**Agilent Technologies**

# RF Power Measurement Basics

**February 20, 2001**

*presented by:*

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# Agenda

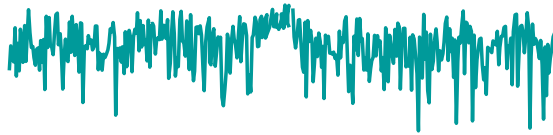**If you have ever asked yourself these questions:**

- **Why measure power?**

- **What does a good sensor look like?**

- **Is there a way to measure peak power?**

- **What about modulated signals?**

- **To what degree am I affected by uncertainty?**
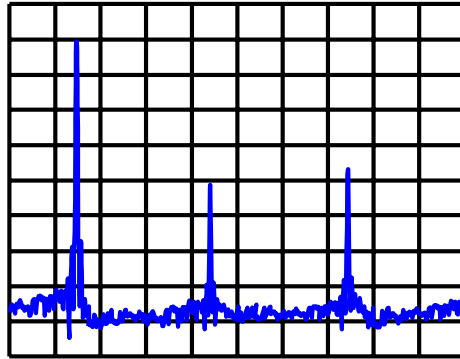
**Then you are in the right place!**

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Slide 2

Slide 3

**Why do we measure signal levels?  A system's output signal level is often the critical factor in the design and performance of RF and microwave equipment.**

**Measurement of the signal level is critical at every system level, from the overall system performance to the fundamental devices.  The large number of signal 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 signal level on to the succeeding component.  If the output signal level becomes too low, the signal becomes obscured in noise.  If the signal level becomes too high, though, the performance goes nonlinear and distortion results.  Or worse!**

**Why Measure Power?**

- At low frequencies, voltage (or current) are measured easily
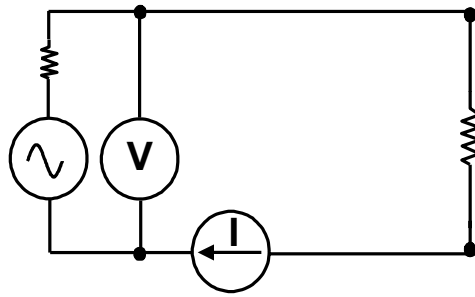
- But at high frequencies, the voltage varies along the transmission line!
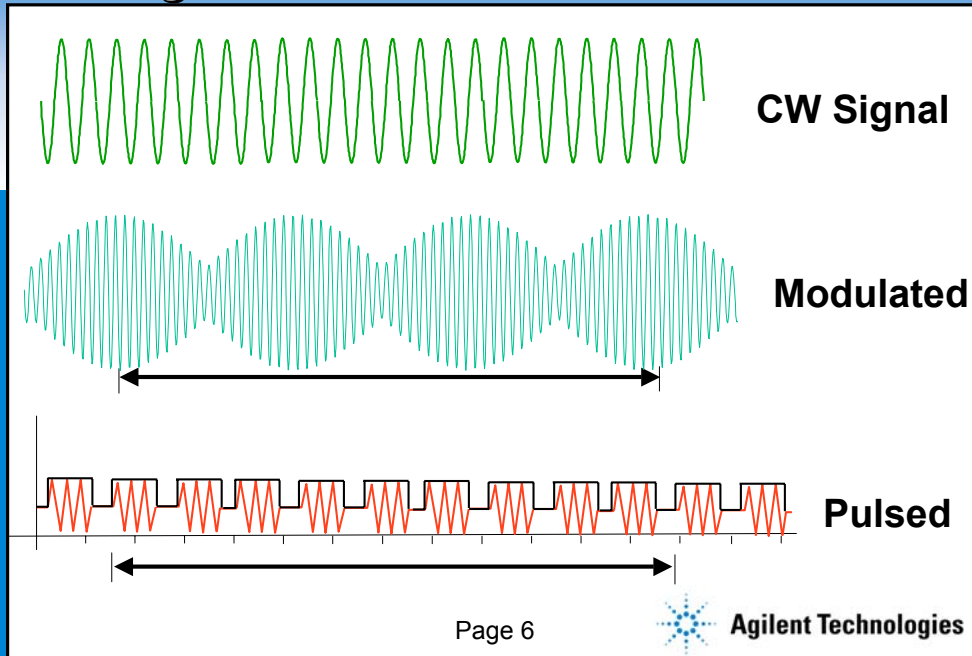
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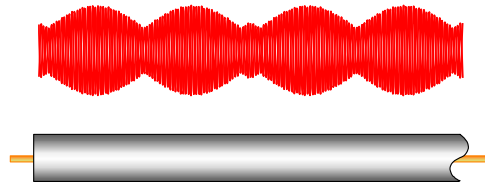
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At DC and low frequencies, voltage measurements are simple and straight forward. If power is needed, it is easily calculated:

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

However, 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.

