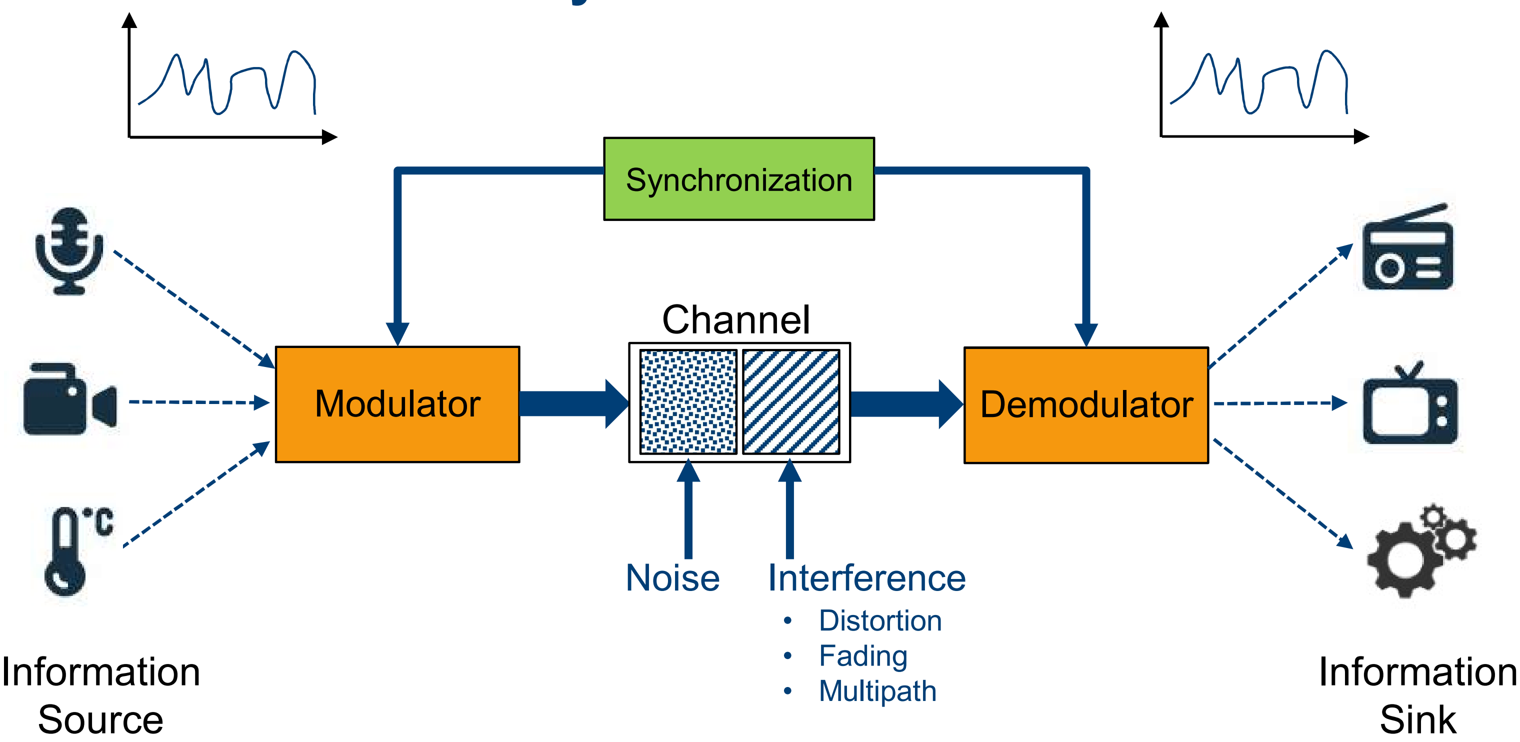
COMMUNICATIONS SYSTEMS: SIGNALS AND NOISE

Communications Systems: Signals and Noise – Agenda

- **What is a Communications System?**
- Basic Signal Model
- Noise: Unintentional Modulation
  - Thermal Noise
  - Phase Noise

Basic Communications System



Basic Signal Model: Unmodulated Signal (Carrier)

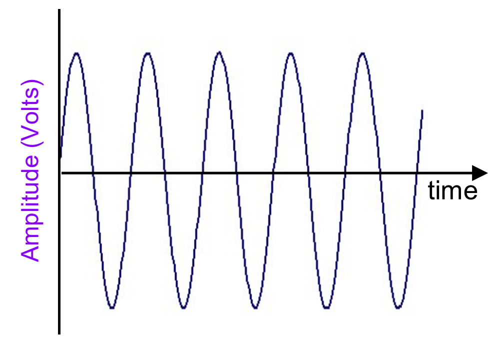
- Ideal CW Signal – Perfect Sine Wave – No noise, no modulation

Time Domain

$$V(t) = A(t)\cos(\omega t + \phi(t))$$

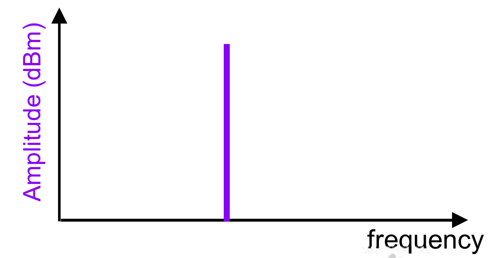
where:

A = amplitude
ω = frequency (rad/s)
ϕ = phase



Frequency Domain

– Single discrete “Zero-bandwidth” line in frequency (spectrum) domain



- An ideal unmodulated signal contains little information
  – *But* is useful in frequency references and local oscillators (LO)

Basic Signal Model: Unmodulated Signal (Carrier) - Demo

What is Modulation?

- Modulation is the modification of a carrier to represent information (analog or digital)
- Carrier characteristics that can be modified: Amplitude, Frequency, and Phase

Modulate:
Modify some characteristic of a *carrier*

→

Demodulate:
Detect the modifications

Any reliably detectable change in signal characteristics can carry information

$$V(t) = A \cos(\omega t + \phi)$$

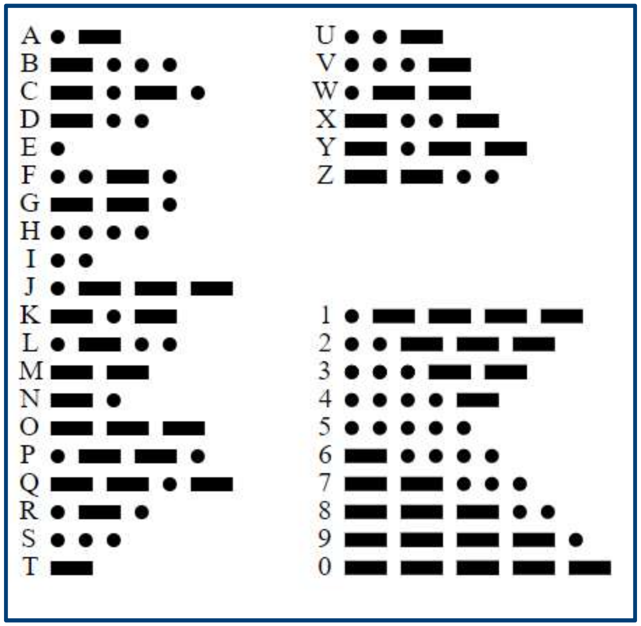
↑ ↑ ↑

Earliest Modulation: Keying (OOK)

