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LCR / Impedance Measurement Basics

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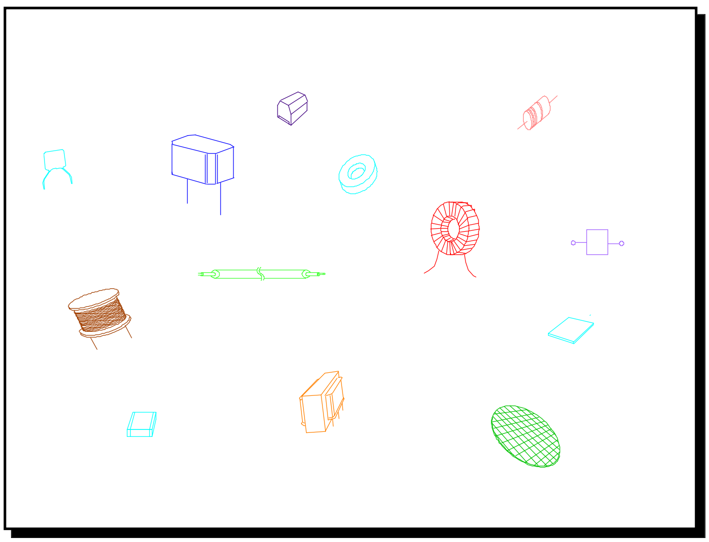

1997 Back to Basics Seminar

Abstract

Today's circuit designers and component manufacturers need to make more demanding measurements on SMD (surface-mount devices) and other components. At the same time the components are becoming harder to measure accurately.

This module will review impedance, component value definitions, and present typical measurement problems and their solutions. Error correction and compensation techniques will be discussed. Finally, products and techniques for specific applications will be suggested.

Author

Greg Amorese joined Hewlett-Packard in 1979 as a Marketing Engineer at the Loveland Instrument Division in Colorado. He transferred to the Kobe Instrument Division (KID) in 1988 to work as their Product Line Manager at Hewlett-Packard's European Marketing Operation. He now works in Santa Rosa, California as the U.S. Sales Manager for KID.

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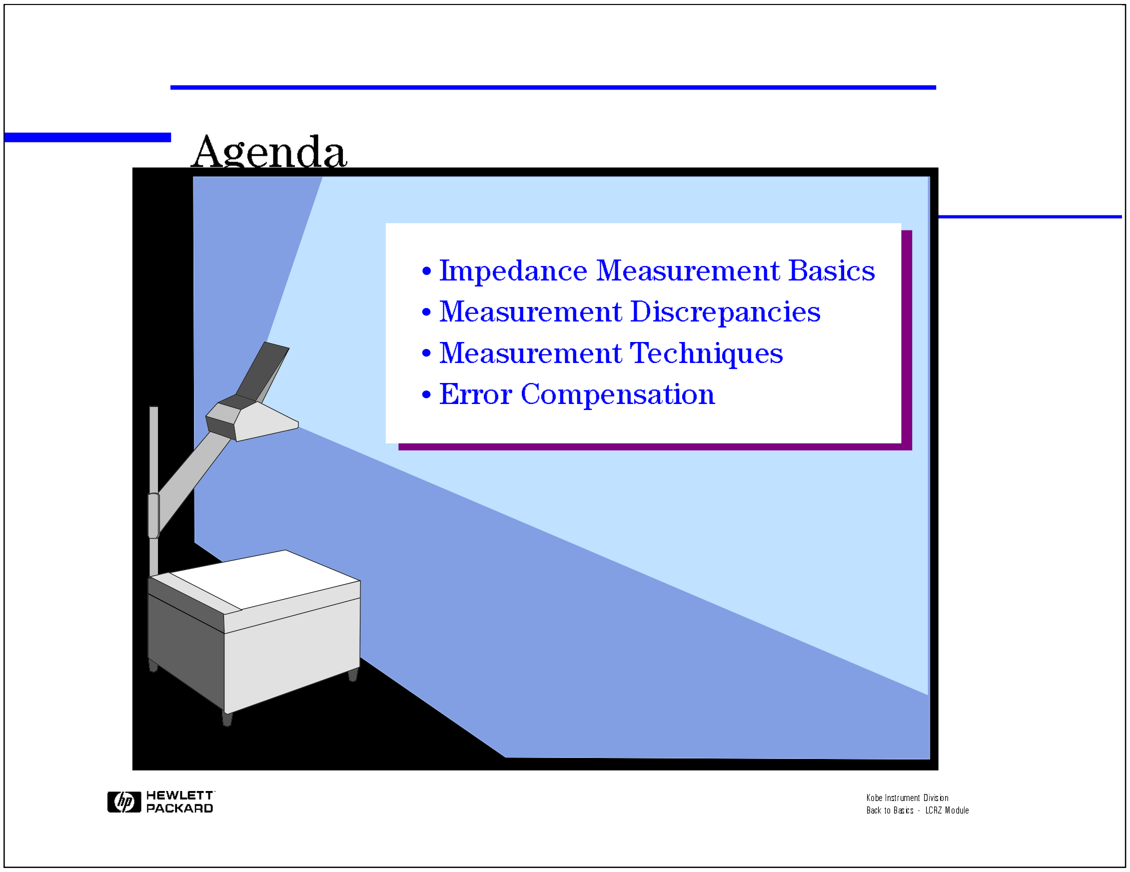


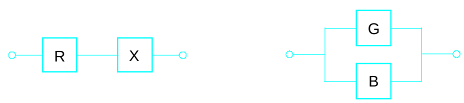
We will start with basics and review the reasons why discrepancies occur in measurements. We will also discuss the different measurement techniques available and cover their advantages and disadvantages. The next topic discusses the sources of errors and methods of reducing them, which we call compensation techniques.

Slide #2

Impedance Measurement Basics

Impedance Definition

- Impedance is the total opposition a device or circuit offers to the flow of a periodic current
- AC test signal (amplitude and frequency)
- Includes real and imaginary elements



$Z = R + jX$ $\quad$ $Y = G + jB$

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This is the definition of impedance. PERIODIC, in this case means an AC test signal as opposed to a static or DC test signal. So, amplitude and frequency should be considered. TOTAL includes both real and imaginary components. This obviously applies to simple components as well as to complex DUT, cables, amplifiers, etc. By definition, impedance is for the series model: Z=R+jX, where the real part R is the resistance and the imaginary part X the reactance. Similarly, admittance is for the parallel model: Y=G+jB, where G is the conductance and B the susceptance.

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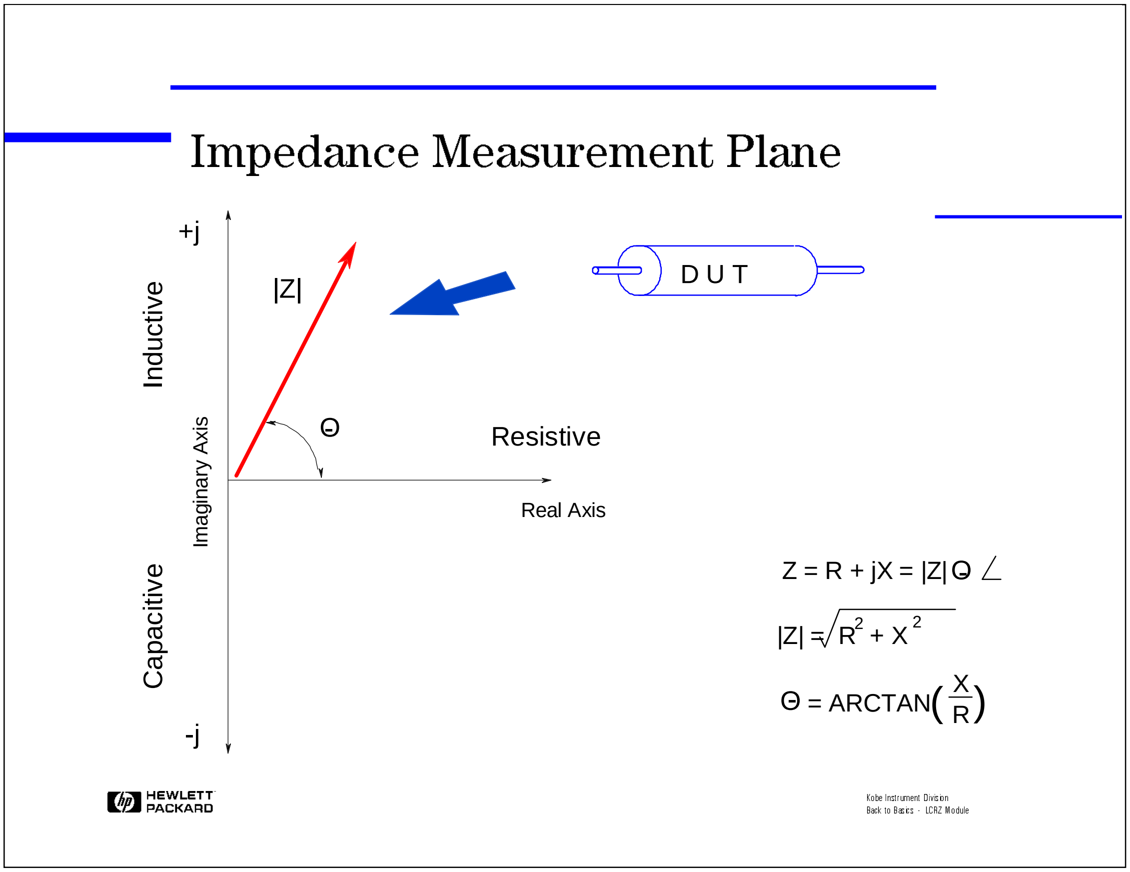

The impedance measurement plane can be visualized with the real element, or resistance, on the x-axis and the imaginary element, or reactance, on the y-axis. Ideal components would lie on an axis. Capacitors are typically found in the lower quadrant, while inductors are in the upper quadrant. The more ideal an inductor or a capacitor, the less resistive it will be, therefore the angle will be close to +90 degrees or -90 degrees.

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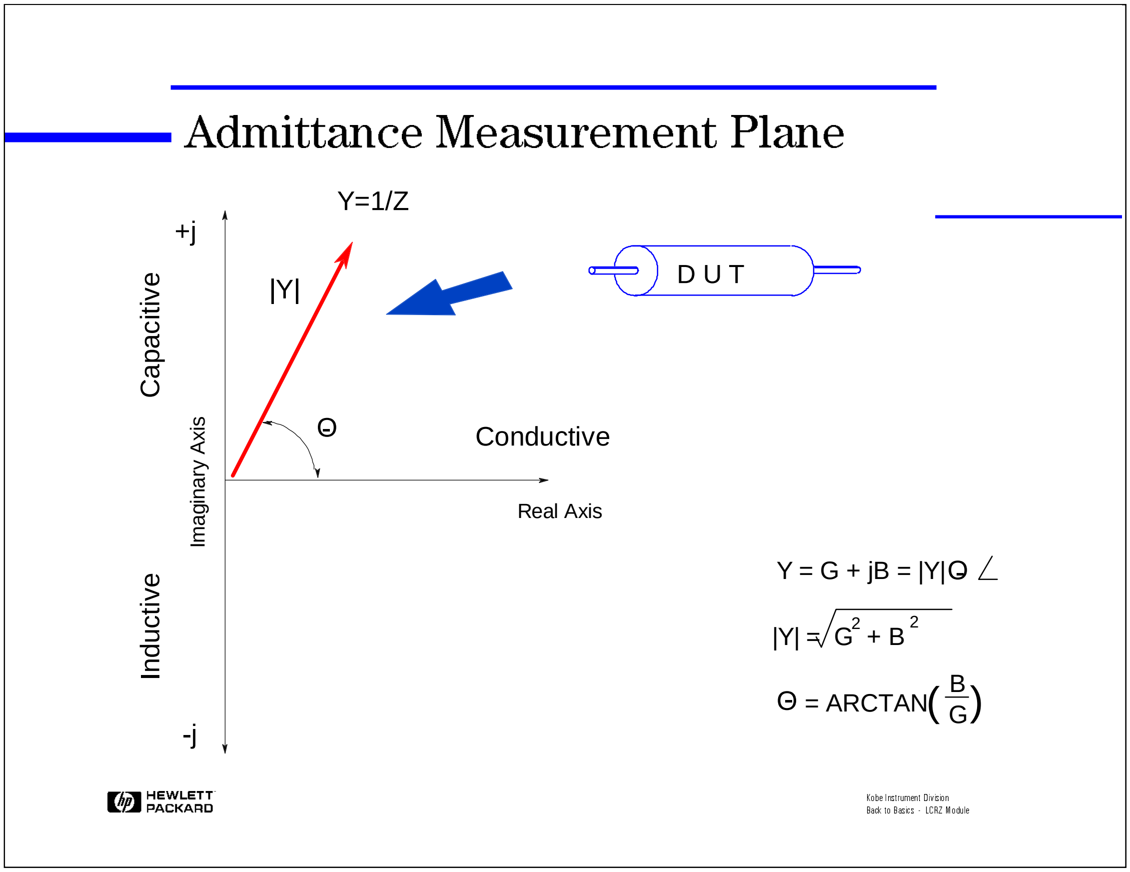

The admittance measurement plane can be visualized with the real element, or conductance, on the x-axis and the imaginary element, or susceptance, on the y-axis..

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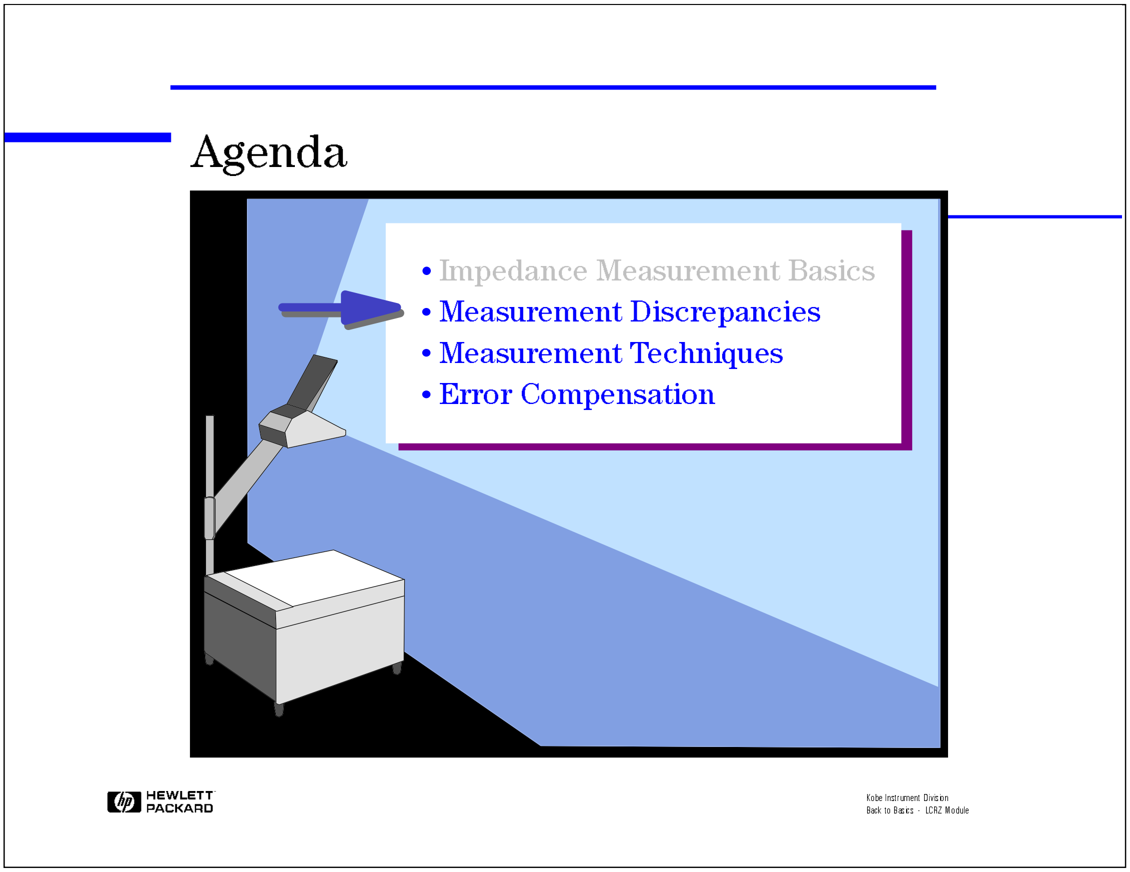
Agenda
• Impedance Measurement Basics
• Measurement Discrepancies
• Measurement Techniques
• Error Compensation
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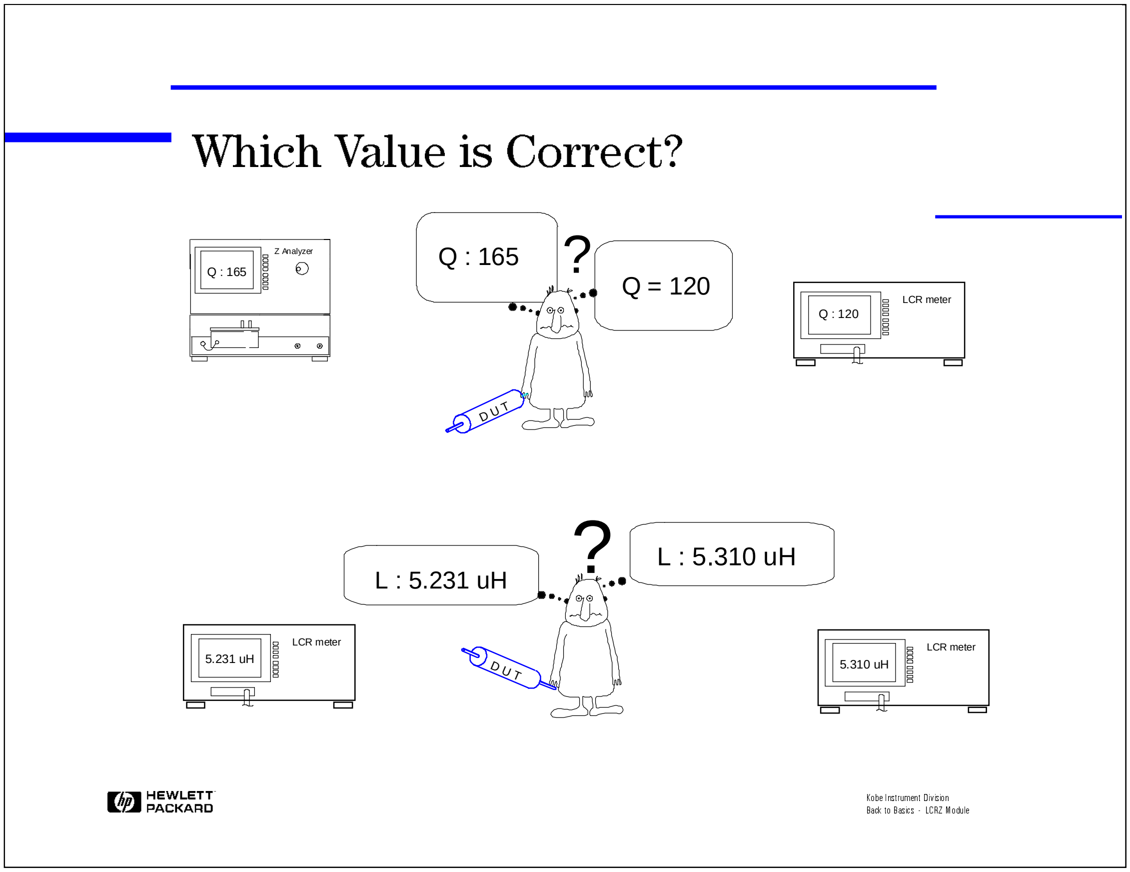

Accurate impedance measurements are dependent upon many factors. All of us have experienced the situation where measurement results didn't match our expectations or didn't correlate. We will now review all the reasons that make these discrepancies and see what to do to avoid them or at least minimize them.

But have you ever experienced one of these two situations? Measuring the same DUT with two different instruments and getting completely different results OR EVEN measuring the same DUT, with the same instrument, within the same week ... and getting two different results?

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Measurement Discrepancy Reasons

- Component Dependency Factors
  - Test signal frequency
  - Test signal level
  - DC bias, voltage and current
  - Environment (temperature, humidity, etc.)
- True, Effective, and Indicated Values
- Measurement Errors
- Circuit Mode (Translation Equations)

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Measurement discrepancies sources are various. The testing conditions or component dependency factors affect the component behavior and the measured values. But which value do instruments measure? It is important to realize that the value we measure is not necessarily the one we want. On top of that, due to the instrument technique and the accessories we use, we introduce additional errors or measurement errors. Finally the choice of a given model necessarily implies errors. Let's review the component dependency factors to begin with.

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Measurement Discrepancy Reasons

Component Dependency Factors

- Test signal frequency
- Test signal level
- DC bias, voltage and current
- Environment (temperature, humidity, etc.)

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This is by no means an exhaustive list of dependency factors. But these factors naturally represent the testing conditions of a given component. In other words, the settings of the test instrument and accessories, as well as the environmental conditions, are the major sources of dependency factors. An obvious question is "WHY?". Why do these parameters affect the component behavior?