## P = I * V

Units of power are Watts or 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 (average) term and has a frequency twice that of the AC signal.  "Power", as most commonly used, refers to average power.  To find this average, 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:                 and

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.

$$V_p = \sqrt{2}V_{rms} \qquad\qquad I_p = \sqrt{2}I_{rms}$$

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**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.**

**Additional waveform information can sometimes be calculated from average power measurements if certain waveform characteristics are known. If, for example, the duty cycle of a rectangular pulsed signal is known, then peak power can be found from the average power measurement by the equation:**

$$P_{peak} = \frac{P_{avg}}{DutyCycle}$$

**Note that the peak power here is only applicable for a true rectangular pulse with no overshoot present.**
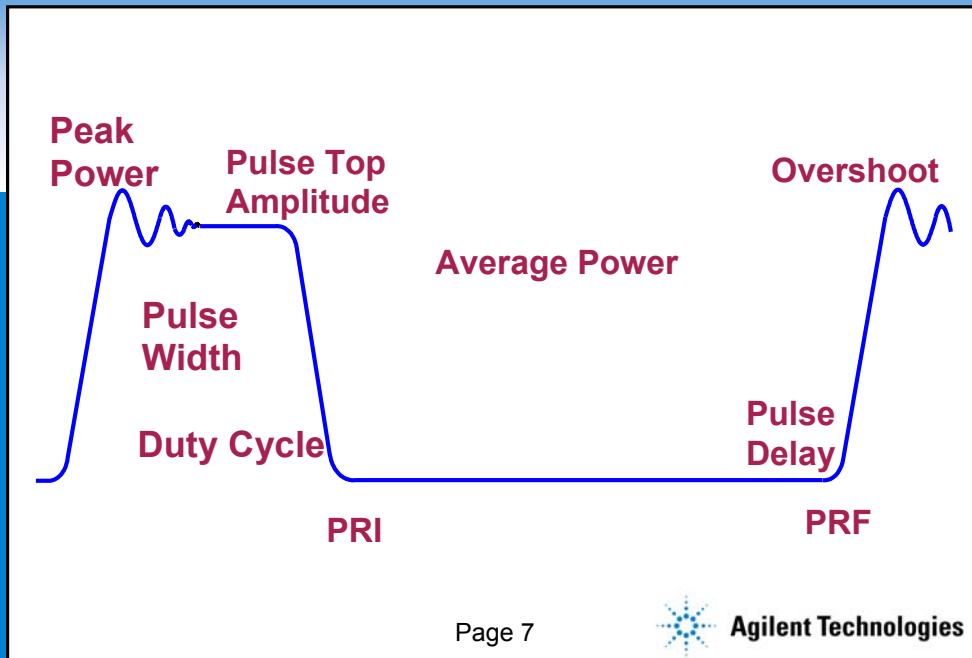
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**There are many different terms used when talking about power, some of which are shown in this slide. For the purposes of this presentation we will focus on three different types of power measurement, Average, peak, and time gated power measurements. Average power provides average power delivered over several cycles and typically is implied when talking about "power". Peak power is the maximum instantaneous power and is required on many of today's complex wireless modulation systems. Finally, Time Gated power measurements allow both peak and average measurements to be made in the time domain, which is of particular interest to TDMA systems such as GSM.**

**Which Instrument Should I Use?**

- Spectrum Analyzer
- Network Analyzer
- Vector Signal Analyzer
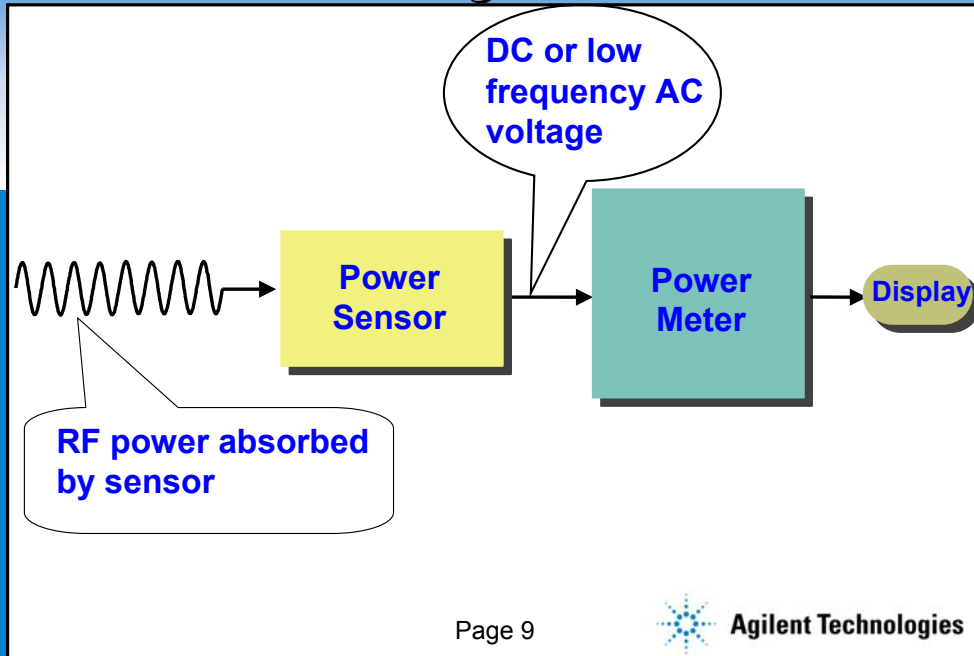- Power Meter

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Although a variety of instruments measure power, the most accurate instrument is a power meter and a sensor. The sensor is an RF power-to-voltage transducer. The power meter displays the detected voltage as a value of power in log (dBm) or linear (watts) units. Typical accuracies of a power meter will be in the hundredths of a dB, while other instruments (i.e., spectrum analyzers, network analyzers) will have power measurement accuracies in the tenths of dBs or more.

One of the main differences between the instruments is that of frequency selective measurements. Frequency selective measurements attempt to determine the power within a specified bandwidth. The traditional Power Meter is not frequency selective in that it measures the average power over the full frequency range of the sensor and will include the power of the carrier as well as any harmonics which may be generated. A Spectrum Analyzer provides a frequency selective measurement since it measures in a particular Resolution Bandwidth.

