Power Measurement Basics

Speaker Name
Keysight Technologies

January 2017

KEYSIGHT TECHNOLOGIES

KEYSIGHT HOTSPOTS
Where Technologies and Experts Meet

Objectives

On completion of this module, you will be able to:

- Understand the importance of power measurements
- Define the three basic types of power measurements
- Describe the power meter/sensor measurement method
- Explain the two most prevalent sensor technologies
- Describe advanced measurements used for the latest RF & microwave applications
- Calculate power measurement uncertainty
- Outline Keysight's broad range of power measurement solutions

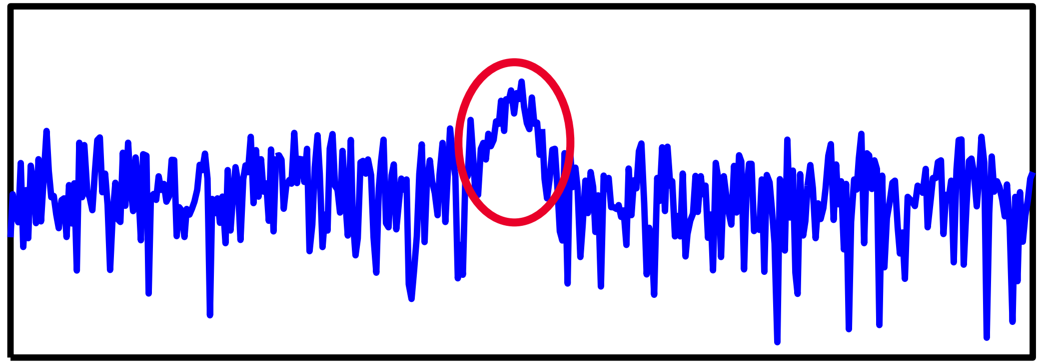
Agenda

- Importance of Power Measurements
- Average, Peak and Pulse Power
- Power Meter & Sensor Measurement Method
- Sensor Technologies
- Keysight Power Measurement Solutions
- Advanced Power Measurements
- Measurement Uncertainty, Standards and Traceability
- Keysight Power Sensor Selection Guides (Appendix)

Signal Power Levels are Critical

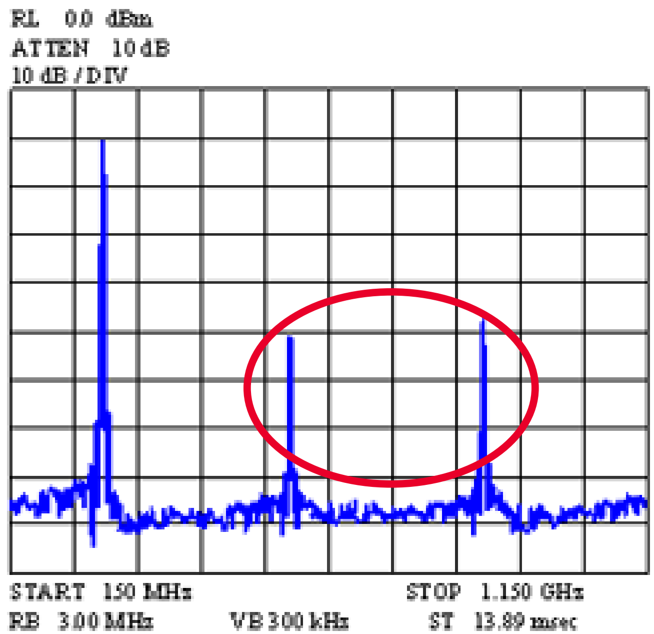
Too low:

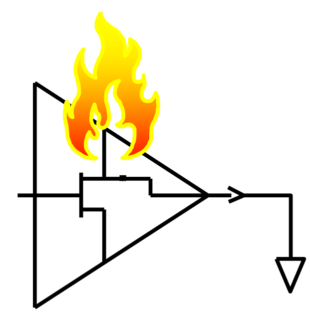
Signal buried in noise



Too high:

Nonlinear distortion...





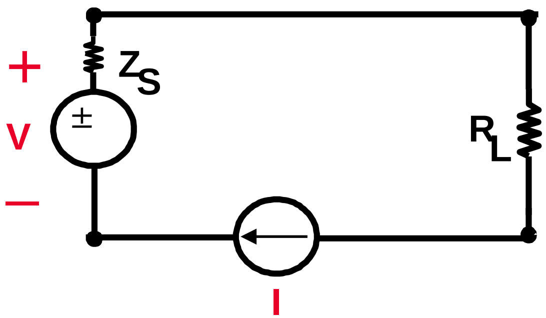
...Or even worse!

Importance of Power Measurements

- Critical to specified performance at every level of a system
- Many measurements made in design and manufacturing
- Measuring equipment and techniques must be:
  - Accurate
  - Repeatable
  - Traceable
  - Convenient

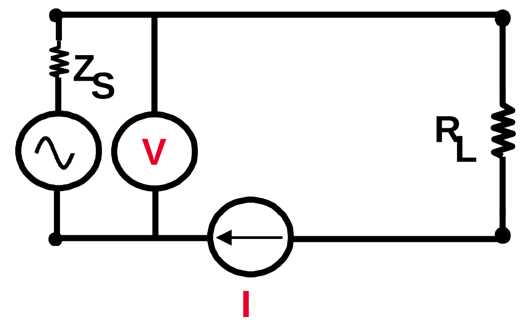
Why Not Measure Voltage?

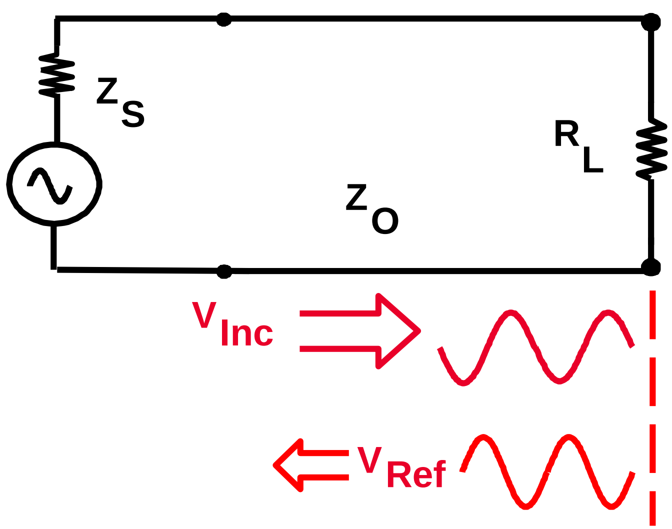
DC



$$P = IV = V^2/R$$

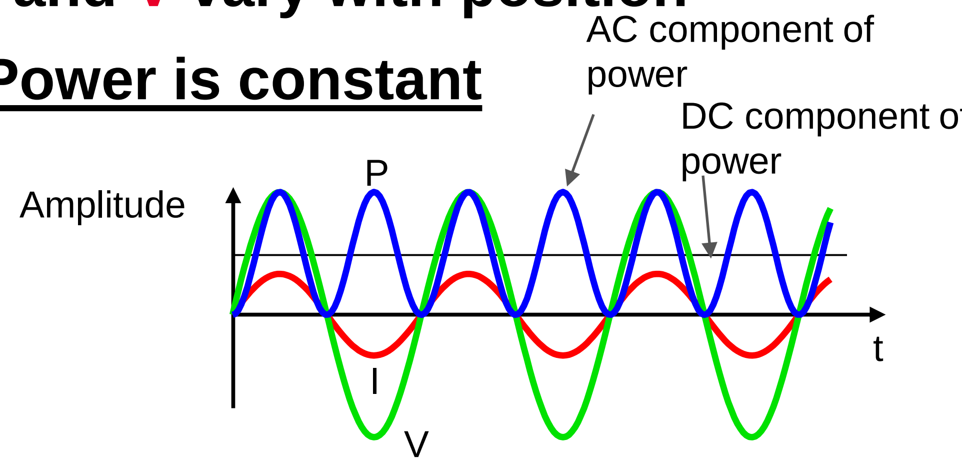
Low Frequency





High Frequency

- **I and V vary with position**
- **<u>Power is constant</u>**



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Units and Definitions

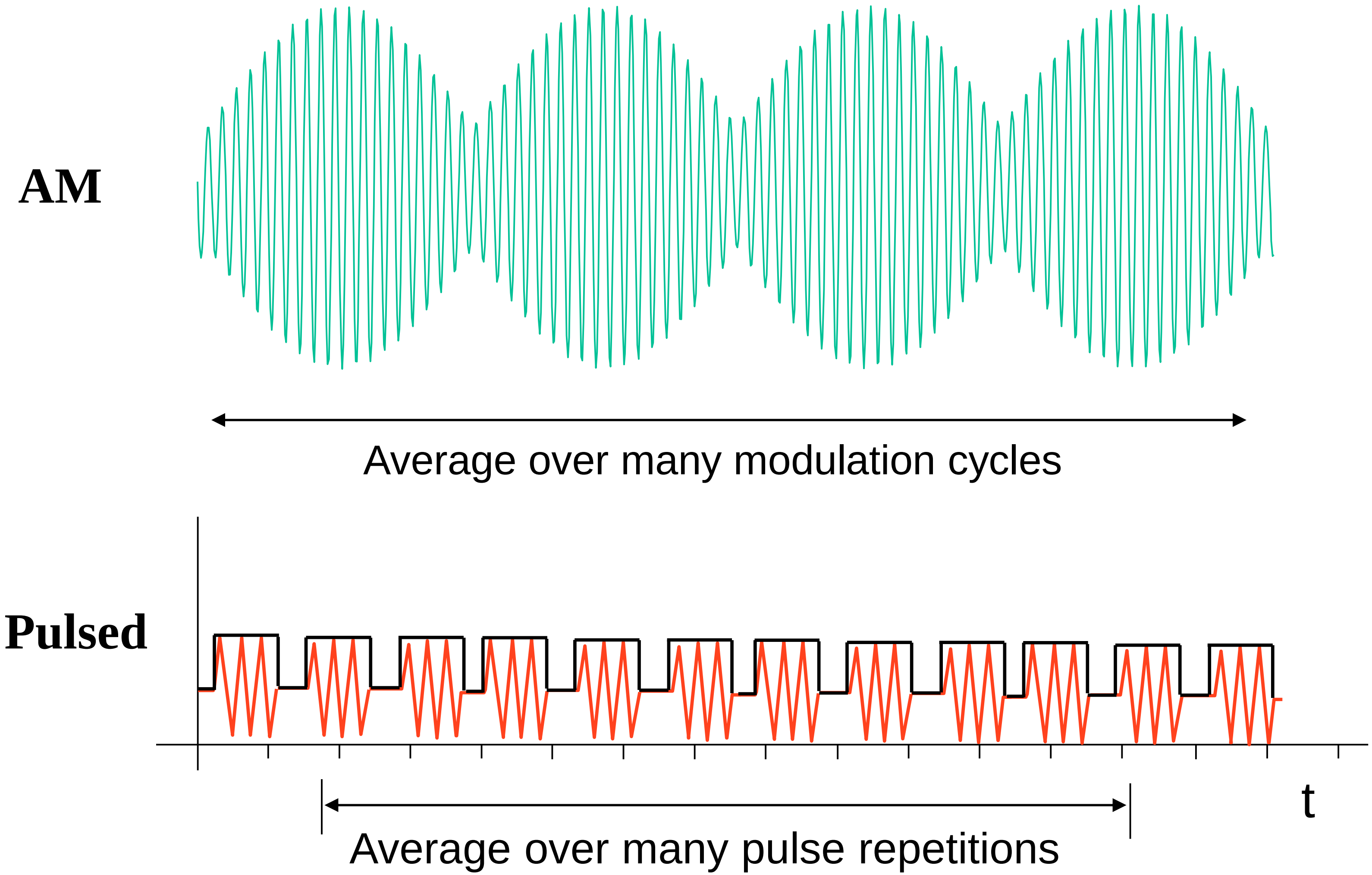
- Power = energy transferred per unit time
- Basic power unit is the watt (W)
  - 1 W = 1 A x 1 V
  - A logarithmic (decibel) scale is often used to compare two power levels
- **Relative** power in decibels (dB):

$$P(dB) = 10\log\left(\frac{P}{P_{ref}}\right)$$

- **Absolute** power is expressed by assigning a reference level to P_{ref} in dBm:

$$P(dBm) = 10\log\left(\frac{P}{1mW}\right)$$

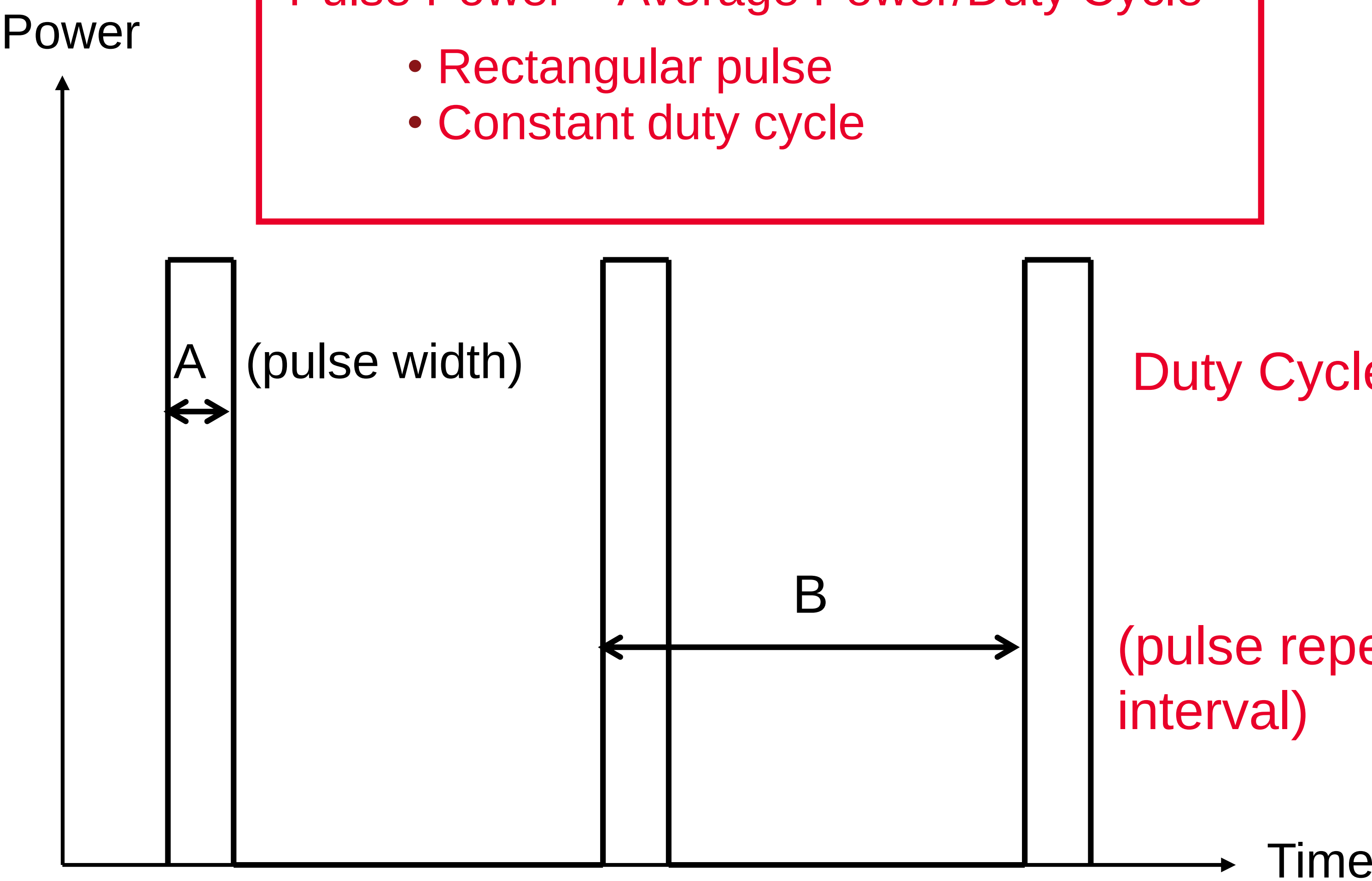
Average Power



Pulse Power

Pulse Power = Average Power/Duty Cycle

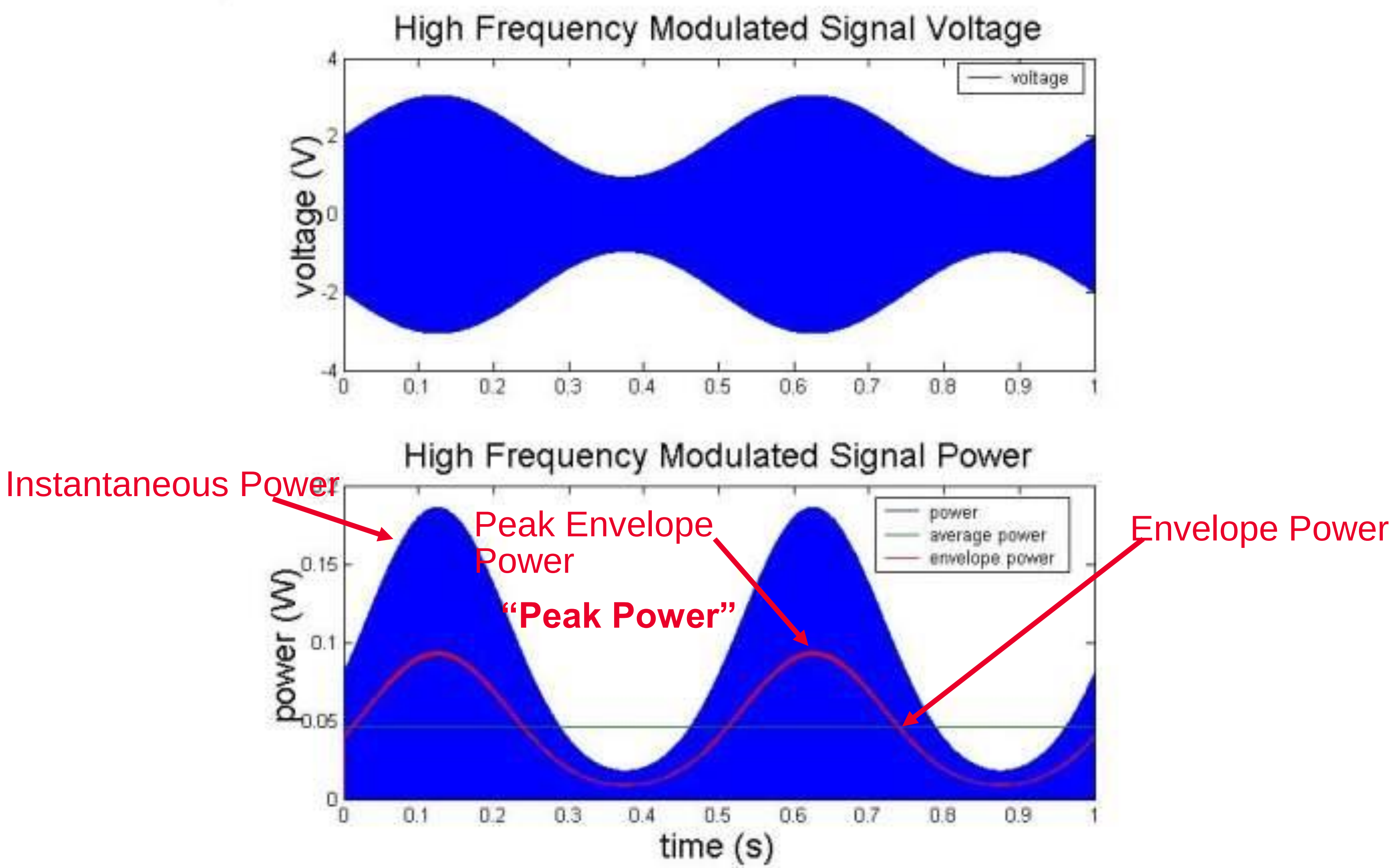
- Rectangular pulse
- Constant duty cycle



