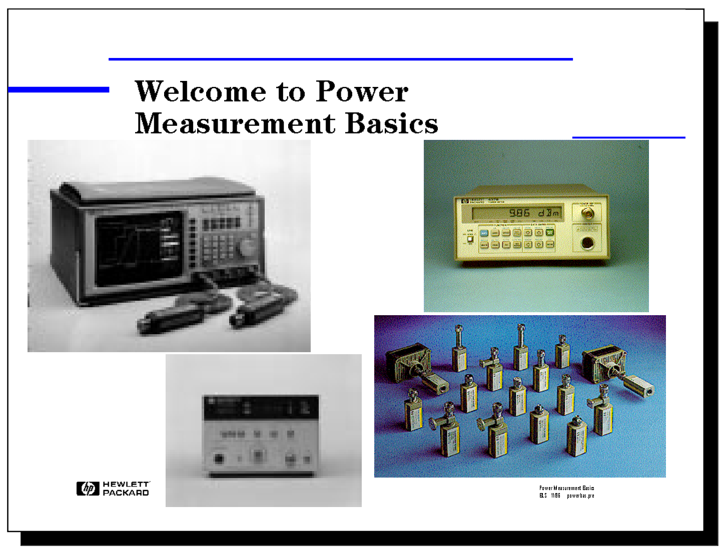
Power Measurement Basics

Boyd Shaw

Hewlett-Packard Company
Microwave Instruments Division
1400 Fountaingrove Parkway
Santa Rosa, California 95403
U.S.A.



1997 Back to Basics Seminar

Abstract

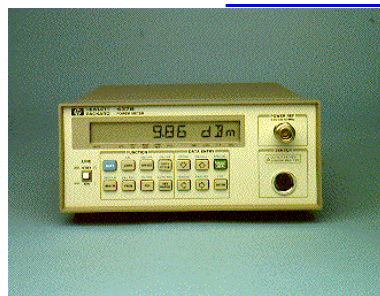
In this presentation you will learn high-frequency power measurements and how they differ in important ways from low-frequency or DC measurements. Definitions and terms involving absolute and ratioed power measurements are also covered. You will learn about the differences in various power measurements and situations where each type of measurement is used. Another section covers measurement uncertainty associated with power measurements, including sensor and source mismatch, sensor errors, and meter errors. An uncertainty calculation example is presented. Next, some of the hardware and theory behind the three major types of power sensors and meters associated with these sensors are given. Finally, considerations in choosing the correct equipment for making particular measurements will be covered.

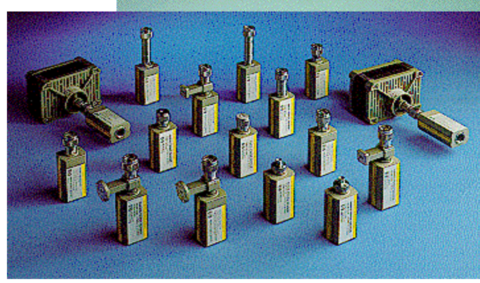
Author

Boyd Shaw is a Business Development Engineer for Hewlett-Packard's Microwave Instruments Division in Santa Rosa, California. He graduated from the University of Colorado at Boulder with a BSEE and an undergraduate business degree with emphasis in Finance. He works in the marketing department with responsibility for application and market knowledge of the family of economy network analyzers and power measurement equipment.

Slide #1

Welcome to Power Measurement Basics





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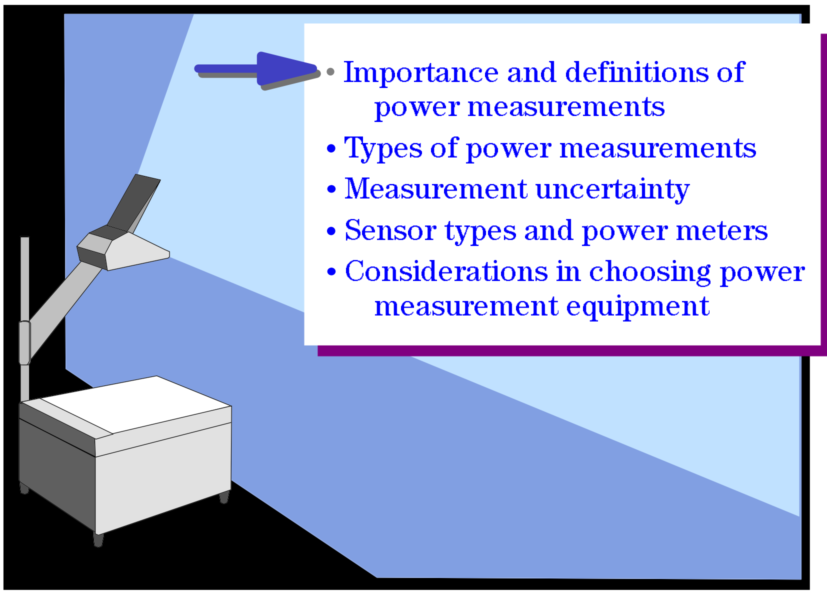
Hello and welcome to Power Measurement Basics!!

Slide #2

Agenda



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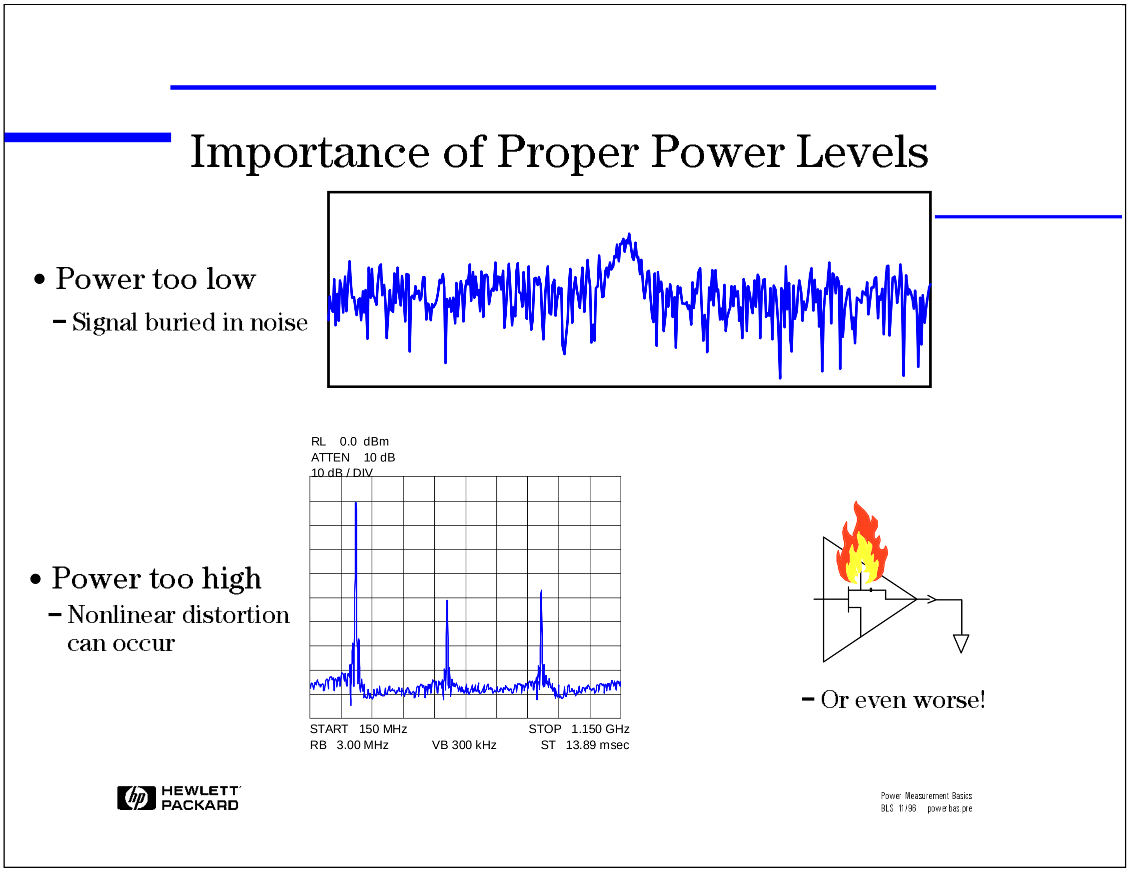
Slide #3



A system's output power level is often the critical factor in the design and performance of RF and microwave equipment. Power is so important that it is frequently measured twice at each level, once by the vendor and again at the incoming inspection stations before beginning the next assembly level.

Measurement of power is critical at every system level, from the overall system performance to the fundamental devices. The large number of power measurements and their importance to system performance dictates that the measurement equipment and techniques be accurate, repeatable, traceable, and convenient.

In a system, each component in a signal chain must receive the proper signal level from the previous component and pass the proper level to the succeeding component. If the output power level becomes too low, the signal becomes obscured in noise. If the power level gets too high, though, the performance goes nonlinear and distortion results. In addition to possible nonlinear performance, higher power levels mean increased complexity of designs, more expensive active devices, greater skill in manufacturing, more difficult testing, and decreased reliability.

The measurement of power in microwave devices in particular can be very important due to the fact that these devices are often run closer to their maximum output power limits, increasing the chance of stress-related failures.

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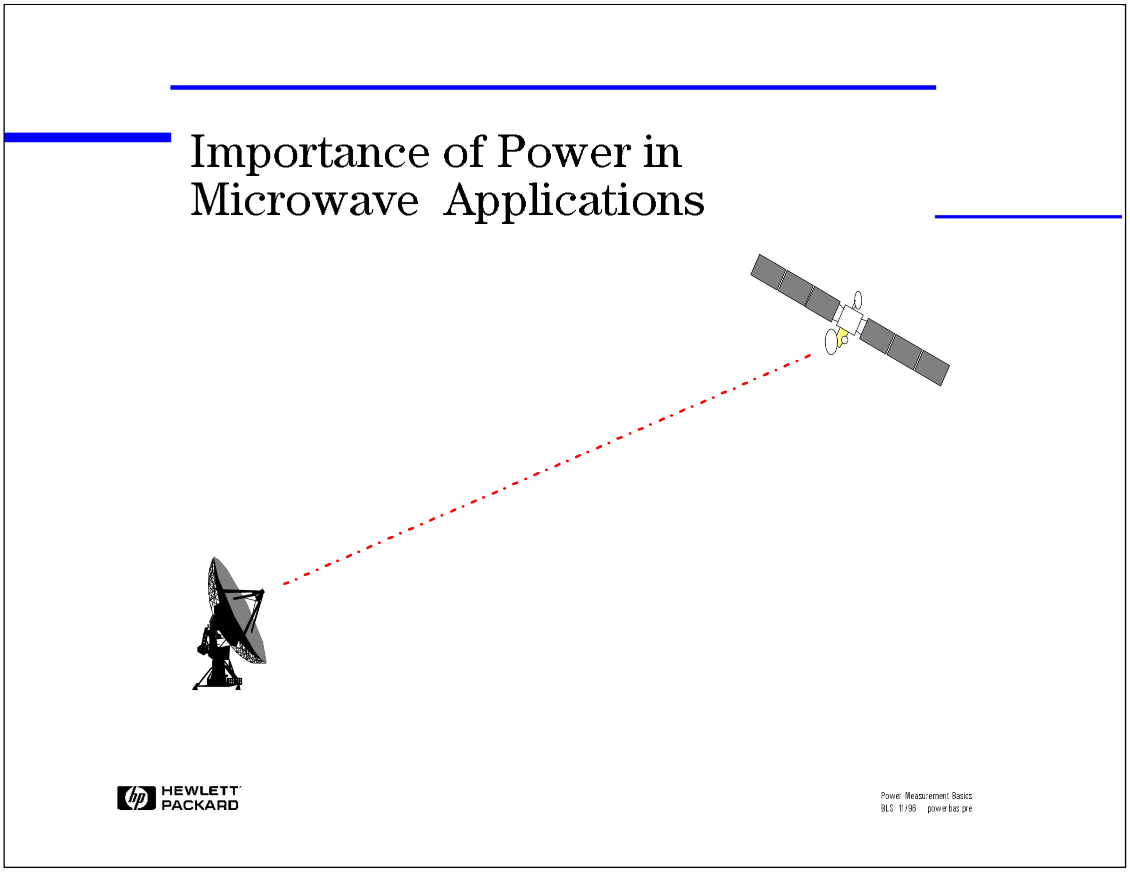

An example of the relationship between power and cost is shown in the figure above. Antenna size is inversely proportional to the power from the transmitter. The higher the power you are transmitting from the ground, the smaller the antenna on the satellite can be. Since the costs associated with launching can be on the order of thousands of dollars for each pound launched, smaller antennas (which weigh less) can result in considerable cost savings.

Since the path loss from a transmitting dish on the earth to a satellite in geosynchronous orbit is around 200 dB, the power being transmitted must be very large. Again, this can be equated to cost. The dish will be more costly due to the complexity of design, and difficulty of testing. Additionally, the high-power devices used in the transmitter will be more costly than devices that operate at less extreme power levels.

Slide #5

Units and Definitions

- Unit of power is the watt (W): 1W = 1 joule/sec
- The watt is a basic unit: 1 volt is defined as 1 W/ampere
- Relative power measurements are expressed in dB: P(dB) = 10 log(P/Pref)
- Absolute power measurements are expressed in dBm: P(dBm) = 10 log(P/1 mW)

Power is defined as the amount of energy flow per unit of time, and the basic unit of power is the watt (W). One watt equals one joule per second. The watt is a basic unit in that other electrical units are derived from the watt. For example, a volt is defined as one watt per ampere.

Often times, one is interested only in relative power which is expressed in decibels (dB). There are two primary benefits to using dB. First, the range of numbers commonly used is more compact; for example +63 dB to -153 dB is more concise notation than $2 \times 10^{+6}$ to 0.5×10^{-15}. The second advantage is apparent when it is necessary to find the gain of several cascaded devices. Multiplication of numeric gain is then replaced by the addition of the power gain in dB of each device.

Absolute power is expressed in terms of dB relative to some power level. For example, power relative to 1 mW is stated in dBm.

