Phase Noise Measurement Techniques

ROHDE&SCHWARZ

Agenda

- What is Phase Noise?
- Why is Phase Noise Important?
- Quantifying Phase Noise
- Causes of Phase Noise
- Phase Noise Measurement Techniques
- Additive Phase Noise
- AM Noise
- Summary

What is Phase Noise?

- **Ideal Signal (noiseless)**

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

  where

  A = nominal amplitude

  ν = nominal frequency

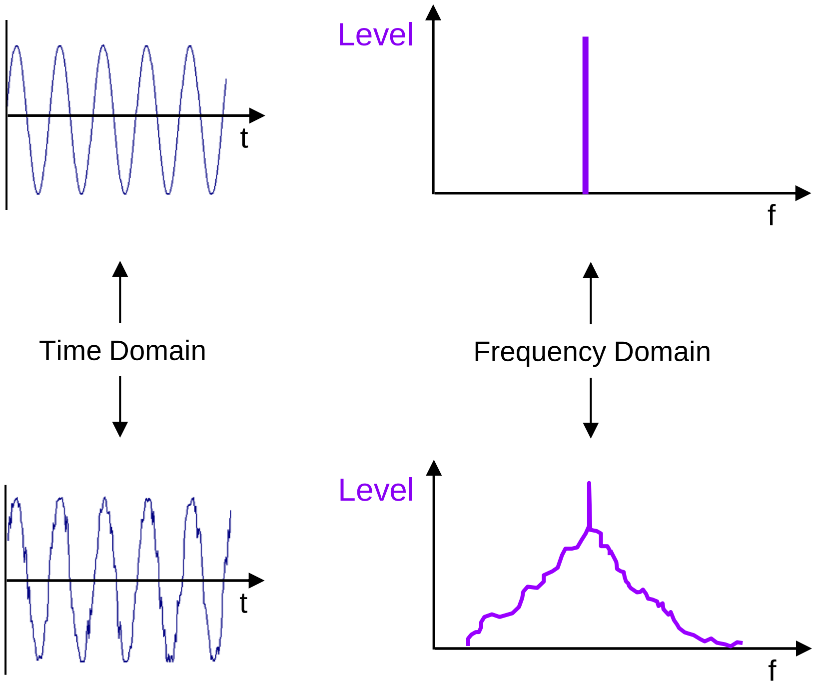
- **Real Signal**

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

  where

  $E(t)$ = amplitude fluctuations

  $\phi(t)$ = phase fluctuations

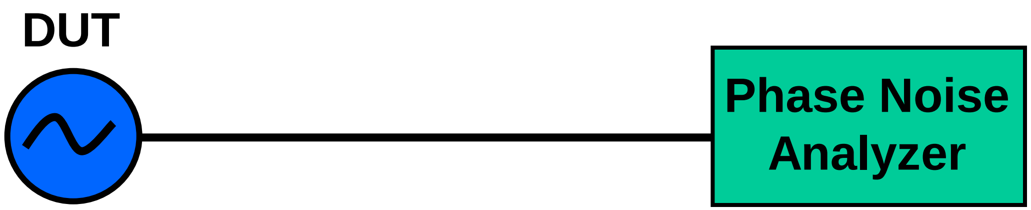


Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain.

Phase Noise is equivalent to jitter in the time domain.

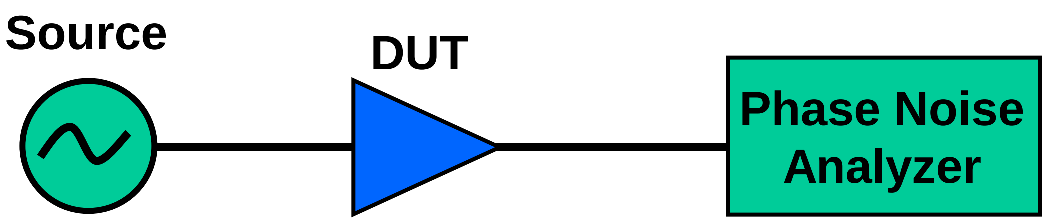
What is Phase Noise?

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



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

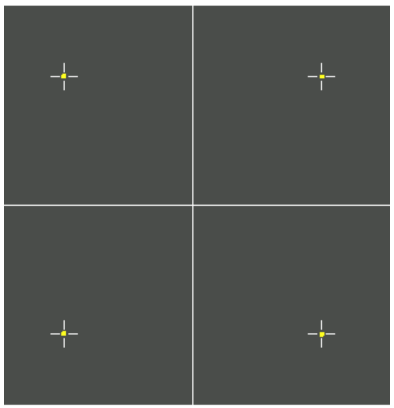
- **Additive Phase Noise**
  2 Port – Added by device (e.g. amp, up/down converter)



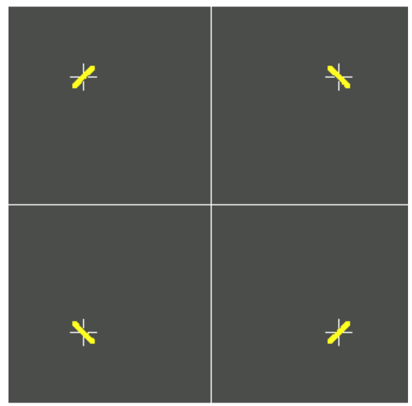
Measure Phase Noise <u>added</u> by DUT

Phase Noise
Important in Digital Modulation

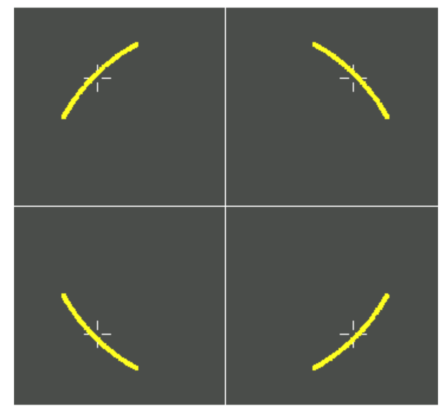
Modulation quality (phase error, EVM) is degraded by phase noise



<0.2% EVM



5% EVM

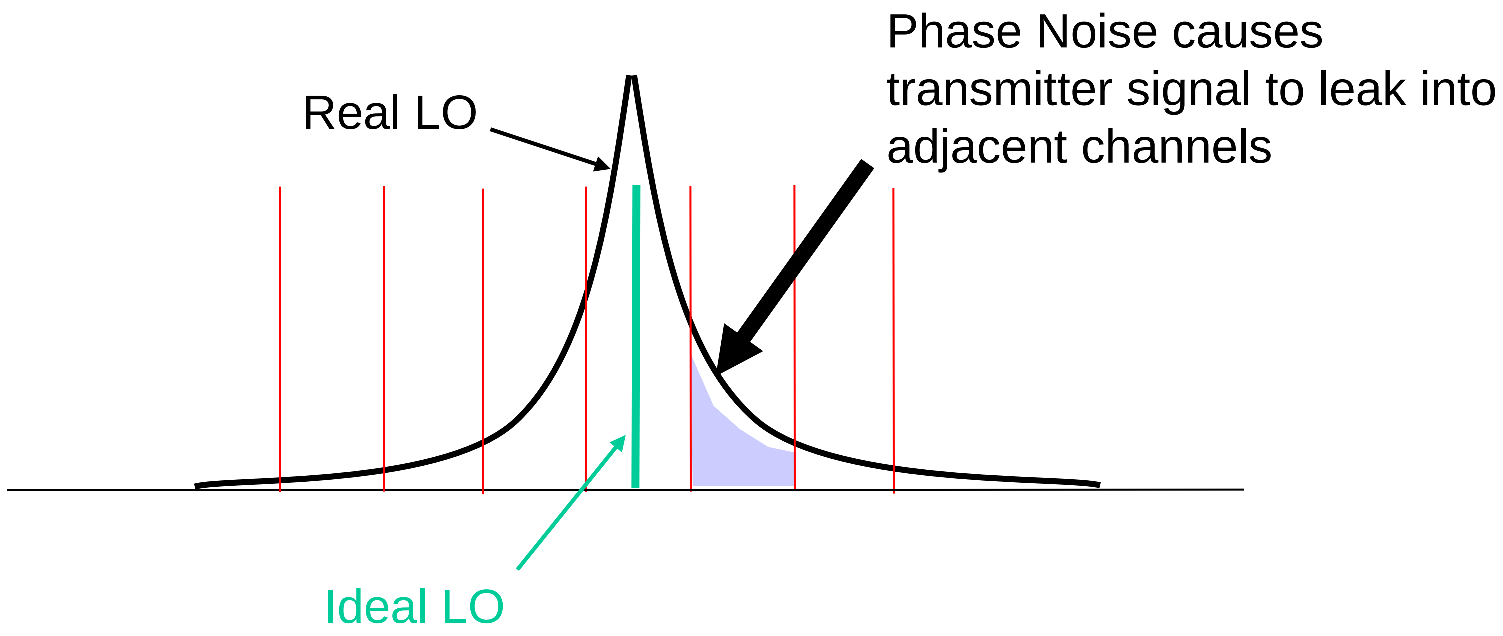


20% EVM

Increasing Phase Noise (QPSK)