Duty Cycle = $\frac{A}{B}$

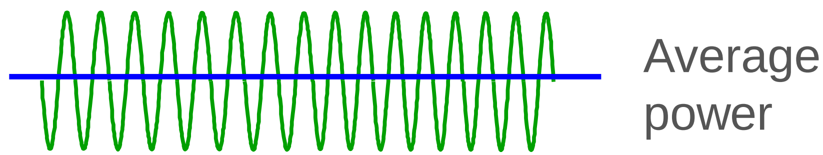
(pulse repetition interval)

Envelope Power and Peak Envelope Power

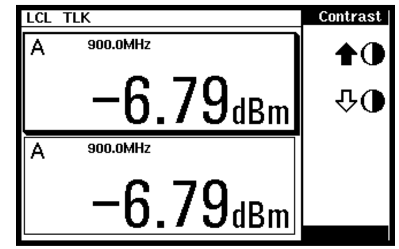


Summary: Types of Power Measurements

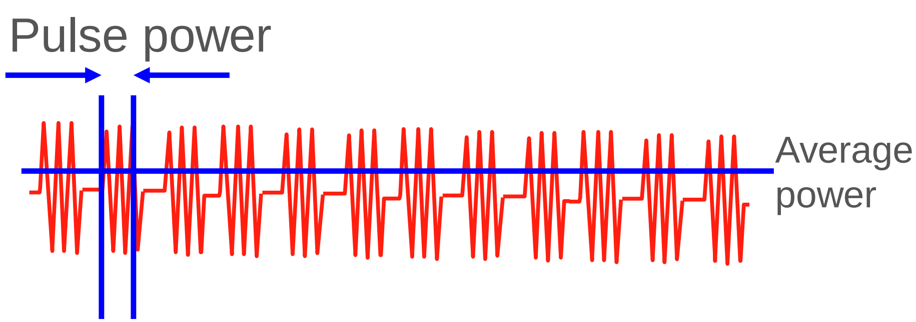
- Average Power



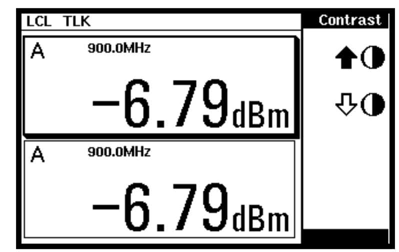
EPM power meter



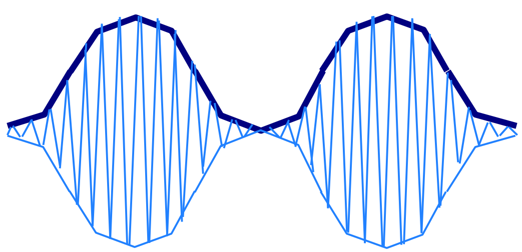
- Pulse Power



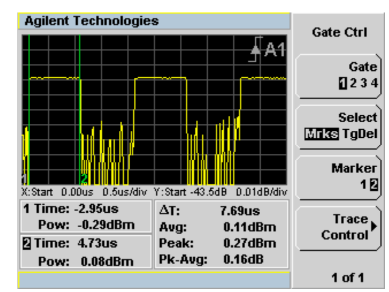
EPM power meter



- Peak Envelope Power



EPM-P or P-Series



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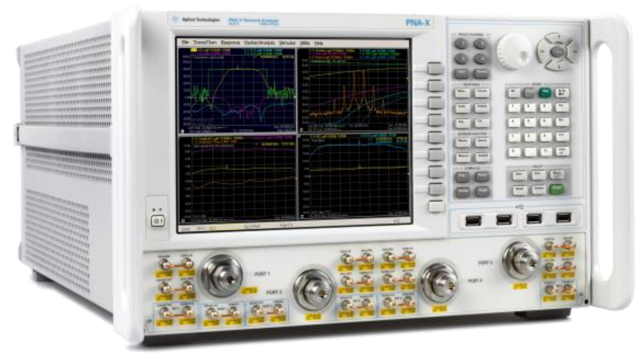
Instruments That Measure RF & Microwave Power

Power Meter and Sensor

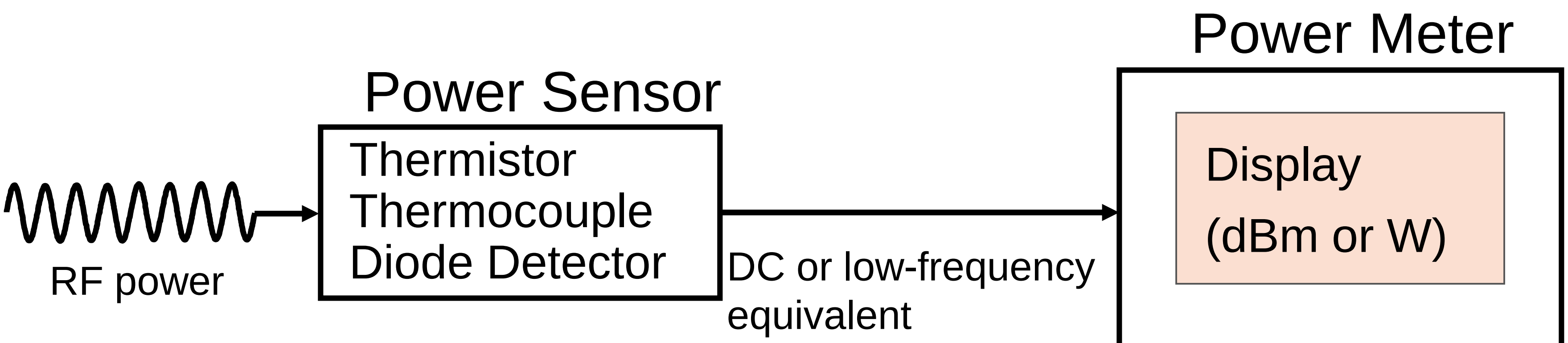
- ± 0. 0X dB
- Broadband
- ≥ – 70 dBm



- ± 0. X dB or greater
- Frequency selective

Vector Signal Analyzer

The Power Meter and Sensor Method



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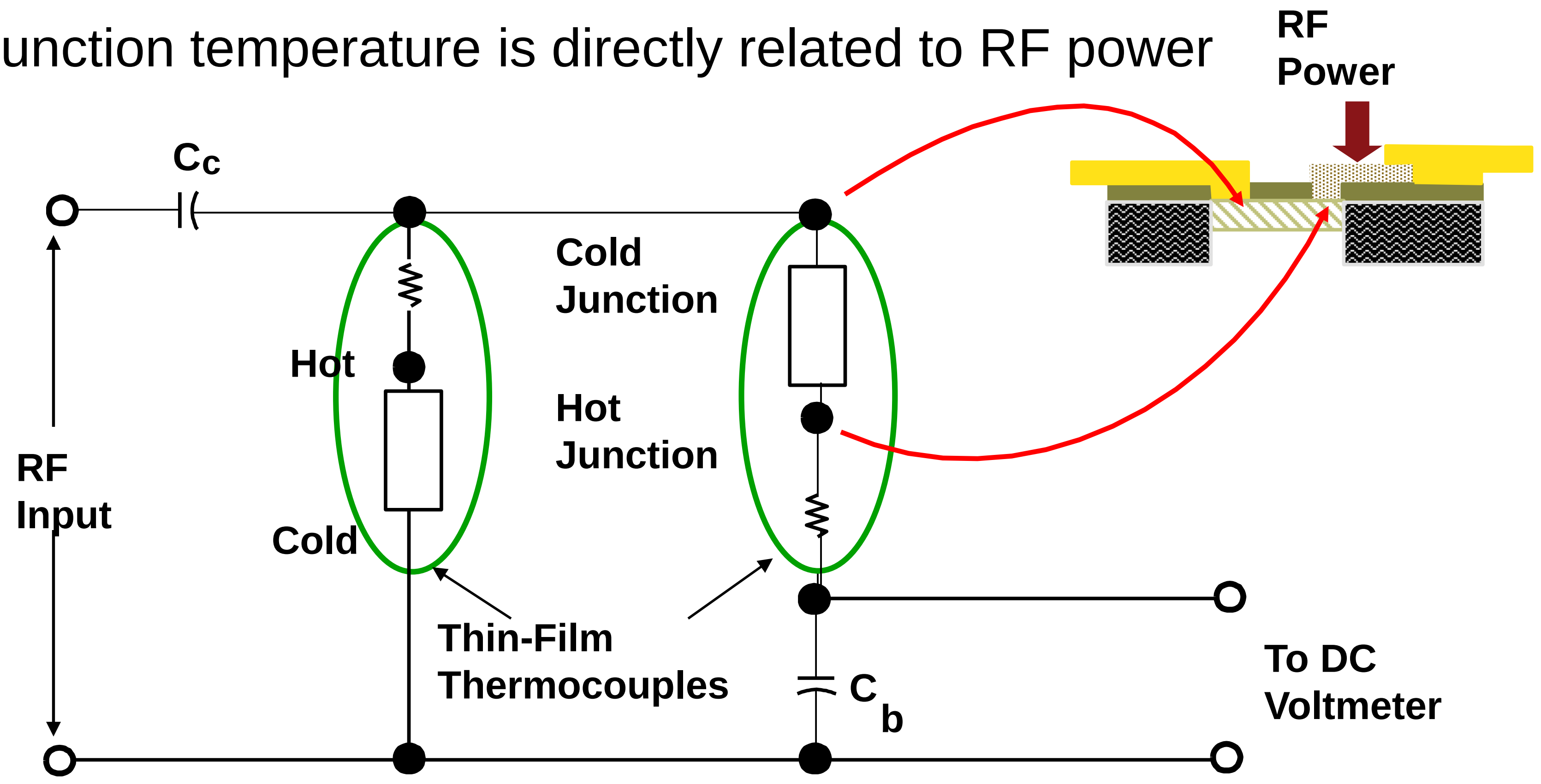
Thermistors

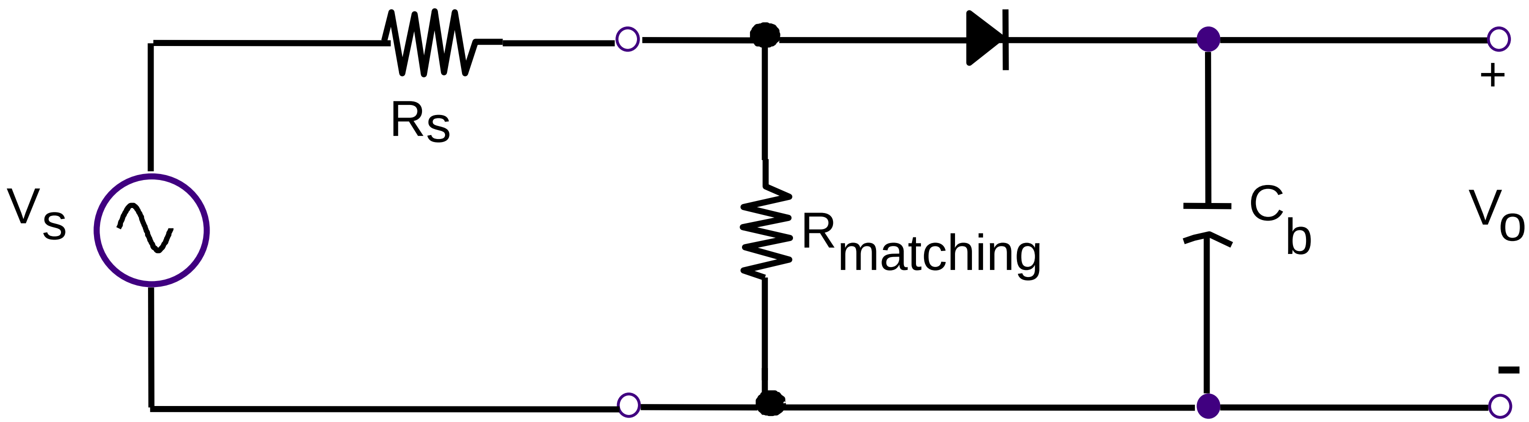
- One of the earliest types of power sensors
- Have been replaced in most applications by thermocouples and diode detectors
- Still used for power transfer standards in metrology applications

Thermocouples

- A junction of two dissimilar metals generates a voltage related to temperature
- Junction temperature is directly related to RF power

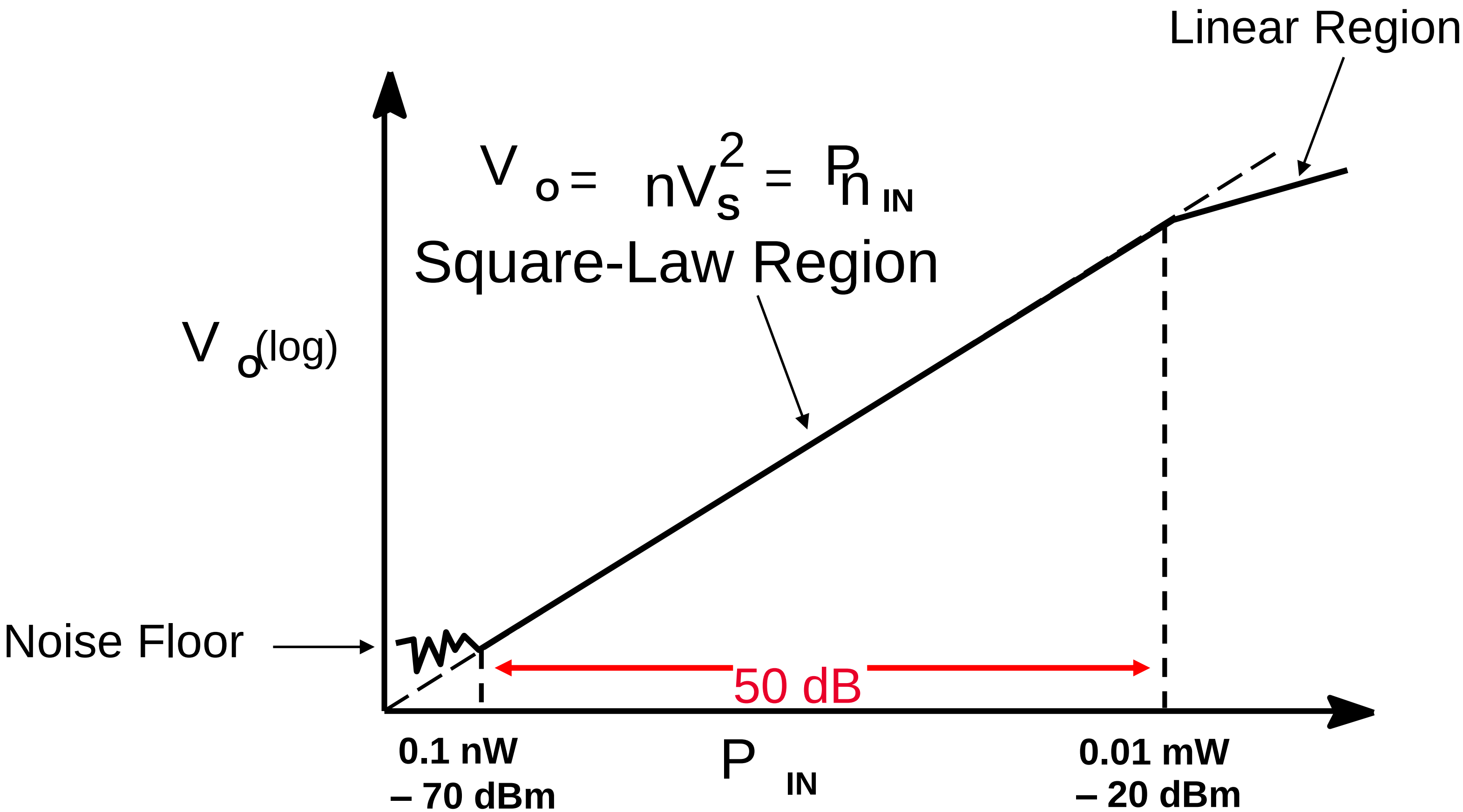


Diode Detectors

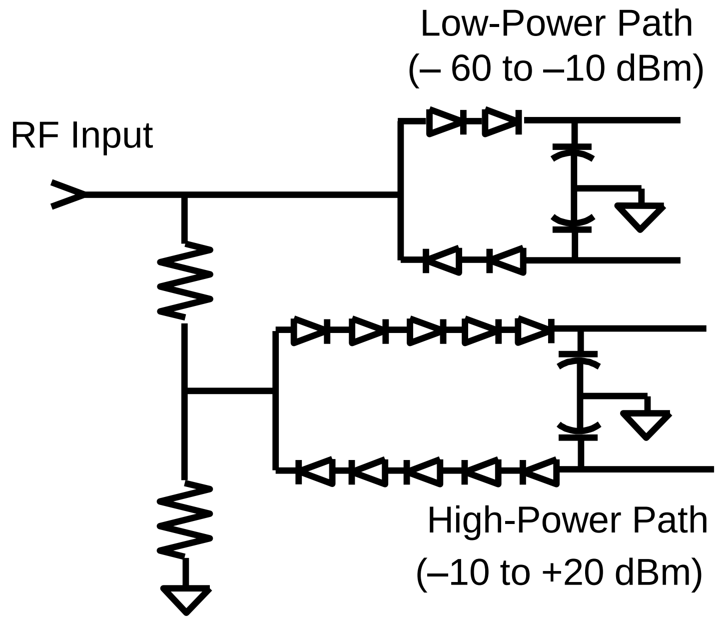


- Diode detector does not measure the heat content of a signal but rectifies the signal
- The matching resistor (approximately 50 ohms) is the termination for the RF signal
- The RF signal voltage (Vs) is converted to a DC voltage (Vo) at the diode
- The bypass capacitor (Cb) is a lowpass filter that removes any RF signal getting through the diode.