The lack of frequency selectivity is the main reason that Power Meters measure down to around -90dBm and instruments such as a spectrum analyzer can measure much lower than this if very narrow resolution bandwidths are used.
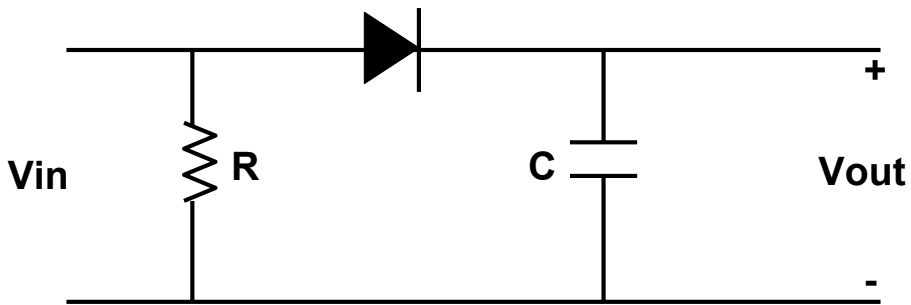
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**Let's now look at the types of hardware, both sensors and meters, that are used in average power measurements.**

**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.**
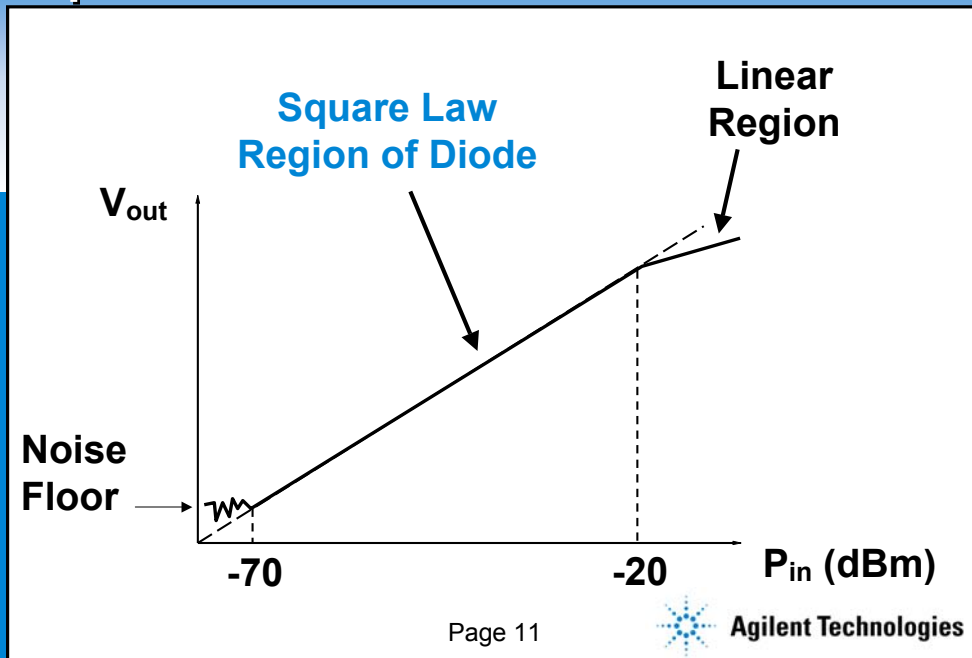
# Diode Detectors



Vin     R          C          Vout  +

                                    -

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Unlike thermistors and thermocouples, a diode does not measure the heat content of a signal but rectifies the signal instead.  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 is used as a low-pass filter to remove any RF signal getting through the diode.

## Square Law

Square Law Region of Diode

Linear Region

$V_{out}$

Noise Floor

-70          -20          $P_{in}$ (dBm)

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Unlike thermistors and thermocouples, a diode does not measure the heat content of a signal but rectifies the signal instead. 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 is used as a low-pass filter to remove any RF signal getting through the diode.

A major attribute of the diode sensor is sensitivity, permitting power measurements as low as -70 dBm (100 pW). Are these true power measurements, independent of signal content? That depends. If we expand the diode equation (see Agilent Technologies Application Note 64-1A) into a power series, we find that the rectified output voltage is a function of the square of the input signal voltage up to a power level of about -20 dBm. This performance yields a rectified output that is proportional to the RF signal power regardless of signal content. As the power level increases above -20 dBm, the rectification process becomes more and more linear and the output voltage becomes a function of the input voltage. For complex signals, the output is then dependent upon the phase relationships among the various components of the input signal.