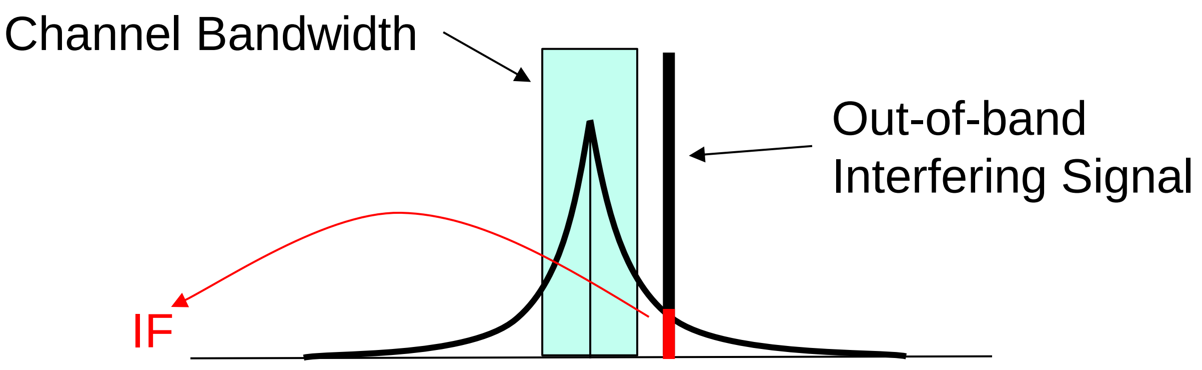
Phase Noise
Important in Communication Systems Transmitters

Adjacent Channel Power



Phase Noise
Important in Receivers

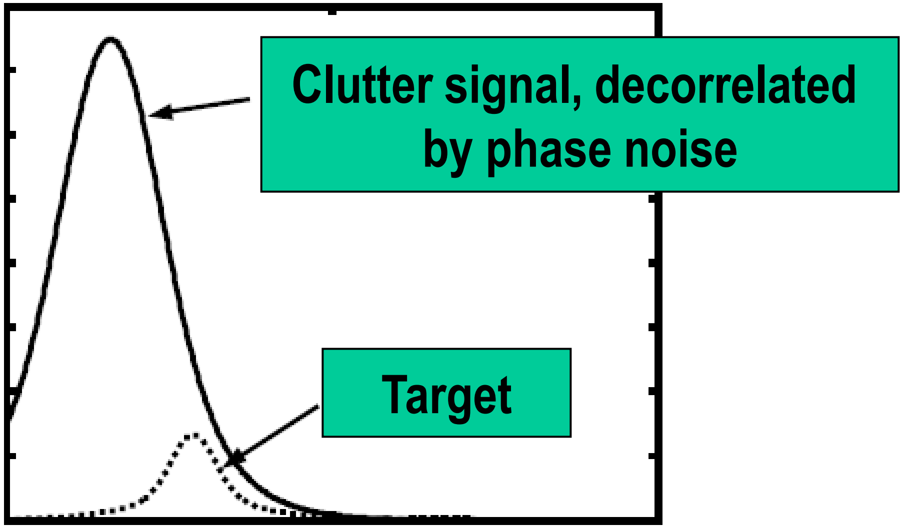
Sensitivity: Big interferer near the transmit channel



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

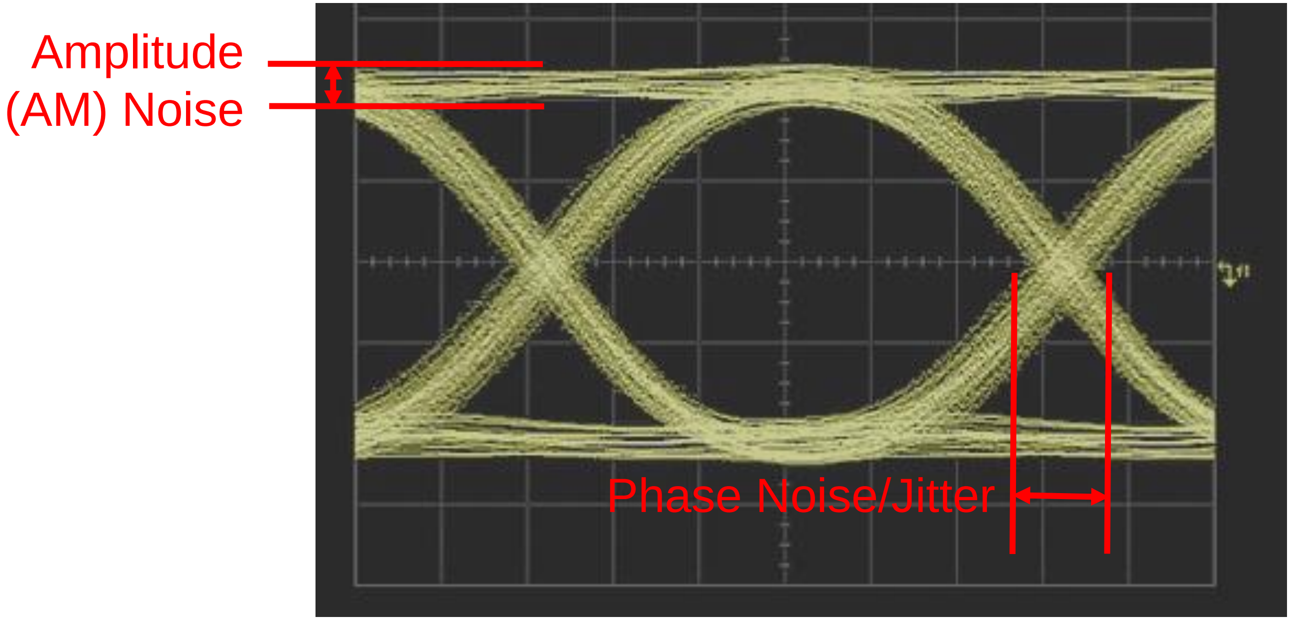
Radar Applications – Moving Target Indication



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

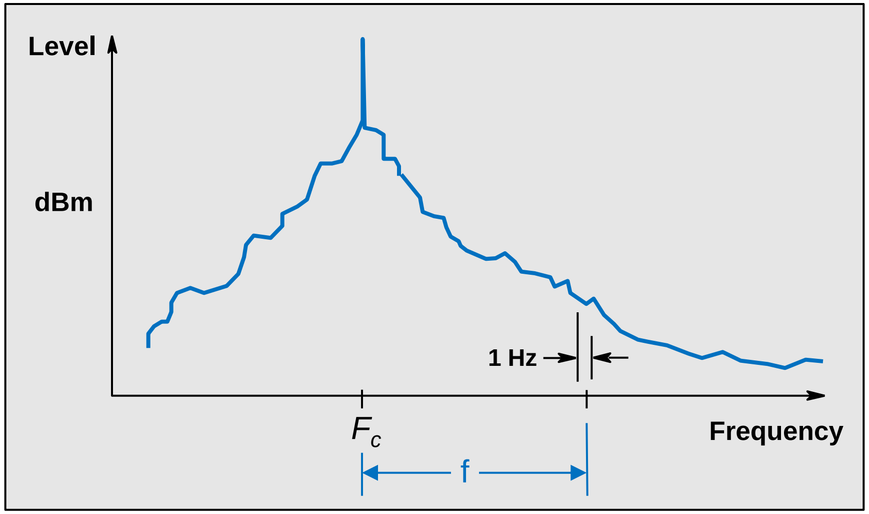
Jitter peaks can cause transmitted symbol errors which increased bit error rate and limits usable data rate

Quantifying Phase Noise

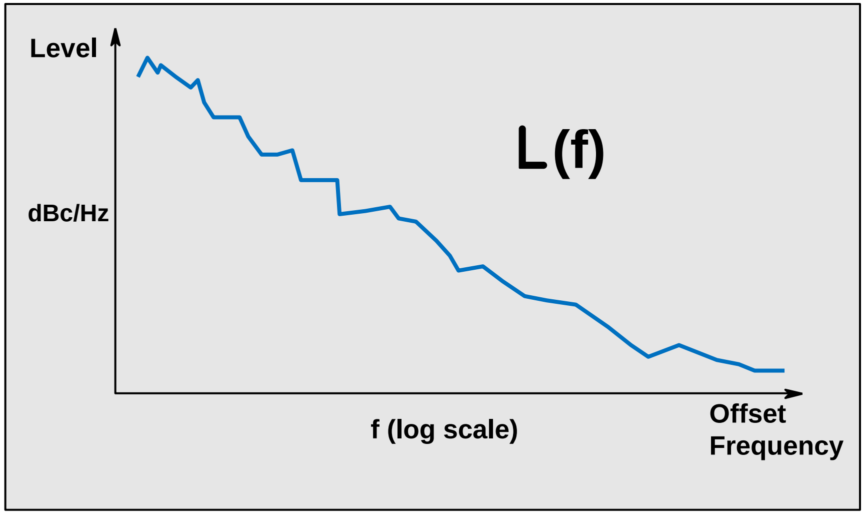
- Phase Noise Units
- Residual Noise
  - Integrated Phase Noise
  - Residual PM
  - Residual FM
  - Jitter: Time and Frequency Domain approaches

Phase Noise – Unit of Measure

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



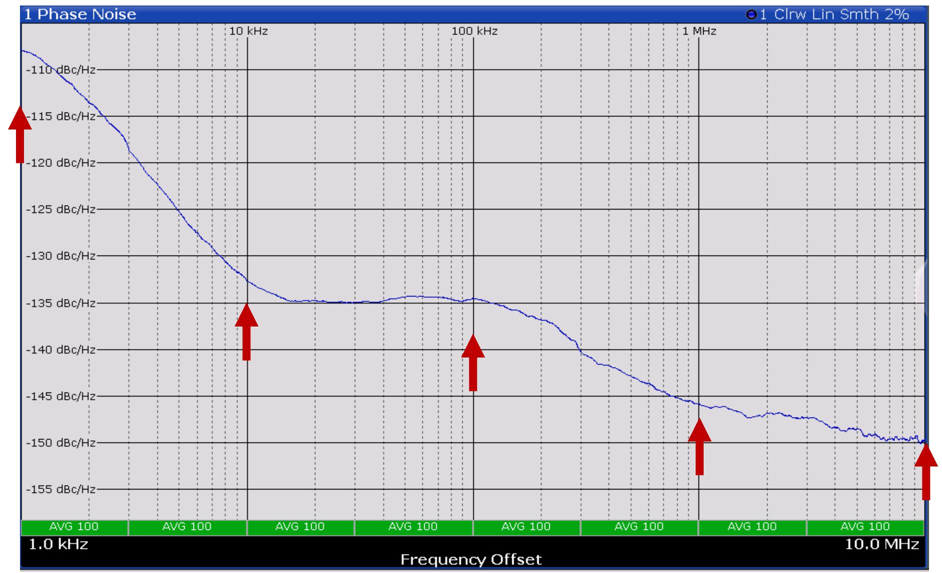
Spectrum View



Phase Noise Plot

Quantifying Phase Noise

- Phase Noise: $\mathcal{L}(f)$ Units of dBc/Hz
  - Plot



  - Spot Noise

2 Spot Noise

Type	Offset Frequency [T1]	Phase Noise [T1]
Fixed	1.00 kHz	-107.89 dBc/Hz
Fixed	10.00 kHz	-132.72 dBc/Hz
Fixed	100.00 kHz	-134.53 dBc/Hz
Fixed	1.00 MHz	-145.83 dBc/Hz
Fixed	10.00 MHz	-149.60 dBc/Hz