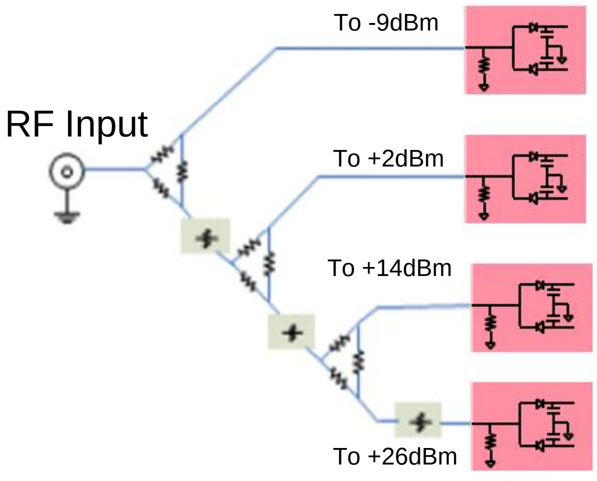
Square-Law Region of Diode Sensors



Multiple Path Diode Architecture



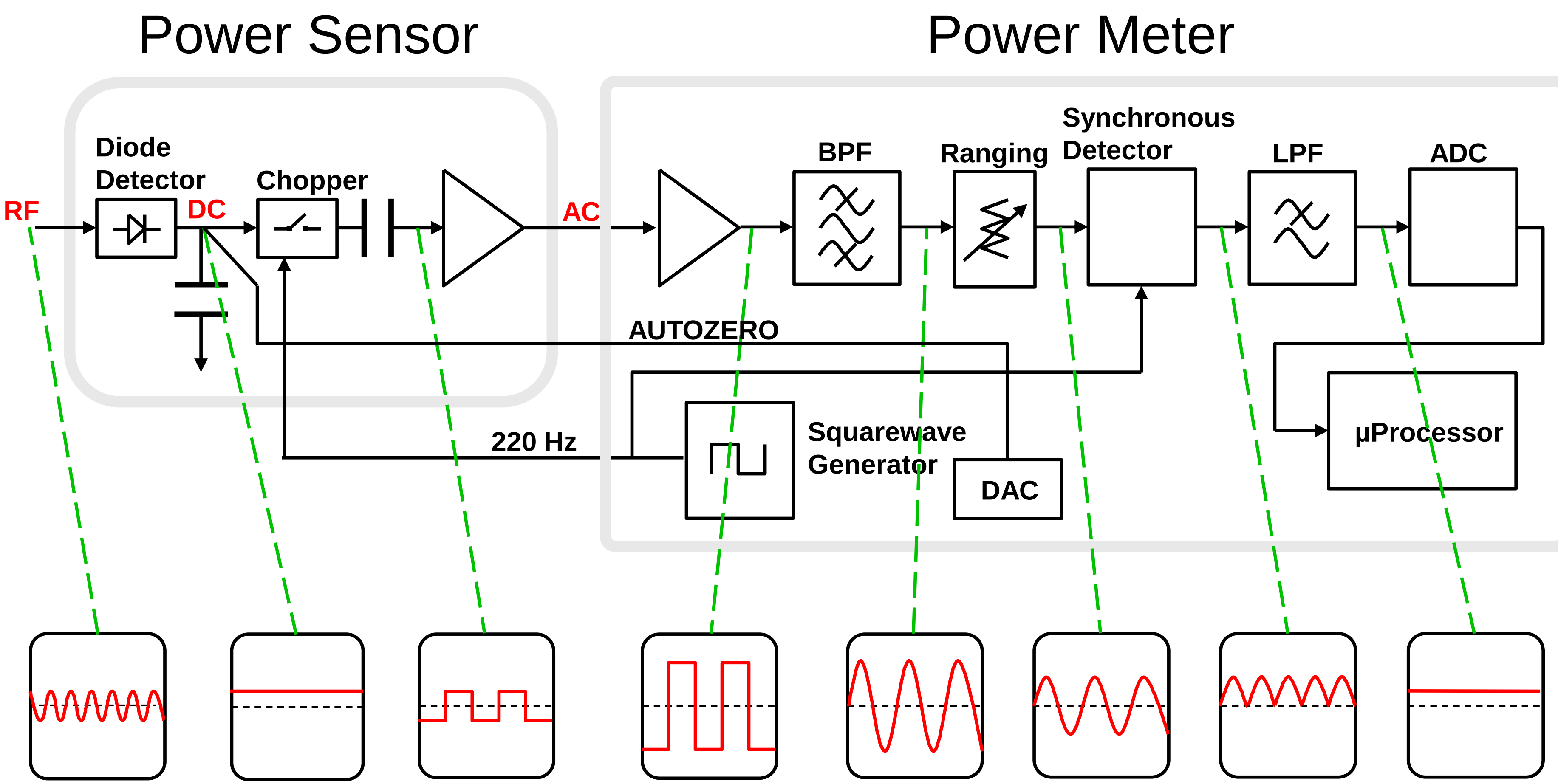
2-path / 80 dB dynamic range with any signal type (U2000/E9300)



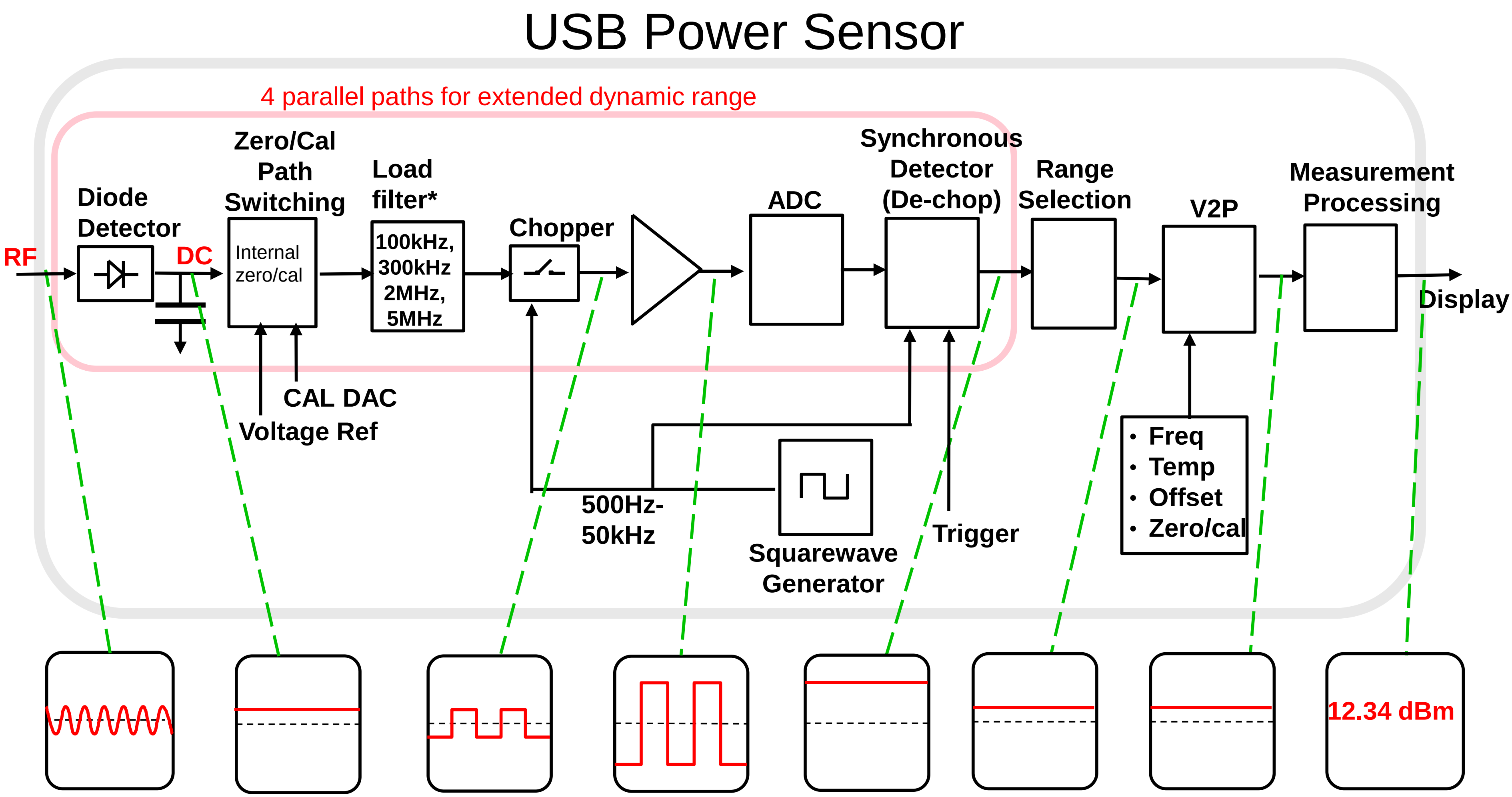
4-path / 96 dB dynamic range with any signal type (U2040)

- Multiple-path design – always operate under diode square law region
- Diode/attenuator/diode topology
- Automatic path switching – best diode for the signal is automatically selected and square-law maintained throughout sensor's dynamic range

Power Sensor and Meter Signal Path



U2040 X-Series Power Sensors – Signal Path



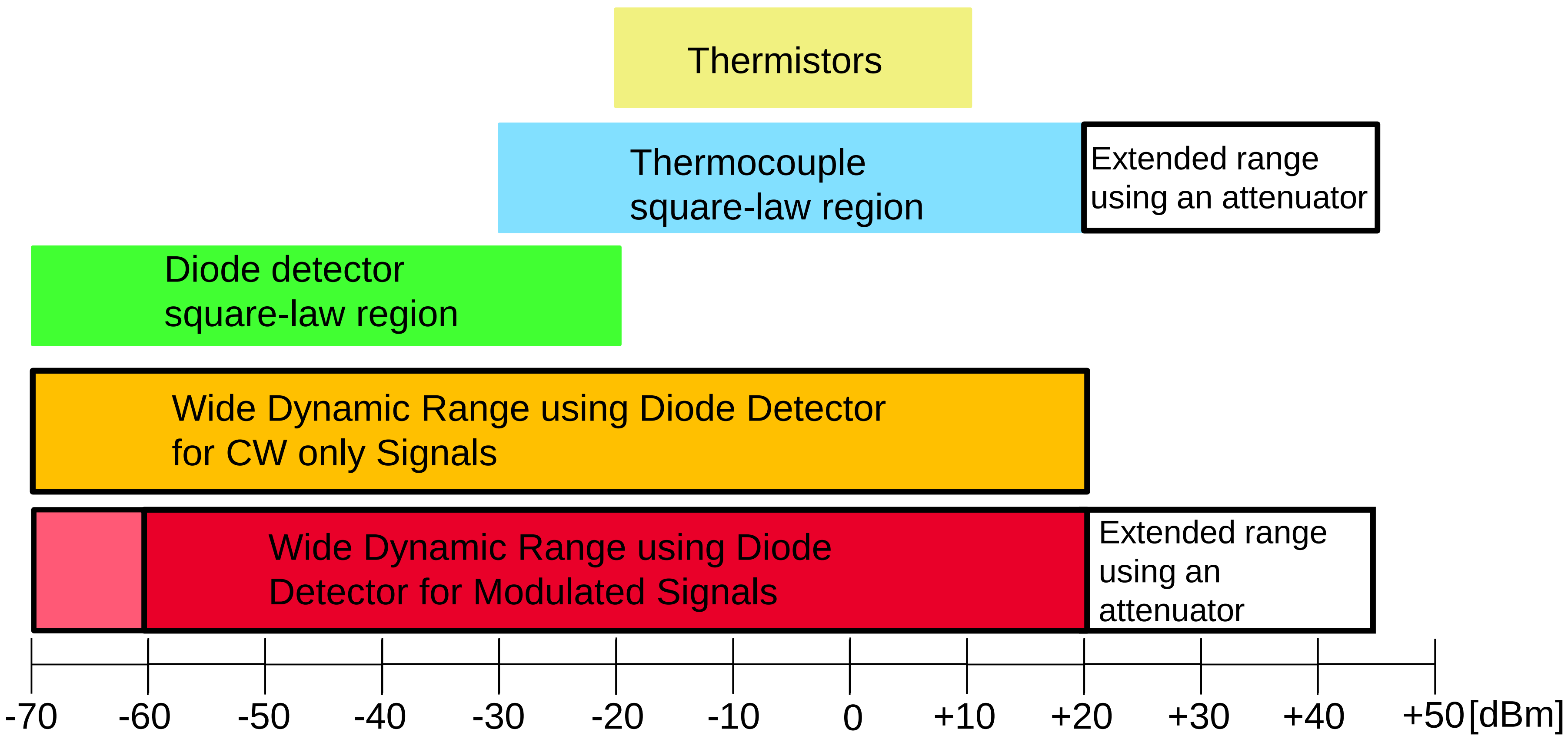
* Bandwidth is selectable dependent on mode

Power Sensor Comparisons

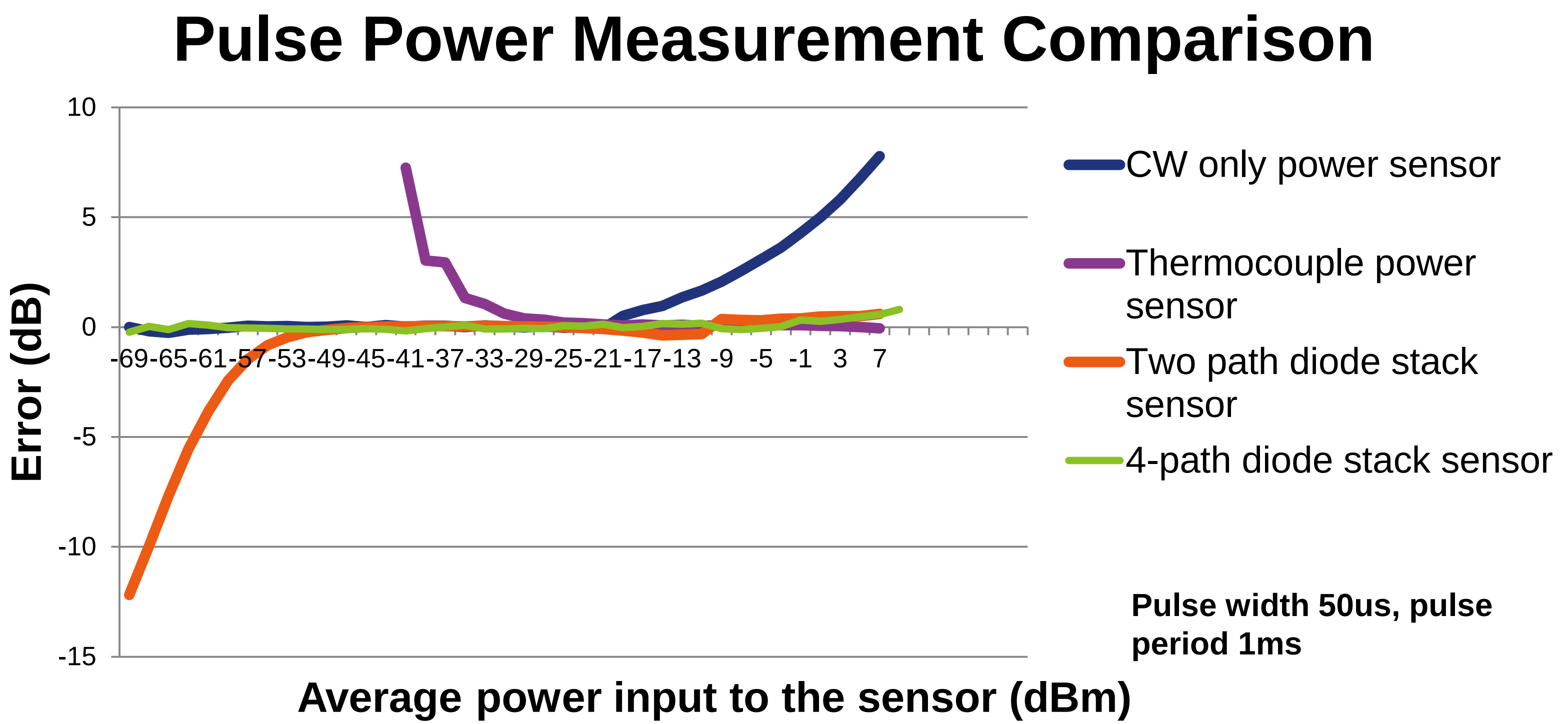
Power Sensor	Advantages	Disadvantages
Thermistor	Directly traceable to NPL/NIST*, good match	Slow, low sensitivity
Thermocouple	Rugged, stable, reliable	Slow, low sensitivity
Diode Detector	Fast, sensitive, enable peak & pulse parameters measurements	Easily overloaded

* Each thermistor mount contains data showing the calibration factor and effective efficiency at six frequencies, directly traceable to the NPL/NIST at those frequencies where NPL/NIST provides calibration service.

Power Range of Various Sensor Types



Pulse Power Measurement Comparison between CW and Average Sensors



- **CW only sensor resulted in high error for pulse signal measurement above -20dBm**
- **Thermocouple power sensor offers the highest accuracy down to ~-35dBm**
- **Two path diode stack sensor provides good accuracy down to ~-60dBm**
- **4-path diode stack sensor provides good accuracy down to ~-70dBm**

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Keysight Power Meter Series

World market leader* with over 60 years of experience in power meter design, offering a complete measurement solutions from 9 kHz to 110 GHz, -70 dBm to +44 dBm.

PERFORMANCE

8990B Peak Power Analyzer

- Peak, Average, CCDF (<160MHz VBW)
- Pulse Measurement
- Radar Pulse Tr < 5ns

NEW!

U2040 X-Series

- World's widest dynamic range
- Peak & Average
- >50,000 readings/sec
- USB or LAN

Option up to 50 GHz

NEW!