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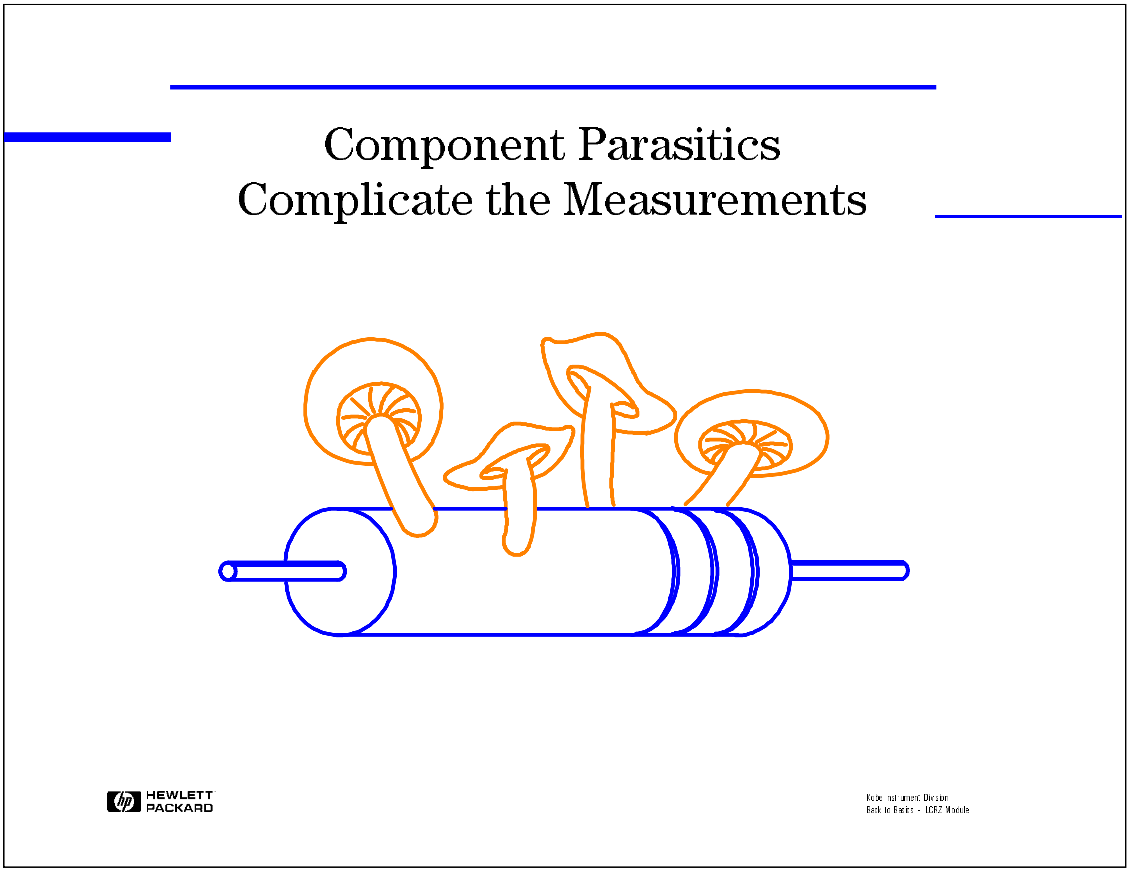

Well, the answer is simple: because all components have parasitics. The quality of component material and design determines the parasitics. Basically there is no perfect component in nature like purely resistive or reactive devices. They all have parasitics and therefore their behavior depends upon them. For instance, all components have frequency limitations.

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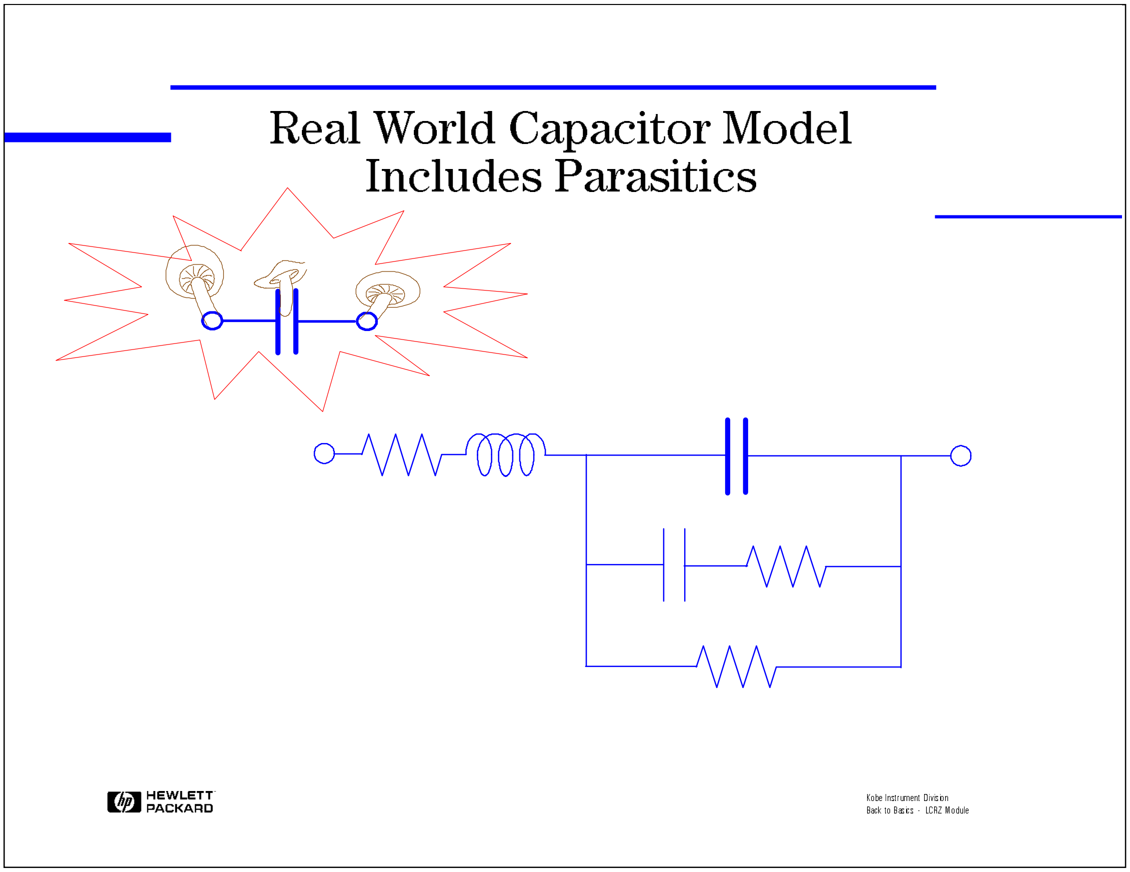

Let's examine a real world capacitor. The design and the quality of its material introduces parasitics. There are unwanted series wire inductance and resistance and unwanted resistance and capacitance across the dielectric. For example, this is a realistic capacitor model taking into account the parasitics. Can we quantify these parasitics? Certainly. The quality factor Q represents the component's non-ideal characteristics. The higher the Q, the better or more ideal the component.

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Quality and Dissipation Factors

- Different from the Q associated with resonators and filters
- $Q = \dfrac{\text{Energy stored}}{\text{Energy lost}} = \dfrac{X_s}{R_s}$
- The better the component, then

  $R \Rightarrow 0 \qquad Q \Rightarrow \infty$
- $D = \dfrac{1}{Q}$, mainly used for capacitors

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The quality factor Q for components differs from the Q associated to filters or resonators. For components, the quality factor serves as a measure of the reactance (or susceptance) purity. In the real world, there is always some associated resistance that dissipate power (lost power), decreasing the amount of energy that can be recovered. Note that Q is dimensionless and that it also represents the tangent of the impedance (or admittance) vector angle theta in the measurement plane. Q is generally used for inductors and D for capacitors.

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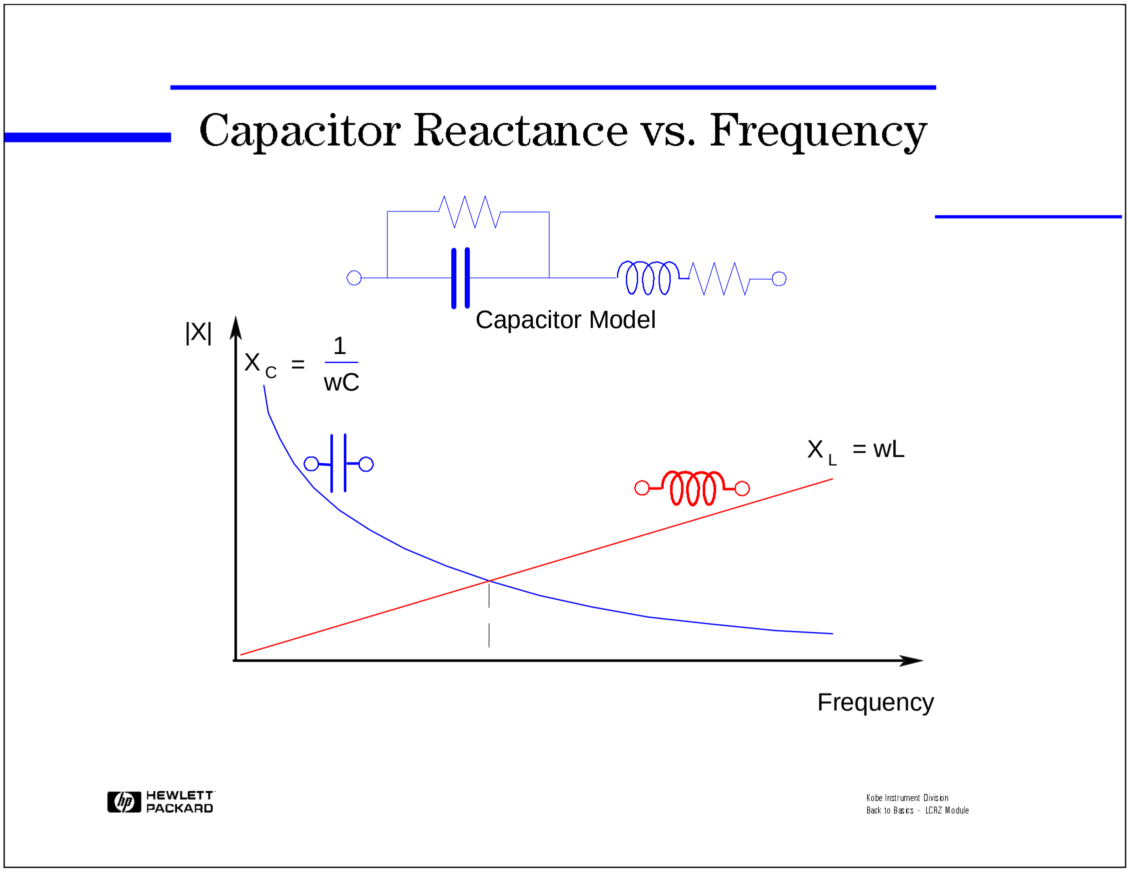
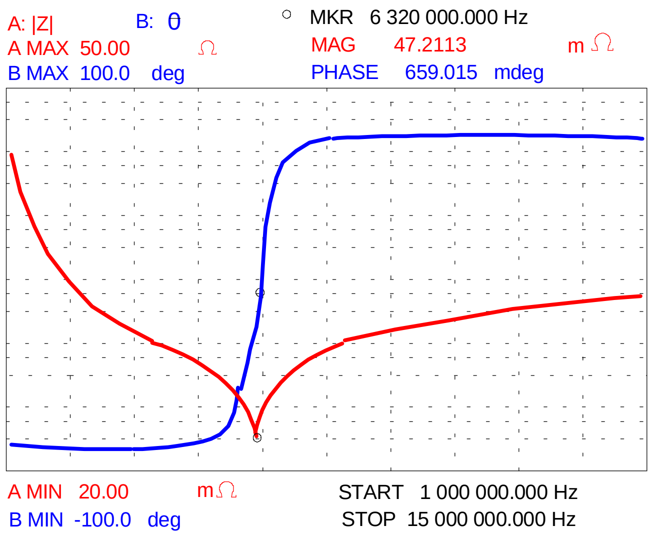


Frequency is the most significant dependency factor. The reactance of an ideal capacitor would vary like the Xc curve. We can oversimplify this real world capacitor model by neglecting the resistors and essentially take into account the series lead reactance Xl.

As a consequence, this capacitor looks like a capacitor in the lower frequency region. The point where the capacitive and inductive reactance are equal is the resonant frequency and the component behaves like a resistor. At higher frequencies, this capacitor behaves like an inductor!

Slide #13

Example Capacitor Resonance Impedance vs. Frequency



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This display shows Z and theta of a capacitor between 1 MHz and 15 MHz. Before resonance, the phase is around -90 degrees and the component effectively looks like a capacitor. The impedance decreases with the frequency until the resonance point, due to the inductive elements of the component. Note that at resonance, the phase is 0 degrees - purely resistive. After resonance the phase angle changes to +90 degrees so the inductive elements dominate. Remember, when you buy a capacitor, you get 3 components!

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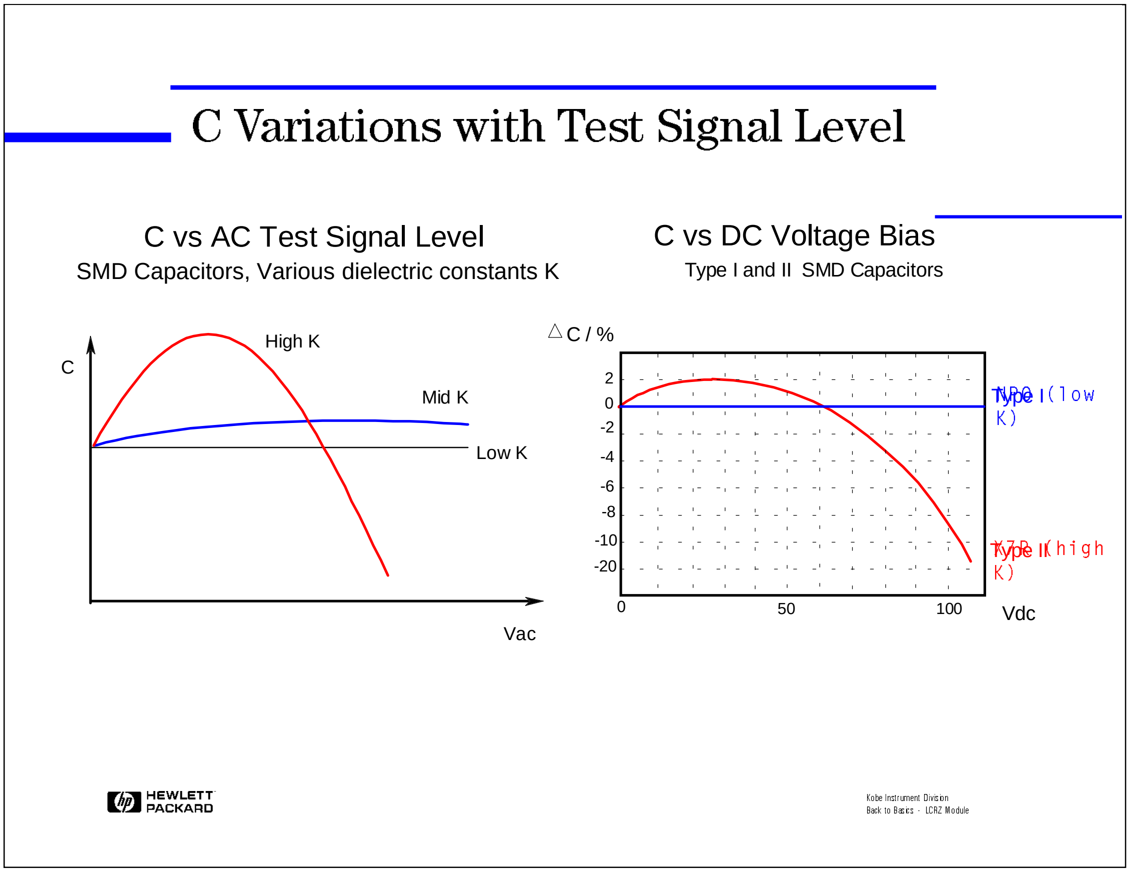

But frequency is not the only factor influencing the behavior of components. For instance, the test signal level is a very important dependency factor for SMD (surface mounted device). SMDs are becoming more and more popular, so let's have a look into a typical chip capacitor performance.

The electrical properties of the dielectric material of ceramic capacitors cause the capacitance to vary with the applied AC test signal. Capacitors with high value dielectric constant (K) exhibit an important dependency.

DC biasing can also change a component's value. It's important to take it into account when designing circuits. For choosing an SMD, DC bias voltage is a crucial parameter to insure the right performance. Type II SMD capacitors are more and more popular because of their high dielectric constant material, like X7R, Y5V or Z5U, which allows larger capacitance per unit volume. But their capacitance varies more with DC biasing than for Type I SMD capacitors.

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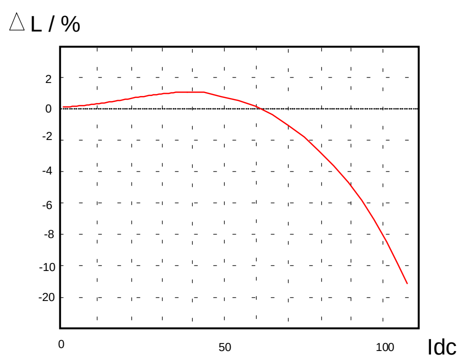
Measurement Discrepancy Reasons

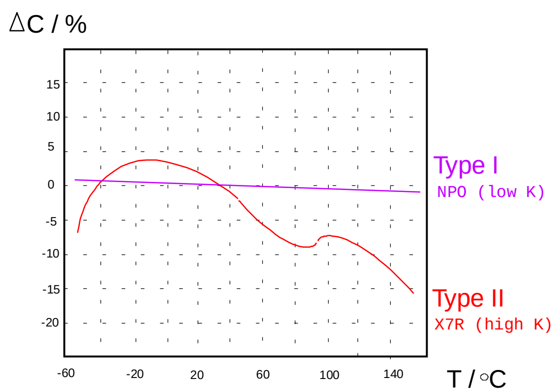
L vs DC Current Bias

Power Inductors



C vs Temperature

Type I and II SMD Capacitors



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Switching power supplies are very common today. They use power inductors for filtering the RFI and the noise produced by high currents. To maintain good filtering and ripple at high current levels, power inductors must be tested at operating conditions to ensure that the inductance roll-off does not affect the performance.

Another drawback of Type II SMD capacitors is their behavior as a function of temperature. They are a lot less stable than Type I capacitors. This factor must be taken into account in the design process.

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Measurement Discrepancy Reasons

Component Dependency Factors

- Test signal frequency
- Test signal level
- DC bias, voltage and current
- Component's current state
- Environment (temperature, humidity, etc.)
- Aging

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Although considered as minor order factors, temperature, humidity and other environmental parameters might become key. For example, quartz pressure probes are commonly used in the oil/gas industry to get data from the wells. The electronic PC boards in these probes are submitted to very high pressure and temperature and require very high quality components. We seldom think about a component's current state. Inductors with magnetic cores have memory just like large capacitors. These devices must be handled with care to avoid dramatic memory (energy!) transfer to the front end of an instrument. Electrostatic Discharge (ESD) sensitive devices also belong to this category of components. One last factor is time. Aging is often important in governmental and military applications with stringent requirements.

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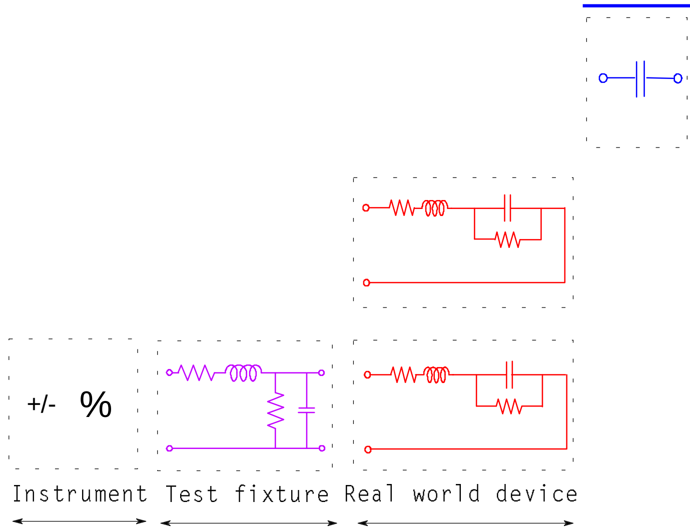
Which Value Do We Measure?

- TRUE
- EFFECTIVE
- INDICATED



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Before proceeding to practical measurements, we need to understand the concept of True, Effective and Indicated values. This is essential since we all tend to forget that the instrument does NOT necessarily measure what we want to measure. By the way, which value do instruments measure?

The TRUE value excludes all parasitics and is given by a math relationship involving the component's physical composition. If you think of a 50 Ohm PC board stripline, it is built up assuming that the dielectric constant K is constant. But in the real world this is not true. The TRUE value has only academic interest.

The EFFECTIVE value is what we generally want to measure because it takes into consideration the parasitics and dependency factors, as this figure shows. When designing and simulating circuits, only EFFECTIVE values should be used to reflect the actual circuit behavior. But the INDICATED value given by the instrument takes into account not only the real world device, but also the test fixture and accessories as well as the instrument inaccuracies and losses. What is the difference between TRUE and EFFECTIVE values? The quality of the component. And what is the difference between EFFECTIVE and INDICATED values? The quality of the instrument and above all the quality of the MEASUREMENT. Our goal is to make the INDICATED value as close as possible to the EFFECTIVE value.