Spot Noise offsets are user-definable (default to decade offsets)

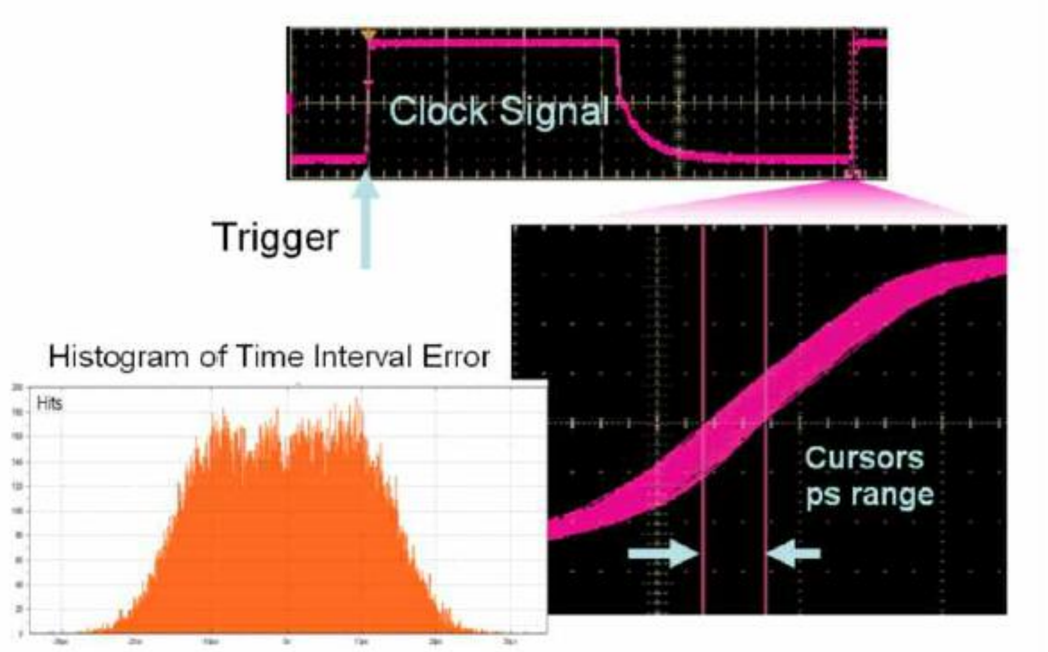
Quantifying Phase Noise – Residual Noise

- Values calculated from integration of phase noise trace
  - Integrated Phase Noise $\int \mathbb{L}(f)df$ (dBc)
  - Residual PM $\frac{180^\circ}{\pi}\sqrt{2\int \mathbb{L}(f)df}$ (deg or rad)
  - Residual FM $\sqrt{2\int f^2 \mathbb{L}(f)df}$ (Hz)
  - Jitter $\frac{1}{2\pi f_c}\sqrt{2\int \mathbb{L}(f)df}$ (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 <u>very</u> expensive

Jitter – Frequency Domain Approach (Phase Noise)

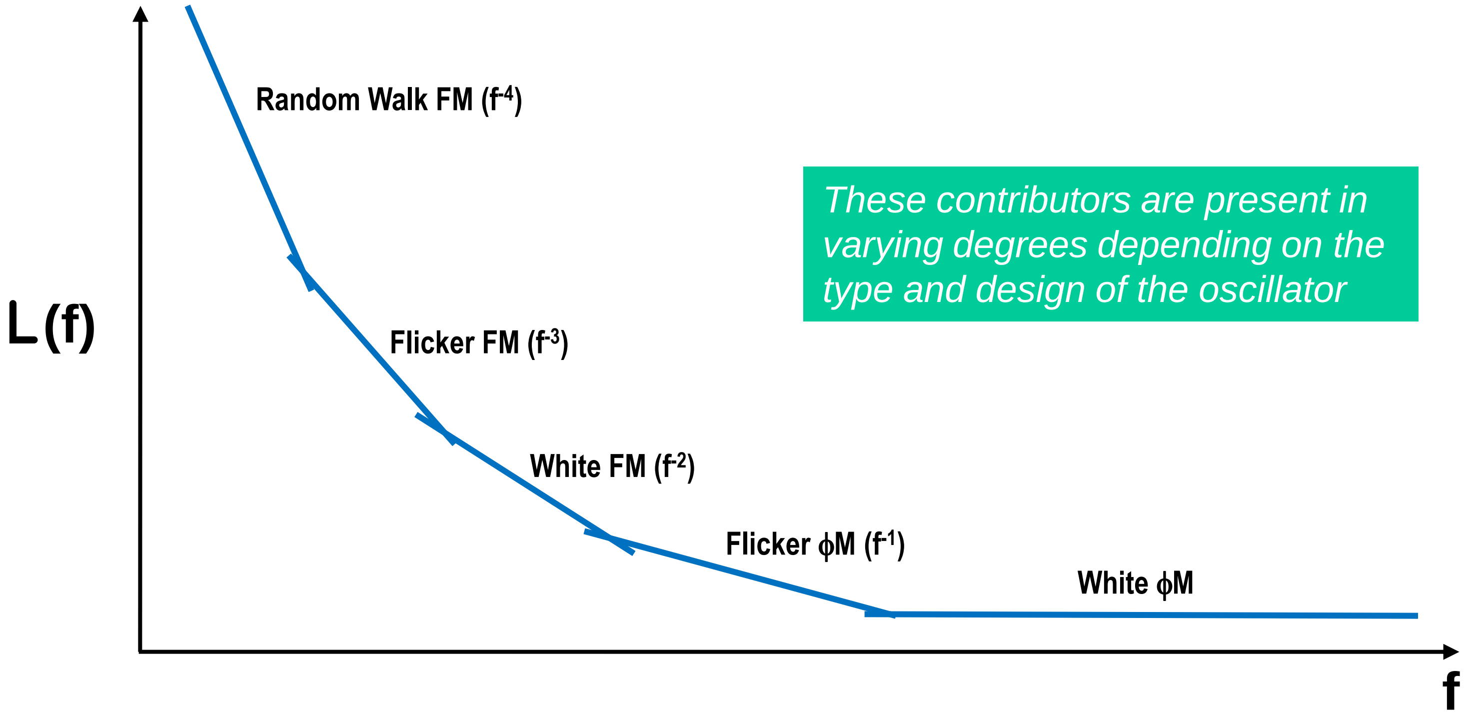
- Jitter: $$\frac{1}{2\pi f_c}\sqrt{2\int \mathcal{L}(f)\,df}$$ Units of sec

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.

Causes of Oscillator Phase Noise



These contributors are present in varying degrees depending on the type and design of the oscillator

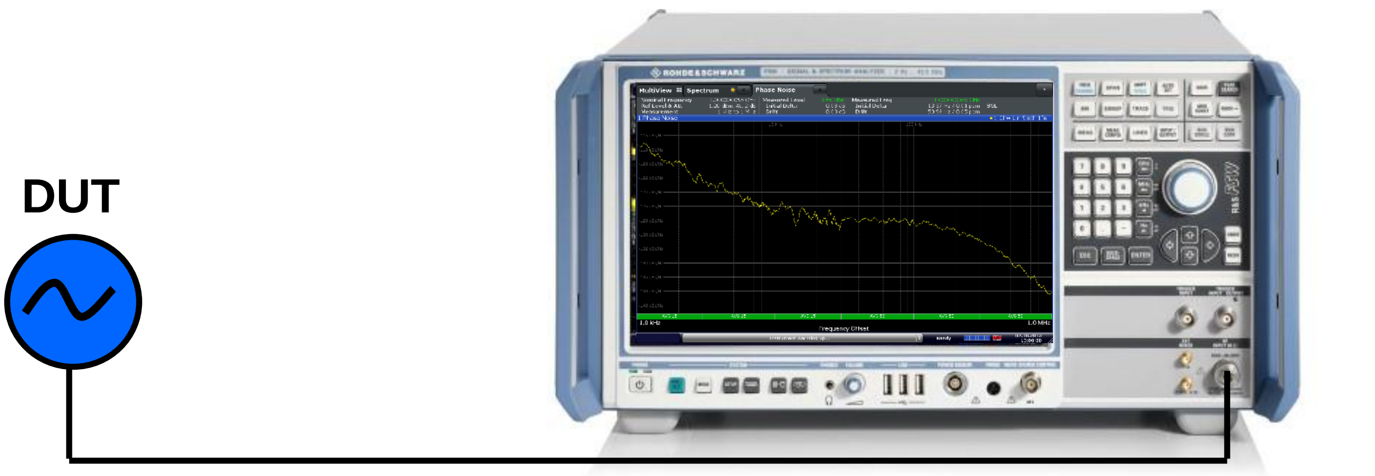
Random Walk:	Close to carrier, generally caused by environmental effects
Flicker FM:	Related to active oscillator physical resonance mechanism, power supply noise
White FM:	Related to passive resonator oscillators
Flicker ϕM:	Related to noisy amplifiers and multipliers
White ϕM:	Far from carrier, generally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