U2020 X-Series

- Peak & Average, CCDF (<=30MHz)

N1911/12A P-Series

- Peak, Average, CCDF (<=30MHz VBW)
- Wireless Networking (WLAN, WiMAX, MIMO)
- Radar Pulse Tr > 13ns

N8262A P-Series LXI

- Peak, Average, CCDF
- (<30MHz VBW)
- Compact, modular, faceless
- For A&D ATE/ CASS

E4416/17A EPM-P

- Peak & Average (<5MHz VBW)
- Wireless Com (GSM, EDGE, WCDMA, Bluetooth, etc.)
- Radar Pulse Tr > 200ns

U2000 Series USB Sensors

- Average Power
- Low Cost Solution
- I&M market, R&D & Mfg

N1913/14A EPM

- Average Power
- R&D & Mfg (Std Rack Size)
- Military & ATE Systems

Handheld Power Meter

- Average Power
- Handheld solutions

PRICE

Average Power Measurements

METROLOGY	MULTI-CHANNEL	WIDE DYNAMIC RANGE		HIGH ACCURACY	LOWEST COST
N432A Thermistor Mount Power Meter	**N1913/14A EPM Power Meter**	**U2040 X-Series USB Wide Dynamic Range Power Sensor**	**U2000 Series USB Power Sensor**	**U8480 Series USB Thermocouple Power Sensor**	**V3500A Handheld Power Meter**
		 **U2041/43XA**			
• High accuracy of ≤ 0.2% ± 0.5 uW • Excellent for 1mW transfer calibration (with 478A-H75/76 thermistor mount sensor) • Built-in 6.5 digit ADC eliminates the needs of external DMM • Digital color LCD display, user friendly interface.	• Single, dual, or four channel measurements • Wide freq/power range of 9 kHz to 110 GHz, -70 dBm to +44 dBm (sensor dependent) • Fast measurement speed of 400 readings/s • Code compatible with legacy E4418/19B, 436A, 437B, and 438A power meters (Opt 200)	• 10 MHz to 18 GHz • World's widest dynamic range of -70 dBm to +26 dBm • Fast measurement speed to 50,000 readings/sec • Internal zero and calibration • Bundled with BenchVue software for easy monitoring	• 9 kHz to 26.5 GHz • Wide dynamic range of -60 dBm to +20 sdBm • Quick and easy setup with USB connectivity • Internal zeroing without disconnecting from DUT • Bundled with N1918A Power Panel software for easy monitoring	• DC to 70 GHz • Dynamic range of -35 dBm to +20 dBm • High accuracy of <0.1dB (~2.3%) with thermocouple sensor • Built-in trigger input port and calibration source	• 10 MHz – 6 GHz • Wide dynamic range of -63 dBm to +20 dBm • Absolute accuracy to +/-0.21 dB • Built-in display & integrated power sensor • Internal power reference enables self calibration
From $9,687	From $4,551	From $3,623	From $3,031	From $2,939	$2,260
1. Calibration 2. Metrology	1. Manufacturing 2. System integration	1. Manufacturing 2. Installation & maintenance 3. Field service	1. Manufacturing 2. Installation & maintenance 3. Field service	1. Instrument / test system calibration 2. Metrology & research applications	1. Installation & maintenance 2. Field service / repair

Peak & Average Power Measurements

HIGH PERFORMANCE	COMPACT	WIDEBAND	WIDE DYNAMIC RANGE	WIDEBAND	WIDE DYNAMIC RANGE
8990B Peak Power Analyzer	**N8262A P-Series Modular Power Meter**	**N1911/12A P-Series power meter**	**E4416/17A EPM-P Power Meter**	**U2020 X-Series USB Peak & Average Power Sensor**	**U2040 X-Series USB Peak & Average Power Sensor**
					 NEW **U2042/44XA**
• 5 ns rise time/ fall time • 100 MSa/s sampling rate • 160 MHz VBW • 2 RF channels+ 2 analog channels • Internal Zero + Calibration	• 1U half-rack size • 100 MSa/s sampling rate • ~ 13 ns rise time/ fall time • 30 MHz VBW • Internal Zero + Calibration • LXI Class C	• 100 MSa/s sampling rate • ~ 13 ns rise/ fall time • 30 MHz VBW • -35 dBm to +20dBm • Internal Zero + Calibration	• 20 MSa/s sampling rate • ~ 13 ns rise / fall time • 5 MHz VBW	• 100 MSa/s sampling rate • ~13 ns rise/ fall time • 30 MHz VBW • 3500 readings/s • -35 dBm to +20dBm • Internal Zero + Calibration	• 20 MSa/s sampling rate • ~100 ns rise/ fall time • Wideband average power, peak power VBW 5 MHz • 50 000 readings/s • -70 to +26dBm • Internal Zero / Cal
Price: $32,416	Price: $13,419	Price from $8,308	Price from $5,265	Price from $7,486	Price from $5,175
1. R&D 2. Design verification	1. System Integration	1. Manufacturing 2. System Integration	1. Manufacturing 2. System Integration	1. Manufacturing 2. Installation & maintenance 3. System integration	1. Manufacturing 2. Installation & maintenance 3. System integration

U2040 X-Series Wide Dynamic Range Power Sensors

The ideal sensor for any wireless signal formats

LTE-Advanced

LTE-TDD/FDD

WCDMA

GSM/EDGE

MCPA

- ***10 MHz to 6/18 GHz***
- ***World widest dynamic range: -70 dBm to +26 dBm***
- ***Broadband coverage***
- ***Super fast speed***
- ***Real time measurements***
- ***Internal zero/calibration***
- ***100 ns rise time / 20 MSa/s***

WLAN 802.11ac

WLAN 802.11a/b/g/n

WiMAX

Bluetooth

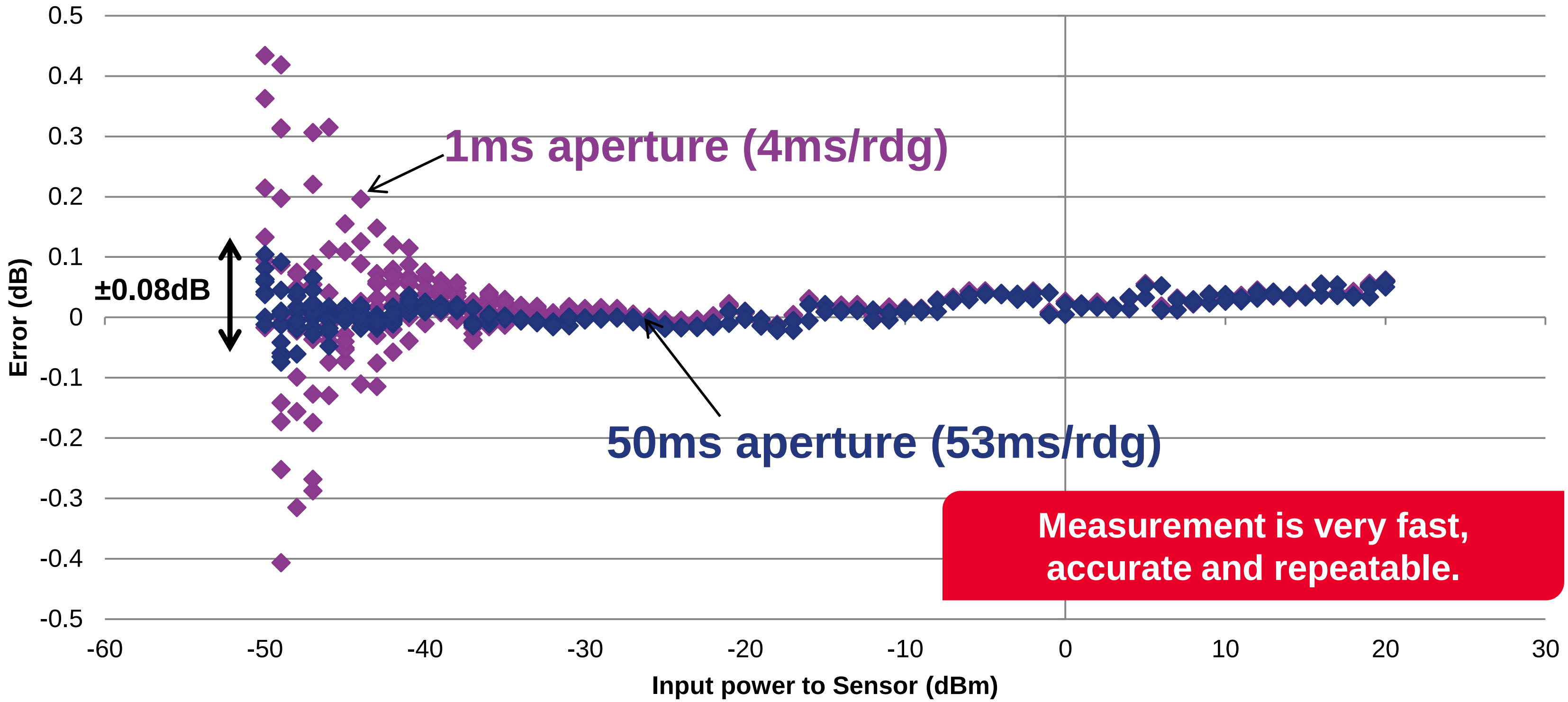
APCO/iDEN

<table>
<tr><th>Model</th><th>Freq range</th><th>Power range</th><th>Connector</th></tr>
<tr><td>U2041XA</td><td>10 MHz to 6 GHz (Average only)</td><td rowspan="4">-70 dBm to +26 dBm</td><td rowspan="4">N-type (male)</td></tr>
<tr><td>U2042XA</td><td>10 MHz to 6 GHz (Peak & Average)</td></tr>
<tr><td>U2043XA</td><td>10 MHz to 18 GHz (Average only)</td></tr>
<tr><td>U2044XA</td><td>10 MHz to 18 GHz (Peak & Average)</td></tr>
</table>

World Widest Dynamic Range Power Sensor

1% error down to -50dBm at avg count of 1 (@ 200ms aperture setting)

2% error down to -50dBm at avg count of 1 (@ 50ms aperture setting)



Measurement is very fast, accurate and repeatable.

Measurement repeatability at 50ms (default aperture) and 1ms, average count of 1 (10 data collected at each power level)

U2049XA TVAC PoE/LAN Power Sensor

World's FIRST!

The ideal sensor for remote monitoring, fault detection, and in-space performance monitoring of satellite systems

- Wide frequency coverage: 10 MHz to 33 GHz
- Widest dynamic range: -70 dBm to +20 dBm
- Patented internal zero/calibration
- TVAC test for operation in vacuum
- PoE/LAN connectivity for long distance remote monitoring
- Best-in-class long term drift performance

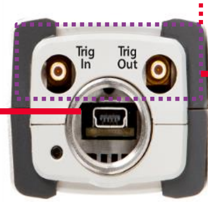
U2020 X-Series USB Power Sensors

USB power sensors with peak and average power measurement capability of a bench power meter

Internal zeroing and calibration eliminates external calibration needs

30MHz VBW, 80MSa/s, 25000 rdg/s, wide 50dB peak dynamic range

Works with any PC and many Keysight instruments



Built-in external trigger in and trigger out / video out / recording out ports

USB allows remote measurements beyond typical cable length

Wideband peak & average USB power sensor

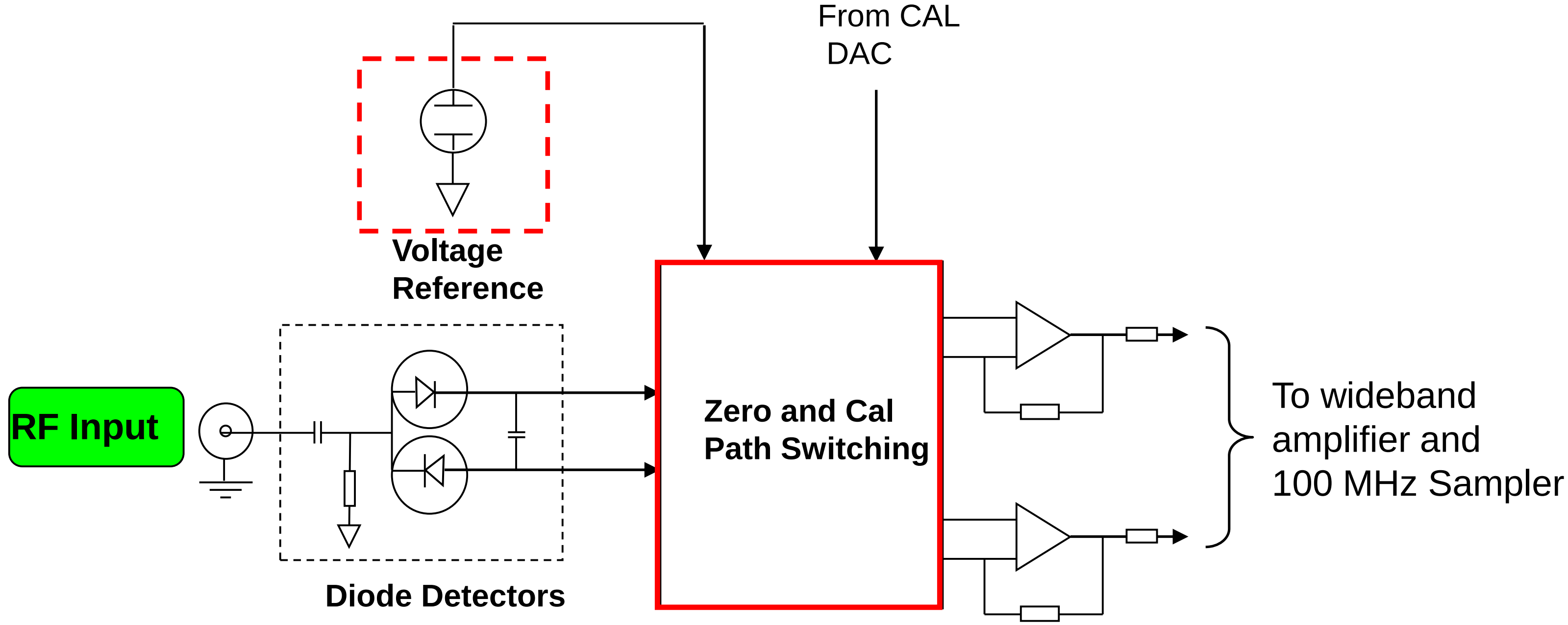
- **Wide 30MHz single shot bandwidth**
- **100 MSa/s cont. sampling**
- **50MHz – 18/ 40GHz**
- **-35 to +20dBm**
- **13ns rise time spec**
- **Internal zero and calibration**
- **Built-in trigger in/out**

Model	Freq range	Power range	Connector
U2021XA	50M – 18GHz,	-35 to +20dBm	N-type (male)
U2022XA	50M – 40GHz	-35 to +20dBm	2.4mm (male)

Internal Zero and Cal

P-Series & U2040/U2020 Series Power Sensors

Internal zero and calibration within the N192XA & U2020/U2040 Series sensors - eliminates multiple connections with external calibration source



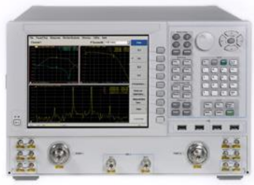
Wideband Power Sensor Block Diagram

USB Power Sensor Compatibility with Keysight Instruments

Perform source power calibration

Perform scalar network analysis of frequency converter

ENA Vector Network Analyzer



PNA series Vector Network Analyzer

FieldFox Handheld Analyzer

Handheld Cable and Antenna Tester

E/MXG Signal Generator

X-series Signal Analyzer

RF Spectrum Analyzer

Handheld Spectrum Analyzer

Perform user flatness correction. Supports two USB power sensors measurement.

Turn the unit into a power meter. Display power measurement with its user interface.

Each compatible instrument comes with built-in firmware to support the USB power sensor, unless specified that N1918A Power Analysis Manager, BenchVue Power Meter App software, or VBA wizard is required.

KEYSIGHT TECHNOLOGIES Compatibility Guide:
http://literature.cdn.keysight.com/litweb/pdf/5989-8743EN.pdf

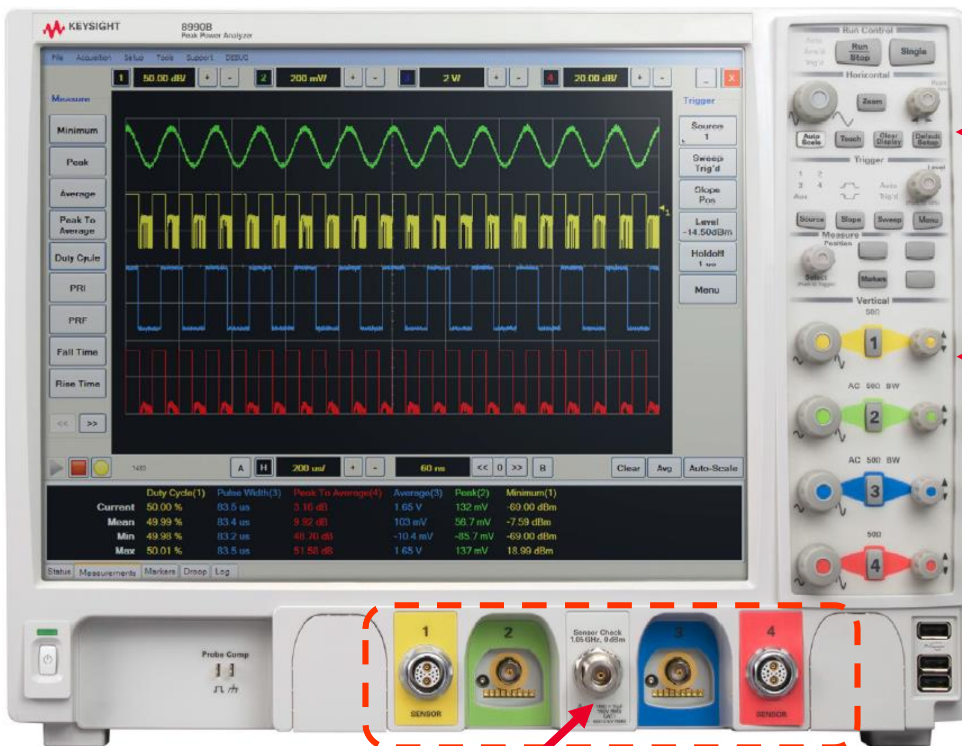
8990B Peak Power Analyzer

Offers fastest rise and fall time of 5ns in the peak power measurement market (160 MHz VBW)

15 inch XGA color display + touch screen

Simple soft key menu

15 automatic pulse characteristics measurements



Standard Keysight Oscilloscope knobs layout – easy to get familiarize

Interactive controls with color coded knobs for each channel.

Easy waveform storage with USB storage device

1.05GHz absolute accuracy source for calibration

Two RF channels and two Analog channels with color coded.

