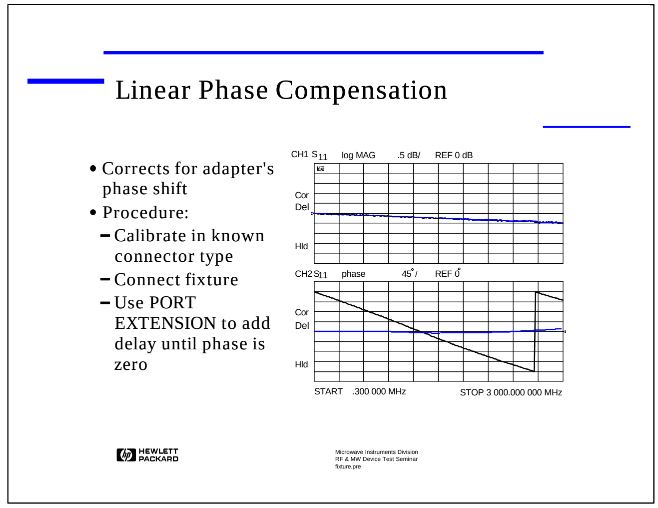

The plots show the measurement of the transistor after a full 2-port 3.5 mm coaxial calibration has been performed at the coaxial/fixture interface. The S22 output match is displayed in a Smith chart format and the measured S21 transmission gain is displayed in a Log magnitude format from 300 kHz to 3 GHz. The effects of the fixture's phase shift, insertion loss and mismatch are still present in this measurement.

The next technique, linear phase compensation, corrects for the phase shift in an adapter or fixture by using the PORT EXTENSIONS function. This method does not correct for mismatches or losses.

To use this method, first perform a calibration at the test ports with a standard cal kit. Next, connect the adapter(s), and connect a short or open for reflection measurements, or a thru for transmission measurements. Then use the PORT EXTENSION feature to add delay until the phase is equal to zero across the frequency range.

The plot shows this method used with the PC board fixture with a short. When a short is used, a PHASE OFFSET of 180 degrees is added to get the phase of the short to be zero. The phase offset should be set back to zero before measuring the DUT. Also, note that the shorts from some HP cal kits have an offset delay, which can cause the port extension value to be too high unless the additional delay is subtracted out.

It is also possible to compensate for the phase by using ELECTRICAL DELAY instead of PORT EXTENSION. However, ELECTRICAL DELAY is only applied to one s-parameter at a time, while PORT EXTENSION applies to all s-parameters measured using that port. Also, it is preferable to use PORT EXTENSION to extend the reference plane so that ELECTRICAL DELAY can be used to measure the actual delay of the device.

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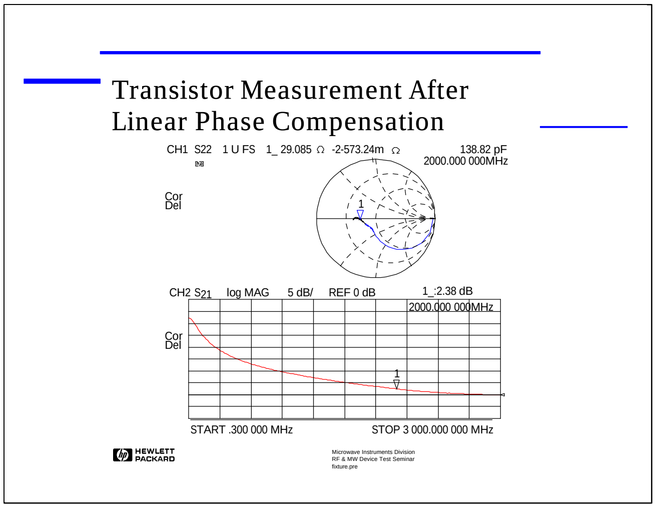

In this example, a coaxial calibration was first performed at the coaxial/fixture interface. Next, a port extensions was applied by placing a short circuit in-fixture and then adding enough delay to zero the displayed phase response. Only the phase shift of the fixture is accounted for with port extensions or electrical delay.

When compared to the previous 3.5mm coaxial calibration, notice that only the S22 response of the Smith chart changes in response to the port extension. The S21 Log magnitude response is not affected by the linear phase compensation.

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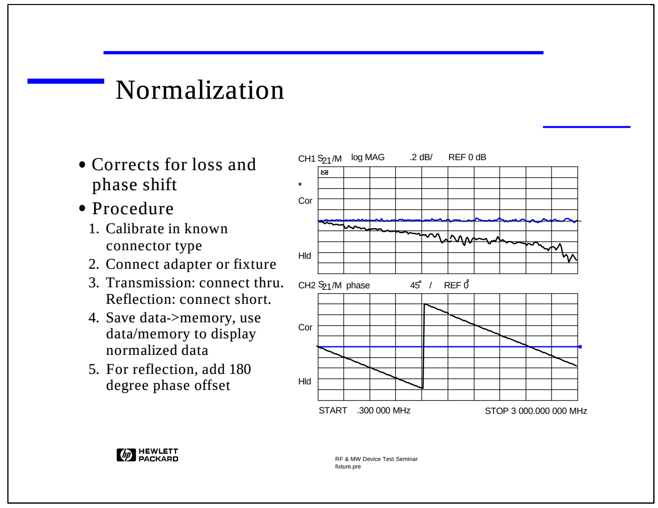

Normalization corrects for both the loss and phase shift of an adapter or fixture for measurement of a single s-parameter. To use this method, perform a calibration at the test ports with a standard cal kit. Connect the adapter. Then, connect a thru for transmission measurements or a short for reflection measurements. From the [DISPLAY] menu, use [DATA->MEMORY] to save the trace to memory, then use [DATA/MEMORY] to display the normalized data. For reflection measurements, use [PHASE OFFSET] to add 180 degrees so that the short's phase value is correct. In this case, the phase offset needs to be kept while measuring the DUT to maintain the correction factor on the phase.

The plots show normalization used with the PC board fixture through line. This method is particularly useful when the fixture demonstrates some insertion loss, as in this example. Note that the normalization corrected both the loss and the phase shift through the fixture.

Since normalization does not correct for mismatch, you may see mismatch error when measuring high reflection devices. This may show up as "gain" on a passive device.

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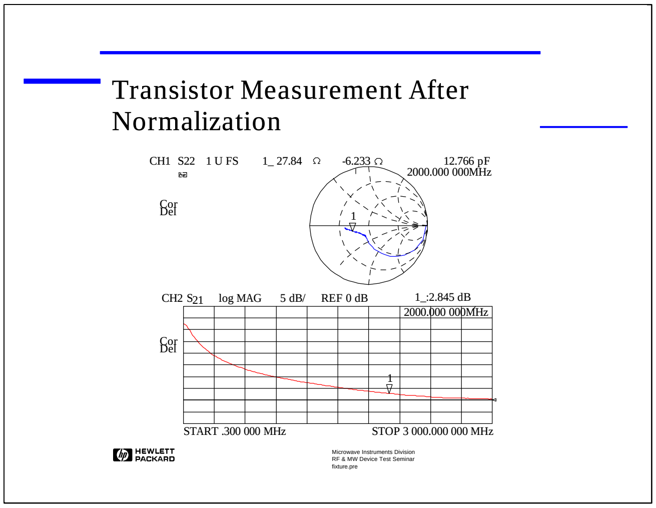
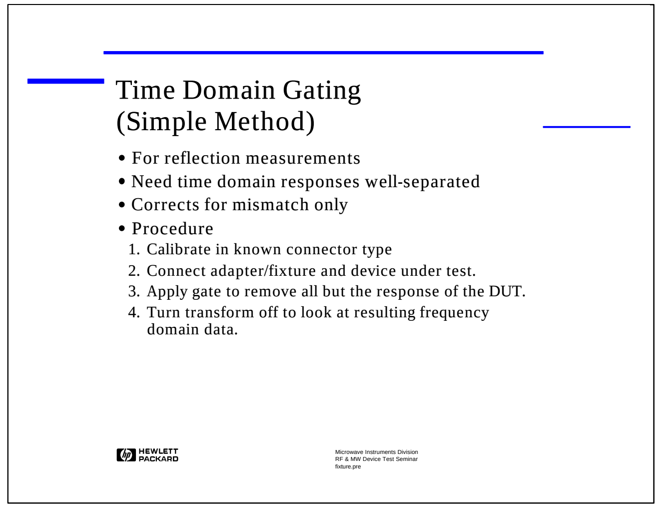


In this example, a coaxial calibration first was performed at the coaxial/fixture interface. Next, a short circuit was used to establish a reference plane for the S22 reflection normalization and a thru was used to establish a reference plane for the S21 transmission normalization. Notice that both plots have changed to account for the correction of both the phase shift and insertion loss through the fixture.



