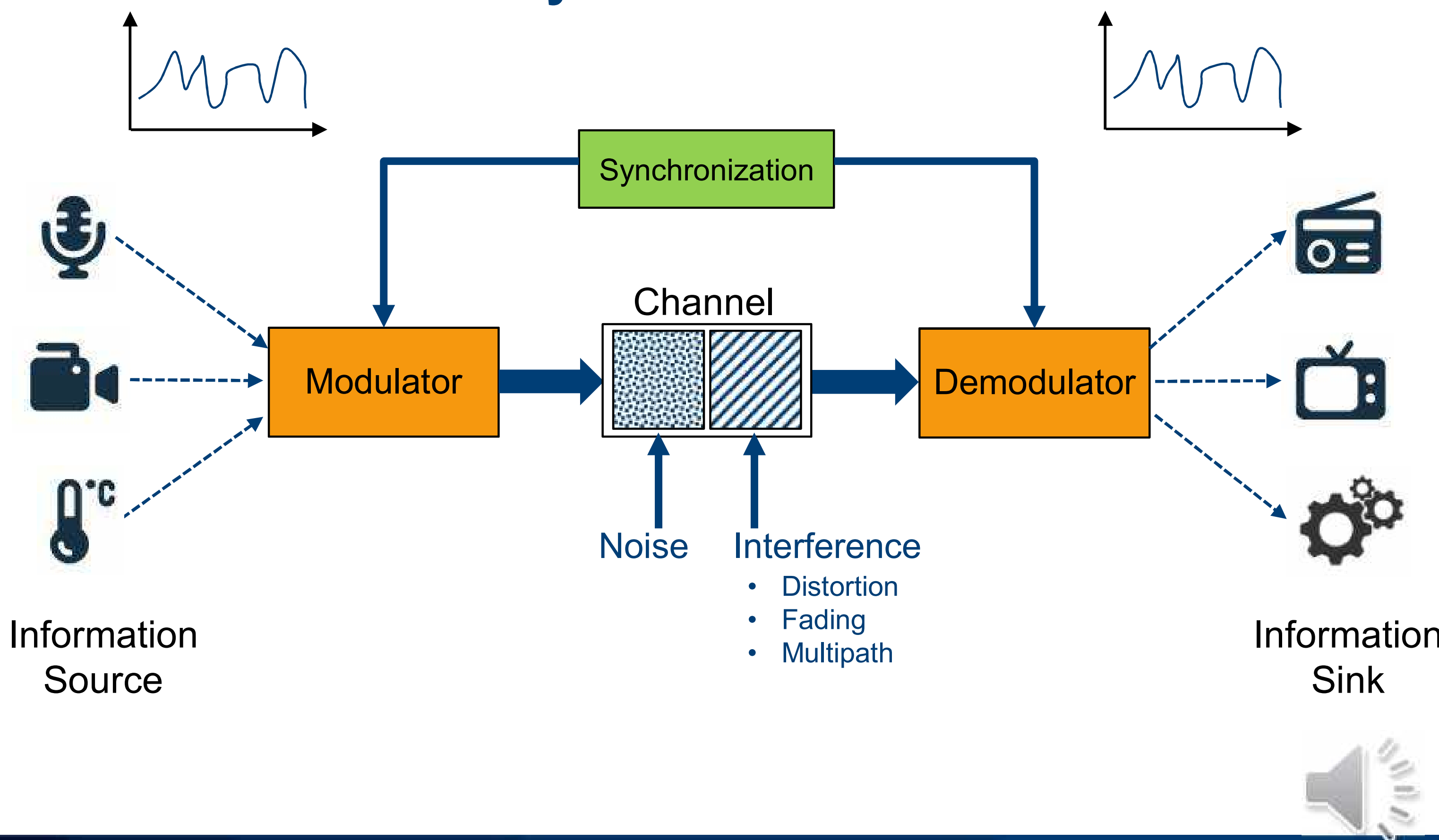
COMMUNICATIONS SYSTEMS: SIGNALS AND NOISE

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

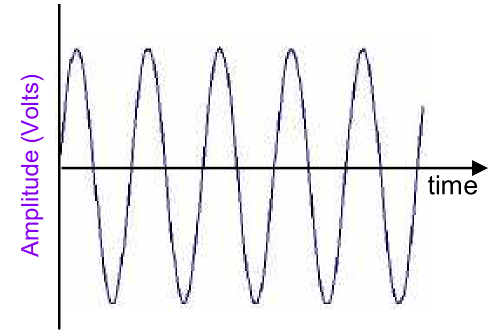
$$V(t) = A(t)\cos(\omega t + \phi(t))$$

where:

A = amplitude

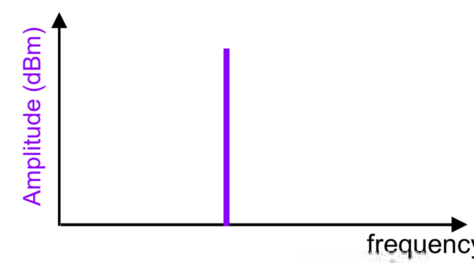
ω = frequency (rad/s)

ϕ = phase



Frequency Domain

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



- An ideal unmodulated signal contains little information
  - *<u>But</u>* 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*