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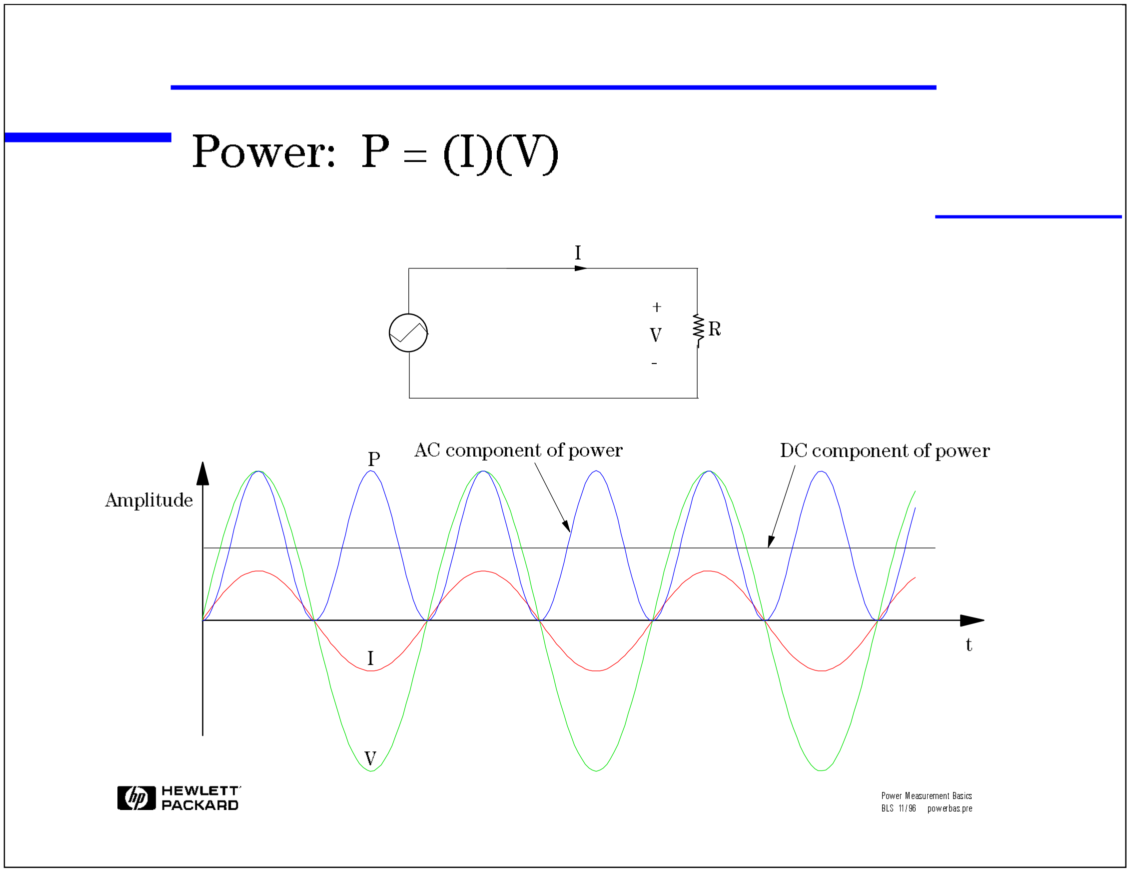


First, let's make sure we understand what is meant when talking about "power". General circuit theory says that for an arbitrary load, power is the product of voltage, current, and the power factor (where power factor is defined as the cosine of the phase angle between the voltage and current). For a purely resistive load the power factor is one and instantaneous power is simply the product of voltage and current. For an AC signal we see that power is time dependent. This product of voltage and current is sinusoidal with a DC term and has a frequency twice that of the AC signal. "Power" as most commonly used, refers to the DC component of the product. To find this DC term, the power curve must be integrated to find the area under the curve and then divided by the length of time over which the area is taken. Note: this length of time should be an exact number of AC periods, but as the number of periods gets higher and higher, whether you measure a precise number of periods or not makes a vanishingly small difference.

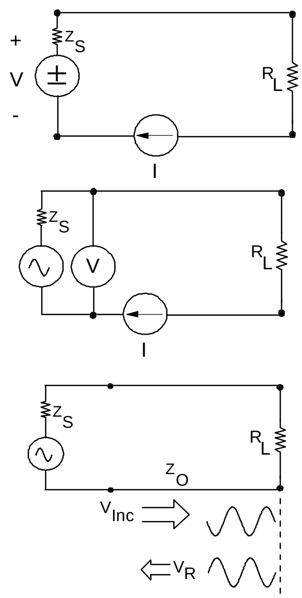
Fundamentally, power is defined as the energy transfer per unit time averaged over many periods of the lowest frequency involved.

For sinusoidal signals, the relationship between peak and rms (root-mean-square) values are:
$V_p = \sqrt{2}\, V_{rms}$ and $I_p = \sqrt{2}\, I_{rms}$. The rms value for a periodic sinusoidal current (voltage) is defined as the constant that is equal to the DC current (voltage) that would deliver the same average power to a resistance R.

Slide #7

Power Measurements at Different Frequencies

- DC
- Low Frequency
- High Frequency



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At DC, the voltage drop across a device and current through the device are measured directly. Power is then found by one of these equations:

$$P = IV = \frac{V^2}{R} = I^2 R$$

At frequencies below approximately 100 kHz, power measurements are not distinctly different and are still usually found from voltage or current. Though the measurement of voltage and current is still practical for frequencies in the tens and hundreds of MHz range, the direct measurement of power is more accurate and easier. As a result, voltage and current are usually the calculated parameters at these frequencies.

As the frequency approaches 1 GHz, direct power measurements become prevalent in most applications because voltage and current measurements become impractical. One reason for this is that voltage and current may vary with position along a lossless transmission line but power maintains a constant value. Another example of decreased usefulness is in waveguide transmission configurations where voltage and current are more difficult to define. For these reasons, at radio and microwave frequencies, power is more easily measured, easier to understand, and more useful than voltage or current as a fundamental quantity.

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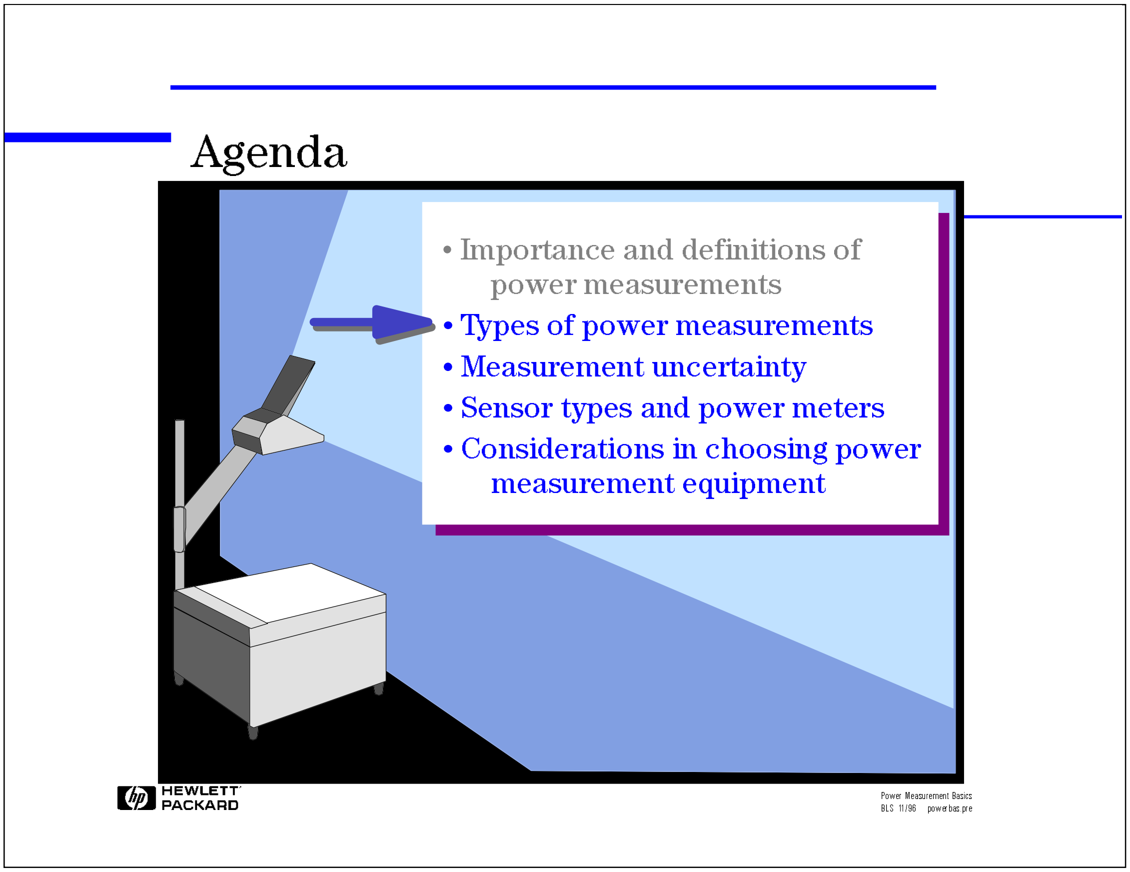
Agenda
• Importance and definitions of power measurements
• Types of power measurements
• Measurement uncertainty
• Sensor types and power meters
• Considerations in choosing power measurement equipment
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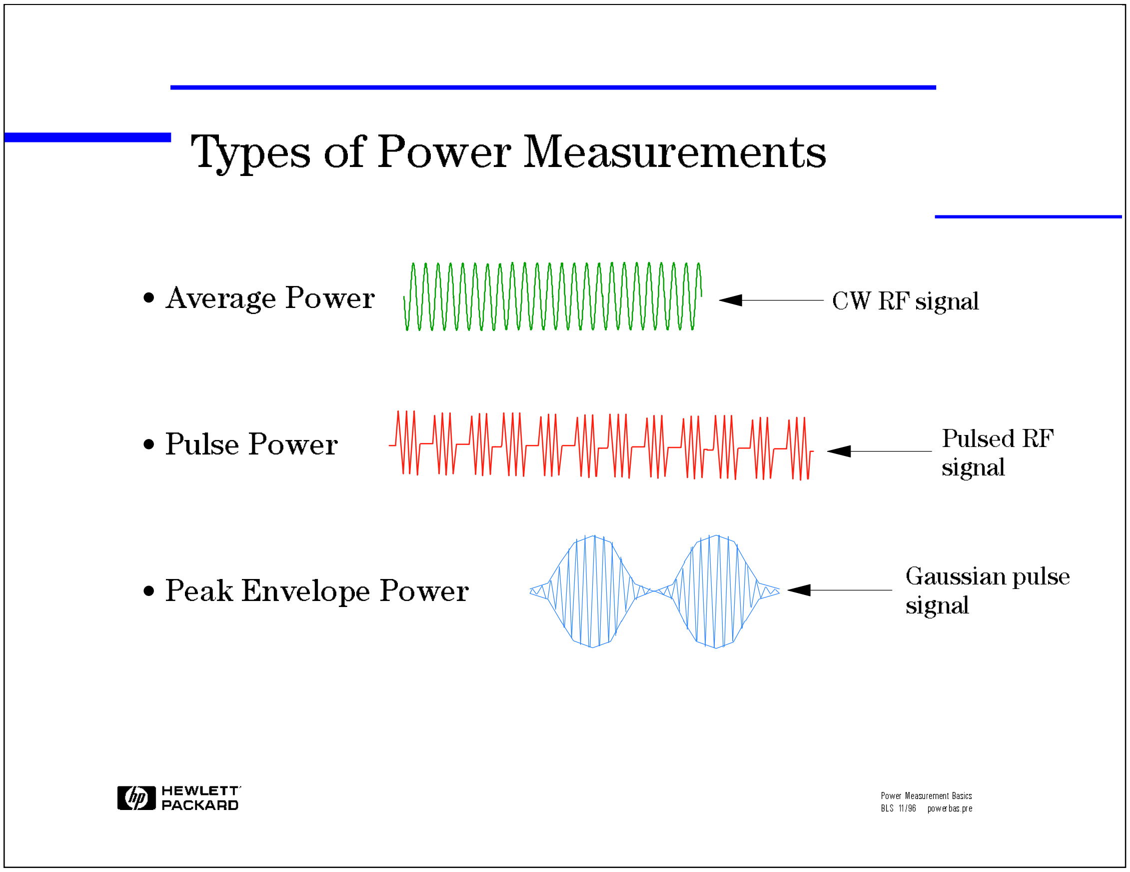
Slide #9



Average, pulse, and peak envelope power measurements are all different types of measurements that will provide different information about a signal. Average power provides average power delivered over several cycles and typically is implied when talking about "power". Pulse power is used in situations where complete characterization of the modulated envelope itself is needed. Finally, peak envelope power should be used to obtain more accurate measurements when the pulse becomes non-rectangular and peak power equations would no longer be accurate. Each type of measurement will be discussed.

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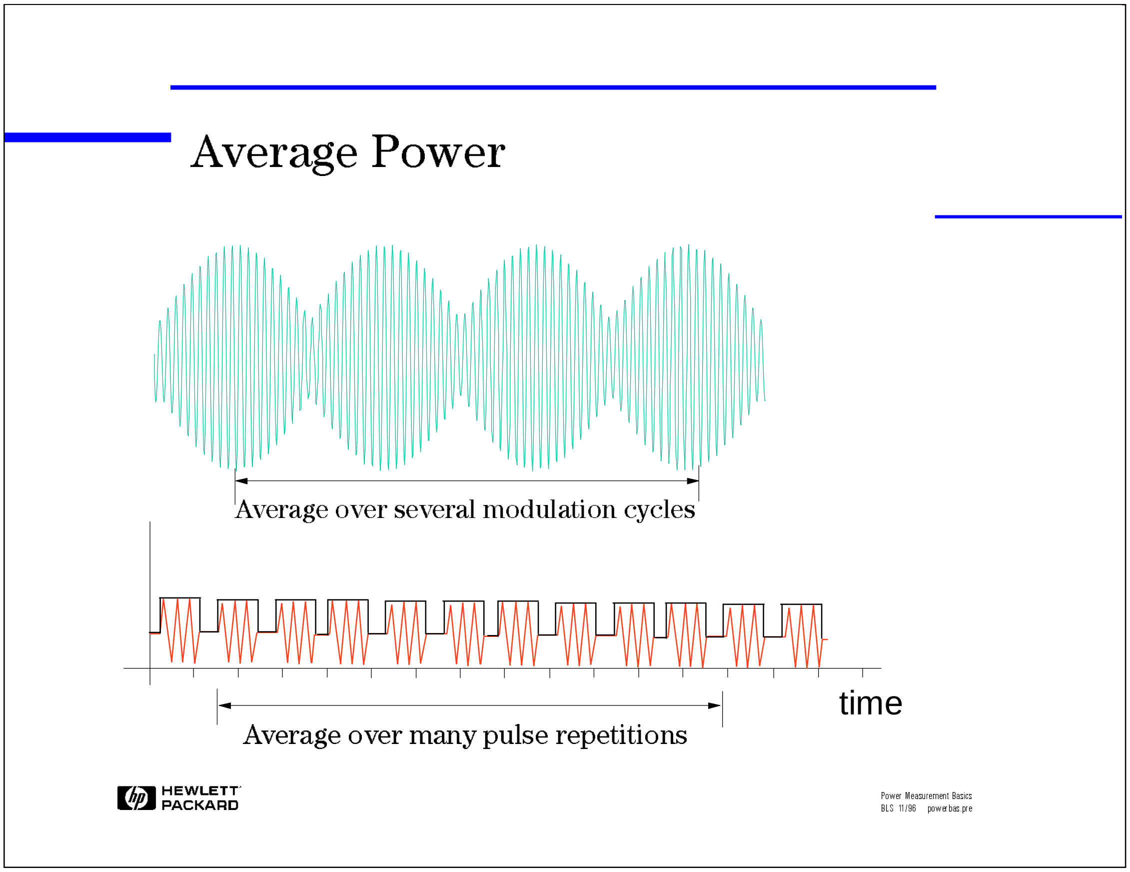


Average power is defined as the energy transfer rate averaged over many periods of the lowest frequency in the signal.