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 Agilent'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 -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.
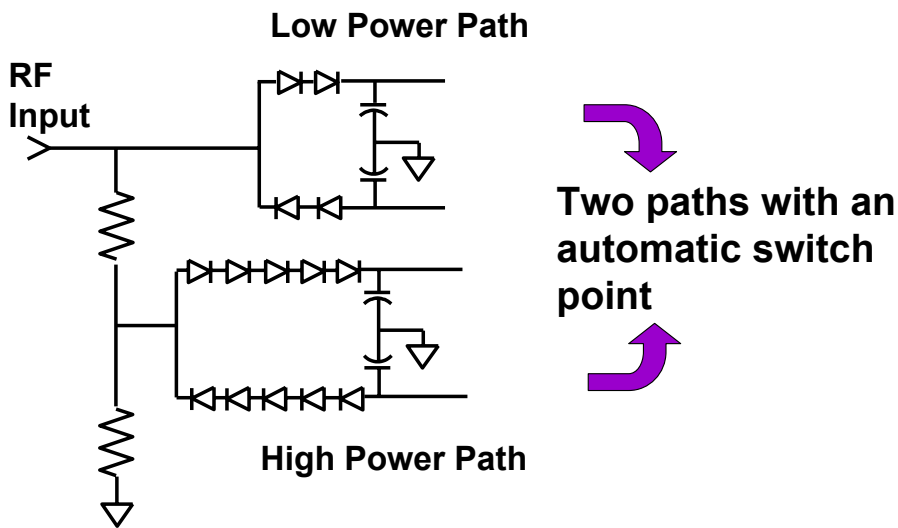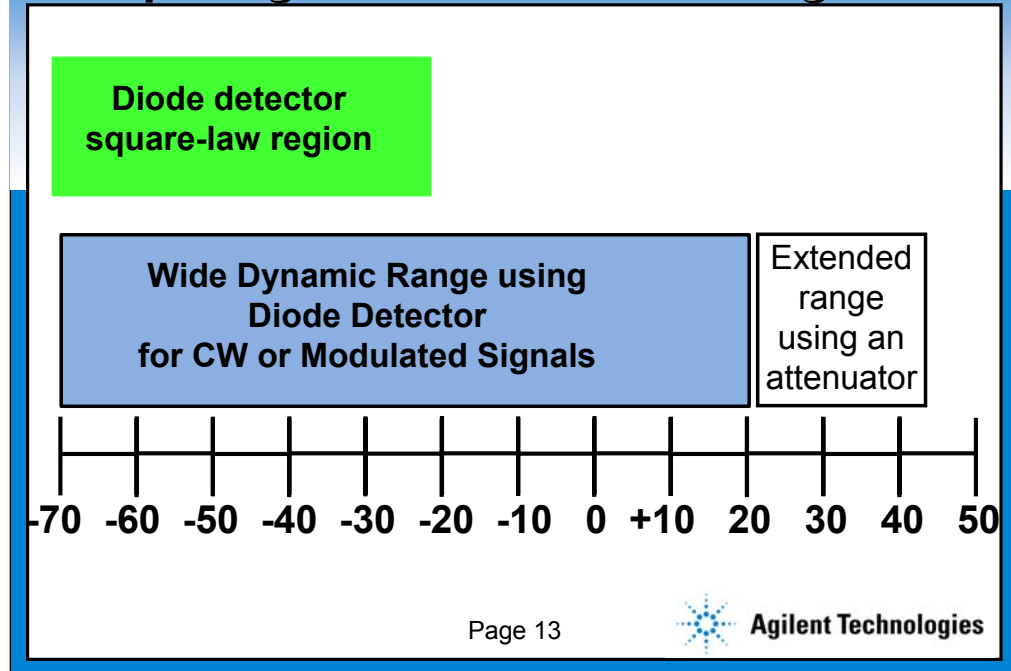
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The corrections for the CW signals are fine but what can be done for other signals which may be modulated? The E9300 Power Sensors are diode power sensors which give 80dB Dynamic Range. To get this range a two path design is used with a separate path for the low power and high power paths. This innovative design is based on a diode stack /attenuator/diode stack topology.

Each diode stack forms a measurement path, the high power path is between -10 to +20dBm and the low power path is between -60 to -10dBm. Only one path is active at any time and switching between paths is fast, automatic and transparent to the user. This topology has the advantage of always maintaining the sensing diodes within their square law region and will therefore respond properly to complex modulation formats as long as the correct range is selected.

The design is further refined by incorporating diode stacks in place of single diodes to extend square law operation to higher power levels at the expense of sensitivity. In the E9300 the low power path uses a two diode stack pair and the high power path a five diode stack pair. FET switches were used off chip to enable the low path diodes to self bias to an off condition when not in use.

## Comparing Sensors- Power Range

Diode detector
square-law region

Wide Dynamic Range using
Diode Detector
for CW or Modulated Signals

Extended range using an attenuator

-70 -60 -50 -40 -30 -20 -10 0 +10 20 30 40 50

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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.

The Wide Dynamic Range Power Sensors are diode sensors and can provide up to 90dB dynamic range. They either work by correcting for the deviation (CW Power Sensors) or by using the two path technique to allow modulated measurements. Wide Dynamic range measurements can be made up to a maximum power of +44dBm.

# Hallmarks of a Good Sensor

- **Sensor diodes always kept in square law region.**
- **Accurate measurement of signals with high peak-to-average ratios.**
- **Accurate measurement of signals with arbitrarily wide modulation bandwidth.**
- **Flat calibration factors give accurate measurement of multi-tone signals.**

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As mentioned the diode stack/attenuator/diode stack technique has the advantage of always using the diodes within their square law region.

In this region, the output current (and voltage) of each diode is proportional to the input power. As a result, the E-Series E9300 power sensors respond accurately to measure average power on signals ranging from the most complex digital format to CW. This means that one E-series E9300 power sensor can be used to measure the average power of any signal.

The E9300 Power Sensor can handle power levels up to +33dBm peak with duration less than 10microseconds mean that these power sensors can be used for signals with high crest factors (or peak to average ratios). If the high peaks could not be handled this would effectively limit the dynamic range of the power sensor.

The fact that it is a pure diode sensor also means that there is no modulation bandwidth limitations that you get with power sensors which use a sampling technique.