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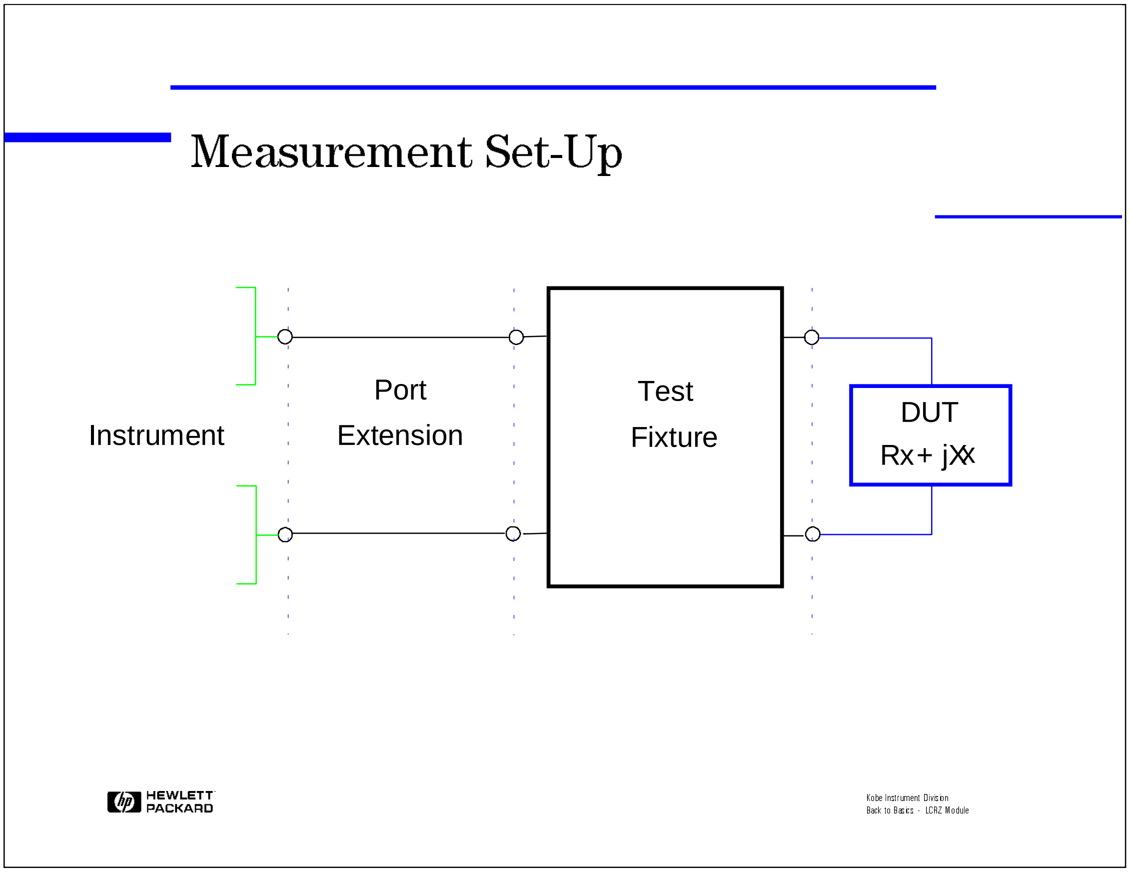

At this stage we must still remember that the INDICATED value is a nominal value with some tolerance or measurement error. We will come back to this in the next section covering measurement techniques. We are now ready to look at the measurement errors that make the INDICATED value so different from the EFFECTIVE value

This is our typical measurement configuration. The test fixture acts as an interface between the instrument ports and the Device Under Test (DUT) and accommodates for the device geometry. The port extension is sometimes needed to extend the instrument terminals to connect to the DUT(s). Two good examples are when performing environmental chamber tests or when testing multiple DUTs through a switching matrix.

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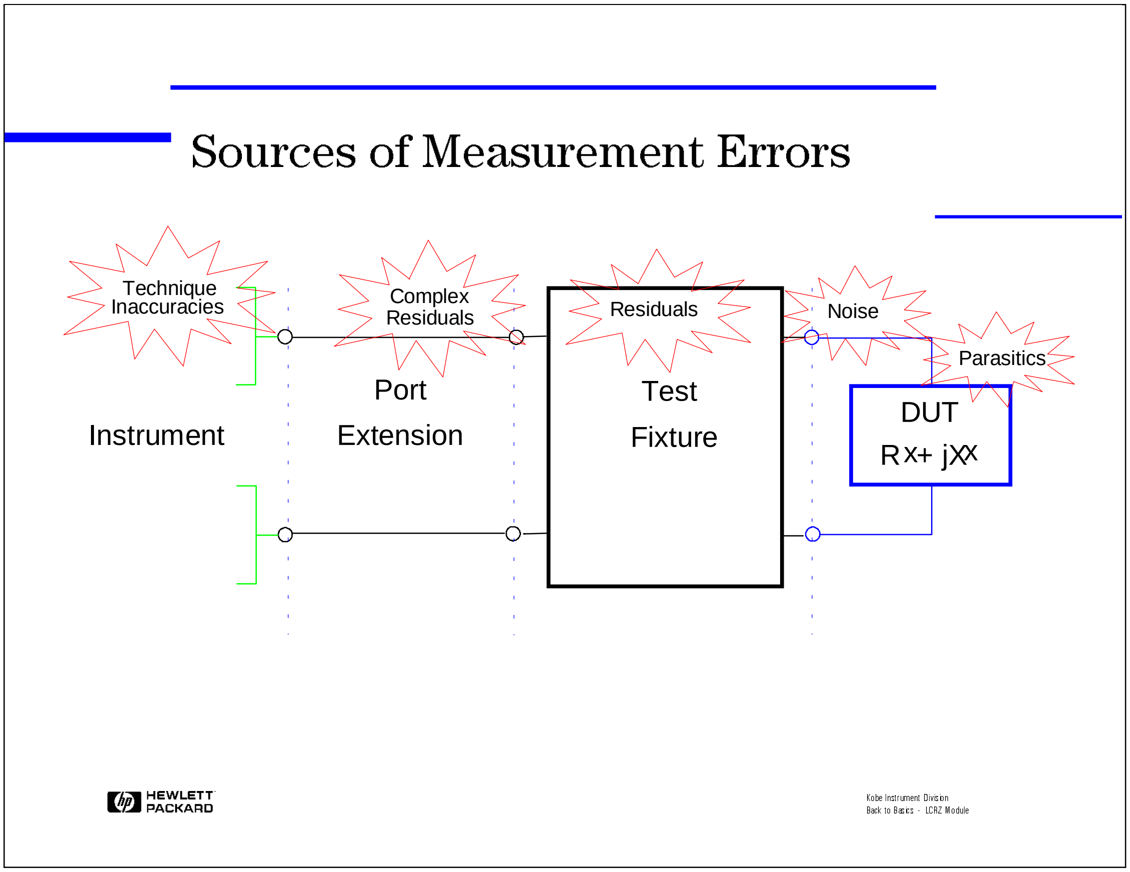
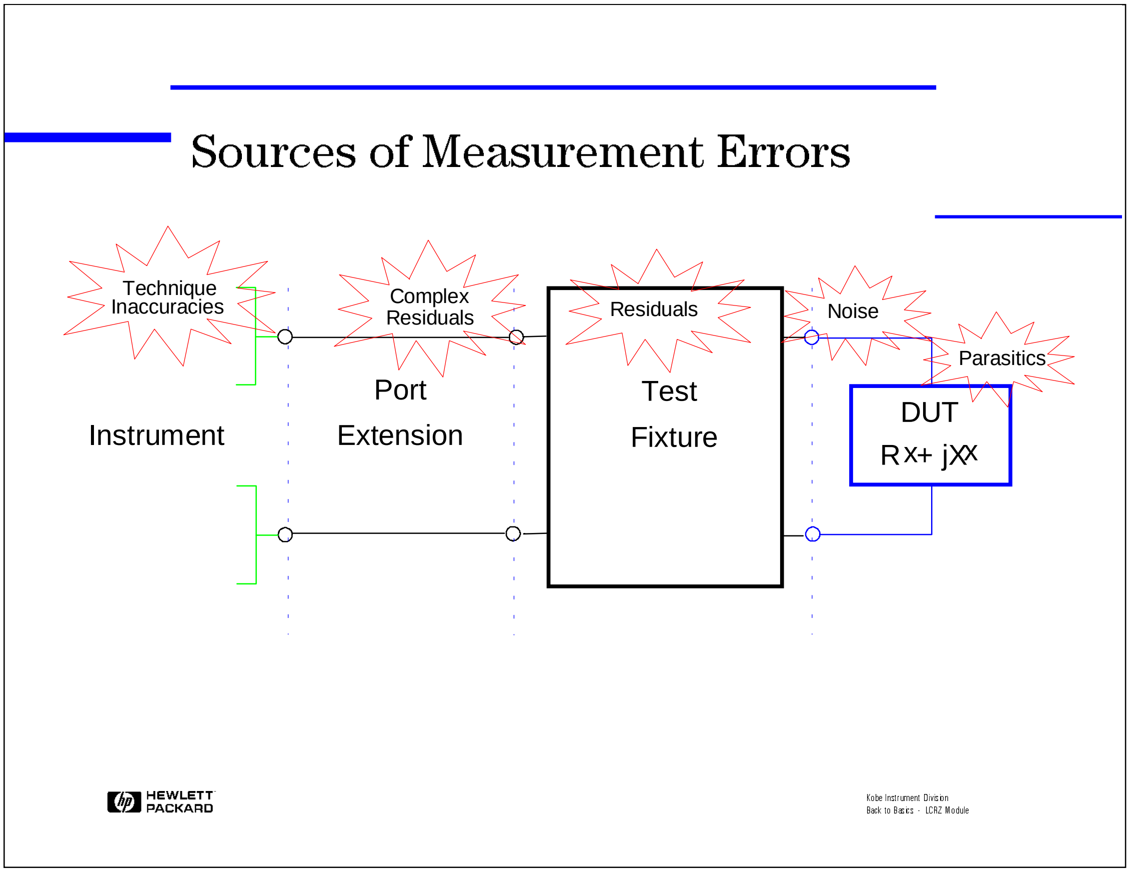


These are the major sources of measurement errors.

Slide #20



TECHNIQUE INACCURACIES reflect the errors of an instrument technique. They can be "removed" by CALIBRATION and this is done when the instrument is manufactured or serviced. CALIBRATION defines a CALIBRATION PLANE at the instrument ports. This is where the specifications of the instrument usually apply.

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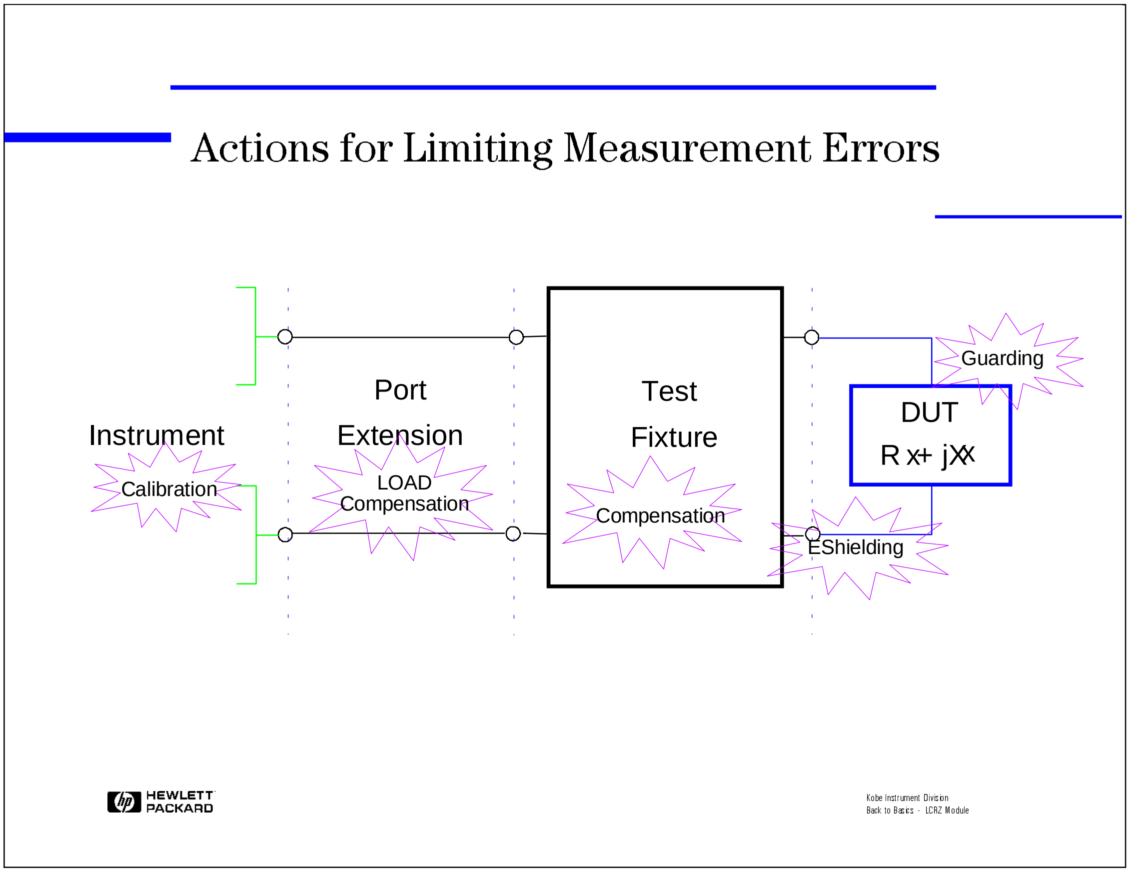

Test fixture RESIDUALS are minimized by proper design, but always exist. They are also measured together with the DUT and therefore must be "removed" by COMPENSATION . Port extension generally adds complex errors because of its non-negligible electrical length and its complex electrical path (i.e. switches). LOAD compensation or electrical delay minimizes these errors. The exposed leads of leaded components catch interference and NOISE. SHIELDING minimizes the amount of interference induced in the measurement circuits. Guarding helps minimizing parasitics and ground loops or common mode currents in the case of floating measurements. Calibration, compensation, correct shielding, and guarding ensure good quality measurements, in other words, an indicated value that is very close to the DUT effective value.

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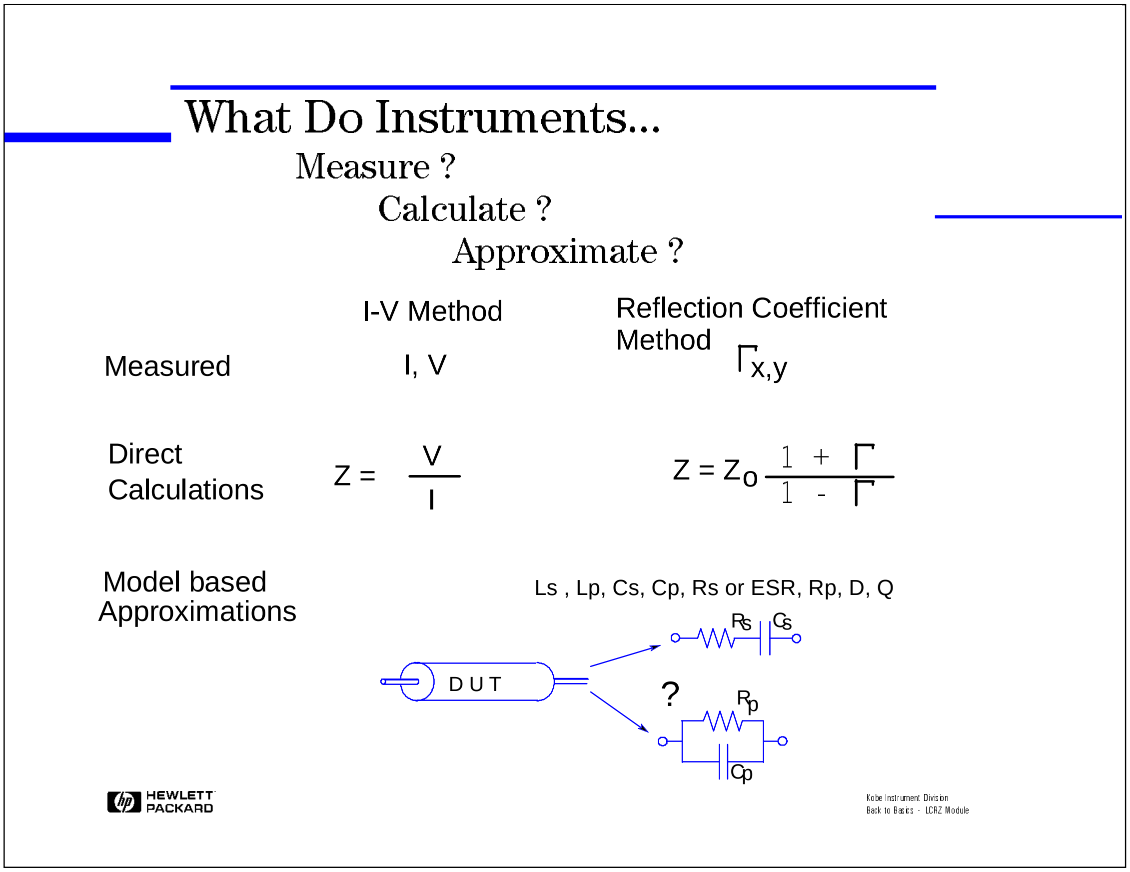


Since all real world components have parasitics, we must lump all the resistive and reactive elements of the component together into an equivalent set of series or parallel elements. These 2 circuit modes allow the instrument to interpret the measurement data and translate it into indicated value according to the user's information (model choice).

Impedance cannot be directly measured like voltage, for instance. The fundamental parameter measured by the instrument depends upon the instrument technique. Then the internal processor makes a direct calculation to compute Z, Y. But usually users ask for parameters like L, C, R, D or Q, which can be derived from simple two element models (series and parallel ones). These are approximate models used to describe the component's behavior. Let's see how these approximations have been made.

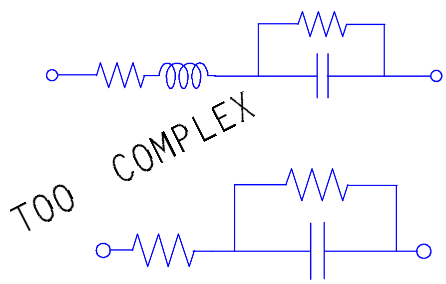
Slide #23

Circuit Mode

Requires Simplified Models

Complete Capacitor Model
Rs,Ls,Rp,Cp ?

No L Capacitor Model



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This complete capacitor model represents the effective value of this capacitor. Obviously, the model depends on the capacitor technology and is tuned through experiments and circuit simulation. It is possible to measure the global Z, theta, R, or X of the real capacitor, but it is too complex to implement in an instrument. The instrument would need very sophisticated simulation capabilities, and be able to optimize the model and calculate the values of its elements. Therefore, all instruments have built-in two-element models : i.e. Rs, Cs, or series model, and Rp, Cp, or parallel model, for capacitors.

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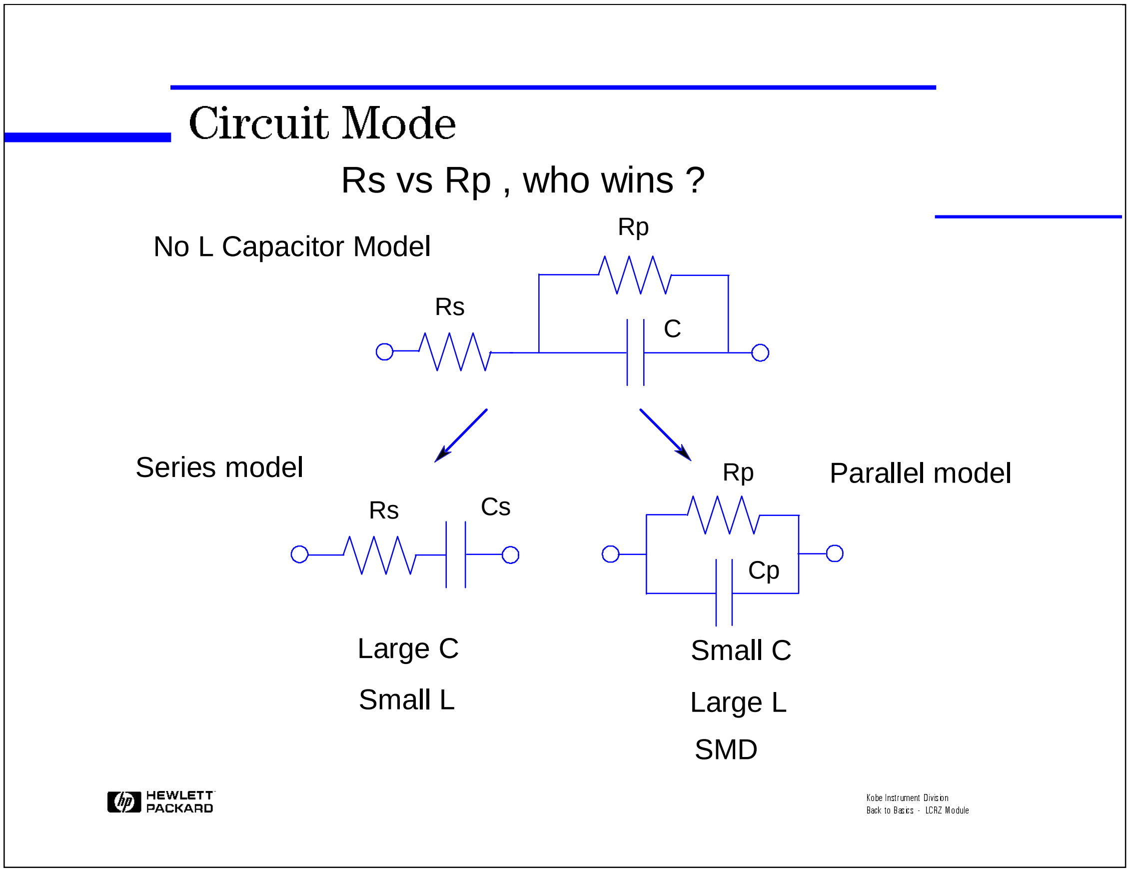


Let us see how to simplify the model and come up with the best approximation. Let's assume that the lead inductance is negligible. Then this new model consists of a perfect capacitor and a series resistor, Rs, as well as a parallel one, Rp. Usually Rs is in the ohms or milli-ohms while Rp is in the mega-ohms or greater.