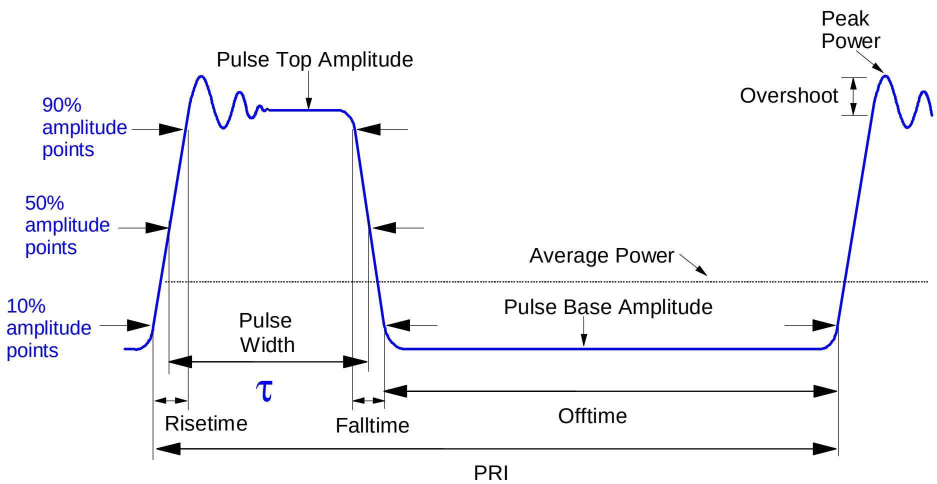
For an AM signal, averaging is taken over many modulation cycles, and for a pulse modulated signal the signal is averaged over several pulse repetitions. Of all the power measurements, average power is the most frequently measured because convenient measurement equipment with highly accurate and traceable specifications is available. Also, pulse power and peak envelope power can sometimes be calculated from average power measurements if certain waveform characteristics are known.

In some instances, average power measurements cannot provide all the information that may be needed. For example, if you want to completely characterize the envelope of a signal, a peak power analyzer must be used.

Slide #11

Pulse Power

- Complete modulation envelope analysis



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If you are operating an amplifier close to its maximum input level, you may be interested in more than just the average power of your signal. You may also like to know the amount of overshoot in the rising edge of your pulse. To find out the amount of this overshoot, you would need to do a pulse power measurement for a complete waveform characterization. Pulse power measurements provide many parameters of a pulse signal. These measurements are made using peak power analyzers which provide envelope statistics using its scope-like output. Common waveform parameters can be seen on the slide. Two additional commonly used parameters not shown on the slide are:

$PRF = 1/PRI$ where PRI is 'pulse repetition interval' and PRF is 'pulse repetition frequency'. Also,
$DutyCycle = (PulseWidth/PRI)(100\%)$

For pulse power, the energy transfer rate is averaged over the width of the pulse τ. Pulse width τ is defined as the time between the 50 percent amplitude points (relative to pulse top amplitude and pulse base amplitude). Pulse power does not measure the peak of the pulse, but rather averages out any aberrations such as overshoot, or ringing. Mathematically, pulse power is given by: $P_{pulse} = \frac{1}{\tau}\int v(t) \bullet i(t)dt$ which can be difficult to measure at RF.

Often, pulse power for a rectangular pulse is also defined by: $P_{pulse} = \frac{P_{avg}}{DutyCycle}$ which is easier to measure at RF and is a good way to find pulse power using an average power meter when you know the duty cycle of the pulse.

Notice, that in finding pulse power, we are interested only in the power contained in each pulse. This is why averaging is done only over the width of the pulse, rather that averaging over many pulse repetitions like was done for average power.

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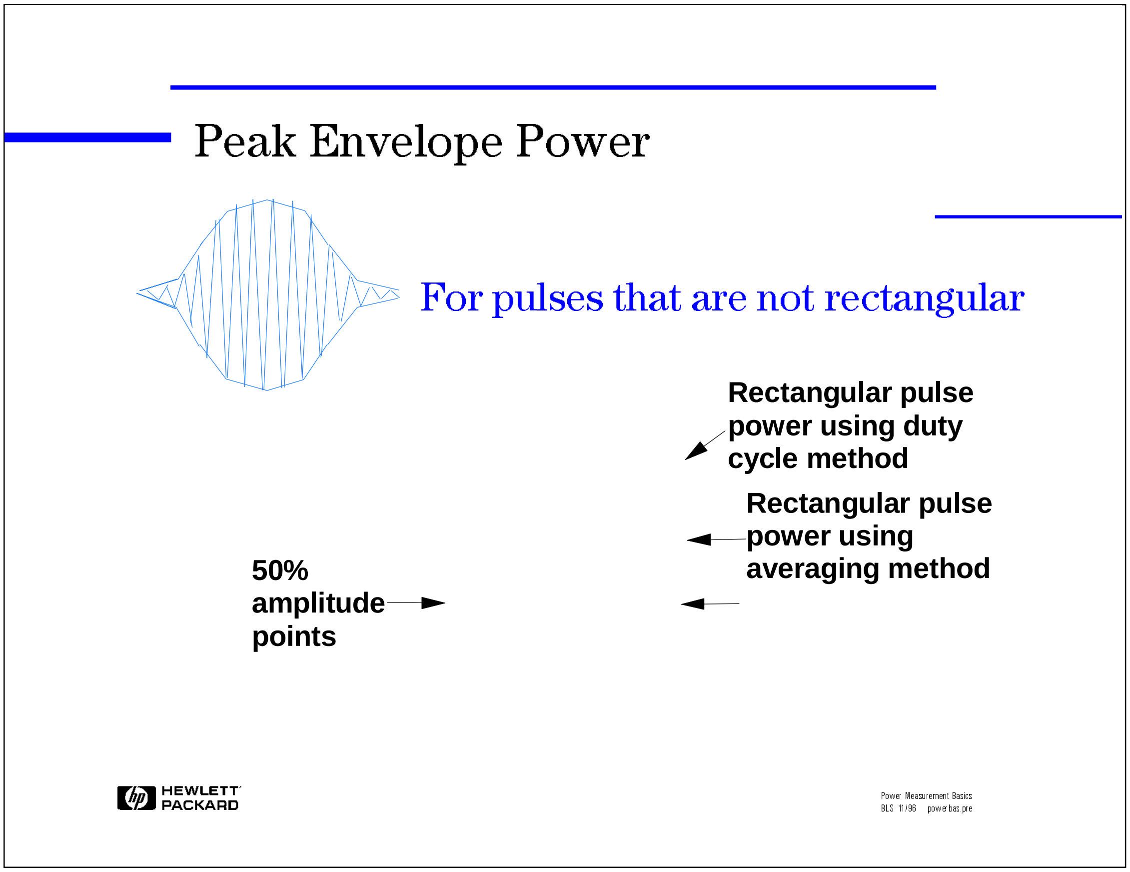
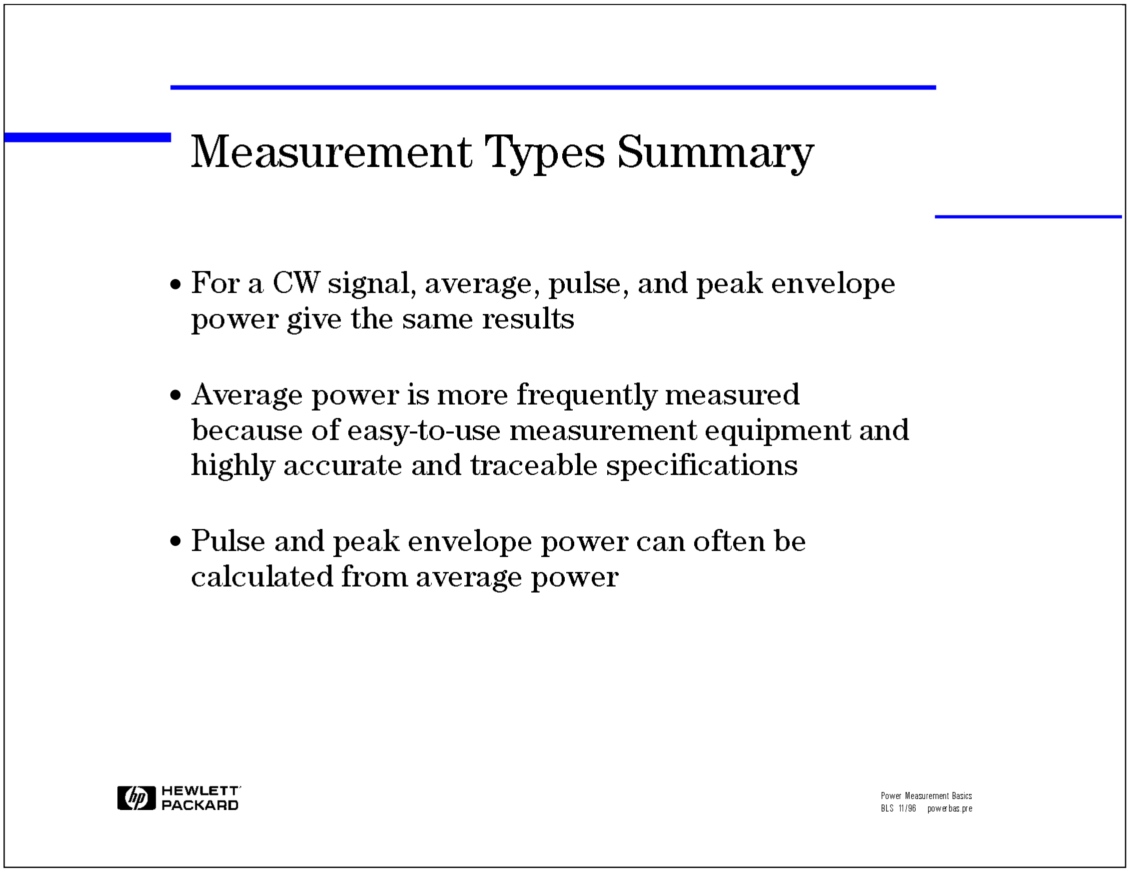


In certain applications, like wireless telephony, the pulse shape is rounded rather than rectangular like the signals discussed in regards to pulse power. This is done to save bandwidth. To narrow the signal in the frequency domain, the sharp edges present in a square wave must be reduced by widening the signal in the time domain. Once the pulse deviates substantially from a pure square wave (like those discussed in the previous page), the equations used to find the power contained in the pulse are no longer accurate. Envelope power is used when pulse power does not give a true picture of the power in a pulse.

Peak envelope power is a term used for describing the maximum pulse envelope power. Envelope power is measured by making the averaging time much less than $1/f_m$, where f_m is the highest frequency component of the modulation waveform. The averaging time is therefore limited on both ends: (1) it must be small compared to the period of the highest modulation frequency, and (2) it must be large enough to be many RF cycles long.

Continuously displaying the envelope power on a peak power analyzer will show the profile of the pulse shape. Peak envelope power is the maximum value of the envelope power. For perfectly rectangular pulses, peak envelope power is equal to pulse power as defined before and a peak power analyzer would be used to completely characterize the waveform.

Slide #13



We have seen here that there are different types of power measurements, and as one may expect, there are various instruments used in sensing power in these different ways. Before we talk about the hardware, let's understand the uncertainties that are inherent in power measurements.

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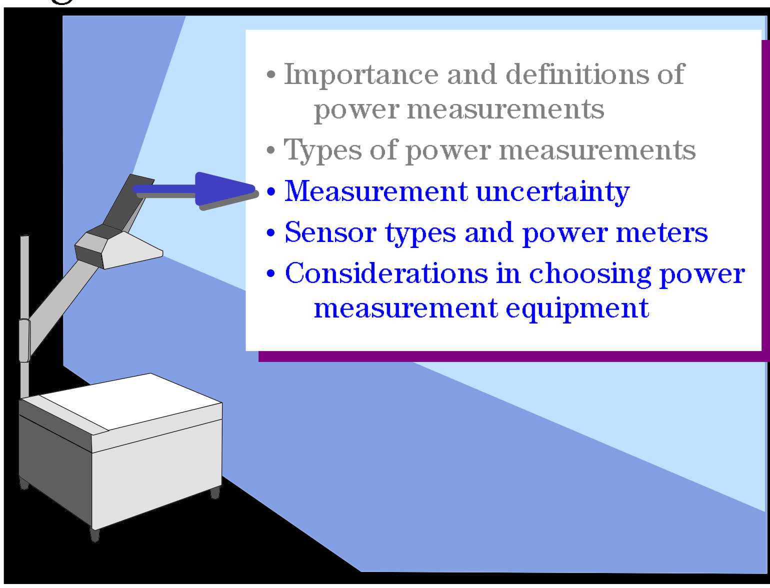
Agenda



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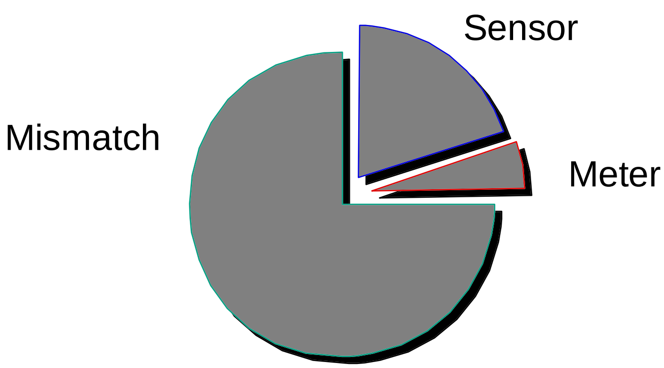
Slide #15

Sources of Power Measurement Uncertainty

- Sensor and source mismatch errors
- Power sensor errors
- Power meter errors



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In power measurements, like all measurements, there are many sources of error. Sensor and source impedance mismatch typically cause the largest errors in power measurements. By knowing the SWR (standing wave ratio) of the sensor and source, uncertainty due to mismatch can be found. Other sensor uncertainties such as effective efficiency and calibration factor are considered also. An analysis of the various instrumentation uncertainties of the power meter follows. Finally, an example combining all errors for a total uncertainty number will be shown.