→

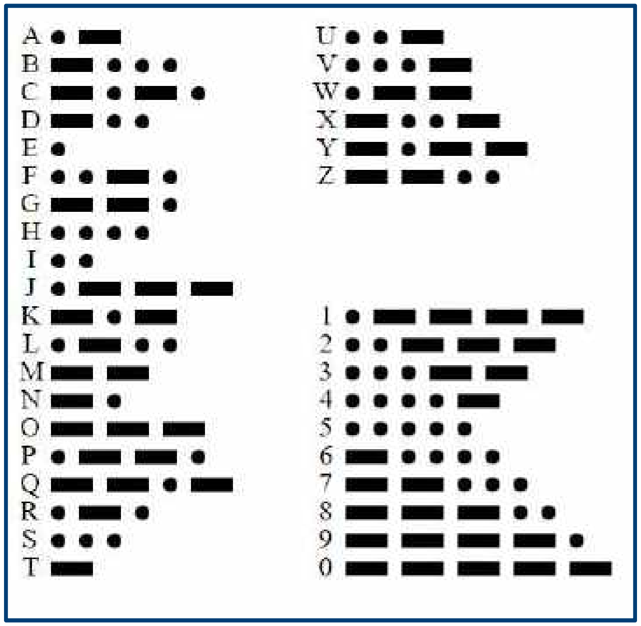
Demodulate:
Detect the modifications

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

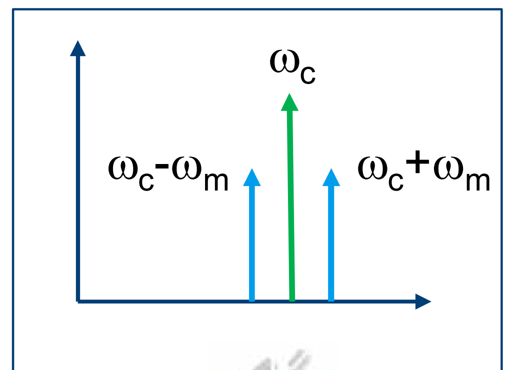
Amplitude Modulation (AM)

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

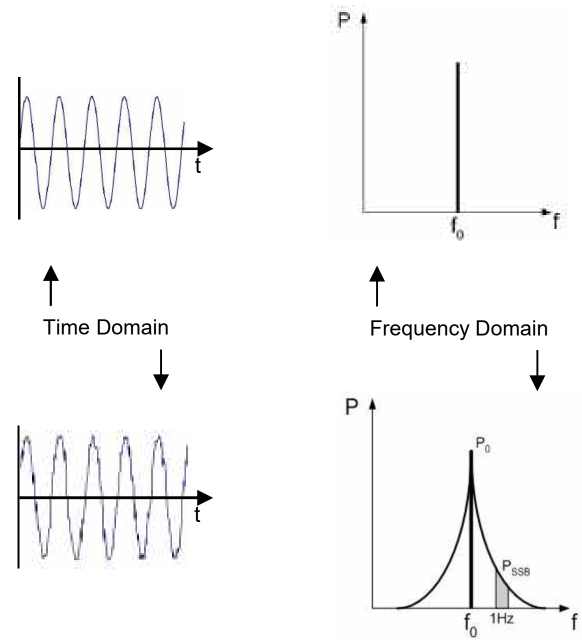
where:

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

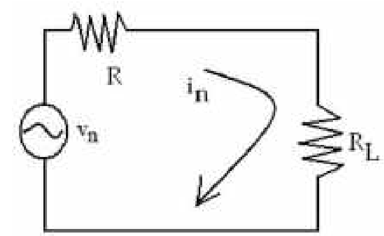


Agenda – Signals and Noise

- ► 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

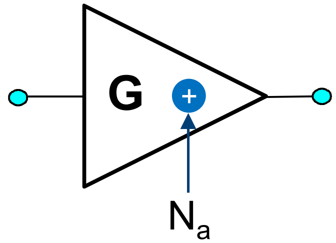
- Types of Excess Noise can include
  - Flicker Noise
  - Shot Noise
  - Burst Noise
  - Coupled Noise

- 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:

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

IEEE Definition of Noise Factor/Noise Figure

► IEEE definition of Noise Factor

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

► Terms:

– N_a: Noise added by device

– G: Gain of device

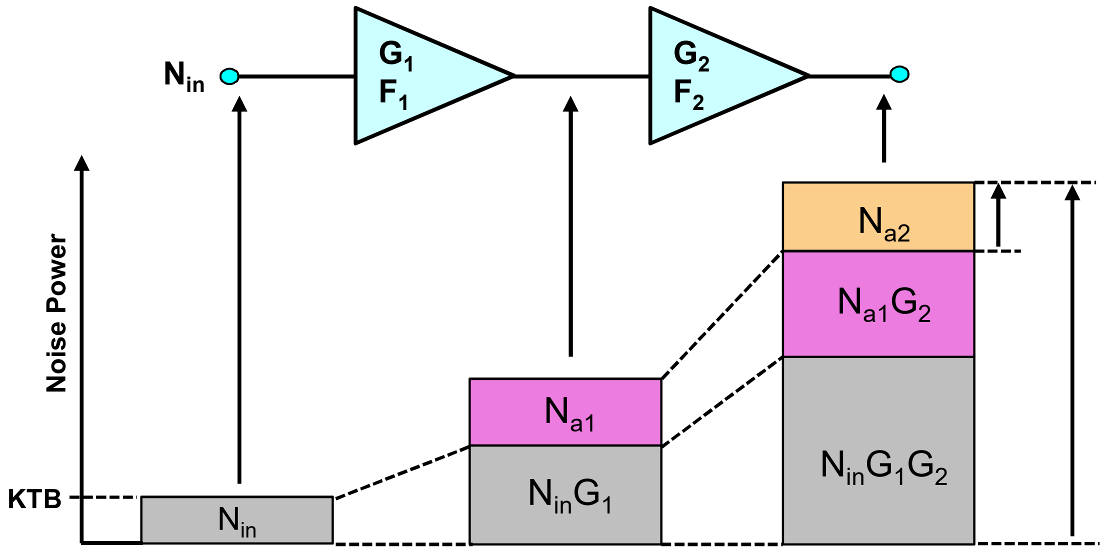
– k: Boltzmann's constant = 1.38 x10^{-23} Joules / K

– T_0: defined as "standard temperature", 290 K = 16.8 C

– B: noise bandwidth of the system in Hertz

Noise Factor = 1 + (Te/To)