8990B Peak Power Analyzer

Key Features

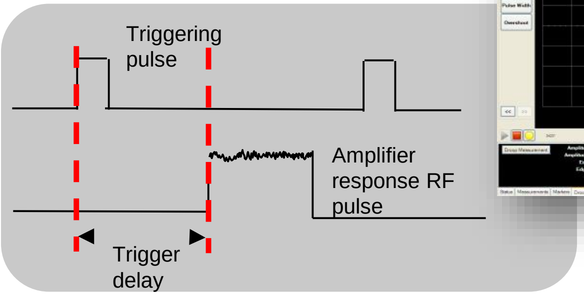
- ✓ 15" XGA Color Display + Touch Screen
- ✓ 4 channels (Two RF and two Analog)
- ✓ Dual Screen Zoom Window
- ✓ 15 Pulse Characterization Measurements
- ✓ Automatic pulse delay measurement between channels

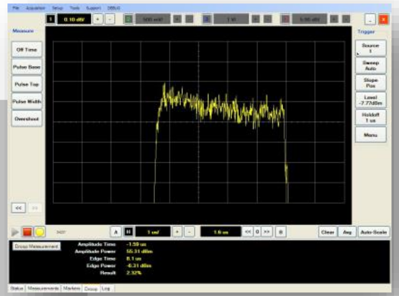
5nsec (System Rise/ Fall Time)
160MHz VBW
Dynamic Range: -35dBm to +20dBm
Sampling Rate: 100MSa/sec
Eff sampling rate: 1GSa/sec

Sensor Model	Freq range	Power range	Connector
N1923A	50M – 18GHz,	-35 to +20dBm	N-type (male)
N1924A	50M – 40GHz	-35 to +20dBm	2.4mm (male)

Power Amplifier/ TR Module Test

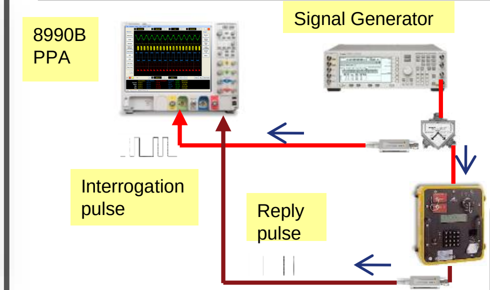
- **Measure Pulse Time Delay measurement**
- **Power Gain Measurement**
- **Pulse Droop Measurements**

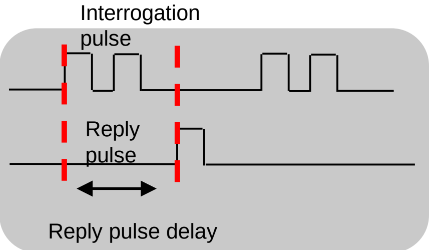




Transponder Test

- **Measure reply pulse delay measurement**
- **Measure peak power, rise/ fall time, pulse width**



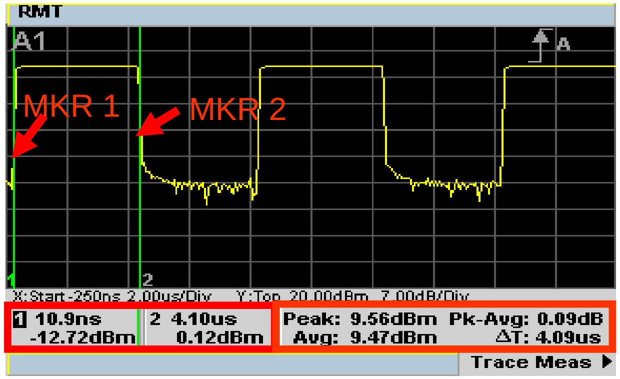


Radar Application

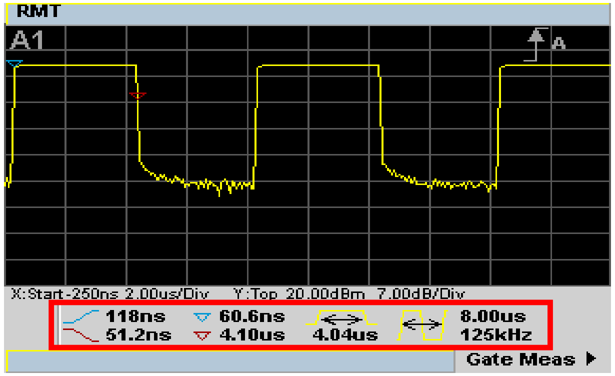
N191X Power Meters and N192X Power Sensors

Keysight's P-Series power meters and power sensors provide *wide bandwidth, fast, accurate* and *repeatable* power measurements for R&D and manufacturing

- **30 MHz** video bandwidth, 13 ns rise/fall time
- Single-shot and real time capture at **100 M-samples per second**
- Zero and calibrate while still connected to the DUT
- Peak, average and peak-to-average ratio power measurements plus automatic time measurements
- 50MHz to 18GHz / 40GHz



Gated power measurements



Pulse parameters analysis

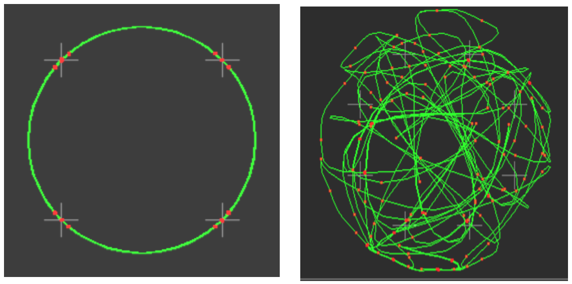
Agenda

- Importance of Power Measurements
- Average, Peak and Pulse Power
- Power Meter & Sensor Measurement Method
- Sensor Technologies
- Keysight Power Measurement Solutions
- Advanced Power Measurements
- Measurement Uncertainty, Standards and Traceability
- Keysight Power Sensor Selection Guides (Appendix)

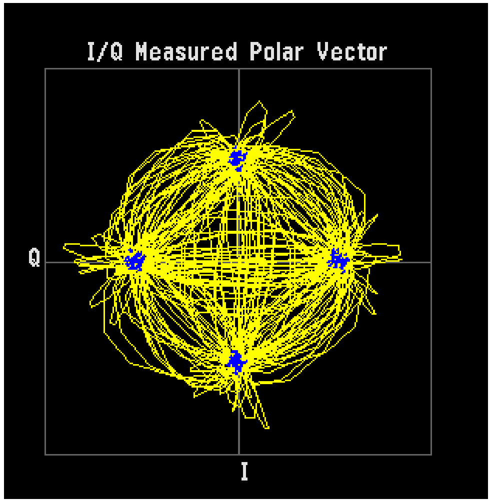
Technology Drivers

- Aerospace and Defense (Radar)
- Digital Wireless Communications

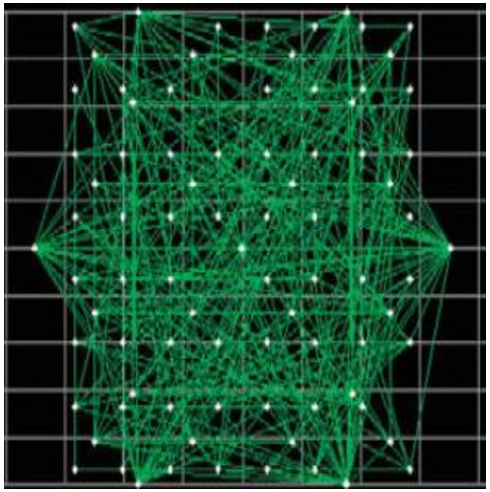
GSM / EDGE



cdma2000



LTE Advanced

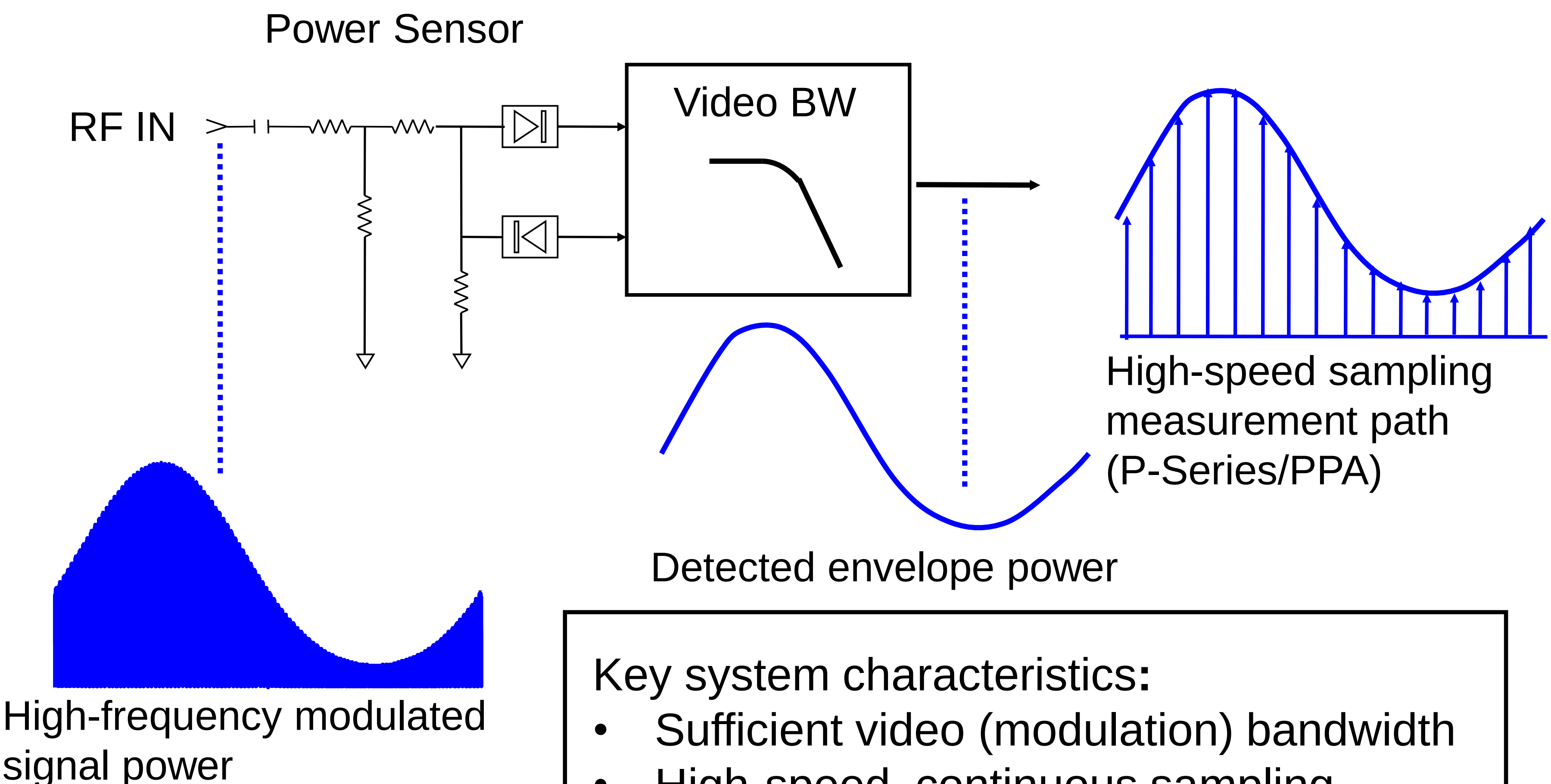


- 2G/3G technology
- TDMA system
- Time-gated average power
- Fast measurements

- 3G technology
- Peak-to-average ratio
- CCDF

- 4G technology
- OFDMA system
- 20MHz to 100MHz VBW

Peak Power Measurement System

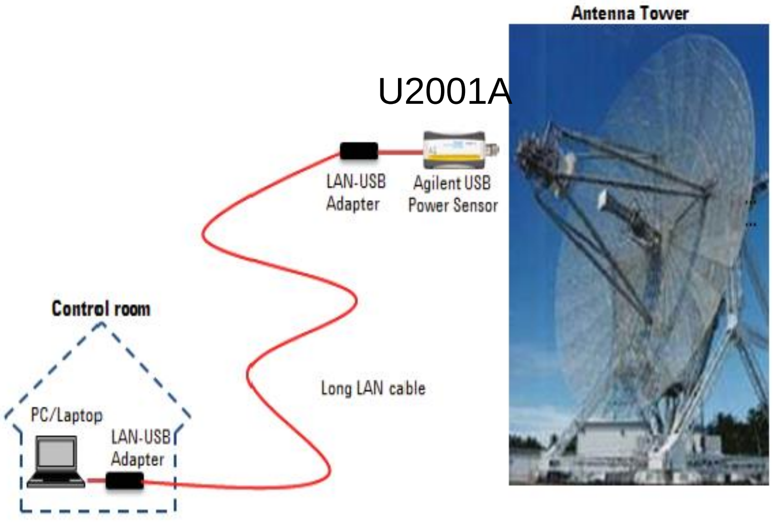


Key system characteristics**:**

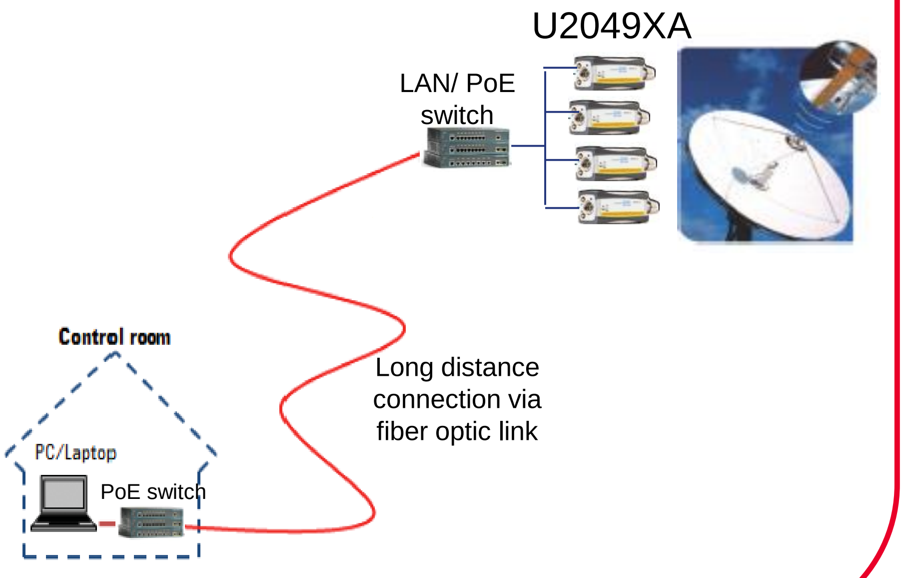
- Sufficient video (modulation) bandwidth
- High-speed, continuous sampling
- High-speed, continuous sampling

Remote Power Measurements

With USB sensor

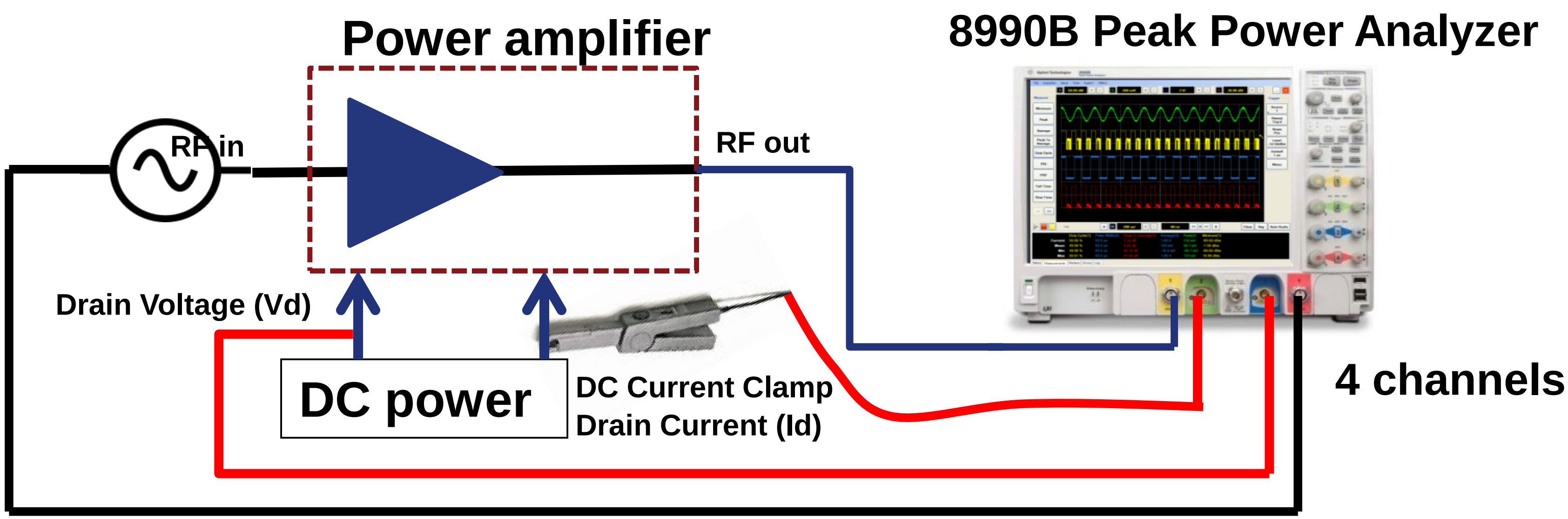


With LAN/PoE sensor



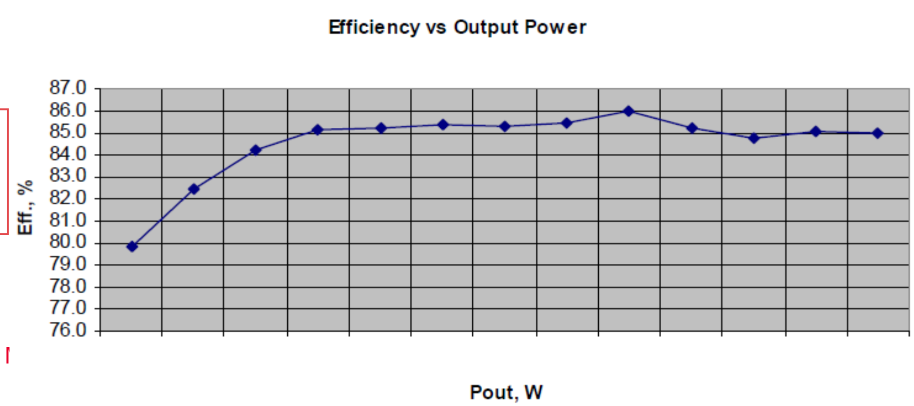
Power Added Efficiency Test (With 8990B)

One of the typical Power Amplifier measurements besides the gain, output power, S-parameters, P1dB, IP3, etc



