Advances in Phase Noise Measurement Techniques

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Agenda

- Phase Noise Review
- Phase Noise Measurement Techniques
  - Direct Spectrum Analyzer
  - Phase Detector
  - Phase Detector with Cross-Correlation
  - Delay Line Discriminator
  - Digital Phase Demodulator
- Additive Phase Noise
- Pulsed Phase Noise
- AM Noise
- VCO Measurements
- Summary

What is Phase Noise?

- **Ideal Signal (noiseless)**

  $V(t) = A \sin(2\pi\nu t)$

  where

  A = nominal amplitude

  ν = nominal frequency

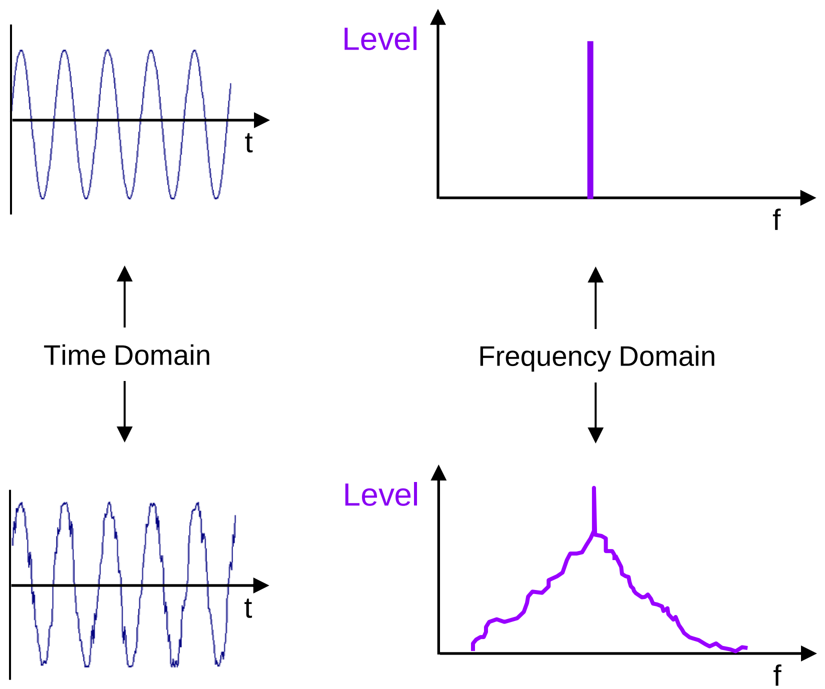
- **Real Signal**

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

  where

  $E(t)$ = amplitude fluctuations

  $\phi(t)$ = phase fluctuations

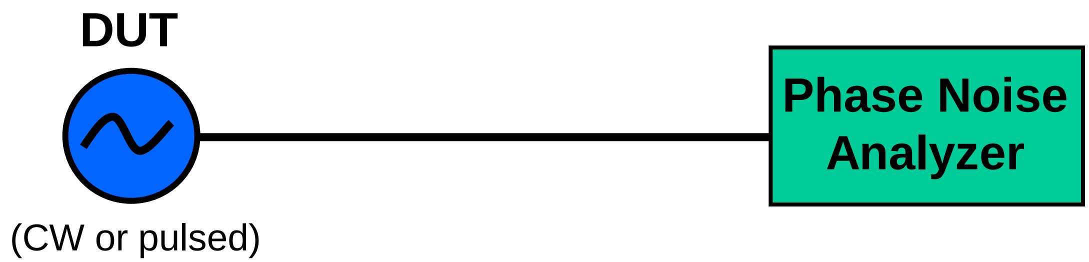


Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain.

Phase Noise is equivalent to jitter in the time domain.

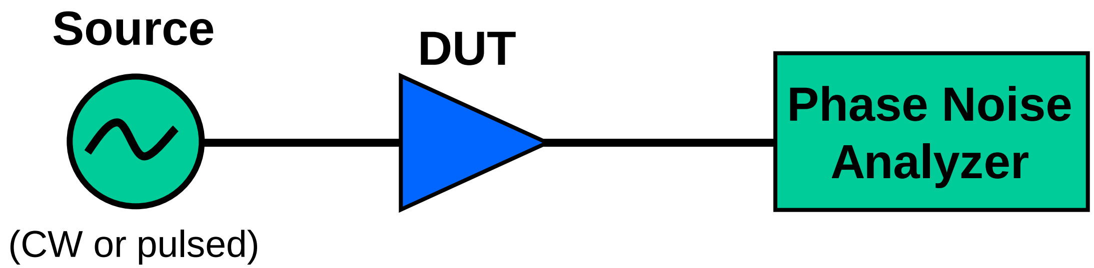
What is Phase Noise?

- **Absolute Phase Noise**
  1 Port – Produced by Signal Source



Measure Phase Noise <u>produced</u> by DUT

- **Additive Phase Noise**
  2 Port – Added by device (e.g. amp, up/down converter)

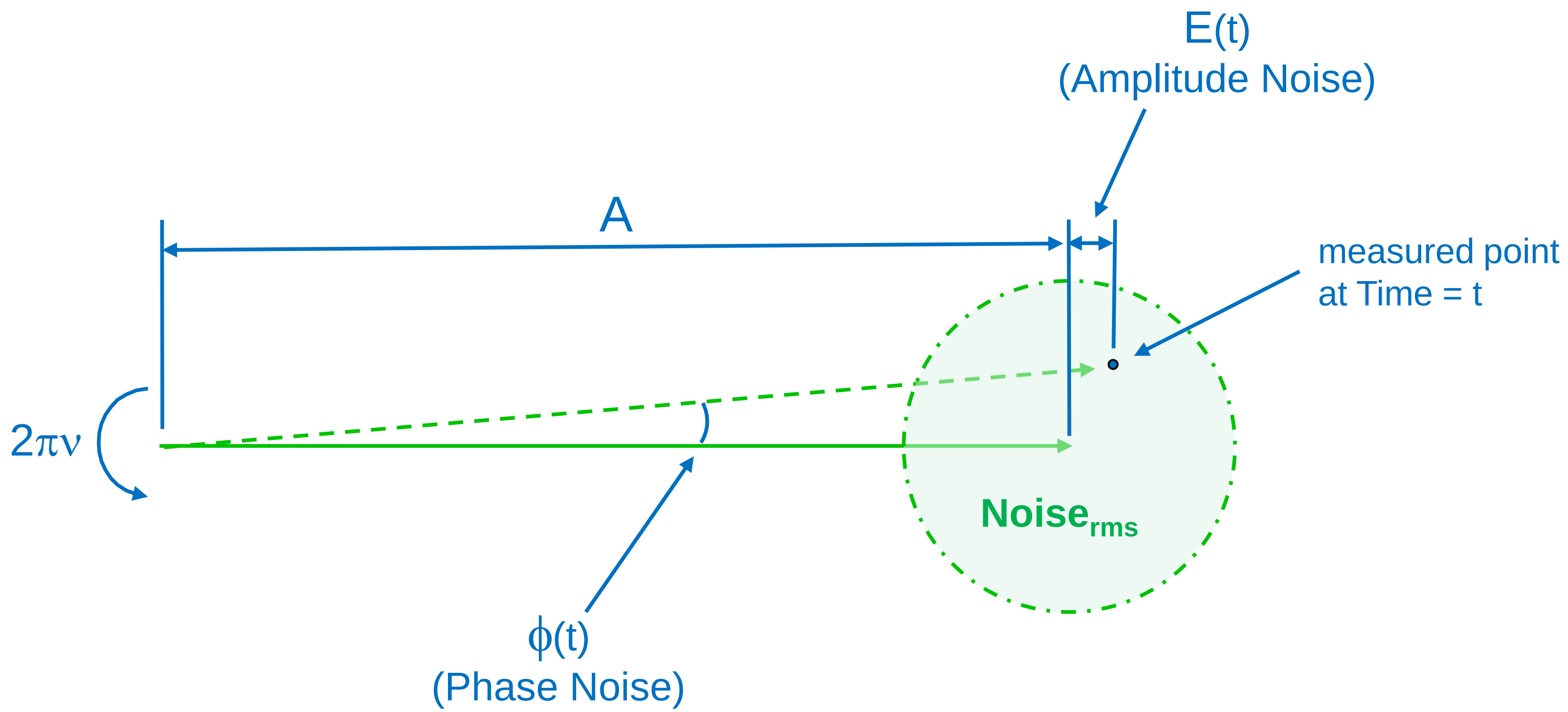


Measure Phase Noise <u>added</u> by DUT

What is Phase Noise?

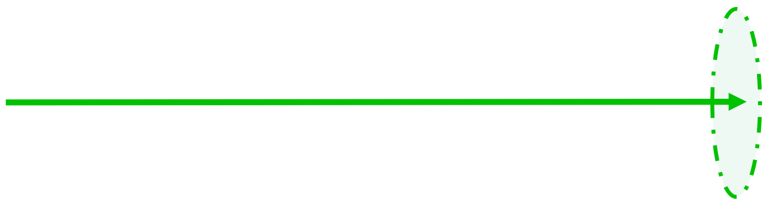
AM Noise and Phase Noise on a Phasor Diagram:

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



What is Phase Noise?

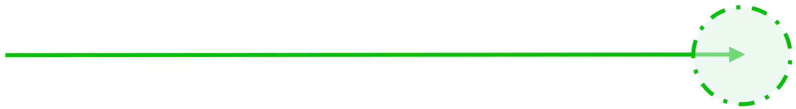
kTB noise has equal contributions from Amplitude Noise and Phase Noise



Noise added by a device dominated by phase noise

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

Quantifying Phase Noise – Measurement Limits

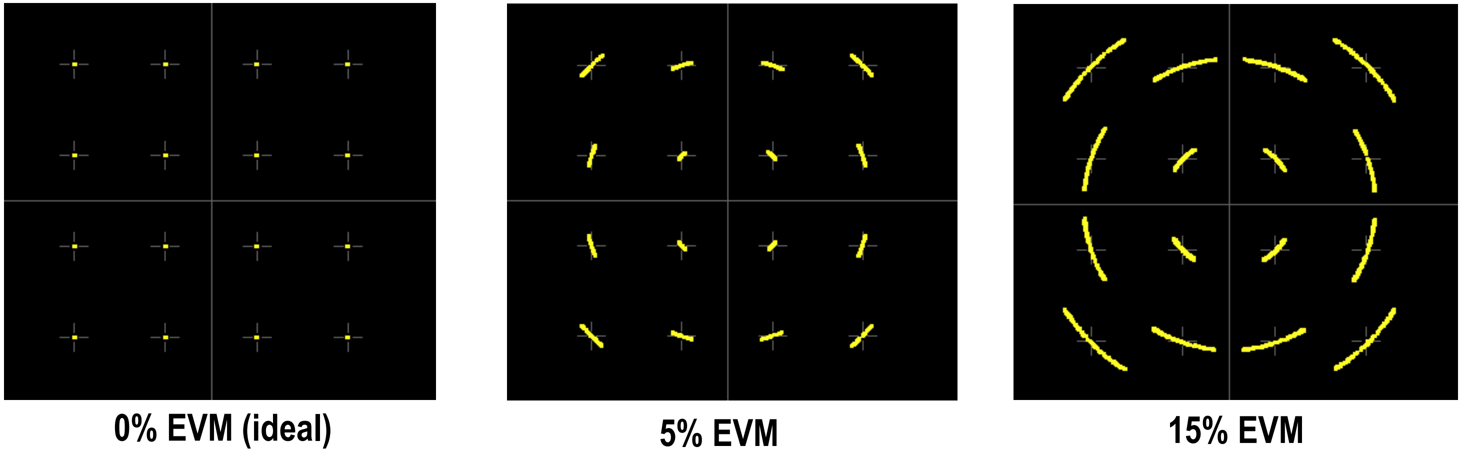


kTB noise
-174dBm/Hz (rms) at room temperature

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

Phase Noise
Important in Digital Modulation

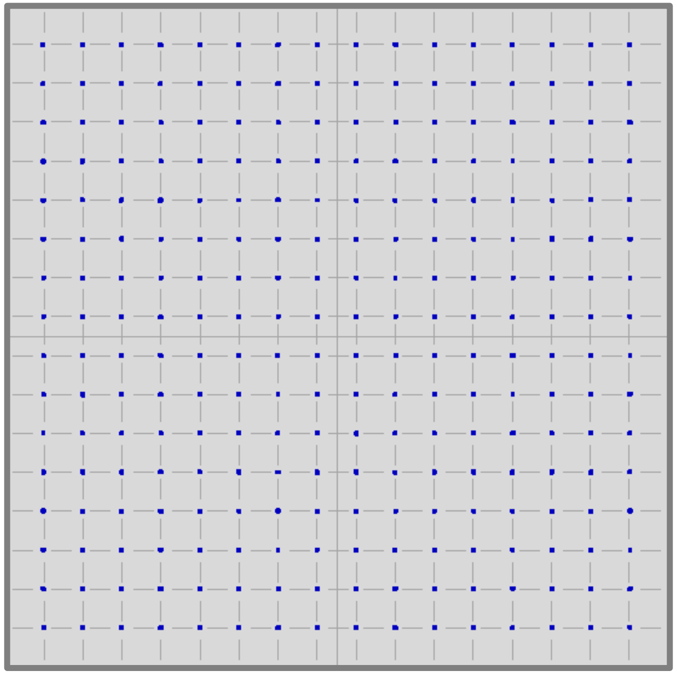
Modulation quality (phase error, EVM)
is degraded by phase noise



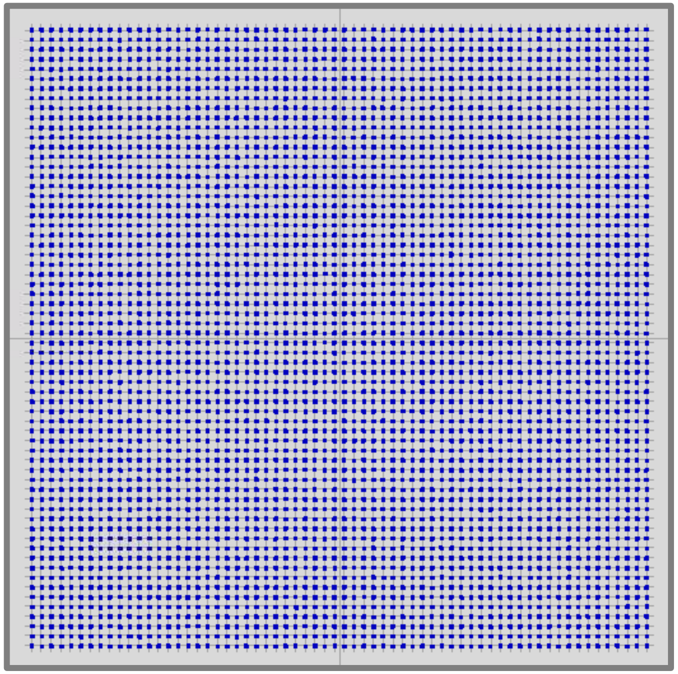
Increasing Phase Noise (16QAM)

Phase Noise
Digital Modulation Example – DOCSIS 3.1

- Cable internet standard is changing from 256QAM (single carrier) to 4096QAM (OFDM)
- Phase noise must be low enough to ensure <0.22% EVM (>53dB MER)



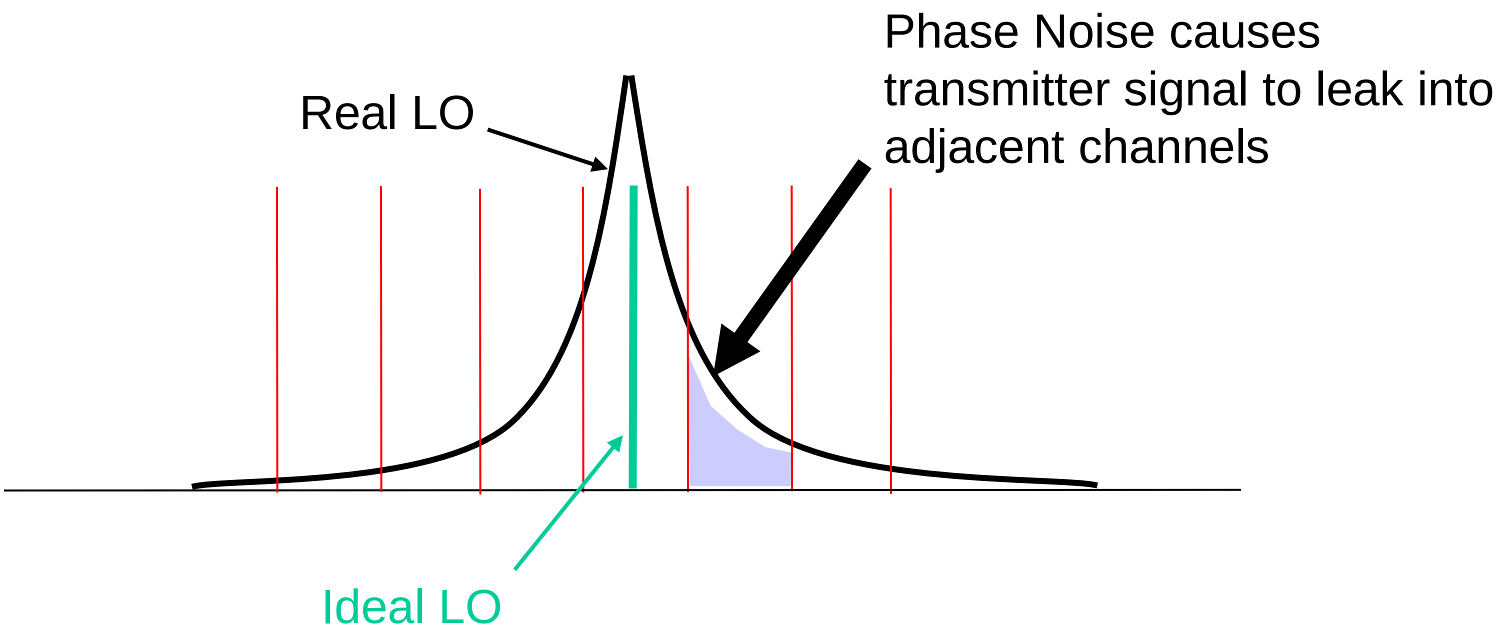
DOCSIS 3.0: 256 QAM



DOCSIS 3.1: 4096 QAM

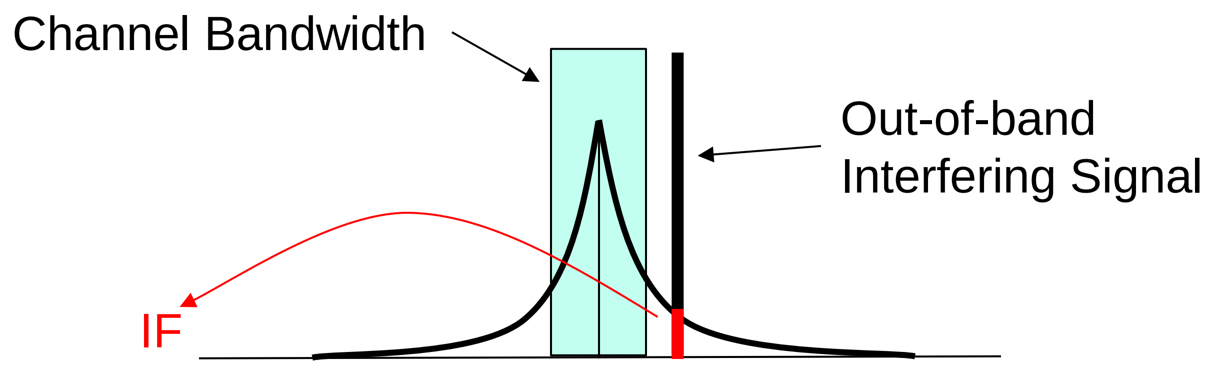
Phase Noise
Important in Communication Systems Transmitters

Adjacent Channel Power



Phase Noise
Important in Receivers

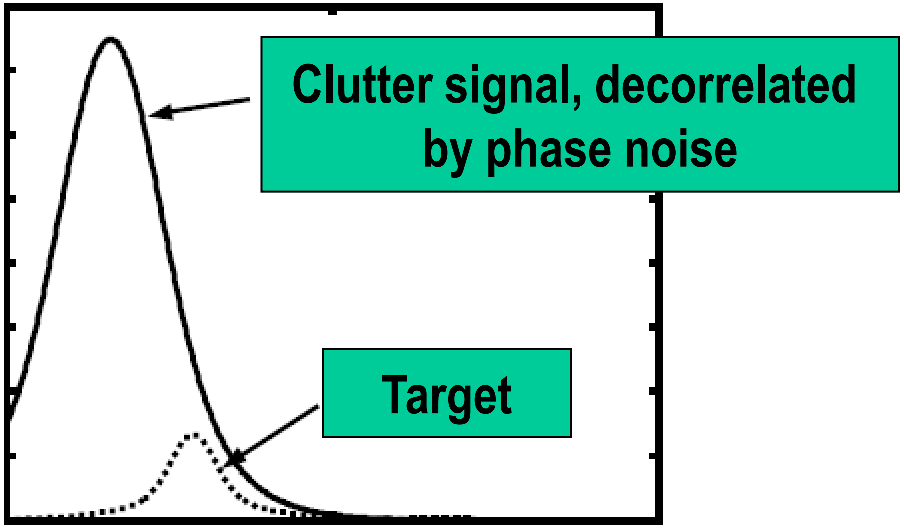
Sensitivity: Big interferer near the transmit channel



Large interferer mixes with LO energy spread by phase noise to produce a signal in the receiver IF – reduced sensitivity