The E9300 Power Sensors have flat calibration factors which is an advantage if multi tone signals are being measured. If there are multi tone signals being input, only one calibration factor can be selected. If the calibration factors are flat over the frequency range of the measurements then the uncertainty in the result will be kept to a minimum.
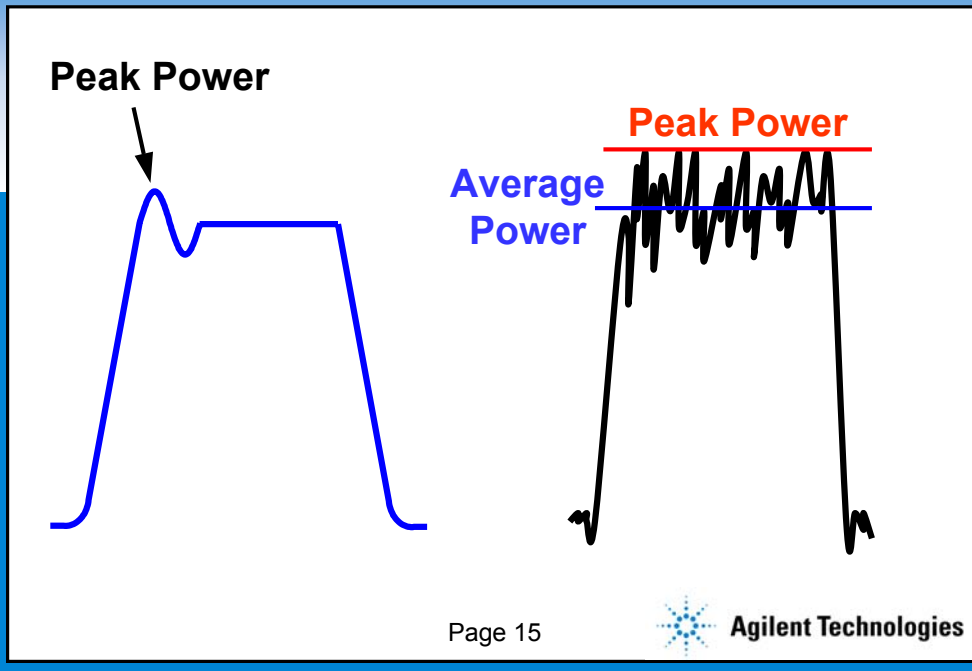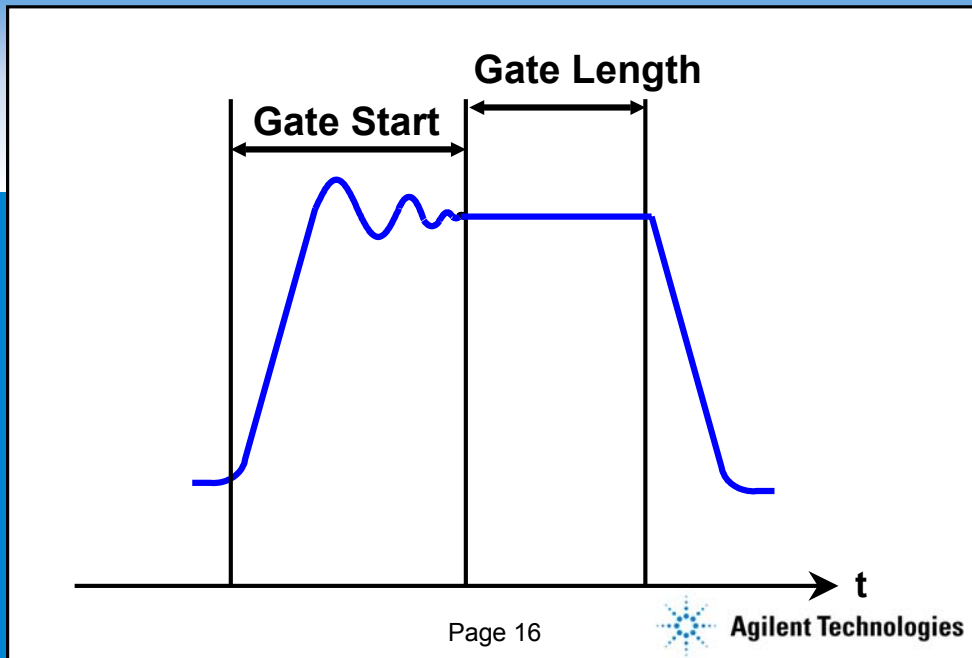
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**Pulse power was traditionally determined by measuring the average power of the pulse and then dividing the measurement result by the pulse duty cycle value to obtain the pulse power reading. The measurement result is a mathematical representation of the pulse power rather than an actual measurement and assumes constant peak power. The pulse power averages out any aberrations in the pulse, such as overshoot or ringing. For this reason it is called pulse power and not peak power or peak pulse power.**

**In order to ensure accurate pulse power readings, the input signal must be a rectangular pulse. Other pulse shapes (such as triangle or Gaussian) will cause erroneous results. This technique is not applicable for digital modulation systems, where the duty cycle is not constant, and the pulse amplitude and shape is variable.**

**For complex digital modulation signals an instantaneous power measurement is required. Peak power meters are designed to provide accurately calibrated detection of envelope power across a wide dynamic range. Like average power meters, they also minimize sensor errors by providing low SWR and compensating for frequency and temperature variations.**