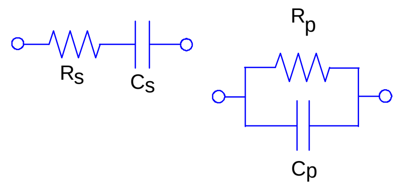
For large C or low impedance devices, the loss due to the series resistance Rs is more significant than the leakage loss due to the parallel resistor Rp. Therefore the Series Model is convenient for large capacitors, while the Parallel Model fits the small capacitors. But what is large and what is small? Typically, large capacitors are 100 uF and greater and small ones are 10 uF and below. However, for SMD capacitors, the parallel model is always better because of very low contact resistance, Rs, and inductance, Ls. On the other hand, we will use the parallel model for large inductors and the series model for small ones.

Slide #25

Which Model is Correct ?

- Both are correct

  $C_s = C_p (1 + D^2)$



- One is a better approximation

- For high Q or low D components,

  $C_s \approx C_p$

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Since the user tells the instrument which model to use, this is another source of measurement discrepancy. Fortunately, both models are always correct and related to each other through this math formula. For low quality devices, one model is always a better approximation, while high quality or low dissipation DUTs exhibit identical series or parallel values (D <<1).

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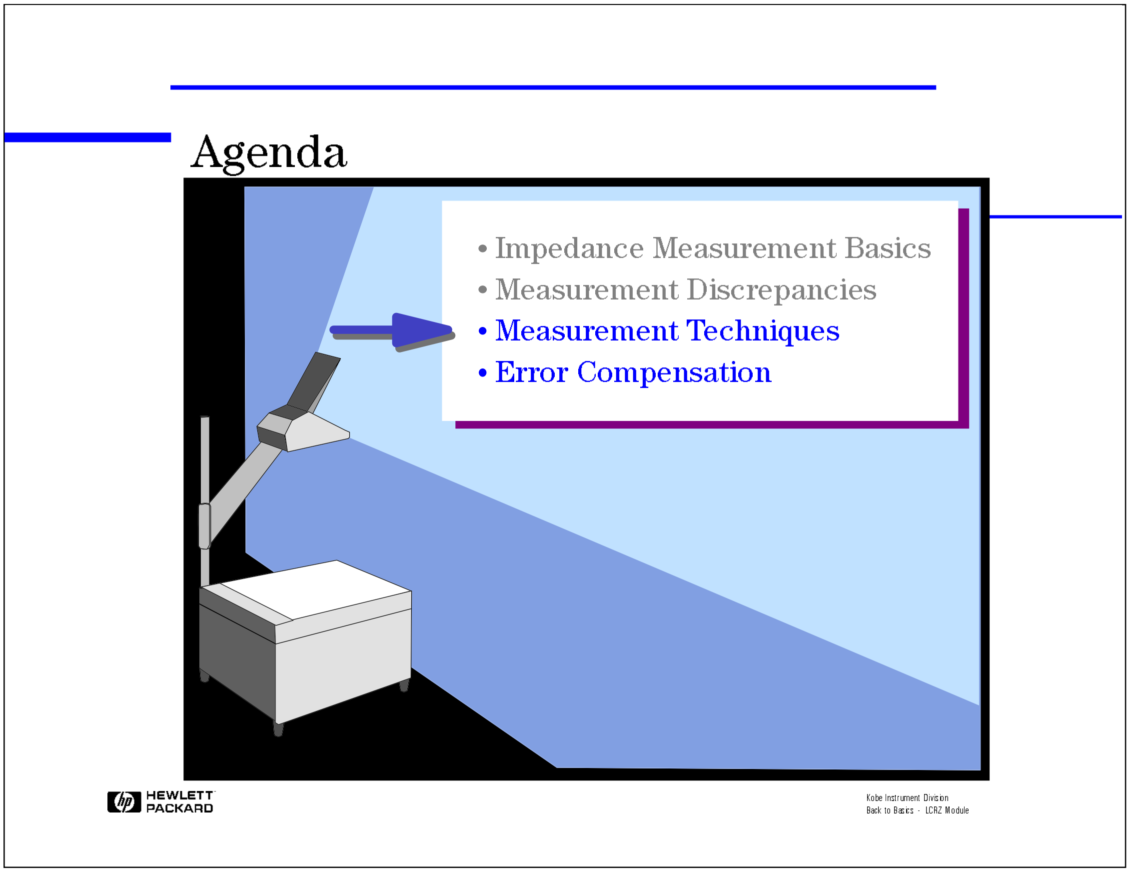
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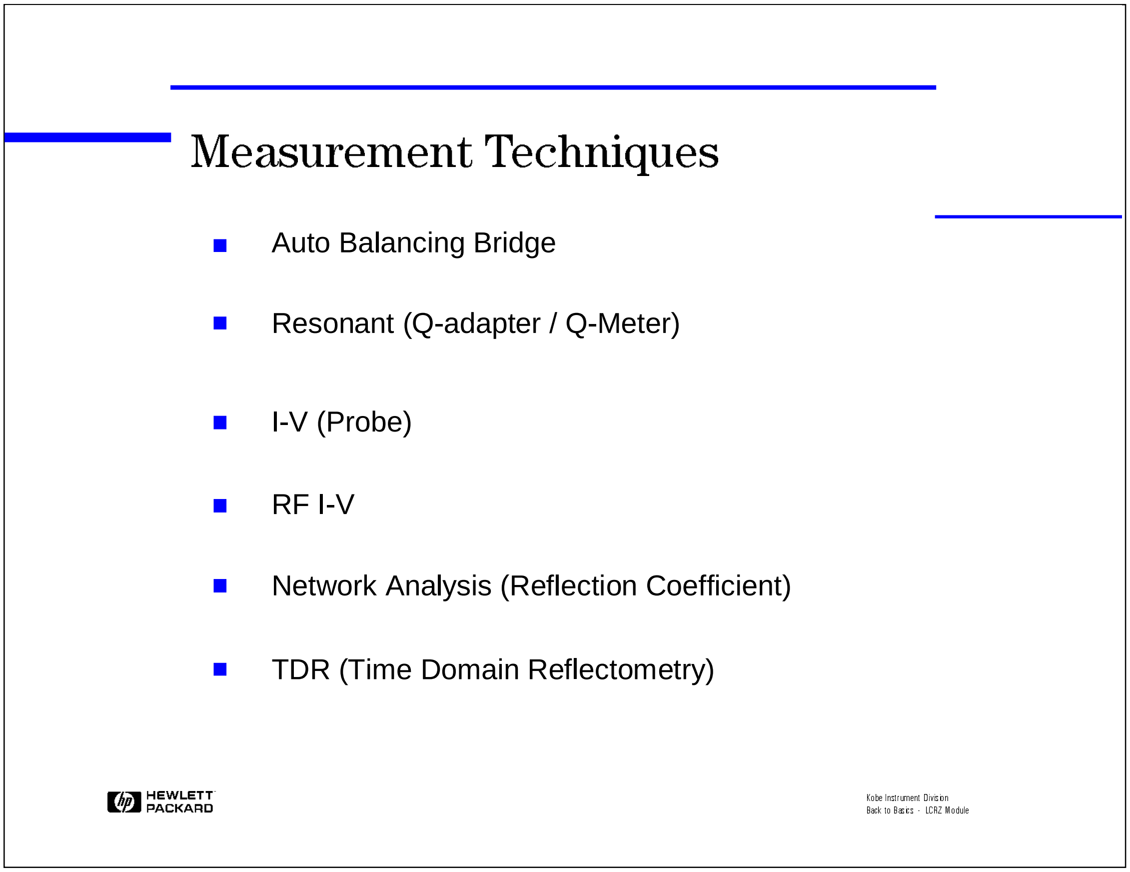

Technique inaccuracies are a major source of measurement discrepancies. Therefore, selecting the appropriate measurement technique is an important aspect in performing impedance measurements. Many techniques are available and in this section we will outline the different techniques along with their advantages and disadvantages.

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Measurement Techniques

Measurement Technique Topics

- Technique Selection Criteria
- Theory of Operation
- Advantages and Disadvantages of each technique
- Expanded connection information and theory for auto balancing bridge (4 terminal pair) instruments
- Error Compensation to minimize measurement error

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Given the measurement requirements and conditions of your application, you will choose the most appropriate measurement technique considering such factors as frequency coverage, measurement range, measurement accuracy and ease of operation. However your choice will always require you to make TRADEOFFS as there is no one measurement method which includes all measurement capabilities. Before getting into details for each technique, let us talk about selection criteria.

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Measurement Technique Selection Criteria

- Frequency
- DUT Impedance
- Required measurement accuracy
- Electrical test conditions
- Measurement parameters
- Physical characteristics of the DUT

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To simplify the decision process, the following criteria can be used in selecting the most appropriate technique for your application. Remember that some trade-offs might have to be made when selecting the best technique.

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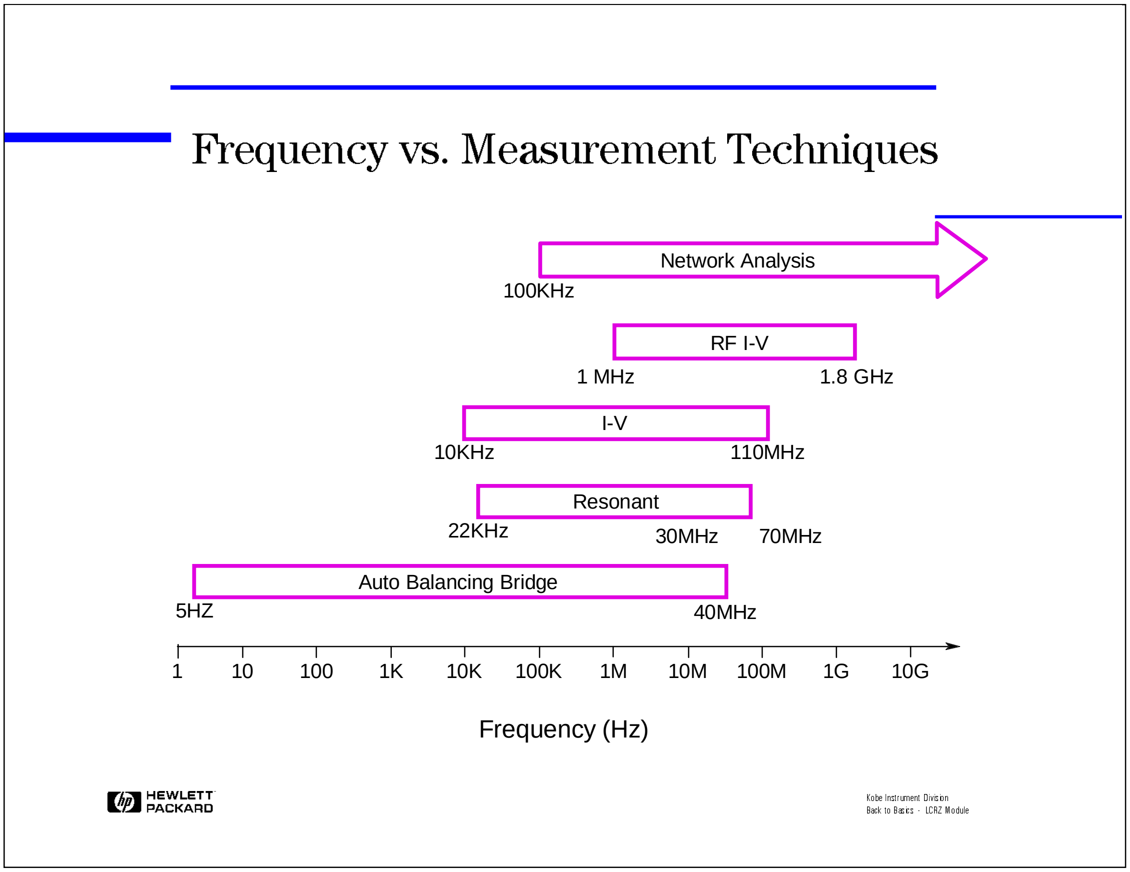

This chart will help you visualize the frequency range for 5 measurement techniques. The frequency range numbers are a mix of practical and theoretical limits and should be used as a reference only. The autobalancing bridge basic accuracy is 0.05% while the network analysis one is 1.5%. This already uncovers possible trade-offs.

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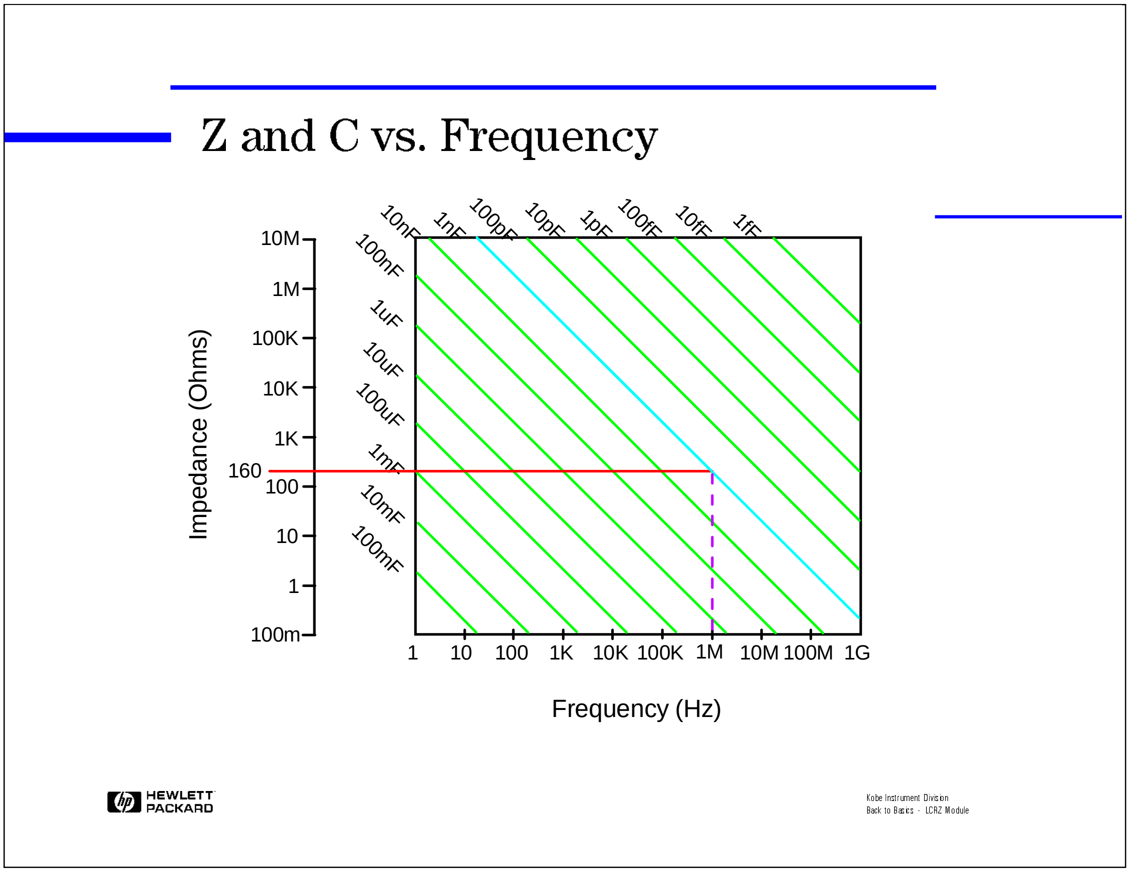
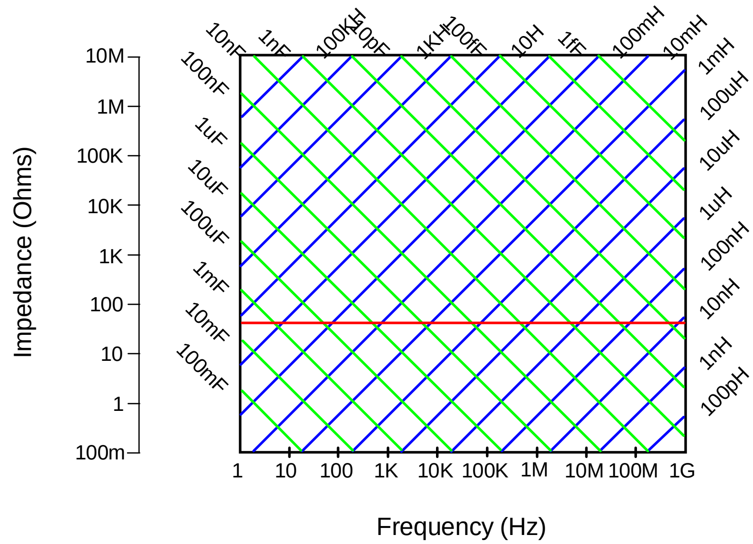


This is a log-log graph giving the impedance of various perfect capacitors (purely susceptive) versus frequency. For instance, a 1nF capacitor (bold diagonal) exhibits an impedance of 160 Ohms @ 1 MHz and 160 KOhms @ 1 KHz. It is important to realize that impedance varies with frequency. This is why a wide impedance range is critical for making correct impedance measurements. But most components are not only reactive, but also resistive or lossy. Therefore to properly choose the instrument with the appropriate impedance range, we must know the global impedance of the DUT, the resistive part AND the reactive one. Remember, most instruments measure R and X (Z=R+jX) and only then calculate Cp or Cs according to the model chosen.

Slide #32

Reactance Chart



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Adding inductance diagonals to the previous graph gives this one for various capacitor and inductor values. Given the component's nominal value and the frequency operating range, it is easy to estimate the impedance range of the DUT.

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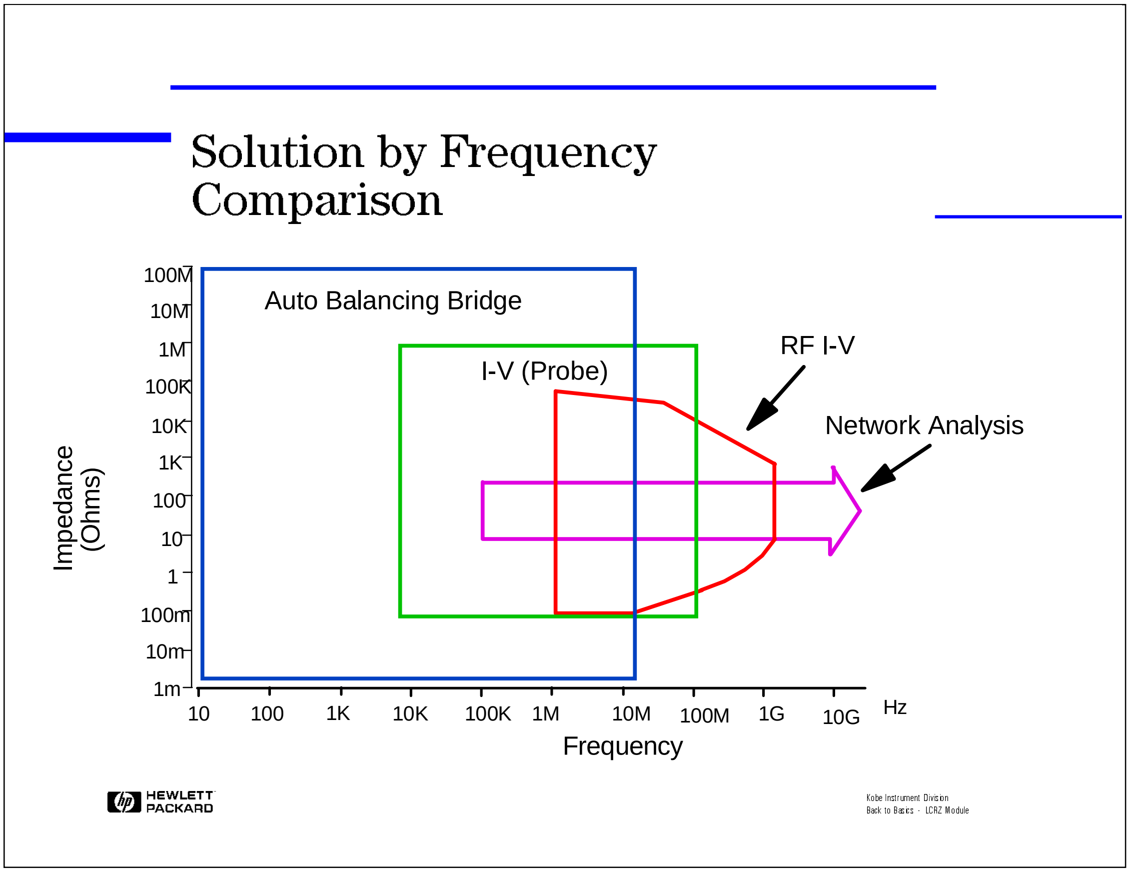

Combining the frequency and DUT impedance criteria into this graph helps visualize the coverage of each technique. The autobalancing bridge provides the widest measurement range with high accuracy, as we have already seen. The I-V technique provides good mid-frequency measurement range. RF I-V method is an excellent choice for high frequency impedance measurement. Network analysis covers the highest frequency range, but it is designed to work around 50 Ohms and impedance range is rather narrow. TDNA and Resonant techniques do not show up, since impedance is not their primary measurement. But we will see in the technical complements that a third dimension is missing on this chart: accuracy!