Time domain gating can be used in reflection measurements to isolate the response of the DUT from the response of the adapter or fixture. For gating to work effectively, the time domain responses need to be well-separated.

There are two ways to use time domain gating. The simpler method corrects for mismatch errors, but not for loss or phase shift. The procedure involves calibrating at the test port of the network analyzer with a standard cal kit, connecting the adapter or fixture and the device under test, going into time domain, and using gating to remove all except the response of the DUT.

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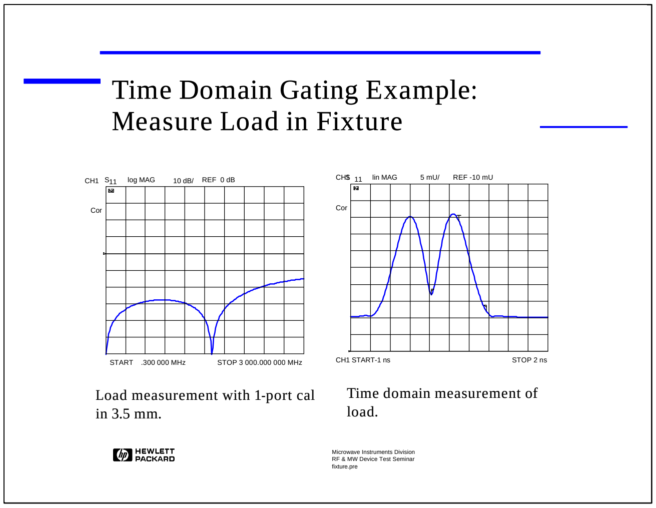

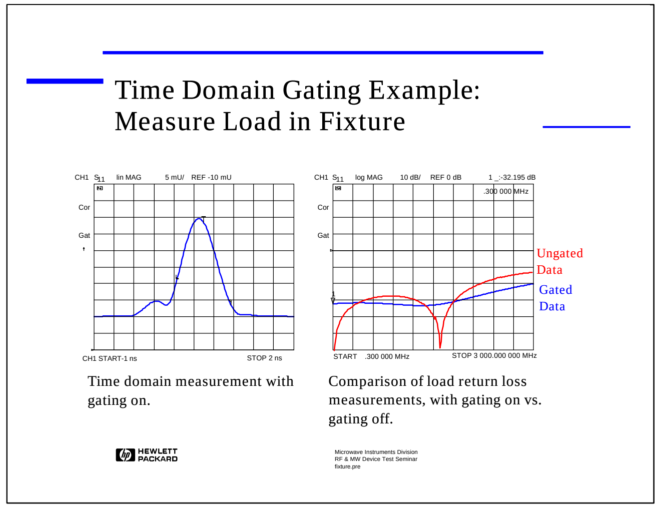

Here is an example, using time domain to measure the load in the PC board fixture. The plot on the left shows the load measurement after a one-port calibration has been performed with a 3.5 mm calibration kit. Notice that instead of the flat response that we would expect to see from a load, we see a ripple that is caused by mismatch.

The plot on the right shows the time domain transform of the same data. The first peak in the trace is due to the SMA to microstrip launch, while the second peak is the load response. Therefore, we set the gate start and stop frequencies to include this second peak.

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The left plot shows the time domain response with gating turned on. Only one main peak is now visible. Finally, after time domain transform is turned off, we can see from the plot on the right that the load response is now smooth, without the ripple caused by the mismatch.

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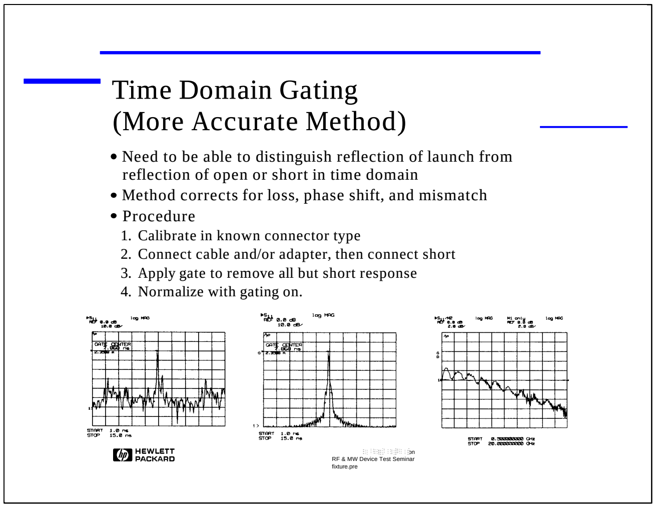
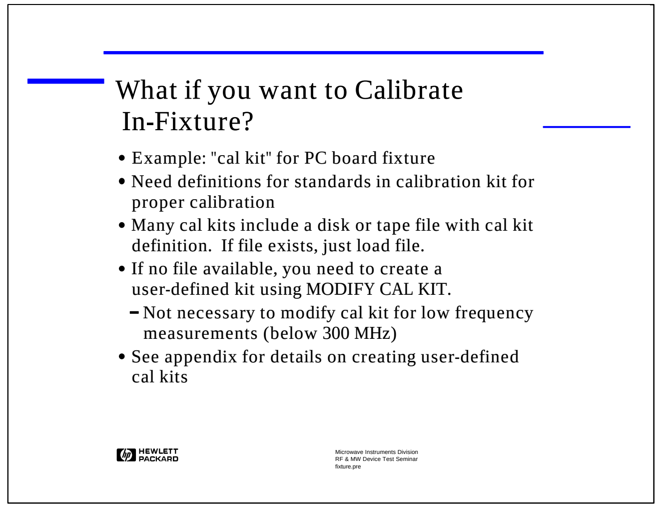


There is also a more accurate way to use time domain gating, which can correct for loss and phase shift as well as mismatch. For this method, the reflection of the launch in time domain must be distinguishable from the reflection of an open or short in the fixture. If the fixture is small, a broad frequency sweep will be needed to provide the necessary resolution.

To use this method, begin by calibrating at the test port with a standard cal kit. Connect the cable and/or adapter, then connect a short. Look at the time domain response and use gating to remove all except the response of the short. Return to the frequency domain and perform a normalization with gating still on, then connect the DUT and measure it. The gating removes the mismatch effects, while the normalization removes loss and phase shift.

The 3 plots show the short's response in time domain, the gated short response in time domain, and the frequency response after normalization.



There may be occasions where you actually want to calibrate in a non-standard connector type or in a fixture. For example, let's say we want to calibrate for a measurement in the PC board fixture, and we want to make our own cal kit. Another example might be calibrating with type-F connectors. We need to let the network analyzer know the correct definitions for our calibration kit standards.

This can be done in one of two ways. If the manufacturer of the cal kit supplied a floppy disk or tape that has a file containing the cal kit definitions, simply load the file directly into the network analyzer. For network analyzers with built-in cal kits, store the new kit as a user kit. If no file is available, you can use MODIFY CAL KIT to create a user-defined cal kit.

The appendix contains extensive details on how to create a user-defined cal kit. For our example, we will consider the challenge of modifying a calibration kit so that we can use the short, open, and load that was built in the PC board fixture to perform a calibration.