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

Absolute Phase Noise Measurement Techniques

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

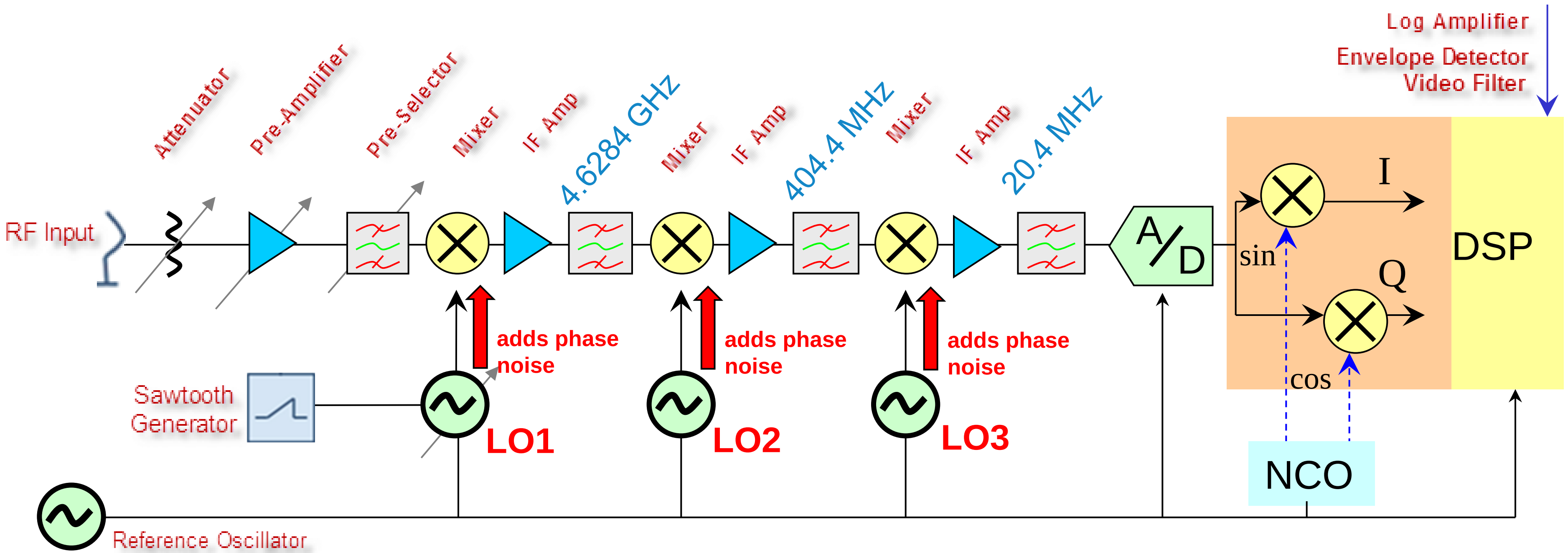
Direct Spectrum Analyzer Measurement



Simple setup, but how good is the measurement?

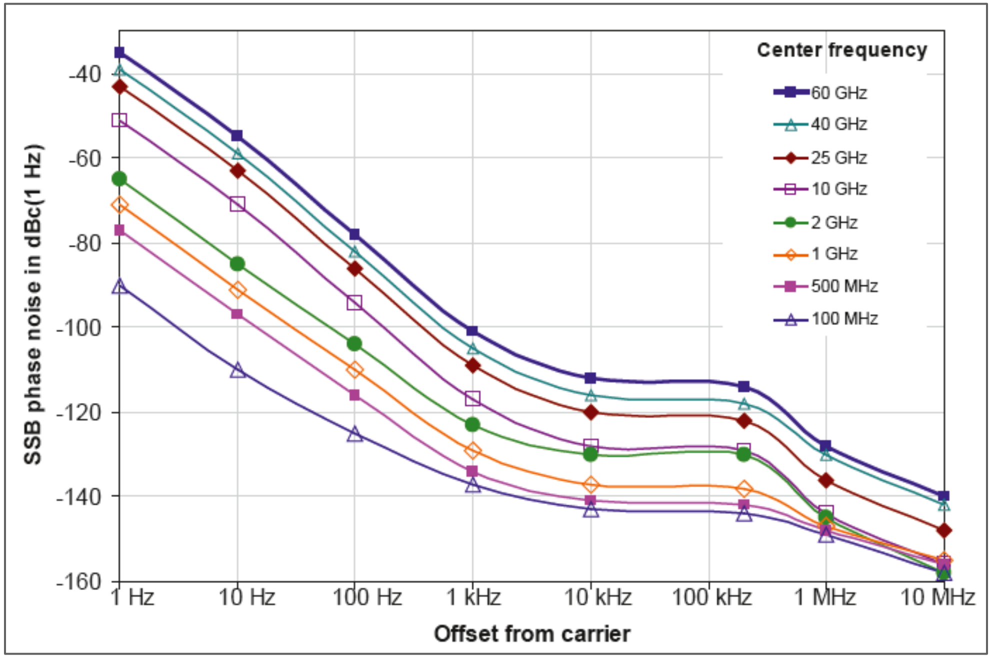
Direct Spectrum Analyzer Measurement

- Spectrum analyzer is a multistage receiver with multiple LOs
- Each LO adds phase noise to the input signal –
  Measurement result is the <u>sum</u> 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 Measurement

- Measurement sensitivity is limited by internal phase noise of spectrum analyzer
- Check data sheet for internal phase noise of spectrum analyzer
- Instrumentation noise always adds to measurement (error, not uncertainty)



R&S FSW Spectrum Analyzer Phase Noise from Data Sheet

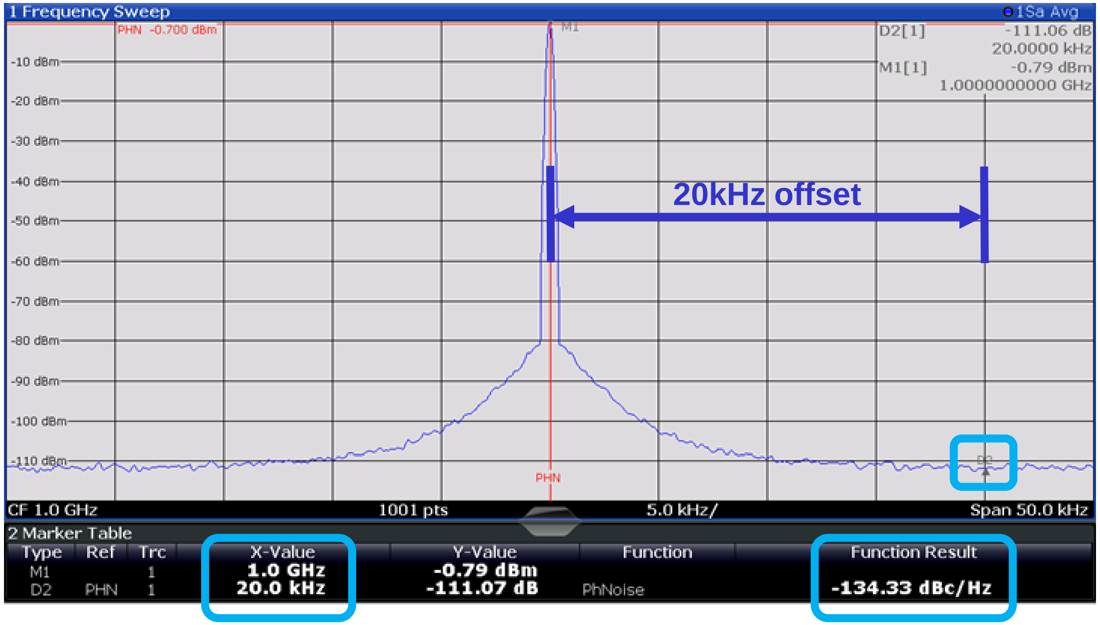
$L_{DUT} - L_{SA}$ (dB)	Meas Error (dB)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
10	0.4
15	0.1
20	0.04

Direct Spectrum Analyzer Measurement

Manual Spot Noise Measurement

- Phase Noise Marker function corrects for ratio of RBW to 1Hz and Effective Noise Bandwidth (ENB) of the RBW filter (typically <1dB)
- Must use averaging to get stable measurement and specifically, <u>power</u> averaging (not log averaging) to avoid measurement error from averaging noise samples in dB domain (-2.51dB)