Phase Noise
Important in Radar

Radar Applications – Moving Target Indication



$$f_d = \frac{-2f}{c} v_r$$

$f = 10\ GHz$

$v_r = 4\ km/hr$

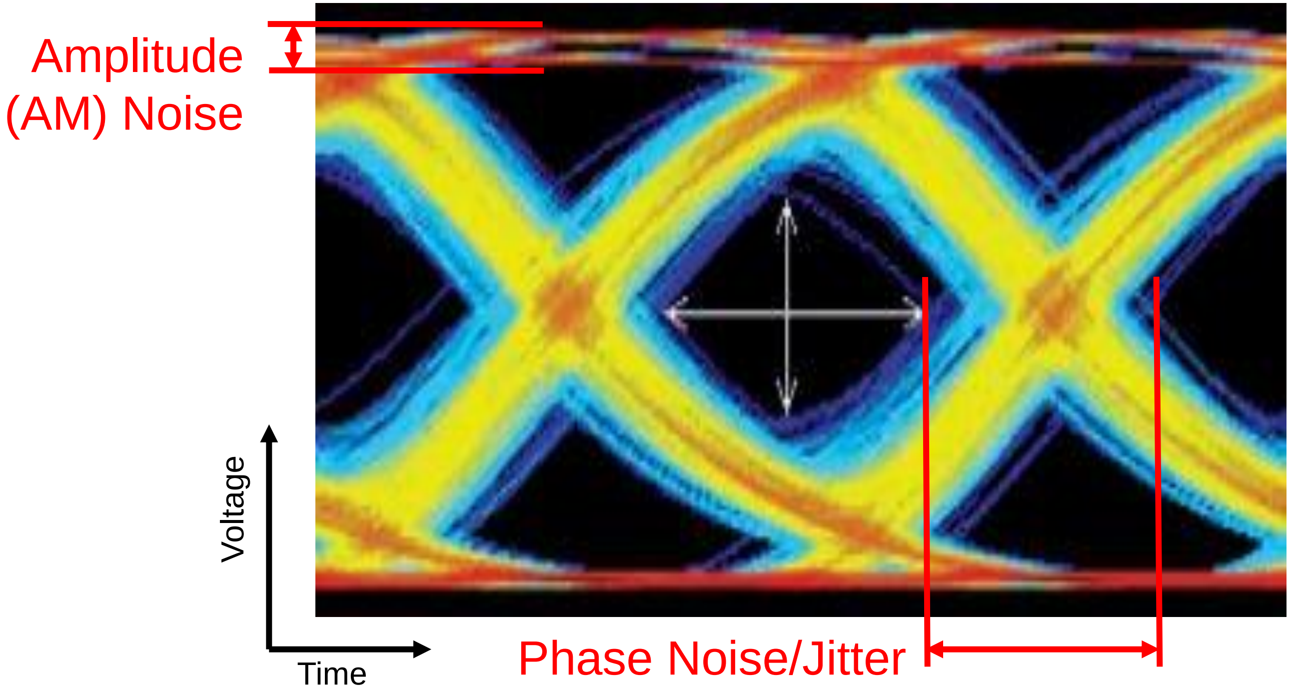
$c = 2.998e8\ m/s$

$f_d = 74\ Hz$

High phase noise in radar LO spreads clutter signal and masks desired low-level target response

Phase Noise
Important in Digital Systems

High Phase Noise = High Jitter



Digital Clock
Eye Diagram
on Oscilloscope

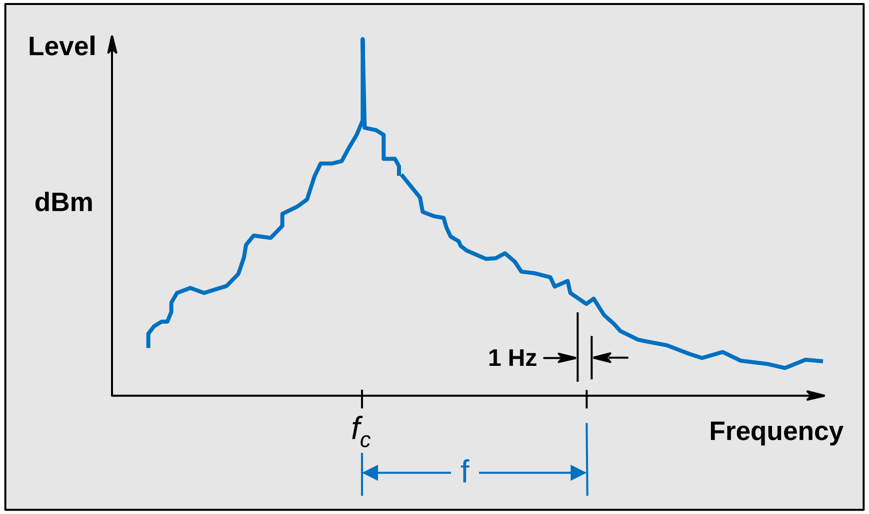
Jitter peaks can cause transmitted symbol errors which increased bit error rate and limits usable data rate

Quantifying Phase Noise

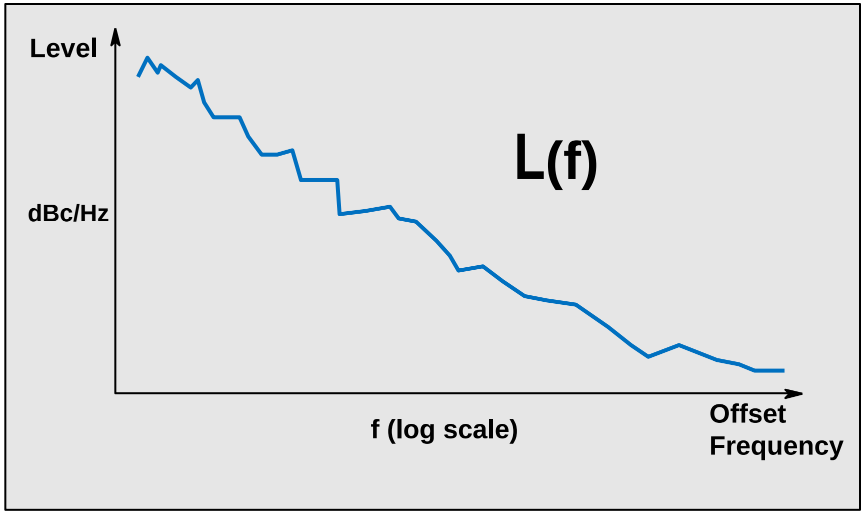
- Phase Noise Definition and Unit of Measure
- Residual Noise (Integrated Parameters)
  - Integrated Phase Noise
  - Residual PM
  - Residual FM
  - Jitter: Time and Frequency Domain Approaches

Phase Noise – Unit of Measure

- Phase Noise is expressed as L(f) (L(f) is pronounced "script L of F")
- L(f) has units of dBc/Hz
- Old definition: L(f) is the single sideband power due to phase fluctuations in a 1Hz bandwidth at a specified offset frequency, f, from the carrier



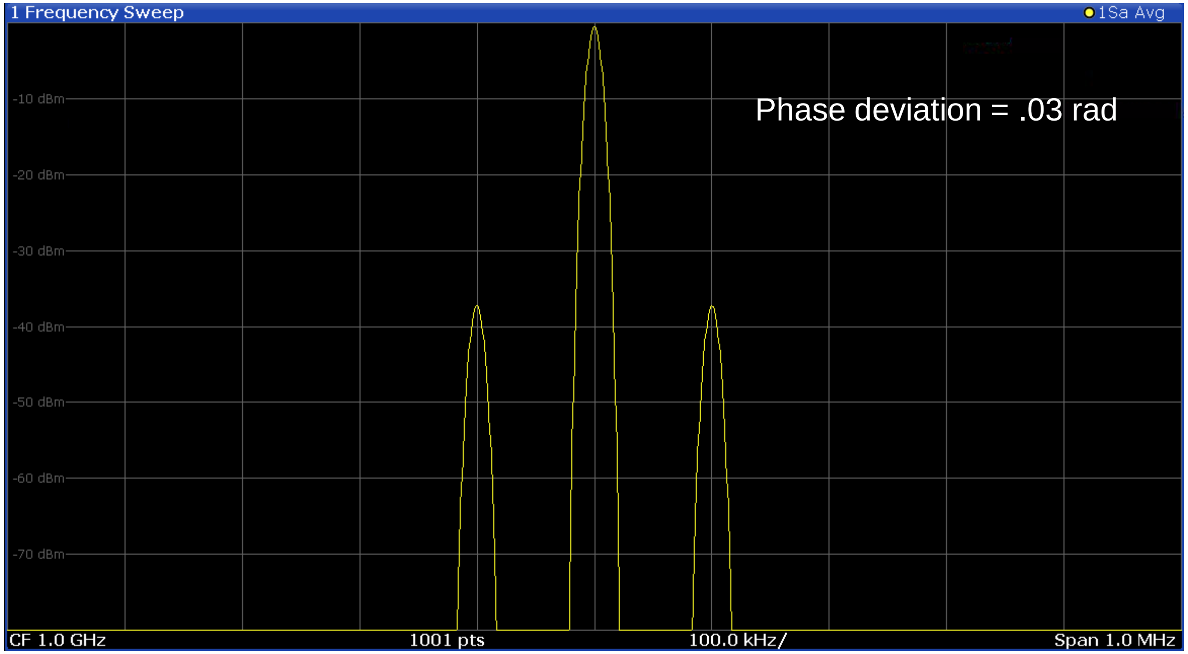
Spectrum View



Phase Noise Plot

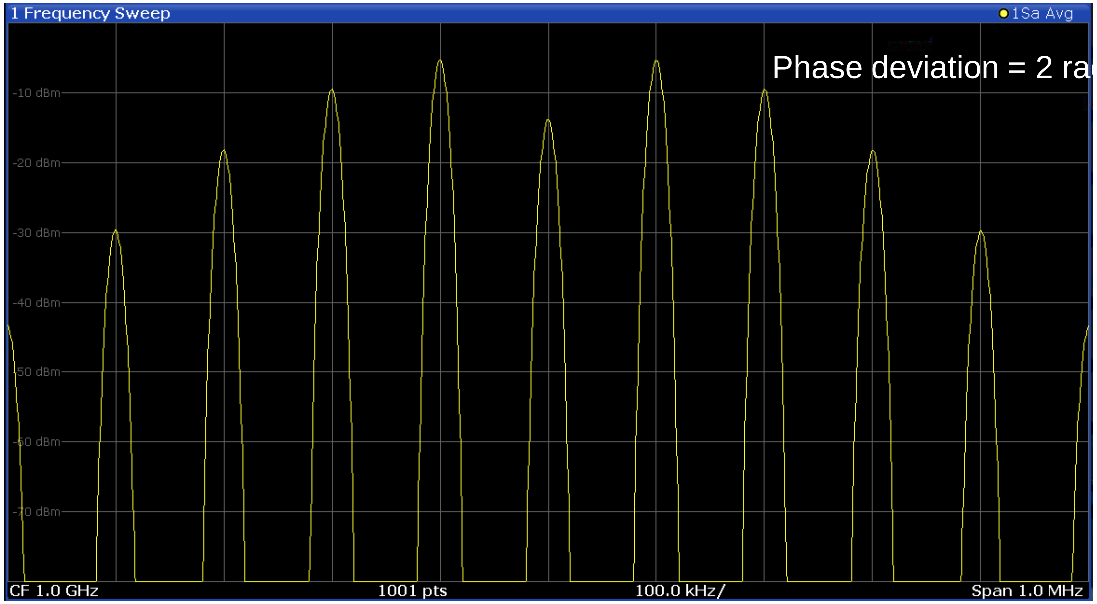
Narrowband Phase Modulation (CW)

- With low modulation index, virtually all sideband energy is in first sideband
- Sideband level is lower than carrier level



Wideband Phase Modulation (CW)

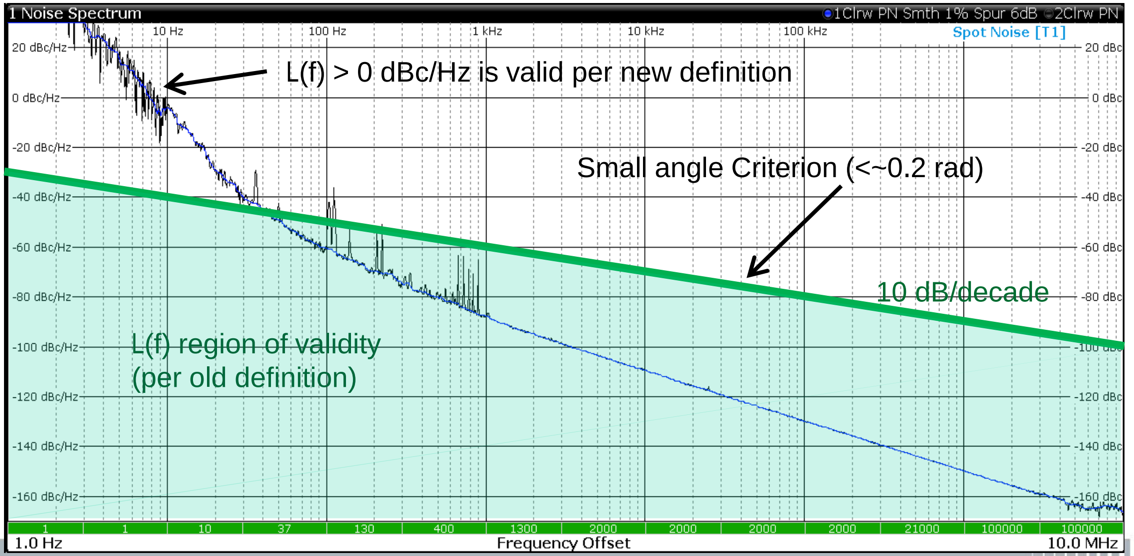
- With high modulation index, energy is in higher sidebands and total sideband energy is larger than carrier energy
- dBc levels >0 are possible
- Old phase noise definition not meaningful with very high levels of phase noise



Single Sideband Phase Noise

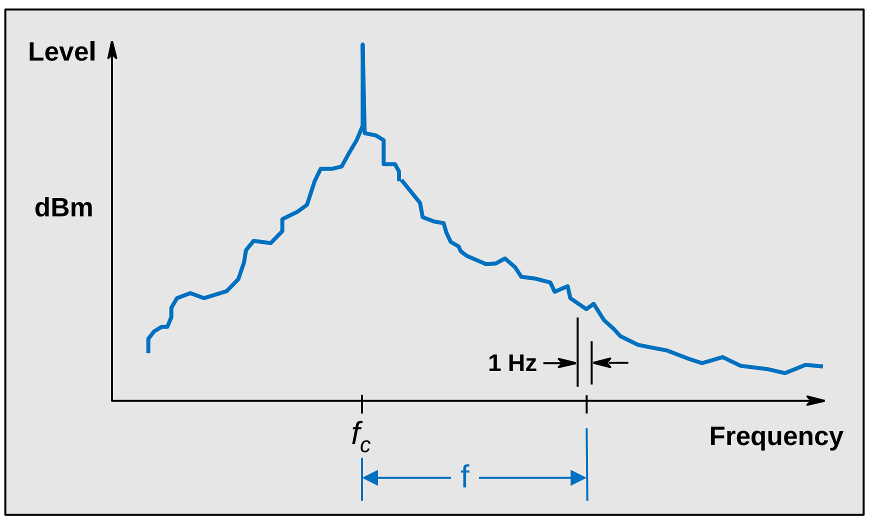
Region of Validity (per old Phase Noise Definition)

- Old phase noise definition:
  - Assumed phase noise energy in single sideband - not true for high phase noise
  - Required total phase deviation <0.2 rad (small angle criterion) for energy to be mostly in first sideband
- New definition includes ALL sideband energy – small angle criterion doesn't apply

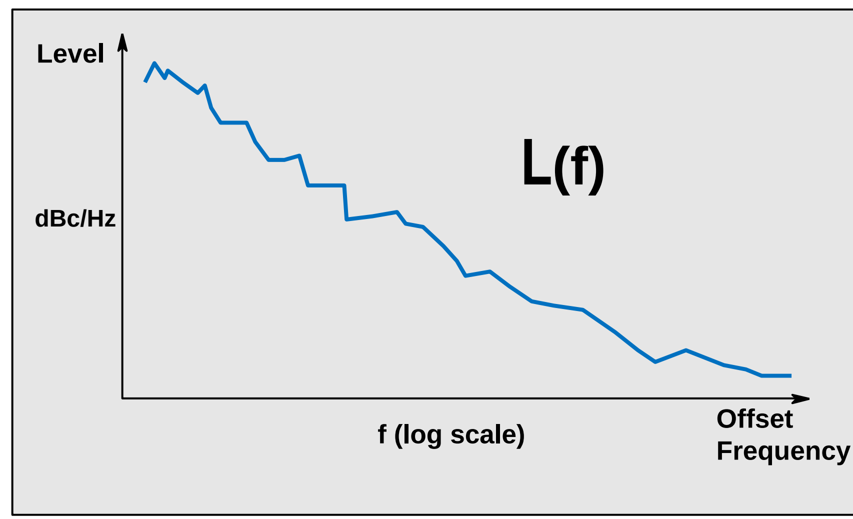


Phase Noise – Unit of Measure

- Phase Noise is expressed as $\mathcal{L}(f)$ ($\mathcal{L}(f)$ is pronounced "script L of F")
- $\mathcal{L}(f)$ has units of dBc/Hz
- Old definition: $\mathcal{L}(f)$ is the single sideband power due to phase fluctuations in a 1Hz bandwidth at a specified offset frequency, f, from the carrier
- New definition: $\mathcal{L}(f)$ is defined as one-half the spectral density of phase fluctuations, $\mathcal{L}(f) = ½ * S_{\phi}(f)$ (IEEE STD 1139-2008)

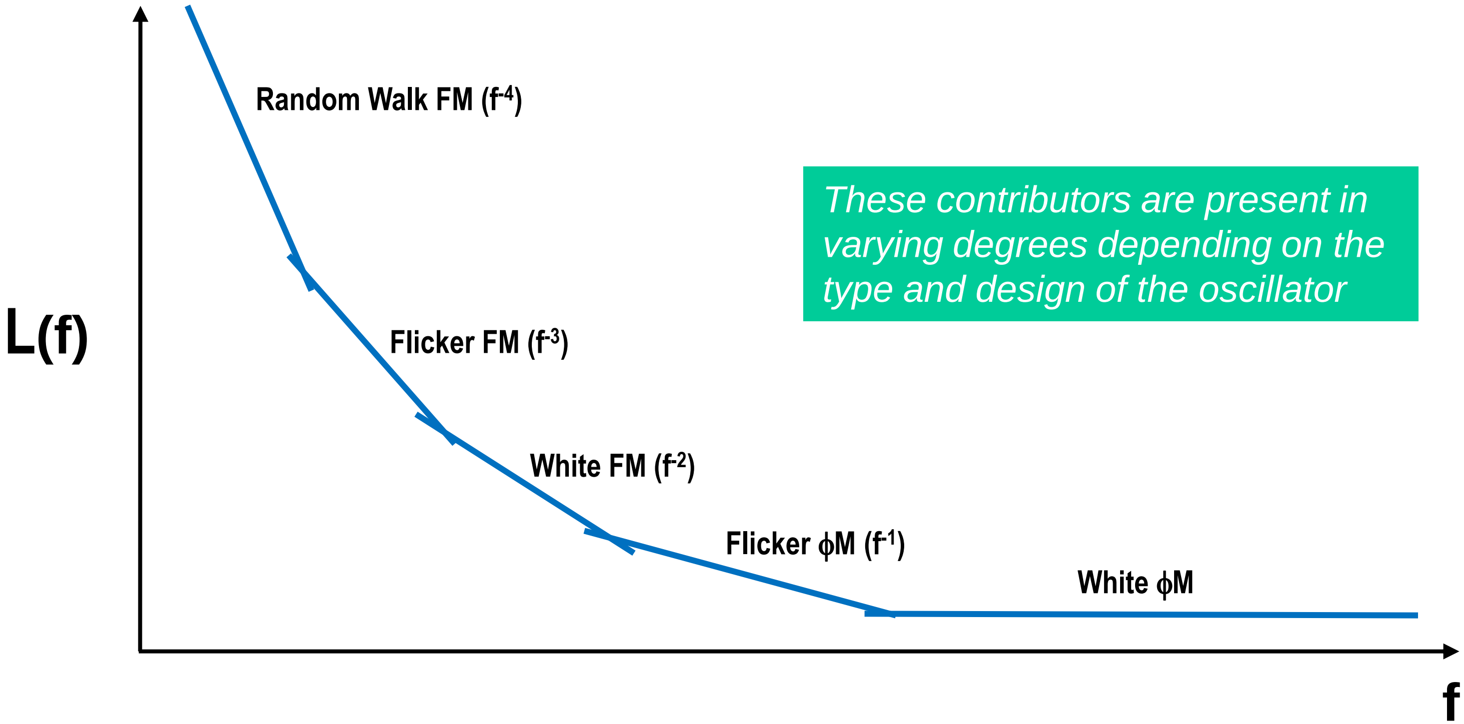


Spectrum View



Phase Noise Plot

Causes of Oscillator Phase Noise



Random Walk FM:	Close to carrier, generally caused by environmental effects
Flicker FM:	Related to active oscillator physical resonance mechanism, power supply noise
White FM:	Related to passive resonator oscillators
Flicker ϕM:	Related to noisy amplifiers and multipliers
White ϕM:	Far from carrier, generally caused by broadband output amplifier noise

Source: Lance, A., Seal, W., & Labaar, F. (1984). Infrared and Millimeter Waves, Vol. 11, Ch. 7