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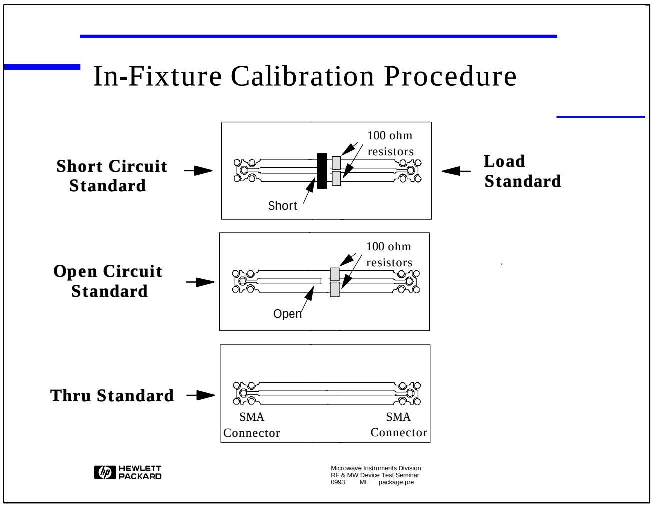
Slide #34

Slide #35



Slide #36

Modifying Cal Kit for PC Board Fixture Standards

- Can build open, short, and load
- Need to determine key characteristics to define
- For PC board fixture standards, important characteristics are:
  - open capacitance
  - thru offset delay
  - can use default values for other characteristics

A complete in-fixture calibration requires the connection of in-fixture open, short, load and thru standards. In this example, the short circuit standard consists of a shorting bar across the transmission line. The load standard consists of two 100 ohm resistors in parallel to ground terminating the line. The open circuit standard is an open stub whose capacitance has been defined. And the thru standard is a 10 psec length of transmission line whose offset delay has been defined.

When connecting an open or short circuit to either port within the fixture, the load standard is used on the other port to provide some amount of signal isolation between the ports.

Let's build a calibration kit for the PC board fixture so that we can calibrate out the errors in this fixture. An earlier slide showed how to make an open, short, load, and thru. To use these as cal standards, we need to determine their key characteristics.

Details about different characteristics and how to calculate their values may be found in the appendix. It turns out that at RF frequencies, the short and the load don't need much detailed definition, other than to note that there is no offset delay since the short and load are located right where the device's ports will be. However, for the open, we need to determine the capacitance of the open, at least for the first term in the polynomial that describes the capacitance as a function of frequency. The offset delay of the thru standard will also have to be modified.

Slide #37

In-Fixture Calibration Kit Modifications

Short Circuit Standard	Use 7 mm Calibration Standard Definition
Load Standard	Use 7 mm Calibration Standard Definition
Open Circuit Standard	Use 7 mm Calibration Standard Definition Modify Open Circuit Capacitance
Thru Standard	Use 7 mm Calibration Standard Definition Modify Offset Delay

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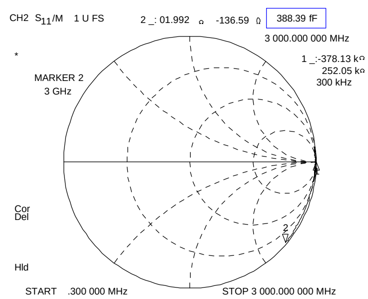
Slide #38

Measure Open Capacitance



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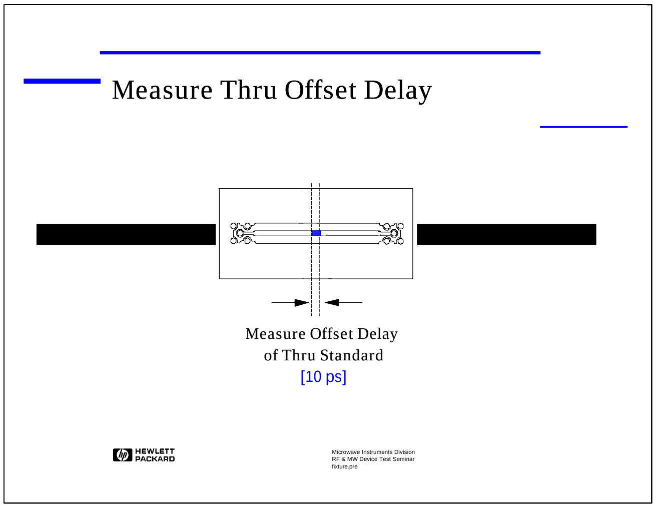
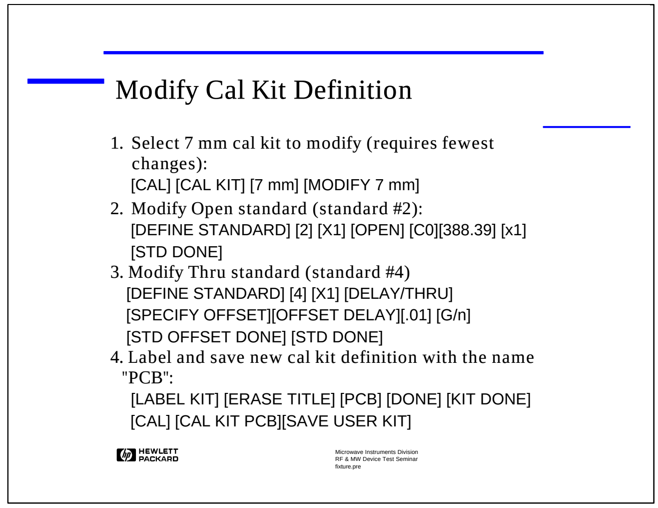
In this example, a 7 mm coaxial calibration kit was used as a "starting point" for the modifications since the default definition values in this kit match very closely the values we want to use for the in-fixture standards, thus minimizing the number of changes necessary.

The definition for the in-fixture short circuit and load standards match the 7 mm standards exactly, and require no change. The definition of the open circuit capacitance and thru offset delay will have to be modified to reflect the difference of the in-fixture calibration standards.

To determine the open capacitance, we can do a calibration with a 3.5 mm calibration kit at the test ports of the network analyzer, and then use port extensions to correct for the phase shift through the fixture. Measuring S11 in the Smith chart format yields the value of the capacitance directly, as shown in the above display.

Slide #39





The electrical delay feature of the network analyzer can be used to measure the amount of offset delay that the thru standard adds, which in this case is 10 psec.

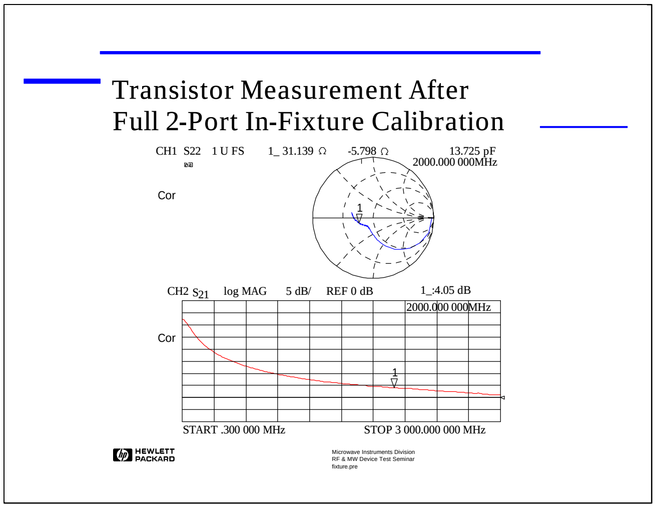
By entering this offset delay value into the calibration kit definition for the thru standard, its effects are mathematically removed from the measurement.

Next we need to enter these values into the cal kit definition that's in the network analyzer. The general steps apply to most vector network analyzers, but the keystrokes listed are for the HP 8753 in particular.

Once the capacitance of the open circuit and the offset delay of the thru standard have been entered, the modified kit can be saved as a user kit with a user-selected name for later use.

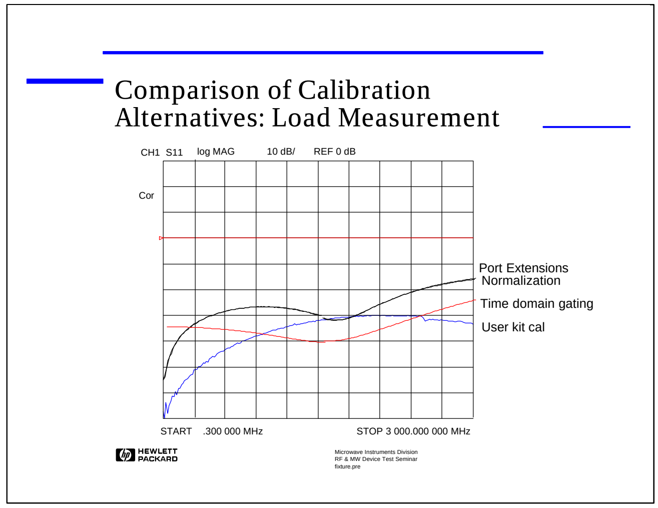
Slide #40

Slide #41



After a full 2-port in-fixture calibration is performed the results show a measurement of the transistor that is fully corrected for the effects of the fixture's phase shift, insertion loss and mismatch.