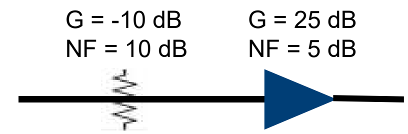
Noise Figure of Cascaded Components



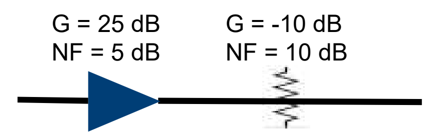
Friis Equation

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

(linear terms, not dB)



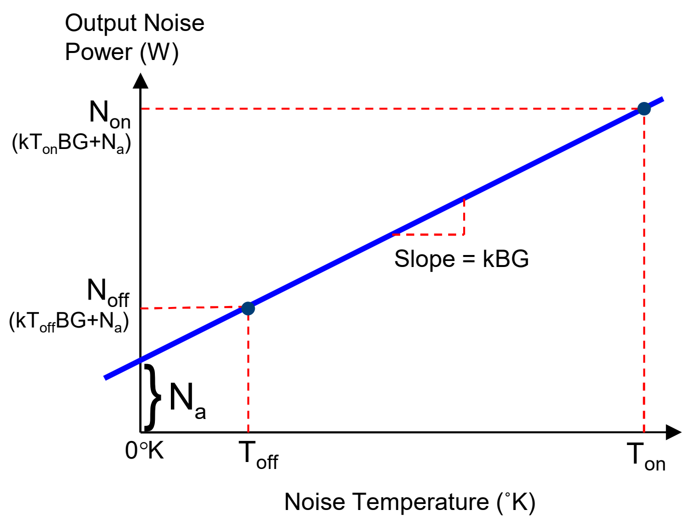
	Gain (dB)	Noise Figure (dB)
Attenuator	-10	10
Amplifier	25	5
Combination	15	15

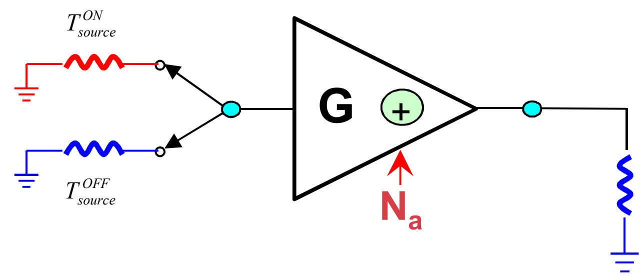


	Gain (dB)	Noise Figure (dB)
Amplifier	25	5
Attenuator	-10	10
Combination	15	5.04

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





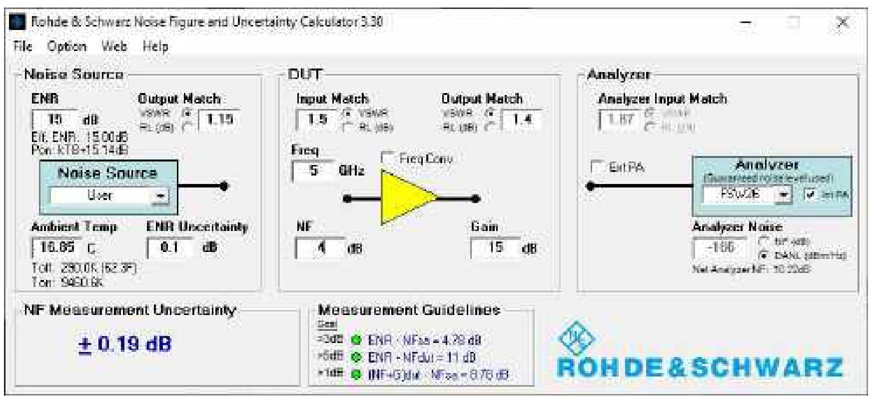
Y Factor

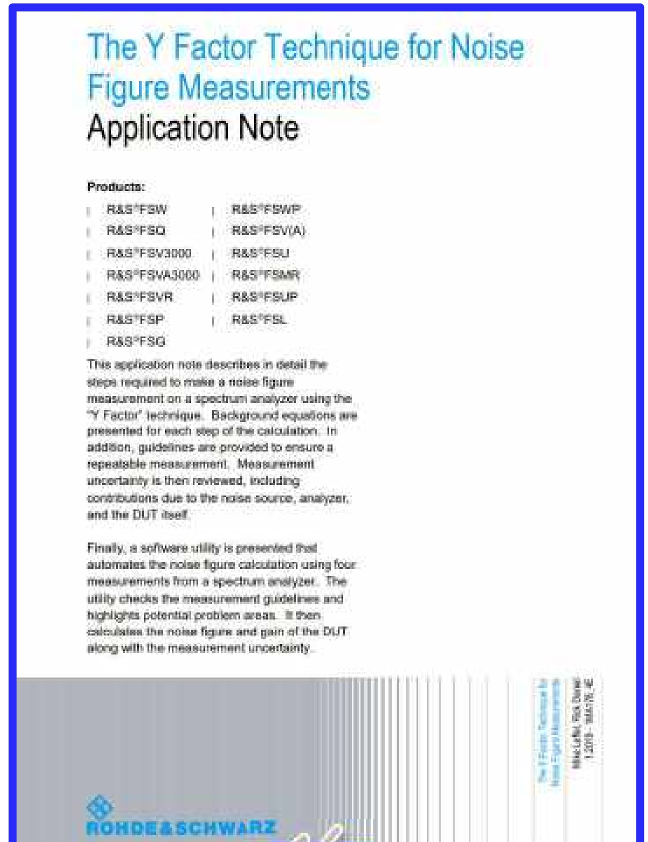
$$Y = \frac{N_{on}}{N_{off}}$$

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

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

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.

ROHDE&SCHWARZ

Noise Demo

Agenda – Signals and Noise

- Basic Signal Model

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

What is Phase Noise?