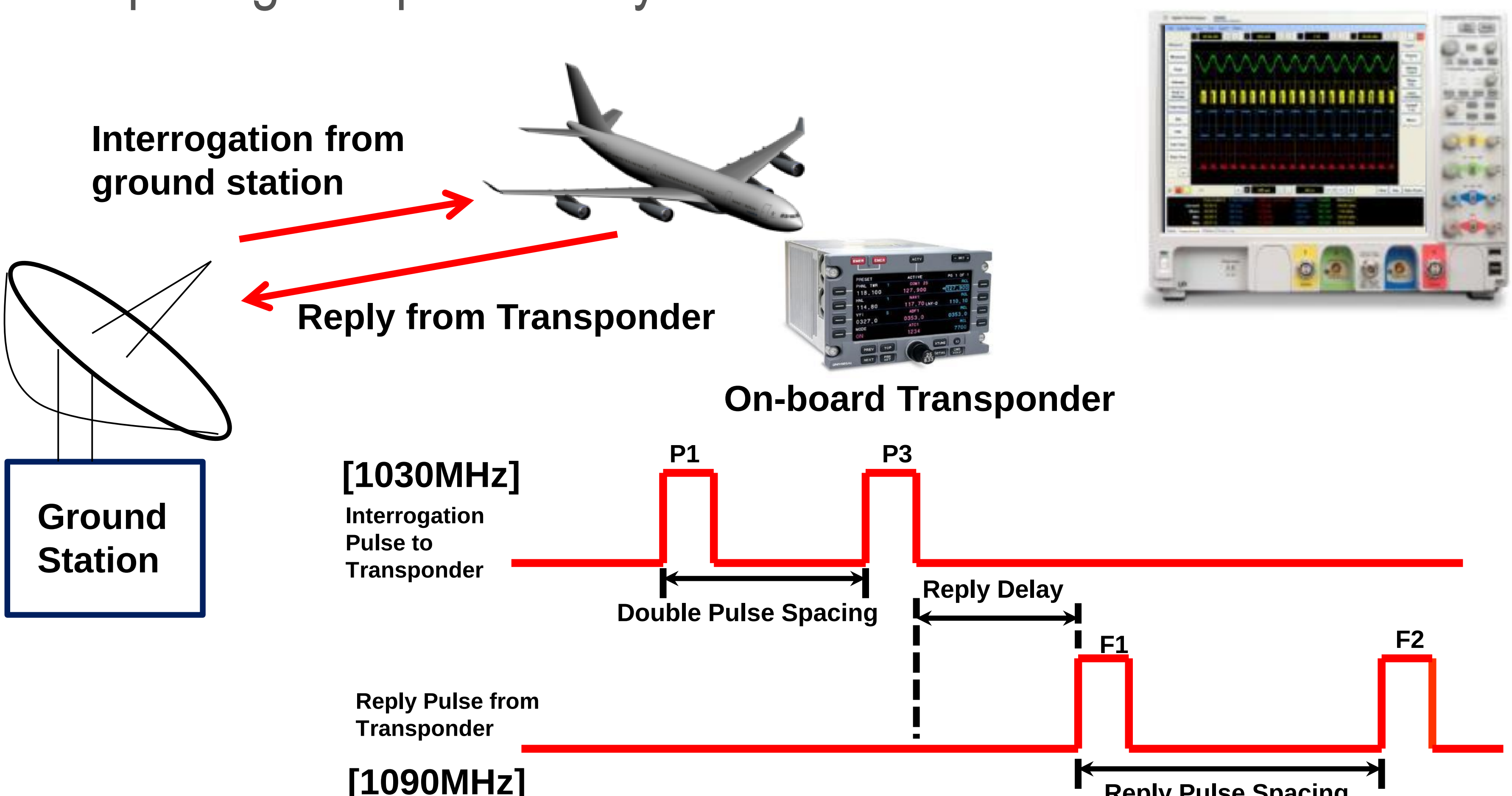
Measure RF, Voltage and Current in one box

$$\text{PAE (in percentage)} = \frac{\text{Power (RF\_out)} - \text{Power (RF\_in)}}{\text{Power\_dc}} * 100\%$$

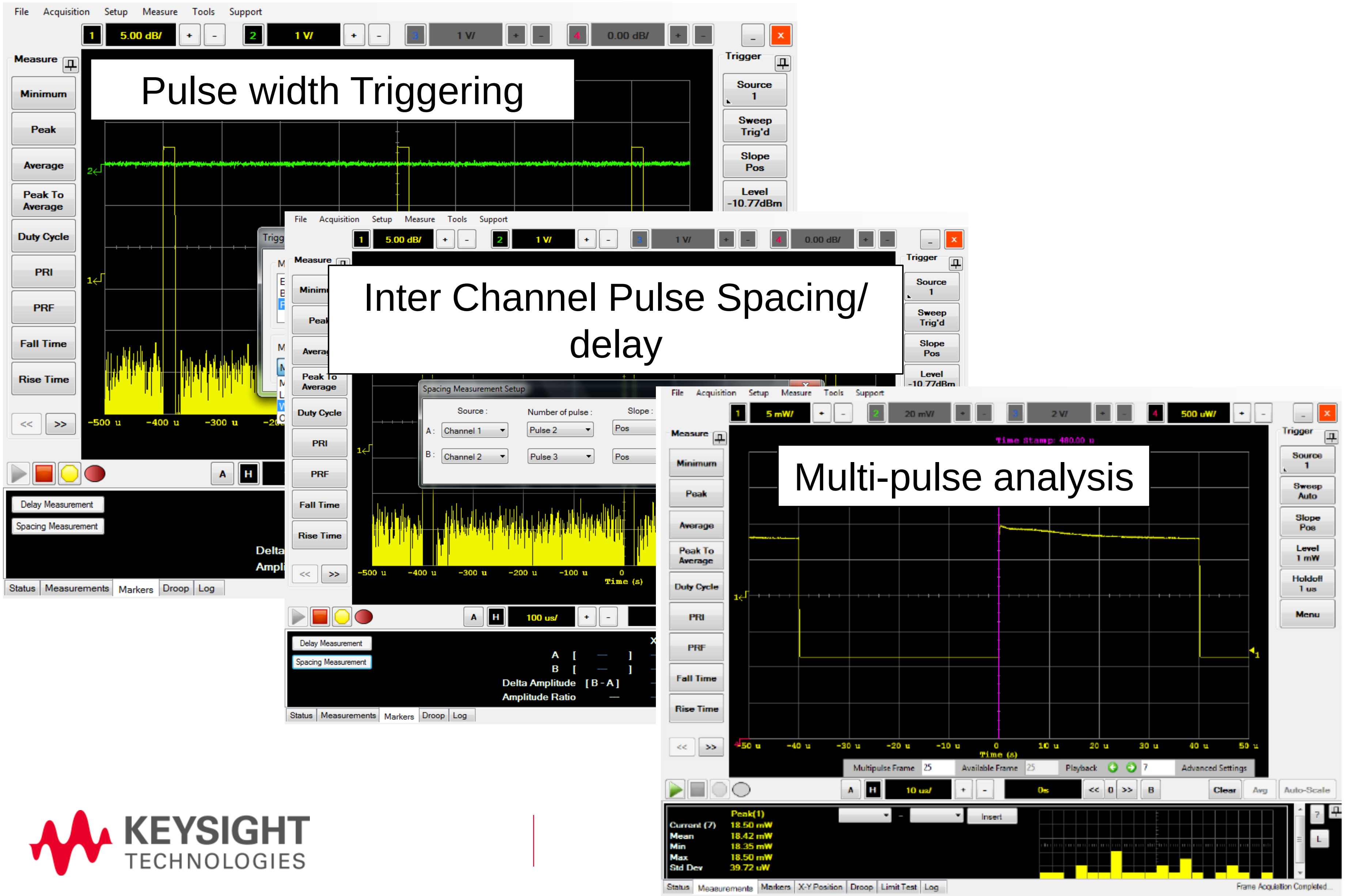


Transponder Test in Radar System

8990B enables automatic pulse parameters, pulse spacing and pulse delay measurements



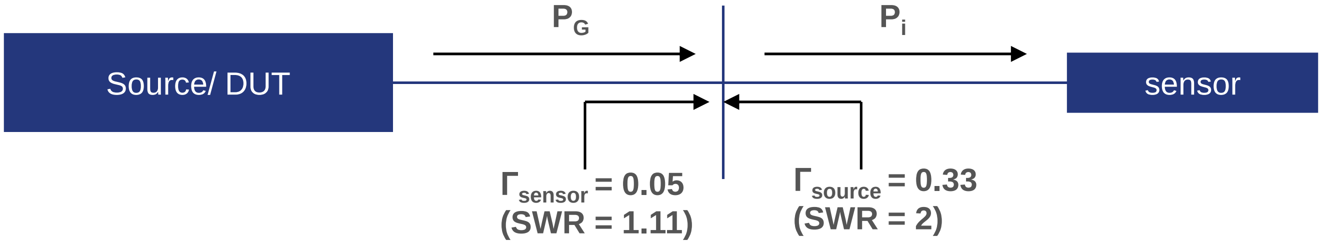
Advance Radar Pulse Measurements



S-Parameter / Gamma Corrections

Gamma Correction

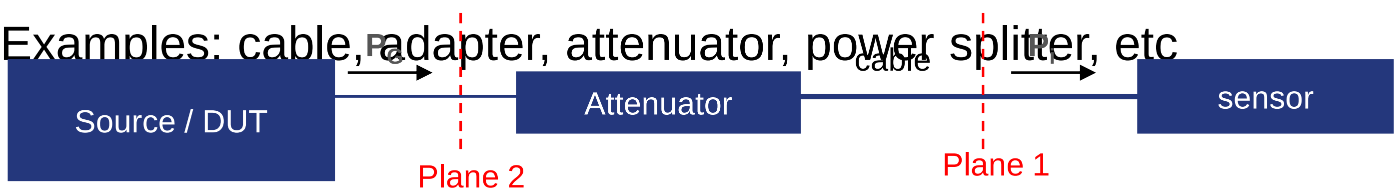
- To correct for mismatch between sensor and DUT



Mismatch error = $2 \times \Gamma_{sensor} \times \Gamma_{source} \times 100\%$ = <u>3.5% (0.15dB)</u>

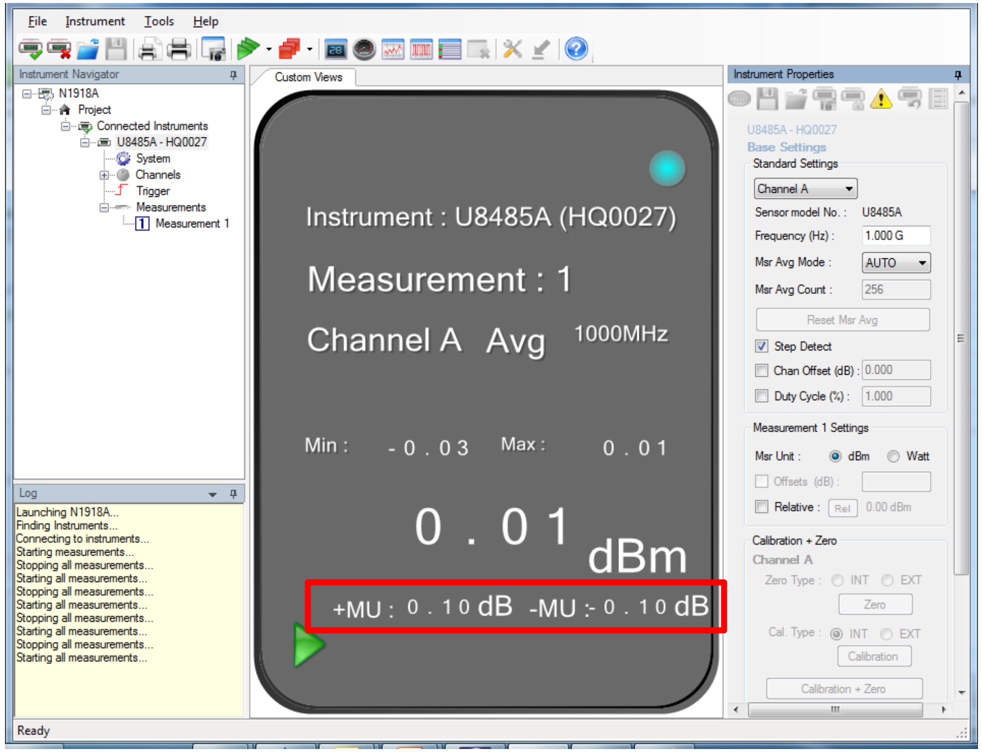
S-parameter Correction

- To correct for any devices connected between sensor and DUT
- Examples: cable, adapter, attenuator, power splitter, etc



Keysight U8480, U2020 or U2040 offer S-parameter/gamma correction capability for improved accuracy

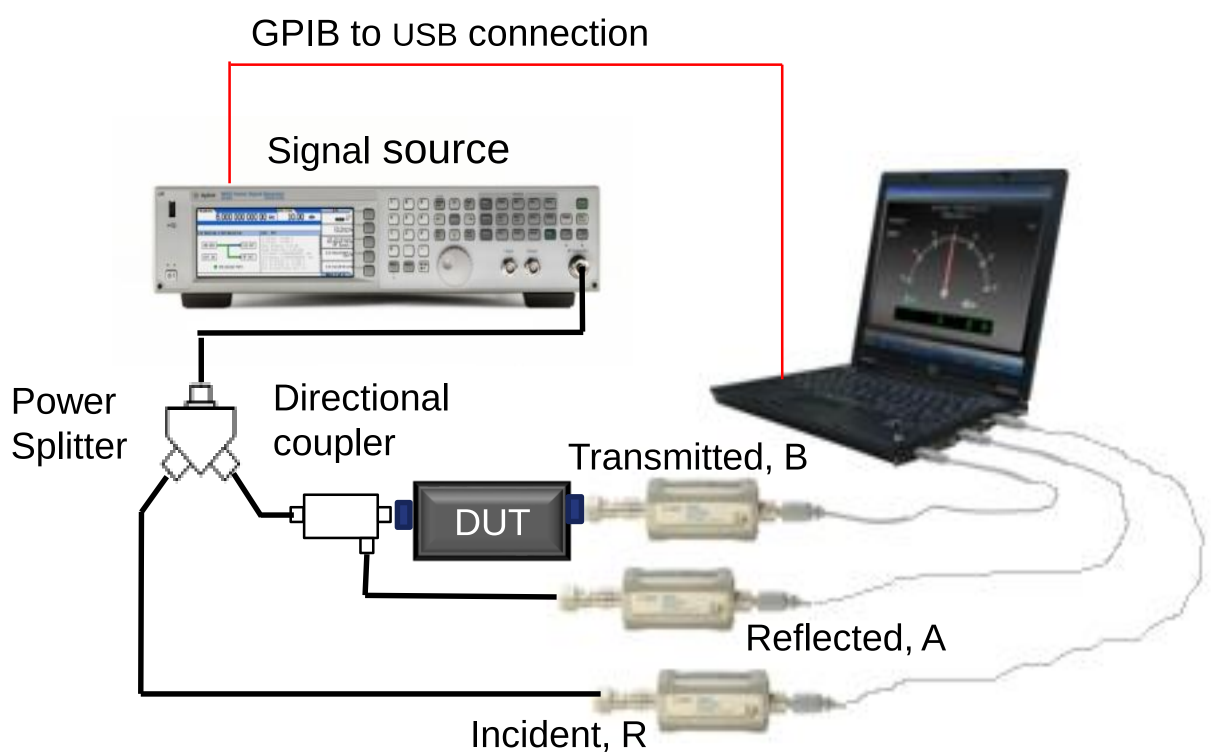
Real Time Measurement Uncertainty Display



Provide real time display of power measurement uncertainties without going through manual mathematic calculations (U8480 series)

RF/MW Component Tests

With USB sensor based scalar network analysis



Allows stimulus-response measurements such as
Gain, Insertion Loss, Frequency Response and Return Loss

Agenda

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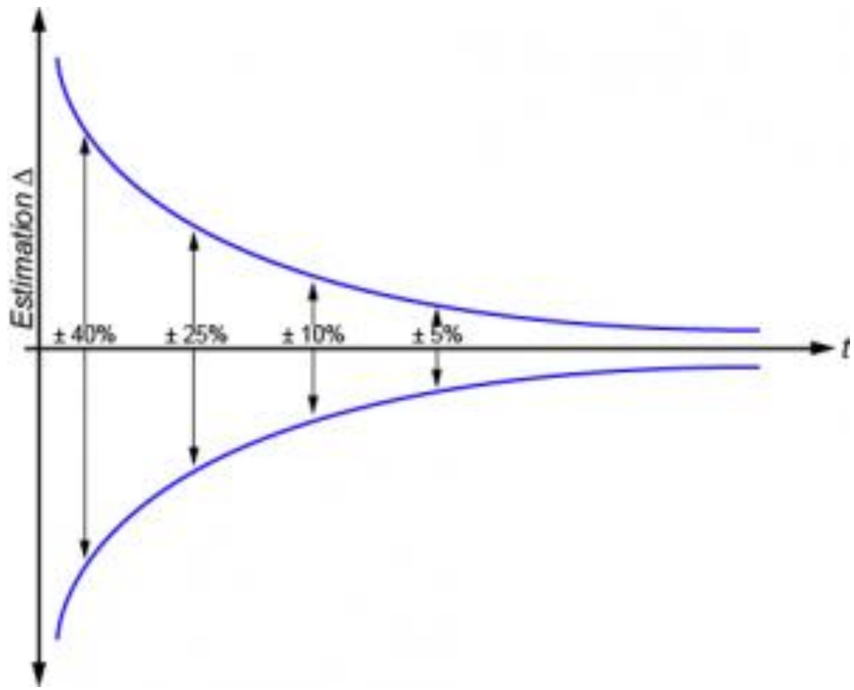
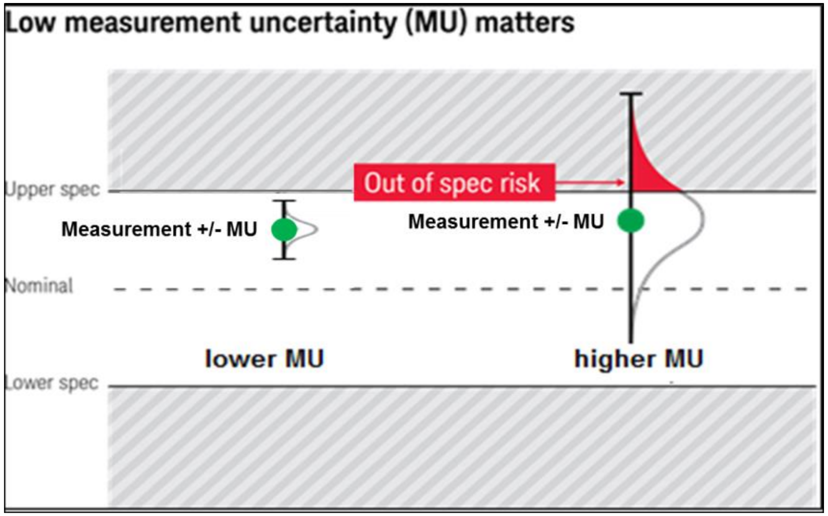
What is Measurement Uncertainty and Why Does it Matter?