Slide #42



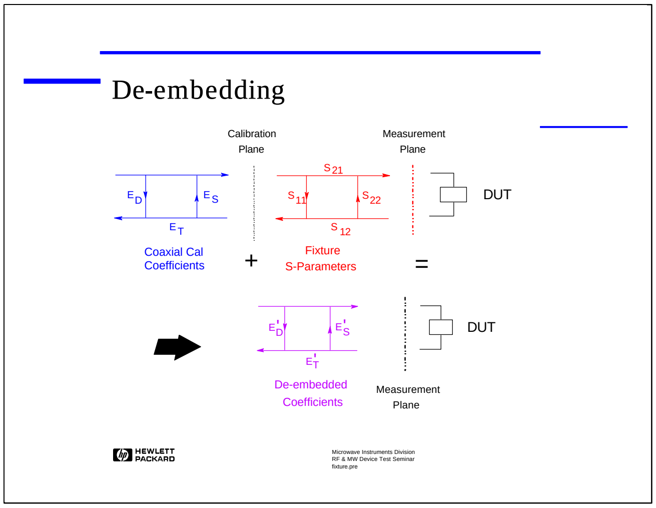
Here is a comparison of the same device measured using different types of error correction. The test device in this case is another load mounted in a PC board fixture, similar to (but not the same) as the one used in the calibration.

There is very little difference between the data traces resulting from port extension vs. normalization, because there is little loss in the PC board fixture for reflection measurements. Both still show the dip caused by mismatch errors.

The trace with time domain gating shows a much flatter line, although some mismatch is still evident. The fixture that was used was too small for time domain to give the proper resolution at 3 GHz, so there is probably some error in the gated measurement.

Finally, the measurement made after a one-port cal using the user-defined cal kit shows very good match at low frequencies, with the return loss becoming smaller as frequency increases.

Slide #43



Slide #44

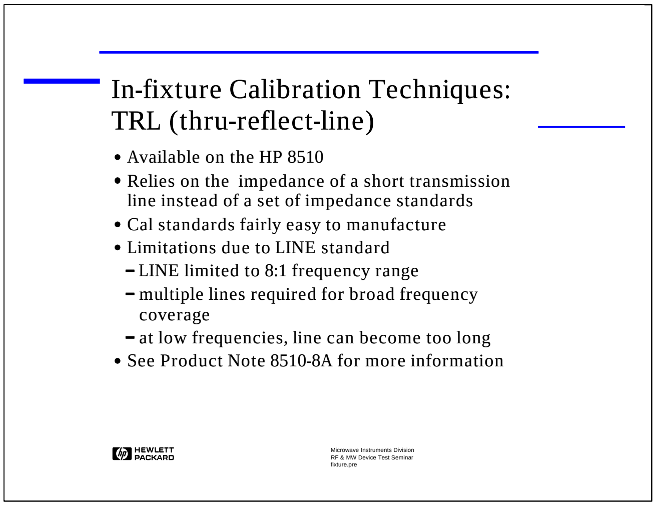
De-embedding

- Removes errors due to loss, phase, mismatch, and crosstalk
- Requires accurate fixture model
  - empirical model from data measurements
  - simulation (modeling)
- De-embedding calculations
  - For HP 85041A fixture, use HP 85014C software
  - HFDS and MDS design systems can de-embed

A method which is primarily used to accurately correct for the effects of fixtures is de-embedding. The idea in de-embedding is to combine the errors determined from a coaxial calibration with the errors in the fixture to obtain a single error coefficient array that corrects for everything up to the measurement plane of the DUT. The advantage of de-embedding is that the process provides fully error-corrected measurements without requiring in-fixture calibration standards to be measured each time a new measurement is made.

De-embedding is a very accurate technique, since it can remove errors due to loss, phase, mismatch, and crosstalk. However, it does require an accurate model of the fixture in the form of s-parameter data files. This can be obtained empirically by making measurements of the fixture, or it can be obtained through simulation or computer modeling of the fixture. Since de-embedding is very math-intensive, software can prove to be extremely helpful. Typically, de-embedding software recalls the fixture data file and combines it with the coaxial calibration error model to create a new error model that includes the effects of the fixture. The HP 85014C software can be used to de-embed the HP 85041A test fixture. HP's HFDS and MDS design systems (CAE software) can also perform de-embedding.

Slide #45

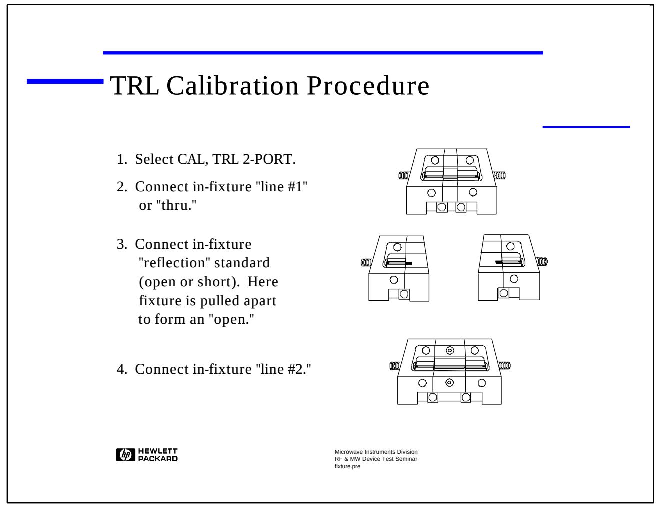


The final accuracy enhancement technique to be discussed is in-fixture calibration. There are several types of in-fixture calibration. One of the most common is TRL, which stands for thru-reflect-line, the three standards that are needed for this calibration. TRL calibration is a feature of the HP 8510 network analyzer.

The standard SOLT calibration depends on a set of 3 well-defined impedance standards (open, short, load), but TRL only relies on the impedance of a short transmission line. Because of this, TRL cal standards are fairly easy to manufacture, especially for in-fixture environments. However, TRL is limited by the restrictions caused by the LINE standard. A single line is only usable over an 8:1 frequency range, so multiple lines are required for broad frequency coverage. Also, the optimal length of the LINE standard is 1/4 wavelength at the geometric mean of the desired frequency span (square root of f1xf2). At low frequencies, this line can become too long for practical use.

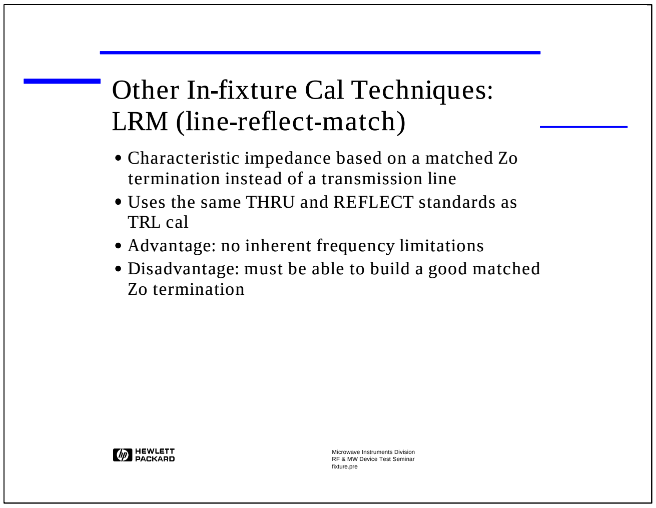
For more details about TRL calibration, see Product Note 8510-8A.