► Combined with two different ON times (“dit” and “dah”)

► Encoded into 26 symbols (alphabet), 10 numerals (0 thru 9) and special characters (. ,)

► Legacy: used since dawn of wireless communications (Marconi transatlantic transmission 1901)



Any reliably detectable change in signal characteristics can carry information

$$V(t) = A(t)\cos(\omega t + \phi)$$

Morse Code - Demo

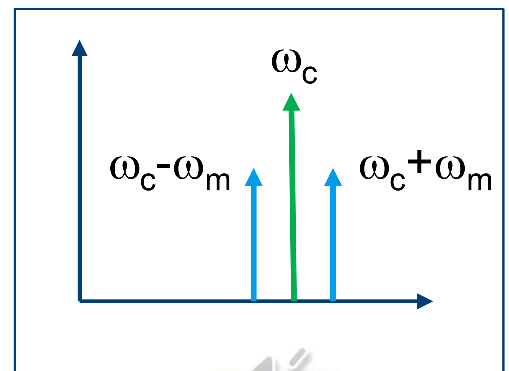
Amplitude Modulation (AM)

- General Waveform definition: $V(t) = A(t)\cos(\omega_c t + \phi_c(t))$
  - Subscript c denotes the "Carrier"
- For AM modulation, the general definition becomes: $V(t) = K[1 + m\omega_m(t)]\cos(\omega_c t + \phi_c(t))$
  - Subscript m denotes the "degree of modulation"
    - Varies from zero to 1 (or 0% to 100%)
- Apply a single-tone sine wave, normalize amplitude (K =1), set carrier phase ϕ_c to zero:

$$V(t) = [1 + m\bullet\cos(\omega_m t)] \bullet \cos(\omega_c t)$$

$$V(t) = \cos(\omega_c t) + m\bullet\cos(\omega_m t) \bullet \cos(\omega_c t)$$

$$V(t) = \cos(\omega_c t) + (m/2)\cos(\omega_c - \omega_m)\, t + (m/2)\cos(\omega_c + \omega_m)\, t$$



AM - Demo

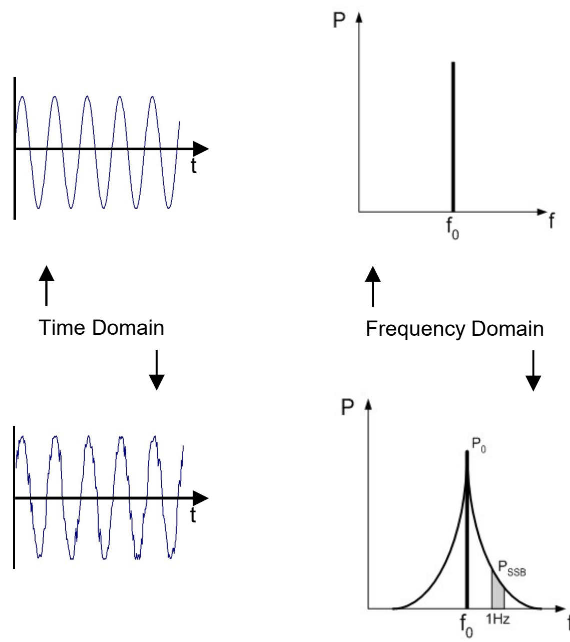
What about synchronization?

Noise – Unintentional Modulation

► Ideal Signal: $V(t) = A \cos(2\pi ft + \phi)$

where:

A = nominal amplitude
f = nominal frequency
ϕ = nominal phase



► Real Signal: $V(t) = [A + E(t)] \cos(2\pi ft + \phi(t))$

where:

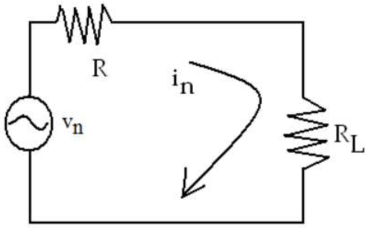
$E(t)$ = *random* amplitude variations
$\phi(t)$ = *random* phase variations

Agenda – Signals and Noise

- Basic Signal Model

- Noise: Unintentional Modulation
  - **Thermal Noise**
  - Phase Noise

Thermal Noise



- Caused by thermal movement of electrons in a conductor
- Quantified as noise voltage present at the terminals of a resistor
- Broadband, but not infinite (rolls off in the THz due to quantum effects)
- Independent of R (theoretical noise power is available to matched load)
- Calculated as kTB (k = Boltzmann's constant, T = Temperature in Kelvin, B = Bandwidth in Hz)
  - Boltzmann's constant: 1.38 x 10^{-23} Joules/K
- Thermal noise is sometimes referred to as 'kTB noise'
- At room temperature, kTB noise is about -174 dBm/Hz (good number to memorize!)
  - Easily scalable: kTB noise in 1 MHz = -174 + $10\log_{10}$(1 MHz / 1 Hz) = -114 dBm
- 'Noise Power' is generally used in terrestrial applications
- 'Noise Temperature' is used in radio astronomy where 'room temperature' has no meaning
  - Average temperature of the universe is 2.7 K

Excess Noise

- Active devices such as diodes and transistors (when biased) generate additional noise beyond thermal noise
  - This is called Excess Noise

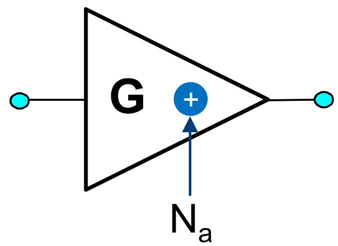
- Types of Excess Noise can include
  - Flicker Noise
  - Shot Noise
  - Burst Noise
  - Coupled Noise

- Excess noise is commonly quantified as Noise Factor or Noise Figure

Noise Added by a Real Device

► A real device has gain (or loss) and adds some quantity of noise: N_a

$$\frac{S_{in}}{N_{in}}$$



$$\frac{S_{out}}{N_{out}} = \frac{S_{in} \cdot G}{N_{in} \cdot G + N_a}$$

► Then noise factor becomes:

$$\text{Noise Factor } F = \frac{\left(\frac{S_{in}}{N_{in}}\right)}{\left(\frac{S_{in}G}{N_{in}G + N_a}\right)} = \frac{S_{in}}{N_{in}} \frac{N_{in}G + N_a}{S_{in}G} = \frac{N_{in}G + N_a}{N_{in}G}$$