**In CDMA and W-CDMA measurements the peak-to-average ratio is often required. To measure this an average power measurement and a peak measurement is taken and the ratio calculated within the measuring instrument.**
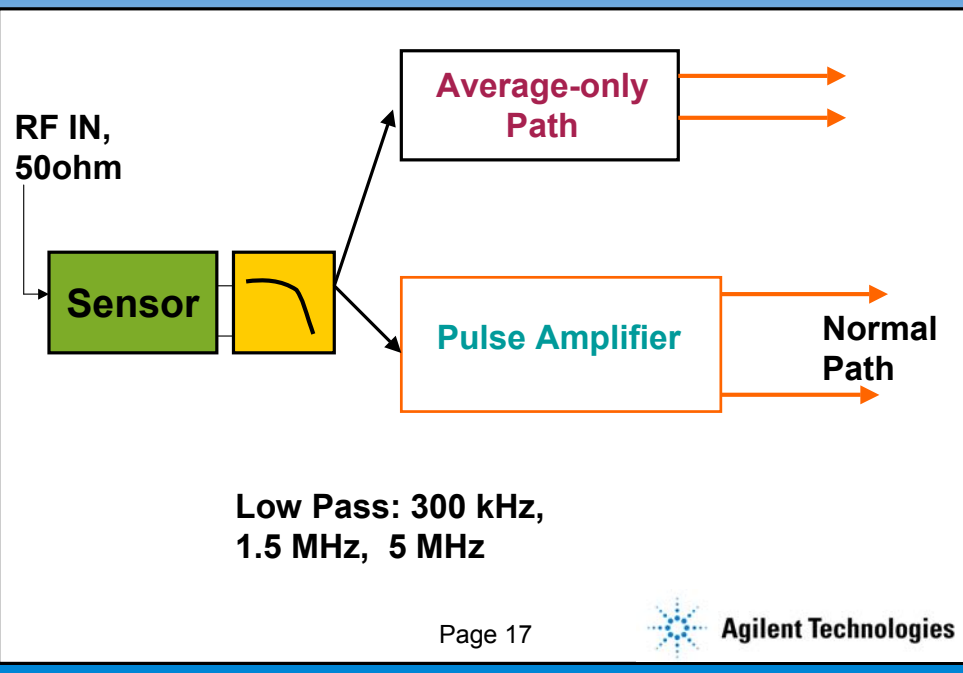
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**Average power is defined as the energy transfer rate averaged over many periods of the lowest frequency in the signal.**

**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.**

**The EPM-P series power meters have a 20 Msamples/second continuous sampling rate that allows for accurate pulse profiling and along with the meter's comprehensive triggering features, such as an external TTL compatible trigger input, internal (level) and GPIB triggering, up to 4 simultaneous time-gated measurements can be made. Individual start (Gate Start) and duration times(Gate Length) can be setup, allowing user's to measure the average, peak or peak-to-average ratio over defined time periods.**

**Peak Power Measurement**

RF IN, 50ohm

Sensor

Average-only Path

Pulse Amplifier

Normal Path

Low Pass: 300 kHz, 1.5 MHz, 5 MHz

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**This slide shows a simplified block diagram of Agilent's new E9320 peak and average power sensor family. The E9320 peak and average power sensors are compatible with the EPM-P series power meters (E4416A single channel and E4417A dual channel) and provide peak, peak-to-average ratio, average power and time-gated measurements on the complex modulation formats used in today's and future wireless communications systems, such as TDMA, CDMA and W-CDMA.**

**Peak and average power sensors are designed for characterizing pulsed and complex modulation signals. The E9320 sensors feature two-mode operation,** Normal **for most peak and average power measurements (with or without time-gating) and** Average only **for power measurements on low level or CW only signals. Both modes use the same diode-sensor bulkhead element. The signal processing is provided by two amplification paths, each optimized to their different data requirements. In the** Average only **mode, amplification and chopping parameters are the same as the previous mentioned wide dynamic range, CW diode sensors, with a typical dynamic range of -65 to +20 dBm.**

**In the** Normal **mode, the separate path pulse amplifier provides bandwidths of 300 kHz, 1.5 MHz and 5 MHz, which allows the user to match the test signal modulation to the instrument data processing. This permits the meter to measure burst average and peak power, to compute peak-to-average ratios, and display other time-gated pulse profiles on the meter's LCD screen. It can also measure and display other complex wideband modulation formats which contain high frequency components up to 5 MHz bandwidth.**

**The Agilent E9320 family of peak and average power sensors currently covers the 50 MHz to 6 and 18 GHz frequency ranges.**