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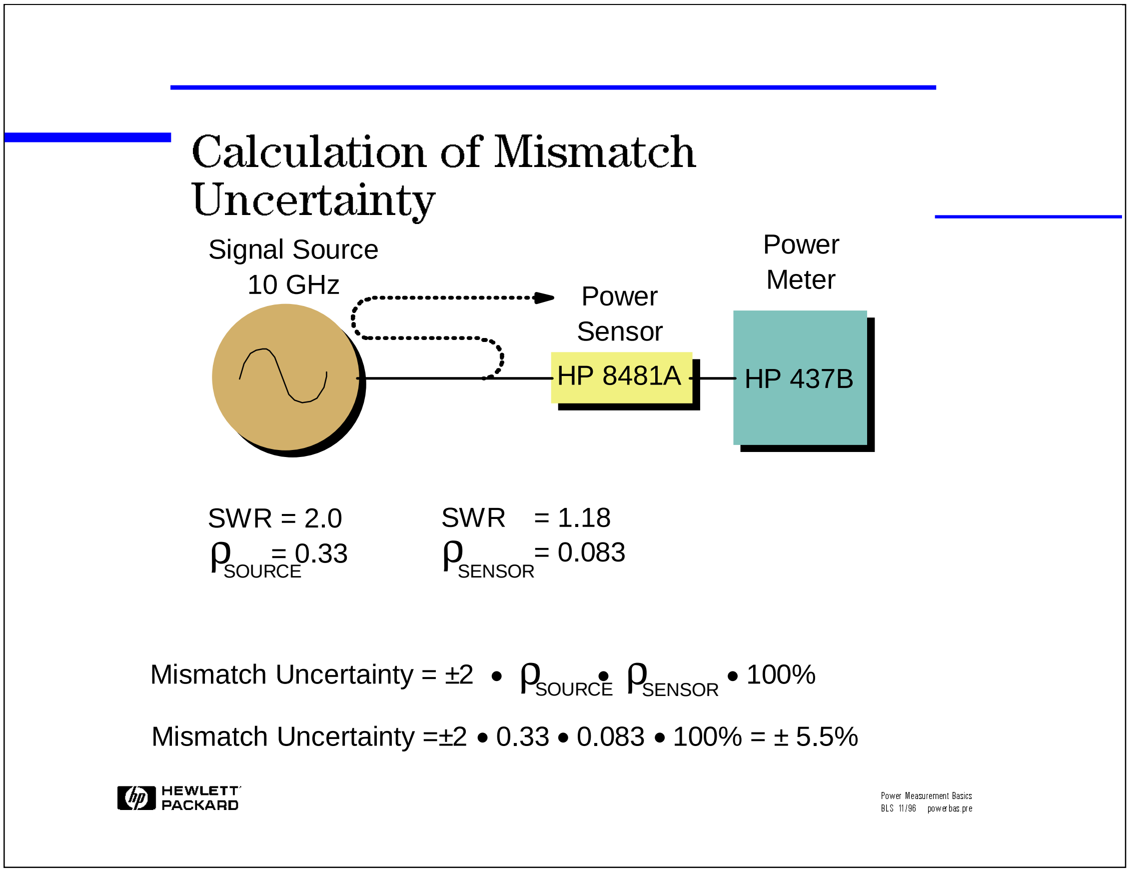

In a power measurement, we are usually interested in the amount of power that is delivered to an impedance of Z_0, so naturally we want the power sensor to be as close to Z_0 as possible. When the sensor is exactly Z_0, none of the signal reflects off the sensor, but rather is completely absorbed. Anytime that the sensor impedance deviates from this impedance, reflections will occur. This means that a portion of the source power never reaches the sensing element (and therefore cannot be measured). Similarly, the source will typically be mismatched also and reflections will occur there also. The exact amount of power actually entering the sensor is unknown since the reflection coefficient, Γ, is not typically known, but rather only the SWR. Although the exact power cannot be found, the maximum and minimum values of the power can be calculated.

Mismatch uncertainty is the uncertainty due to the imperfect matches of the source and sensor. The amount of mismatch uncertainty is found using known SWR values for both the sensor and the source. The HP 8481A Power Sensor has a SWR of 1.18 at 10 GHz and the source has a SWR of 2.0. A mismatch uncertainty percentage is found by using the equation in the figure. In this example, the mismatch alone contributes 5.5% uncertainty to the measurement!

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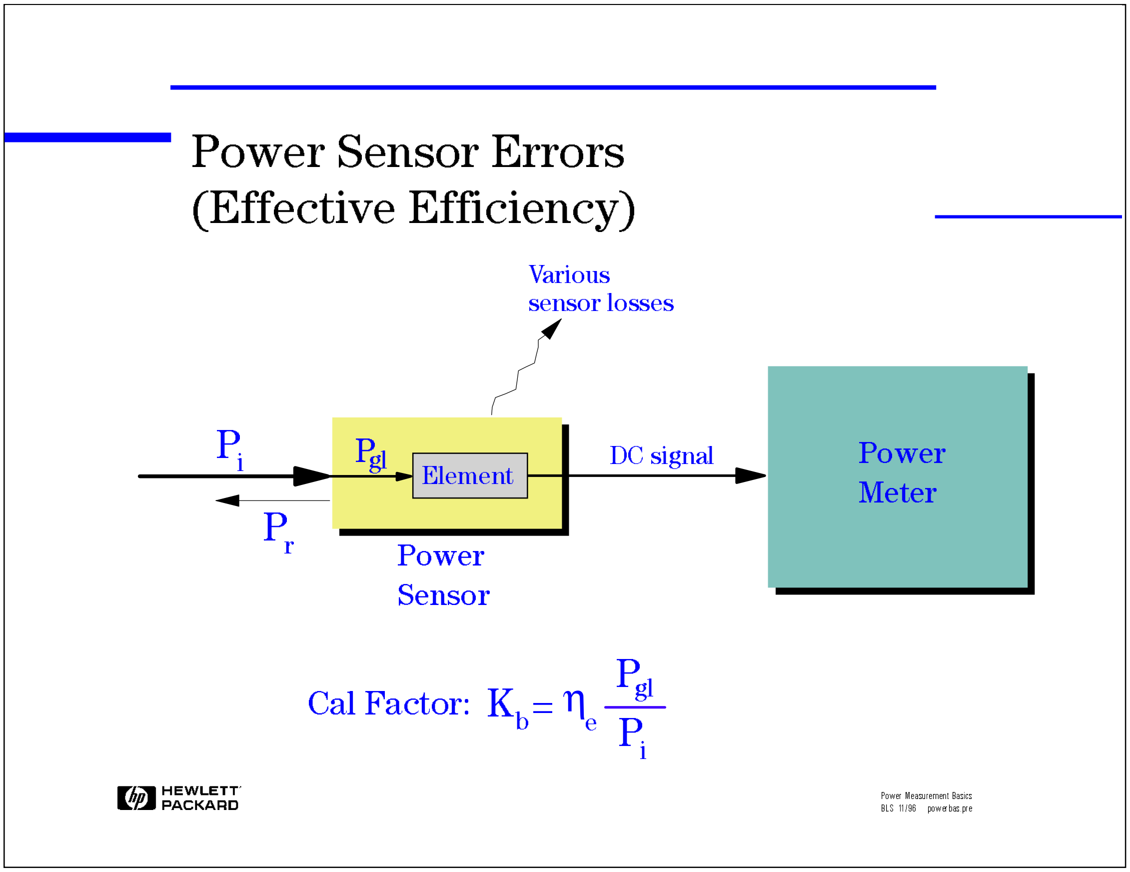

Another major source of error in power measurements is due to the imperfect efficiency of the power sensor. For a power sensor the "power in" is the net power delivered to the sensor; it is the incident power minus the reflected power. But the element of the sensor does not dissipate all the power entering the sensor. Some of the power is turned into heat in the instrumentation of the sensor. The metered power indicates only the power that the sensing element itself dissipates.

Calibration factor, K_b, takes into account the imperfect efficiency of the sensor and the mismatch loss, which accounts for the reflected signal. In the slide you see that calibration factor, $K_b = \eta_e \frac{P_{gl}}{P_i}$, where η_e is the effective efficiency and $\frac{P_{gl}}{P_i}$ is the mismatch loss. The calibration factor is unique to each sensor and is determined by the manufacturer on the production line. The calibration factor is printed on the label and a data sheet is shipped with each sensor. The calibration uncertainty, though, is common to a sensor model and is specified by the manufacturer. For the HP 8481A at 10 GHz the calibration factor uncertainty is 1.9%.

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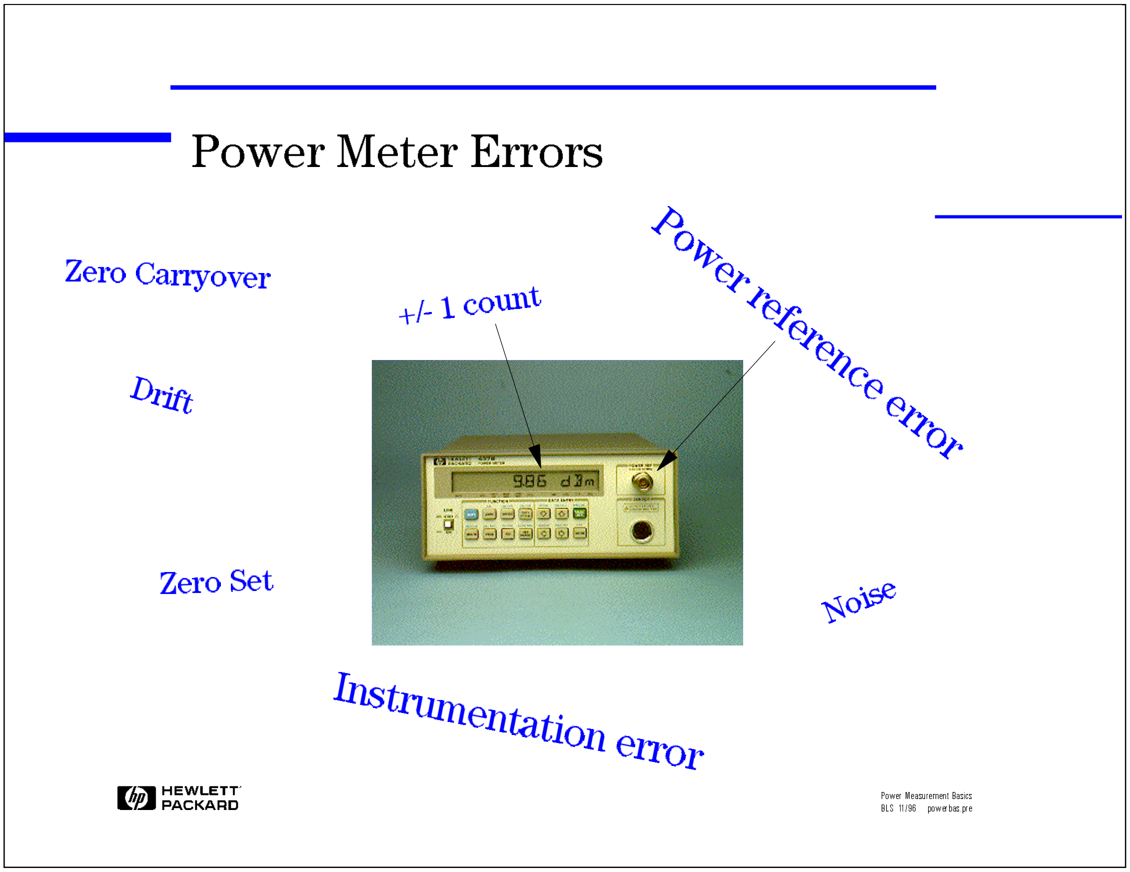
Slide #18



There are a number of errors associated with the electronics inside the power meter. These errors should be included for a complete uncertainty analysis, even though they typically are smaller than the mismatch and sensor errors.

Power reference error

Thermocouple or diode sensors require a highly accurate, known power source to verify and adjust for the sensitivity of the individual sensor. For example, the HP 436A, HP 437B, and the HP 438A Power Meters all have a 1.0 mW, 50 MHz power source. Power reference error deals with the uncertainty in the output of this power source. The HP 437B has a power reference specified to ± 1.2% uncertainty for one year.

Instrumentation error

Instrumentation uncertainty is the combination of such factors as meter tracking errors, circuit non-linearities, range-changing attenuator inaccuracy, and amplifier gain errors. The instrument manufacturer guarantees the accumulated uncertainty is within a certain limit. The instrumentation uncertainty for the HP 437B is ± 0.5%.

Slide #19

Calculating Power Measurement Uncertainty

Mismatch uncertainty:	± 5.5%
Cal factor uncertainty:	± 1.9%
Power reference uncertainty:	± 1.2%
Instrumentation uncertainty:	± 0.5%

Now that the uncertainties have been determined, how are they combined?

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Here are the largest sources of individual uncertainty for our example power measurement. Now we want to find out how these uncertainties act together to affect the final measurement result. Power measurement uncertainties are typically denoted in one of two ways: worst-case and root-sum-of-the-squares (rss). Let's examine these two methods.