IEEE Definition of Noise Factor/Noise Figure

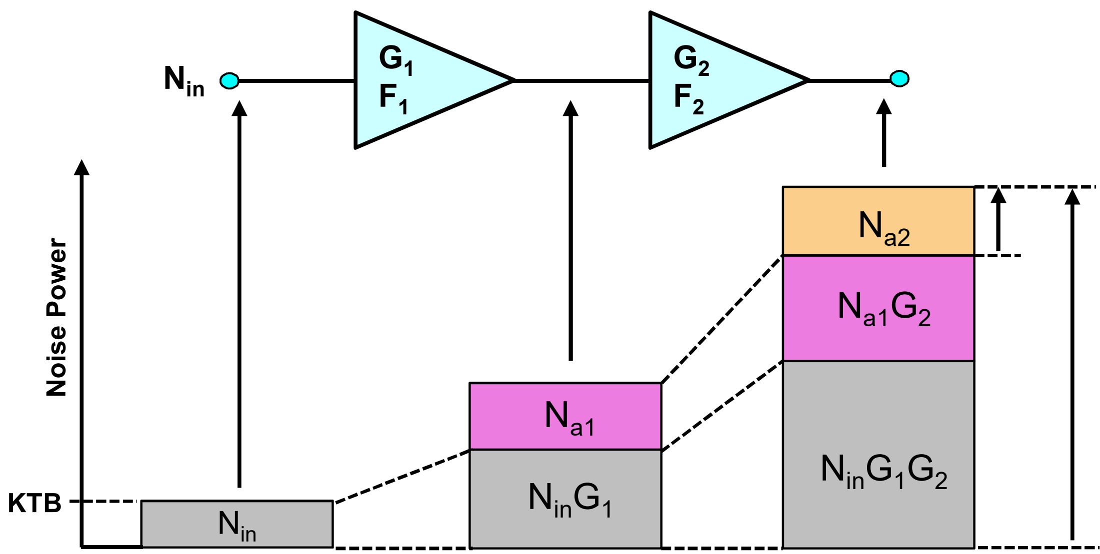
- IEEE definition of Noise Factor

$$\text{Noise Factor (lin) } F = \frac{N_a + kT_o BG}{kT_o BG} \qquad \text{Noise Figure (dB)} = 10\log_{10}(F)$$

- Terms:
  - N_a: Noise added by device
  - G: Gain of device
  - k: Boltzmann's constant = 1.38 x10^{-23} Joules / K
  - T_0: defined as "standard temperature", 290 K = 16.8 C
  - B: noise bandwidth of the system in Hertz

Noise Factor = 1 + (Te/To)

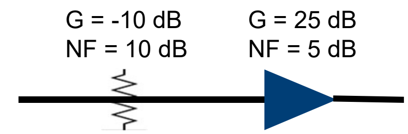
Noise Figure of Cascaded Components



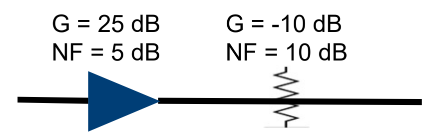
Friis Equation

$$F = F_1 + \frac{F_2 - 1}{G_1}$$

(linear terms, not dB)



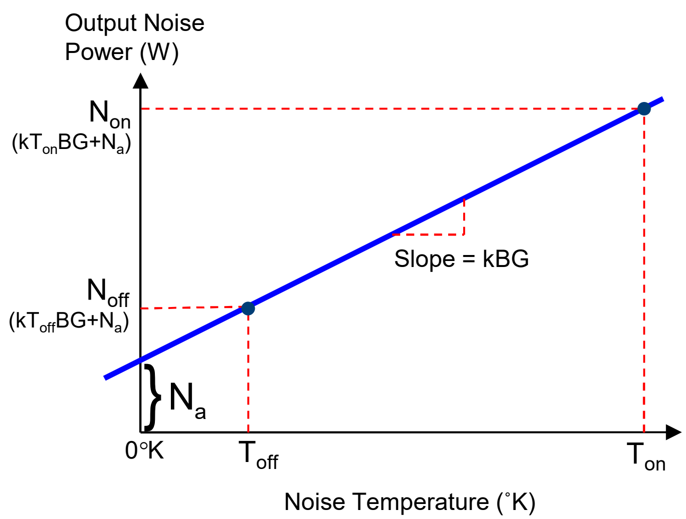
	Gain (dB)	Noise Figure (dB)
Attenuator	-10	10
Amplifier	25	5
Combination	15	15

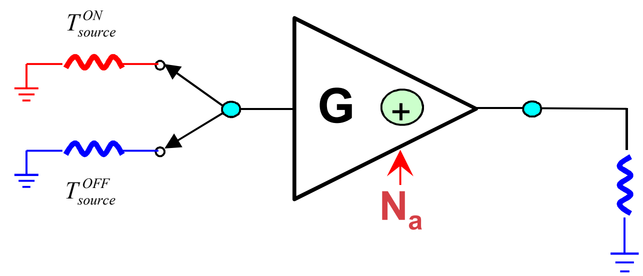


	Gain (dB)	Noise Figure (dB)
Amplifier	25	5
Attenuator	-10	10
Combination	15	5.04

Measuring Noise Figure: Y-Factor Technique

- Excess Noise Ratio (ENR) of noise source must be accurately known
- Noise Source provides the known input signal at two levels
- Make two measurements with a calibrated receiver
- Calculate Gain and N_a of the device under test