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

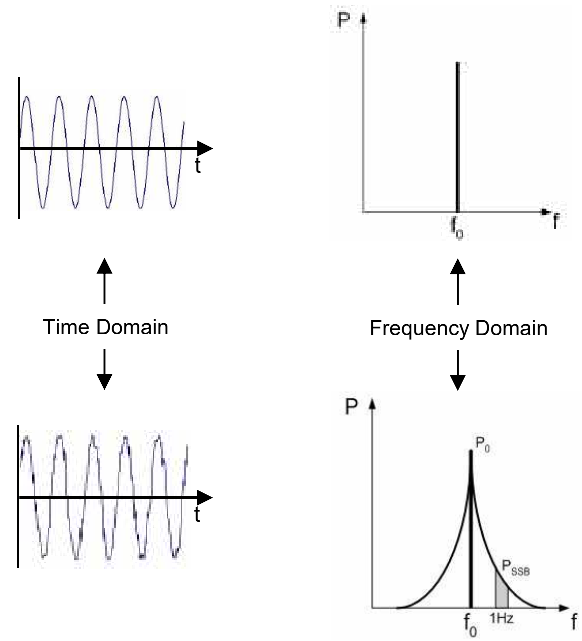
  where:

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

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

  where:

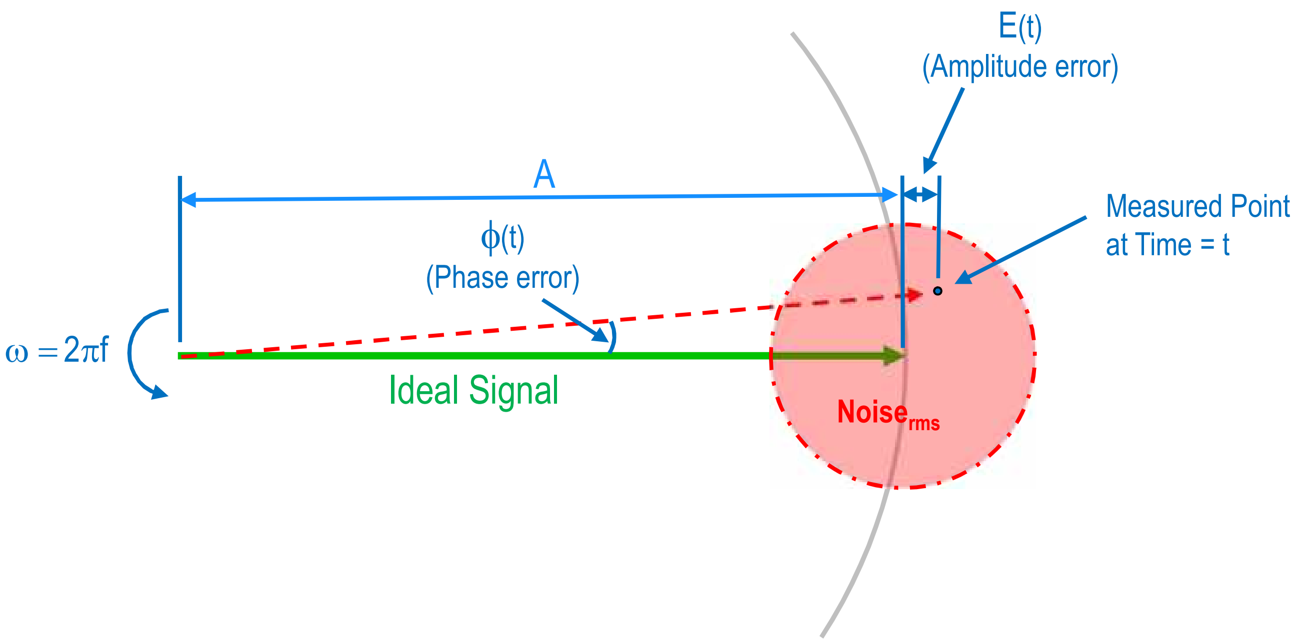
  $E(t)$ = random amplitude variations
  $\phi(t)$ = random phase variations



The Phasor Diagram

► AM Noise and Phase Noise on a Phasor Diagram:

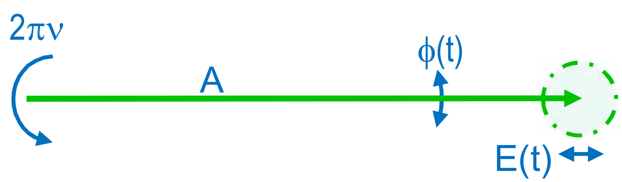
$V(t) = [A + E(t)]\ \sin(\omega t + \phi(t))$



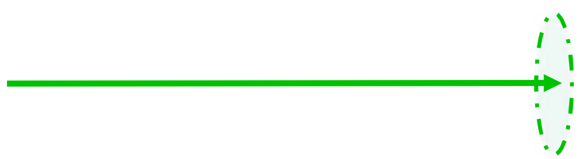
Types of Noise

► 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



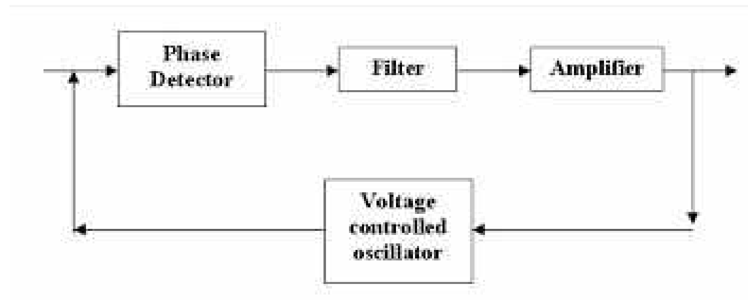
Noise added by a device dominated by <u>phase</u> noise

Noise added by a device dominated by <u>amplitude</u> noise (AM)

Where does phase noise come from? Signal sources

Voltage Controlled Oscillator (VCO)