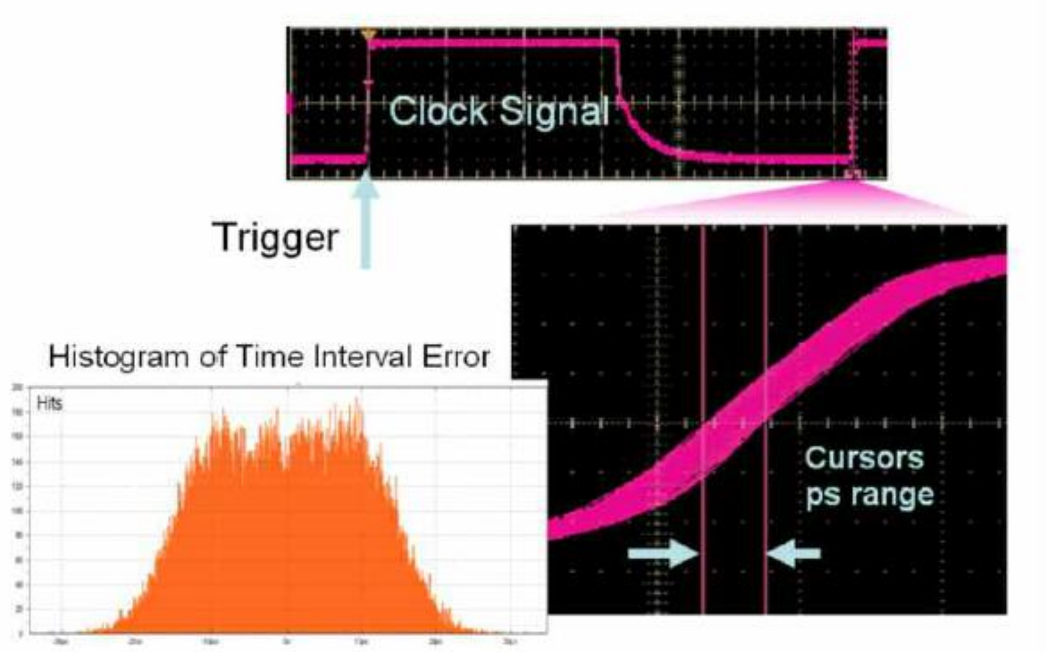
Residual / Integrated Noise

- 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 Residual Noise

Trace	Start Offset	Stop Offset	Int PHN	PM	FM	Jitter
T1	1.00 kHz	10.00 MHz	-77.46 dBc	10.85 m° / 189.39 µrad	544.60 Hz	30.14 fs

Jitter – Time Domain Approach



- Oscilloscopes measure jitter directly in the time domain, but the scope's internal jitter (phase noise) limits sensitivity to the range of picoseconds
- Some very high-end scopes can measure in the range of 100 femtoseconds, but are very expensive

Jitter – Frequency Domain Approach (Phase Noise)

- Jitter: $$\frac{1}{2\pi f_c}\sqrt{2\int \mathcal{L}(f)\,df}$$ Units of sec

2 Residual Noise

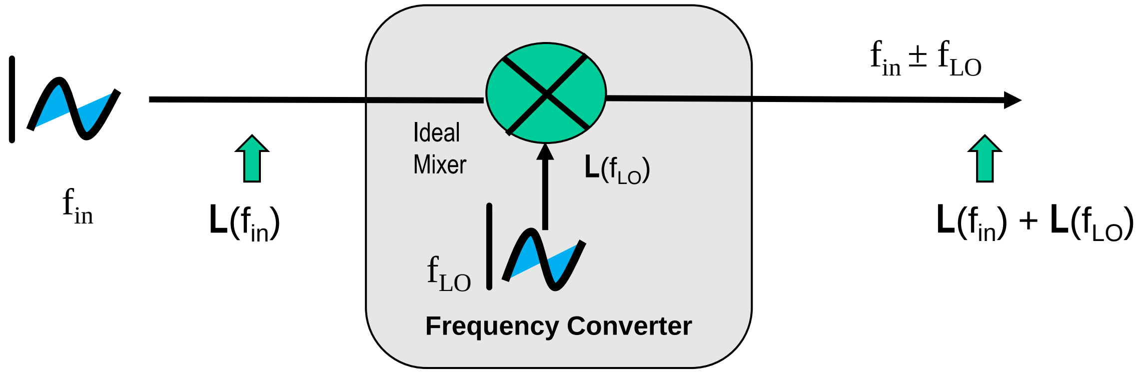
Trace	Start Offset	Stop Offset	Int PHN	PM	FM	Jitter
T1	1.00 kHz	10.00 MHz	-77.46 dBc	10.85 m° / 189.39 µrad	544.60 Hz	30.14 fs

- RMS Jitter can be calculated by integrating phase noise.
- Phase noise techniques can measure jitter with excellent sensitivity. Jitter measurements well below 10 femtoseconds (1 fs = 10^{-15} s) are possible (much more sensitive than an oscilloscope).
- Phase noise plot makes it easy to distinguish random and deterministic jitter (difficult using an oscilloscope).
- Only clocks can be measured, not random data streams.

Phase Noise of Frequency Multiplied Signals

- The Phase Noise of a signal passed through an ideal multiplier (one that adds no noise) will increase since a given amount of phase deviation represents a higher fraction of the smaller signal period
- This is expressed by: $\mathcal{L}(Nf) = 20\log(N) * \mathcal{L}(f)$
  - 2x → phase noise increases by 6dB
  - 10x → phase noise increases by 20dB
- Correspondingly, a frequency divider decreases the phase noise of a signal
  - ÷2 → phase noise decreases by 6dB
  - ÷10 → phase noise decreases by 20dB

Phase Noise of Frequency Converters



- The Phase Noise of a signal passed through an ideal frequency mixer (one that adds no noise) will increase by the phase noise of the LO
- The phase noise <u>increases</u> whether the input signal is up or down converted
- This is expressed by: $\mathbf{L}(f_{out}) = \mathbf{L}(f_{in}) + \mathbf{L}(f_{LO})$ (must add linear values, not dBc/Hz values)

Agenda

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- Phase Noise Measurement Techniques
  - Direct Spectrum Analyzer
  - Phase Detector
  - Phase Detector with Cross-Correlation
  - Delay Line Discriminator
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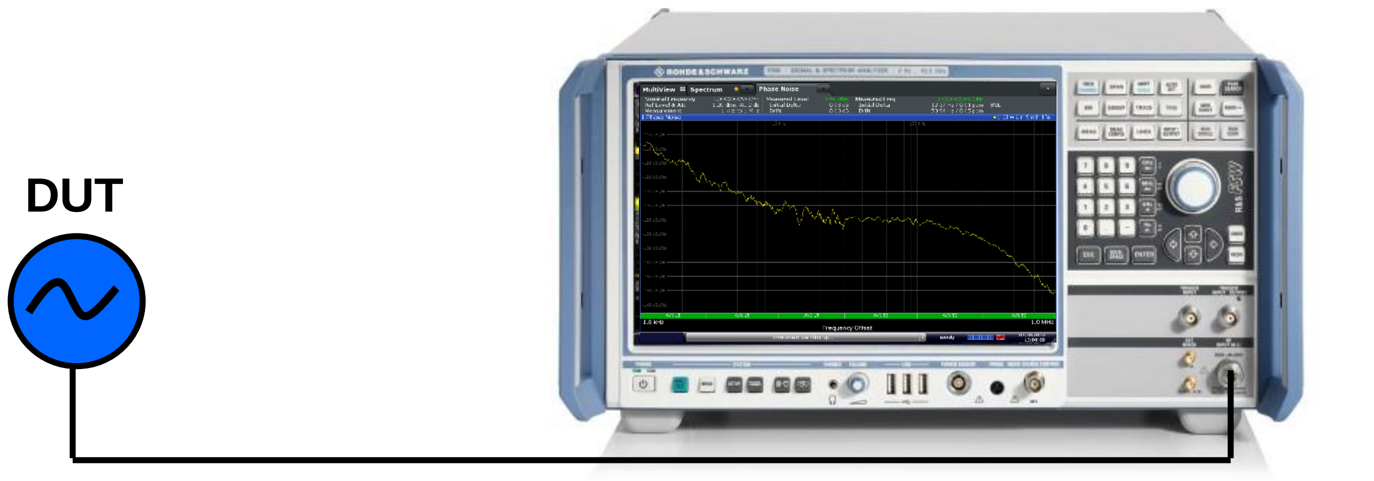
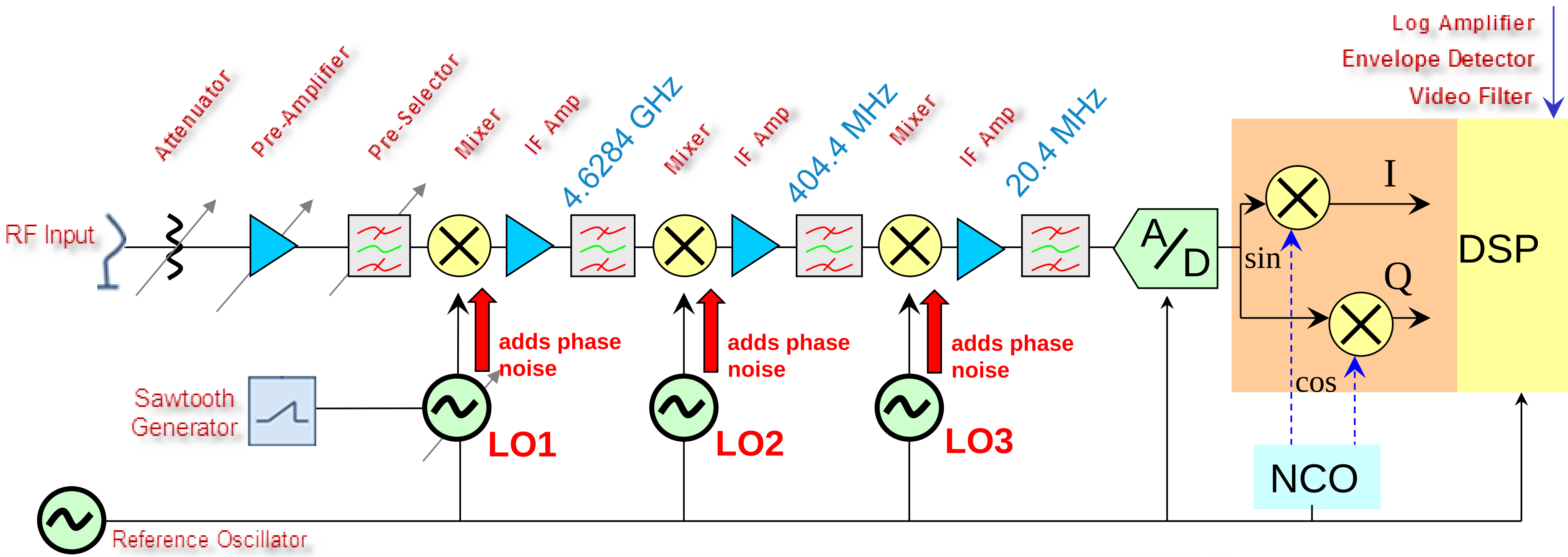
Direct Spectrum Analyzer



Simple setup, but how good is the measurement?

Direct Spectrum Analyzer

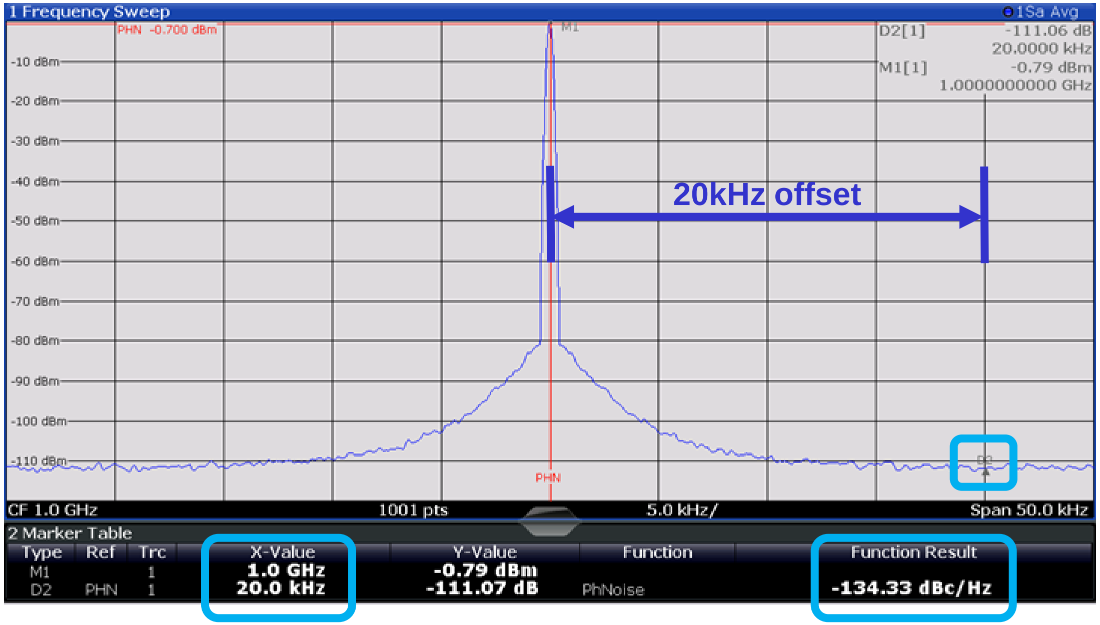
- Spectrum analyzer is a multistage receiver with multiple LOs
- Each LO adds phase noise to the input signal –
  Measurement result is the sum of phase noise from DUT and all LOs
- Full signal amplitude is present at every stage of the SA receiver – Measuring low level phase noise is limited by the SA's dynamic range
- SA minimum resolution bandwidth limits close-in offset



Direct Spectrum Analyzer
Manual Spot Noise Measurement

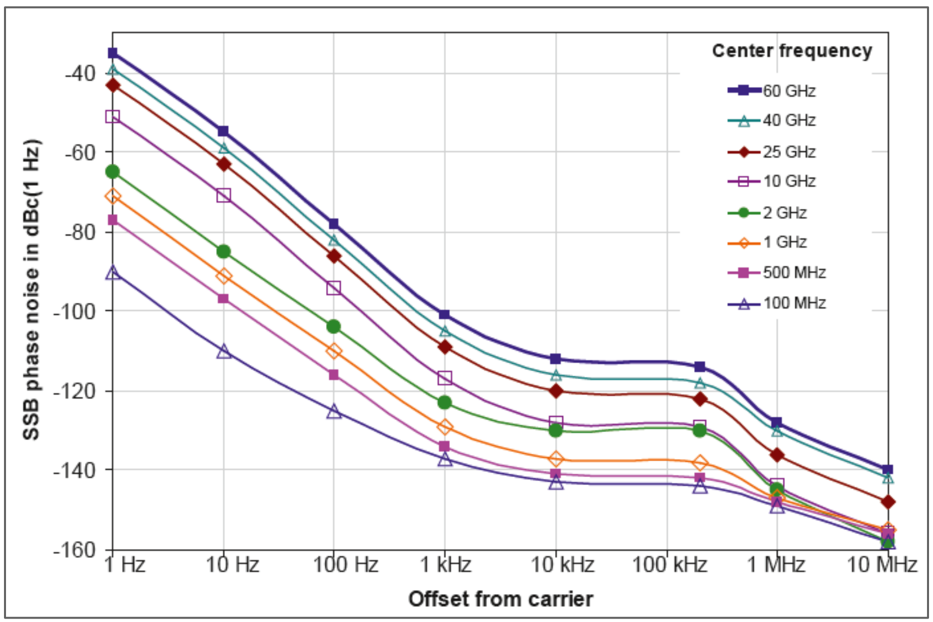
- Phase Noise Marker function corrects for ratio of RBW to 1Hz, 10log(RBW), and Effective Noise Bandwidth (ENB) of the RBW filter (typically <1dB)
- Must use proper detector and averaging type to get good measurement

- This technique is correct, but is the measurement accurate?
  - What about the noise of the analyzer?
  - What if we want a phase noise curve instead of a point measurement?
  - What about AM noise?
  - What if we want to measure closer than 1Hz to the carrier?



Direct Spectrum Analyzer

- 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 at least 10dB lower than DUT phase noise



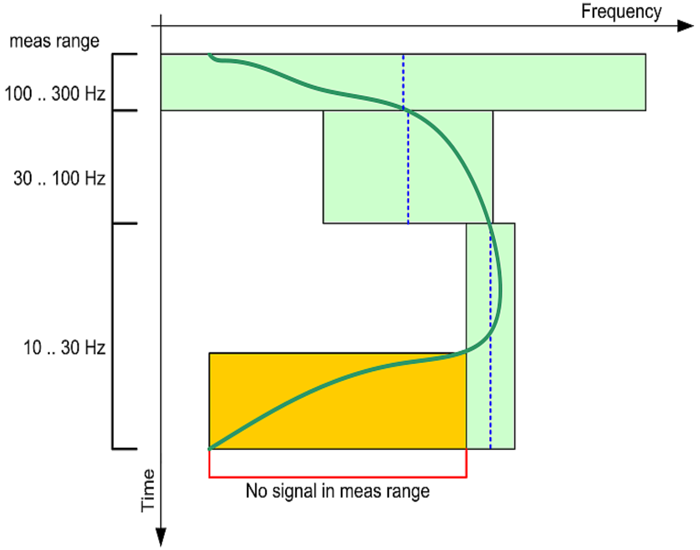
R&S FSW Spectrum Analyzer Phase Noise from Data Sheet

$L_{DUT} - L_{SA}$ (dB)	Meas Error (dB)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
10	0.4
15	0.1
20	0.04

Target Margin

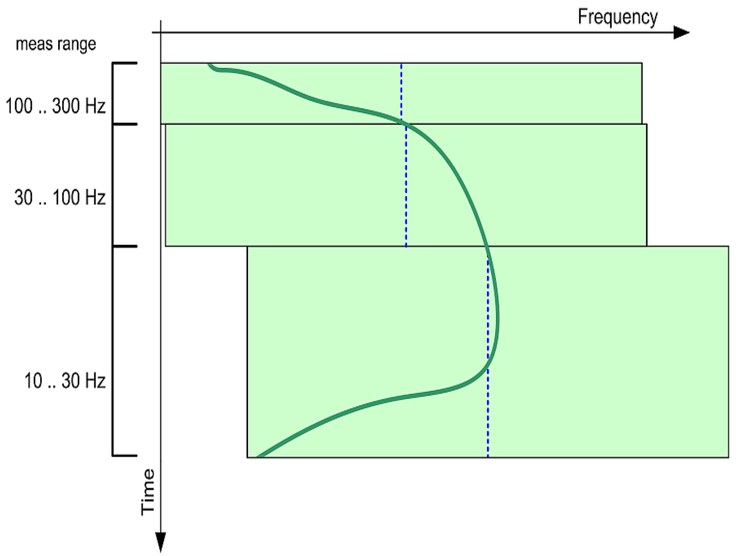
Direct Spectrum Analyzer
Drifting DUT using traditional approach

- Measurement is done in half-decade spans
- Center frequency re-tuning done at start of each half-decade
- Measurement bandwidth is reduced for each half-decade making measurement less tolerant of drift
- Close-in offsets take longer to measure which gives the signal more time to drift
- Measurement error occurs if DUT drifts out of RBW filter



Direct Spectrum Analyzer
Drifting DUT using advanced IQ capture/DSP approach

- Measurement is still done in half-decade spans
- Signal is captured with wider IQ bandwidth in all half-decades
- Drifting signal stays within captured bandwidth
- Bandwidth reduction done in DSP
- Drift is tracked using digital PLL
- Even drifting signal is measured correctly
- Additional benefit: IQ capture approach also provides AM rejection



Direct Spectrum Analyzer – Summary

Advantages

- Fast and easy measurement setup
- High offset frequency range (up to 30GHz)
- Spectrum Analyzer can make many other signal measurements:
  - Harmonics
  - ACPR
  - Spurious emissions, etc.