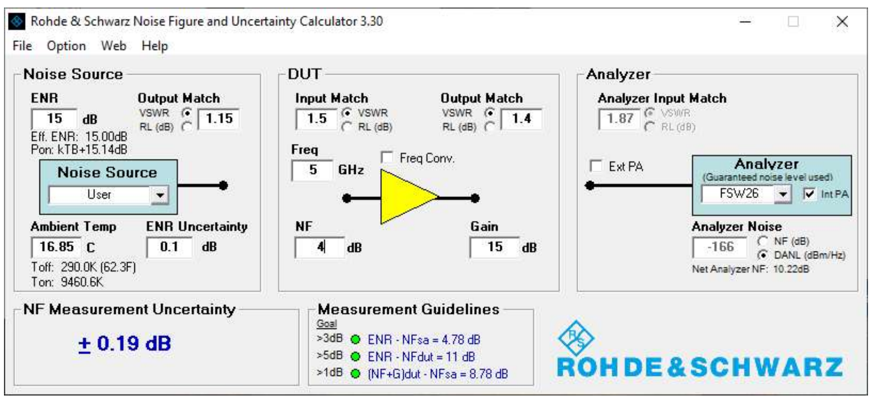
Y Factor

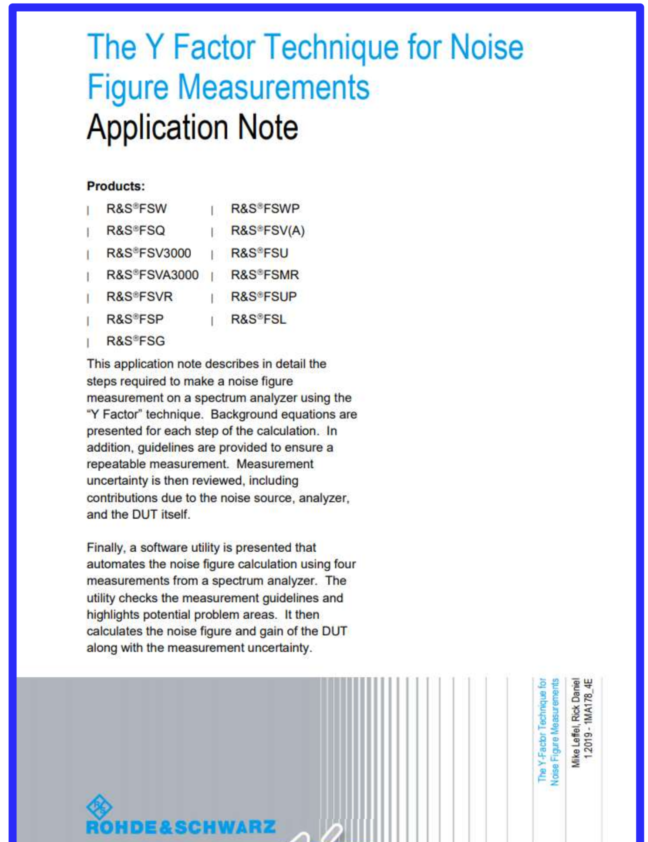
$$Y = \frac{N_{on}}{N_{off}}$$

$$F_{dB} = ENR_{dB} - 10\log(Y-1)$$

Noise Figure Application Note

- ► Application Note 1MA178
  - – Describes the Y Factor technique in detail
  - – Discusses contributing factors to NF measurement errors and provides a PC utility for calculating overall measurement uncertainty




The Y Factor Technique for Noise Figure Measurements
Application Note

Products:

R&S®FSW	R&S®FSWP
R&S®FSQ	R&S®FSV(A)
R&S®FSV3000	R&S®FSU
R&S®FSVA3000	R&S®FSMR
R&S®FSVR	R&S®FSUP
R&S®FSP	R&S®FSL
R&S®FSG	

This application note describes in detail the steps required to make a noise figure measurement on a spectrum analyzer using the "Y Factor" technique. Background equations are presented for each step of the calculation. In addition, guidelines are provided to ensure a repeatable measurement. Measurement uncertainty is then reviewed, including contributions due to the noise source, analyzer, and the DUT itself.

Finally, a software utility is presented that automates the noise figure calculation using four measurements from a spectrum analyzer. The utility checks the measurement guidelines and highlights potential problem areas. It then calculates the noise figure and gain of the DUT along with the measurement uncertainty.

The Y Factor Technique for Noise Figure Measurements
Mike Leffel, Rick Danzl
1.2019 - 1MA178_4E

ROHDE&SCHWARZ

Noise Demo

Agenda – Signals and Noise

- Basic Signal Model

- Noise: Unintentional Modulation
  - Thermal Noise
  - **Phase Noise**

What is Phase Noise?

- Ideal Signal: $V(t) = A \cos(2\pi ft + \phi)$

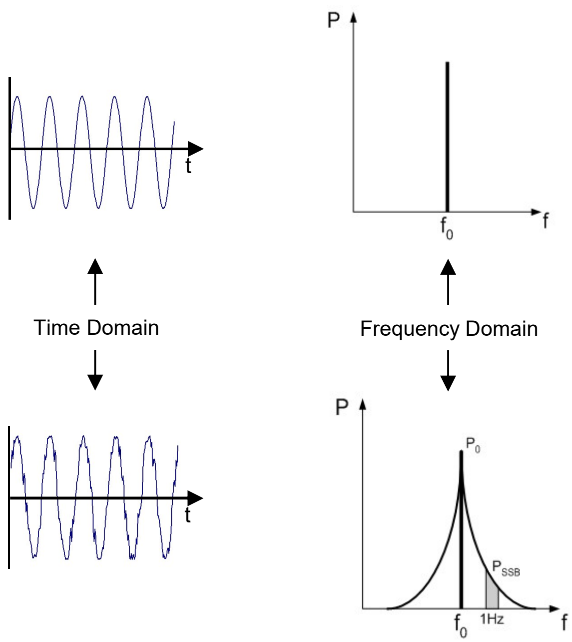
  where:

  A = nominal amplitude
  f = nominal frequency
  ϕ = nominal phase

- Real Signal: $V(t) = [A + E(t)] \cos(2\pi ft + \phi(t))$

  where:

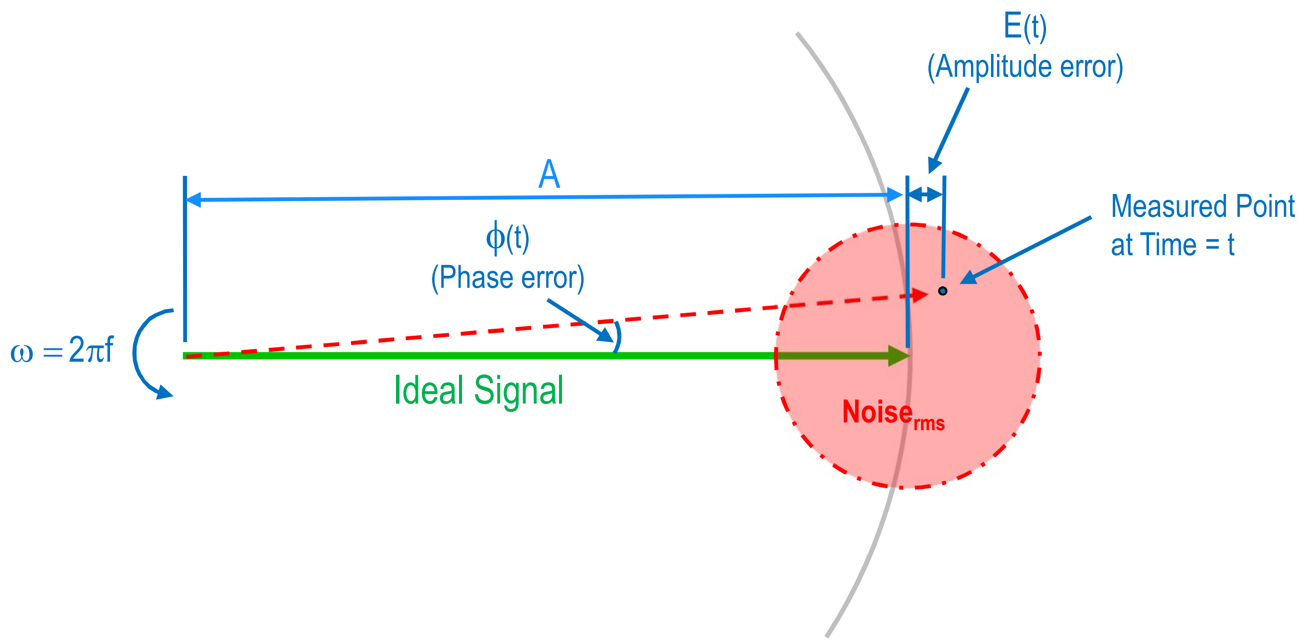
  $E(t)$ = random amplitude variations
  $\phi(t)$ = random phase variations



The Phasor Diagram

- AM Noise and Phase Noise on a Phasor Diagram:

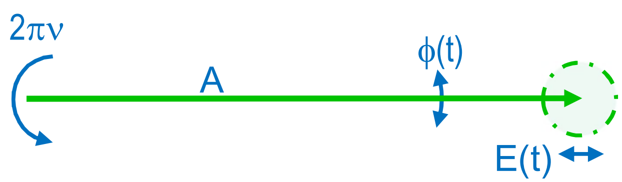
$V(t) = [A + E(t)] \sin(\omega t + \phi(t))$