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Which is the Best ?

- All are good
- Each has advantages and disadvantages
- Multiple techniques may be required

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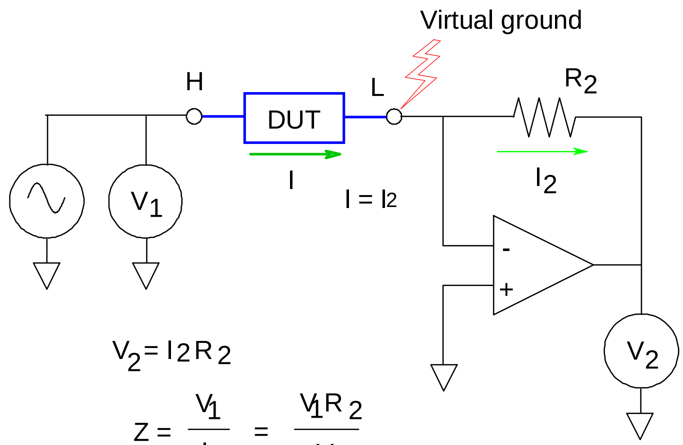
No individual measurement technique is ideal for all situations and each technique has major benefits associated with it. An excellent example is cable testing. The autobalancing bridge provides impedance information while the TDNA technique provides useful discontinuity information. In this case, the two measurement techniques aid each other and provide a complete cable test solution.

Slide #35

Auto Balancing Bridge
Theory of Operation



$V_2 = I_2 R_2$

$$Z = \frac{V_1}{I_2} = \frac{V_1 R_2}{V_2}$$

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Slide #36

Measurement Technique Topics

Advantages and Disadvantages of each technique

Auto Balancing Bridge

Advantages and Disadvantages

- Most accurate, basic accuracy 0.05%
- Widest measurement range
- C,L,D,Q,R,X,G,B,Z,Y,O,....
- Widest range of electrical test conditions
- Simple-to-use
- Low frequency, f < 40MHz

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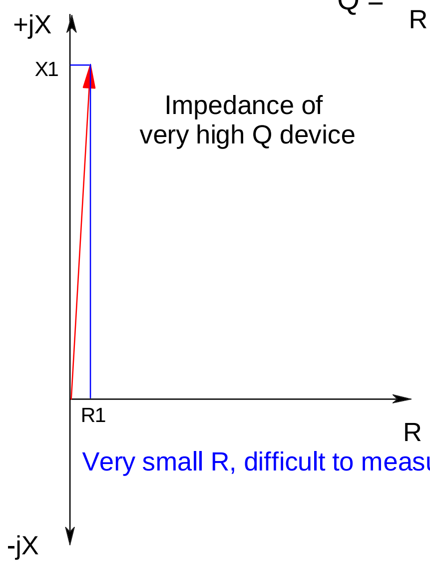
Let us summarize the advantages and disadvantages of each of the measurement techniques.

The Autobalancing bridge technique is by far the best technique for measurements below 40 MHz. It provides the most accurate measurements possible and has the widest impedance measurement range. Both of these are critical for accurate component analysis. A wide range of AC and DC stimulus can be applied to the component. In addition, because this is a low frequency technique, it is the simplest measurement technique to use.

Slide #37

Performing High Q / Low D Measurement is Difficult

$$Q = \frac{X_l}{R}$$

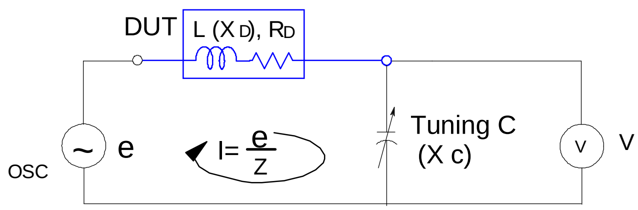


Very small R, difficult to measure

Slide #38

Resonance (Q - Meter) Technique
Theory of Operation

- Tune C so the circuit resonates
- At resonance $X_D = -X_C$, only R_D remains



$$X_C = \frac{V}{I} = \frac{R_D V}{e} \quad \text{(at resonance)}$$

$$Q = \frac{|X_D|}{R_D} = \frac{|X_C|}{R_D} = \frac{|V|}{e}$$

Slide #39

Advantages and Disadvantages of each technique

Resonant Method
Advantages and Disadvantages

Very good for high Q - low D measurements

Requires reference coil for capacitors

Limited L,C values accuracy

Vector		Scalar
75KHz - 30MHz	■	22KHz - 70MHz
automatic and fast	■	manual and slow
easy to use	■	requires experienced user
limited compensation	■	No compensation

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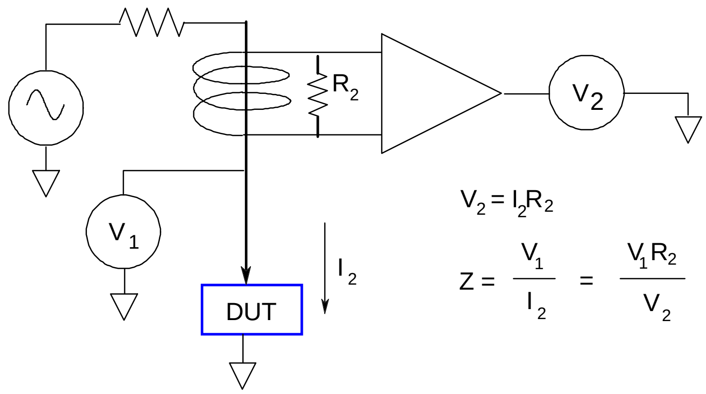
The Resonant technique, or Q-meter, used to be a very manual measurement technique. However, the design of automatically tunable air capacitor standards allows today fast and error free measurement of high Q or low D components. In low D capacitor test, it is still difficult to achieve high accuracy measurements due to the need for very stable reference inductors, which are difficult to design.

Testing chip or SMD capacitors requires specific test fixtures which have strays, essentially stray capacitance, that influence the value of the tuning capacitance. With the new automatic technique, test fixture parasitics can be compensated for by offset compensation. This requires accurate design and evaluation of the stray capacitance of the test fixture.

Slide #40

I - V Probe Technique
Theory of Operation



$$V_2 = I_2 R_2$$

$$Z = \frac{V_1}{I_2} = \frac{V_1 R_2}{V_2}$$

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Slide #41

Advantages and Disadvantages of each technique

I-V (Probe)

Advantages and Disadvantages

- Medium frequency, 10KHz < f < 110MHz
- Moderate accuracy and measurement range
- Grounded and in-circuit mesurement
- Simple - to - use

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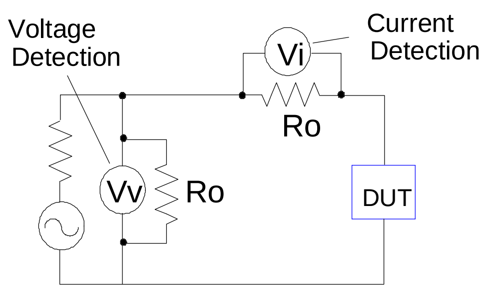
The I-V, or "probe technique", provides very good mid-frequency range performance, extending up to 100 MHz. Another key feature of this technique is that it is a floating measurement technique, thus grounded and in-circuit measurements are very easy.

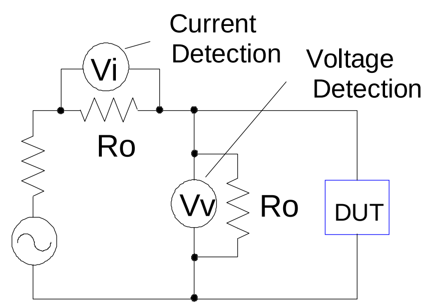
Slide #42

RF I-V
Theory of Operation

High Impedance Test Head



Low Impedance Test Head



Slide #43

Advantages and Disadvantages of each technique

RF I-V

Advantages and Disadvantages

- High frequency, 1MHz < f < 1.8GHz
- Most accurate method at > 100MHz
- Grounded device mesurement

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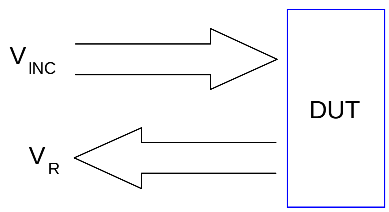
The RF I-V technique provides very good high-frequency range performance, extending up to 1.8 GHz. This is the most accurate technique at frequencies higher than 100 MHz.

Although this is a 50 Ohm system, the technique has a very good impedance measurement range with quite good accuracy.

Slide #44

Network Analysis (Reflection) Technique
Theory of Operation



$$\Gamma = \frac{V_R}{V_{INC}} = \frac{Z_L - Z_O}{Z_L + Z_O}$$

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Slide #45

Network Analysis

Advantages and Disadvantages

- High frequency
  - Suitable, f > 100 kHz
  - Best, f > 1.8 GHz
- Moderate accuracy
- Limited impedance measurement range (DUT should be around 50 ohms)

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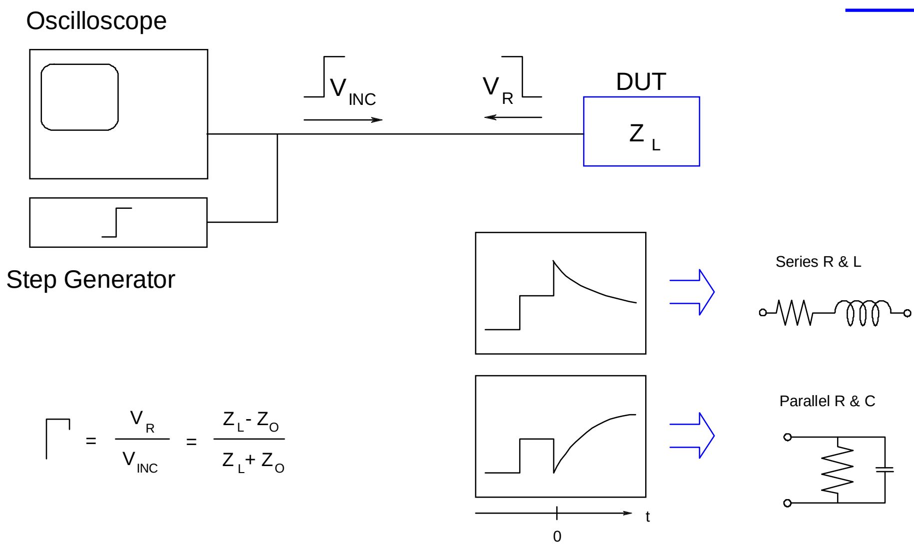
Network analysis is the best solution for very high frequency measurements, extending up to tens of GHz. Measurements as low as 100 KHz are possible with this technique (directional bridge low-end limit). Given the existence of the autobalancing bridge, I-V probe, and RF I-V techniques, it is advised that the network analysis technique be used for measurements above 1.8 GHz. Above 1.8 GHz, the reflection technique is the only measurement technique currently available.

Slide #46

TDR
Theory of Operation



$$\Gamma = \frac{V_R}{V_{INC}} = \frac{Z_L - Z_O}{Z_L + Z_O}$$

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Slide #47

Advantages and Disadvantages of each technique

TDNA (TDR)
Advantages and Disadvantages

- Reflection and transmission measurements
- Single and multiple discontinuities or impedance mismatches ("Inside" look at devices)
- DUT impedance should be around 50 ohms
- Not accurate for mΩ or M Ω DUTs or with multiple reflections
- Good for test fixture design, transmission lines, high frequency evaluations

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MTEC26
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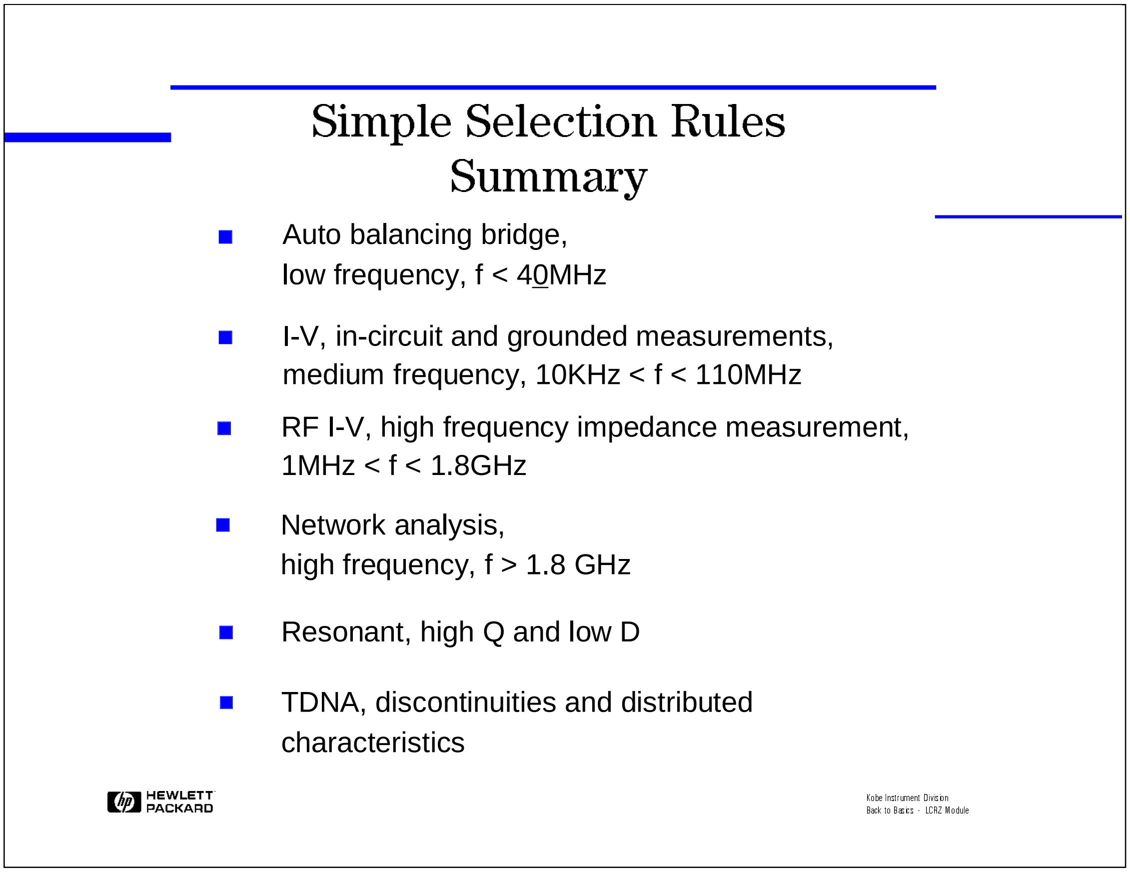
Although this is a 50 Ohm system, the technique has a very good impedance measurement range with quite good accuracy.

Slide #48



Here we attempt to provide a simple summary for proper technique selection. Usually frequency is the first decision factor to use when choosing a measurement technique. Then consider the other criteria:

* DUT impedance

* Required measurement accuracy

* Electrical test conditions

* Measurement parameters

* Physical characteristics of the DUT

Often the DUT's impedance range is completely ignored, which leads to big discrepancies with the measurement result expectations.

Slide #49

Measurement Methods and HP products

Measurement Method	HP Products	Frequency range
Auto Balancing Bridge (Four-Terminal Pair)	HP 4263A LCR Meter HP 427xA LCR Meters HP 4284A Precision LCR Meter HP 4285A Precision LCR Meter HP 4192A LF Impedance Analyzer HP 4194A Impedance/Gain-Phase Analyzer	100Hz to 100 kHz spot 100Hz to 10MHz spot 20Hz to 1MHz spot 75KHz to 30MHz 5Hz to 13MHz 10Hz to 40MHz
Resonant (Q-Meter)	HP 42851A Q Adapter (with HP 4285A)	75KHz to 30 MHz
I-V (Probe)	HP 41941A Impedance Probe (with HP 4194A) HP 4193A Vector Impedance Meter	10KHz to 100MHz 400KHz to 110MHz
RF I-V	HP 4286A RF LCR Meter HP 4291A Impedance/Material Analyzer	1 MHz to 1 GHz 1 MHz to 1.8 GHz

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This table gives a listing of different Hewlett-Packard products and the techniques that they use. Selecting the proper instrument for a specific measurement may not be a trivial task. As we have been discussing, many parameters need to be considered to make the correct choice. We will show some selection examples at the end of this section.

Slide #50

Measurement Methods and HP products (cont.)

Measurement Method	HP Products	Frequency range
Network Analysis (Reflection Coefficient)	HP 4195A Network/Spectrum Analyzer with HP 41951A Impedance Test Set	100 kHz to 500MHz
	HP 4396A Network/Spectrum Analyzer with HP 43961A Impedance Test Kit	100 kHz to 1.8 GHz
	HP 8751A Network Analyzer	5Hz to 500MHz
	HP 8752C/8753D RF Network Analyzers	300KHz to 1.3GHz/6GHz
	HP 8510B Network Analyzer	45 MHz to 100GHz
	HP 8719C/8720C Network Analyzers	130MHz to 13.5GHz/20GHz
TDNA (TDR)	HP 54121T Digitizing Oscilloscope and TDR	
	HP 8752C/8753D RF Network Analyzers	
	HP 8510B Network Analyzer	
	HP 8719C/8720C Network Analyzers	

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MTEC28

Slide #51

Selecting a Test Frequency

- Ideal case is at operating conditions
- Reality, must make trade-offs
- Too high a frequency adds measurement, test fixture and instrument errors
- mΩ and MΩ DUTs more difficult to measure

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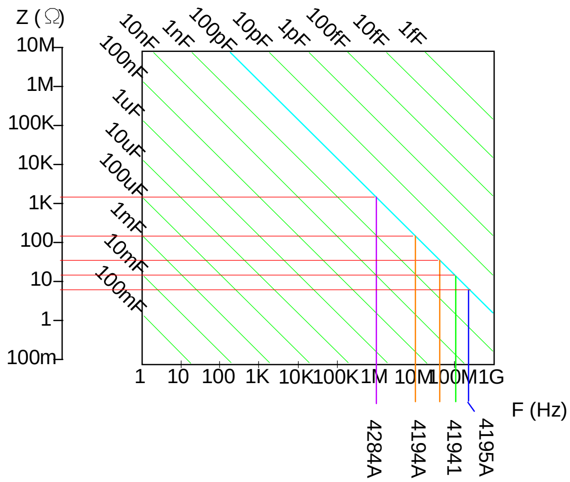
You might need to consider measurement method advantages and disadvantages when selecting a test frequency of devices. Ideally the best test frequency for a given component is at the operating frequency . Since the instrument measurement techniques have limitations, you might need to reconsider the test frequency based on the component behavior as a function of frequency. For instance, the instrument might be able to make high frequency measurement like the 4195A, while the test fixture used might be frequency limited by the parasitics. The measurement accuracy of instrument is also a very good example : let's see the case of 100 pF that operates at 200 MHz.