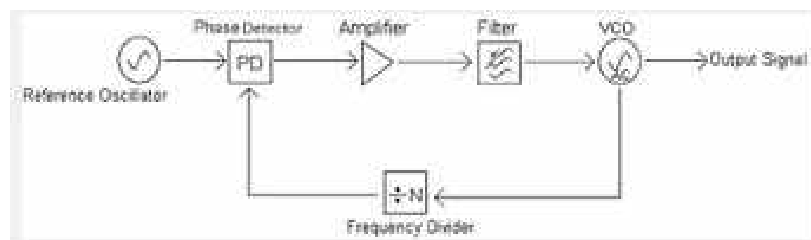
Crystal Oscillator



Phase Locked Loop (PLL) Synthesizers

YIG Oscillator

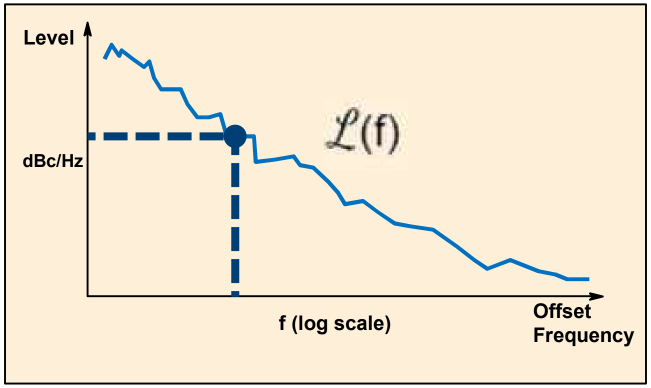
Dielectric Resonator Oscillator (DRO)