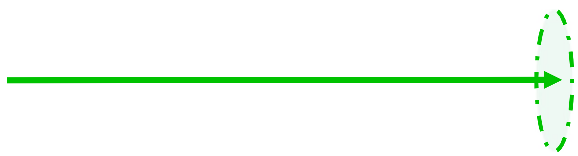
Types of Noise

- AM Noise and Phase Noise on a Phasor Diagram:

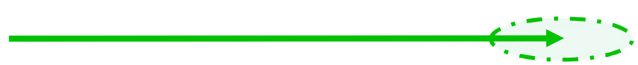
$$V(t) = [A + E(t)]\sin(2\pi\nu t + \phi(t))$$



Thermal noise has equal contributions from Amplitude Noise and Phase Noise



Noise added by a device dominated by phase noise

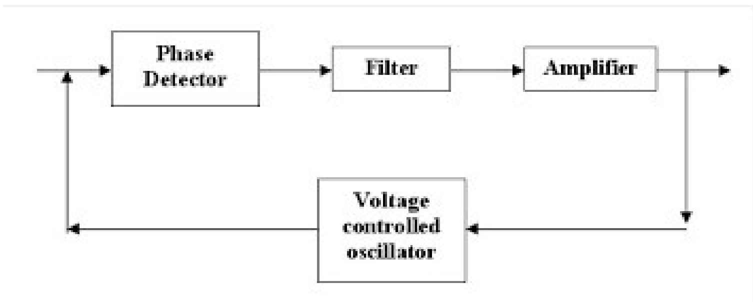


Noise added by a device dominated by amplitude noise (AM)

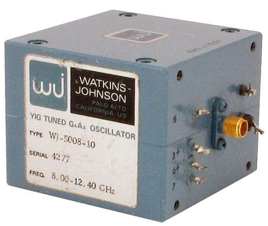
Where does phase noise come from?
Signal sources

Voltage Controlled Oscillator (VCO)

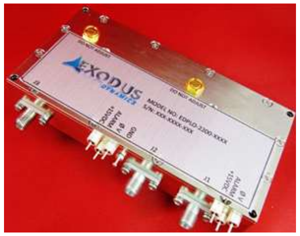
Crystal Oscillator



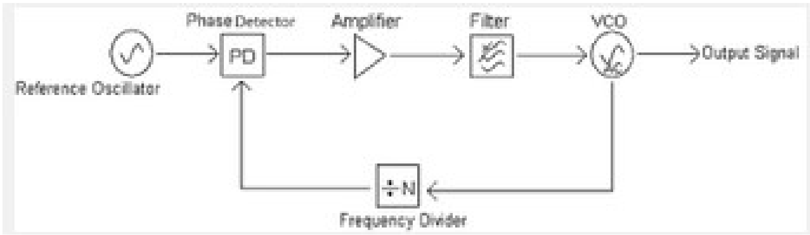
Phase Locked Loop (PLL) Synthesizers



YIG Oscillator



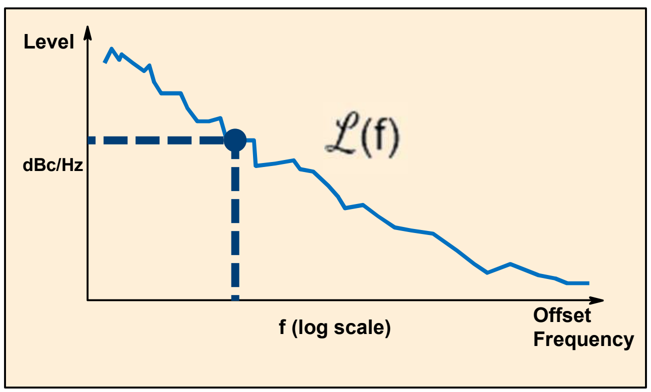
Dielectric Resonator Oscillator (DRO)



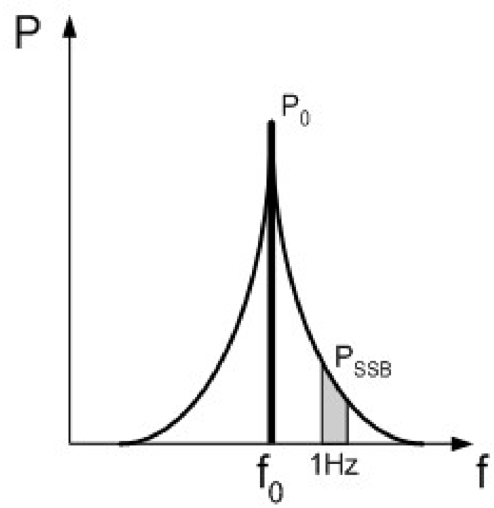
Phase Noise – Unit of Measure

- Phase Noise is expressed as $\mathscr{L}(f)$
- $\mathscr{L}(f)$ is defined as one-half the spectral density of phase fluctuations, $\mathscr{L}(f) = ½ * S_{\phi}(f)$ (per IEEE STD 1139-2008)
- $\mathscr{L}(f)$ has units of dBc/Hz