Limitations

- Sensitivity is limited by phase noise of the internal LO's in the instrument
- Sensitivity also limited by dynamic range since low level noise must be measured in the presence of the carrier
- Most SA's cannot reject AM noise
- Lower offset frequency is limited to 1Hz due to minimum 1Hz RBW

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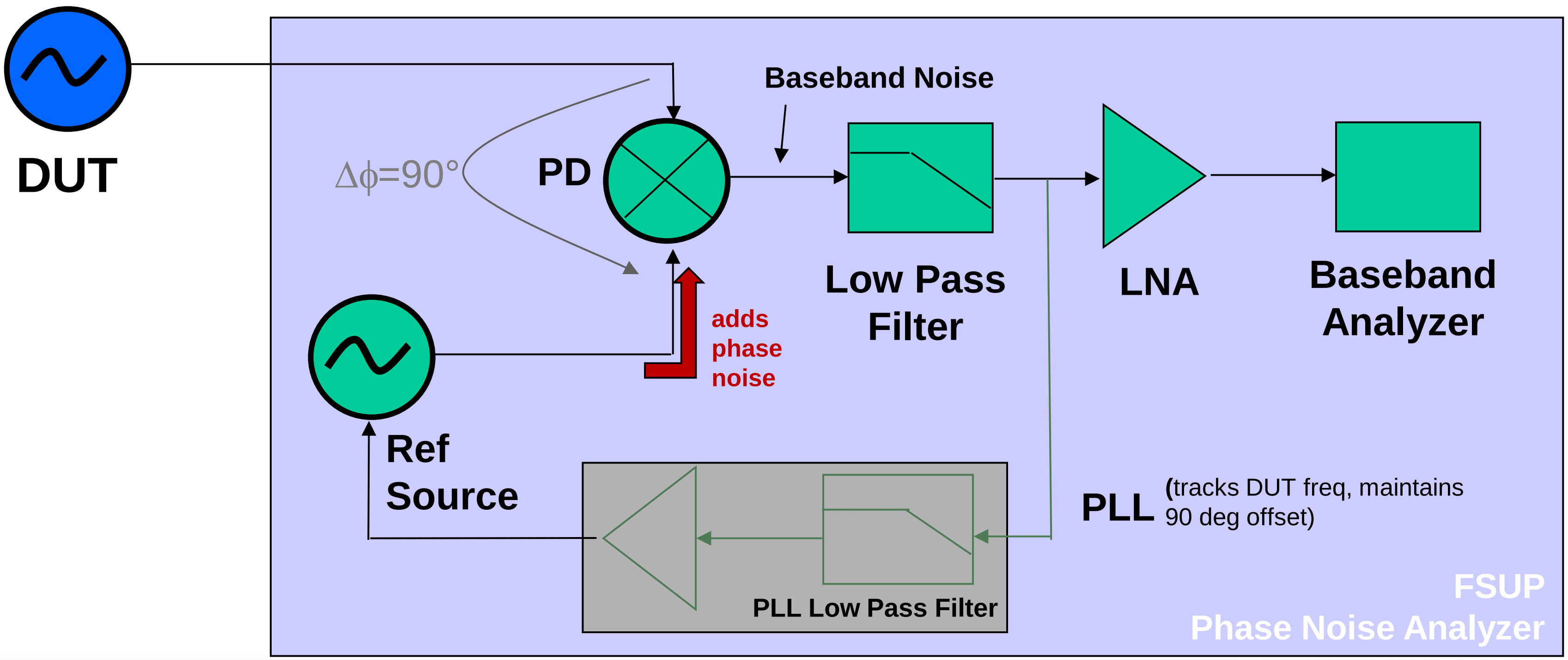
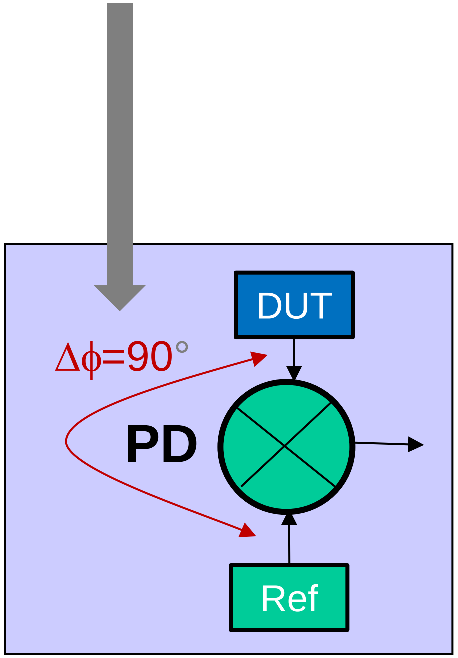
Phase Detector

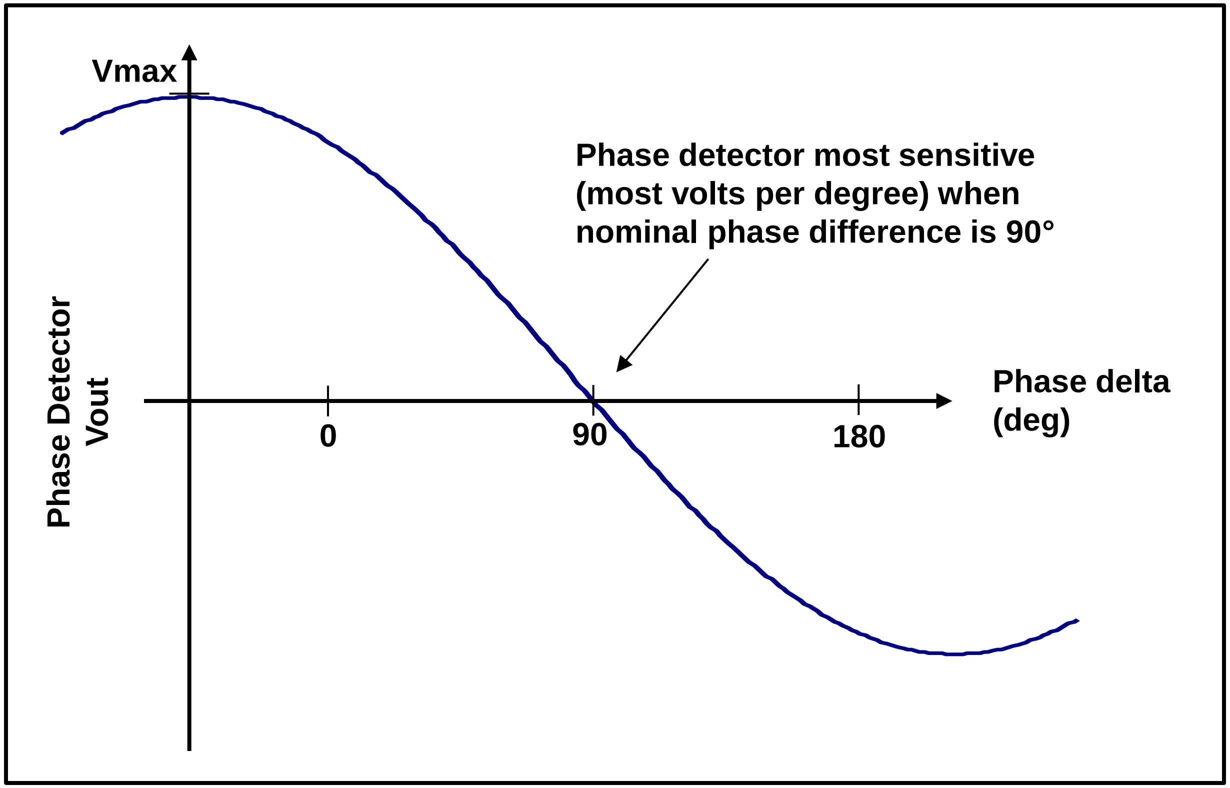
- Phase Detector converts phase fluctuations to voltage fluctuations
- Only Ref Source phase noise adds to signal's phase noise
- Main carrier energy is removed by Phase Detector (PD) and LPF
- LNA and Baseband Analyzer measure noise signal with high sensitivity
- PD provides AM noise rejection
- Offsets closer than 1Hz can be measured (down to 0.01Hz)



Phase Detector

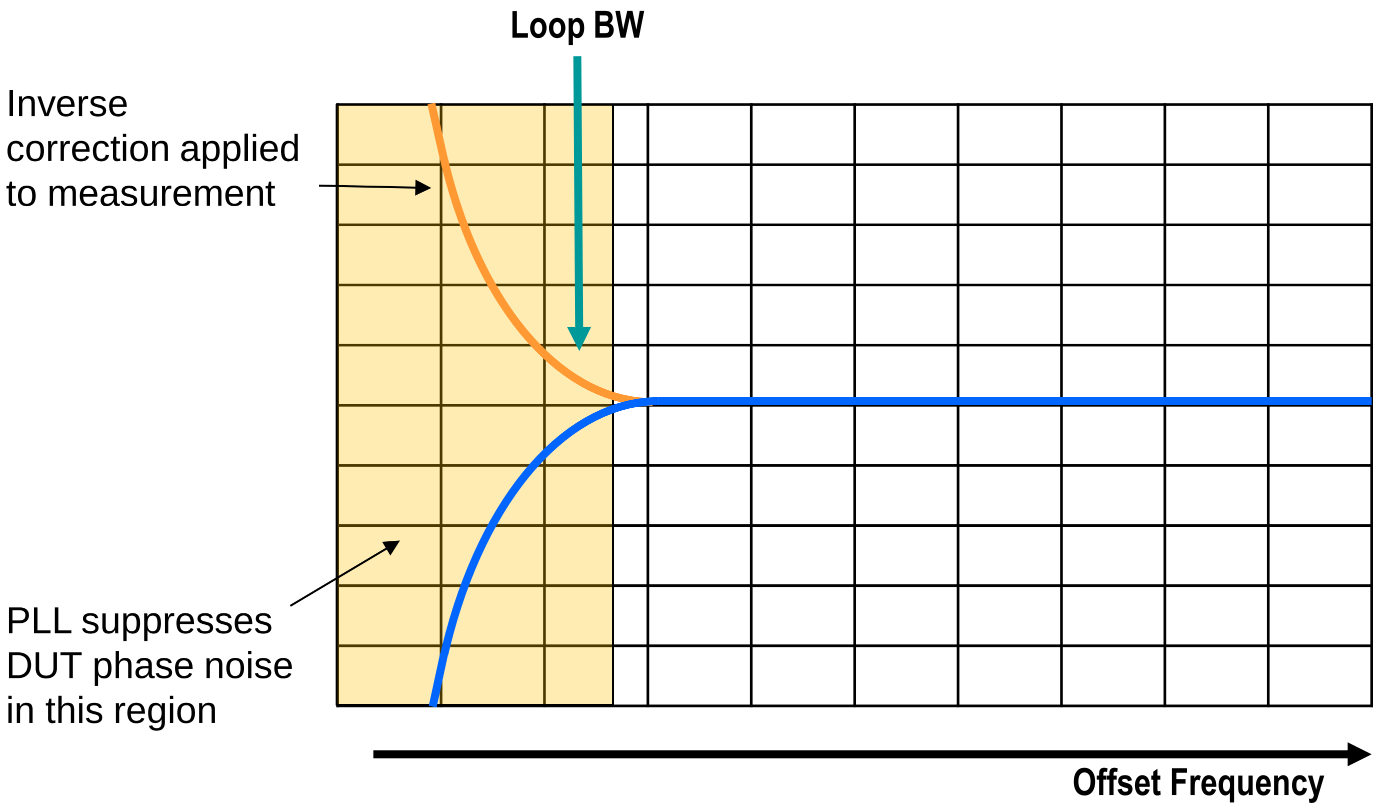
Why offset DUT and Reference by 90°?





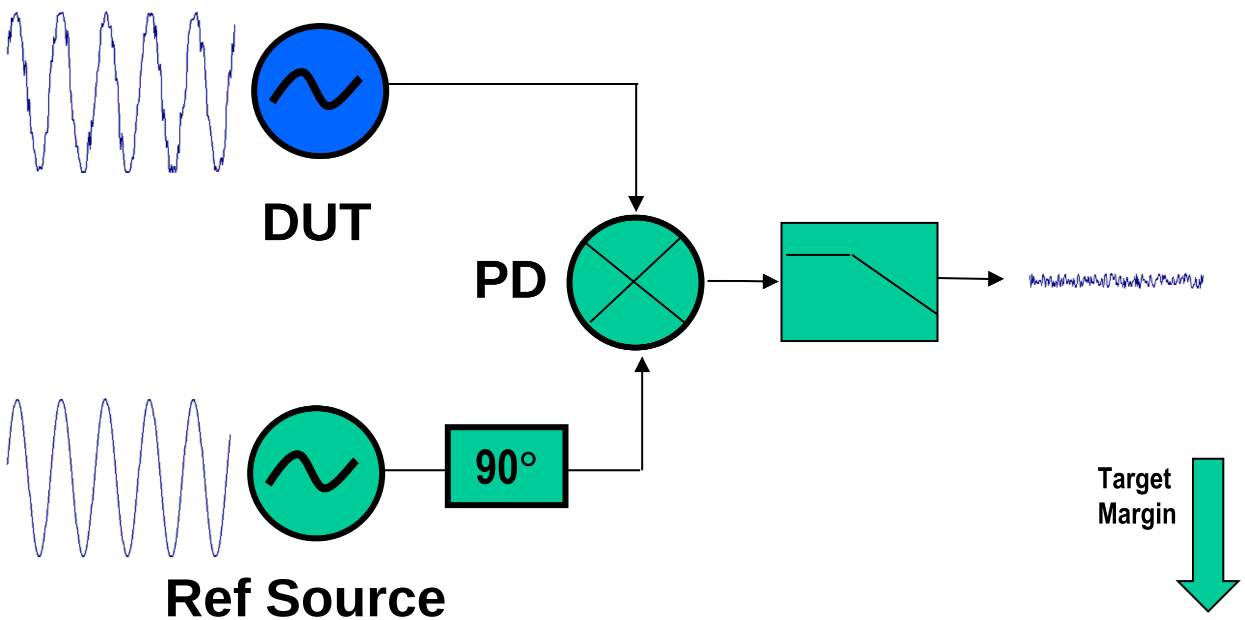
Phase Detector

- PLL bandwidth set as low as possible and still track DUT drift
- Phase noise at offsets below PLL loop bandwidth is suppressed by the PLL
- Measurement system applies inverse correction curve to measured values
- High uncertainty at low offsets more than 1-2 decades below loop BW



Phase Detector

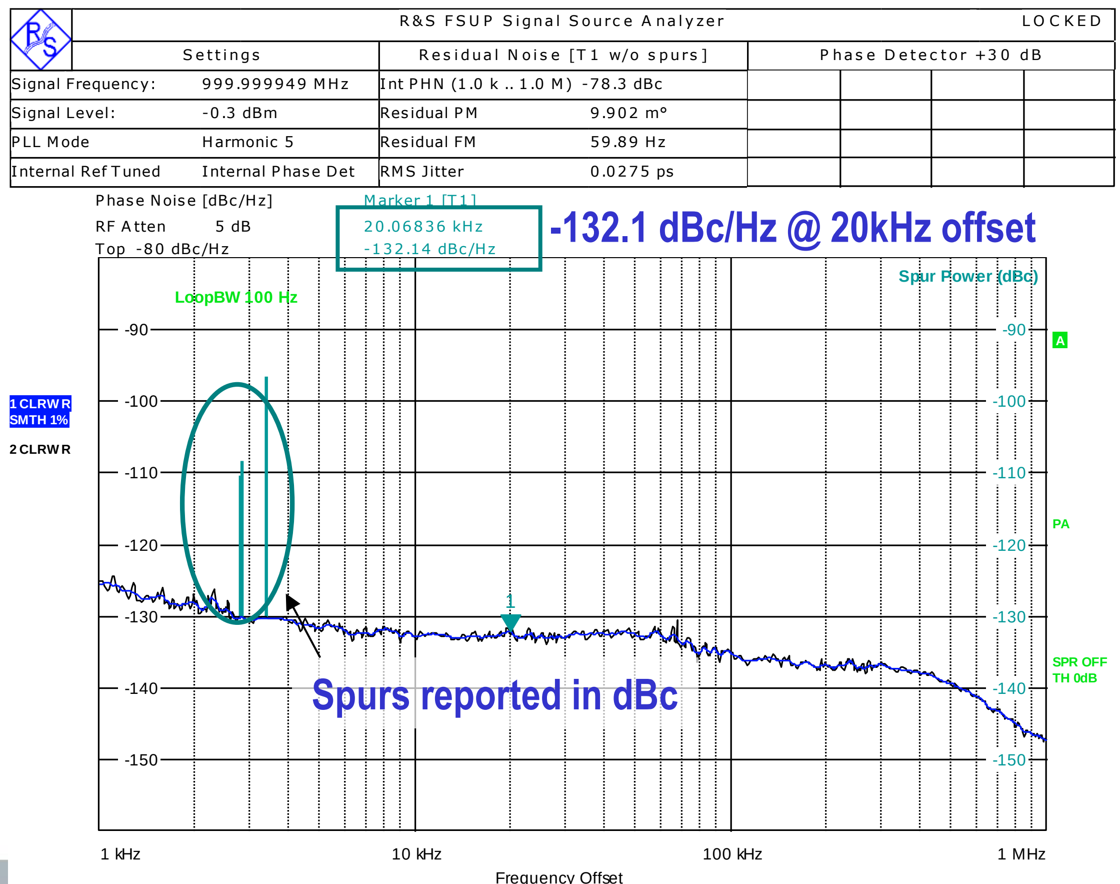
- Phase detector approach has better sensitivity than direct spectrum analyzer method, but same relationship between DUT noise and instrument noise applies
- Must check instrument phase noise spec to validate measurement
- Still want at least 10dB margin, if possible



$L_{DUT} - L_{REF}$ (dB)	Meas Error (dB)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
10	0.4
15	0.1
20	0.04

Phase Detector

- Same presentation of results as with Spectrum Analyzer measurement.
- Phase Noise curve, Spot Noise, and Residual calculations are available.
- Spur detection algorithm displays and reports spurs separately (in dBc).



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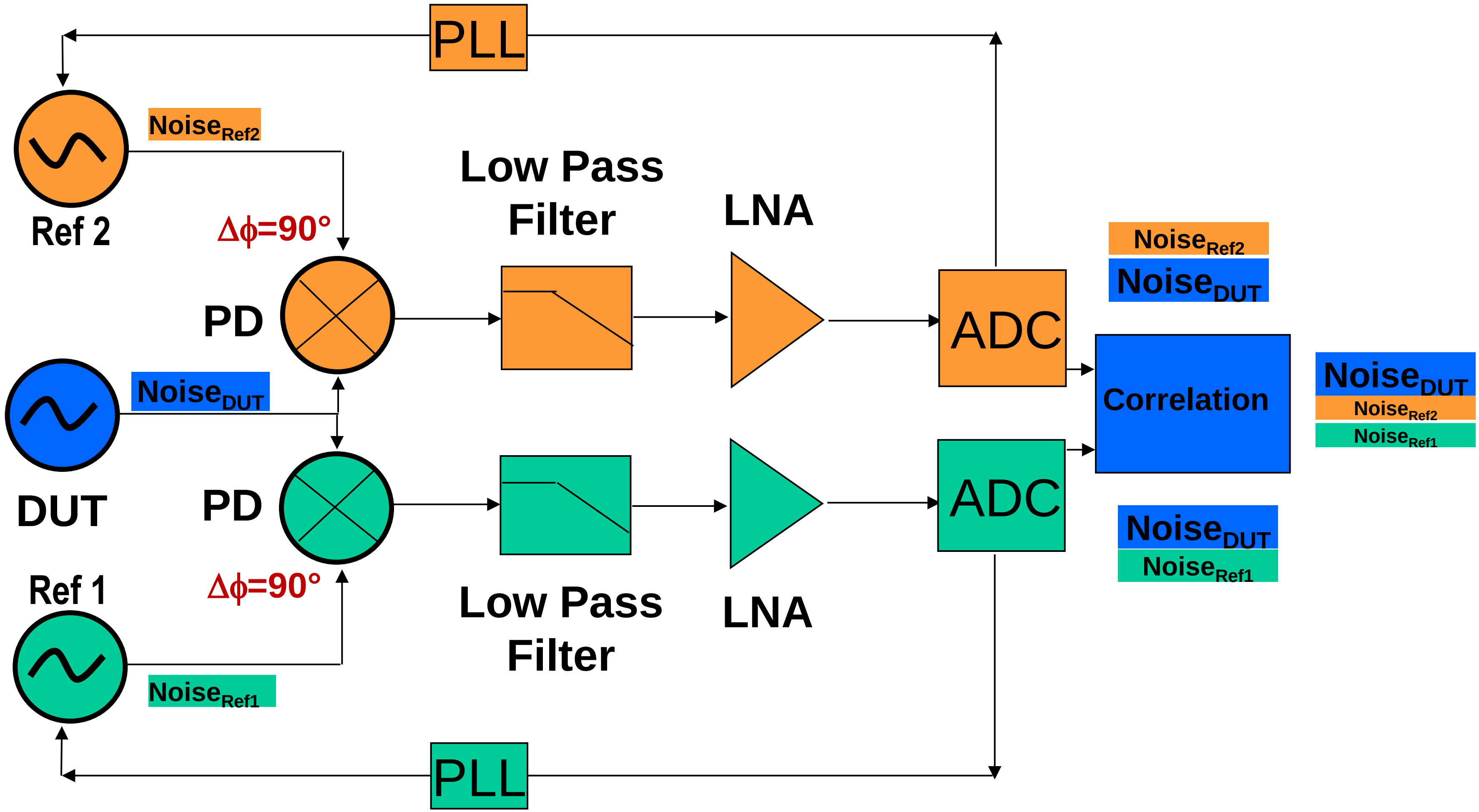
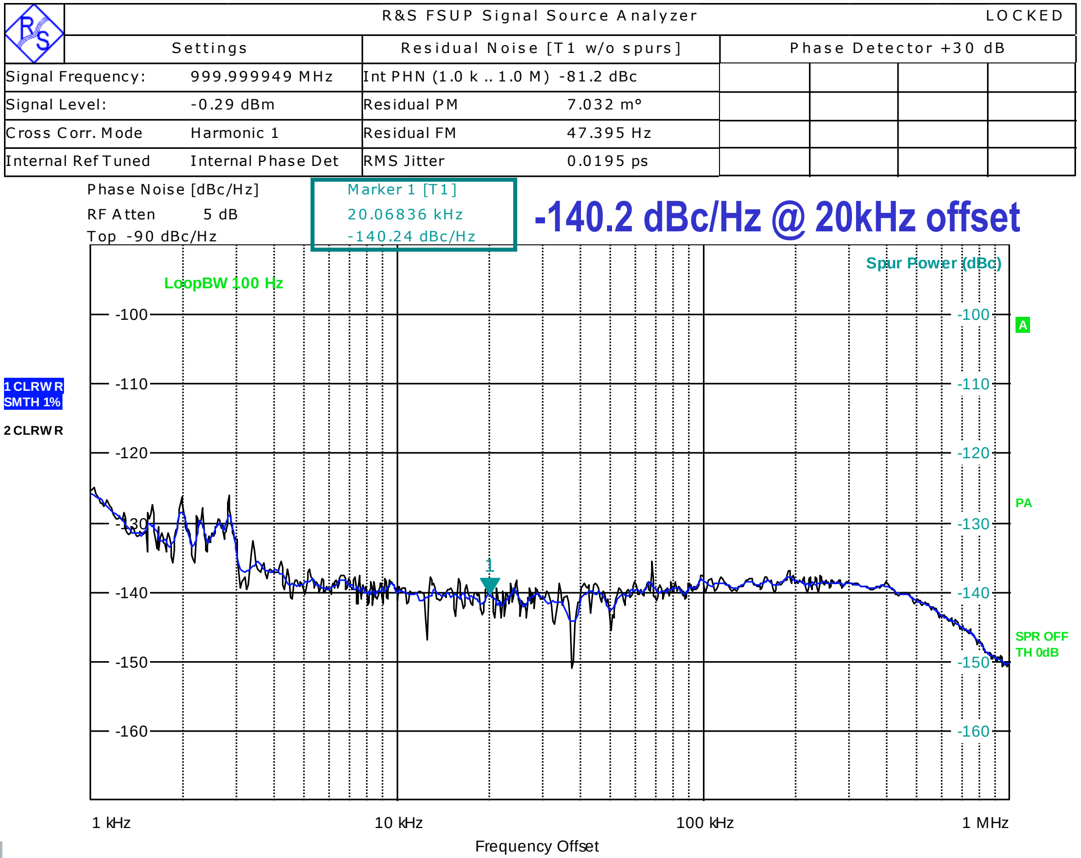
Phase Detector with Cross-Correlation