Slide #46



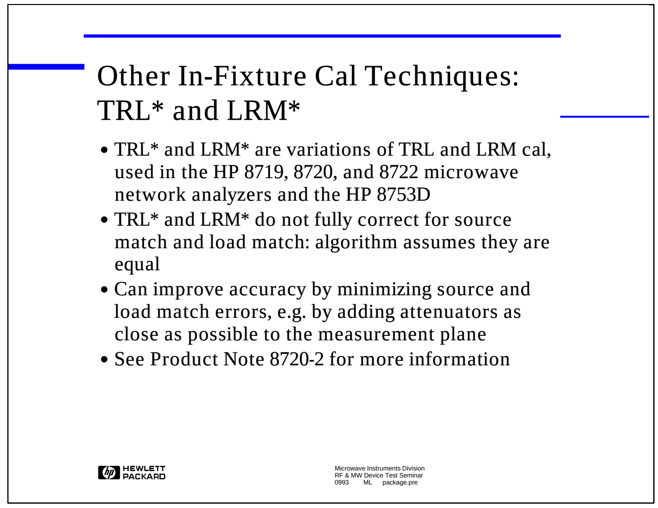
The TRL calibration procedure is quite simple. Only 3 standards need to be measured. The "thru" can either be a real thru or a short transmission line. The "reflect" standard can be anything with a high reflection, as long as it is the same on both ports. The actual magnitude of the reflection need not be known. The third standard is the "line," which must not be the same length as the "thru" standard. The Zo of this line establishes the reference impedance for the measurement after calibration is completed. The attenuation of this line need not be known, and the electrical length only needs to be specified within 1/4 wavelength.

Slide #47



Another type of in-fixture calibration is LRM (line-reflect-match), which is a variation of TRL. LRM uses the same thru and reflect standards as TRL, although the thru is referred to as a line. However, LRM uses a matched Zo termination to establish the characteristic impedance, rather than using a transmission line like TRL. Since the line standard is not used, there are no inherent frequency limitations.

Slide #48



Two other in-fixture calibration techniques are TRL* and LRM*, which are features of the HP 8719, 8720, and 8722 network analyzers as well as the HP 8753D. As their names imply, TRL* and LRM* are versions of TRL and LRM calibration which have been adapted from the 4-channel receiver architecture of the HP 8510 to the 3-channel receiver architecture of the HP 8720 family and HP 8753D RF vector network analyzer. The primary difference is that due to the 3-channel receiver, TRL* and LRM* do not fully correct for source match and load match. The calibration procedure can determine the product of the source match and load match errors, but it cannot determine these two errors separately. Therefore, the algorithm assumes that source and load match on ports 1 and 2 are equal.

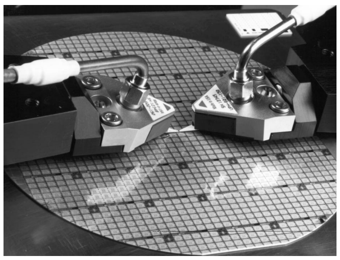
The accuracy of TRL* and LRM* calibration can be increased by improving the raw source and load match. This can be done by adding attenuators as close as possible to the measurement plane. When this is done properly, the differences between TRL and TRL* calibration are typically quite small.

For more details, see Product Note 8720-2.

Slide #49

Solutions for On-wafer Measurements

- Use wafer probes with probe stations
- Available from Cascade Microtech, Inc.



probe.tif

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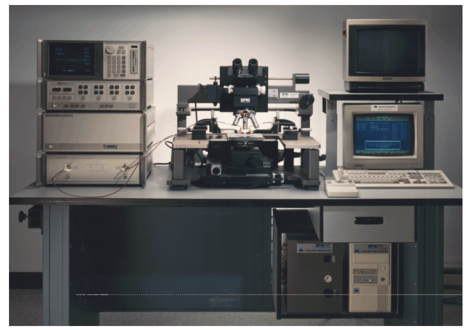
Finally, here are some solutions for making on-wafer measurements. The interface between the coaxial test instrument and the coplanar on-wafer environment can be achieved by using wafer probes. These are typically used with manual or automatic probe stations. Cascade Microtech, Inc. in Beaverton, Oregon supplies a variety of wafer probes and probe stations.

Slide #50

Summit 10000 Probe Station With HP 8510C



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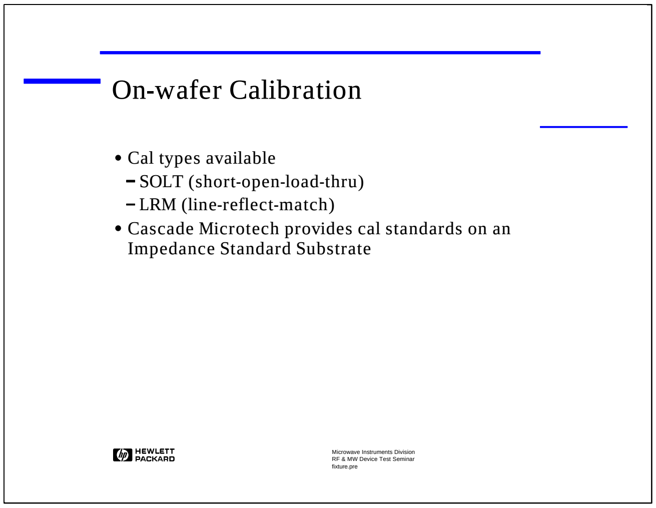
This is a photograph of Cascade's wafer probing systems. This is the Summit 10000, an automatic PC-based system which includes software to control the wafer probes and perform calibrations. It is shown here with the HP 8510C network analyzer.

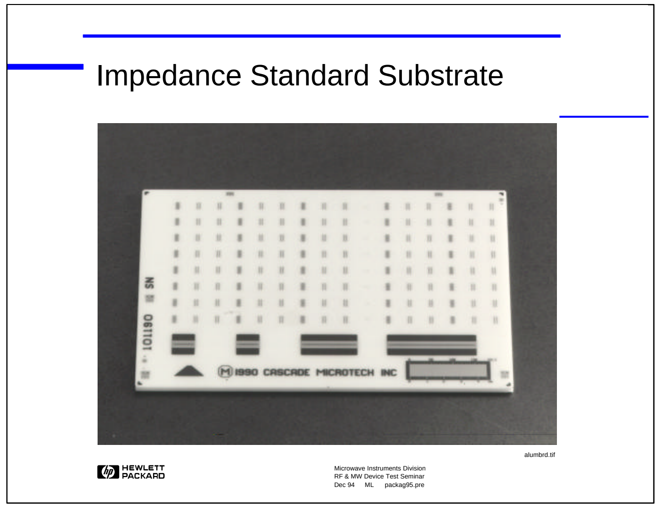
Slide #51



Like adapters and fixtures, wafer probes also introduce error into a measurement system. On-wafer calibration can correct for these errors. Several calibration types are available, including LRM and SOLT.

Cascade Microtech provides calibration standards on their Impedance Standard Substrate.

Slide #52



This is a picture of the Impedance Standard Substrate. The actual size of this substrate is less than one square inch (6.45 cm^2).

Slide #53

Summary of Adapter and Fixture Correction Techniques

Method	Parameter	Errors Reduced Phase	Loss	Match	Assumptions
Swap Equal Adapters	All	X	X	X	Adapters are well-matched
Adapter Removal Calibration	All	X	X	X	
Port Extensions	S11,S21,S12 or S22,S12,S21	X			
Normalization	Single s-parameter	X	X		
Time domain gating	S11 or S22	?	?	X	Time domain responses well-separated
De-embedding	All	X	X	X	Modeled or measured s-parameter data available for fixture
In-fixture cal (TRL/LRM etc.)	All	X	X	X	In-fixture cal standards available

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Here is a summary of the error correction techniques that have been discussed in this module. This table shows which errors are corrected by particular techniques, as well as which s-parameter measurements can use this technique. Note that the errors corrected by time domain gating depends on which technique is being used. Both techniques correct for mismatch, but the simple method does not correct for loss or phase shift.

Slide #54

Summary of Adapter and Fixture Correction Techniques

Method	Simplicity	Accuracy
Swap Equal Adapters	A	B
Adapter Removal Calibration	C	A
Port Extensions	A	C
Normalization	B	B
Time domain gating (simple)	B	B
Time domain gating (accurate)	B	A
De-embedding	C	A
In-fixture cal (TRL/LRM etc.)	C	A

A = high B = medium C = low

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This summary table compares the relative simplicity of performing one of the error correction techniques, compared with the resulting accuracy.