Spot Noise: dBc/Hz @ f_{offset}



Phase Noise Plot

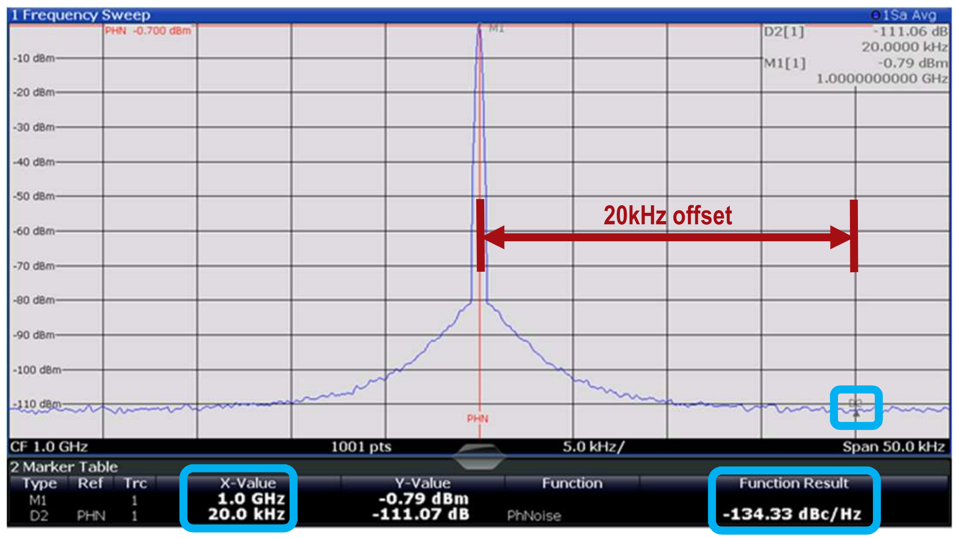


Spectrum View

Measuring with a Spectrum Analyzer

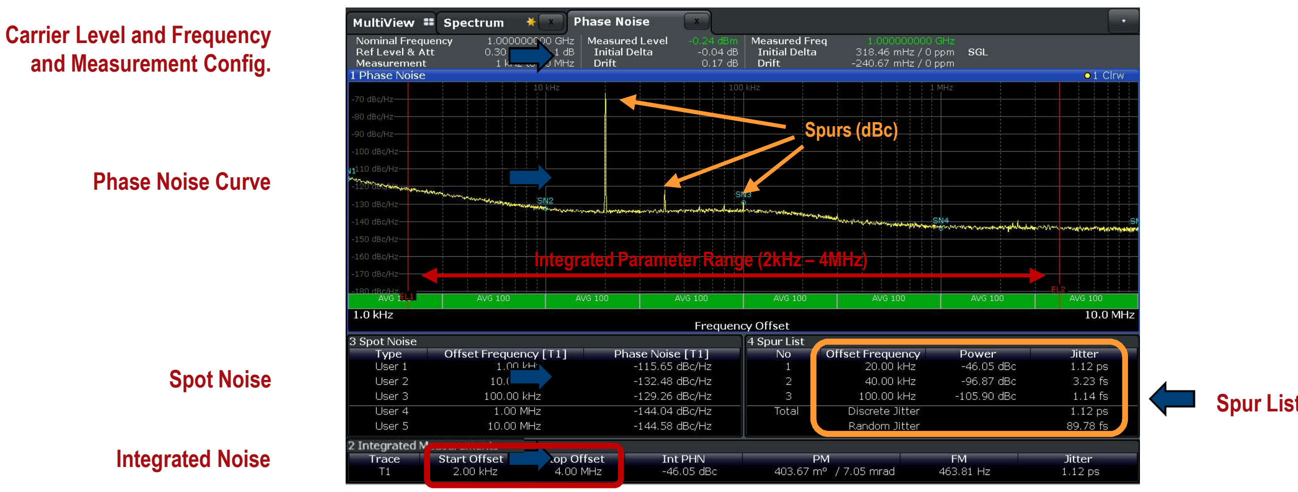
Spectrum Analyzer
Manual Spot Noise Measurement

- ► Phase Noise Marker function corrects for ratio of RBW to 1 Hz and Effective Noise Bandwidth (ENB) of the RBW filter (typically <1 dB)
- ► Must use proper detector and averaging type to get good measurement



Spectrum Analyzer
Phase Noise Measurement Personality

- ► Phase noise is measured over a user specified offset range
- ► Spot noise is available (phase noise at discrete offsets)
- ► Spurs may be displayed in a table
- ► Integrated parameters are calculated from phase noise trace



Integrated Noise

► Values calculated from integration of phase noise curve

– Integrated Phase Noise $\int \mathcal{L}(f)df$ (dBc)

– Residual PM $\frac{180^\circ}{\pi}\sqrt{2\int \mathcal{L}(f)df}$ (deg or rad)

– Residual FM $\sqrt{2\int f^2 \mathcal{L}(f)df}$ (Hz)

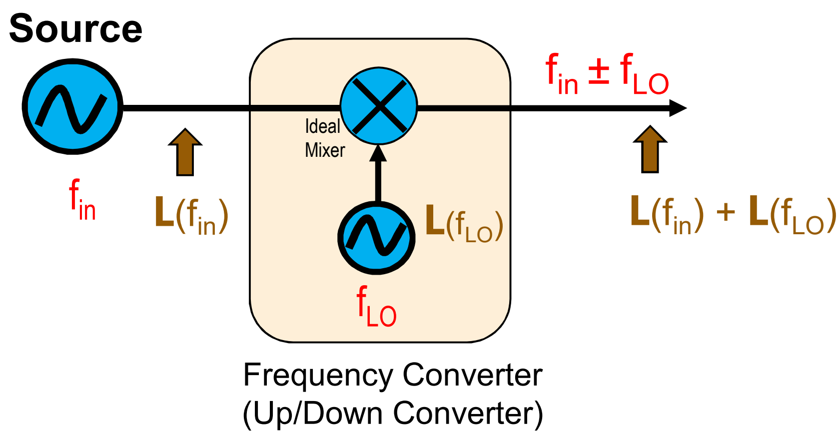
– Jitter $\frac{1}{2\pi f_c}\sqrt{2\int \mathcal{L}(f)df}$ (sec)

2 Integrated Measurements

Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM	Jitter
1	1	1.000 Hz	1.000 MHz		-71.73 dBc	0.02 °/366.60 µrad	950 mHz	583.460 fs

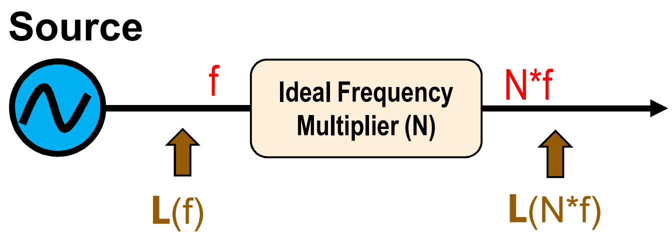
Phase Noise of Frequency Converters

- The Phase Noise of a signal passing through an ideal frequency Up/Downconverter (one that adds no noise) increases by the phase noise of the LO
- The phase noise always increases (whether the input signal is up or down converted)
- This is expressed by: $\mathbf{L}(f_{out}) = \mathbf{L}(f_{in}) + \mathbf{L}(f_{LO})$



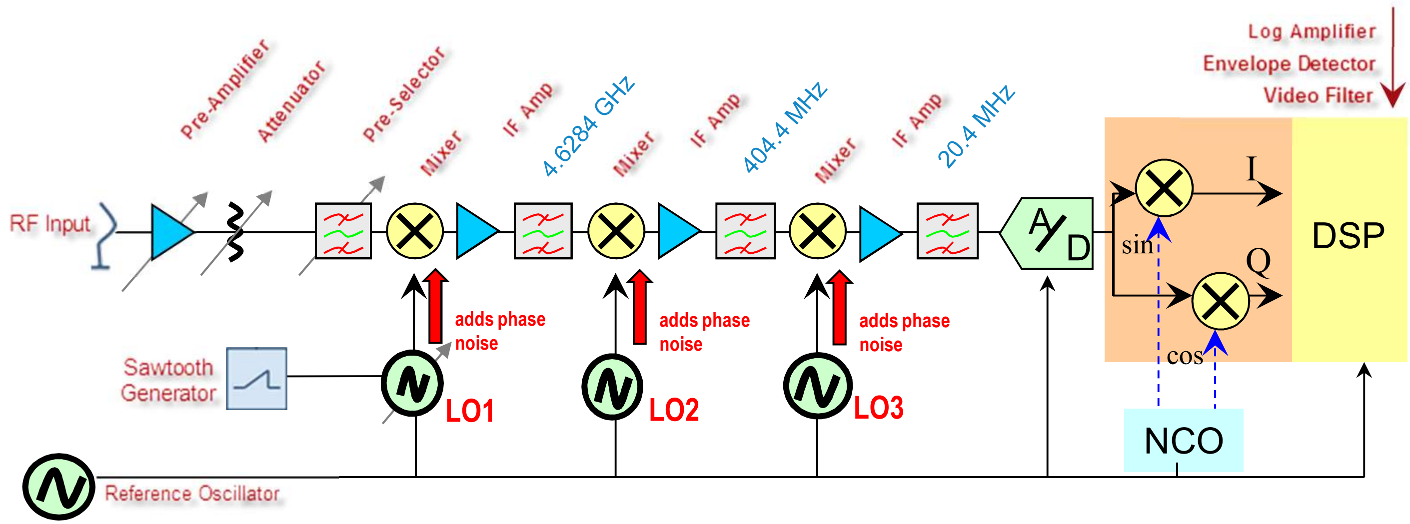
Phase Noise of Frequency Multipliers/Divider