- Dispersion of the values attributed to a measured parameter
- A measured value is only complete if it is accompanied by a statement of the associated uncertainty
- The actual test equipment accuracy is only as good as the measurement uncertainty of last calibration



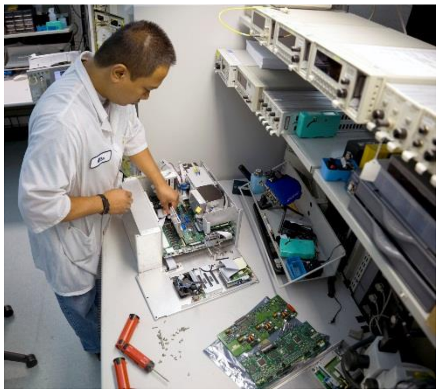
Advantage of Test Equipment's Low Measurement Uncertainty



Large measurement uncertainty increases the risk that your instrument is operating out-of-spec, risking measurement errors that impact the quality or performance of the your design. Lower measurement uncertainty of your test equipment and knowledge of what it is can save you cost, schedule time, and increase the reliability of your design

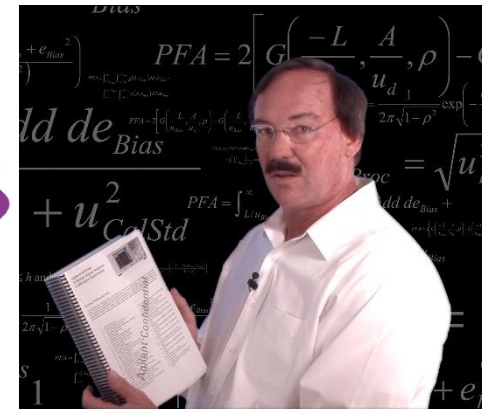
Tolerance margins in your measurements can be made tighter, reducing false pass/fail rate, thus enabling more accurate design calculations and allowing you to have more confidence in your measurements.

Measurement Uncertainty versus Measurement Accuracy



Engineer

Two sides of the same coin

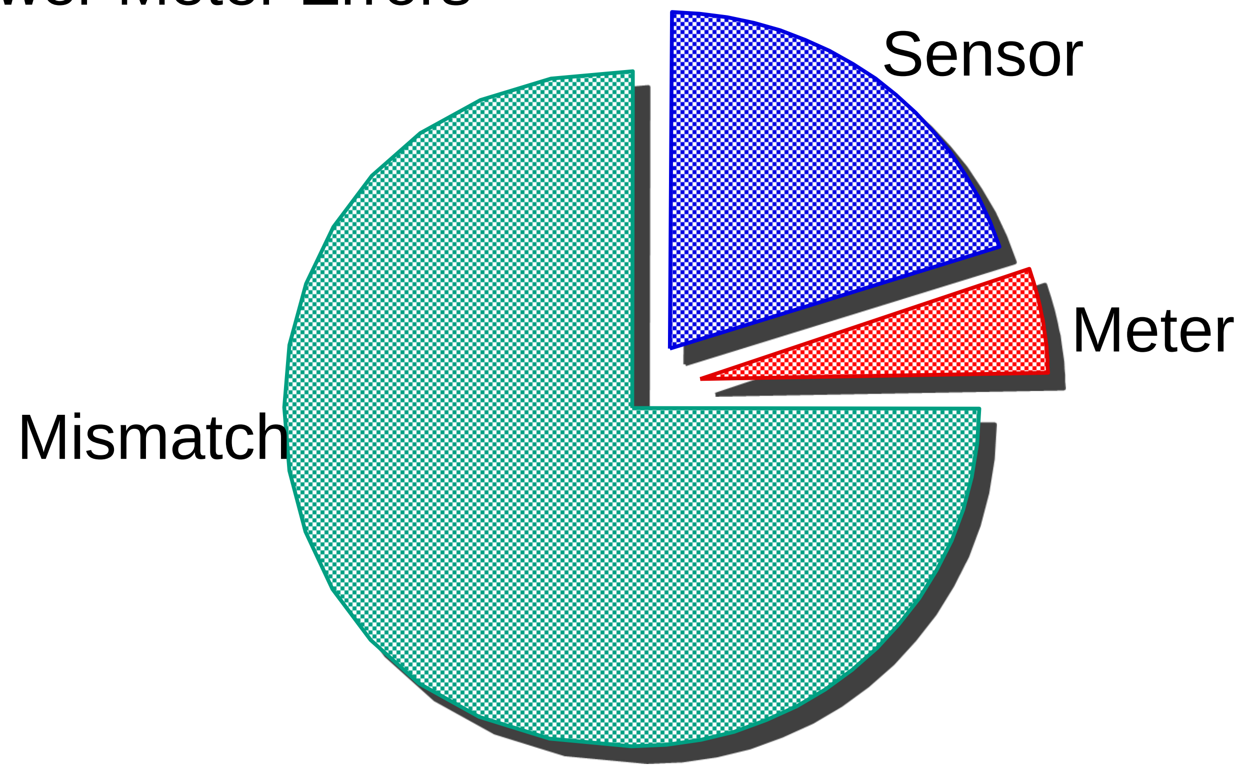


Metrologist

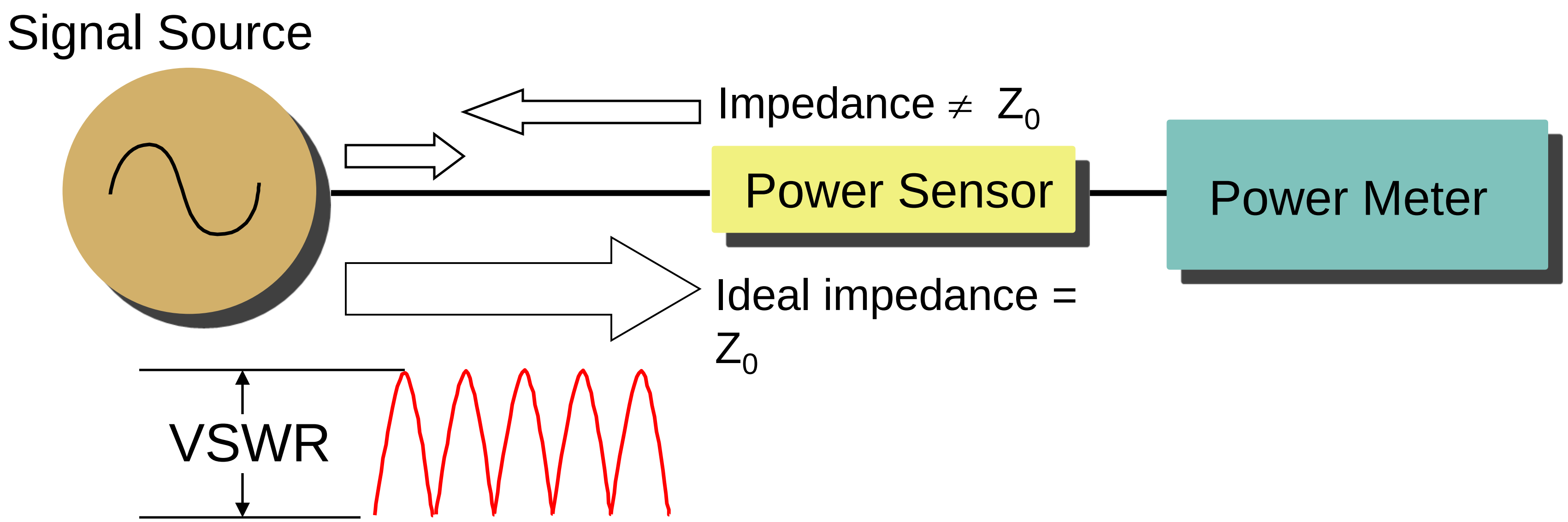
Responsible for the integrity of measurements

Sources of Power Measurement Uncertainty

- Sensor and Source Mismatch Errors
- Power Sensor Errors
- Power Meter Errors

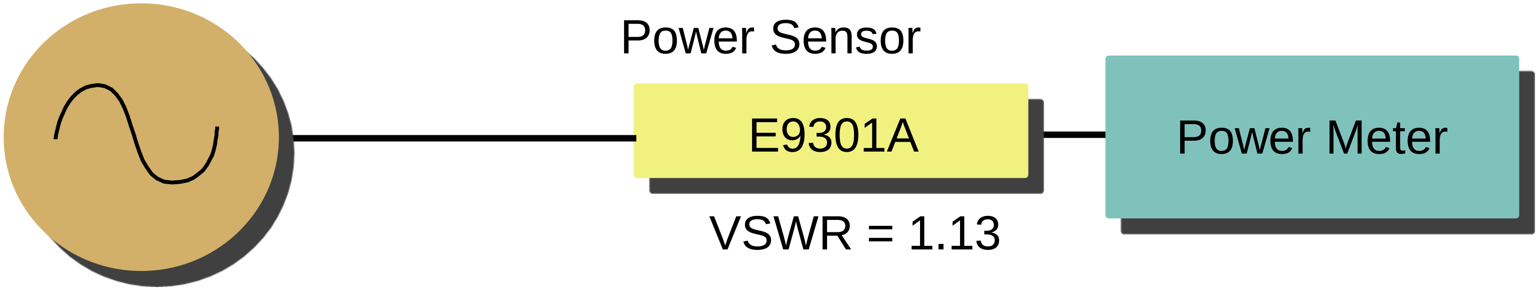


Sensor and Source Mismatch



Calculation of Mismatch Uncertainty

Signal Source
(2 GHz, 0 dBm)



VSWR = 1.13

$\rho_{SENSOR} = 0.06$

VSWR = 2.0

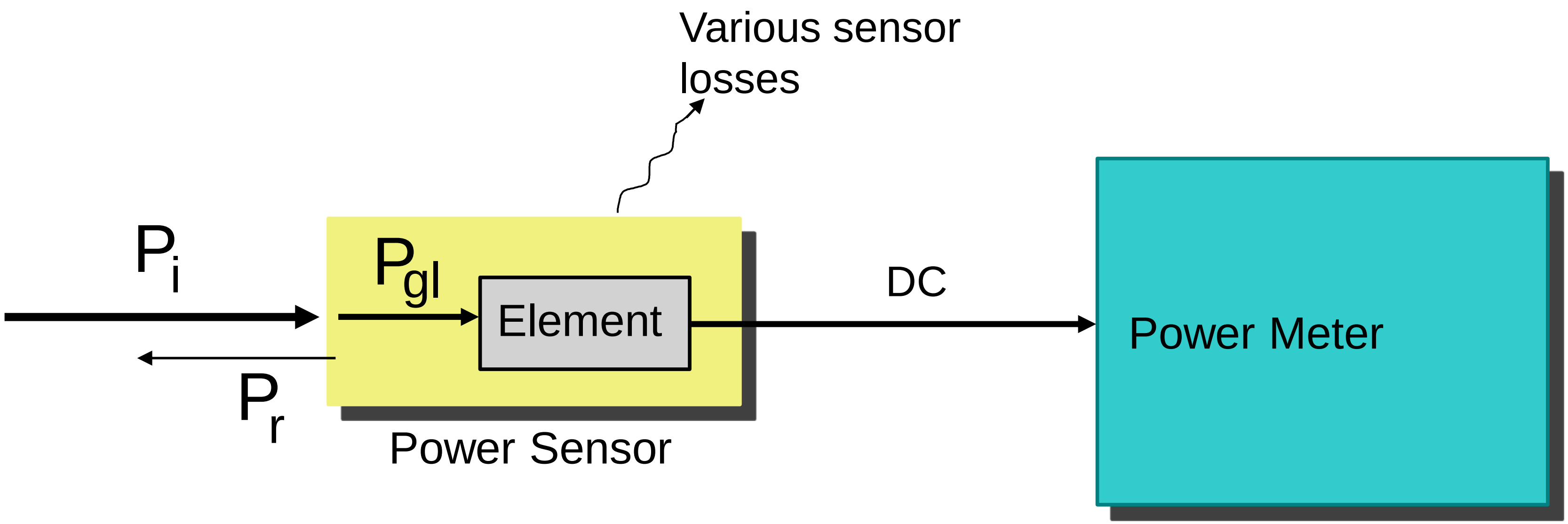
$\rho_{SOURCE} = 0.33$

$$\rho = \frac{\textbf{VSWR} - 1}{\textbf{VSWR} + 1}$$

$$\text{Mismatch Uncertainty} = \pm 2 \times \rho_{SOURCE} \times \rho_{SENSOR} \times 100\%$$

$$= \pm 2 \times 0.33 \times 0.06 \times 100\% = \boxed{\pm 3.96\%}$$

Power Sensor Uncertainties



$$\text{Cal Factor } K_b = \eta_e \frac{P_{gl}}{P_i}$$ (η_e = Effective Efficiency)

- Printed on sensor label (8480 series)
- Stored in EEPROM (E-series and P-series)

Power Meter Instrumentation Uncertainties

Drift

Noise

Power Reference Uncertainty

± 0.6 %

Zero Set

Instrumentation Uncertainty

± 0.5 %

What is an Acceptable Measurement Uncertainty?

- Which is the smaller error**:** ± 1.0 dB … or ± 20% ?

  ➡ Answer**:** ± **20% !**

  (± 1.0 dB is + 26%**,** – 21%)

- Sensor and meter uncertainties are specified in percentage (linear) and dB (log)

- Marketing Manager's Law of Small Numbers:

"A small-numbered uncertainty specification sounds better than a large-numbered one."

Calculating Power Measurement Uncertainty

1. Identify significant uncertainties

- Mismatch uncertainty: ± 3.96%
- Power linearity: ± 2.0% [1]
- Cal factor uncertainty: ± 1.8% [1]
- Power reference uncertainty: ± 0.6% [1]
- Instrumentation uncertainty: ± 0.5%

[1] Specifications apply for an E9301A sensor and Keysight power meter over a temperature range of 25 ±10 degrees C.

2. Combine uncertainties

- Worst-case or Root Sum of the Squares (RSS) method

Worst-Case Uncertainty

- **Worst-case situation is assumed**
  - All sources of error at their extreme values
  - Errors add constructively
- **In our example measurement:**

3.96% + 2.0% + 1.8% + 0.6% + 0.5% = ± 8.86%

Or, in log terms:

+ 8.86% = 10 log (1 + 0.089) = + 0.37 dB

– 8.86% = 10 log (1 - 0.089) = – 0.40 dB

- **Extremely conservative**

RSS (Root Sum of the Squares) Uncertainty*

Source of Uncertainty	Value (± %)	Probability Distribution	Divisor	Standard Uncertainty U_i (k=1)
Source/Sensor Mismatch at 2 GHz	3.96	U-shaped	1.414	2.8
Calibration Factor Uncertainty at 2 GHz	2.0	Normal	2	1.0
Linearity at 0 dBm	1.8	Normal	2	0.9
Power Reference Uncertainty	0.6	Normal	2	0.3
Instrumentation Uncertainty	0.5	Normal	2	0.25

Combined Standard Uncertainty = u_c = RSS of u_i

** In accordance to guidelines published in the ISO Guide to the Expression of Uncertainty in Measurement and ANSI/NCSL Z540-2-1996, US Guide to the Expression of Uncertainty in Measurement.*

Combined Standard Uncertainty (U_c)

- **In our example:**

$$u_c = \sqrt{(2.8)^2 + (1.0)^2 + (0.9)^2 + (0.3)^2 + (0.25)^2}$$

$$= \pm 3.13\%$$

- **Expanded uncertainty (k = 2)**

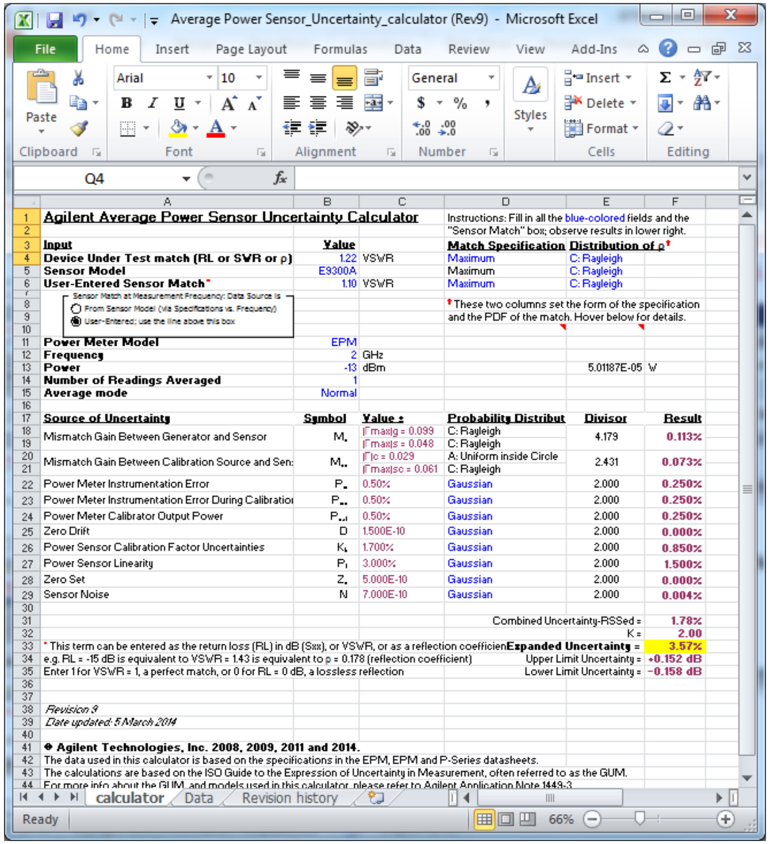
$$= k \times u_c = \pm 6.26\%$$

		Worst-case
$= 10 \log (1 + 0.063) =$	+ 0.27 dB	*+ 0.37 dB*
$10 \log (1 - 0.063) =$	– 0.28 dB	*– 0.37 dB*

- **Keysight AN 1449-3 covers uncertainty calculations**

Keysight Power Measurements Uncertainty Calculators

P-Series Power Meter’s Uncertainty Calculator
EPM power meter’s Uncertainty Calculator
EPM-P/E9320 Uncertainty Calculator
U2000/U8480 USB Sensor Uncertainty Calculator
U2020 USB Sensor Uncertainty Calculator
8990B PPA Uncertainty Calculator
N432A Thermistor Power Meter Uncertainty Calculator

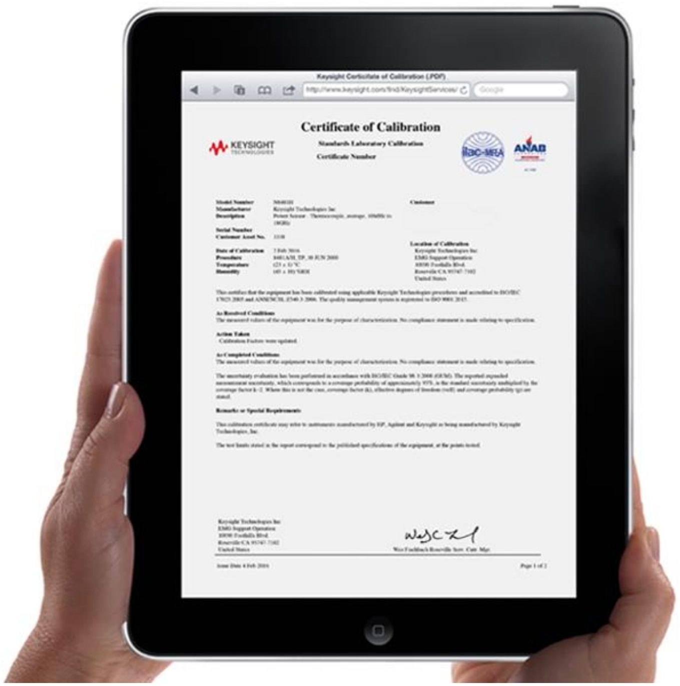


Download:
http://www.keysight.com/main/facet.jspx?&cc=US&lc=eng&k=uncertainty+calculator&sm=g

Standards Lab Calibration

Small measurement uncertainty. Greatest Confidence.