Slide #52

Measurement Tradeoff Example

Want to measure 100 pF ideal capacitor @ 200 MHz



Accuracy comparison

4284A @ 1MHz (1600Ω) : 0.05%

4194A @ 10MHz (160 Ω) : 1.3 %

4194A @ 40MHz (40 Ω) : 5.2 %

41941A @ 40MHz (40 Ω) : 3.6 %

41941A @ 100MHz (16 Ω) : 6.2 %

4195A @ 200MHz (8 Ω) : 1.9 %

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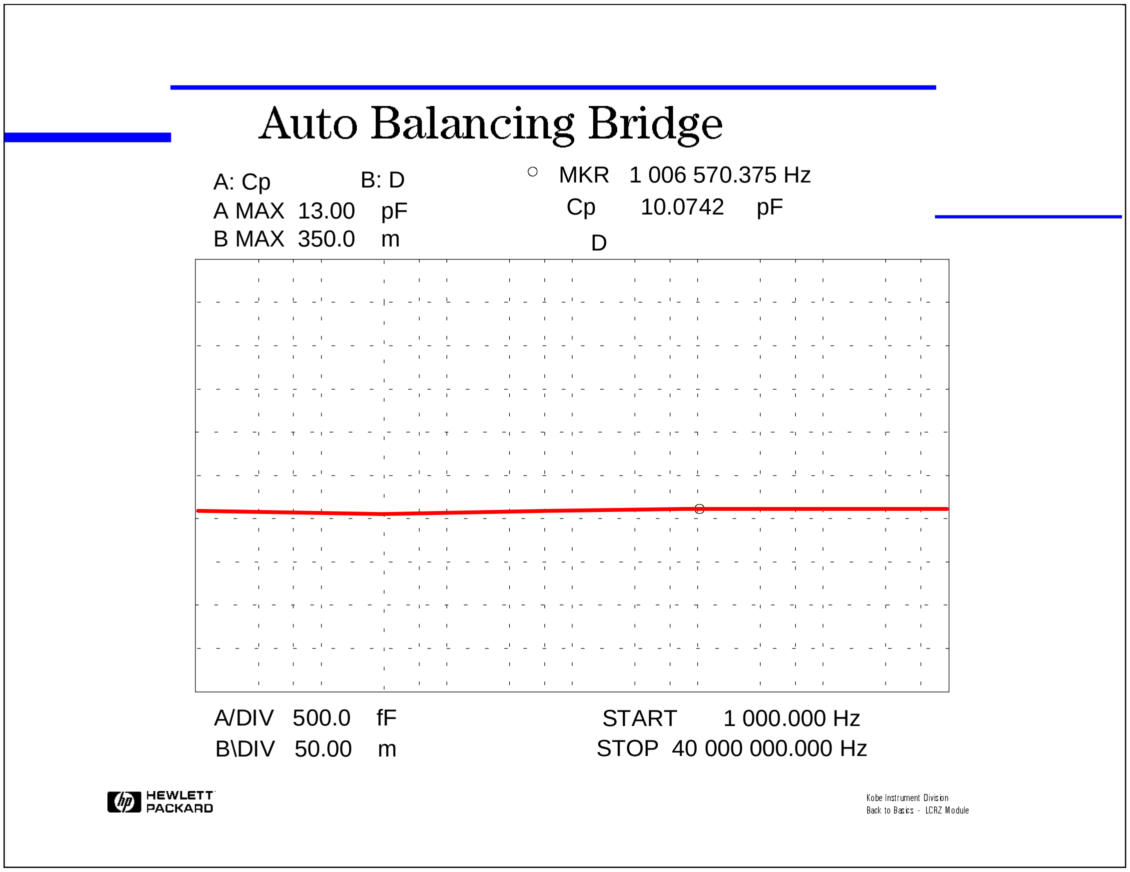
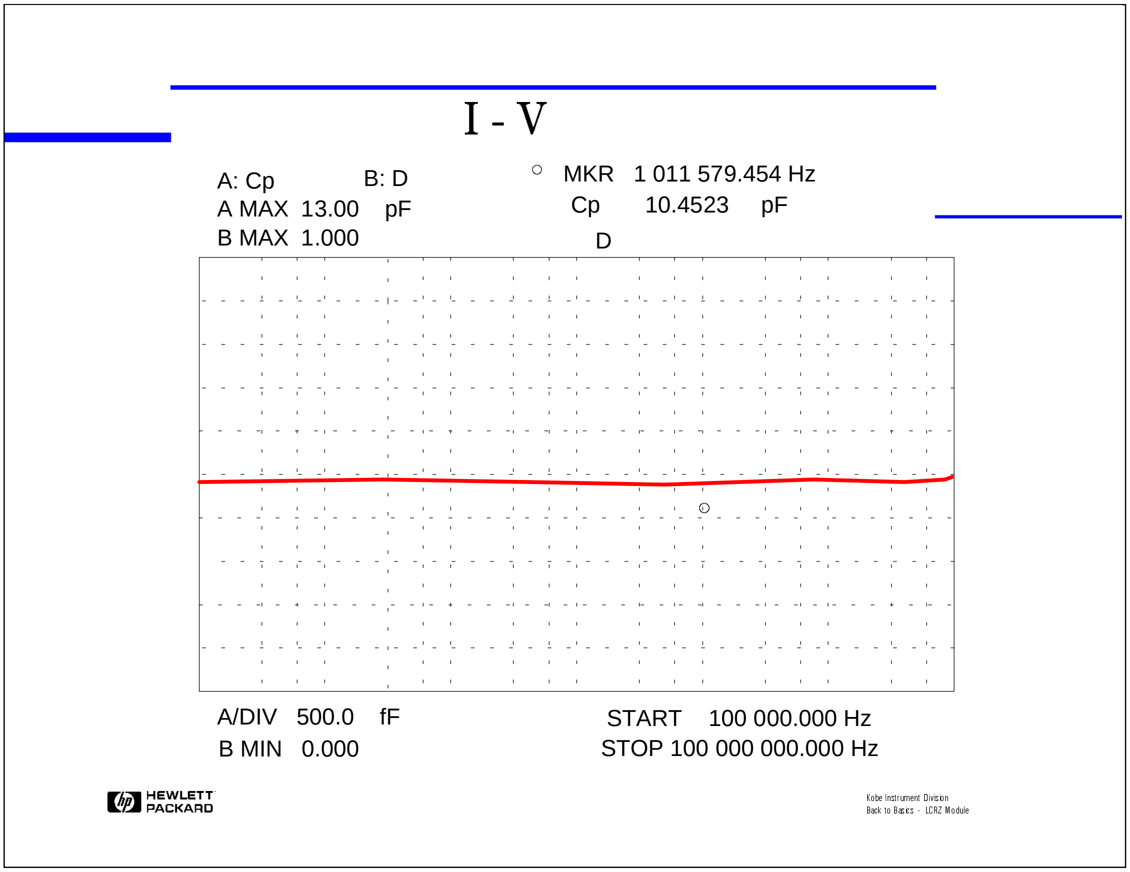
The "Z and C vs. Frequency" chart shows the impedance variation of this 100 pF capacitor (assumed to be perfect). This example pinpoints that we might need to characterize this component at 1 MHz in order to insure high accuracy, provided that this measurement result reflects the a predictable component behavior at 200 MHz. Another key point is that different techniques have different measurement accuracy at the same operating conditions: here the HP 4194A four-TP autobalancing bridge and the HP 41941A probe at 40 MHz. So a trade-off or a double measurement might be required depending on the application.

Slide #53



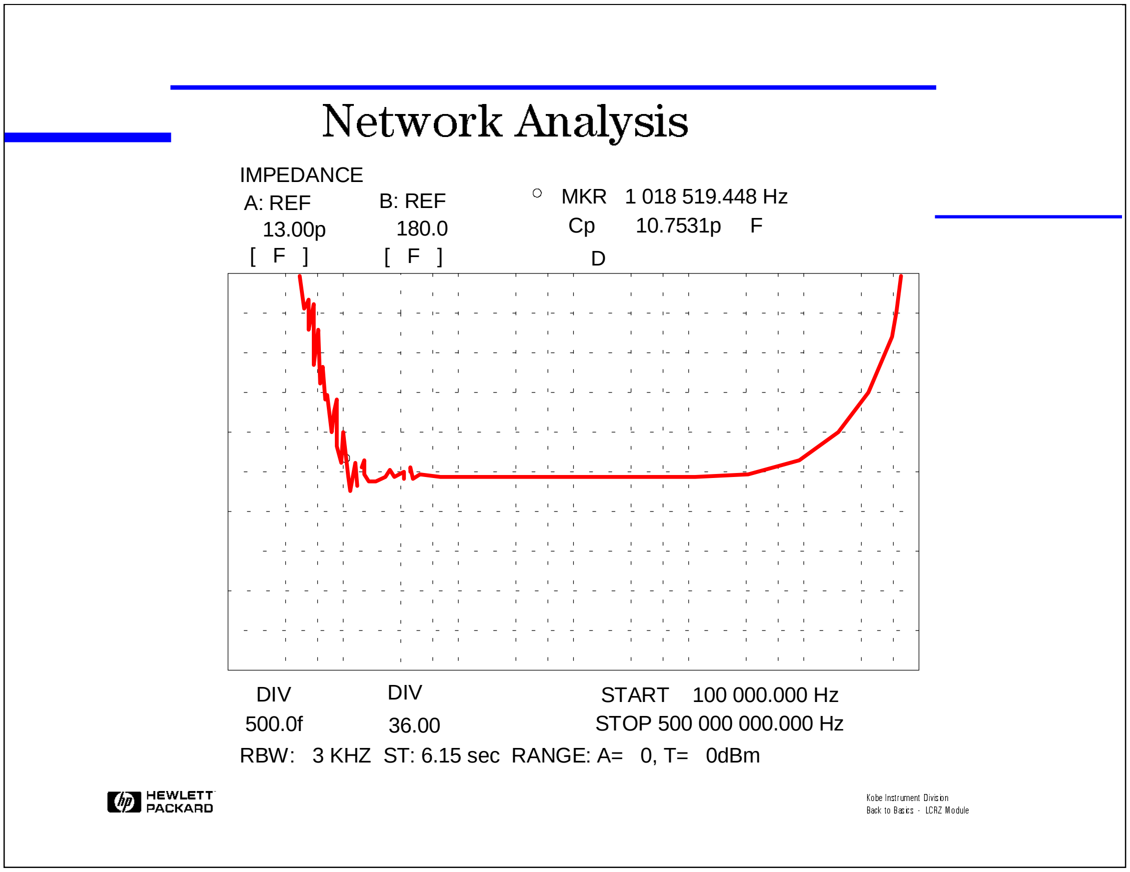
This measurement has been made with the HP 4194A Impedance Analyzer which is an autobalancing bridge. From 1 MHz to 40 MHz, the measurement was very stable and shows the parallel capacitance with very high resolution. The variation on the full frequency range is less than 100 fF! There are some fluctuations in the lower end because of the higher impedance of the capacitor.

Slide #54



Using the same instrument with the HP 41941A I-V probe gave these results. The fluctuations are limited to approximately 200 fF, but the high end and low end frequency limitations appear clearly here. However, even though the accuracy of this technique is generally less than the autobalancing bridge technique, this measurement gives very satisfactory results up to 100 MHz.

Slide #55



The last measurement has been done on a HP 4195A Network Analyzer with the HP 41951A Impedance kit. In the low frequencies, the impedance of the capacitor is far enough from the 50 Ohm system impedance to very clearly demonstrate the impedance range limitation of this technique. Closer to 50 Ohms, the results are similar to the ones given by the other techniques. In the higher frequencies, we start to see the resonant frequency. Actually this instrument does not go high enough in frequency to visualize the resonance point, but at least gives some useful information (further analysis would need to be done using a higher frequency reflection technique instrument).

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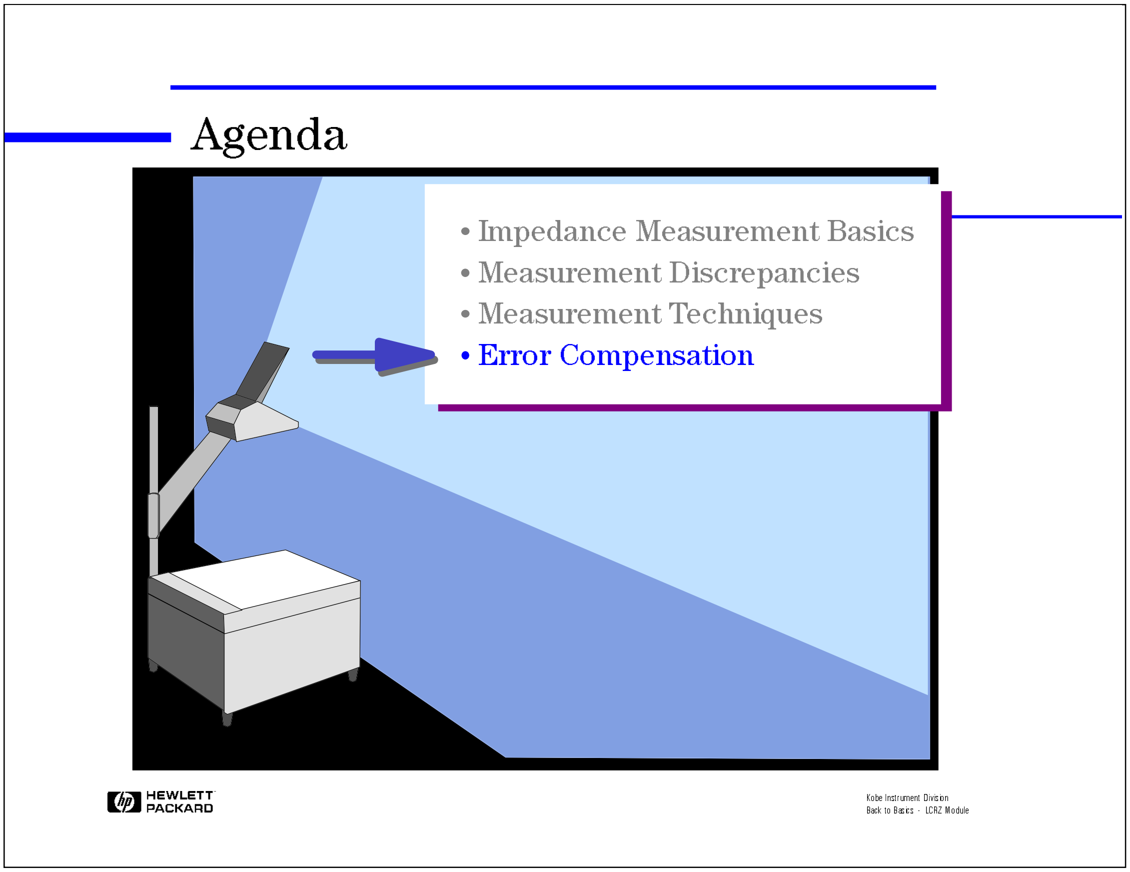
Agenda
• Impedance Measurement Basics
• Measurement Discrepancies
• Measurement Techniques
• Error Compensation
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Slide #57

Error Compensation to Minimize Measurement Errors

- Compensation and Calibration (Compensation = Calibration)
  - Definition of Compensation and Calibration
  - Cable correction
- OPEN/SHORT Compensation
  - Basic Theory
  - Problems which can not be eliminated by OPEN/SHORT compensation
- OPEN/SHORT/LOAD Compensation
  - Basic Theory
  - Load device selection
- Practical Examples
- Summary

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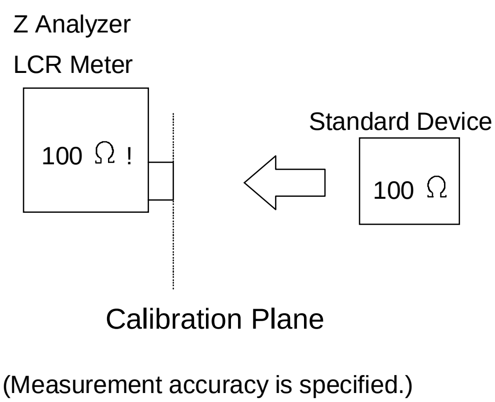
We need to consider these subjects to perform effective error compensation for impedance measurements.

Slide #58

Definition of Calibration

- To define the "Calibration Plane" at which measurement accuracy is specified



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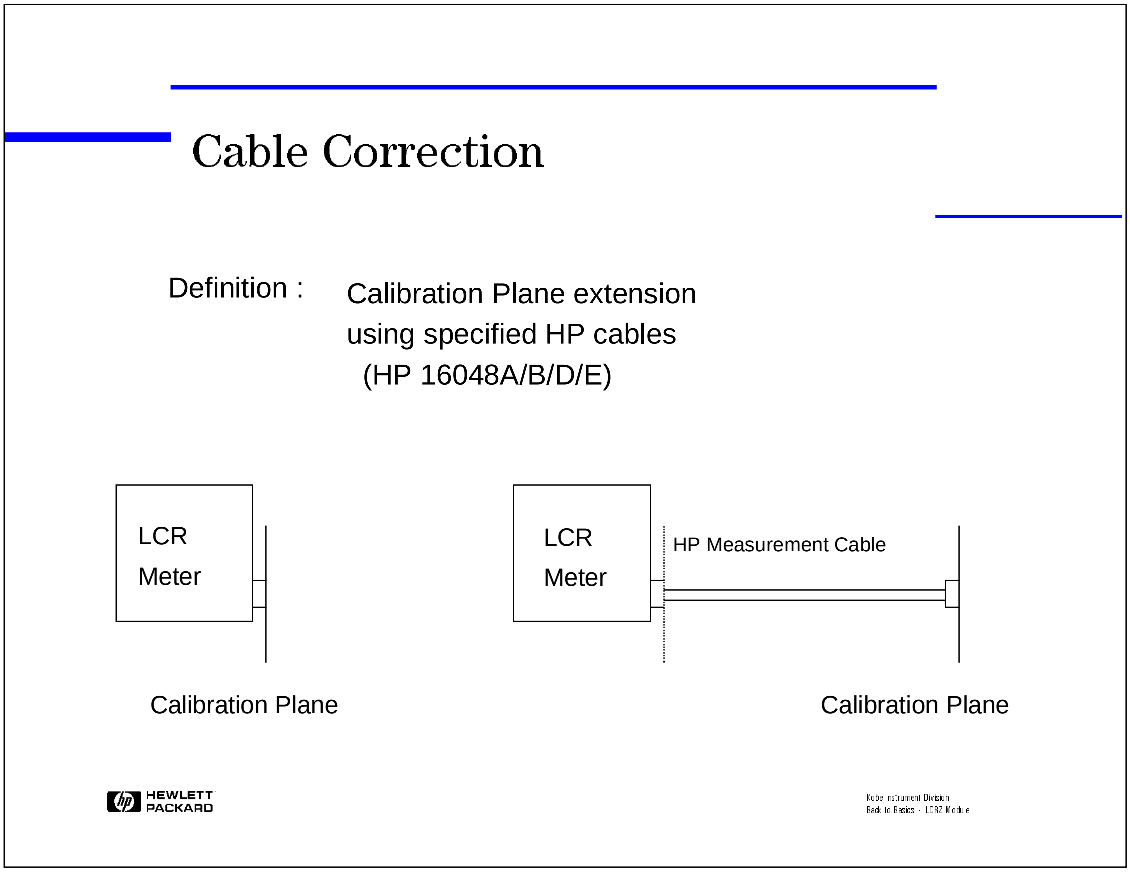
We need to understand that "Compensation" is different from "Calibration".

"Calibration" is to define a reference plane where the measurement accuracy is specified. This plane is called the "Calibration Plane". The calibration plane is generally at the UNKNOWN terminals of an instrument's front panel. In most LCR meters, calibration is done at production or servicing

Slide #59

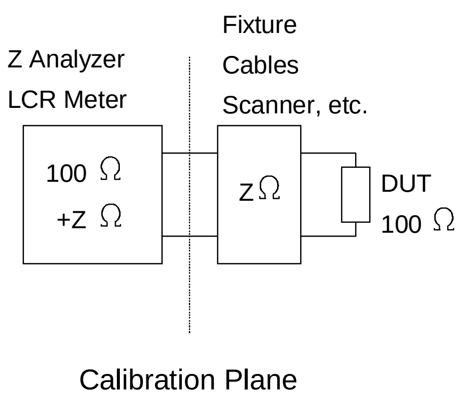


HP impedance measurement instruments have a Cable Correction function. Cable correction extends the calibration plane from the front panel to the end of cable. Cable correction is effective only when using a HP specified extension cable whose length and electrical characteristics are well understood. Cable Correction compensates for the phase shift in the feed back loop of the measurement circuit which can make it unbalanced and reduce the measurement error (also caused by the phase shift) by a calculation.

Slide #60

Definition of Compensation

To reduce the effects of error sources existing between the DUT and the instrument's "Calibration Plane".



- 2 types of compensation
  - OPEN/SHORT compensation
  - OPEN/SHORT/LOAD compensation

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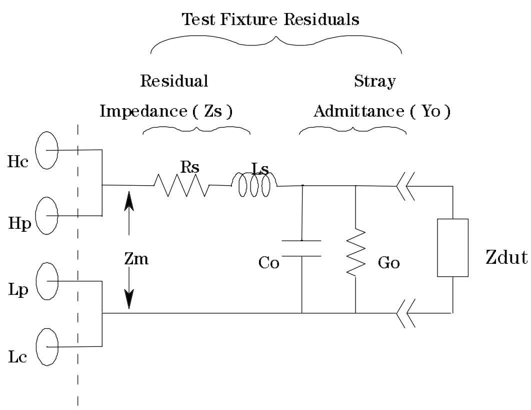
"Compensation" reduces the measurement error induced by test fixtures between the DUT and the calibration plane. When a Device Under Test (DUT) is directly connected to the calibration plane, the instrument can measure it within the specified measurement accuracy. However, test fixtures are usually connected between the calibration plane and the DUT in actual measurements, and they degrade the total measurement accuracy by their residuals. There are two types of compensation techniques that need to be discussed, OPEN/SHORT and OPEN/SHORT/LOAD.