- The Phase Noise of a signal passing through an ideal multiplier (one that adds no noise) will increase since a given amount of phase deviation represents a higher fraction of the shorter signal period
- This is expressed by: $L(Nf) = 20Log_{10}(N) + L(f)$, dBc/Hz
  - N = 2 results in a 6 dB increase, N = 10 results in a 20 dB increase
- Correspondingly, a frequency divider decreases the phase noise of a signal
  - N = ½ results in a 6 dB decrease, N = 1/10 results in a 20 dB decrease



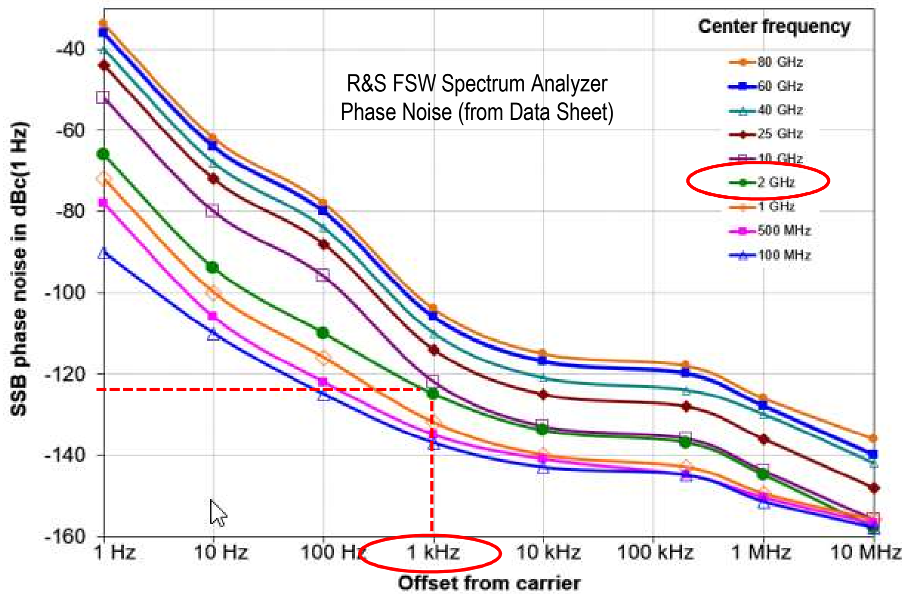
Spectrum Analyzer Internal Phase Noise

- Spectrum analyzer is a multistage receiver with multiple LOs
- Limitations of Spectrum Analyzer approach:
  - Measurement result is the <u>sum</u> of phase noise from DUT and all LOs
  - Full RF signal amplitude is present at every stage of the SA receiver so dynamic range is a limitation



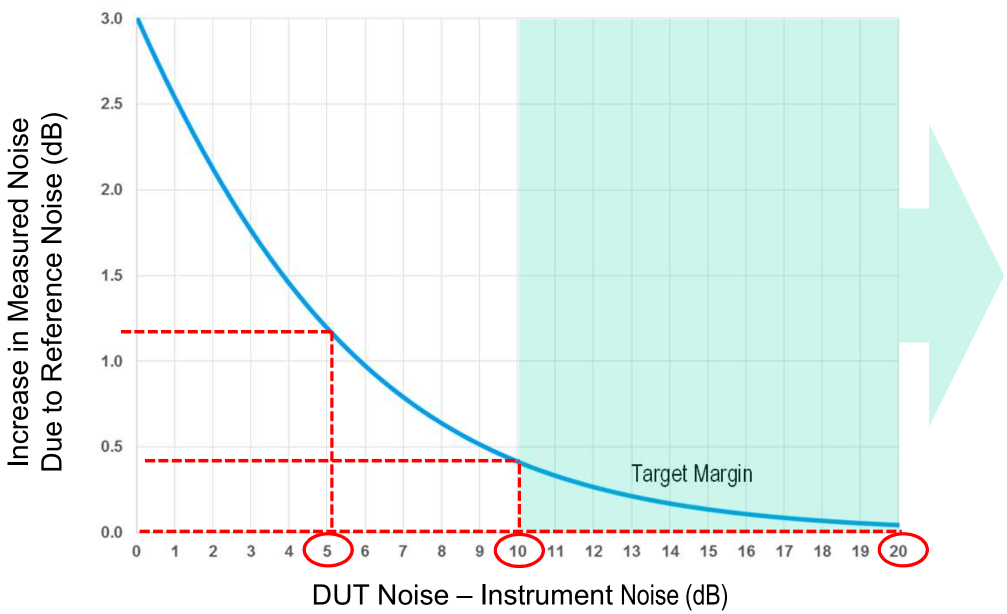
Spectrum Analyzer Internal Phase Noise

- Measurement sensitivity is limited by internal phase noise of spectrum analyzer
- Only way to validate measurement is to compare to SA phase noise specs
- Instrumentation noise always adds to measurement (error, not uncertainty)
- Would like SA phase noise to be lower than DUT phase noise (how much?)