**Let's Take a Break For...**

# Our first

# Q & A

# Session!

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**Unlike thermistors and thermocouples, a diode does not measure the heat content of a signal but rectifies the signal instead. 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 is used as a low-pass filter to remove any RF signal getting through the diode.**
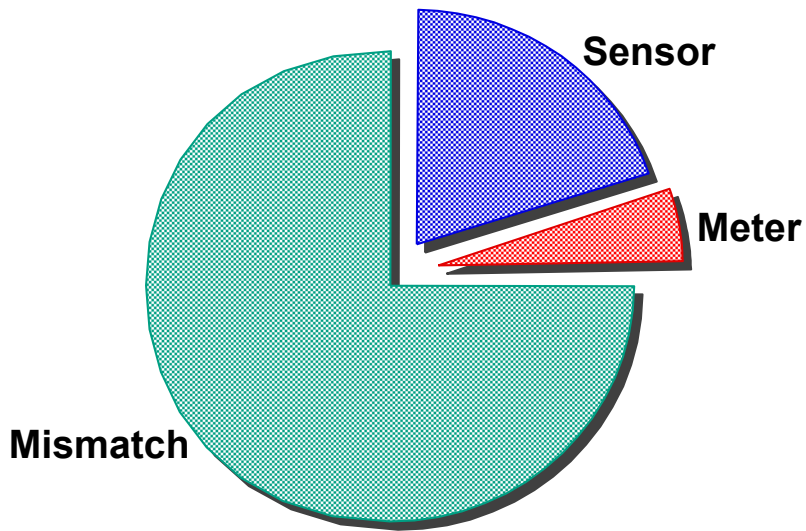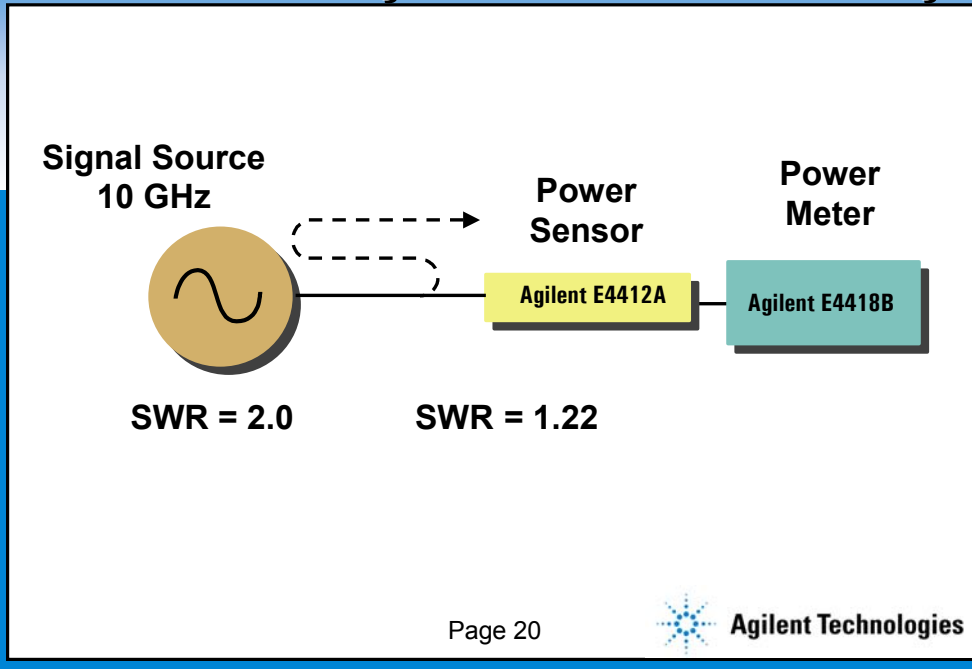
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**In power measurements, like all measurements, there are many sources of error.  Sensor and source impedance mismatch typically cause the largest errors in power measurements.  By knowing the SWRs (standing wave ratios) of the sensor and source, uncertainty 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.**

**Mismatch Always Means… Uncertainty!**

Signal Source
10 GHz

Power
Sensor

Power
Meter

Agilent E4412A

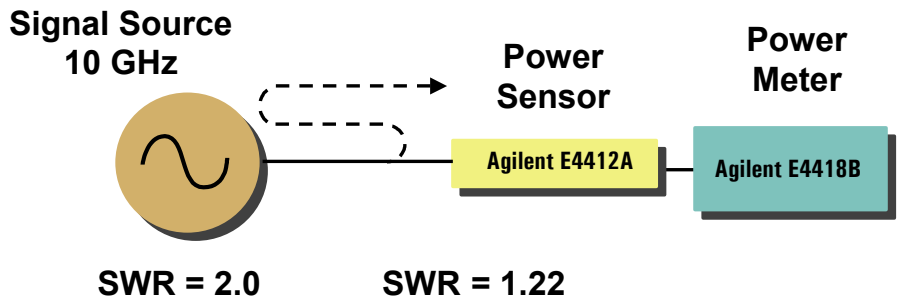Agilent E4418B

SWR = 2.0

SWR = 1.22

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In a power measurement, we are usually interested in the power 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 from 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 too.  The exact power level actually entering the sensor is unknown since the complex reflection coefficient 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 degree of mismatch uncertainty is found using known SWR values for both the sensor and the source.  The Agilent E4412A Power Sensor has a SWR of 1.22 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 contributes 6.6% uncertainty to the measurement.
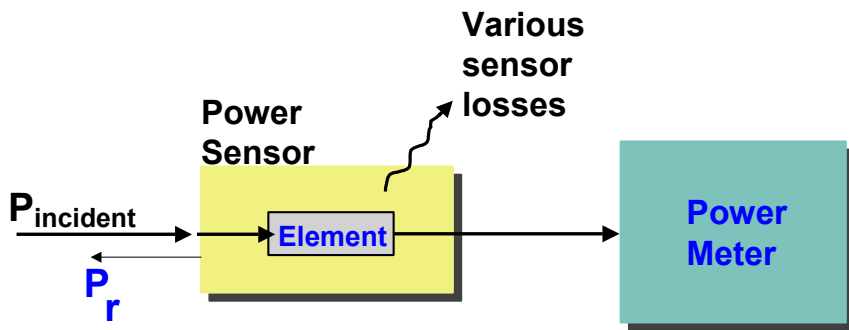
**Mismatch Always Means… Uncertainty!**