Slide #61

OPEN/SHORT Compensation

- Basic Theory -



$$Zs = Rs + j\ wLs$$

$$Yo = Go + j\ wCo$$

$$Zdut = \frac{Zm - Zs}{1 - (Zm - Zs)Yo}$$

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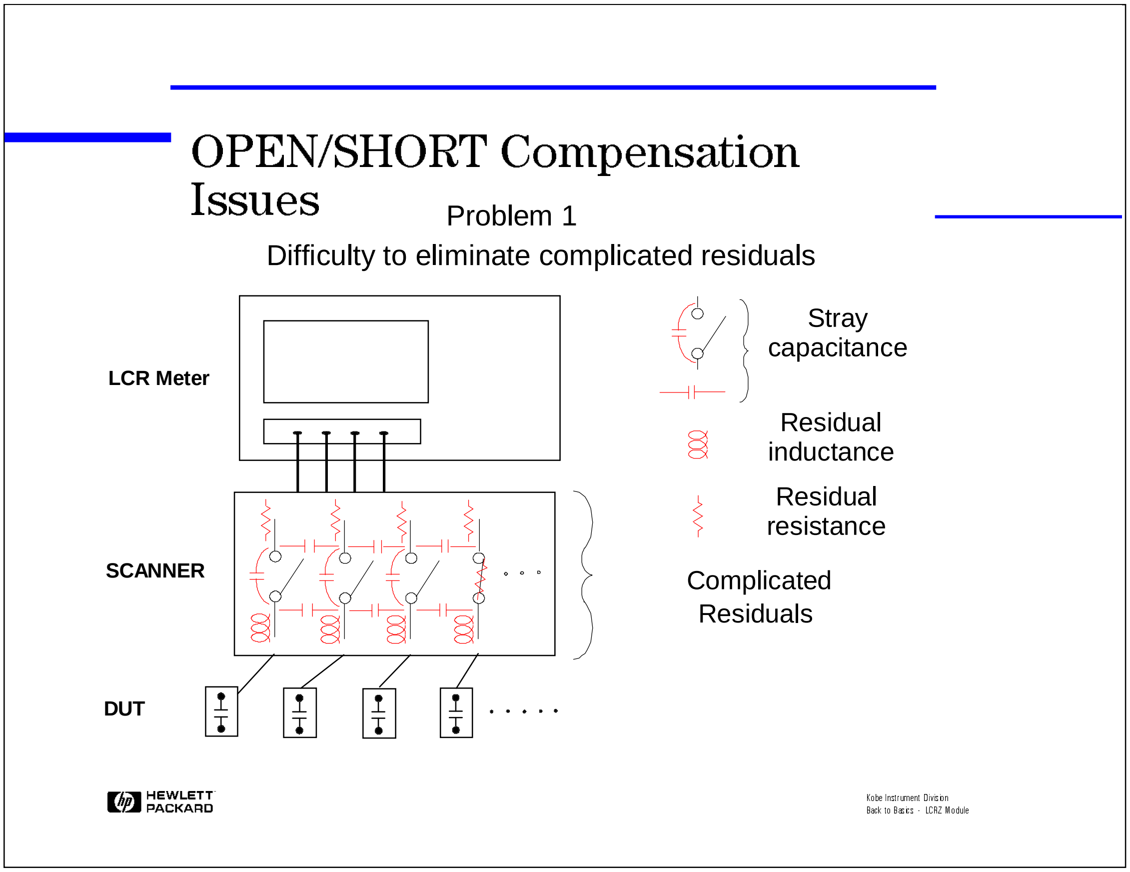
OPEN/SHORT compensation is the most popular compensation technique. In OPEN/SHORT compensation, the residuals of a test fixture can be modeled as an equivalent circuit. Since Zs<<1/Yo, stray admittance Yo can be measured when the test terminals are open. Residual impedance Zs can be measured when the test terminals are shorted. Then the DUT measurement data Zm is compensated by the calculation using OPEN and SHORT measurement data, then the true value Zdut can be obtained. Note that each parameter has real and imaginary components. In the case of simple measurements using a HP test fixture directly connected to the calibration plane, the OPEN/SHORT compensation is sufficient in removing residuals.

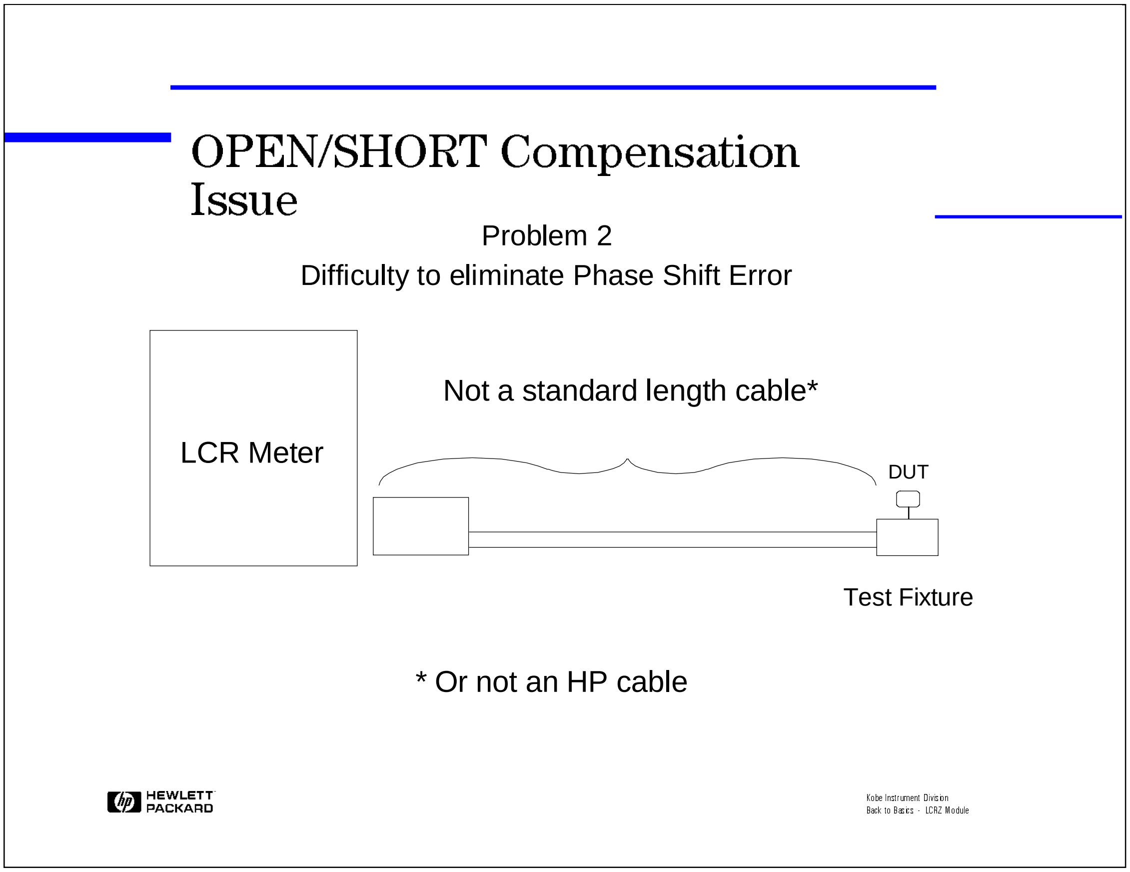
Slide #62



OPEN/SHORT compensation is insufficient in some measurement cases.

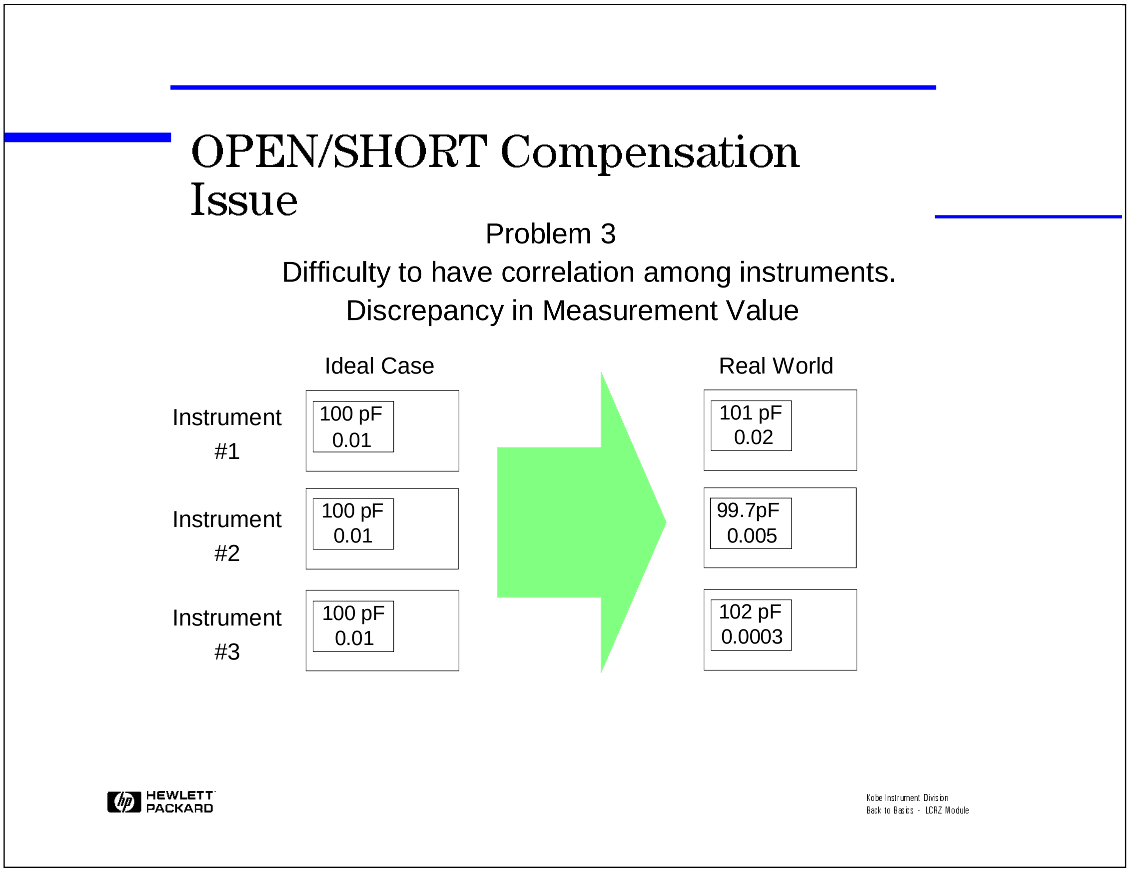
OPEN/SHORT compensation is often insufficient to remove complicated residuals of fixtures, such as scanners, handlers, custom-made test fixtures, external DC bias circuitry, balun transformers, filters and amplifiers.

Slide #63



OPEN/SHORT compensation is insufficient for correcting measurement error caused by using a non-HP cable because it cannot compensate the phase shift.

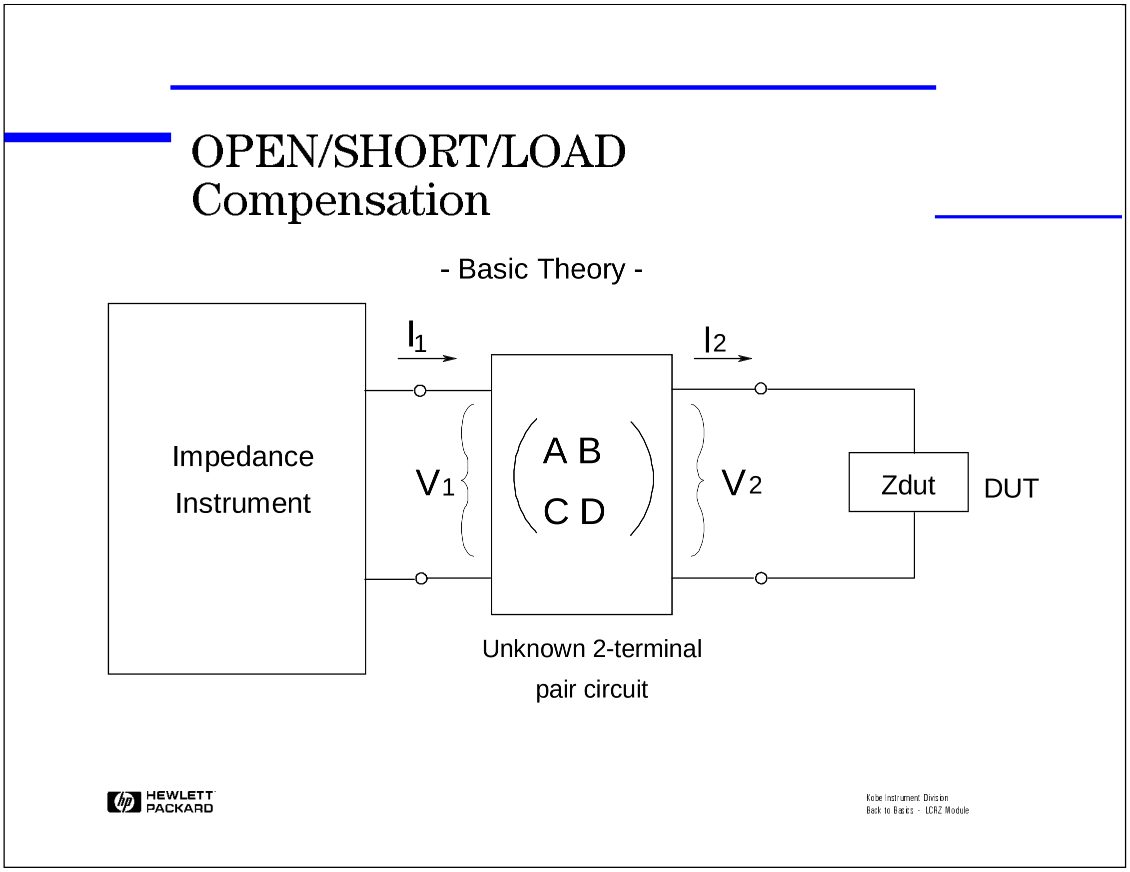
Slide #64



The measurement results of many instruments may slightly differ, even if measuring the same DUT. This difference may be well within the instrument's specified accuracy. It is impossible to improve correlation among the instruments with the OPEN/SHORT compensation technique.

To solve these problems, the following OPEN/SHORT/LOAD compensation technique is necessary.

Slide #65



OPEN/SHORT/LOAD compensation requires the measurement data of a standard device with a known impedance value in addition to the OPEN/SHORT measurement data. The residuals of a test fixture are defined as a four-terminal network expressed with A, B, C, D parameters. Assuming that the impedance measurement value of a DUT with a true value Z1 becomes Z2 at the test terminals, the following equation can be derived.

Z1 = (A*V2+B*I2) / (C*V2+D*I2)

= (A*Z2+B) / (C*Z2+D)

where Z1 = V1/I1 and Z2 = V2/I2

Slide #66

OPEN/SHORT/LOAD Compensation

- Basic Theory -

$$Zdut = \frac{Zstd\,(Zo-Zsm)\,(Zxm-Zs)}{(Zxm-Zs)\,(Zo-Zxm)} \;*$$

Zo : OPEN measurement value

Zs : SHORT measurement value

Zsm : Measurement value of LOAD device

Zstd : True value of LOAD device

Zxm : Measurement value of DUT

Zdut : Corrected value of DUT

* These are complex vectors. Conversions to real and imaginary components are necessary

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Parameters A,B,C,D are removed with the following assumptions:

1) The measurement value becomes Zo when the test terminals are open.

2) The measurement value becomes Zs when the test terminals are shorted.

3) The measurement value of a device (LOAD) whose reference value is Zstd becomes Zsm. Then it is possible to apply the compensation equation. The DUT measurement value Zxm is compensated with Zo, Zs, Zsm and Zstd.

Slide #67

OPEN/SHORT/LOAD Compensation

- Eliminates complicated residuals
- Eliminates phase shift error
- Maximizes correlation between instruments

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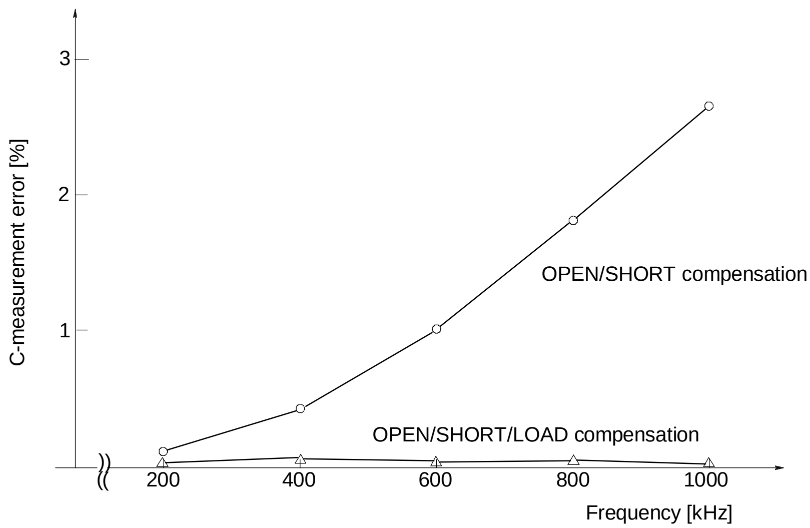
OPEN/SHORT/LOAD compensation is effective to solve problems which cannot be corrected with OPEN/SHORT compensation.

Slide #68

OPEN/SHORT/LOAD Compensation Effects



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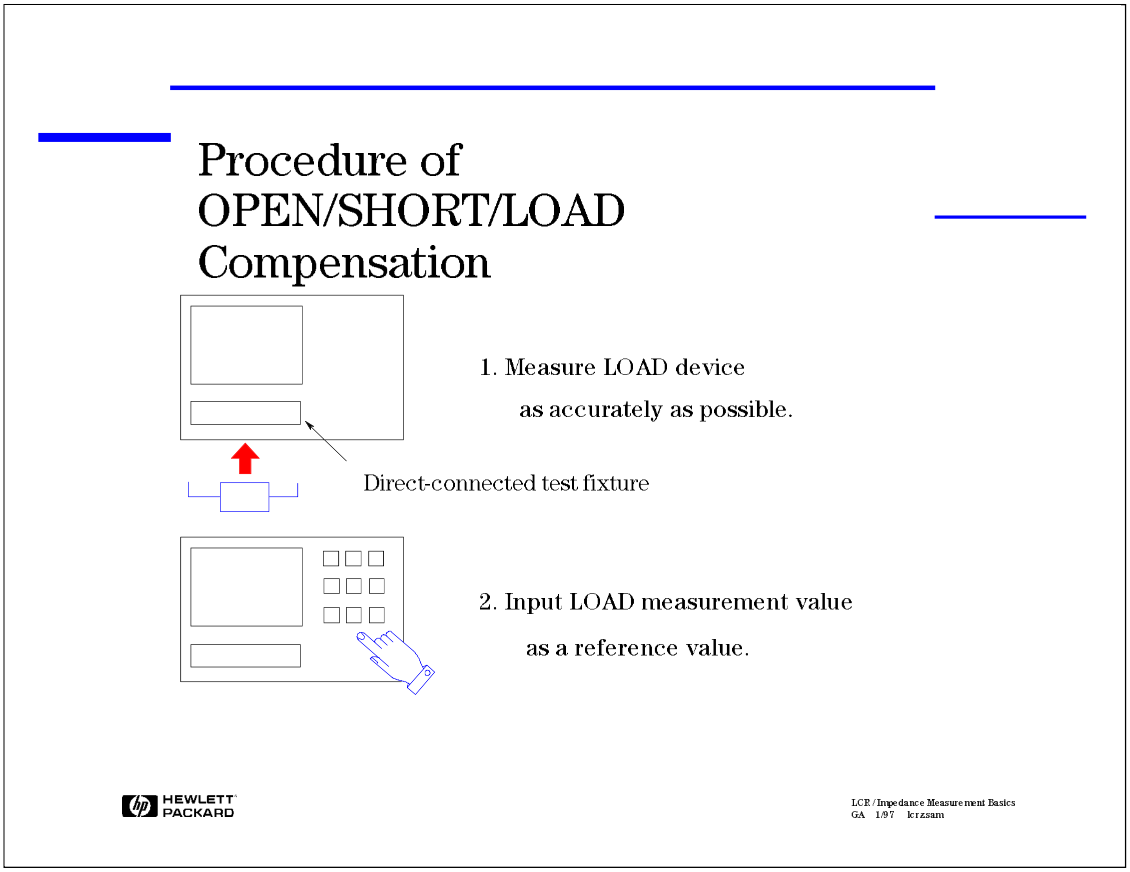
This is an measurement example to show the effects of the OPEN/SHORT/LOAD compensation. In this example, a 100pF capacitor is measured with the HP4285A, extending its test terminals using the HP16048E (4 meter cable) which cannot be corrected with cable correction function. As shown in the plot, the OPEN/SHORT/LOAD compensation can remove the errors which cannot be corrected with the OPEN/SHORT compensation.

(If the test terminals are extended with a long cable at a high frequency, a large phase shift will occur and the measurement circuit can be unbalanced. This problem cannot be solved even with the OPEN/SHORT /LOAD compensation.)