Note that for this example the uncertainties listed above are for 10 GHz and 10 dBm. The power reference and instrumentation uncertainties are specified for the entire range of the power meter and are specified by the manufacturer. The calibration factor uncertainty is specified at different frequency points within the range of the sensor and can be found in the technical specifications of the sensor. The mismatch uncertainty will depend on both the SWR of the source and the sensor. The maximum SWR of the sensor for a certain frequency range can be found in the technical specifications and the SWR of the source will need to be found from specifications related to the source.

At this power level (10 dBm) zeroing errors and noise are not included. At lower power levels, say below -60 dBm for a diode sensor, these errors can be very significant and should be included in any uncertainty analysis.

Slide #20

Worst-Case Uncertainty

- In our example worst case uncertainty would be:

= 5.5% + 1.9% + 1.2% + 0.5% = ± 9.1%

+9.1% = 10 log (1 + 0.091) = + 0.38 dB

- 9.1% = 10 log (1 - 0.091) = - 0.41 dB

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One value of total uncertainty frequently assigned to a power measurement is the worst-case uncertainty. This situation comes about if all the possible sources of error were at their extreme values and in such a direction as to add together constructively and therefore achieve the maximum possible deviation between the measured and actual power value.

This worst-case approach results in an uncertainty of ± 9.1%, or + 0.38, - 0.41 dB.

Note: It is VERY unlikely that all errors will add together, making this worst-case scenario extremely conservative.

Slide #21

RSS Uncertainty

• In our example RSS uncertainty would be:

$$= \sqrt{(5.5\%)^2 + (1.9\%)^2 + (1.2\%)^2 + (0.5\%)^2}$$

$$= \pm\, 6.0\%$$

$$+\,6.0\% = 10 \log (1 + 0.060) = +0.25 \text{ dB}$$

$$-\,6.0\% = 10 \log (1 - 0.060) = -0.27 \text{ dB}$$

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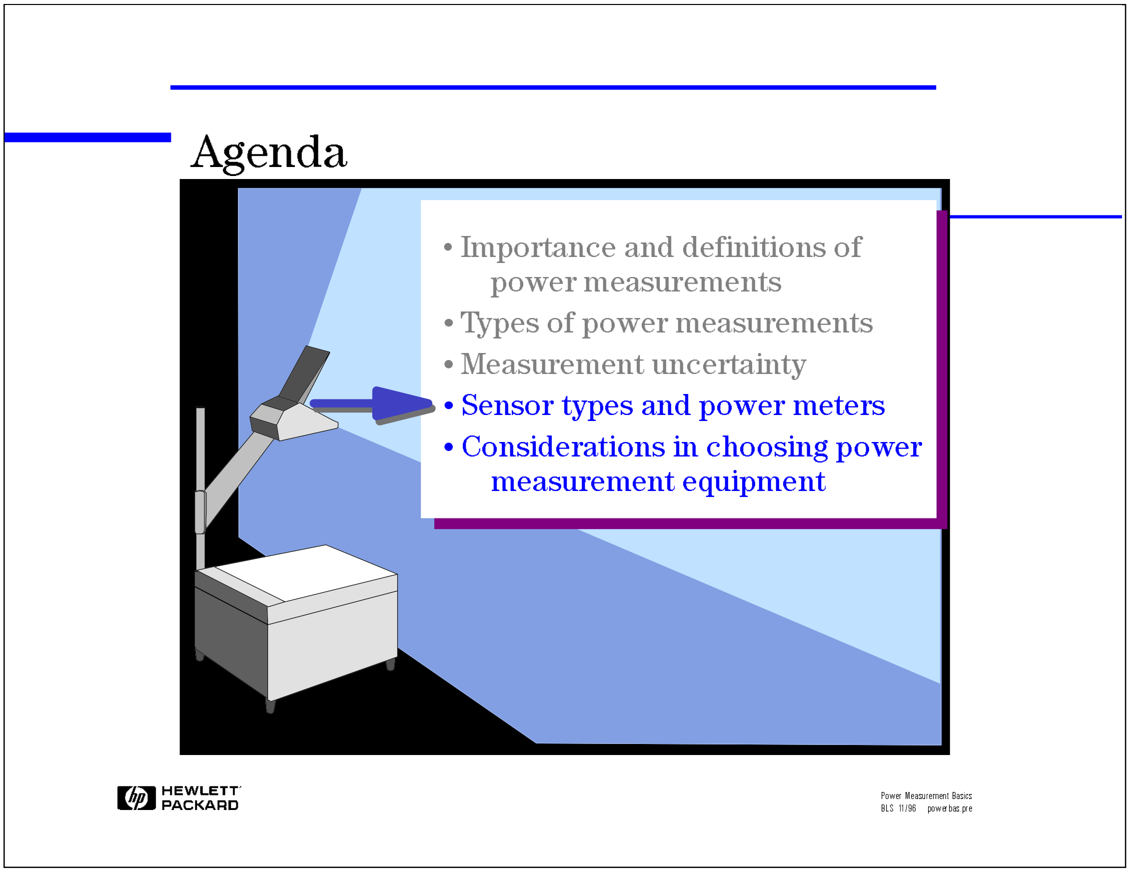
The worst-case uncertainty is a very conservative approach. The probability of the true value of every source error being near the extreme value and in the worst possible direction is very low.

A more realistic method of combining uncertainties is the root-sum-of-the-squares (rss) method. The rss uncertainty is based on the fact that most of the power measurement errors, although systematic and not random, are independent of each other. Since they are independent of each other, they are random with respect to each other and combine like random variables.

The rss method of combining the errors obtains an overall uncertainty of ± 6.0%, or + 0.25, - 0.27 dB.

Slide #22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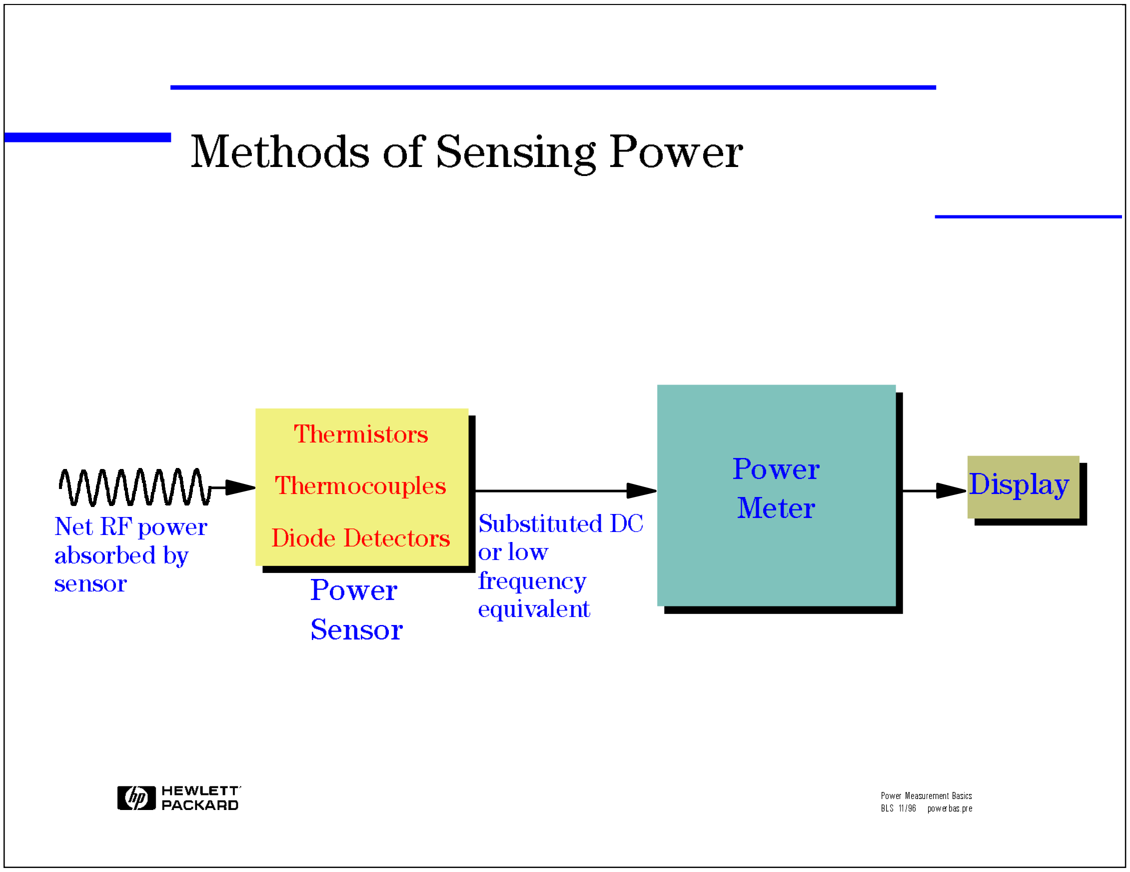


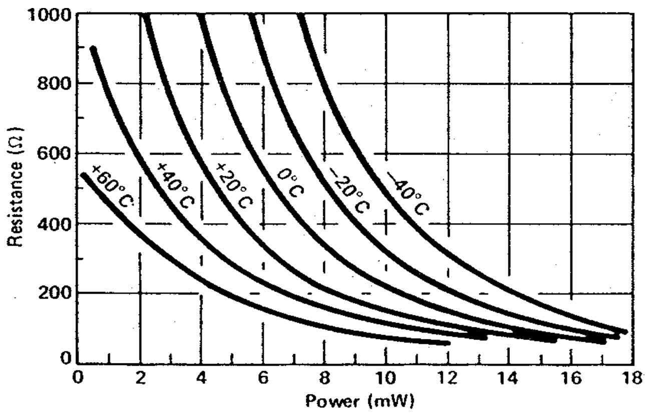
So far, we have seen the types of power measurements that are performed and the uncertainties associated with the measurements. Let's now look at the types of hardware, both sensors and meters, that are used in power measurements.

The basic idea behind a power sensor is to convert high frequency power to a DC or low frequency signal that the power meter can then measure and relate to a certain RF power level. The three main types of sensors are thermistors, thermocouples, and diode detectors. There are benefits and limitations associated with each type of sensor. We will briefly go into the theory of each type and then talk about the advantages and limitations associated with each sensor.

Slide #24

Thermistors
Thermocouples
Diode Detectors

Characteristic curves of a typical thermistor element



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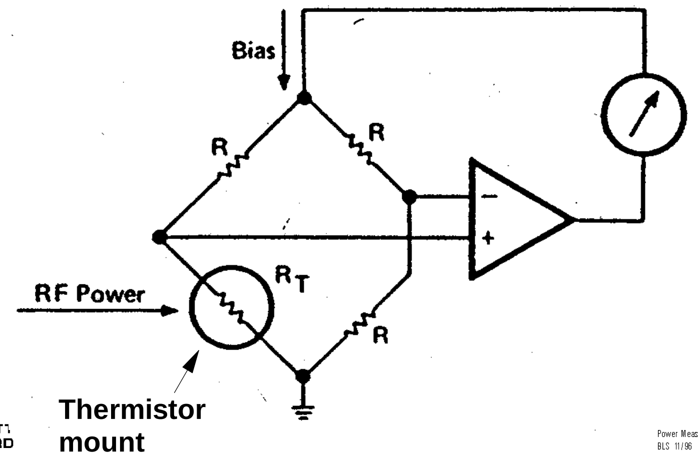
Bolometers in general, operate by changing resistance due to a change in temperature. A thermistor is a type of power sensor classified as a bolometer. A thermistor is a semiconductor which changes resistance due to a change in temperature resulting from incident RF power being dissipated in the element. A small bead of metallic oxides typically 0.4 mm in diameter with 0.03 mm wire leads comprises the actual thermistor elements.

The resistance versus power correlation of a thermistor is highly nonlinear and this correlation varies significantly from one thermistor to the next. To depend on the precise quantitative shape of such curves would result in difficult measurements. Instead, the technique that is used is to maintain the thermistor at a constant resistance by means of a DC bias. As RF power is dissipated in the thermistor, tending to lower the resistance, the bias power is decreased by just the proper amount to keep the resistance of the thermistor the same. The decrease in bias power should be identical to the increase in RF power. That decrease in bias power is then displayed on a meter to indicate RF power absorbed. Self-balancing bridges monitor the resistance of the thermistor.

Slide #25

Thermistors
Thermocouples
Diode Detectors

- A self-balancing bridge containing a thermistor



We know that when a simple Wheatstone bridge is balanced, meaning both sides of the bridge are the same, there is no voltage across the bridge and the inputs of the amplifier are essentially equal. The bridge is balanced when there is no RF power incident on the thermistor. As RF power is applied to the thermistor, the thermistor is warmed and its resistance decreases. This change in resistance unbalances the bridge and produces a differential input to the amplifier. The amplifier, being in a feedback loop, automatically decreases the DC bias to the bridge just enough to allow the thermistor to cool back down, increase resistance, and bring the bridge back into balance. The decrease in DC power to the thermistor is equal to the increase in RF power incident upon the thermistor. A meter measures the amount of power that the amplifier must decrease to re-balance the bridge and this decrease in power is related to the increase in RF power that was incident on the thermistor element. This type of measurement, which requires no external reference source, is said to be "closed loop".

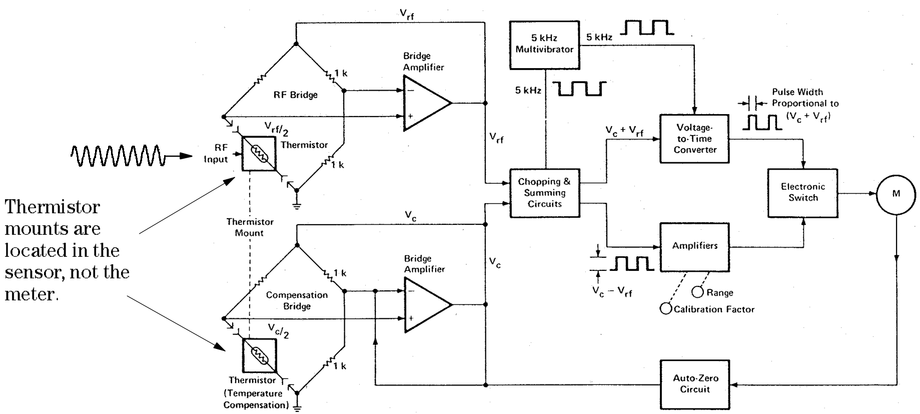
The HP 478A and HP 8478B coaxial, and the HP 486A waveguide thermistor sensors operate in the above fashion. The technique is known as DC substitution because we are indirectly measuring RF power by a direct measurement of DC power.