Signal Source
10 GHz

Power
Sensor

Power
Meter

Agilent E4412A

Agilent E4418B

SWR = 2.0          SWR = 1.22

Mismatch Unc. $= \pm 2 * \rho_{SOURCE} * \rho_{SENSOR} * 100\%$

$= \pm 2 * 0.33 * 0.10 * 100\% = \pm 6.6\%$

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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,
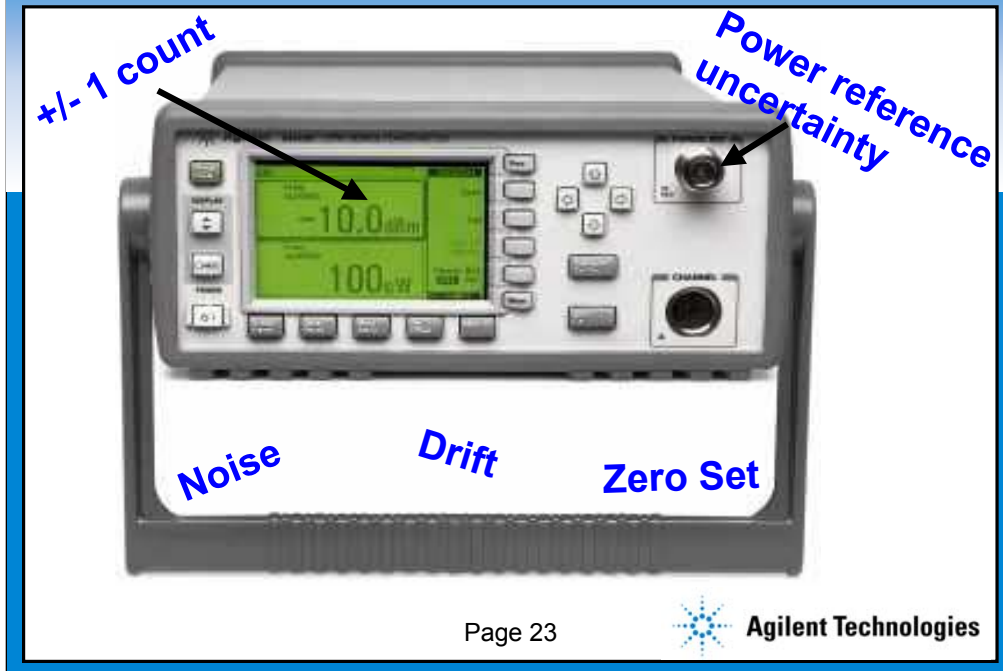
$$Kb = \eta\, e\, \frac{P_{gl}}{P_i}$$

where      is the effective efficiency and        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 E4412A at 10 GHz the calibration factor uncertainty is 3.1% at 0 dBm.

$$\frac{P_{gl}}{P_i}$$

Since the calibration factor correction data will seldom be used manually, it is no longer listed on the sensor label of the Agilent E-series sensors.  The data is always uploaded into the power meter on power-up or when a new sensor is connected.  The new sensors store cal factor tables for two different input power levels to improve accuracy of the correction routines.  If the cal factor changes upon repair or recalibration, the new values are loaded into the sensor EEPROM.

## A Meter's Instrumentation Uncertainties

+/- 1 count

Power reference uncertainty

−10.0 dBm

100 nW

Noise    Drift    Zero Set

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

**Power reference uncertainty**

**Thermocouple or diode sensors require a highly accurate, known power source to verify and adjust for the sensitivity of the individual sensor. The Agilent E4418B Power Meter has a 1.0 mW, 50 MHz power source. Power reference uncertainty deals with the uncertainty in the output of this power source. The E4418B has a power reference specified to 1.2% uncertainty for one year.**

**Instrumentation uncertainty**

**Instrumentation uncertainty is the combination of such factors as meter tracking, circuit non-linearities, range-changing attenuator inaccuracy, and amplifier gain uncertainties. The instrument manufacturer guarantees the accumulated uncertainty is within a certain limit. The instrumentation uncertainty for the E4418B is +/- 0.5%.**

## Calculating the Uncertainty

Mismatch uncertainty:                    ± 6.6%

Cal factor uncertainty:                  ± 3.1%

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 uncertainties for our example power measurement.  Now we want to determine 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, 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.

## Worst-Case

- **In our example, the *worst-case* uncertainty would be:**

**= 6.6% + 3.1% + 1.2% + 0.5%  =  ± 11.4%**

**+11.4%  =  10 log (1 + 0.114)  =  + 0.47 dB**

**- 11.4%  =  10 log (1 - 0.114)  =  - 0.53 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 +/- 11.4%, or + 0.47, - 0.53 dB.**

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

## Root-Sum-of-Squares

- **The *RSS* (more likely) uncertainty would be:**

$$= \sqrt{(6.6\%)^2 + (3.1\%)^2 + (1.2\%)^2 + (0.5\%)^2}$$

$$= \pm 7.4\% \text{ which is,}$$

$$+ 7.4\% = 10 \log (1 + 0.074) = + 0.31 \text{ dB}$$

$$- 7.4\% = 10 \log (1 - 0.074) = - 0.33 \text{ dB}$$

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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 +/-7.4%, or + 0.31, - 0.33 dB.

A more rigorous approach to uncertainty can be found in  Agilent Technologies Application Note 64-1A, Fundamentals of RF and Microwave Power Measurements.  This approach follows a new guideline published by the American National Standards Institute and the National Conference of Standards Laboratories (ANSI/NCSL) and is now being implemented for many metrology applications in industry and government.

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**Unlike thermistors and thermocouples, a diode does not measure the heat content of a signal but rectifies the signal instead. 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 is used as a low-pass filter to remove any RF signal getting through the diode.**