- Uncorrelated noise from Ref 1 and Ref 2 is suppressed by the cross-correlation function
  - Ref Noise Suppression: 10dB for 100 CC, 20dB for 10000 CC
- DUT noise is common to both paths and is unaffected by cross-correlation

Phase Detector with Cross-Correlation

- Same presentation of measured data
- CC effectively reduces the phase noise of the reference source
- Improves sensitivity over single reference source by up to 20dB



Phase Detector Method – Summary

Advantages

- Carrier is suppressed so analyzer dynamic range is not a limiting factor as it can be with the spectrum analyzer method
- Measurements at very small offsets are possible (down to 0.01Hz)
- Phase Detector has inherent AM suppression
- Cross-Correlation improves the sensitivity of the test system
  - 10dB for CC=100 , 20dB for CC=10000

$$cross\ corr_{improvement} = 10log_{10}(\sqrt{n})$$

Limitations

- Restricted upper offset range (limited by bandwidth of baseband analyzer)
- Spectrum Analyzer is still necessary for measurement of other parameters:
  - Spurious Emissions, ACPR, Harmonics

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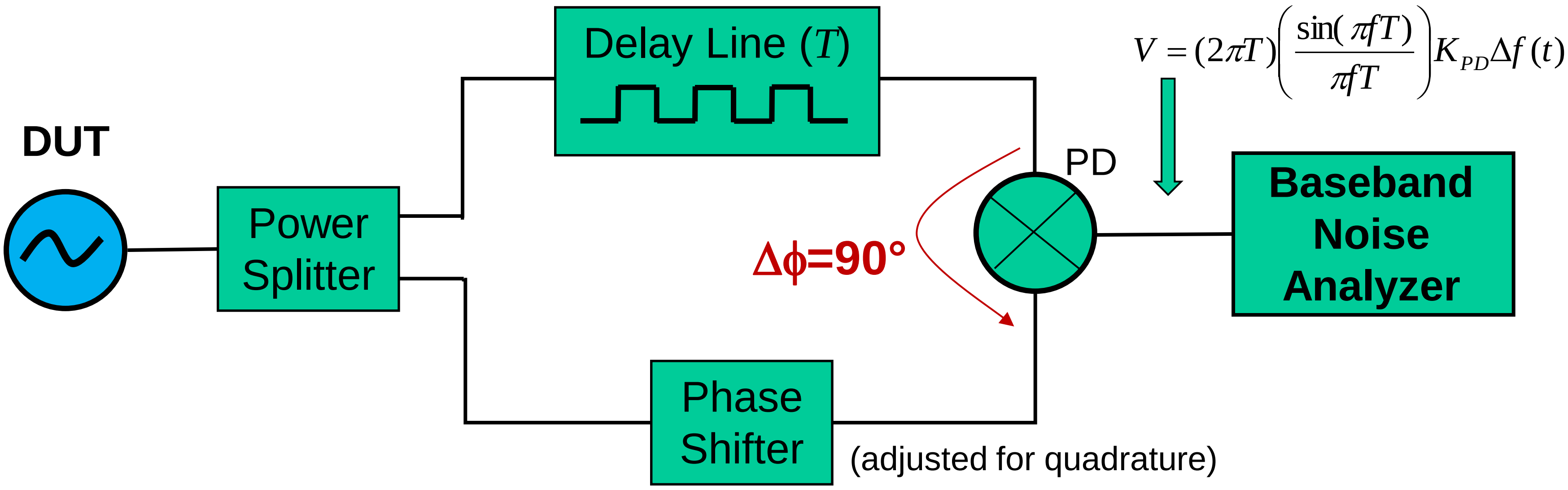
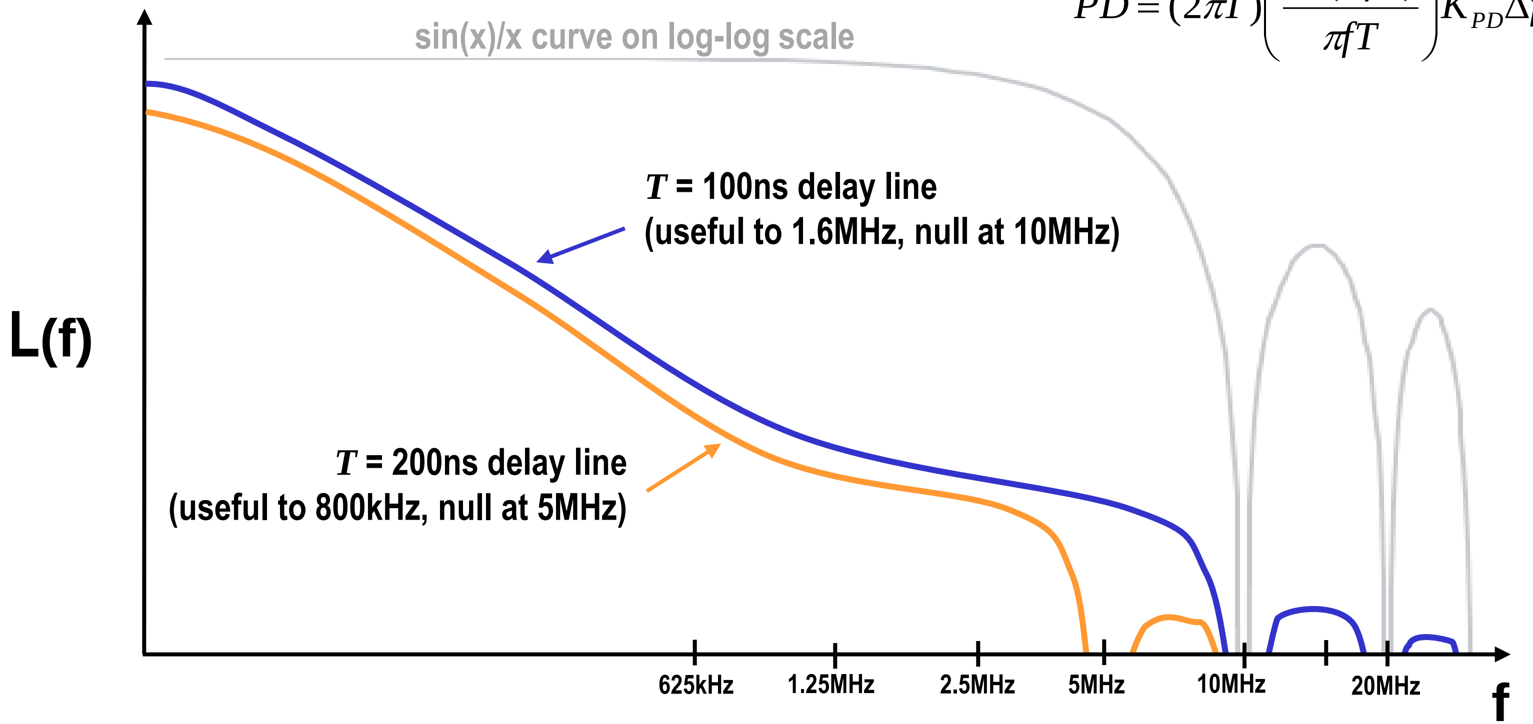
Delay Line Discriminator



- The delay line converts frequency fluctuations to phase fluctuations, then the phase detector converts the phase fluctuations to voltage fluctuations
- No reference source required – good for noisy or drifting DUTs
- Maximum offset limited to ~$1/(2\pi T)$ due to sin(x)/x term (max offset 1MHz for T = 160ns)
- Longer delay (T) gives better sensitivity, but reduces maximum usable offset
- Longer delay line also has higher loss which reduces PD sensitivity
- Manual adjustment of phase shifter over 180° required for calibration

Delay Line Discriminator

$$PD = (2\pi T)\left(\frac{\sin(\pi f T)}{\pi f T}\right) K_{PD} \Delta f(t)$$



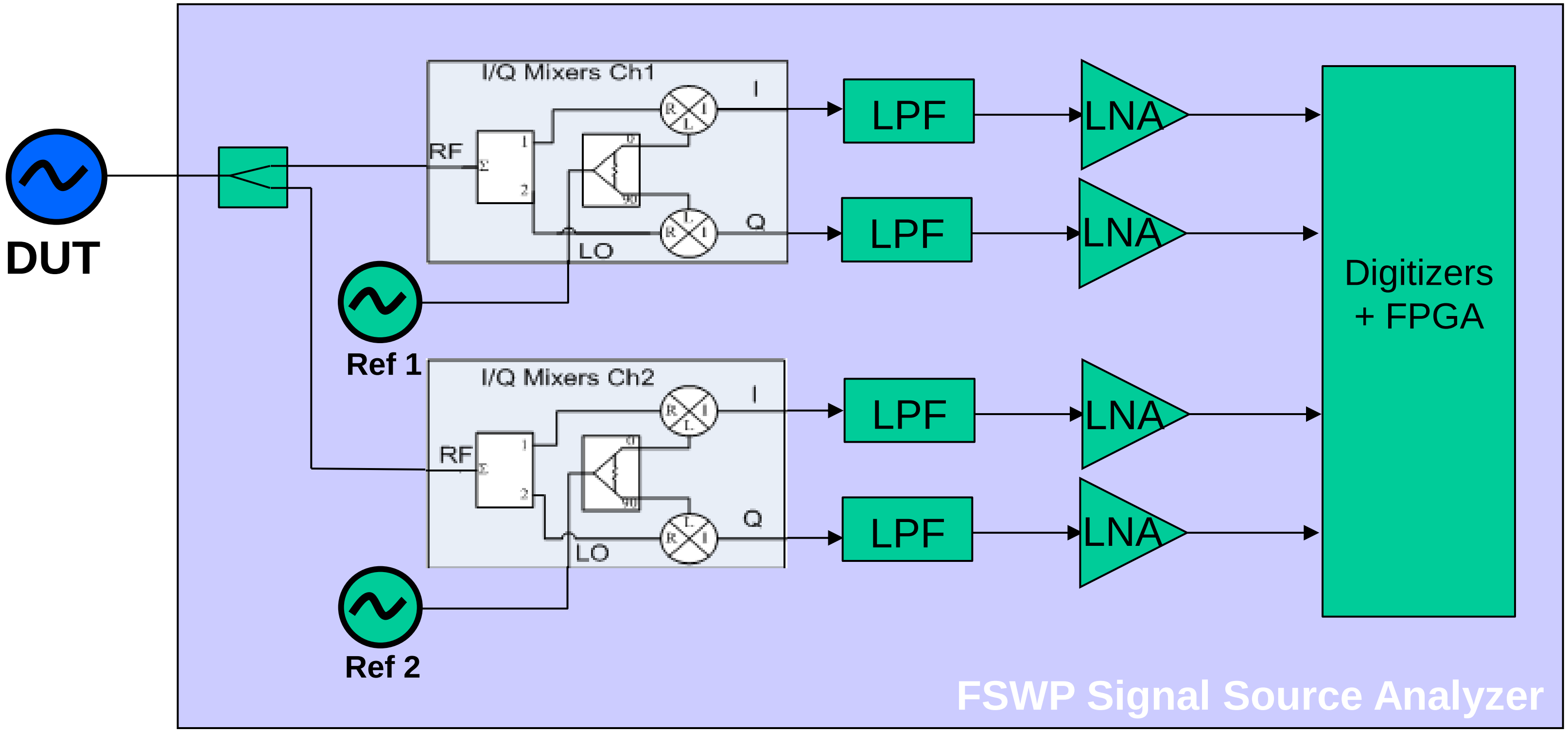
- First measurement null occurs at f = $1/T$
- Useful offset range up to f ≈ $1/(2\pi T)$
- Longer delay line gives better sensitivity, but reduces upper offset limit

Agenda

- Phase Noise Review
- Phase Noise Measurement Techniques
  - Direct Spectrum Analyzer
  - Phase Detector
  - Phase Detector with Cross-Correlation
  - Delay Line Discriminator
  - Digital Phase Demodulator
- Additive Phase Noise
- Pulsed Phase Noise
- AM Noise
- VCO Measurements
- Summary

Digital Phase Demodulator

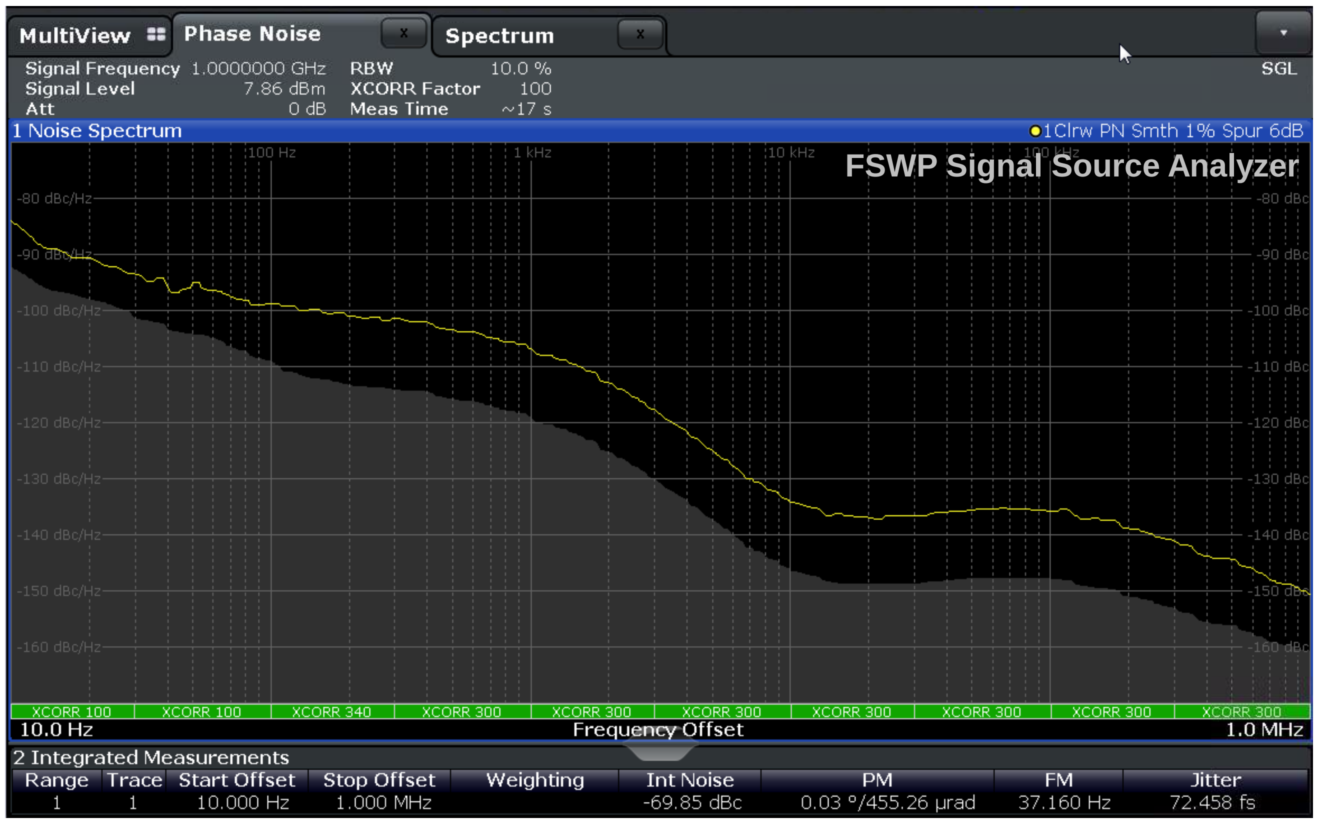
- Different approach to measurement with many advantages
  - Phase noise measured from demodulated PM
  - No phase detector or PLL – no loop BW correction, greatly simplified calibration
  - Easy measurement of absolute, pulsed, additive, and pulsed additive phase noise
  - Very low-noise Ref Sources and high-speed cross correlation to increase sensitivity



Digital Phase Demodulator

- Measurement speed improvement of >10x over traditional techniques
- High sensitivity measurement from 10Hz – 1MHz in less than 20s
- Can measure frequency offsets from 0.01Hz to 300MHz

Shaded gray area shows cross-correlation gain which indicates measurement floor for instant verification of measurement margin



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- Phase Noise Review
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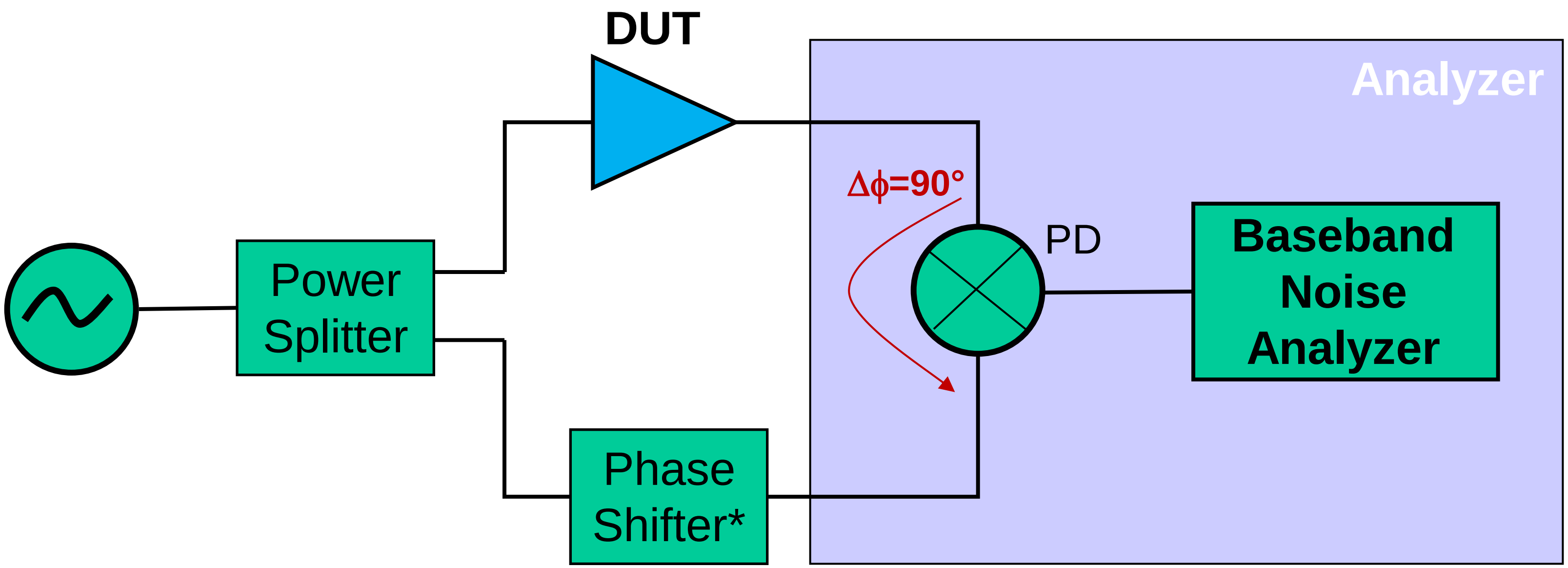
Additive Phase Noise – Phase Detector

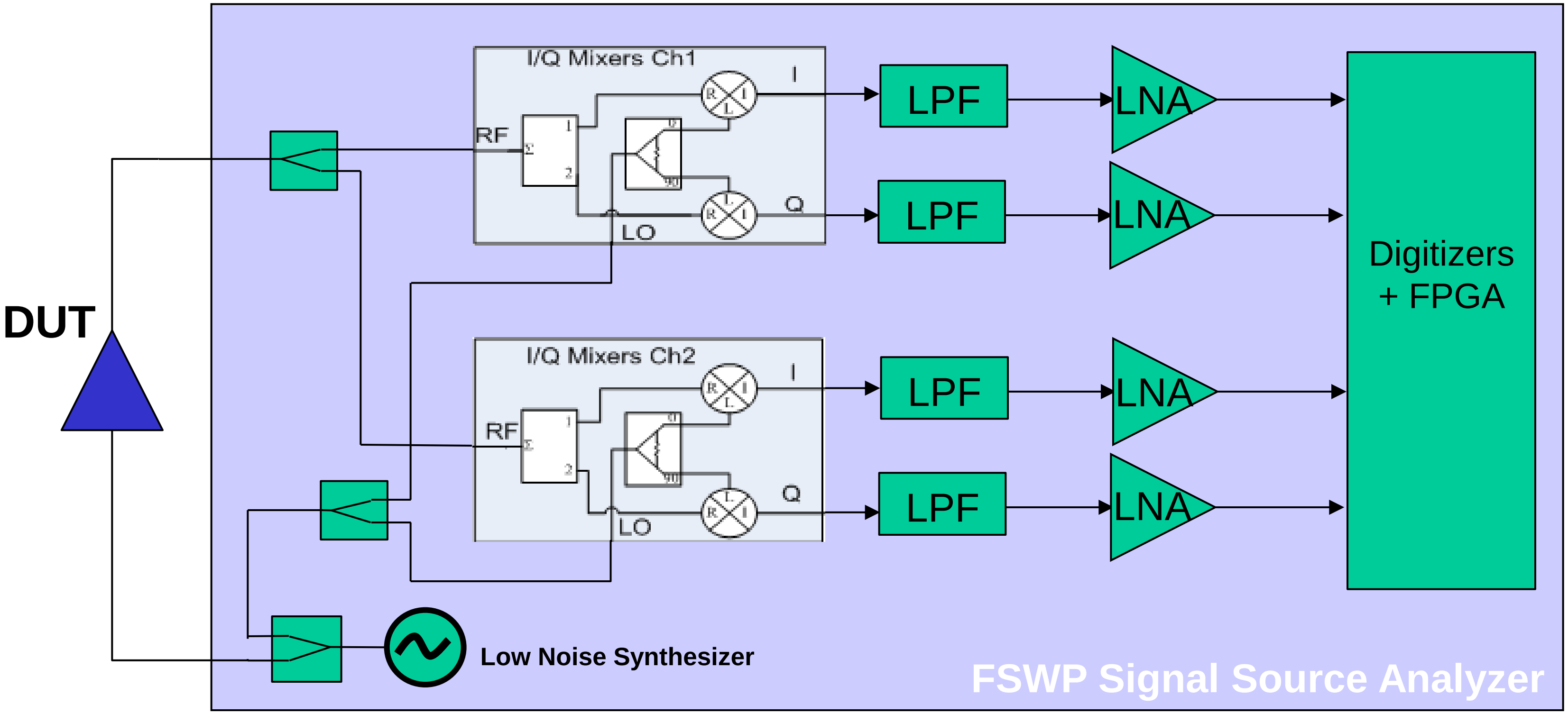
- Two-port DUT (e.g. amplifier)
- Source noise is correlated on both PD inputs – cancels out so only added noise of DUT is measured
- Manual adjustment of phase shifter over 180° required for calibration
- Phase detector may be external or internal to analyzer