Slide #55

Techniques Available in Vector Network Analyzers

Technique	HP 4396	HP 8751	HP 8752, 8753	HP 8753D	HP 8719, 8720/22,	HP 8510
Swap Equal Adapters	X	X	X	X	X	X
Adapter Removal Cal						X
Port Extension	X	X	X	X	X	X
Normalization	X	X	X	X	X	X
Time Domain Gating			X	X	X	X
De-embedding					X	X
TRL/LRM						X
TRL*/LRM*				X	X	X

This table shows which error correction techniques can be used with particular HP network analyzers.

Slide #56

Fixture Calibration Summary (Part 1)

Package Type	Frequency	Fixture	Calibration Method
200 mil Stripline	DC - 12 GHz	HP 11608A	Normalization
70, 100 mil Stripline	DC - 18 GHz	HP 85041A	De-embedding with HP 85014C

This table and the one on the next slide list a variety of fixtures available from HP and some third-party companies, along with a brief description of error correction techniques that may be used with each fixture.

Slide #57

Fixture Calibration Summary (Part 2)

Package Type	Frequency	Fixture	Calibration Method
50, 80, 150 mil, micro-x 100 mil 12.9 mm flange	DC - 18 GHz	MAURY MTF953	SOLT cal in-fixture
SOT-23/30/89/143/223 S-Mini, SS-Mini & others	DC - 6 GHz	ICM TF 2000/ TF 3000	TRL or OSL cal in-fixture
SM4T, SMTO-8/8B, PlanarPak Surface mount	DC - 18 GHz	ICM TFP-XXXX	SOLT cal in-fixture
TO-8, 12, 39 & DIP	DC - 6 GHz	ICM catalog	Normalization or SOLT cal in-fixture
Beam Lead, microstrip,	DC - 50 GHz	ICM catalog	Depends on fixture

Other: ICM provides universal fixtures up to 50 GHz

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Appendix A
User-Defined Calibration Kits

Appendix A Slide #1

Appendix A: User-Defined Calibration Kits

Creating and Defining a Custom Calibration Kit

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Appendix A Slide #2

Cal Kit Definition Process

1. Define characteristics of cal devices.	Determine electrical and mechanical characteristics.
2. Create Standard Definition Table.	Enter values for standards and label corresponding standard number.
3. Create Class Assignments Table.	Assign standard numbers to cal menus and label cal menus.
4. Modify cal kit.	Enter definitions into network analyzer and save data.
5. Calibrate and verify.	Perform cal, measure verification device.

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The process for defining a cal kit consists of 5 main steps. First, select the appropriate devices and determine their electrical and mechanical characteristics. Next, create a standard definition table which labels each standard and contains the values that define each device. Then, create a class assignment table, which determines which cal standards will be used for particular steps in a calibration procedure. Once this is done, enter the data from these two tables into the network analyzer and save the new cal kit definition. Finally, perform a calibration and verify that the calibration was good by measuring a device with known characteristics. Let's review these steps in more detail.

Appendix A Slide #3

Selecting and Defining Cal Devices

- Devices needed depends on type of cal
  - Most common is SOLT: uses short, open, load, thru
  - Other examples
  - TRL: uses thru, reflect, line
  - Waveguide: uses short, offset short, load, thru
- Need to measure characteristics for standard definitions
  - See references for details

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The first step is to select and define the cal standards or devices. Which standards are necessary depends on the type of calibration you want to perform. At RF frequencies, the most common calibration uses a short, an open, a load (Zo termination), and a thru. This is often referred to as SOLT, OSLT, or some other combination of these letters. At higher frequencies, TRL cal is often used. This type of cal requires a thru, a reflection standard (open or short), and a nonzero-length transmission line as its calibration standards. For waveguide calibrations, typical standards are a short, offset short, load, and thru.

The characteristics for each device need to be measured either mechanically or electrically. An explanation of how to do this is beyond the scope of this seminar. For more information, refer to the references at the end of this section.

Appendix A Slide #4

Standard Definition Table

Example: HP 85032B 50 ohm Type-N Calibration Kit

STANDARD DEFINITIONS

STANDARD		C0 $\times 10^{-15}$F	C1 $\times 10^{-27}$F/Hz	C2 $\times 10^{-36}$F/Hz	C3 $\times 10^{-45}$F/Hz	FIXED OR SLIDING	OFFSET			FREQUENCY (GHz)		COAX or WAVEGUIDE	STANDARD LABEL
NO.	TYPE						DELAY ps	LOSS MΩ/s	Z_0 Ω	MINIMUM	MAXIMUM		
1	SHORT						0	700	50	0	999	COAX	SHORT (M)
2	OPEN	108	55	130	0		0	700	50	0	999	COAX	OPEN (M)
3	LOAD					FIXED	0	700	50	0	999	COAX	BROAD-BAND
4	DELAY/THRU						0	700	50	0	999	COAX	THRU
5													
6													
7	SHORT						17.544	700	50	0	999	COAX	SHORT (F)
8	OPEN	62	17	28	0		17.544	700	50	0	999	COAX	OPEN (F)

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The second step in defining a cal kit is to create a standard definition table. This slide shows the table for the HP 85032B 50 ohm type-N calibration kit, used with HP's RF network analyzers. As you can see, there are a number of characteristics that are used to describe the various calibration standards. Also note that each standard is assigned a unique standard number, as well as a standard label. These will be discussed in more detail later.

Appendix A Slide #5

What do you need to define each device?

	Open	Short	Load	Delay/Thru/ Line	Arbitrary Impedance
Capacitance	X				
Inductance		X			
Offset delay	X	X	X	X	X
Offset Zo	X	X	X	X	X
Offset loss	X	X	X	X	X
Min/max frequency	X	X	X	X	X
Coax/waveguide	X	X	X	X	X
Fixed/sliding/ offset			X		
Terminal impedance					X

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Appendix A Slide #6

Descriptions of Characteristics

Offset delay	Models electrical length of standard (relative to calibration plane)
Offset loss	Models loss due to skin effect of offset coax standards
Offset Zo	Characteristic impedance within the offset length
Open circuit capacitance	Coefficients for polynomial which models phase shift caused by fringing capacitance
Short circuit inductance	Coefficients for polynomial which models phase shift caused by residual inductance (HP 8510 only)
Coax or Waveguide	Selects dispersion model for calculating offset delay

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This table shows which of the standard characteristics is needed to define each type of calibration device. You can compare this with the standard definition table in the previous slide to see that each device in the HP 85032B cal kit does indeed have the appropriate characteristics defined. An exception is the inductance for the short. The HP 8510 network analyzers are the only ones that explicitly allow the user to enter values for inductance into the cal kit definition.

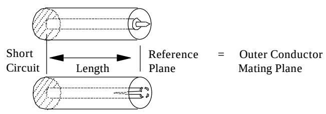
Here are some brief descriptions of the various standard definition characteristics. The open circuit capacitance coefficients are listed in the standard definition table as C0, C1, C2, and C3. Similarly, the short circuit inductance coefficients are listed in the table as L0, L1, L2, and L3.

Appendix A Slide #7

Offset Delay

Models electrical length of standard (relative to calibration plane)

$$\text{Delay (seconds)} = \frac{\sqrt{\epsilon_r}\ \text{x Length (m)}}{\text{Speed of light (m/s)}} = \frac{L\sqrt{\epsilon_r}}{c}$$



ϵ_r = relative permittivity constant of dielectric
For 2-port standard, L = length between the input and output reference planes

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Appendix A Slide #8

Offset Loss

Models loss due to skin effect of offset coax standards

$$\text{Offset Loss } \left(\frac{G\,\Omega}{S}\right)\Bigg|_{1\text{ GHz}} = \frac{c\sqrt{\epsilon_r}\ Z_o}{\text{Length}} \ \text{x}\ \frac{\text{Loss (dB)}}{10\log(e)}$$

$$= \frac{Z_o}{\text{Offset delay}}\ \text{x}\ \frac{\text{Loss (dB)}}{10\log(e)}$$

Where: loss (dB) = loss of line at 1 GHz
Z_o = characteristic impedance of offset line = offset Z_o
e = 2.71828
c = speed of light

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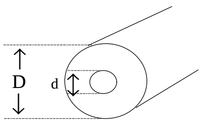
Appendix A Slide #9