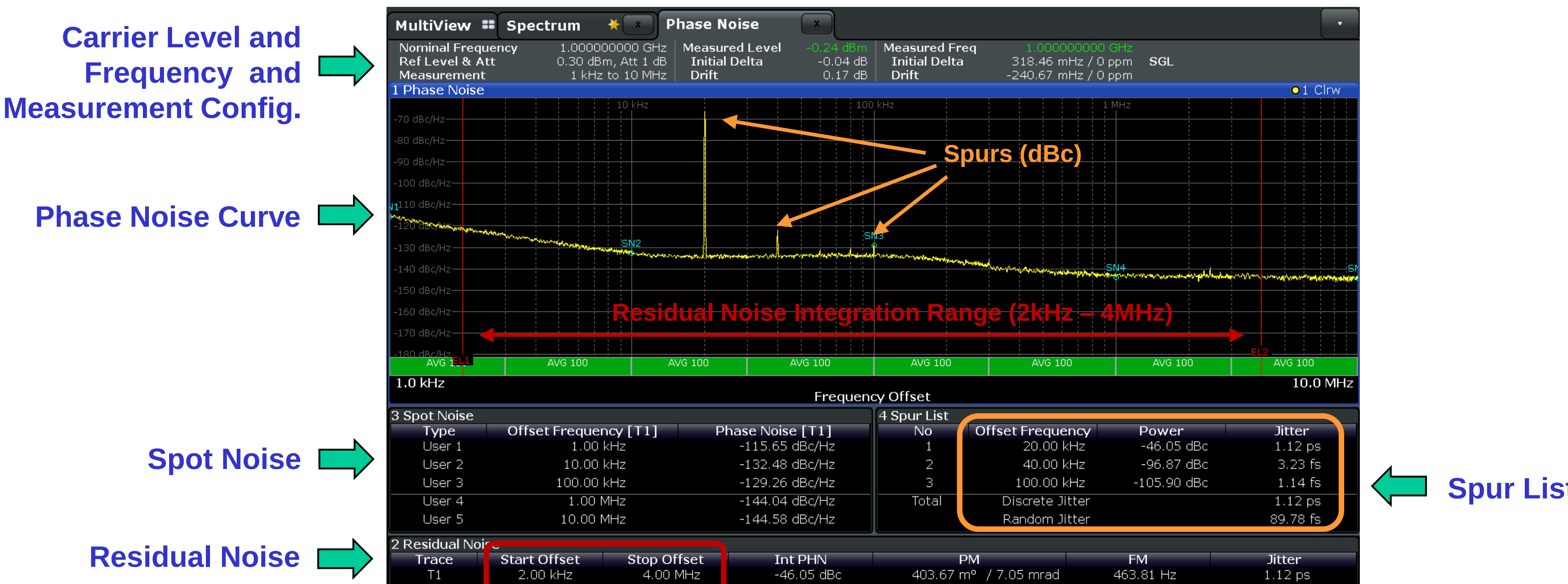
- This <u>technique</u> is correct, but is the measurement accurate?
  - What about the noise of the analyzer?
  - What if we want a phase noise curve instead of a point measurement?
  - What about AM noise?
  - What if I want to measure closer than 1Hz to the carrier?



Direct Spectrum Analyzer Measurement

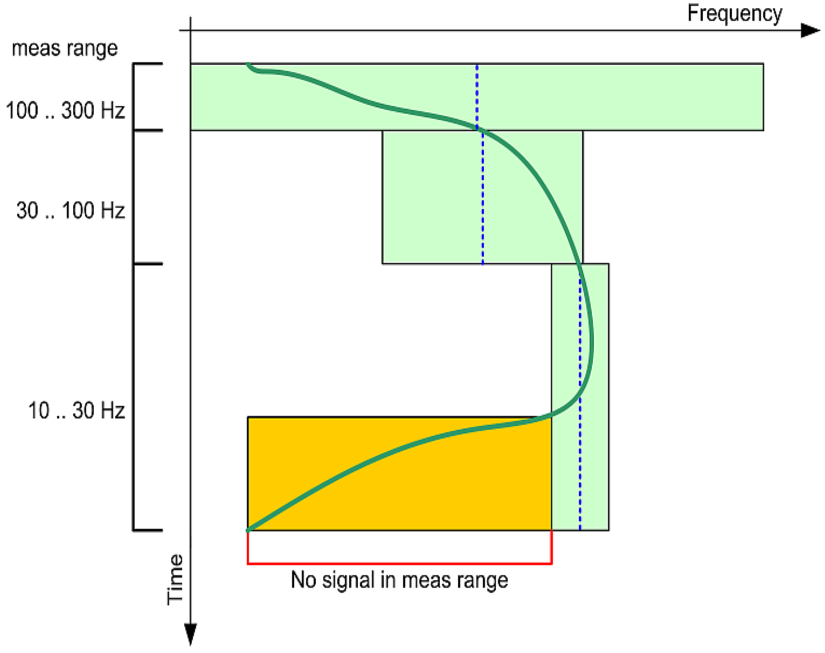
Phase Noise Measurement Personality

- Phase noise is measured over a user specified offset range
- Spot noise is available
- Residual PM, FM, Integrated Phase Noise, and RMS Jitter are calculated from phase noise trace over user specified integration range
- Convenient, fast, and nicely formatted, but still has the limitations of the spectrum analyzer measurement method (phase noise of analyzer, limited close-in capability, etc.)



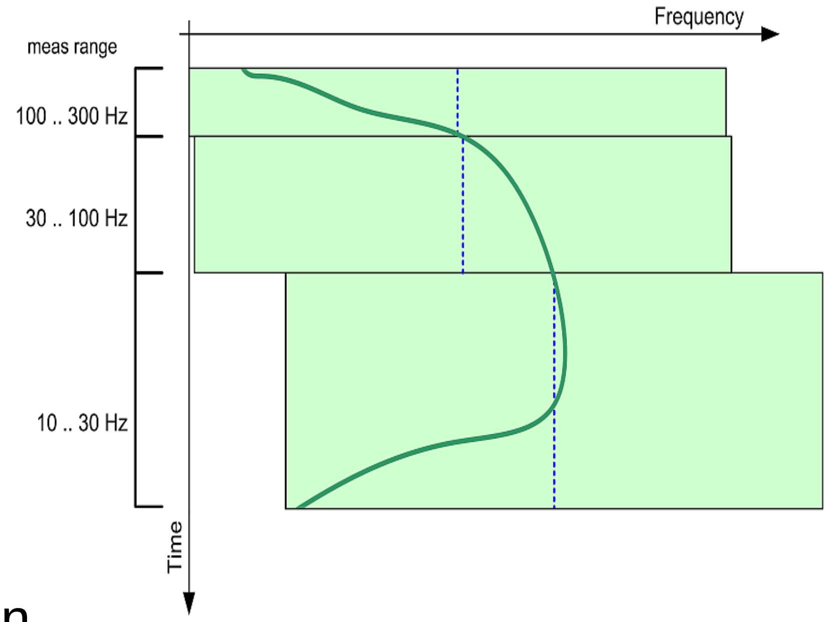
Direct Spectrum Analyzer Measurement
Drifting DUT using traditional approach

- 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 drift more difficult to track
- 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 Measurement
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 using DSP
- Drift is compensated using digital PLL
- Even drifting signal is measured correctly
- Additional benefit: IQ capture approach also provides AM rejection



Direct Spectrum Analyzer Measurement – Summary

Advantages

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

Limitations

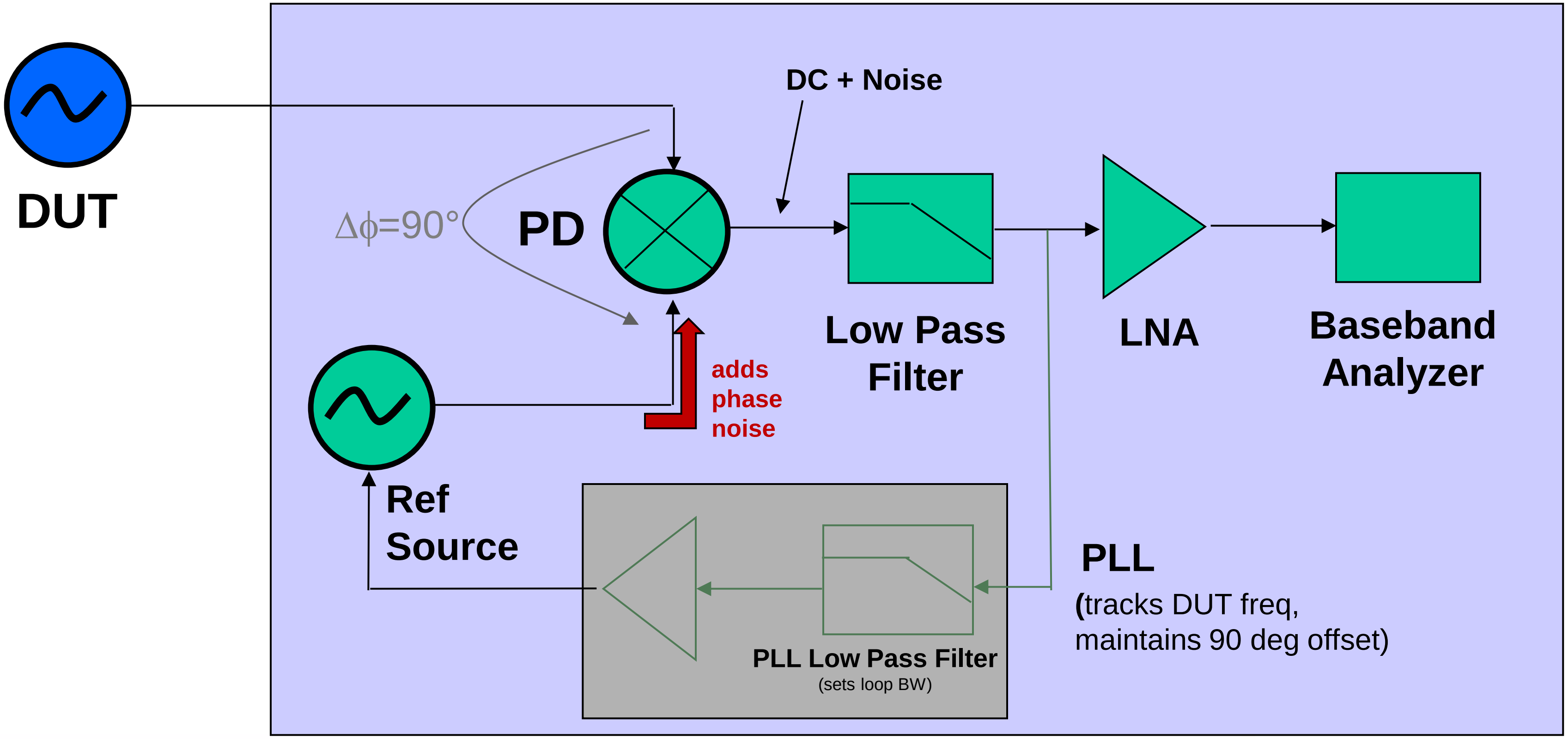
- Sensitivity is limited by inherent phase noise of the internal LO's in the instrument
- Sensitivity also limited by dynamic range since low level noise must be measured in the presence of the carrier
- Most SA's cannot reject AM noise
- Lower offset frequency is limited to 1Hz due to minimum 1Hz RBW