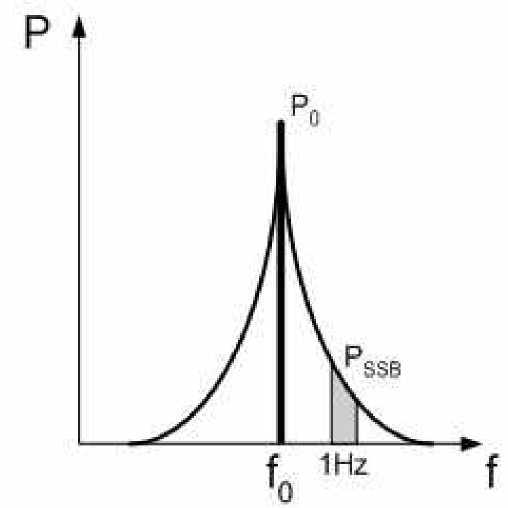
Phase Noise – Unit of Measure

- 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}

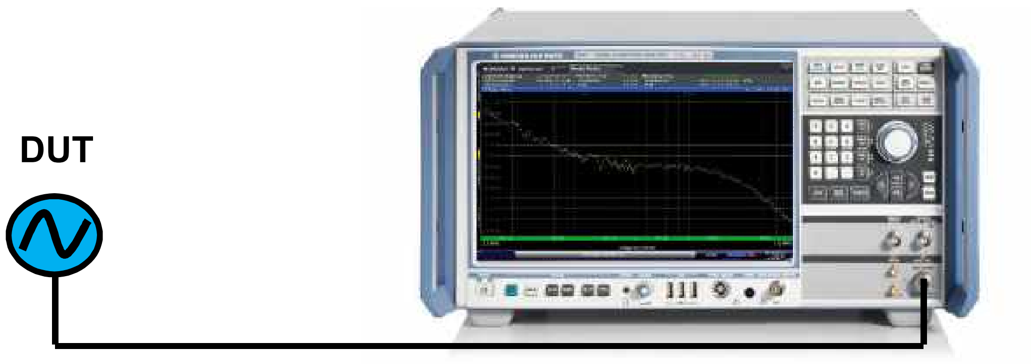


Phase Noise Plot



Spectrum View

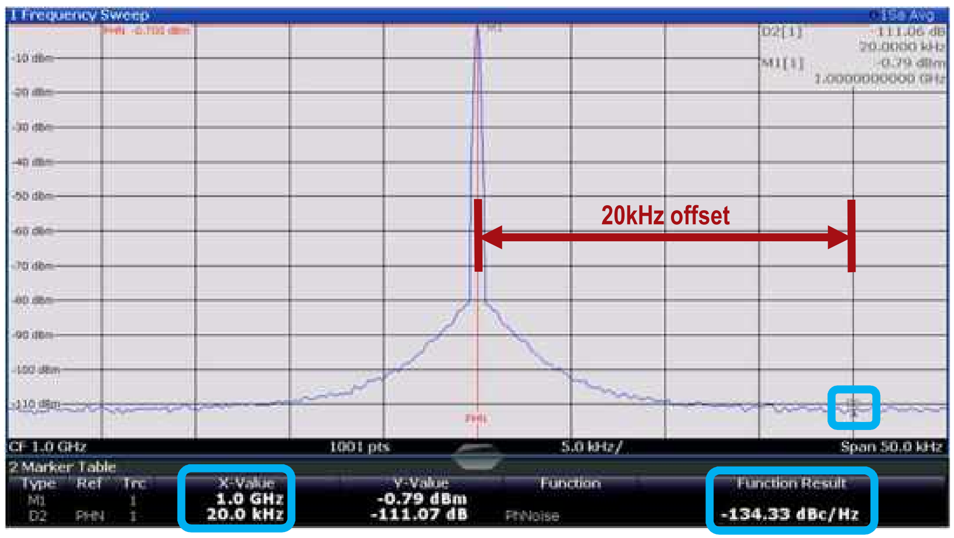
Measuring with a Spectrum Analyzer



Spectrum Analyzer
Manual Spot Noise Measurement

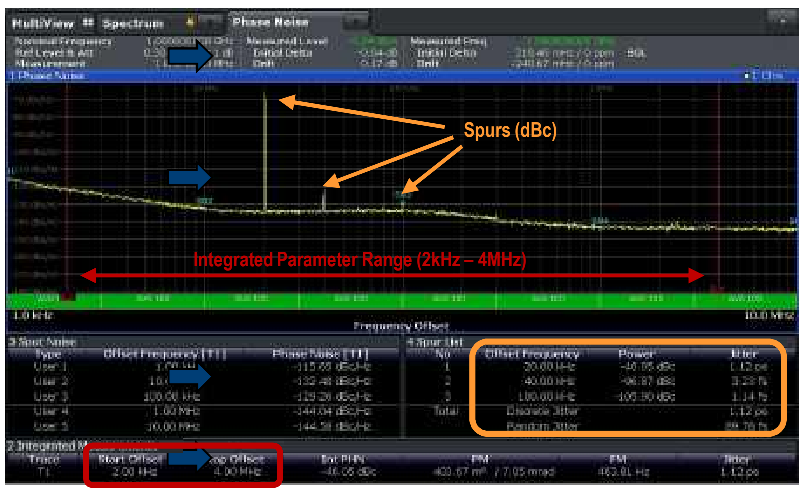
► Phase Noise Marker function corrects for ratio of RBW to 1 Hz and Effective Noise Bandwidth (ENB) of the RBW filter (typically <1 dB)

► 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)

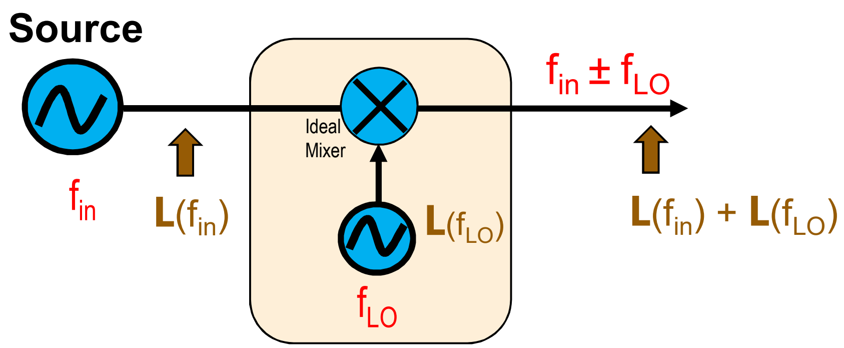
– Jitter $\frac{1}{2\pi f_c}\sqrt{2\int \mathcal{L}(f)df}$ (sec)

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

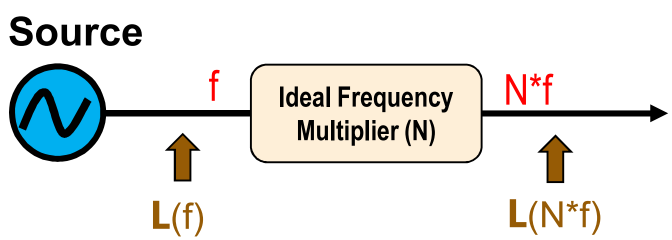
- The Phase Noise of a signal passing through an ideal frequency Up/Downconverter (one that adds no noise) increases by the phase noise of the LO
- The phase noise always increases (whether the input signal is up or down converted)
- This is expressed by: $\mathbf{L}(f_{out}) = \mathbf{L}(f_{in}) + \mathbf{L}(f_{LO})$



Frequency Converter
(Up/Down Converter)

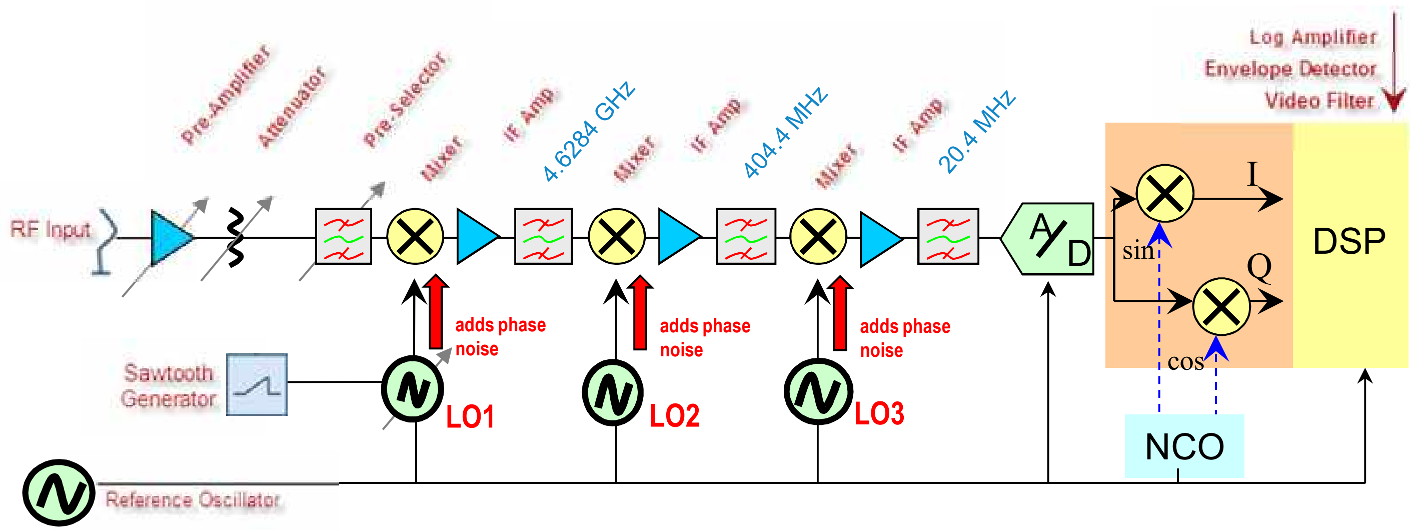
Phase Noise of Frequency Multipliers/Divider

- 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 <u>decreases</u> the phase noise of a signal
  - N = ½ results in a 6 dB decrease, N = 1/10 results in a 20 dB decrease