Offset Z_o

Characteristic impedance within offset length



$$Z_o = \frac{1}{2\lambda}\sqrt{\frac{\mu}{\epsilon}}\; ln\left(\frac{D}{d}\right)$$

$$= 59.9585\sqrt{\frac{\mu_r}{\epsilon_r}}\; ln\left(\frac{D}{d}\right)$$

Where: D = outer conductor diameter
d = inner conductor diameter

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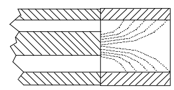
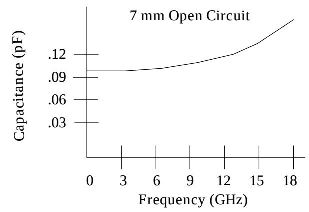
Appendix A Slide #10

Open Circuit Capacitance

Models phase shift caused by fringing capacitance





$$C_{eff}(F) = C_o \times 10^{-15} + (C_1 \times 10^{-27})f + (C_2 \times 10^{-36})f^2 + (C_3 \times 10^{-45})f^3$$

Where: C_o, C_1, C_2, C_3 are capacitance coefficients
f = frequency (Hz)

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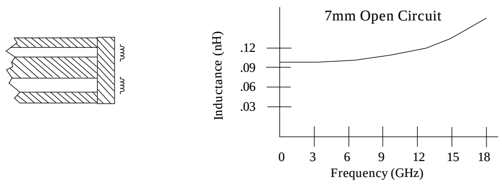
Appendix A Slide #11

Short Circuit Inductance

Models phase shift caused by residual inductance

(Used by HP 8510 only)



$L_{eff}(H) = L_o \times 10^{-12} + (L_1 \times 10^{-24})f + (L_2 \times 10^{-33})f^2 + (L_3 \times 10^{-42})f^3$

Where: L_o, L_1, L_2, L_3 are inductance coefficients
f = frequency (Hz)

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Modeling Short Inductance Using Offset Delay

- Method can be used for network analyzers other than HP 8510 (e.g. HP 8720)
- Effect of short inductance is modeled as part of the offset delay:

$$\text{Offset delay (s)} = \frac{Lo}{Zo}$$

Lo = first inductance coefficient (in henries)
Zo = characteristic impedance of the line that is shorted

- Approximation is accurate within 3% if $Lo \leq \frac{Zo}{20 \times \text{freq (Hz)}}$

Example: At 20 GHz, approximation is good for Lo ≤ 0.1 nH and Zo ≥ 40 ohms.

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Appendix A Slide #12

Appendix A Slide #13

Minimum/Maximum Frequency

- Sets standard's usable frequency range
  (Example: sliding load has 2 GHz minimum frequency)
- Separates multiple standards in one class
  (Example: series of lines for TRL cal)
- Always use small frequency overlap with multiple standards
  (Example: fixed load 0 to 2.0 GHz, sliding load minimum frequency set to 1.999 GHz)
- For waveguide, minimum frequency=cutoff frequency

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Appendix A Slide #14

Coaxial or Waveguide

Selects Dispersion Model For Offset Delay

Coaxial dispersion
Delay = Linear delay + skin effect inductance

Waveguide dispersion

$$\text{Delay} = \frac{\text{Linear delay}}{\sqrt{1 - \left(\frac{fco}{f}\right)^2}}$$

where fco = cutoff frequency

Note: Always enter linear delay as offset delay

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Appendix A Slide #15

Standard Label

- Identifies device (e.g. SHORT, OPEN, THRU)
- Maximum 10 characters in label
- Appears in CAL menus only when multiple standards are available
  - Example: OPEN(M) and OPEN(F) for type-N cal kit
  - Example: LOWBAND, BROADBAND, SLIDING for choice of loads
- **Labels for male (M) or female (F) connectors refer to sex of the test port, not the cal standard**

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Once a calibration standard has been defined, it needs to be given a STANDARD LABEL. This label is used to identify the standard during a calibration. It is used in the calibration submenus whenever there is more than one standard that can be used for that step in the calibration. For example, selecting LOAD as the standard to be measured might bring up a menu with the choices of LOWBAND, BROADBAND, or SLIDING loads for the user to measure. These three names are the standard labels for the 3 loads in the cal kit.

In some cases, the cal kit definition for a male device may differ from that of a female device, so the standard labels may say something like OPEN(M) and OPEN(F) to distinguish the two. It is a convention in HP network analyzers that the labels for male (M) and female (F) actually refer to the sex of the test port, NOT the cal standard.

Appendix A Slide #16

Class Assignments

Calibration Type	No. of Classes	Errors Corrected
Response	1	1
Response & Isolation	2	2
1-port	3	3
One path two-port	6	6
Full 2-port	12	12
TRL	4	12

- Class assignments associate standard numbers with particular calibration steps
- Number of classes equals number of standards needed for particular cal

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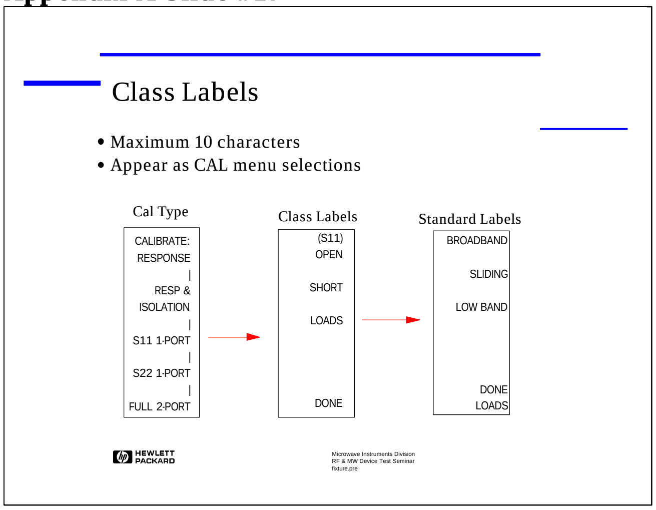
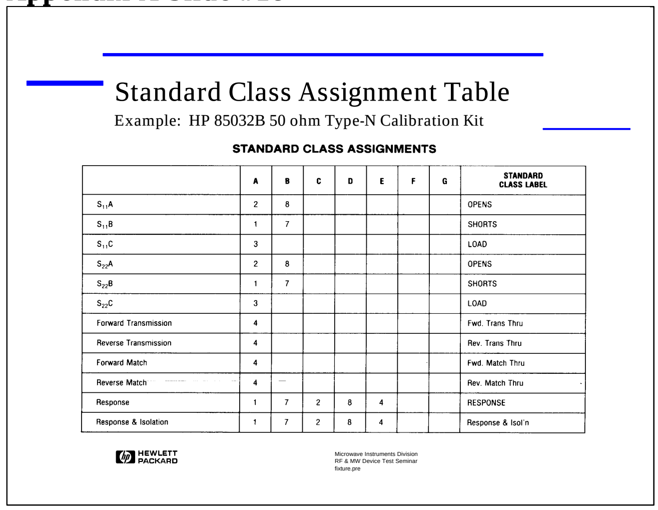
The third step in defining a cal kit is to create the class assignment table. Class assignments are a way of grouping together all of the standards that can be used in a particular step during the calibration process. The number of classes that are required for a particular calibration is equal to the number of standards that need to be measured for that cal.

Appendix A Slide #17



Each class is assigned a label which can have a maximum of 10 characters. The class label appears in the cal menus as the name of the group of devices that need to be measured. For example, for a one-port cal, three classes of cal standards need to be measured. These are displayed when the user selects a one-port cal. They are the open, short, and loads. Selecting [LOADS] brings up the next menu which displays the standard labels for the three devices which may be used as the load standard.