A Keysight Standards Lab Calibration is an exacting process that focuses on the crucial parameters you specify. We can perform these calibrations on more than 500 instruments and devices, and we will compare yours to either a primary standard or a reference that has been directly calibrated by a national metrology institute (NMI).



– Depend on accurate measurements based on very low measurement uncertainties

– Count on fast & predictable turnaround time

– Reduce your calibration costs

– Get documented compliance with ANSI/NCSL Z540.3-2006 and ISO/IEC 17025:2005

www.keysight.com/find/StandardsLab

Choose the standard of test equipment calibration suitable for your measurement needs

Standards Compliance

Deliverables	Keysight Calibration	Keysight Cal + Uncertainties	Keysight Cal + Uncertainties + Guardbanding[3]	Accredited Calibration	Standards Lab Calibration
ANSI Z540.3-2006			✓		
ISO 17025:2005		✓	✓	✓	✓
ANSI Z540.1-1994		✓	✓		
ISO 9001:2015	✓	✓	✓	✓	✓

Europe / Middle East / Africa / India Calibration Service Selection Guide

Deliverables	Keysight Calibration	Keysight Cal + Uncertainties	Keysight Cal + Uncertainties + Guardbanding[3]	Accredited Calibration	Standards Lab Calibration
Primary lab standards[1]					✓
Locally accredited				✓	✓
Measurement guardband			✓	✓	✓
Measurement uncertainties		✓	✓	✓	✓
Adjustments	✓	✓	✓	✓	✓
As received data report	✓	✓	✓	✓	✓
As completed data report[2]	✓	✓	✓	✓	✓
Calibration certificate	✓	✓	✓	✓	✓
Sample calibration certificates	PDF	PDF	PDF	PDF	PDF

1. Primary lab standards, such as a Josephson junction, used for lowest measurement uncertainty comparable to a National Measurement Institute.
2. Provided when adjustment(s) are made.
3. Guardbanding is not available / provided when the device has no associated specification, for example when characterizing power sensors for cal factor.

Power Sensor Calibration Traceability Example

Calibration Standard or System	**Cal factor measurement uncertainty:**	**TAT** (days)
NIST/NMI primary standard	-	X
NIST/NMI CN mount	-	X
NIST/NMI thermistor cal (such as 8487B)	0.57% @ 8 GHz (see curve)	8 – 12 weeks weeks
Roseville Standards Lab (8487A-H84)	0.67% @ 8 GHz	**15 days**
Roseville Keysight cal + uncertainty (8487A)	**0.98% @ 8 GHz**	**7 days**

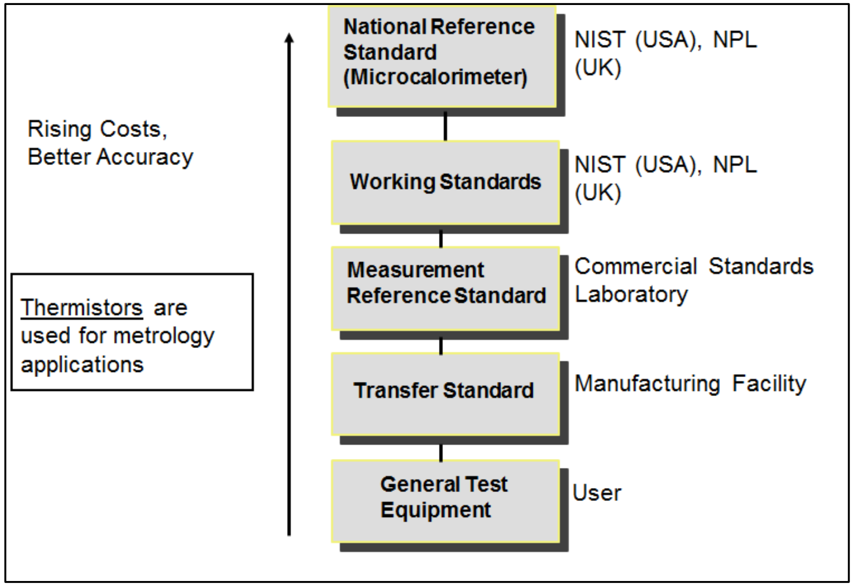
http://www.nist.gov/calibrations/rf-microwave.cfm#611

National Standards and Traceability

Offers increased confidence in your power measurements and enhances audit success rate

Property of the result of a measurement or the value of a standard whereby it can be related to the international system of units (SI units) via national metrology institutes, through an <u>unbroken chain</u> of comparisons all with stated uncertainties.

Source: International Vocabulary of Basic and General Terms in Metrology (VIM)



Calibration should not be treated as a commodity

Why accredited calibration matters

Accreditation is a formal audit by a representative of an Accreditation Body to assess conformance of a cal lab to internationally accepted standards (ISO/IEC 17025: 2005) and ensures traceability back to SI units through the national metrology institutes

Calibration Laboratory	Keysight Roseville	Cal Lab ABC
A2LA Certification Number	1920.01	1395.09
I. Electrical – DC/Low Frequency		
DC Voltage	✓	✓
DC Current	✓	✓
Resistance	✓	✓
AC Current	✓	✓
AC Voltage	✓	
AC Voltage Flatness	✓	
Resistance	✓	
Capacitance	✓	
II. Electrical – RF / Microwave		
Frequency Modulation	✓	
Digital Modulation	✓	
RF Absolute Power	✓	
Tuned RF Power	✓	
Power Sensor Calibration Factor	✓	
Thermal Noise Figure System	✓	
Pulse	✓	
CISPR Pulse Response	✓	
Attenuation	✓	
Reflection S11 / S22	✓	

Cal Lab ABC is NOT accredited for these

All Keysight calibrations are performed by a lab with the scope-of-accreditation for the relevant parameters

Summary

- Accurate power measurements (made with a power meter/sensor combination) are crucial in RF and microwave applications.
- The three fundamental power measurements are average, peak and pulse.
- Modern wireless and radar technologies require time-gated and advanced measurements.
- Keysight provides solutions for basic and advanced measurements.
- Measurement uncertainty is often calculated using the RSS method.
- The accuracy of Keysight power sensors is traceable to national standards.

For More Information

Keysight Website

- URL: http://www.keysight.com/find/powermeters

Keysight Literature

- Application Note AN 1449–1, 2, 3 and 4, *Fundamentals of RF and Microwave Power Measurements (Parts 1, 2, 3 and 4).*
- Product Note, *Choosing the Right Power Meter and Sensor* (Lit. No. 5968-7150E).
- Application Note AN 64-4D, 4 steps for making better power measurements (Lit. No. 5965-8167E)

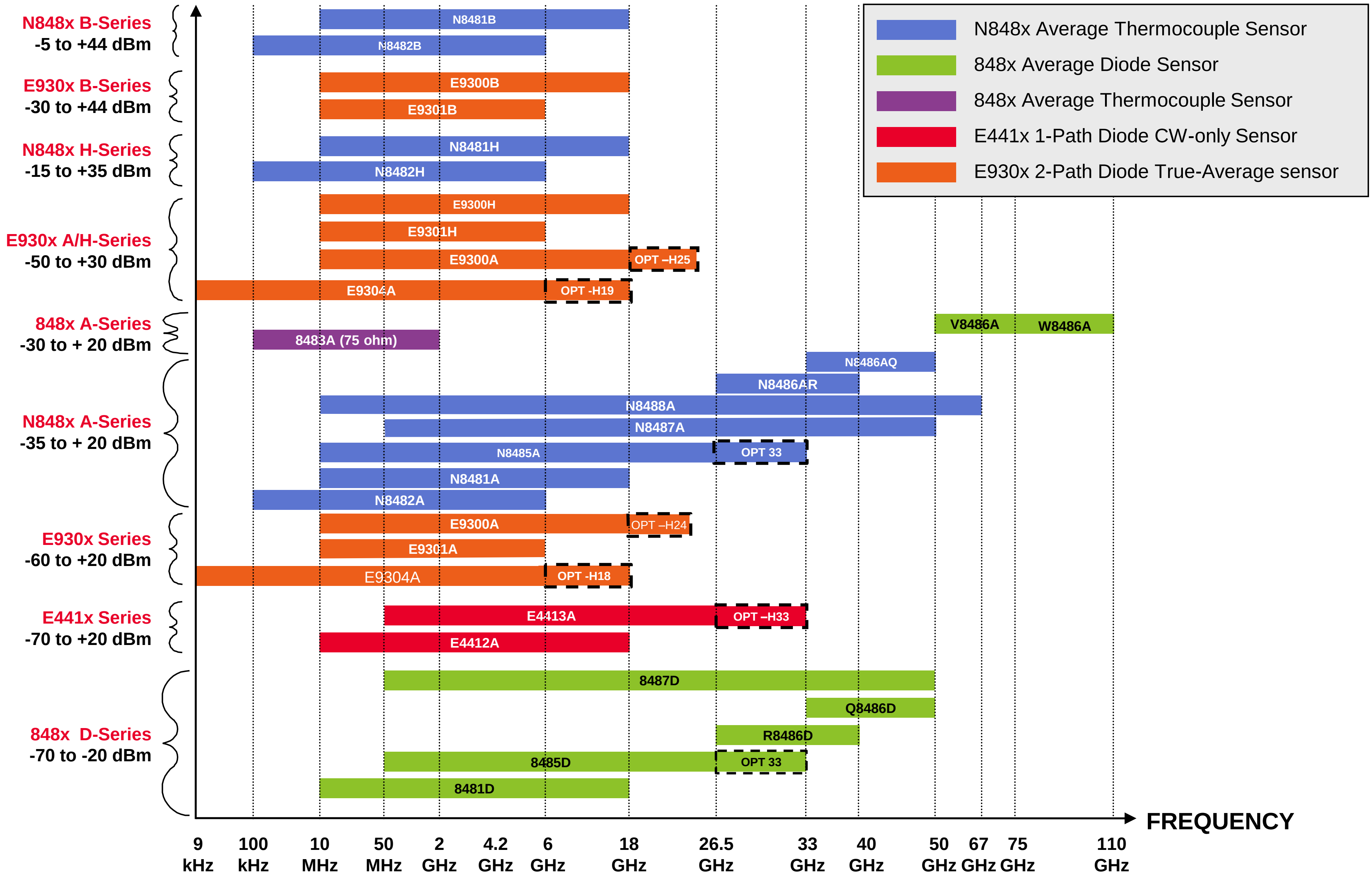
Thank you!

Appendix:

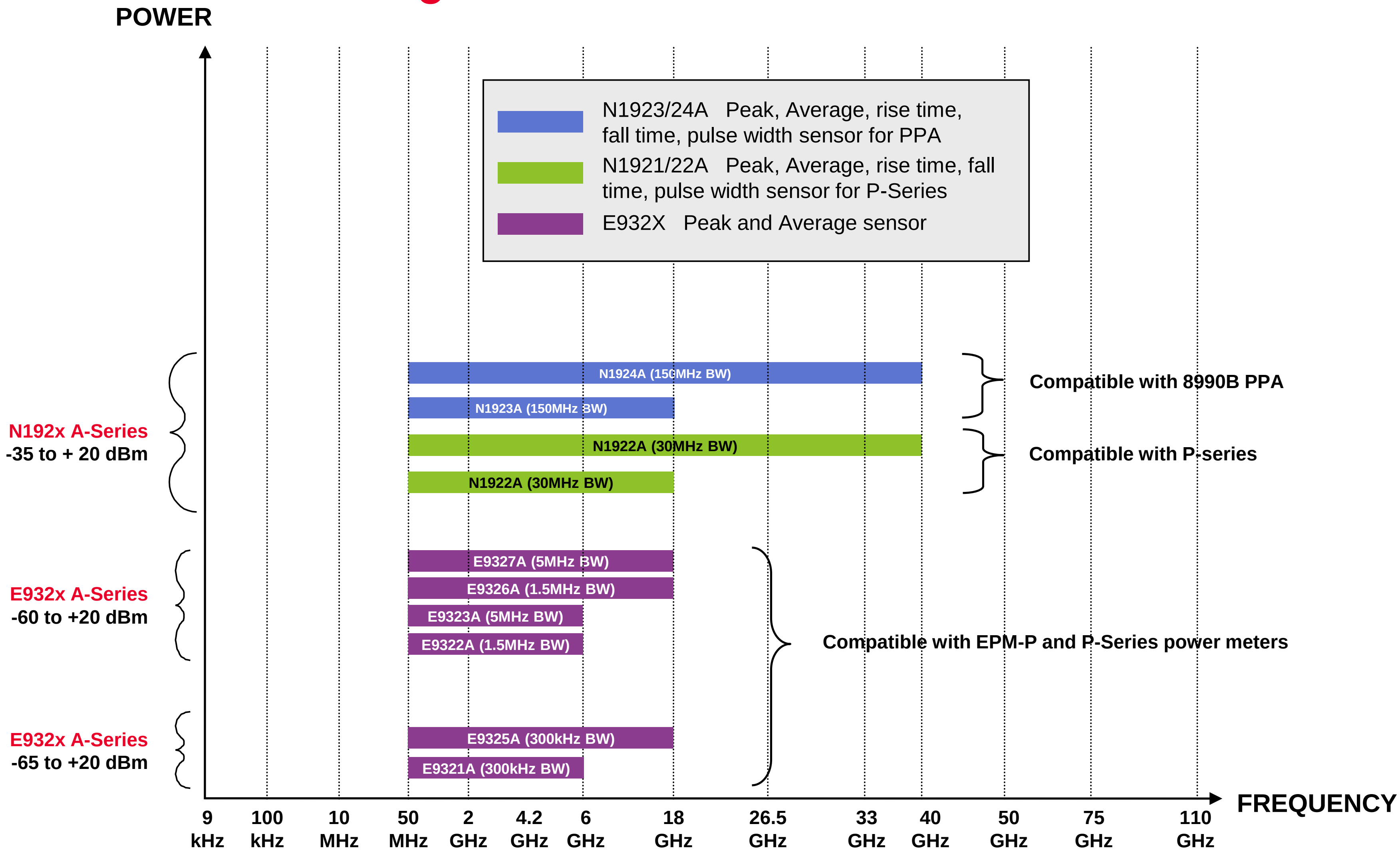
Power Sensor Selection Guides

Average/CW Power Sensors

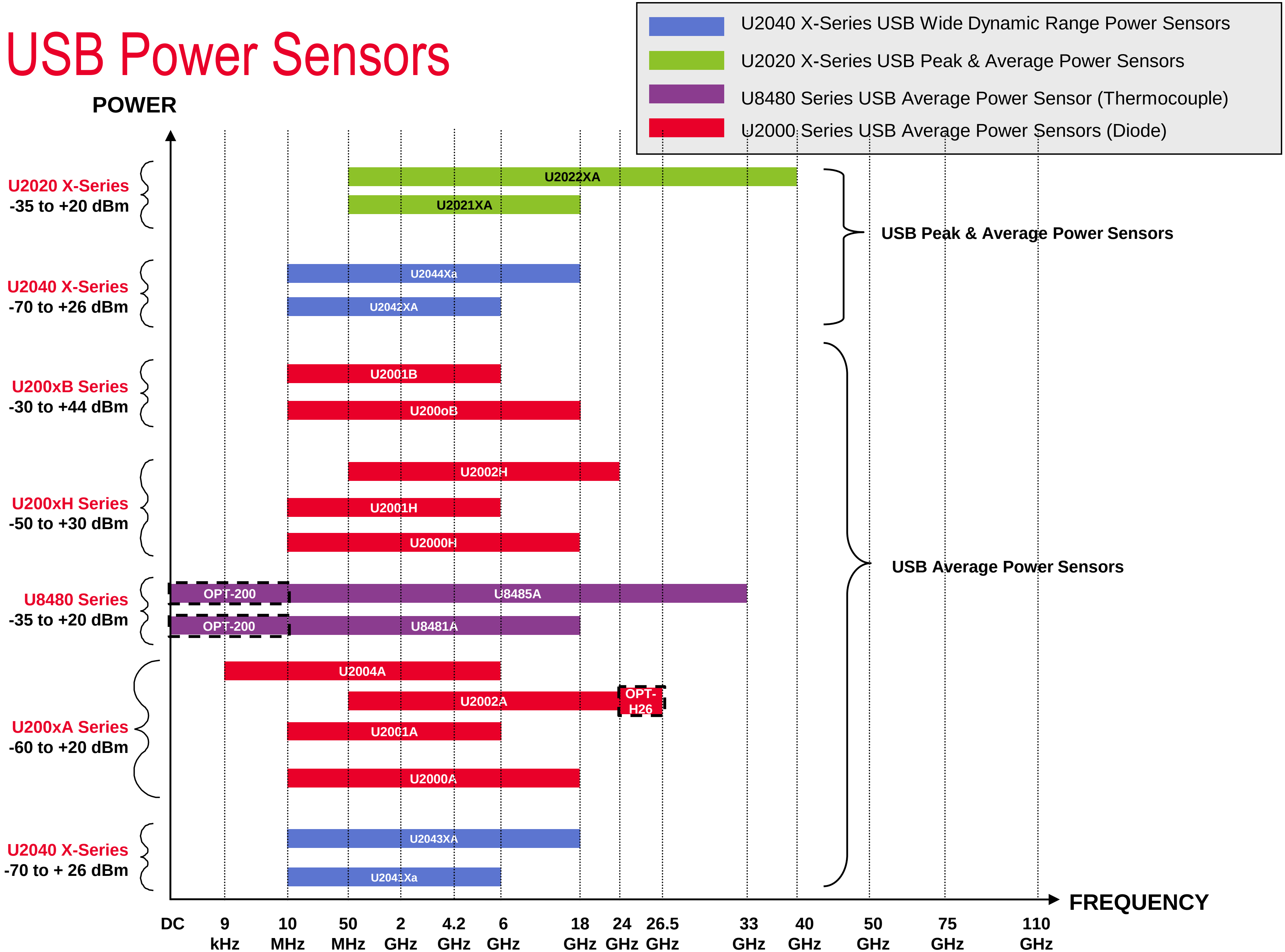
POWER All the following sensors are compatible with EPM, EPM-P and P-series power meters



Peak & Average/CW & Wideband Power Sensors



USB Power Sensors



Thank You

Any Questions?