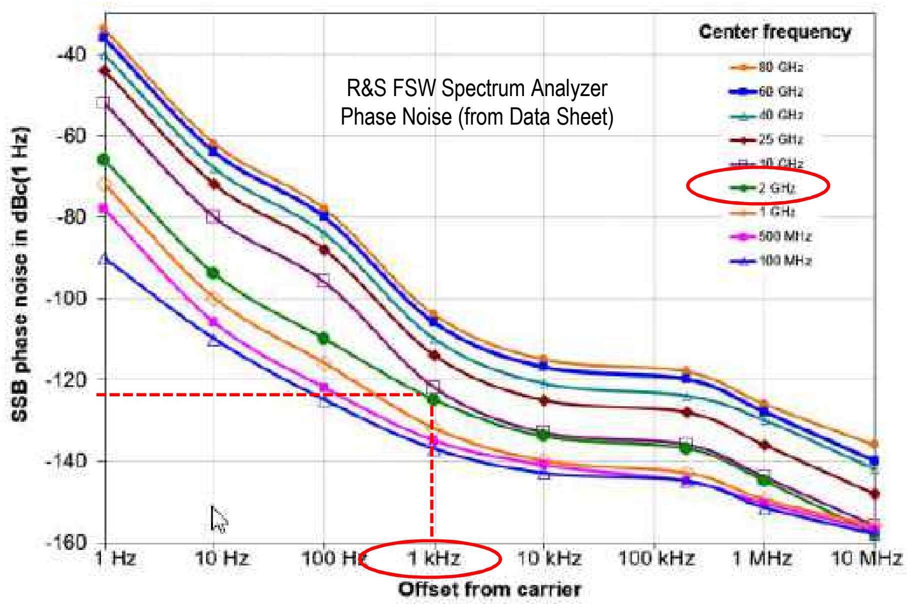
Spectrum Analyzer Internal Phase Noise

- 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



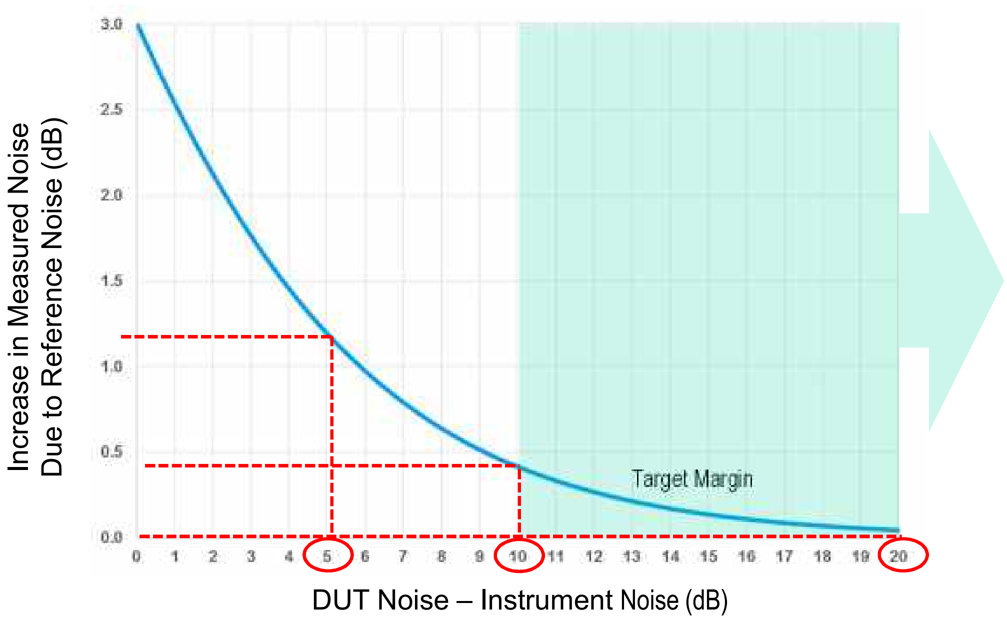
Spectrum Analyzer Internal Phase Noise

- 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