The main problem with a simple, self-balancing bridge, is that the thermistor resistance also changes as the ambient temperature changes. Simply touching a thermistor, for example, would warm the element, change the resistance, and be detected erroneously as a change in RF power. To correct for this, thermistor sensors (like the HP sensors listed above), add a second thermistor for sensing ambient temperature.

Slide #26

Power Meters for Thermistor Mounts

- HP 432A Power Meter



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Modern meters which work with temperature compensated thermistor-mount sensors need two self-balancing bridges. The first bridge, the RF bridge, for adjusting to changes in RF power, and a second bridge, the compensating bridge, compensating for changes in ambient temperature.

The power meter is initially zero-set with no applied RF power. If ambient temperature variations change the thermistor resistance after zero-setting, the bridge circuits each respond by applying the same new voltage to balance the bridges. If RF power is applied to the detecting thermistor, the RF bridge corrects for the change in resistance as was shown in the previous slide.

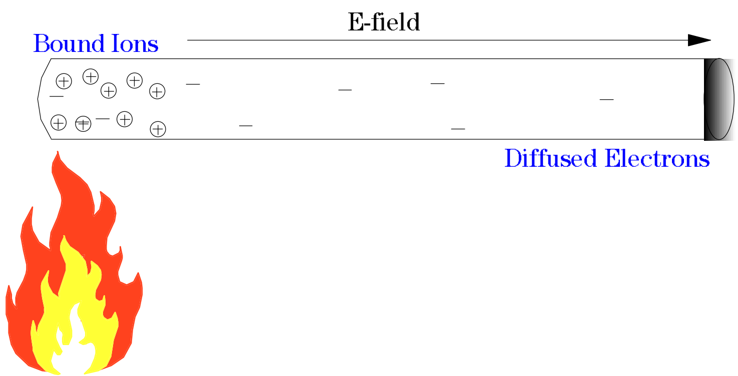
The HP 432A Power Meter has two self-balancing thermistor bridges. In addition, there is the meter logic section and the auto-zero circuit. The RF bridge, which contains the detecting thermistor, automatically varies the DC voltage V_{rf} to balance the bridge. The compensating bridge, containing the compensating thermistor, balances the bridge by automatically varying the DC voltage V_c.

The HP 432A Power Meter uses DC power to maintain balance in both bridges in the thermistor. It has the added convenience of an automatic zero set, eliminating the need for the operator to precisely re-set zero for each range. The HP 432A features an instrumentation accuracy of one percent. It also provides the ability to externally measure the internal bridge voltages with precision digital DC voltmeters. This reduces the instrumentation uncertainty to 0.2 percent.

Slide #27

Thermistors
Thermocouples
Diode Detectors

• Physics of a thermocouple



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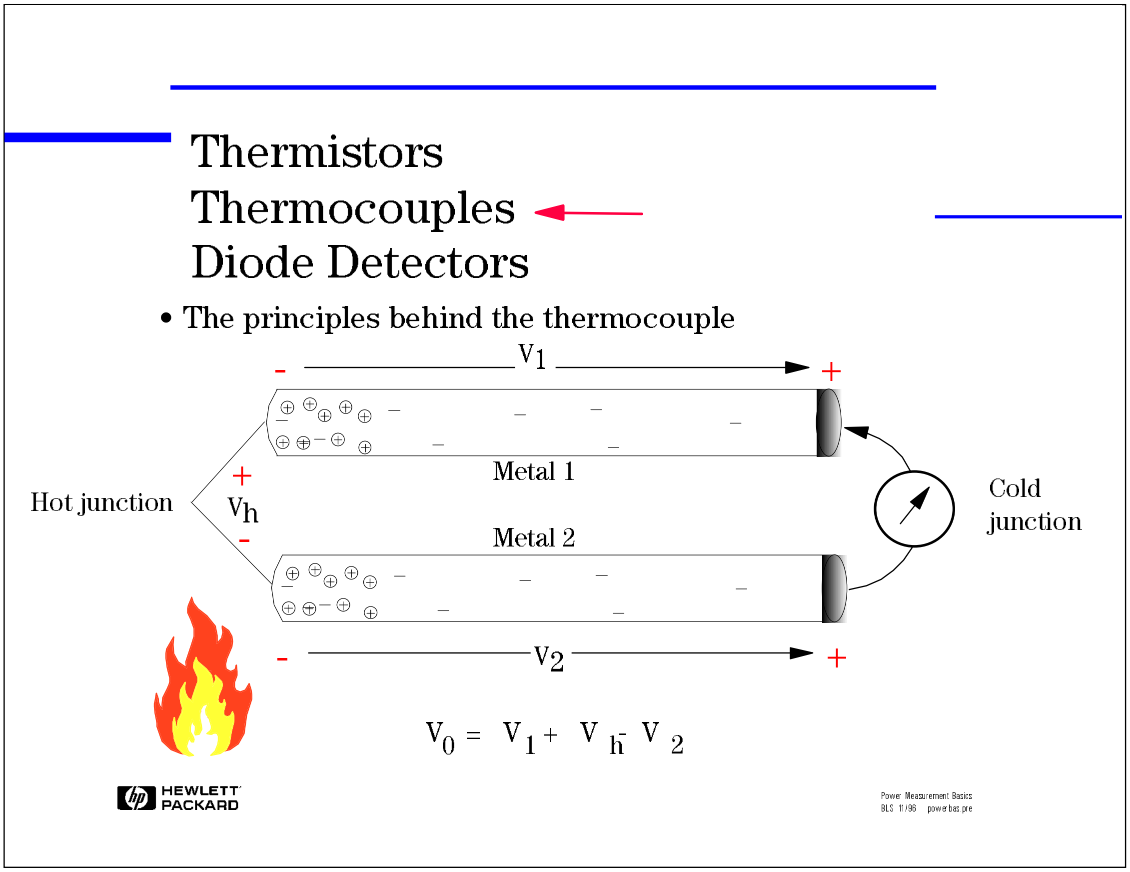
Thermocouple technology is the result of combining thin-film and semiconductor technologies to give a very accurate, rugged, and reproducible power sensor. Thermocouple sensors have been the detection technology of choice for sensing RF and microwave power since their introduction in 1974. The two main reasons for this are: 1) they exhibit higher sensitivity than thermistor technology, and 2) they feature an inherent square-law detection characteristic (RF power in is proportional to DC voltage out). Since thermocouples, like thermistors with a self-balancing bridge, always respond to the true power of a signal, they are ideal for all types of signal formats from CW to complex digital phase modulations. In addition, they are more rugged than thermistors, make useable power measurements down to -30 dBm, and have lower measurement uncertainty due to a lower SWR.

The above example shows what happens when a metal rod is heated at one end. As a result of increased thermal agitation, many additional electrons become free from their atoms on the left end. The increased free electron density on the left causes diffusion toward the right. Each electron migrating to the right leaves behind a positive ion. That ion attracts the electron back to the left with a force given by Coulomb's law. Equilibrium occurs when the rightward diffusion force equals the leftward force of Coulomb's law. The leftward force can be represented by an electric field pointing toward the right. The electric field gives rise to a voltage source.

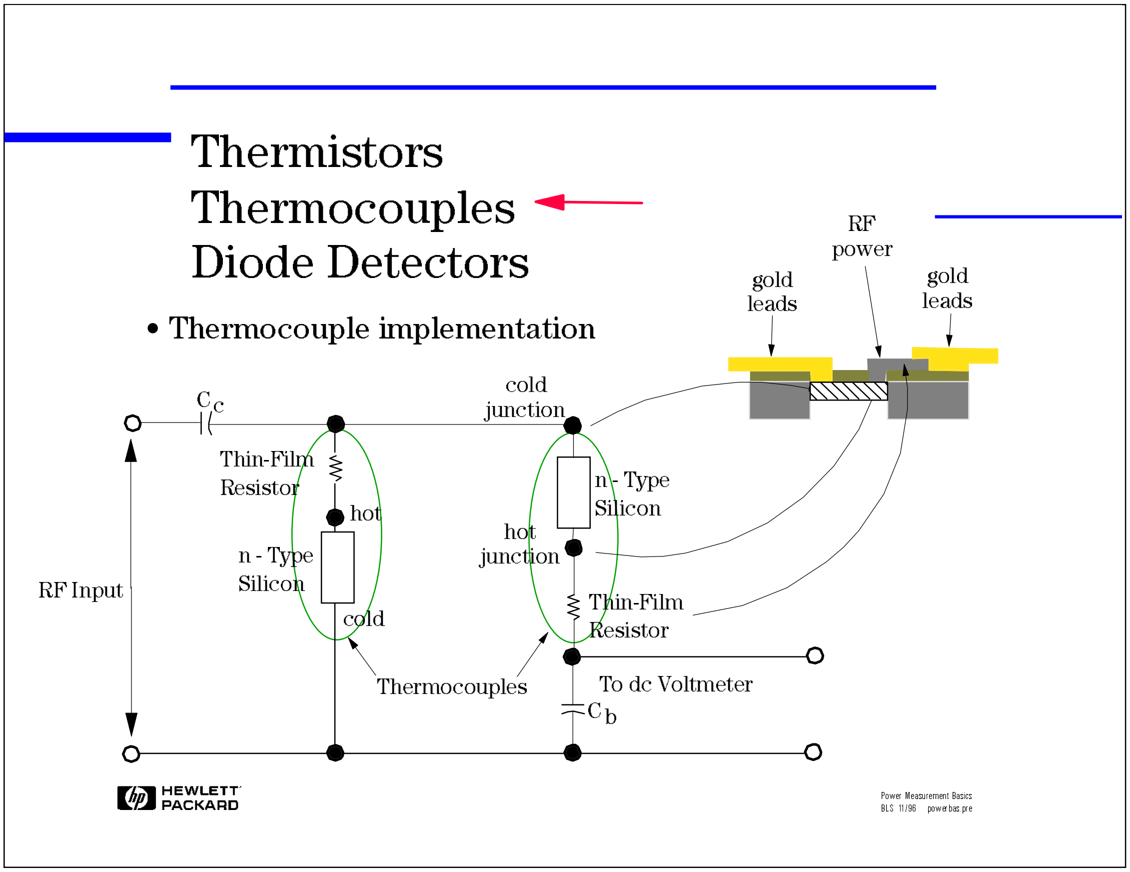
Slide #28



Thermocouple sensors are based on the fact that a metal generates a voltage due to temperature differences between a hot and a cold junction and that different metals will create different voltages. A thermocouple is based on the idea of this difference in voltages between the two metals. If the two metals are put together in a closed circuit, current will flow due to the difference in the voltages. If the loop remains closed, current will flow as long as the two junctions remain at different temperatures. In a thermocouple, the loop is broken and a sensitive voltmeter is inserted to measure the net thermoelectric voltage of the loop. The voltage can be related to a temperature change which can be related to the increased temperature due to RF power incident upon the thermocouple element.

Since the voltage produced in a thermocouple is on the order of microvolts, many pairs of junctions or thermocouples are connected in series so that the first junction of each pair is exposed to heat and the second junction is not. In this way the net voltage produced by one thermocouple adds to that of the next, and the next, and so on, yielding a larger thermoelectric output. Such a series connection of thermocouples is called a thermopile. This larger signal makes for simpler sensing circuitry.

Slide #29

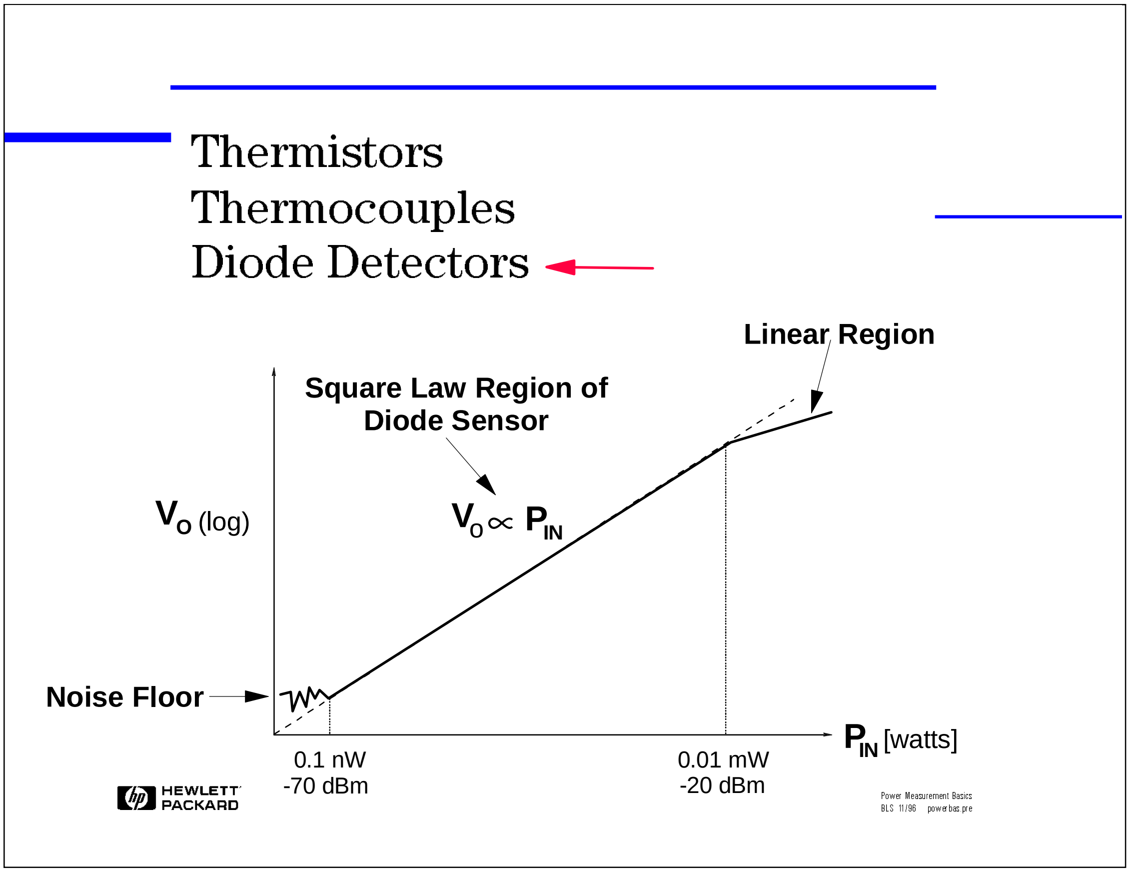


One way to implement thermocouple technology to make power sensors is like the method shown above. The sensor contains two identical thermocouples on one chip, electrically connected as in the figure. For DC, the thermocouples are in series, while at RF frequencies they are in parallel. The two thermocouples in parallel form a 50 ohm termination for the RF transmission line.