Absolute Phase Noise Measurement Techniques

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

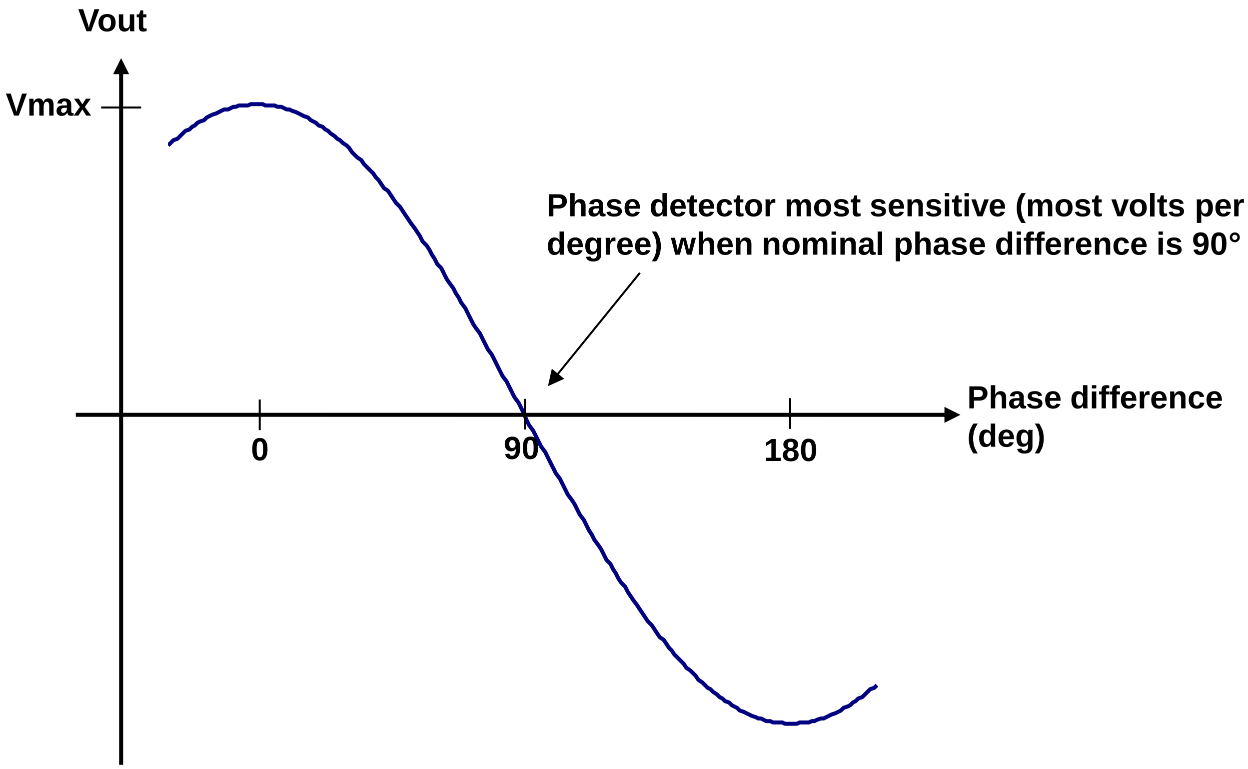
Phase Detector Method

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



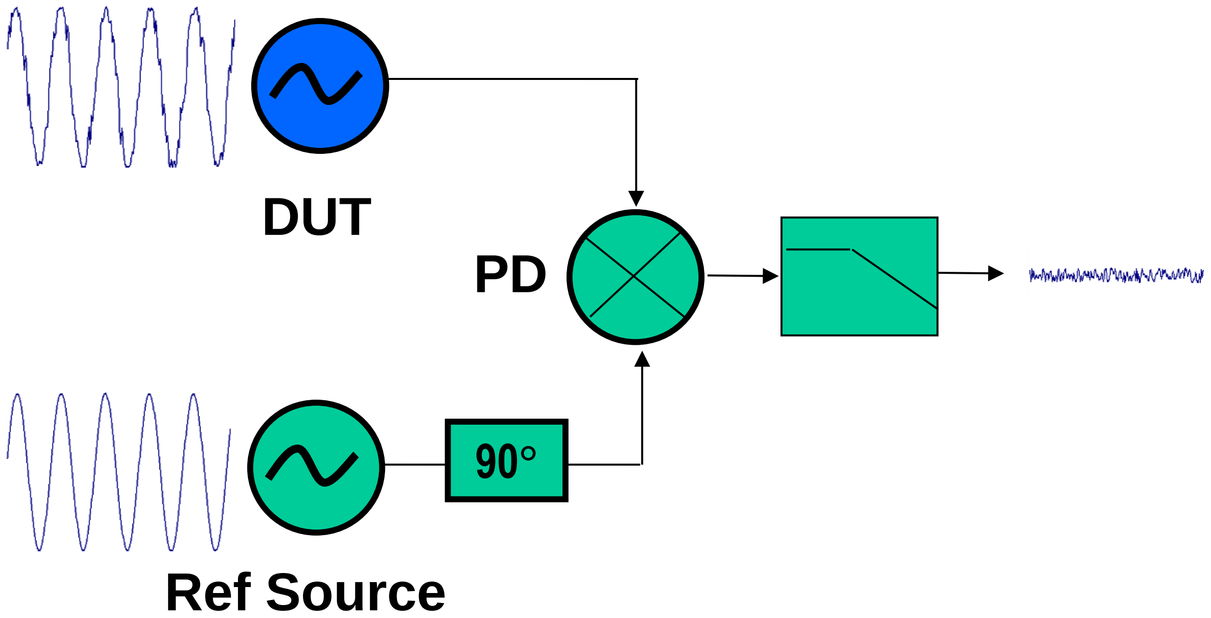
Phase Detector Method

- Why offset DUT and Reference by 90°?



Phase Detector Method

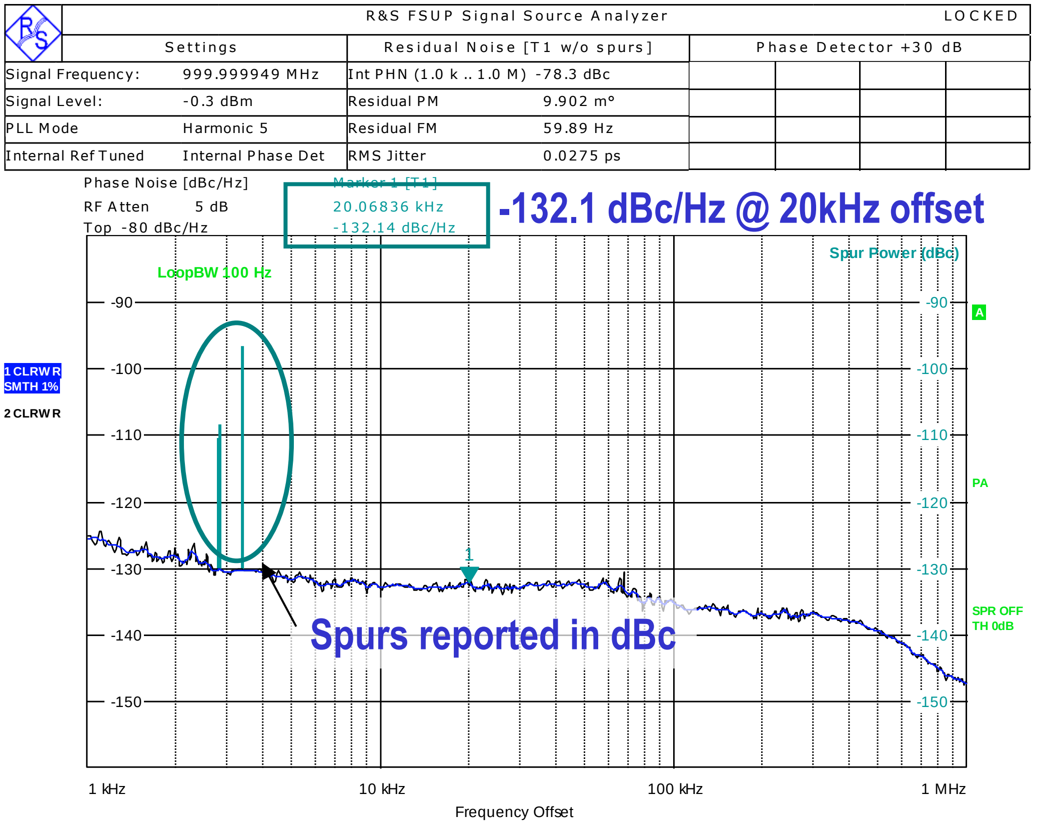
- Spectrum analyzer added phase noise of several internal LO's
- With phase detector approach, only the single reference source phase noise is added – lower measurement floor, better sensitivity
- Same relationship between DUT noise and instrument noise applies, but instrument phase noise is lower



$L_{DUT} - L_{REF}$ (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 Method