Slide #69

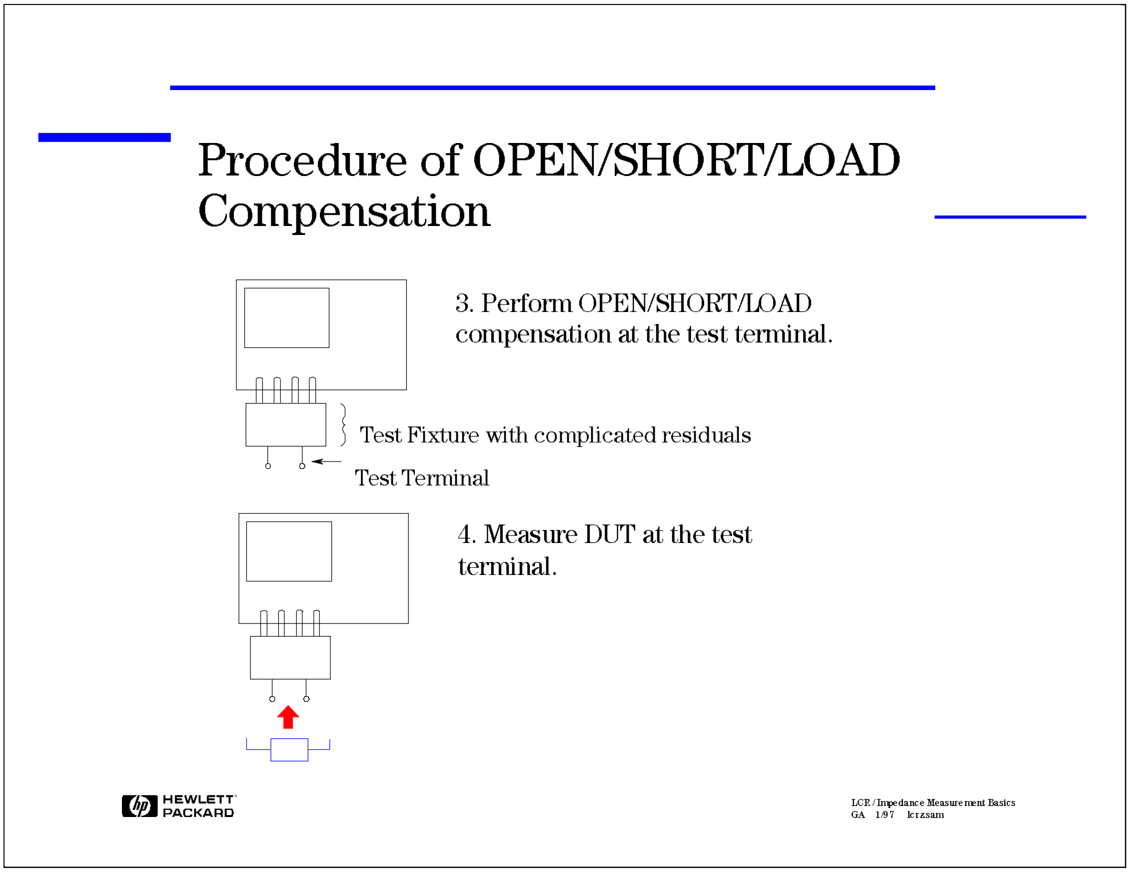


This procedure shows how to perform OPEN/SHORT/LOAD compensation.

1) Measure the reference value of the LOAD device with the most accurate setup. (HP direct-connect type test fixture, OPEN/SHORT compensation, integration time, averaging).

2) Input the LOAD's reference value into the instrument as a reference data.

Slide #70



3) Connect the test fixture/cable to be compensated. Open the test terminals and perform the OPEN compensation. Short the test terminals and perform the SHORT compensation. Connect the LOAD to the test terminals and perform the LOAD compensation.

4) Measure a DUT at the test terminals. Then we can obtain an accurate measurement of the DUT.

Slide #71

LOAD Device Selection

- Consideration 1 -

- When you measure DUTs which have various impedance values,

  ➔ Select a LOAD device whose impedance value is 100Ω ~ 1kΩ.

- When you measure a DUT which has only one impedance value,

  ➔ Select a LOAD device whose impedance value is close to that of the DUT to be measured.

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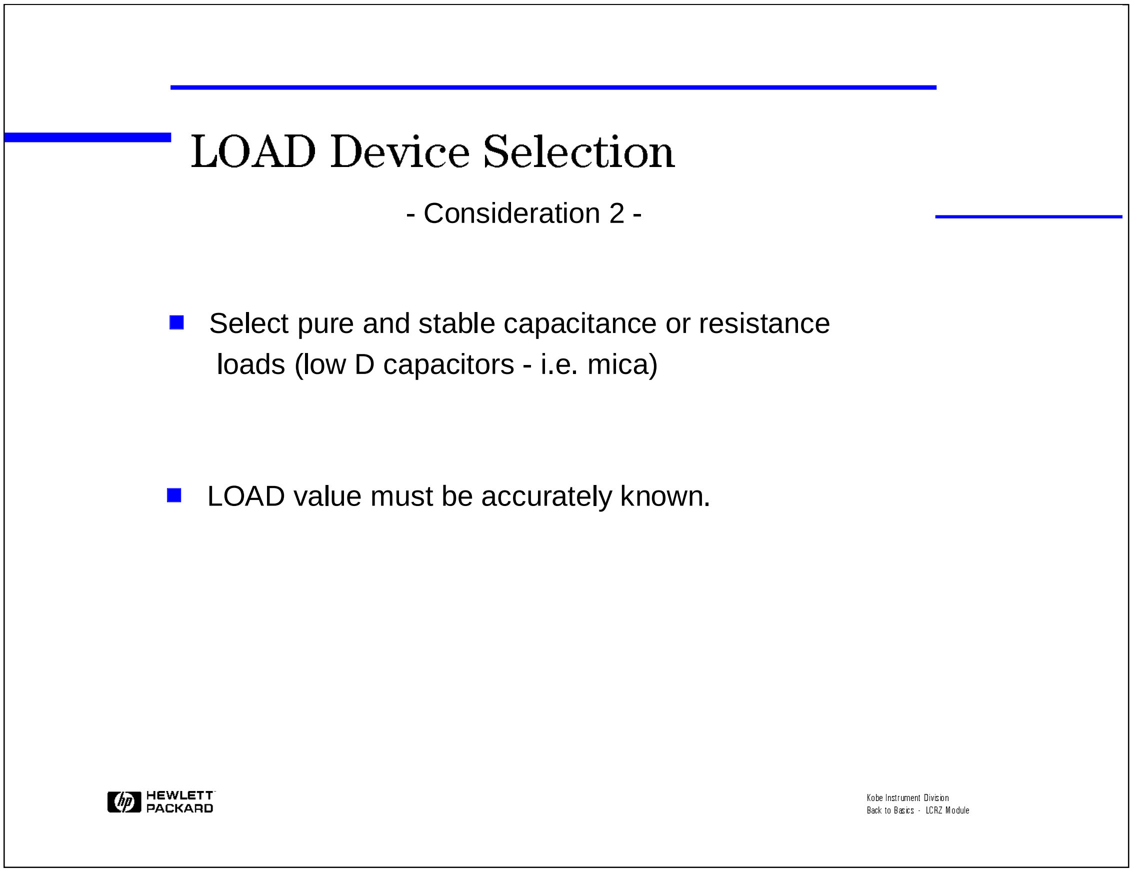
It is important to use a proper LOAD device for accurate measurements.

When measuring the DUT's various impedance values, it is recommended to use a 100 ohm to 1 kohm device as a LOAD, because the LCR Meters/Impedance Analyzers can optimally measure this impedance range with be best accuracy.

When measuring a DUT of one impedance value it is recommended that the LOAD have a impedance value close to that of the DUT.

Slide #72



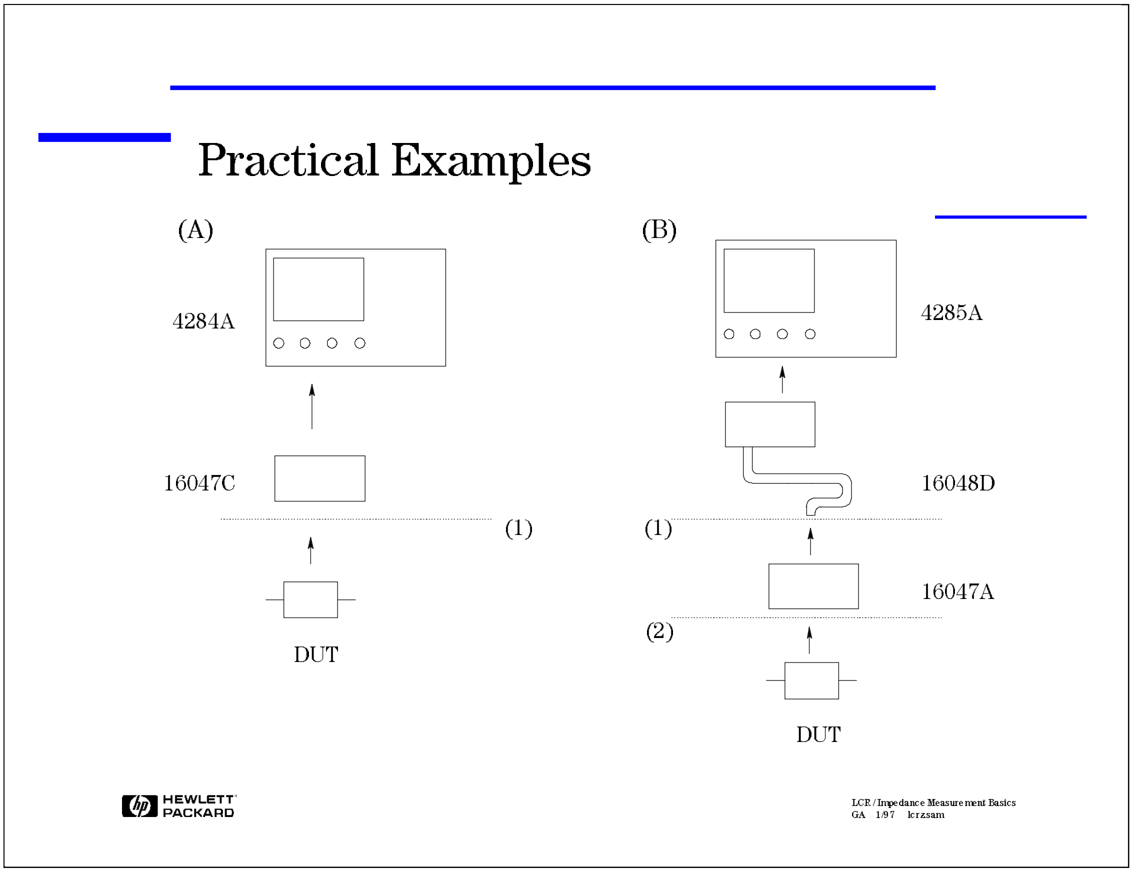
There is no restriction that a inductor must be used for inductance measurements, or a capacitor must be used for capacitance measurements.

Since the LOAD device must be stable, capacitors or resistors are better suited than inductors. Inductors are more susceptible to environment conditions like humidity and temperature.

When measuring low loss (low D, high Q) DUTs, it is necessary to use a very low loss LOAD. The LOAD's true value must be known accurately.

When measuring the LOAD's true value, it is important to use a test condition with the highest accuracy.

Slide #73

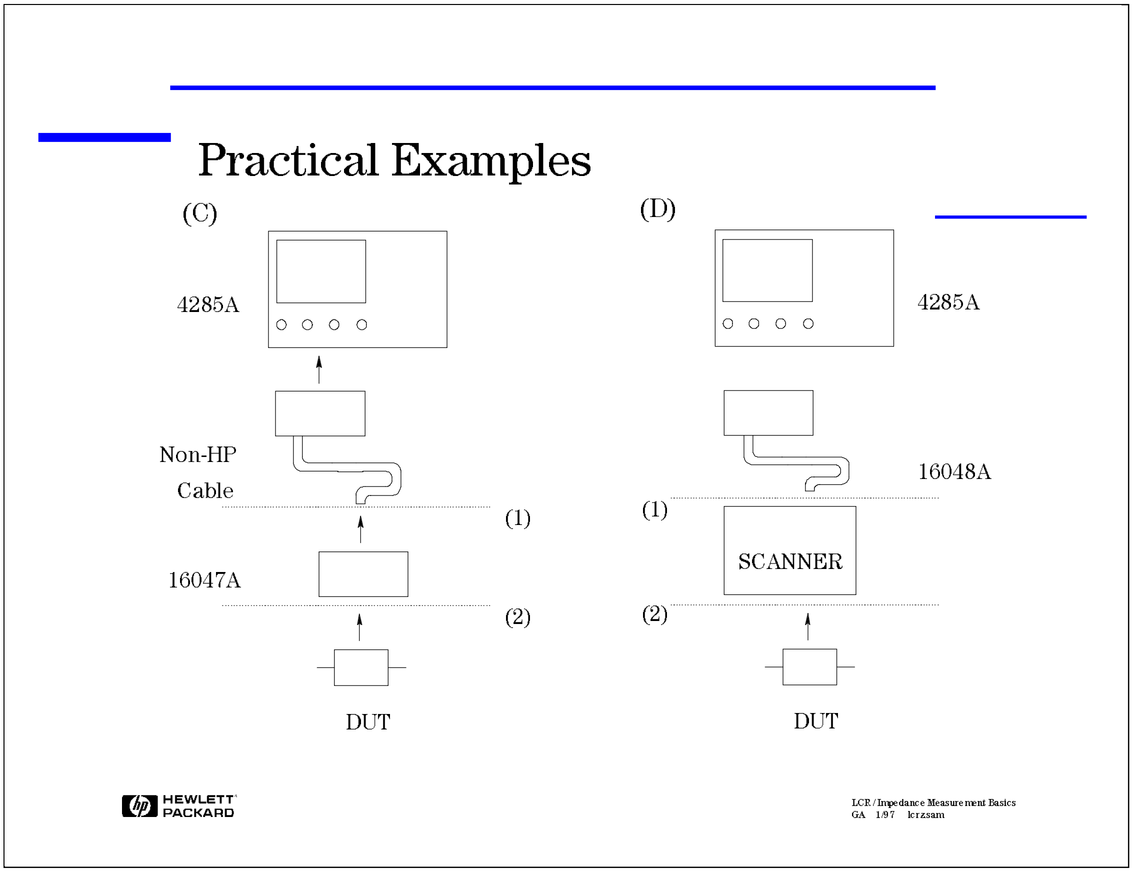


Here are some examples of error compensation:

A) Performing the OPEN/SHORT compensation to remove the residual of the HP16047C at (1).

B) Performing the Cable Correction to extend the calibration plane to (1), then performing the OPEN/SHORT compensation at (2).

Slide #74



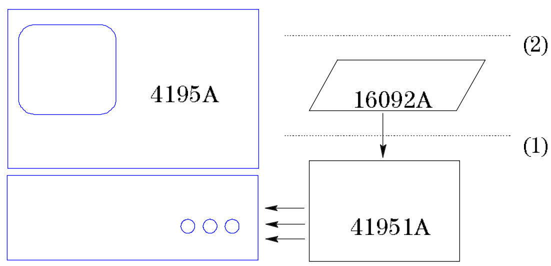
C) Performing the OPEN/SHORT/LOAD correction at (2) to remove the error caused by the phase shift in a Non-HP cable and the residuals of the HP16047A.

D) Performing the Cable Correction to extend the calibration plane to (1), then performing the OPEN/SHORT/LOAD compensation at (2) to remove the error caused by the complex residuals of a scanner.

Slide #75

Practical Example

(E)



E) Performing Calibration at (1), then performing the OPEN/SHORT compensation at (2) to remove the residuals of the HP16092A.

* When using the instruments with the Calibration function using OPEN/SHORT/LOAD terminations, Calibration must be performed first.

Slide #76

Summary

Calibration and Compensation Comparison

	Theory
Calibration	• Eliminate instrument system errors • Define the "Calibration Plane using a CAL standard
Cable correction	• Eliminate the effects of cable error • Extend "Calibration Plane" to the end of the cable
Compensation	• Eliminate the effects of error sources existing between "Calibration Plane" and DUT
OPEN/SHORT Compensation	• Eliminate the effects of simple fixture residuals
OPEN/SHORT/LOAD Compensation	• Eliminate the effects of complex fixture residuals

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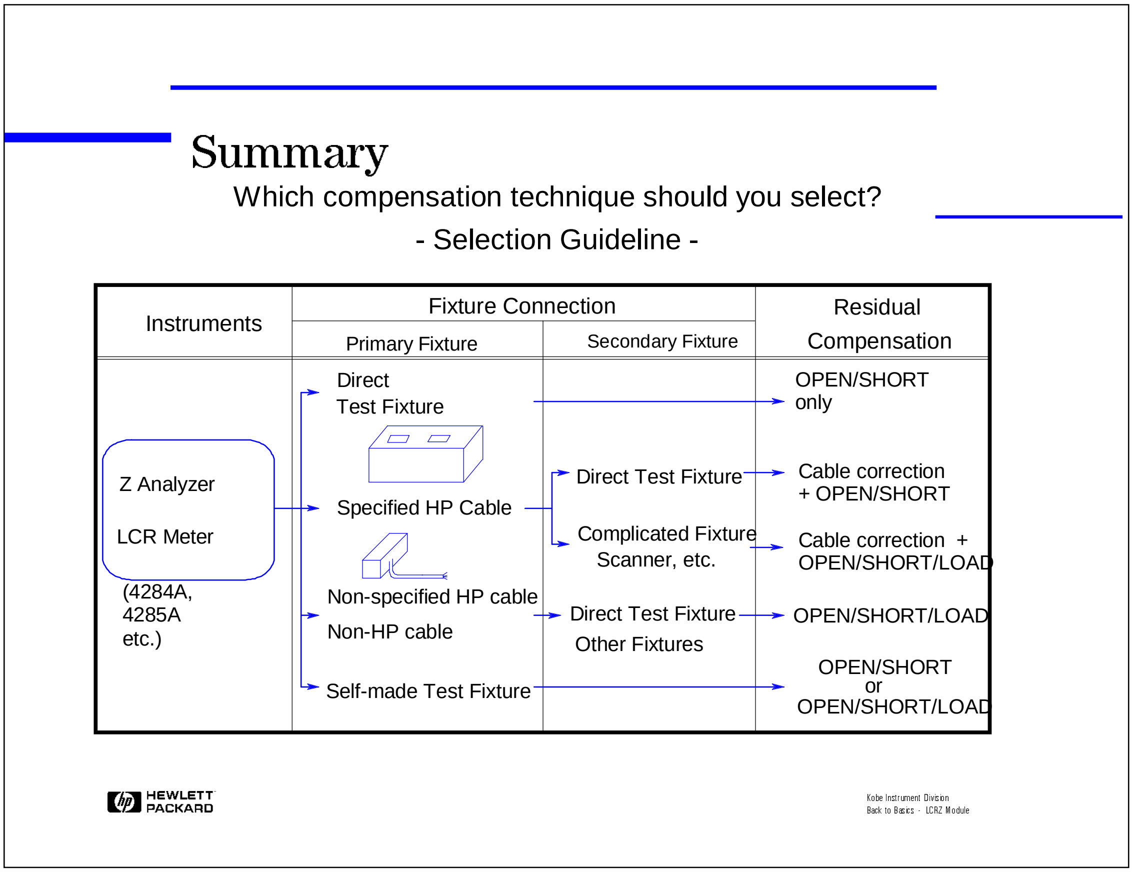
This table summarizes compensation descriptions.

Slide #77



This table summarizes compensation selection rules.

References

HP Lit. Number	*Title*
5950-3000	Impedance Measurement Handbook
5952-1430E	LCR Meter, Impedance Analyzers and Test Fixtures Selection Guide
5965-1244E	Accessories Selection Guide for Impedance Measurements
5091-6553E	Effective Impedance Measurement Using OPEN/SHORT/LOAD Correction
5091-4134E	Effective Transformers/ LF Coils Testing - HP 4263A/B LCR Meter -
5091-4783E	Effective Electrolytic Capacitors Testing - HP 4263A/B LCR Meter -
5091-4132E	Contact Resistance and Insulation Resistance Measurements of Electromechanical Components - HP 4338A/B Milliohmmeter, HP 4339A/B High Resistance Meter
5091-4133E	Insulation Resistance Measurements of Plate-type Materials - HP 4339A/B High Resistance Meter -
5091-6669E	Effective Insulation Resistance Testing using a Scanner - HP 4339A/B High Resistance Meter -
5950-2949	Optimizing Electronic Component and Material Impedance Measurements - HP 4284A Precision LCR Meter -
5950-2975	Impedance Testing using Scanner - HP 4284A Precision LCR Meter -
5091-1596E	High accuracy & fast RF inductor testing (HP 4285A)
5090-2994	Capacitive measurements of liquid crystal cells (HP 4284A)
5950-2935	Solid material dielectric constant meas. (HP 4194A)
5950-2923	Constant current measurements (HP 4194A)
5952-7871	Static head testing for disk drives (HP 4194A)
5950-2919	Multi-frequency C-V measurements for semiconductor (HP 4194A)
5950-2882	Impedance characteristics of resonators (HP 4194A)
5950-2856	Component & circuit evaluation (HP 4194A)
5962-9522E	Dielectric Constant Measurements using the HP 16451B Test Fixture
5962-6922E	Evaluating Temperature Characteristics using a Temperature Chamber & the HP 4291A
5962-6973E	Permittivity Measurements of PC Board and Substrate Materials using the HP 4291A and HP 16453A
5962-6972E	Permeability Measurements using the HP 4291A and HP 16454A
5962-9725E	Electronic Characterization of IC Package using the HP 4291A and the Cascade Microtech Prober
5964-1690E	On-Chip Semiconductor Device Impedance Measurements using the HP 4291A
5964-6522E	Materials Characterization with a New Dielectric Spectrometer BDS 6000 and the HP 4291A

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