Measurement Error due to Instrumentation Noise

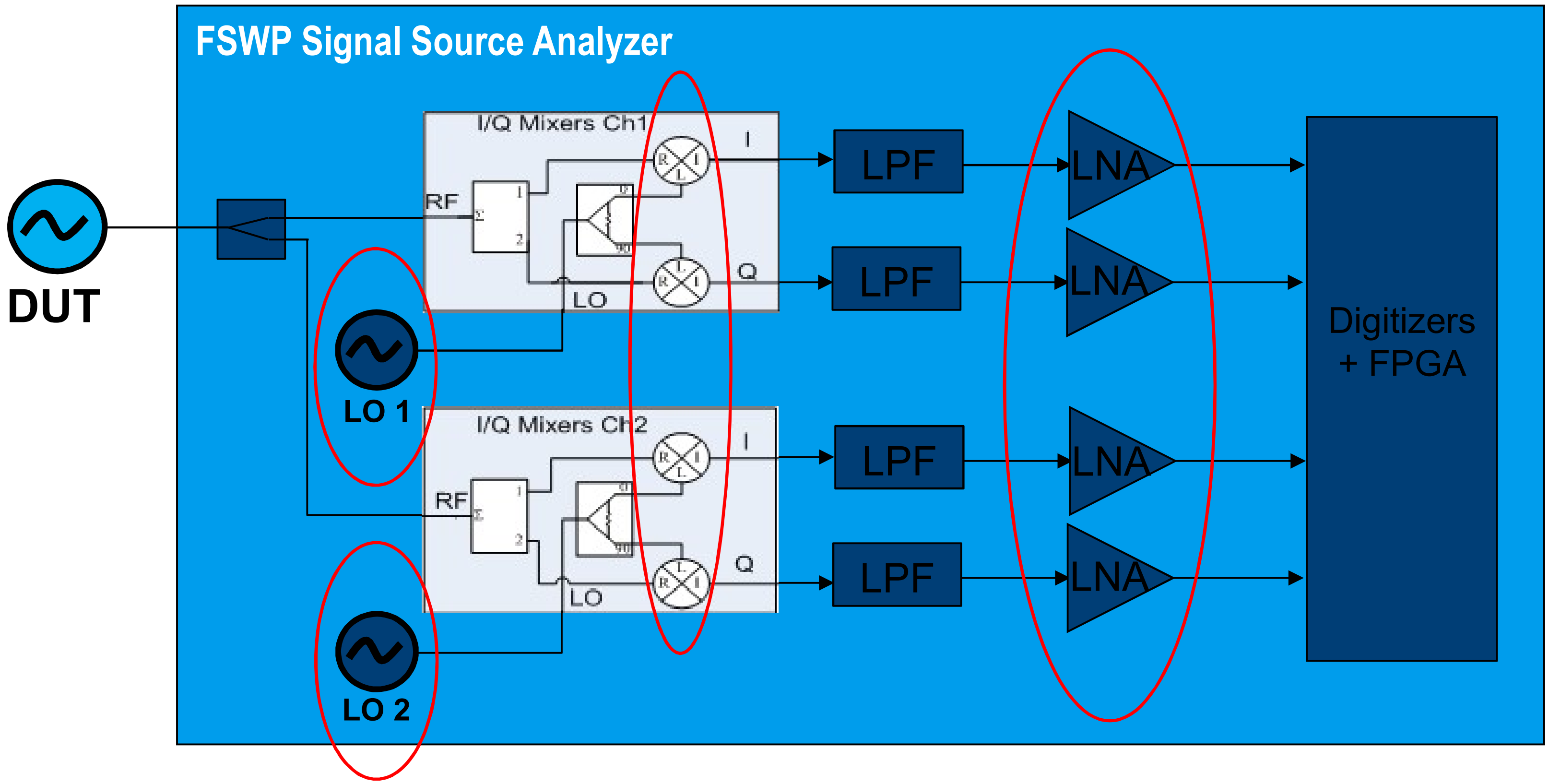
► How much error does the instrument's own phase noise contribute to the measurement?



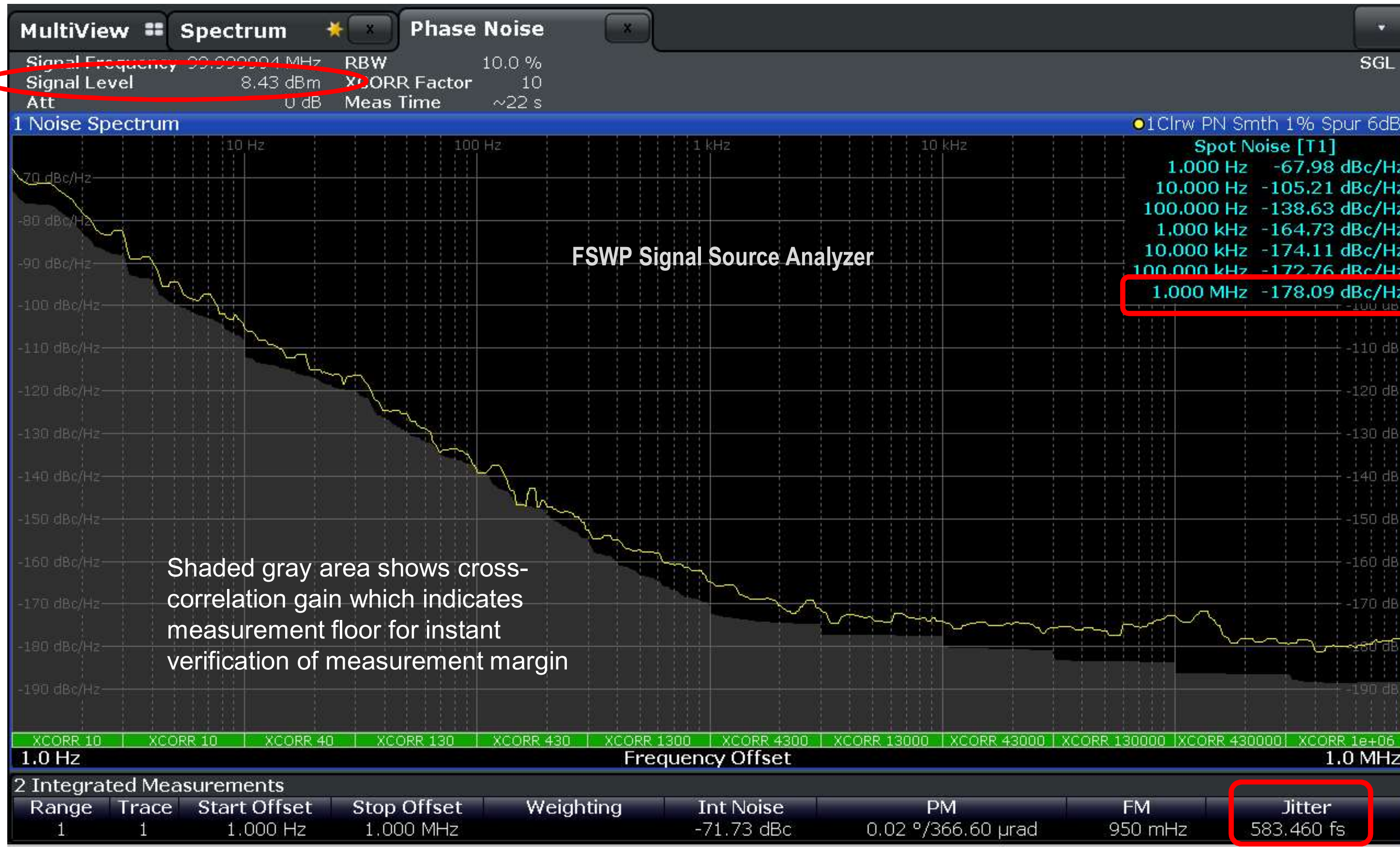
Quantifying Phase Noise – Measurement Limits

- kTB noise (-174 dBm/Hz at room temp) has equal contributions from AM and Phase Noise
- Theoretical measurement floor for each parameter is -177 dBm/Hz
- Phase noise is expressed as dBc/Hz so the theoretical measurement floor becomes -177 dBm/Hz – P_{signal} (dBm)
- Example:
  - DUT with +20 dBm output level can be theoretically measured as low as -197 dBc/Hz
- In practice, instrumentation noise prevents measurements to these levels

Additive Phase Noise – Digital Phase Demodulator



FSWP Phase Noise Measurement



Spectrum Analyzer or Dedicated Phase Noise Analyzer?

FSW

FSWP

Phase Noise Demo

COMMUNICATIONS SYSTEMS: SIGNALS AND NOISE