* Phase shifter adjusted for calibration and set for quadrature during measurement

Additive Phase Noise – Digital Phase Demodulator

- Internal hardware automatically reconfigures when additive is selected
- No phase detector or need for quadrature – No phase shifter!
- Greatly simplifies measurement setup and calibration
- Internal Low Noise Synthesizer as DUT stimulus
- High speed cross correlation to increase sensitivity



Additive Phase Noise – Digital Phase Demodulator

- Internal Low Noise Synthesizer as DUT stimulus

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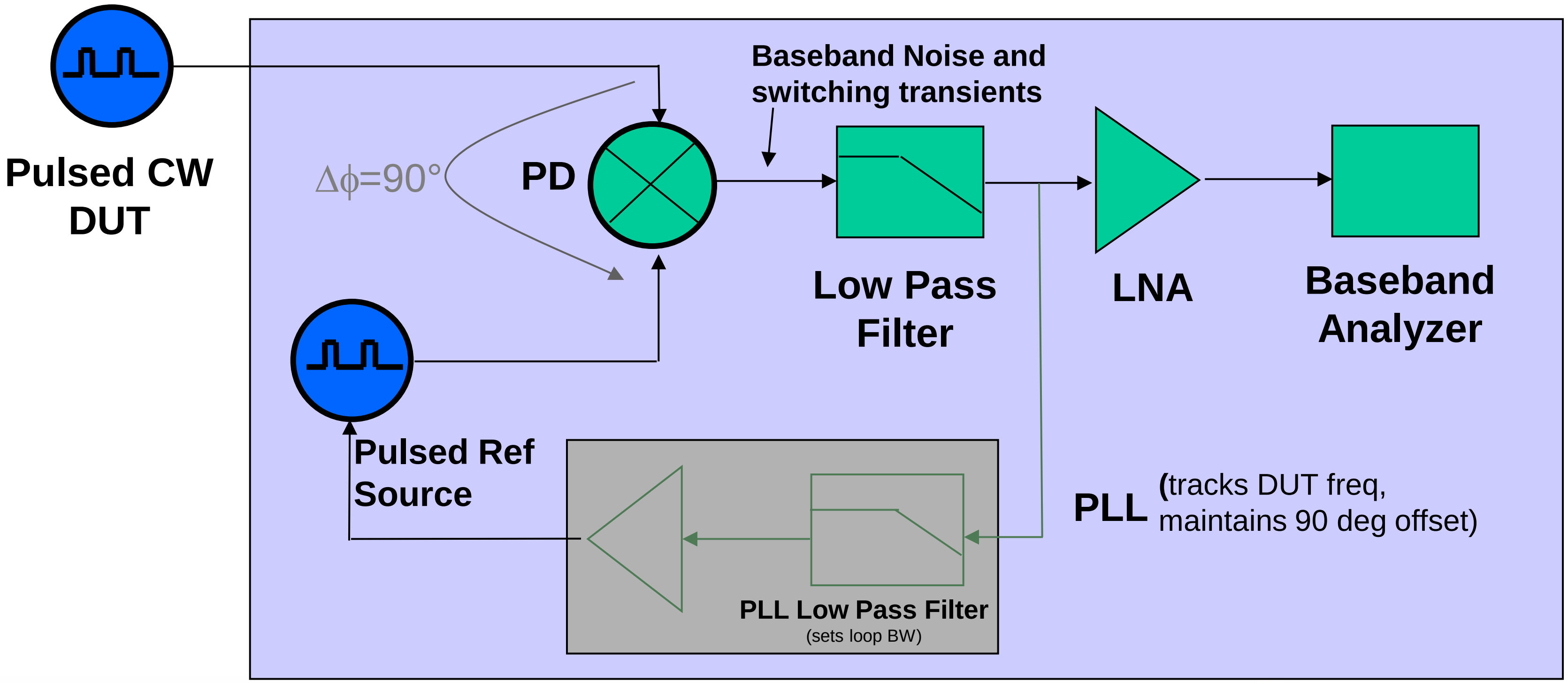
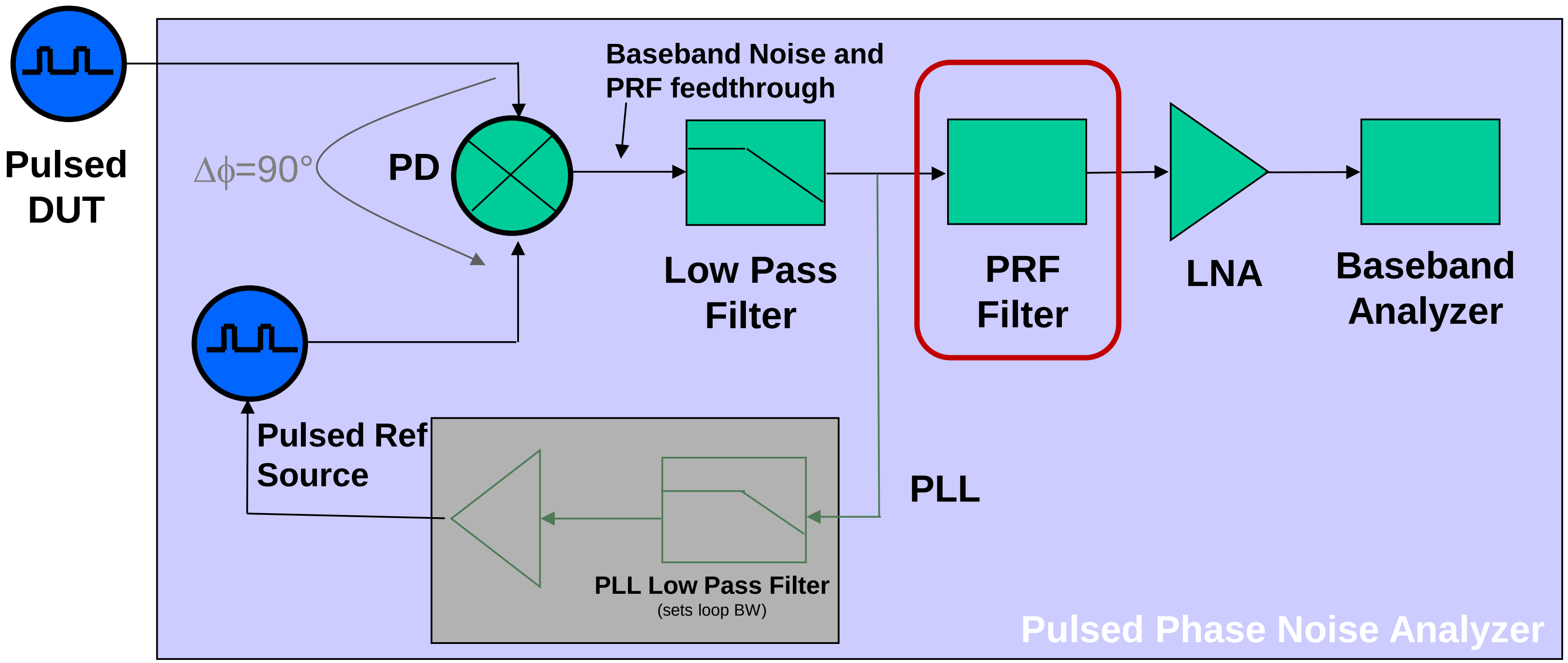
Pulsed Phase Noise – Phase Detector

- CW Ref Source causes DC shift at the PD when DUT pulse is off – must also pulse Ref Source in sync with DUT to keep output of PD at 0 volts
- Pulse edges of DUT and REF are not perfectly synchronized so switching transients will occur at pulse edges – PRF feedthrough
- LPF cutoff is too high to attenuate PRF feedthrough

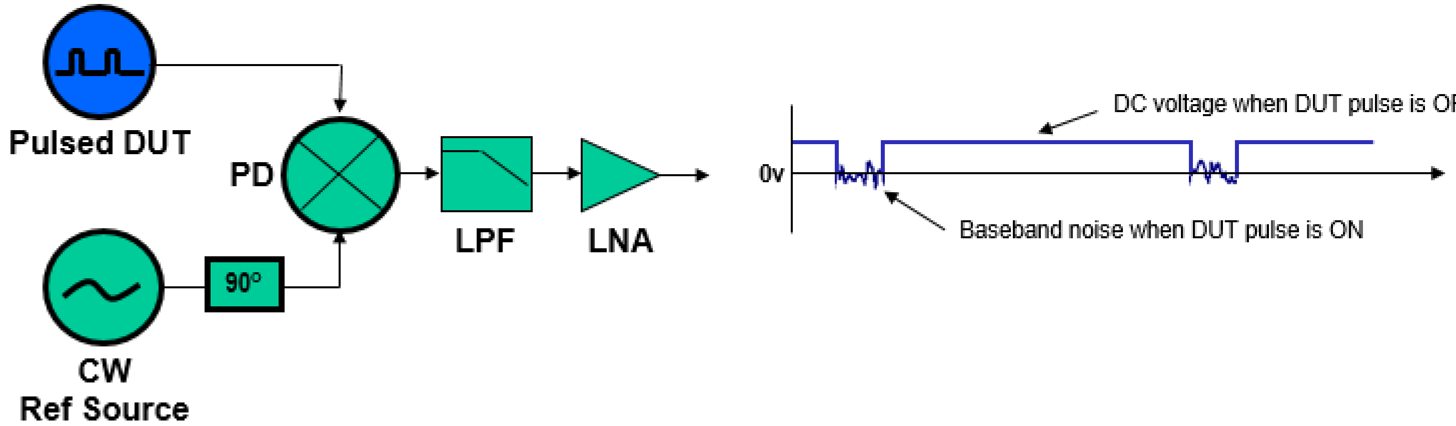


Pulsed Phase Noise – Phase Detector

- PRF is LPF that attenuates PRF feedthrough
- PRF filter must have flat passband and sharp cutoff
- Different PRF filter required for every PRF frequency



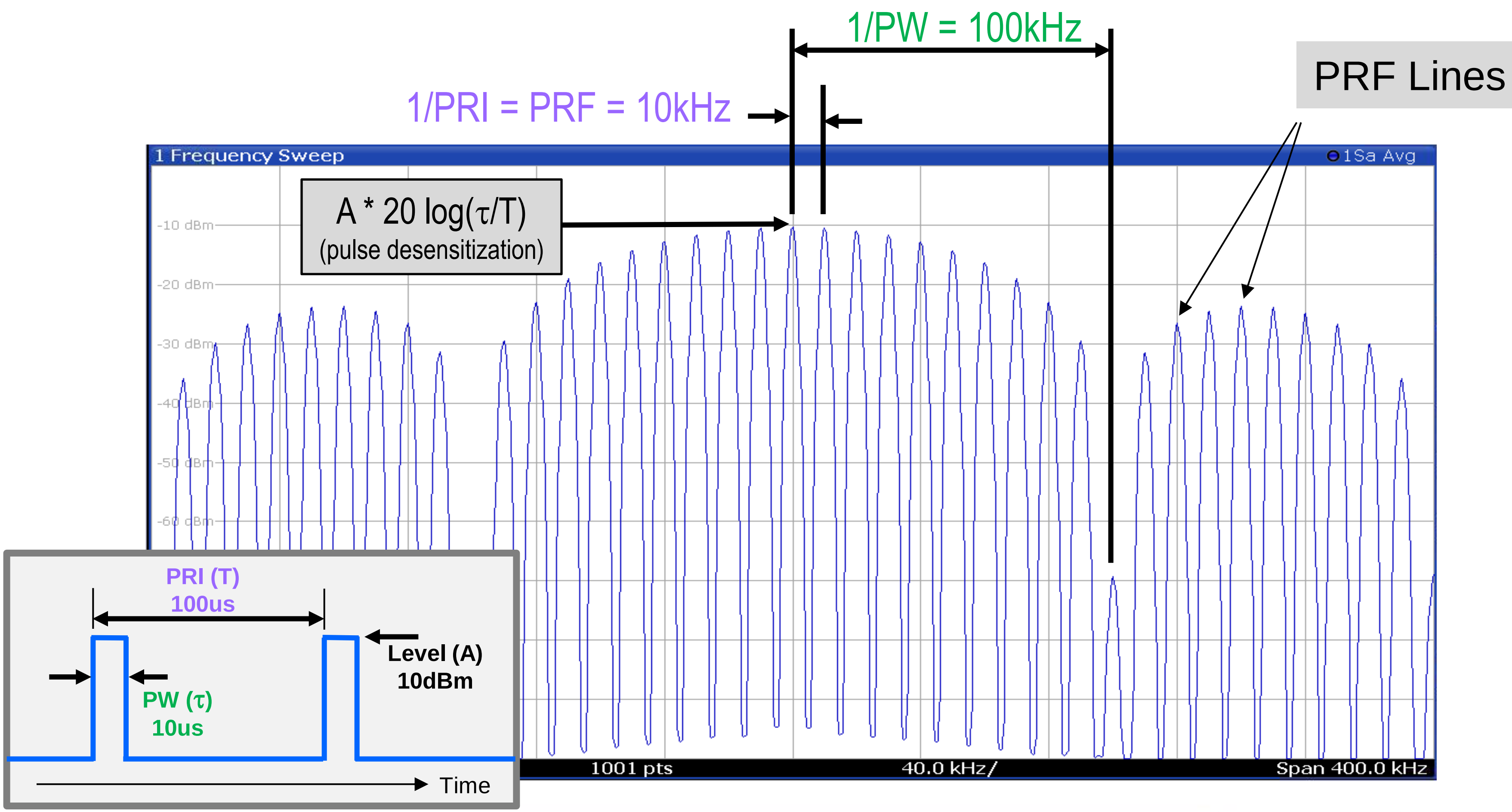
Pulsed Phase Noise – CW Ref Source



- When DUT pulse is OFF the Ref Source causes a DC shift at the phase detector output
- This DC level causes problems:
  - Even small DC voltage can saturate high-gain LNA
  - DC looks like frequency error to PLL – tracking issues
- To avoid these problems we must pulse the Ref Source in sync with DUT pulse

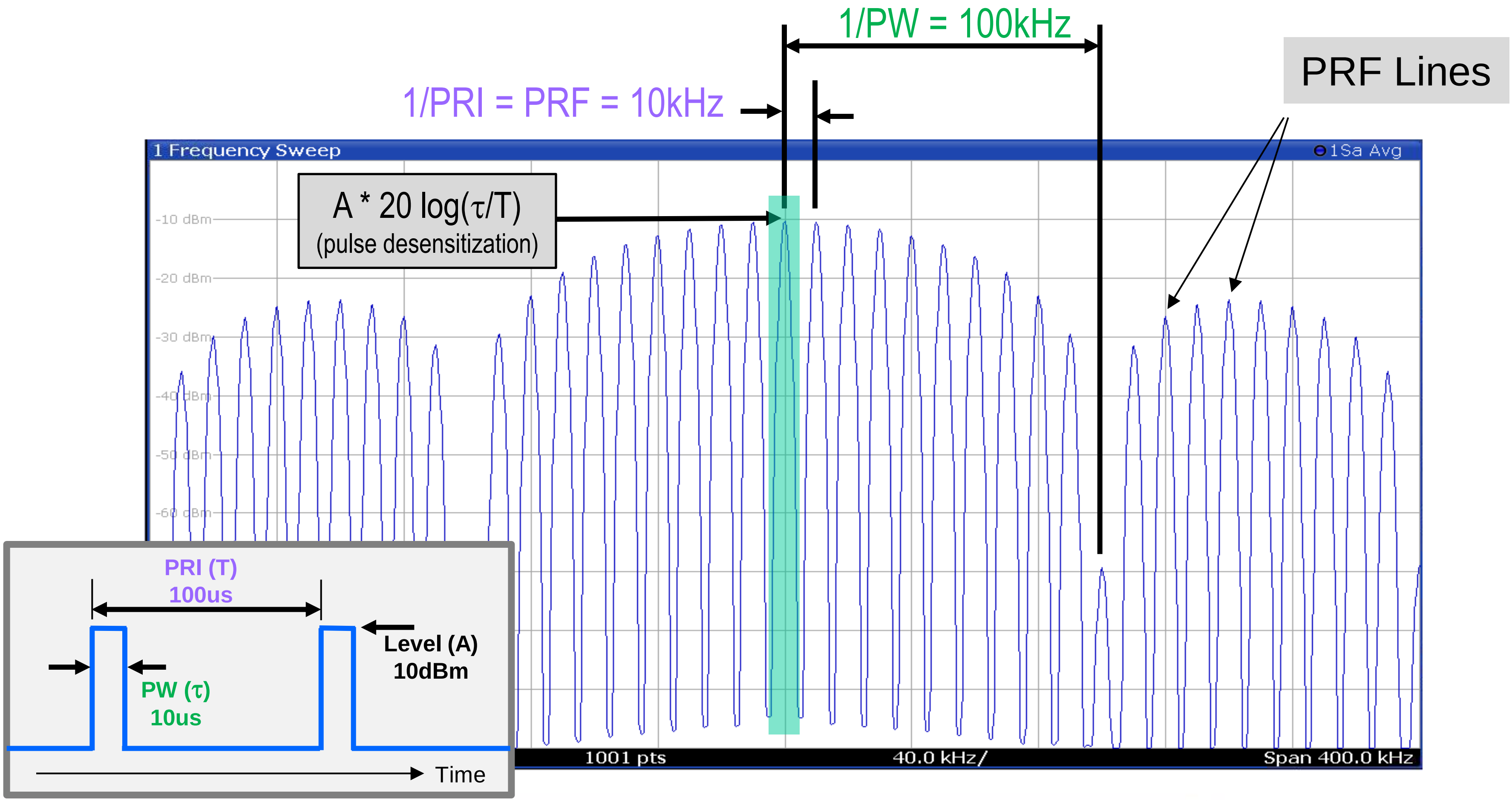
Pulsed Phase Noise – Pulse Spectrum

- Spectrum of pulsed CW signal contains one line at the center frequency and many other PRF lines



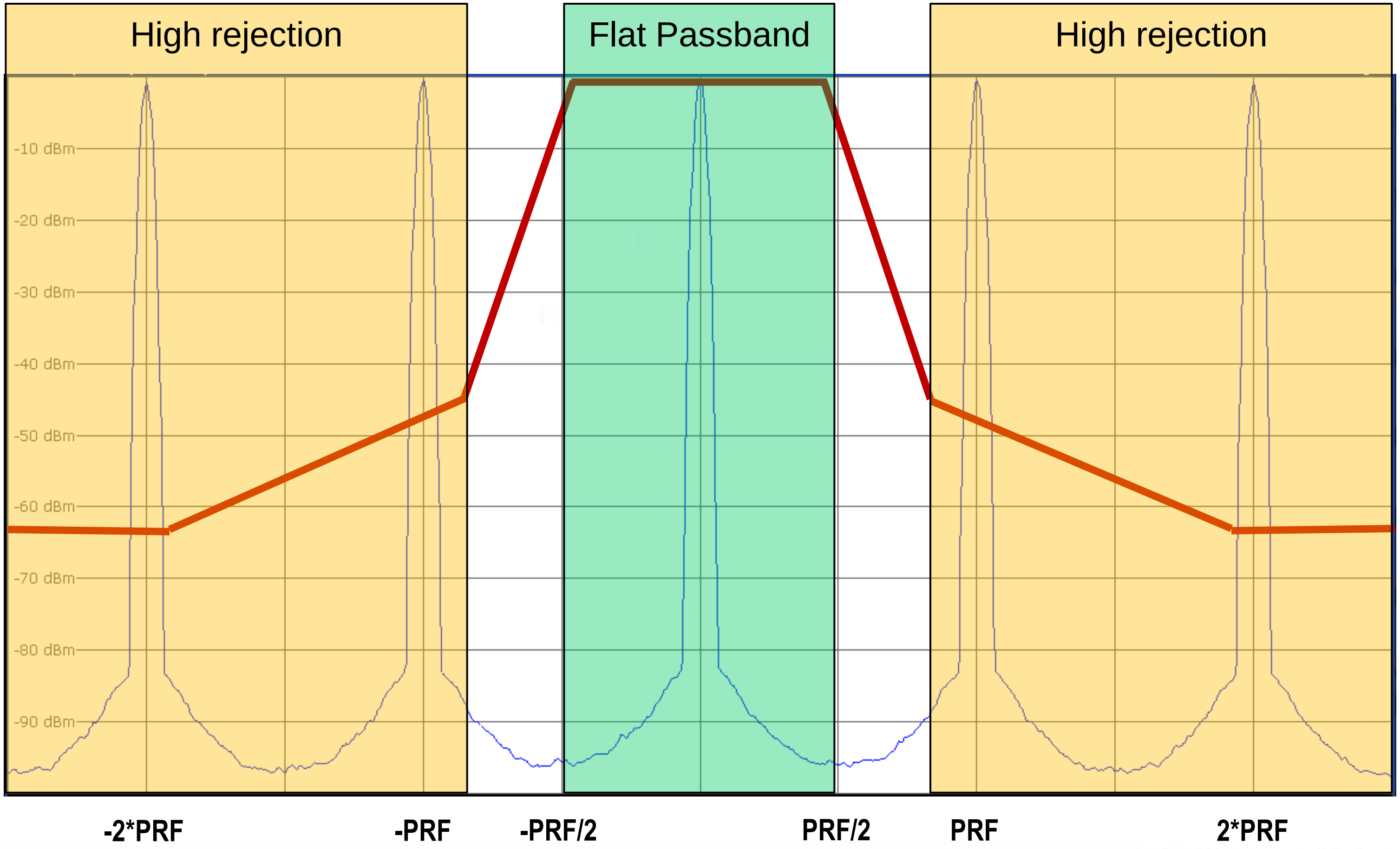
Pulsed Phase Noise – Pulse Spectrum

- PRF filter is narrow to pass center line and attenuate all other PRF lines
- Center line is lower than pulse level due to pulse desensitization: 20*log(*duty cycle*)