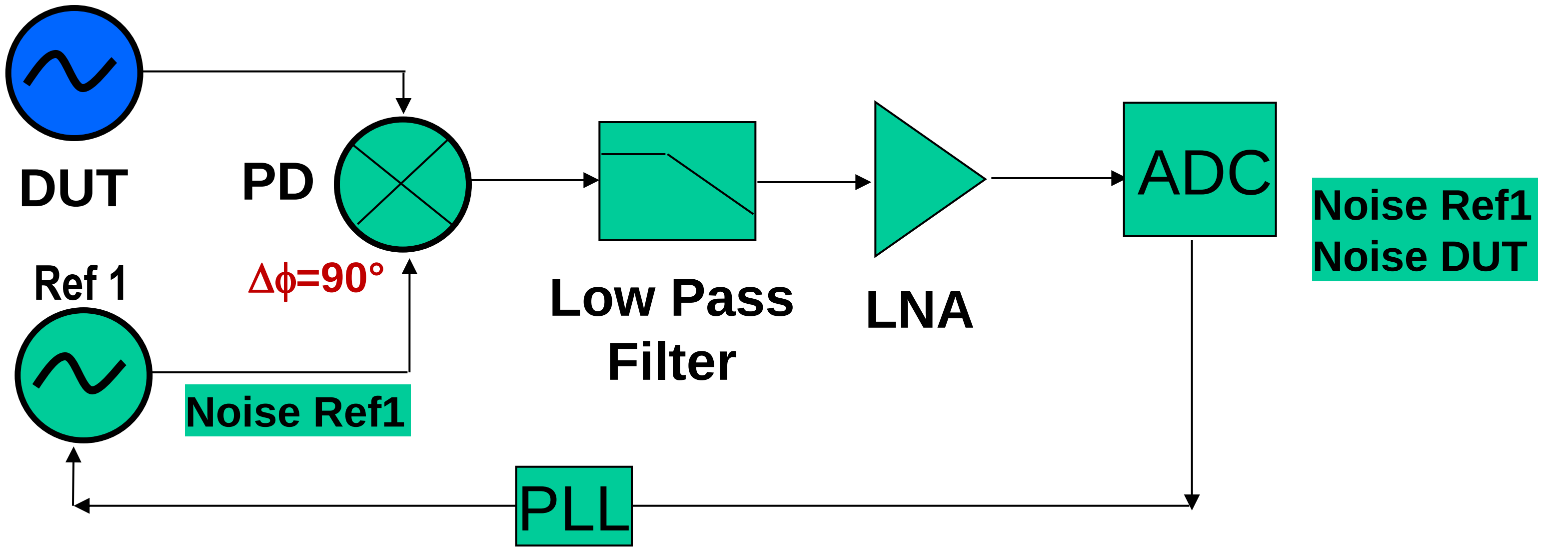
- Same presentation of results as with Spectrum Analyzer measurement.
- Phase Noise curve, Spot Noise, and Residual calculations are available.
- Spur detection algorithm displays and reports spurs separately (in dBc).
- Sensitivity is limited by the phase noise of the reference source which is lower than the multiple LO's in the spectrum analyzer.



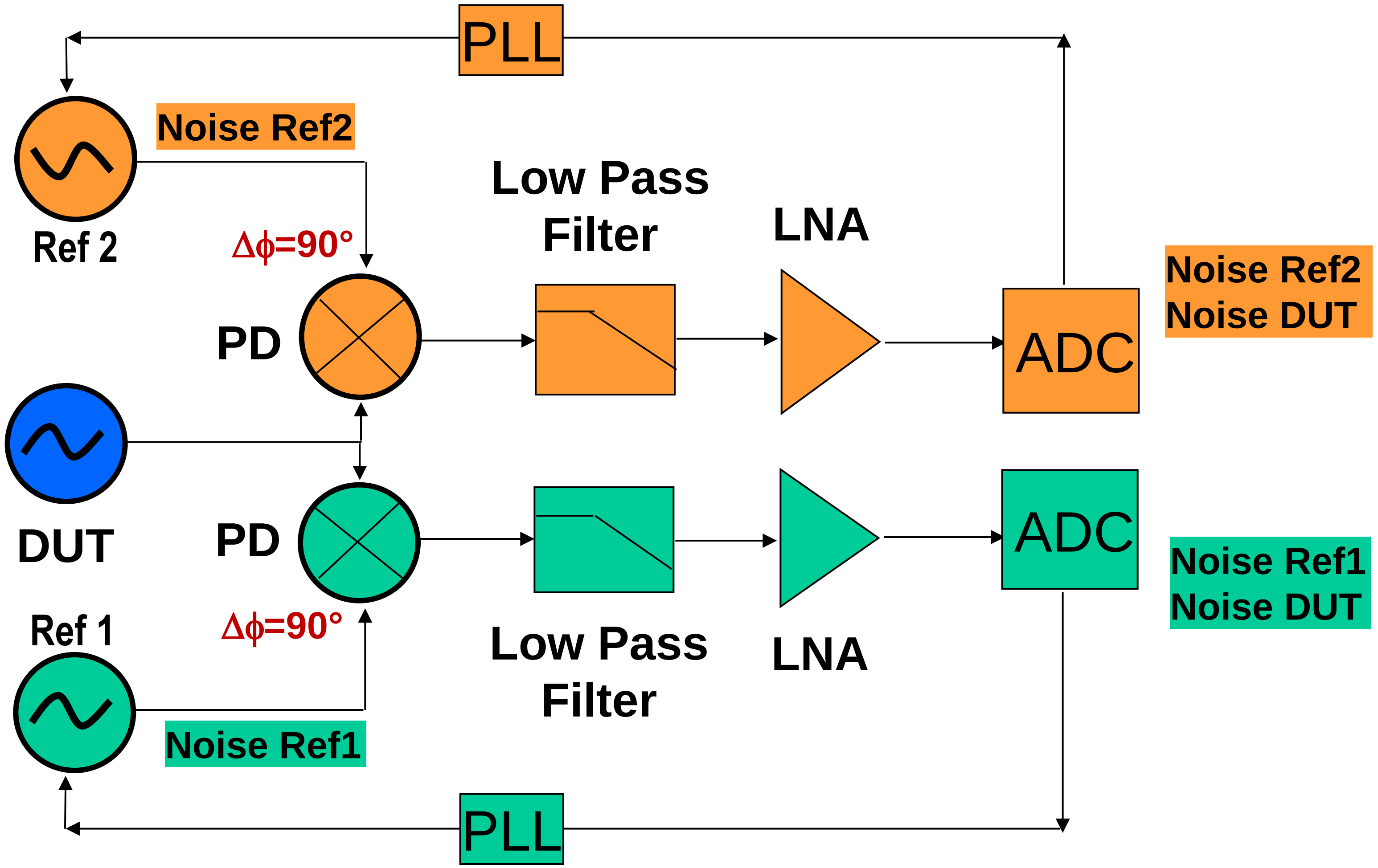
Absolute Phase Noise Measurement Techniques