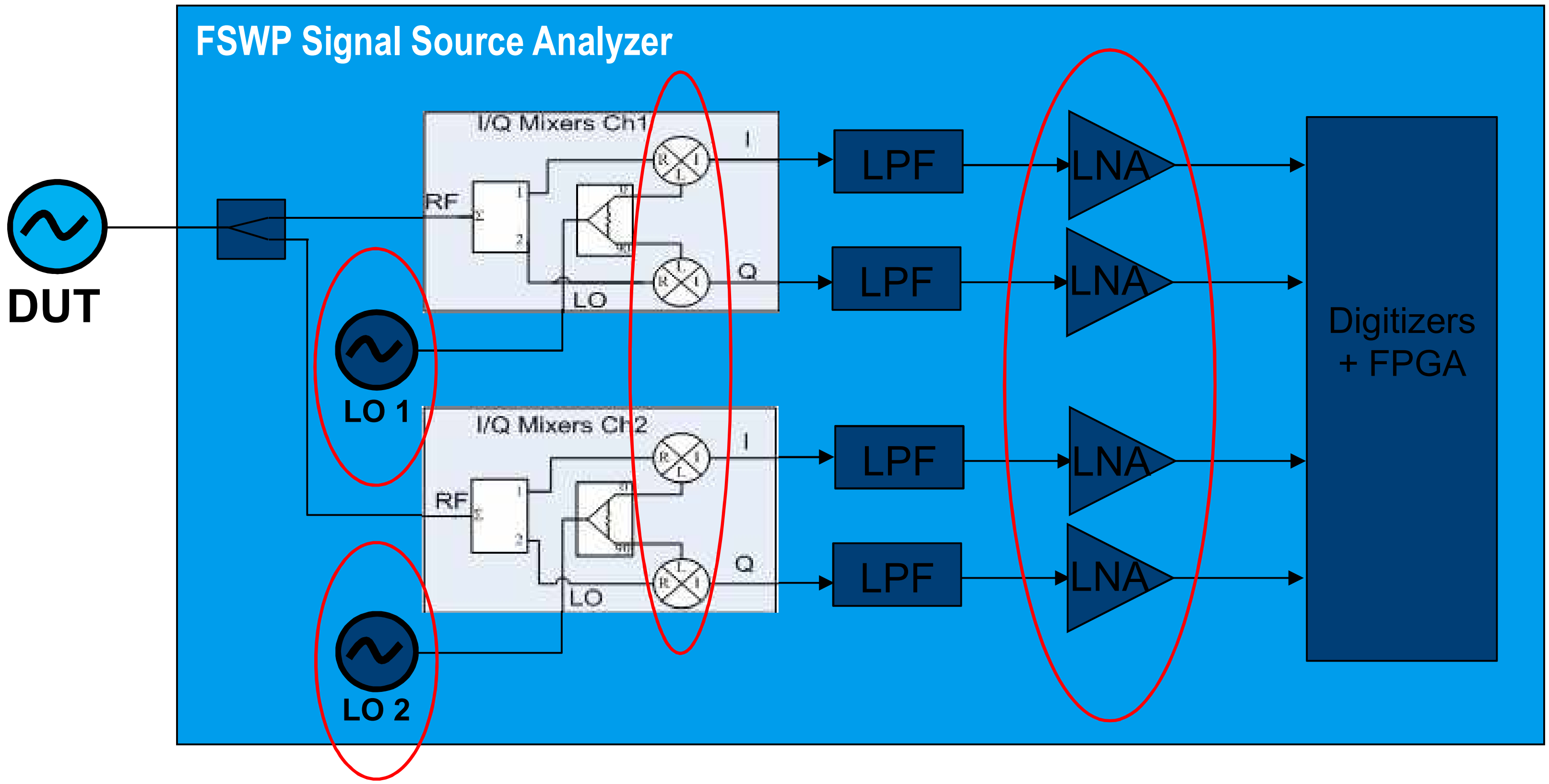
► How much error does the instrument's own phase noise contribute to the measurement?



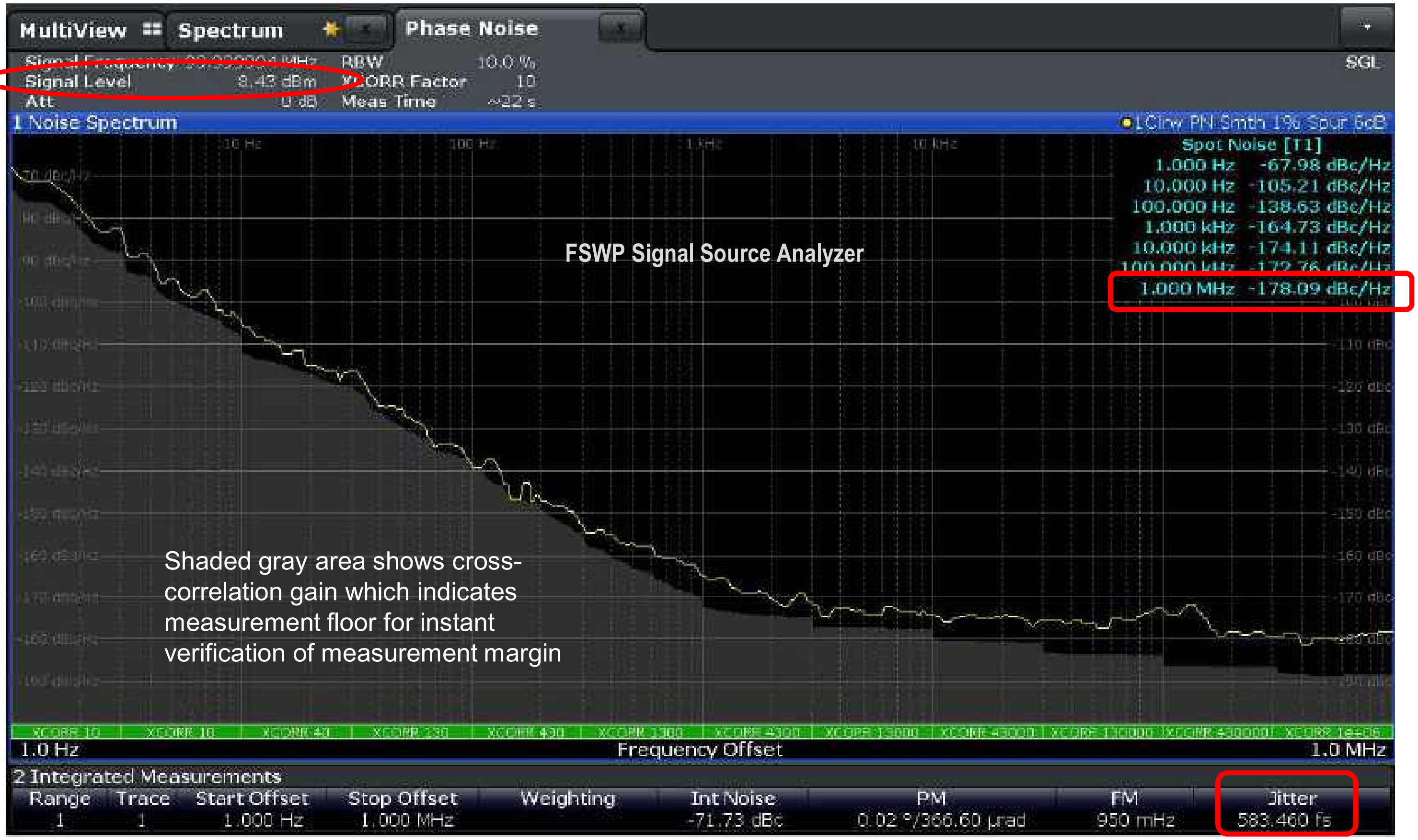
Quantifying Phase Noise – Measurement Limits

- 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