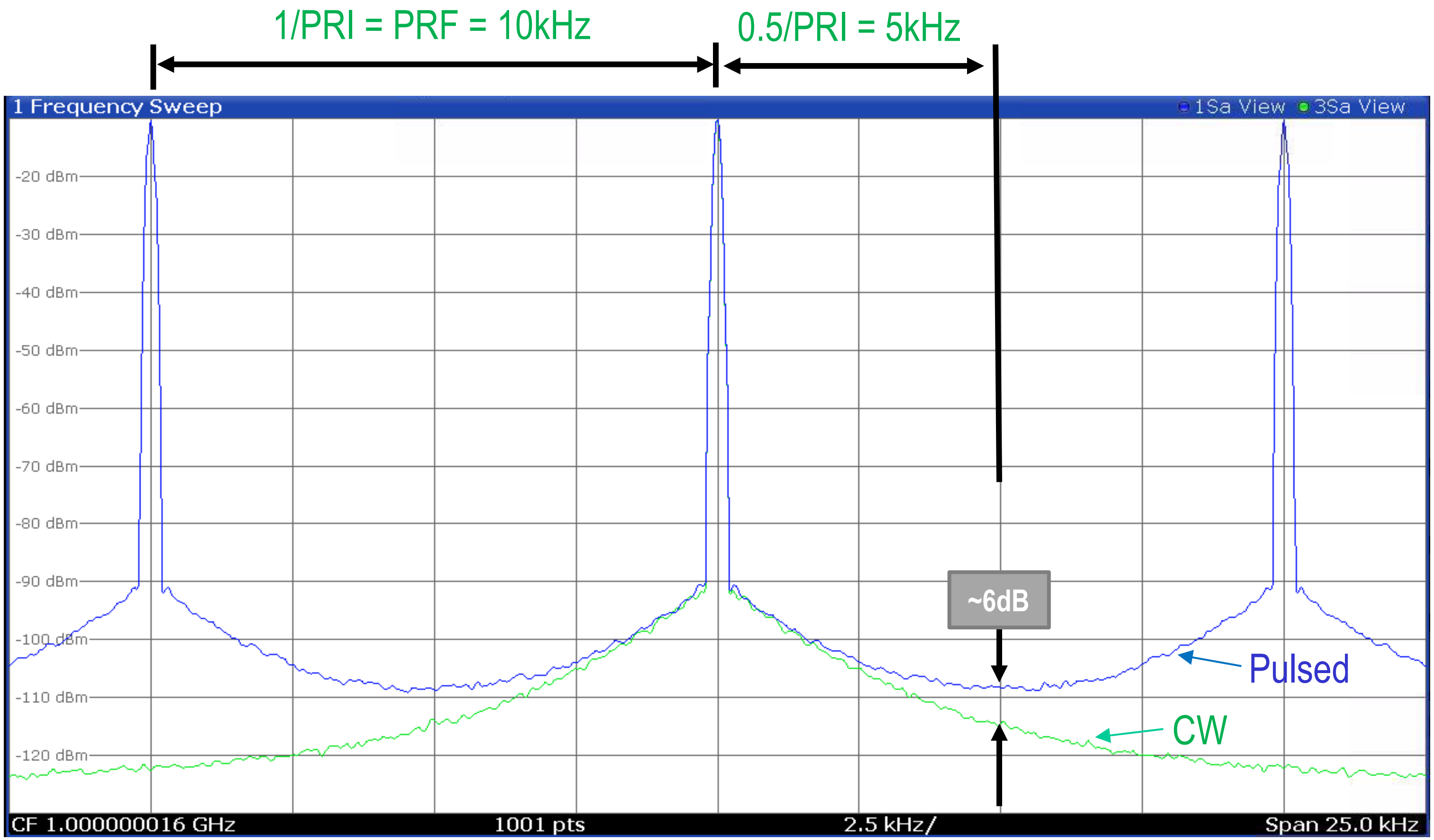
PRF Filter

- PRF must have flat passband out to PRF/2 but high attenuation at >PRF
- Difficult to achieve



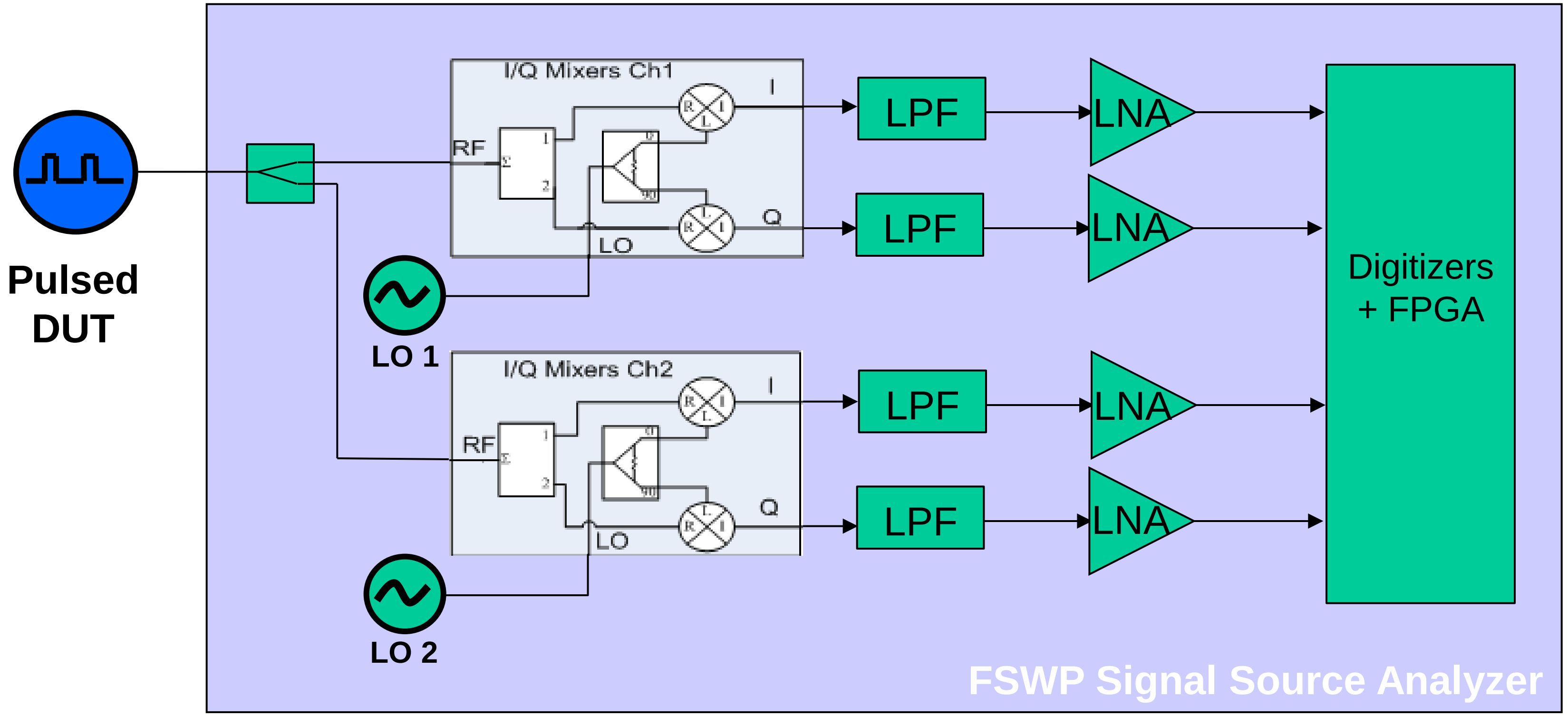
Pulsed Phase Noise

- Max offset limited to PRF/2 for pulsed signals due to PRF lines
- Pulsed phase noise ~6dB higher at PRF/2 due to coherent combining



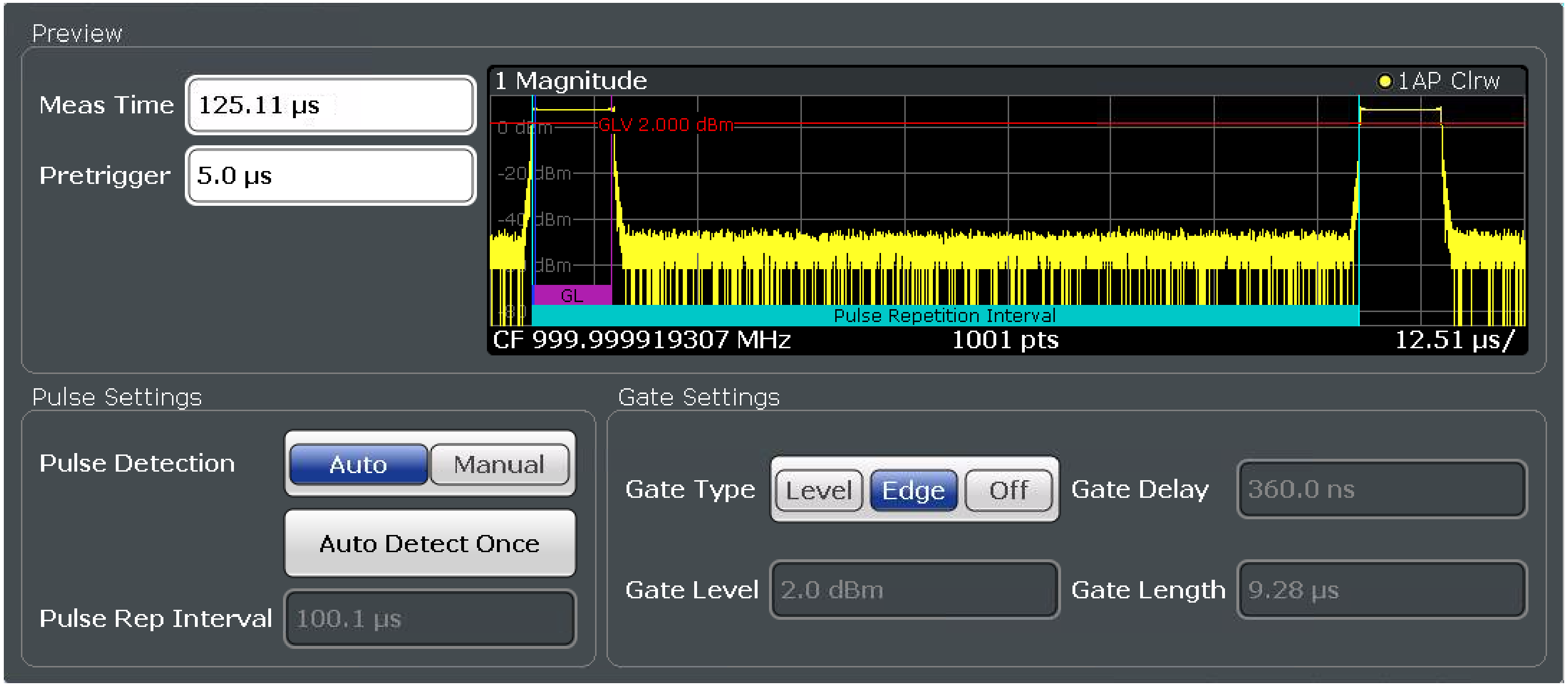
Pulsed Phase Noise – Digital Phase Demodulator

- Same block diagram as for CW phase noise measurements
- No phase detector so no need to pulse the reference sources
- PRF filter and PW gating are implemented in DSP to easily handle different PRFs
- Pulsed-Additive phase noise can also be measured without complex calibration required



Pulse Configuration Setup

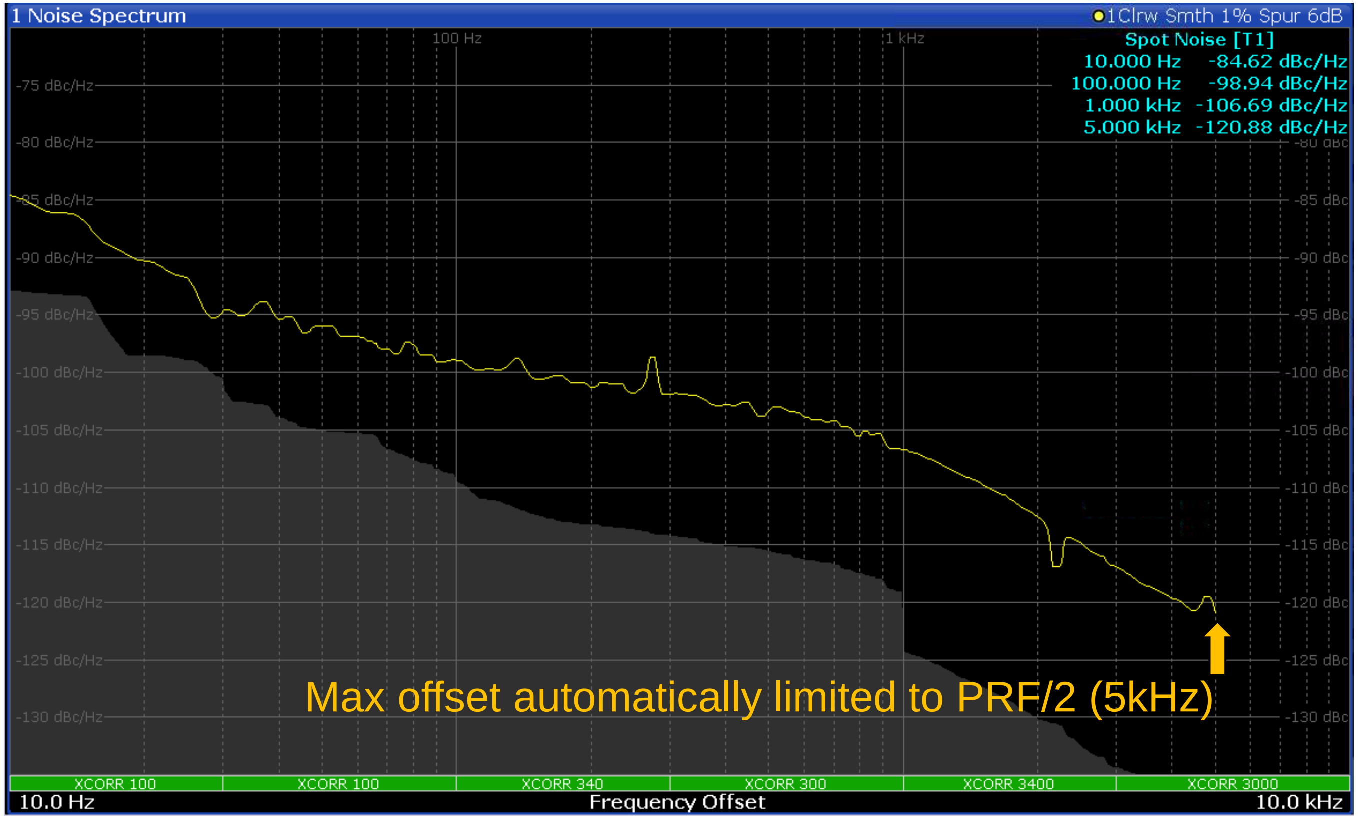
- PW and PRI are automatically detected using zero-span measurement
  - PW is used to set measurement gate time
  - PRI is used to set maximum offset



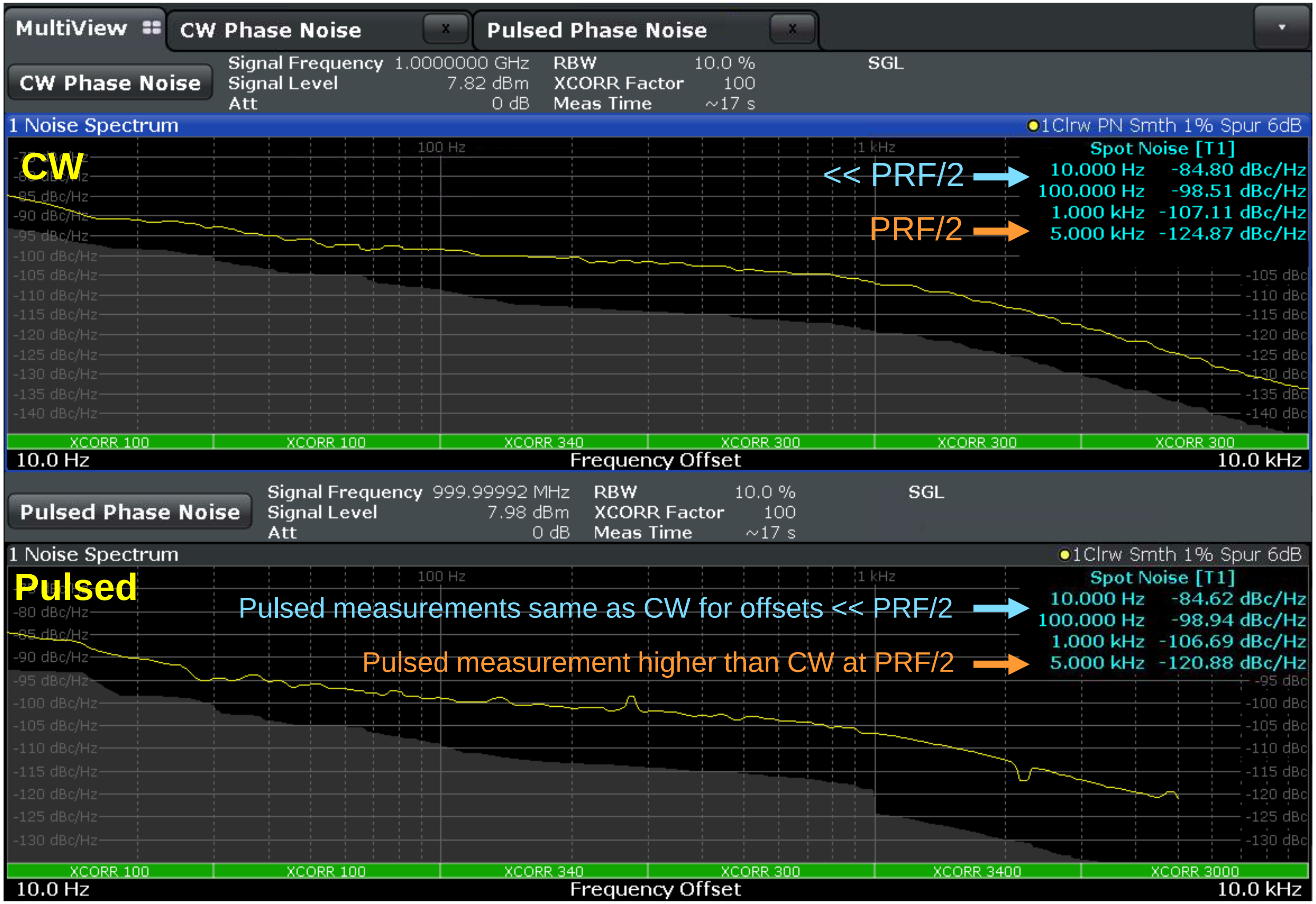
Pulse Configuration Dialog

Pulsed Phase Noise Measurement

- Measurement truncated to max offset of PRF/2
- Measurement time same as for CW



Pulsed vs CW Phase Noise Measurement



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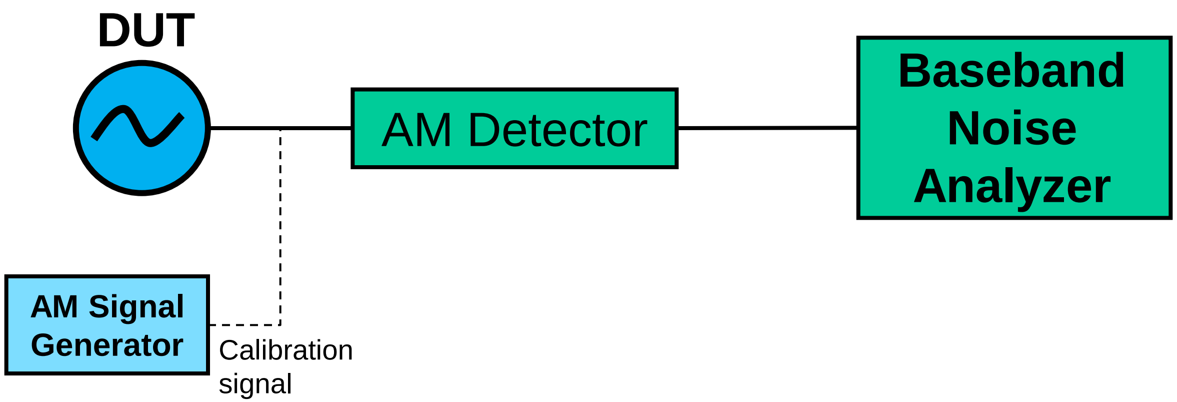
AM Noise Measurement – Diode Detector

- Recall the expression of a real-world sine wave:

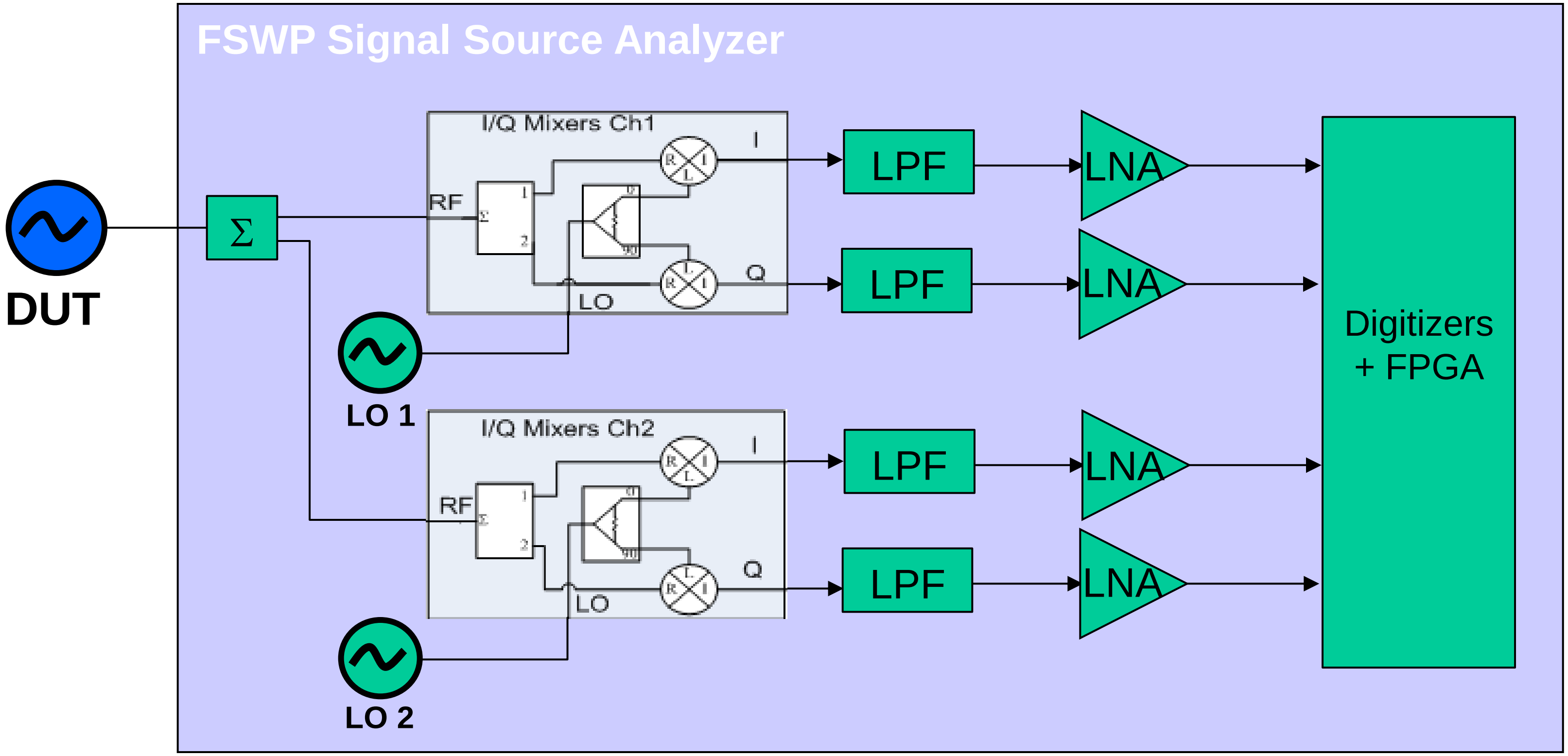
$$V(t) = [A + E(t)] \sin(2\pi\nu t + \phi(t))$$

- E(t) is the AM noise component
- AM noise is usually lower than phase noise – especially at close-in offsets
- AM Noise is traditionally measured using an external diode detector along with the baseband noise analyzer
- Calibration of the measurement is done using a signal generator with a known AM modulation index



AM Noise – Digital AM Demodulation

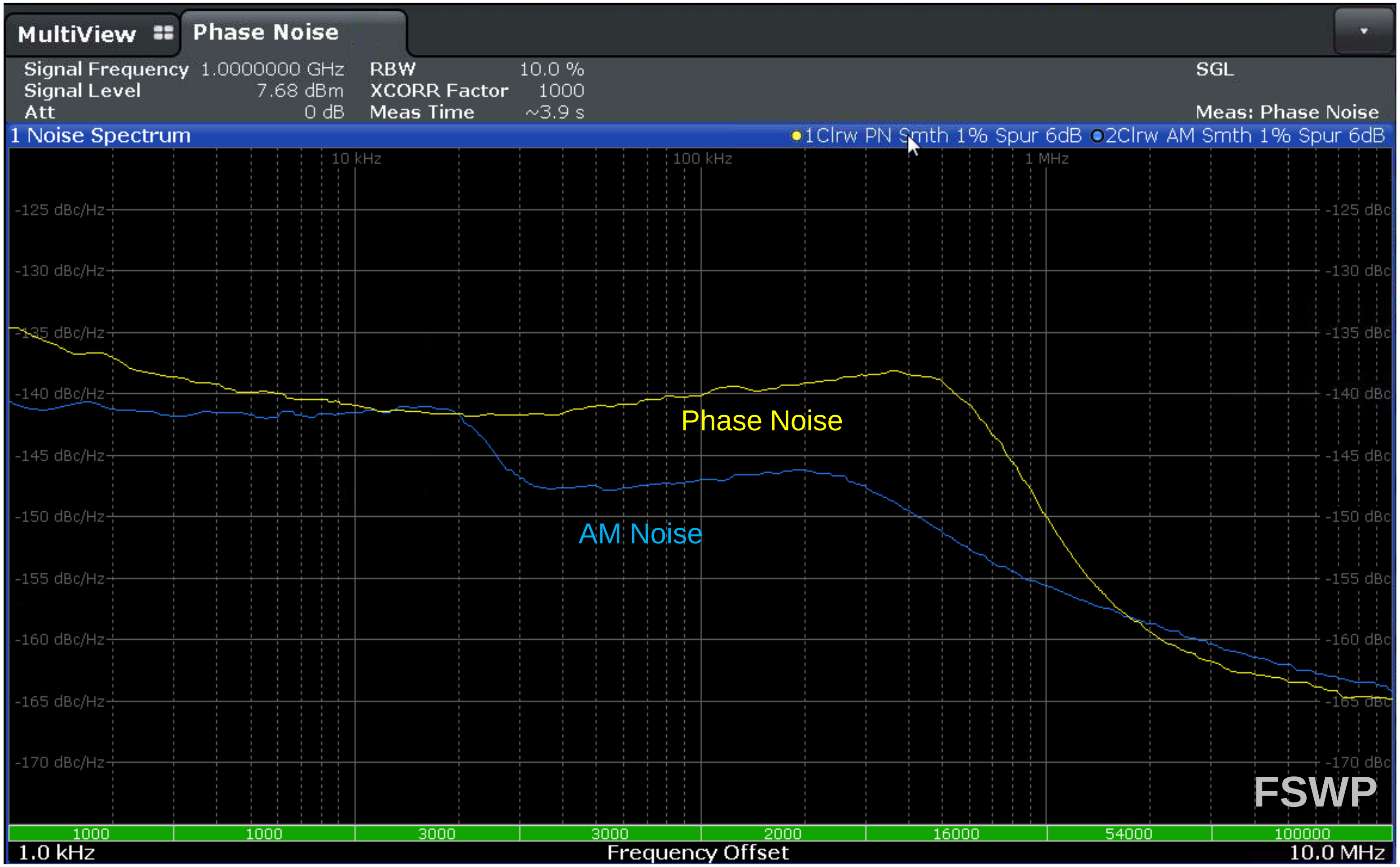
- Same block diagram – AM Noise measured from demodulated AM
- Much simpler setup with no need for detector diode or complicated calibration
- Permits simultaneous measurement of phase noise and AM noise
- High speed cross correlation to increase sensitivity



AM Noise – Digital AM Demodulator

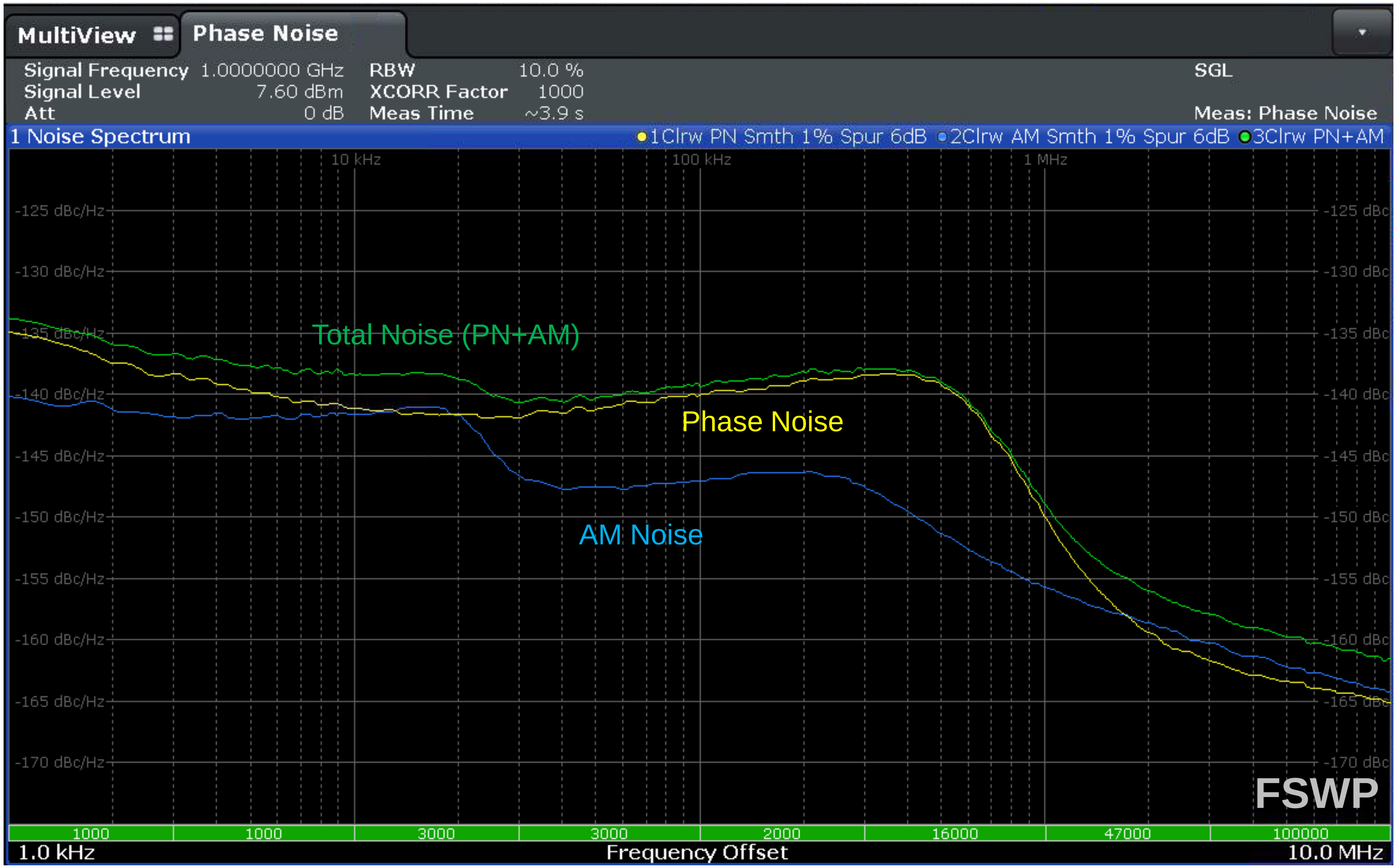
AM Noise and Phase Noise

- Simultaneous measurement of AM Noise and Phase Noise



AM Noise, Phase Noise, and Total Noise

- Simultaneous measurement of AM Noise and Phase Noise with Total Noise



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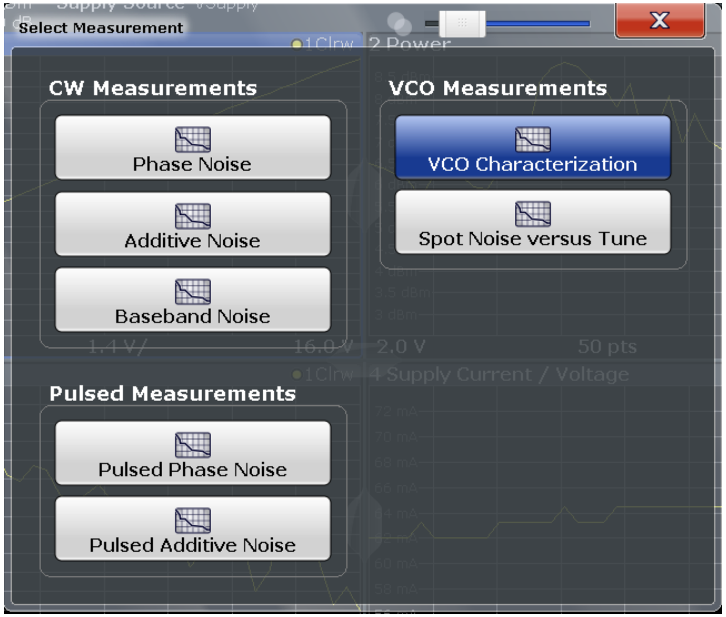
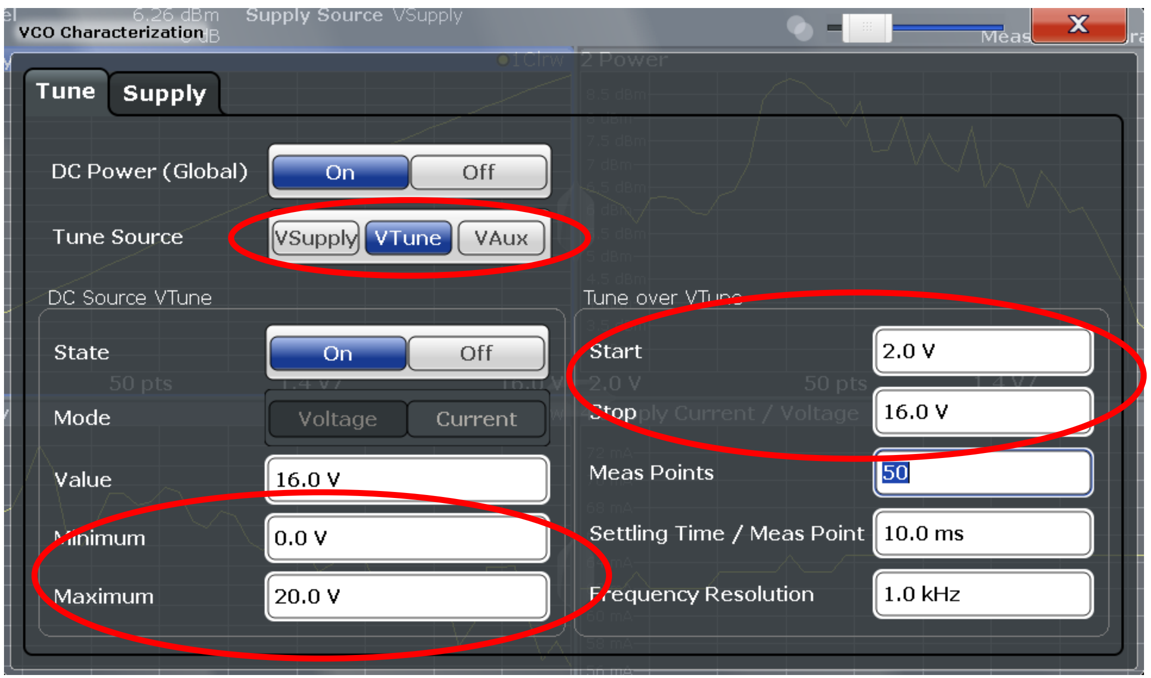
VCO Measurements

- VCO measurements include:
  - Frequency vs. tune
  - Power vs. tune
  - Tuning sensitivity vs. tune
  - Supply current vs. tune
  - Spot noise vs. tune



VCO Measurements

- FSWP maximum/minimum voltage can be different tuning ranges
- V_{tune}, V_{aux} and V_{supply} can be swept



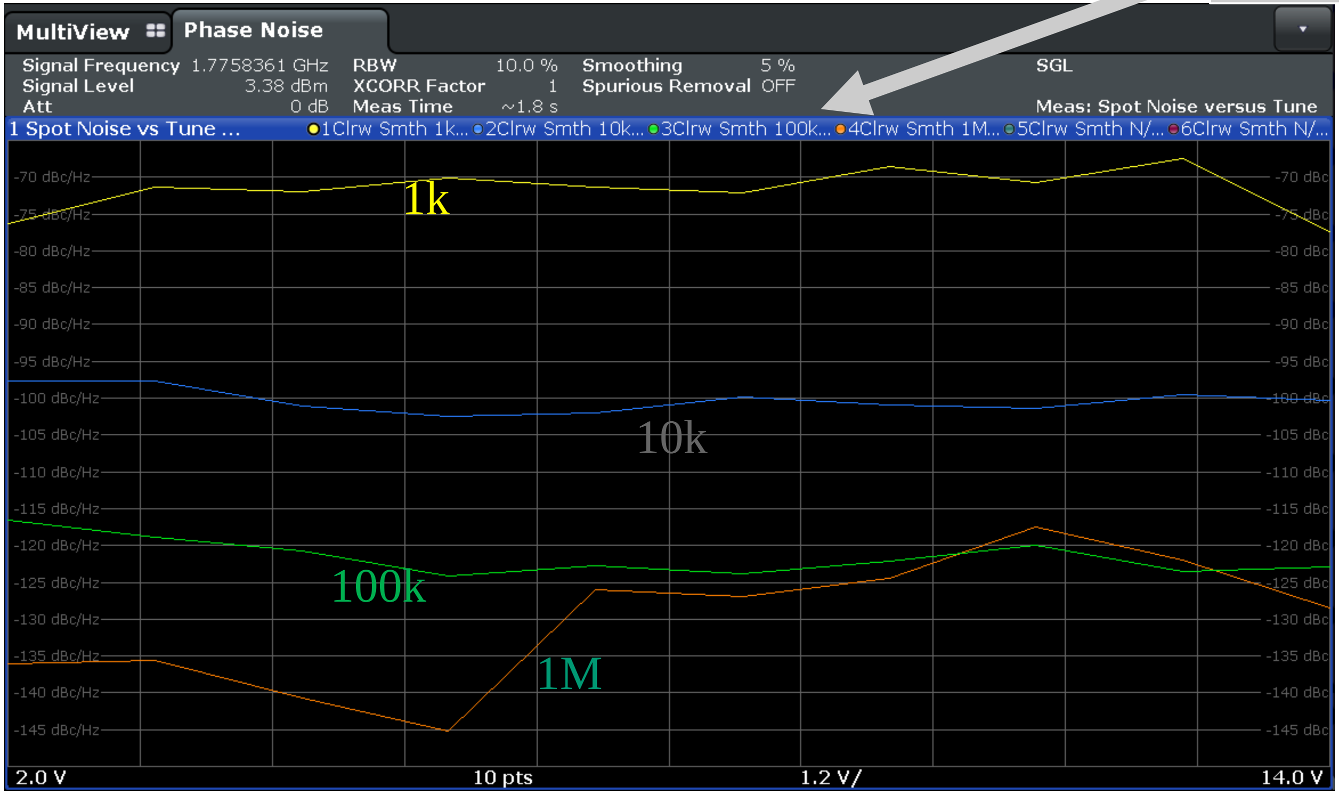
VCO Measurements

- Results

VCO Measurements

- Spot noise vs. tune

Different Offset Ranges



Digital Phase Demodulator – Summary

Advantages

- No PLL or compensation for noise suppression within loop BW required
- Much faster than other methods (for same sensitivity)
- Pulsed, Additive, and Pulsed Additive phase noise can be easily measured
- Phase Noise and AM Noise can be measured simultaneously
  - AM noise rejected in phase noise measurement (>50dB)
  - Phase noise rejected in AM noise measurement (>50dB)
- No complex calibrations required for AM and Additive phase noise
- Measurements at very small offsets are possible (down to 0.01Hz)
- Cross-Correlation improves the sensitivity of the test system

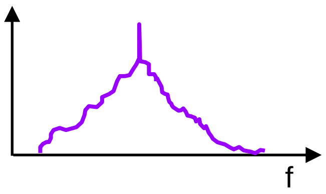
Limitations

- Additive phase noise frequency range limited to 18GHz (FSWP)
- Spectrum analyzer still required for other measurements such as ACLR, Harmonics, and Spurious (SA option available in FSWP)

Measurement Technique Summary

	Absolute	Additive	Pulsed	Pulsed-Additive	AM Noise
Direct SA	☑ Limited sensitivity and close-in offset	☒	☒	☒	☒
Phase Detector	☑	☑ Difficult cal required	☑ PRF filter required	☑ Difficult cal and PRF filter required	☑ Detector diode and AM cal source required
Delay Line Discriminator	☑ Max offset limited by sin(τ)/τ	☒	☒	☒	☒
Digital FM/AM Demodulator	☑	☑	☑	☑	☑

Summary



- Phase noise is unintentional phase modulation on a signal that spreads the spectrum and degrades performance in many RF applications
- Absolute Phase Noise can be measured using several methods
  - Direct Spectrum Analyzer
  - Phase Detector (+ Cross-Correlation)
  - Delay Line Discriminator
  - Digital Phase Demodulator (+ Cross-Correlation)
- Traditional Pulsed PN, Additive PN, and AM Noise measurements require complicated setups with complex calibration schemes
- Digital PM/AM Demodulation technique with very-low-noise reference sources makes Absolute Phase Noise, Additive Phase Noise, Pulsed Phase Noise, Additive-Pulsed Phase Noise, and AM Noise measurements with simple setup, no complex calibrations, and with state-of-the-art sensitivity and speed
- VCO Measurements verify performance versus tune voltage

Thank You!

ROHDE&SCHWARZ