Appendix A Slide #18



Standard Class Assignment Table

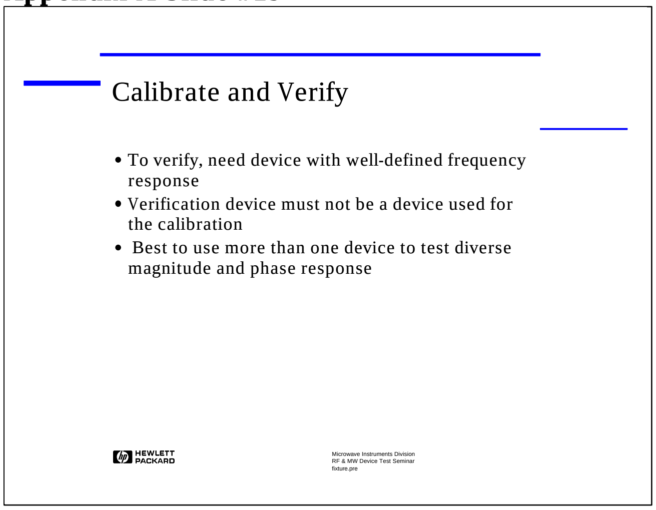
Example: HP 85032B 50 ohm Type-N Calibration Kit

STANDARD CLASS ASSIGNMENTS

	A	B	C	D	E	F	G	STANDARD CLASS LABEL
$S_{11}A$	2	8						OPENS
$S_{11}B$	1	7						SHORTS
$S_{11}C$	3							LOAD
$S_{22}A$	2	8						OPENS
$S_{22}B$	1	7						SHORTS
$S_{22}C$	3							LOAD
Forward Transmission	4							Fwd. Trans Thru
Reverse Transmission	4							Rev. Trans Thru
Forward Match	4							Fwd. Match Thru
Reverse Match	4							Rev. Match Thru
Response	1	7	2	8	4			RESPONSE
Response & Isolation	1	7	2	8	4			Response & Isol'n

This is the class assignment table for the HP 85032B cal kit. The class labels in the far right column identify the name of the class (as shown in the calibration menus), while the description in the far left column provides information on which calibration step is being described. For example, the top 3 rows are labeled as S11A, S11B, and S11C. These three classes are used during S11 one-port cals and full two-port cals. The first row shows that either standard 2 or 8 can be measured for the OPENS class. Referring back to the Standard Definition Table, we see that standard 2 is the OPEN(M) and standard 8 is the OPEN(F). Similarly, the second row shows that either standard 1, the SHORT(M), or standard 7, the SHORT(F), can be selected for the SHORTS class. Finally, the third row shows that only standard 3 is available as a cal device for the LOAD class

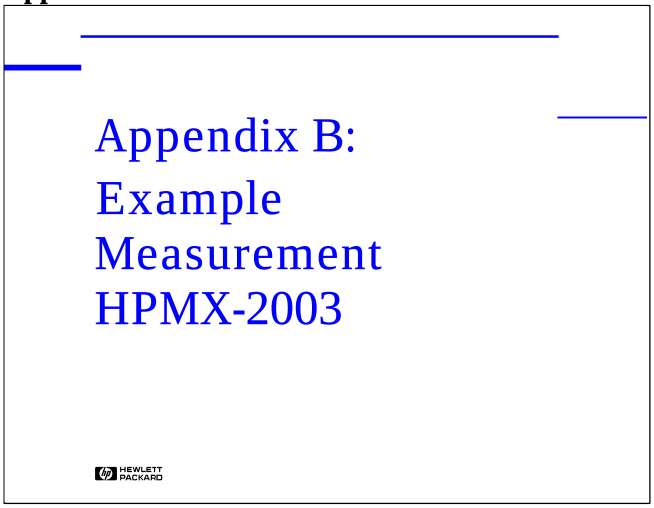
Appendix A Slide #19



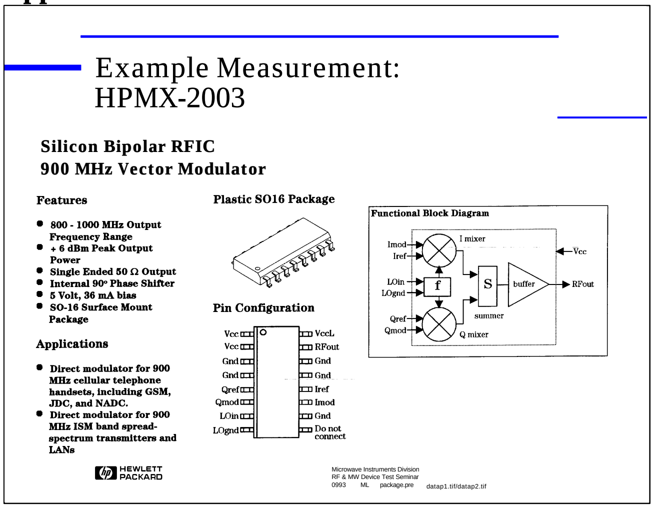
The next step is to use the [MODIFY CAL KIT] menus to enter the standard definitions and class assignments into the network analyzer, and save the newly defined cal kit. Finally, the cal kit definitions need to be verified. To do this, perform a calibration with the new cal kit. Then, measure one or more devices that have already been measured and characterized on a known system, and check how closely the measurements agree with the known data for that device.

Appendix B
Example Measurement HPMX-2003

Appendix B Slide #1



Appendix B Slide #2

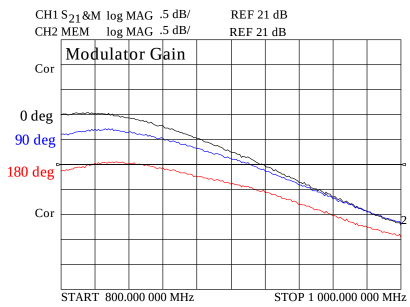


Some example results of measurements on an HPMX-2003 Vector Modulator are shown in the following slides. These measurements were made after calibrating out the effects of the RFIC fixture.

Data is typically taken at several different DC voltage settings for the I and Q inputs, corresponding to different phase differences in these inputs.

Appendix B Slide #3

Example Measurement: Modulator Gain



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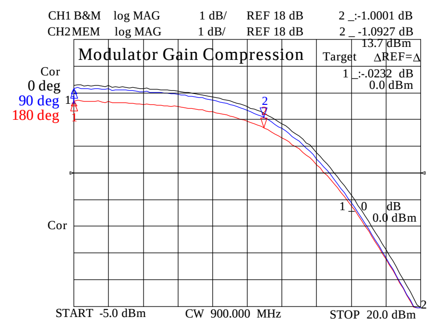
Appendix B Slide #4

Example Measurement: Modulator Gain Compression



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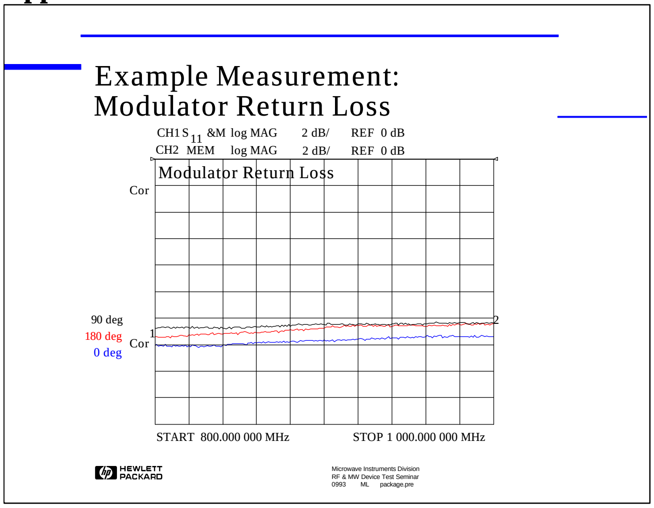
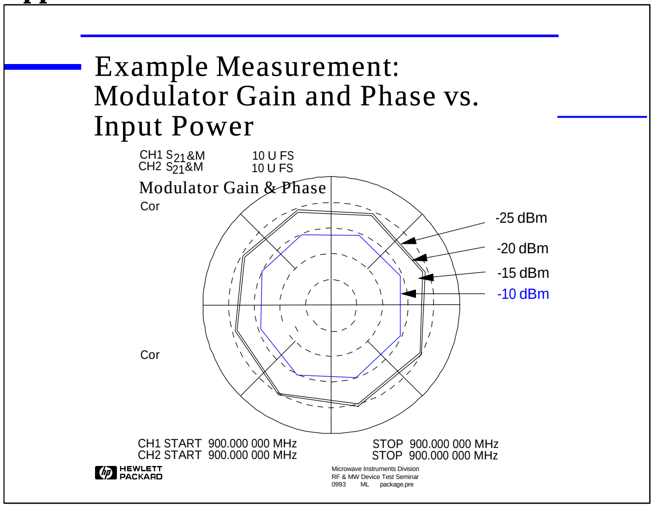
Appendix B Slide #5



Appendix B Slide #6



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