The most frequent criticism of thermocouple measurements is that such measurements are open-loop (meaning that they require an external reference source to correct for differences between sensors), while thermistor power measurements are inherently more accurate because of their direct DC-substitution, closed-loop process.

This problem can be solved by including a power-reference oscillator whose output power is controlled very accurately. To verify the accuracy of the system, or adjust for a sensor of different sensitivity, the user connects the thermocouple sensor to the power-reference output and using a calibration adjustment, sets the meter to display 1.00 mW. This feature effectively transforms the system to a closed-loop substitution-type system, and provides confidence in traceability back to internal company standards or NIST standards.

Slide #30



Rectifying diodes have long been used as detectors and for relative power measurements at microwave frequencies. Diodes convert high frequency energy to DC by using rectification properties, inherent to their non-linear current-voltage (i-v) characteristics. The advantage of the diode is that they can be used for measurement of extremely low powers. You can see in the slide above that their square-law region is from -70 to -20 dBm.

Many types of diodes have been used for power measurement and today the most commonly used type is the low-barrier Schottky diode. In this presentation we will discuss the diode-type that is used in HP's diode sensors, that is, PDB (planar-doped-barrier) diodes. PDB diodes have better performance than Schottky diodes at microwave frequencies. Sensors based on this technology are able to detect and measure power as low as -70 dBm at frequencies up to 18 GHz.

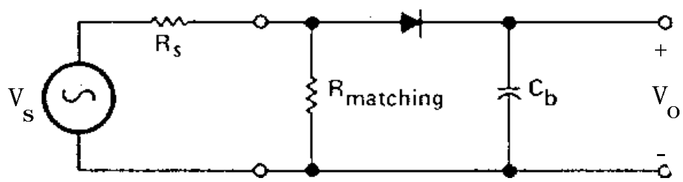
PDB diode technology provides some 3000 times (35 dB) more-efficient RF-to-DC conversion compared to the thermocouple previously discussed. Diode sensor technology excels in sensitivity, although realistically, thermocouple sensors maintain their one primary advantage as pure square-law detectors for the range -30 to +20 dBm.

In detecting power levels of 100 pW (-70 dBm) the diode detector output is about 50 nV. The low signal level requires sophisticated amplifier and chopper circuit design to prevent leakage signals, noise, and thermocouple effects from dominating the signal of interest.

Slide #31

Thermistors
Thermocouples
Diode Detectors

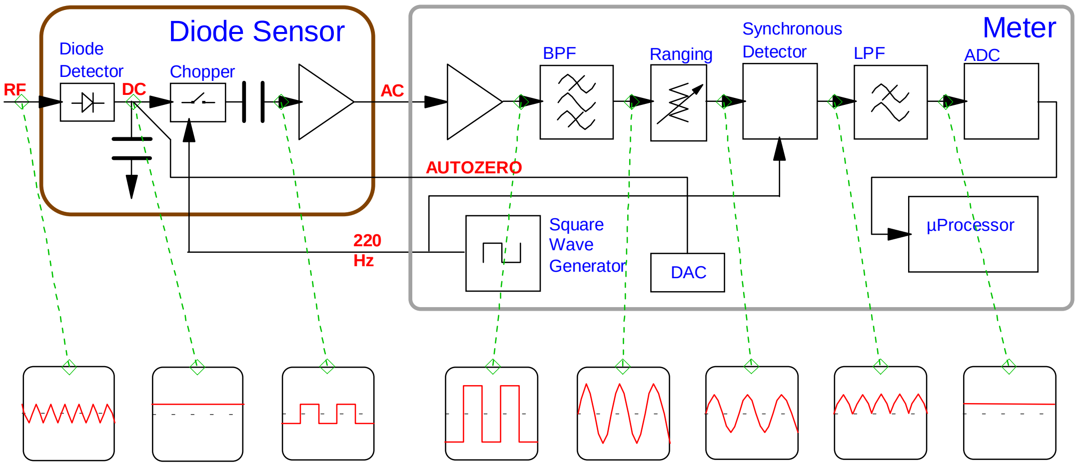
• How does a diode detector work?



This slide shows a simplified circuit of a diode detector. The matching resistor (approximately 50 ohms) is the termination for the RF signal. RF voltage is turned to a DC voltage at the diode and the bypass capacitor, C_b , is used as a low-pass filter to remove any RF signal getting through the diode. Finally, the DC voltage, V_o , is chopped, turned into an AC signal, and sent to the power meter which recovers the DC voltage and relates it to a RF power.

Slide #32

The Basic Power Meter



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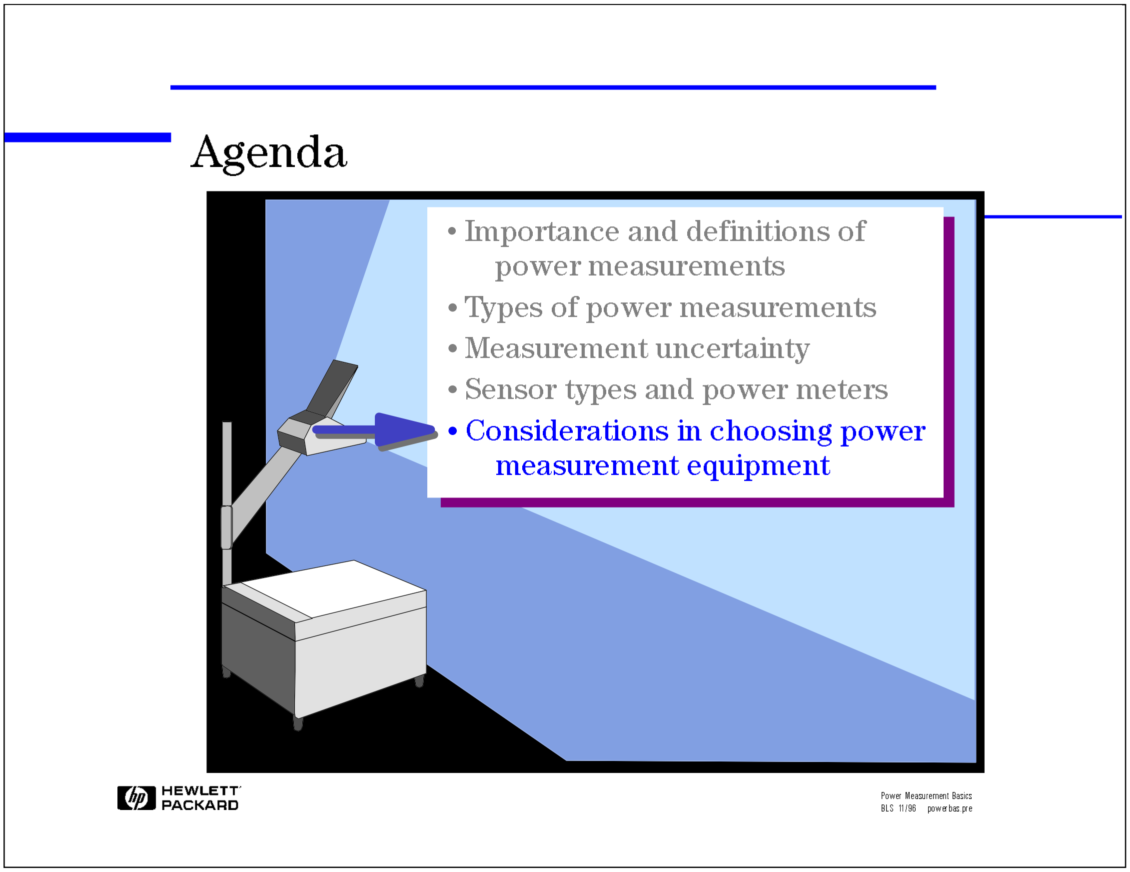
For the "Basic Power Meter", we will discuss the HP 437B. This meter works with both thermocouple and diode detector mounts because the electronic circuits for the two types of sensors have the same basic goals. First, voltages on the order of 100 nV are to be measured -- so choppers, AC amplifiers, and synchronous detectors are needed. Second, power measurements with both kinds of sensors need a power-reference oscillator. The oscillator must have a precisely known power output to adjust the calibration of the power meter to fit the particular sensor being used.

The DC output from either the thermocouple or the diode detector is very low-level (on the order of nV or µV), so it is difficult to transmit on an ordinary cable because small, undesired thermocouple effects affect the measurement. For this reason HP includes the low-level DC circuitry in the power sensor, so only relatively high-level signals appear on the cable. To handle such low DC voltage, you must "chop" the signal to form a square wave, amplify this with an AC-coupled system, then synchronously detect the high-level AC. The chopper and first AC amplifier are included in the power sensor itself.

Once inside the meter, the AC signal is amplified again and passed through a bandpass filter. The narrowest bandwidth is chosen for the weakest signals and the most-sensitive range. As the power meter is switched to higher ranges the bandwidth increases so that measurements can be made more rapidly. A synchronous detector then rectifies the signal which then passes through a low pass filter. A analog-to-digital converter takes the DC signal and equates it to a certain power level.

Slide #33


Agenda
• Importance and definitions of power measurements
• Types of power measurements
• Measurement uncertainty
• Sensor types and power meters
• Considerations in choosing power measurement equipment
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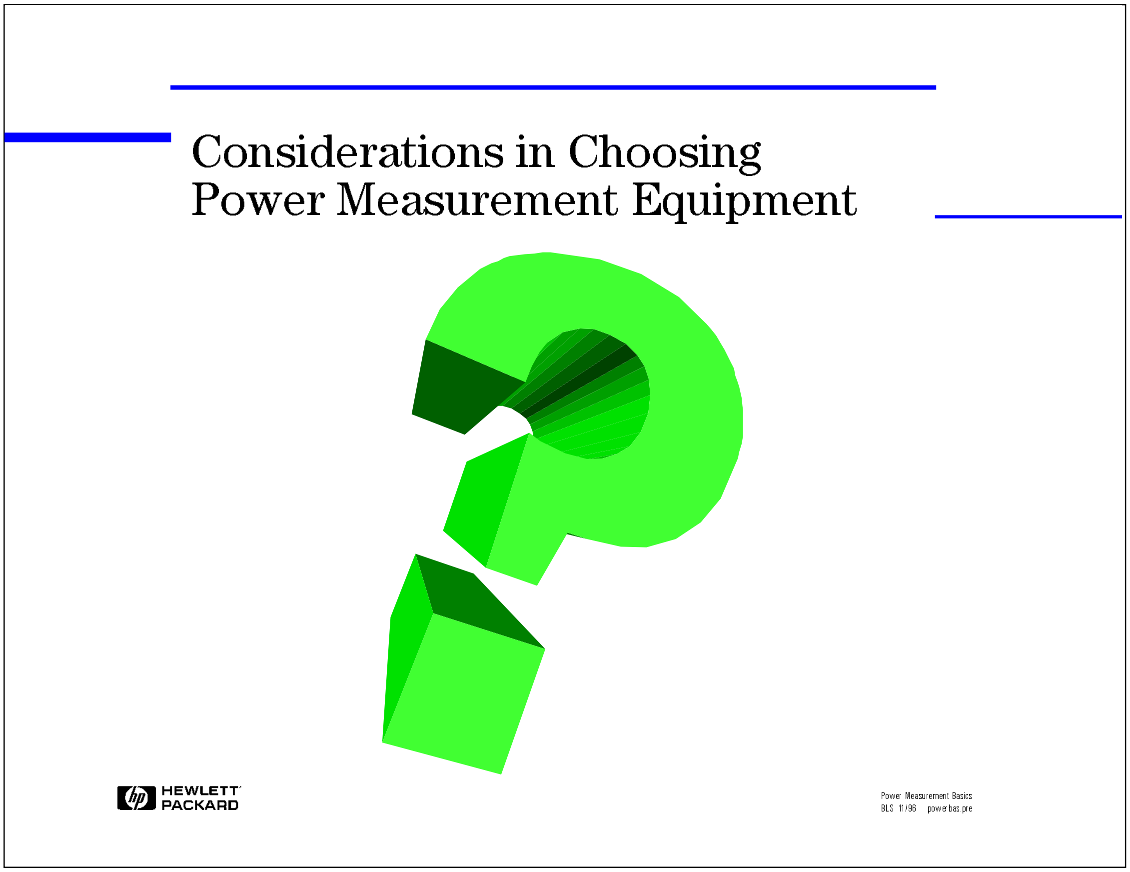
Slide #34



Now for the real question: What should be considered when using or buying power measurement equipment?

Naturally, each method of power measurement has some advantages over the others. Factors such as price, speed of response, traceability, power ranges, susceptibility to overload, frequency ranges, reflection coefficient, and others must all be considered when making a decision.

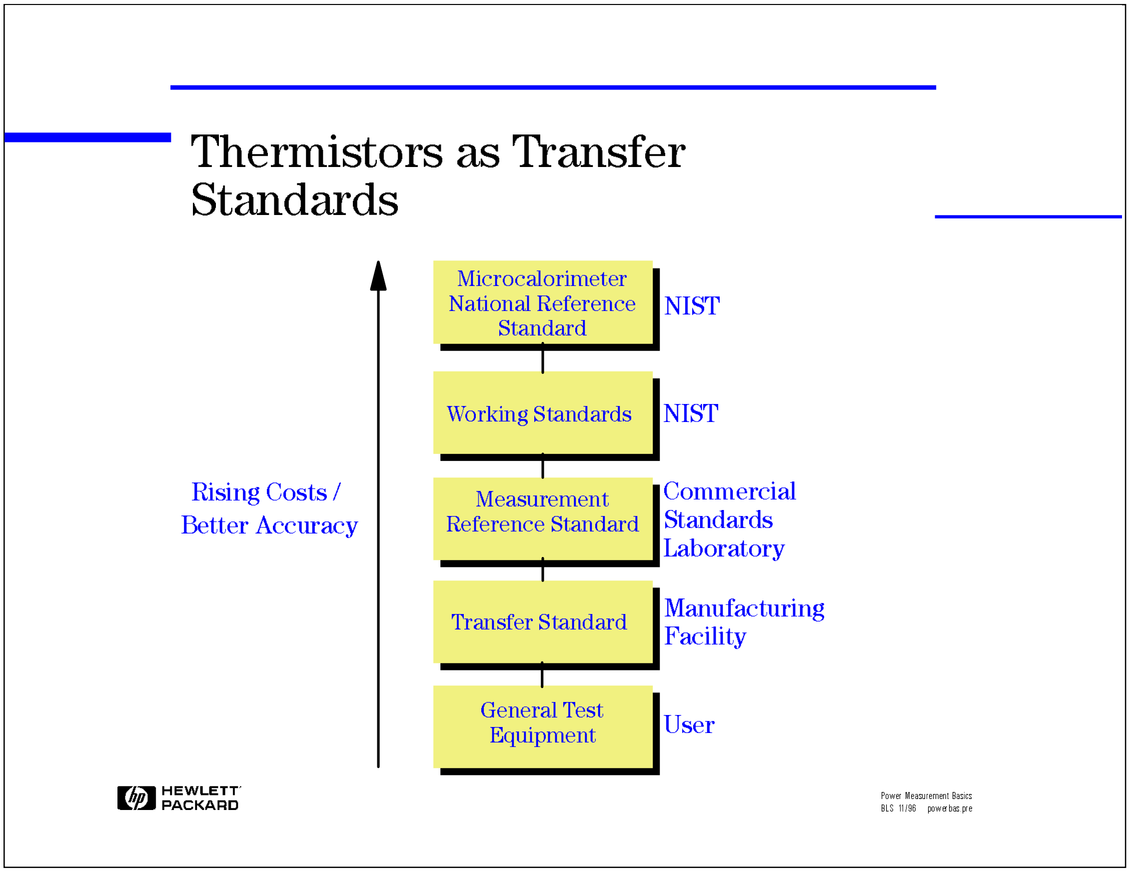
The price of power sensors typically depend on the frequency ranges covered and the sensitivity of the sensor rather than the type of sensing element that is used. Sensors covering larger frequency ranges, of course, cost more and highly sensitive or high power sensors will also be more expensive. Additionally, power sensors with waveguide mounts typically cost more than coaxial mounts.

To measure low power signals with high accuracy, power meters are designed to have a highly-filtered narrow bandwidth to pass the desired signal only and reject the noise. Narrow bandwidth however, leads to longer response times. Additionally, in heat responding power sensors, like the thermistor and thermocouple, response time is also limited by the heating and cooling time constants of the heat sensing element.

The typical thermistor power measurement has a 35 millisecond time constant and 0 to 99 percent response time of about five time constants or 0.175 seconds. The power meters for thermocouple and diode sensors have 0 to 99 percent response times of 0.1 to 10 seconds, depending on the range of the power meter. The more sensitive ranges require the longest times.

For manual measurements, the speed of response is seldom a problem. By the time the operator turns on the RF power and is ready to take data, the power meter has almost always reached a steady reading. Speed considerations should be considered, though, when automated measurement systems are used and the power meter output is being used to control other instruments.

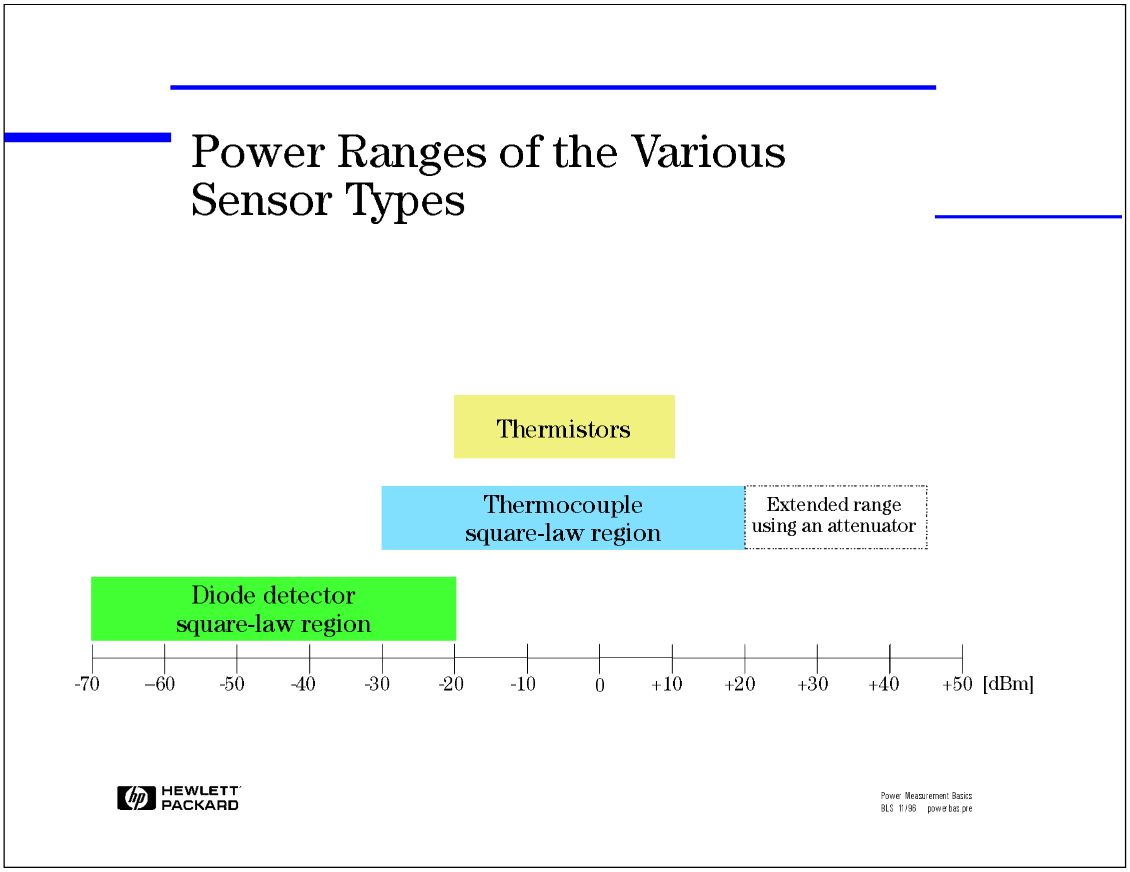
Slide #35



It is important that power measurements can be duplicated at different times and at different places. This requires well-behaved equipment, good measurement technique, and a common agreement as to what is the standard watt. The U.S. National Institute for Standards and Technology (NIST) in Boulder, Colorado maintains the National Reference Standard in the form of a microwave microcalorimeter. A power sensor referenced back to that Standard, is said to be traceable to NIST. The usual path of traceability for a power sensor is shown on the slide. Since any errors introduced in the watt at NIST will flow down to all other standards, extreme care is taken to make it as accurate as possible.

To transfer power parameters such as calibration factor, effective efficiency and reflection coefficient, NIST's Measurement Services Program accepts thermistor mounts, both coaxial and waveguide. This makes thermistors the sensor of choice for most metrology applications.

Slide #36



Thermistors offer high accuracy, but have a more limited operating range than a thermocouple or diode detector sensor. Thermistor mount specifications are for the range from -20 dBm to +10 dBm.

Thermocouples cover a very large range of powers. Their true square-law region is from -30 dBm to +20 dBm, and with an attenuator can operate up to +44 dBm. Three families of thermocouple sensors cover the complete -30 to +44 dBm range. The A- Series covers -30 to +20 dBm, the H-Series covers from -10 to +35 dBm, and the B-Series covers from 0 to +44 dBm.

Diode detectors (D-Series) have the best sensitivity, allowing them to work well below -20 dBm (stated range is -70 to -20 dBm), but above -20 dBm they begin to deviate substantially from the square-law detection region.

Slide #37

Susceptibility to Overload

	8478B Thermistor Mount	8481D PDB Diode Mount	8481A Thermocouple Mount	8481H Thermocouple Mount
Max Average Power	30 mW	100 mW	300 mW	3.5 W
Max Energy Per Pulse	10 W·µs		30 W·µs	100 W·µs
Max Envelope Power	200 W	100 mW	15 W	100 W

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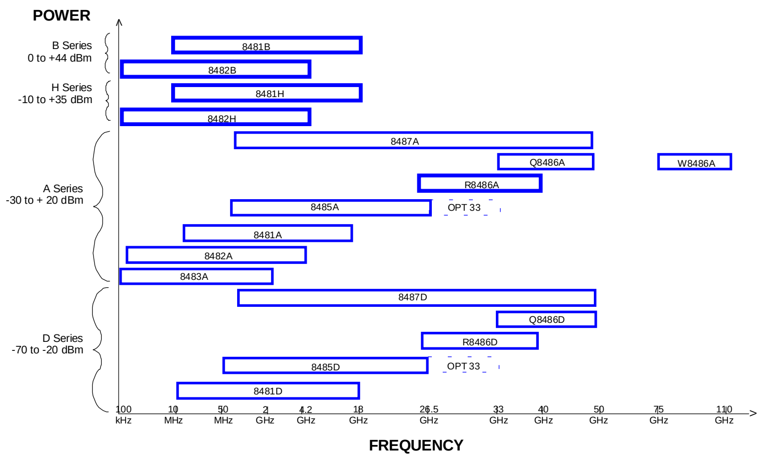
The maximum RF power that may be applied to a power sensor is limited in three ways. The first limit is an average power rating. Too much average power usually causes damage because of excessive heat. The second limit is the energy in a pulse. If the pulse power is too high for a short time, in spite of the average power being low, the pulse may cause a temporary hot spot somewhere in the sensor. Damage occurs before the heat has time to disperse to the rest of the sensor. The third limit is peak power envelope. This limit is usually determined by breakdown phenomena that damage sensor components. These limits are usually stated on the manufacturer's data sheet. The power limits of any sensor may be moved upward by adding an attenuator to absorb the bulk of the power. Then the power limits are likely to be dictated by the attenuator characteristics, which being a passive component, are often fairly rugged and forgiving.

The above figure of power limits shows that the HP 8481H Power Sensor, which consists of a 20-dB attenuator integrated with a thermocouple sensor element, excels in all respects except for peak envelope power where the thermistor mount is better.

Slide #38

Frequency Ranges



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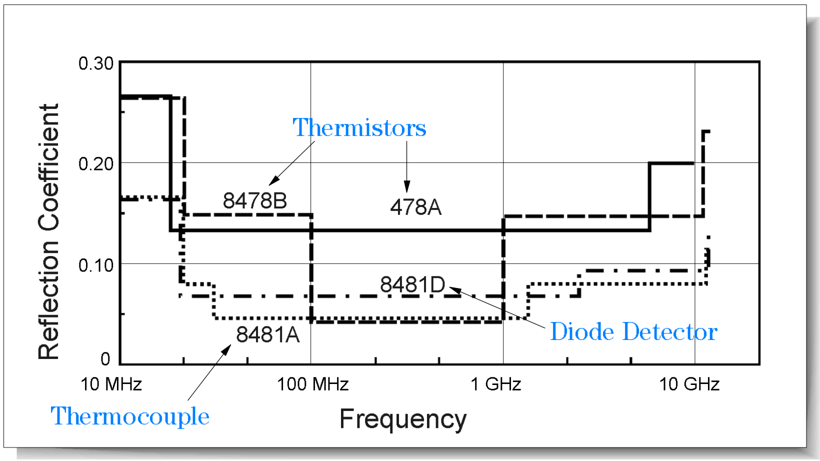
All three types of HP power sensors have models that cover a frequency range from 10 MHz to 18 GHz with coaxial inputs. A special thermistor mount operates down to 1 MHz and the HP 8482A, 8482B, 8482H, and 8483A thermocouple power sensors operate down to 100 kHz. The effective efficiency at each frequency is correctable with the Calibration Factor adjustment of the power meter, so that it is not particularly critical in deciding on a measurement system.

Additionally, HP has thermistor waveguide mounts covering 8.2 - 40 GHz. These sensors have the advantage of being closed-loop so that there is no need for a low-frequency power reference oscillator. Finally, HP has waveguide thermocouple sensors which cover 26.5 to 110 GHz and waveguide diode detectors for 26.5 to 50 GHz. The waveguide thermocouple and diode sensors utilize a special 50 MHz injection configuration which allows the reference oscillator output to be applied to the sensor element in parallel with the usual waveguide input to allow for adjustment of the calibration factor. This injection configuration is used becasuse such a low-frequency (50 MHz) signal cannot propagate into the sensor through a waveguide input.

Slide #39

Reflection Coefficient



A sensor's reflection coefficient performance is most important because mismatch uncertainty is usually the largest source of error in power measurements. Examining the slide, one can see that thermocouple and diode sensors typically have a lower reflection coefficient than thermistor sensors.

For power measurements in rectangular waveguide, thermistor mounts have an advantage over thermocouples and diode detectors due to the special injection configuration that was discussed on the previous page. This injection configuration requires a special waveguide-to-coax adapter. The loss of this adapter and its reflection coefficient obscures the sensor calibration factor, increases the overall reflection coefficient, and increases the uncertainty.

It should be realized that HP's reflection coefficient specifications are usually conservative and that actual performance is often substantially better, yielding lower uncertainty in practice.

Slide #40

Any Questions?

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Slide #41

Review Time !

1. For a rectangular pulse, you can find the power contained in the pulse using an average power meter if you know a certain parameter of the waveform. What is this parameter?

2. In power measurements, various errors associated with the sensor circuitry contribute the most to measurement error. This is closely followed by mismatch uncertainty error. True or False?

3. We discussed three types of power sensors: thermistors, thermocouples, and diode detectors. Two of these sensors make open-loop measurements and one makes closed-loop measurements. Which type makes the closed-loop measurements?

4. DC signals output from the sensing element are directly sent to the meter via a cable for additional processing. True or False?

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1. To find the power contained in a pulse by using an average power meter, you must know the **duty cycle** of the waveform. Remember the equation: $P_{pulse} = \frac{P_{avg}}{DutyCycle}$

2. **False**. Mismatch error causes, by far, the most measurement uncertainty. Remember in our example that mismatch uncertainty accounted for 5.5%, while the next largest error only contributed 1.9%.

3. **Thermistors** are the only sensors discussed which makes closed-loop measurements. Both thermocouples and diode detectors require an external power reference source to account for differences between individual sensors. A thermistor does not require such a source.

4. **False**. The DC signal output from the sensing element is on the order of nV. This signal could never be detected if it was sent over the cable. That is why the DC signal is chopped (to make it AC), amplified inside the sensor itself, and then sent across the cable to the meter.

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