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

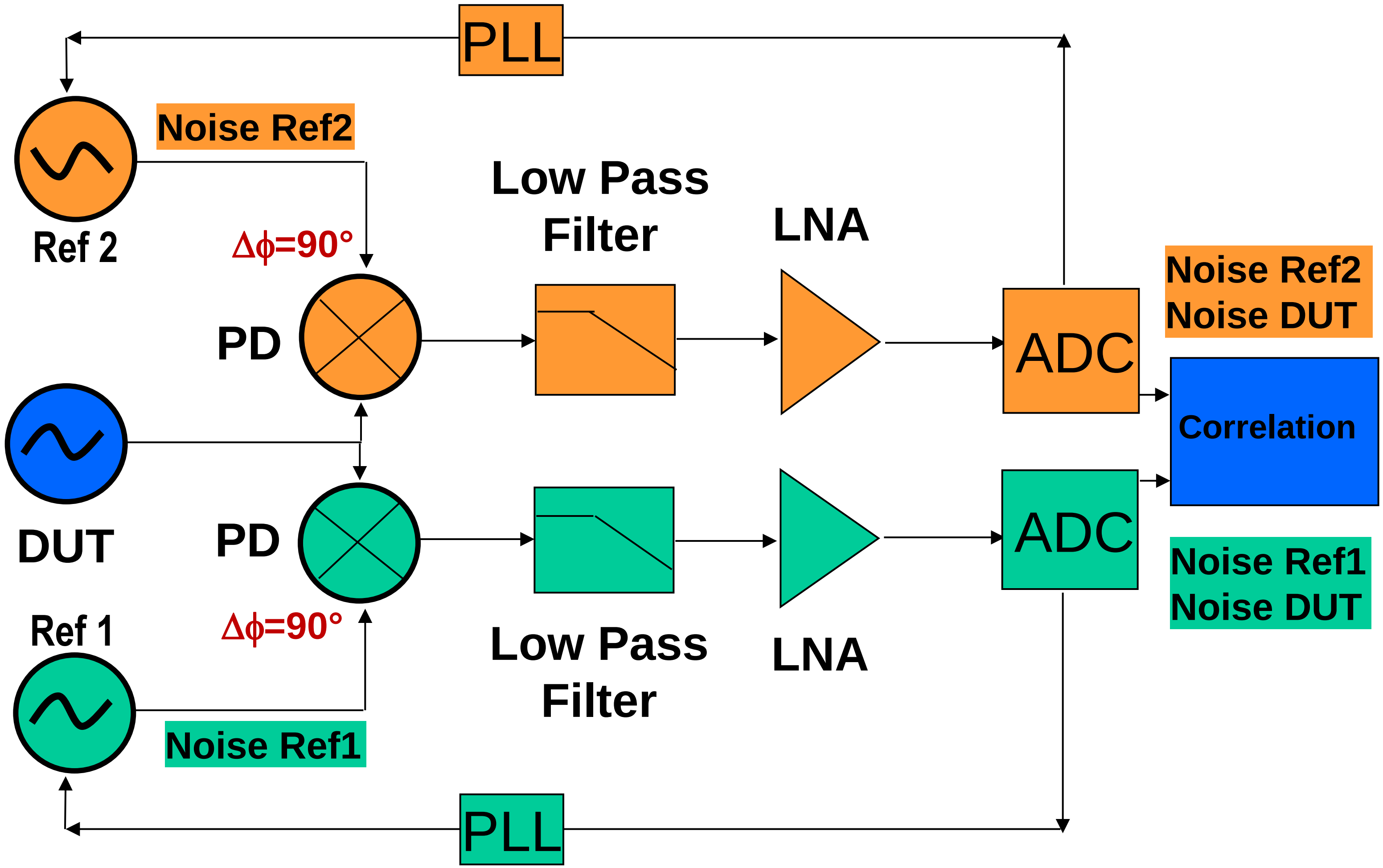
Phase Detector with Cross-Correlation



Phase Detector with Cross-Correlation



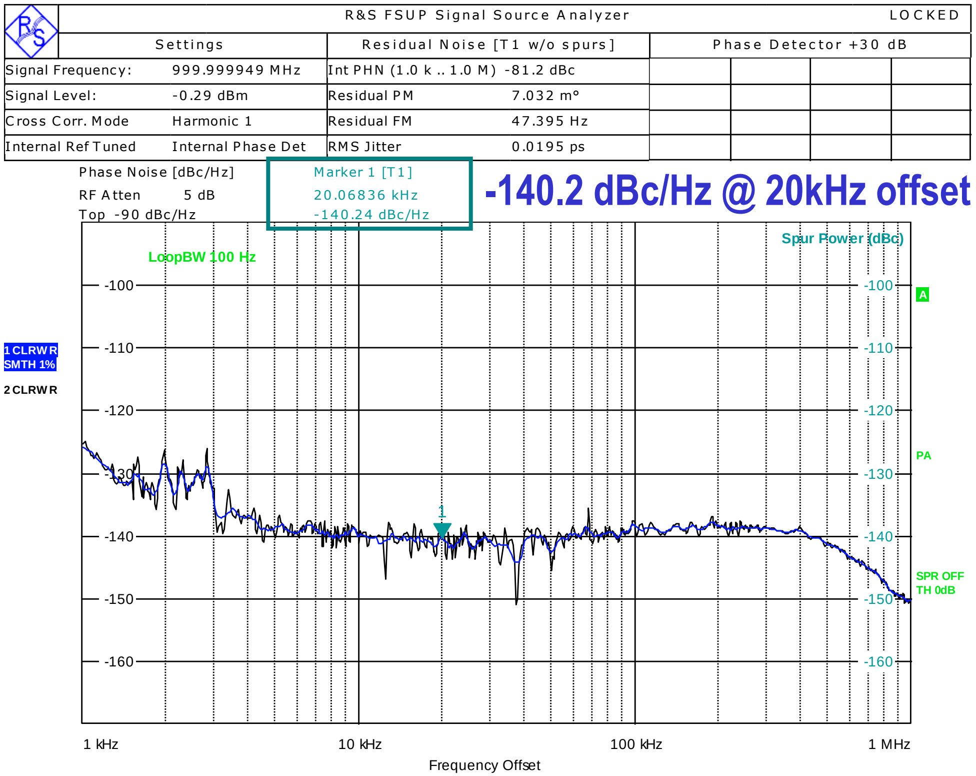
Phase Detector with Cross-Correlation



- 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
- Cross-correlation effectively reduces the phase noise of the reference oscillator
- Up to 20dB sensitivity improvement over the standard phase detector method is possible



Phase Detector Method – Summary

Advantages

- Carrier Suppression
  - 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 Noise and AM Noise can be distinguished
  - AM Noise is inherently suppressed by the phase detector
- Cross-Correlation improves the sensitivity of the test system
  - 10dB for CC=100 , 20dB for CC=10000

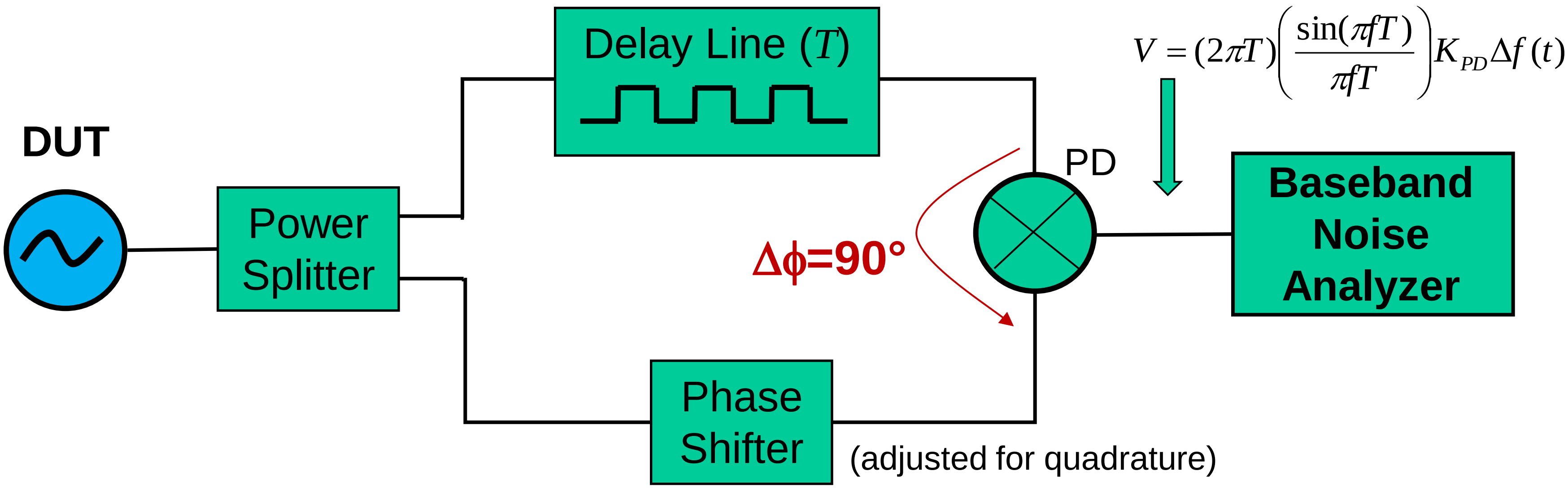
Limitations

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

Absolute Phase Noise Measurement Techniques

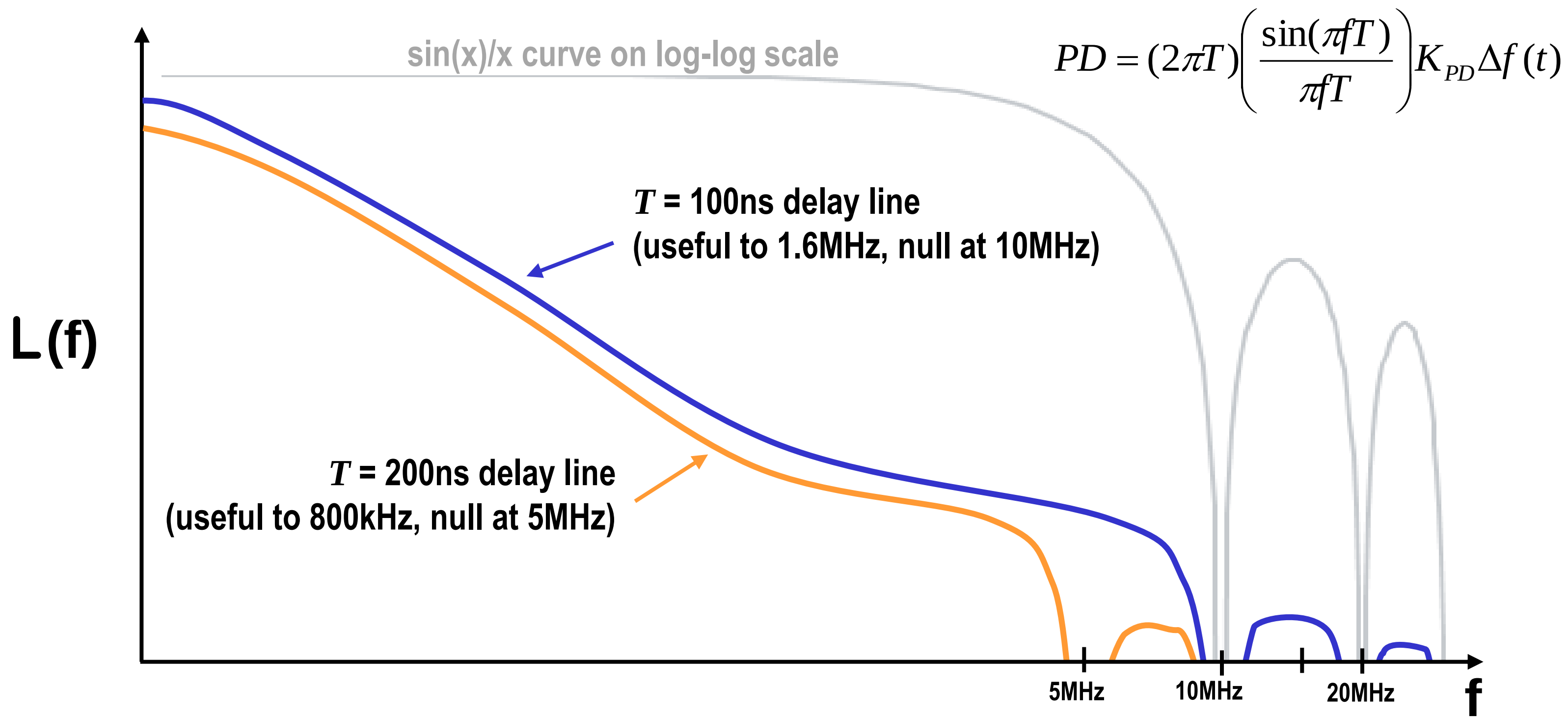
- Direct Spectrum Analyzer
- Phase Detector
- Phase Detector with Cross-Correlation
- ➡ Delay Line Discriminator

Delay Line Discriminator



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

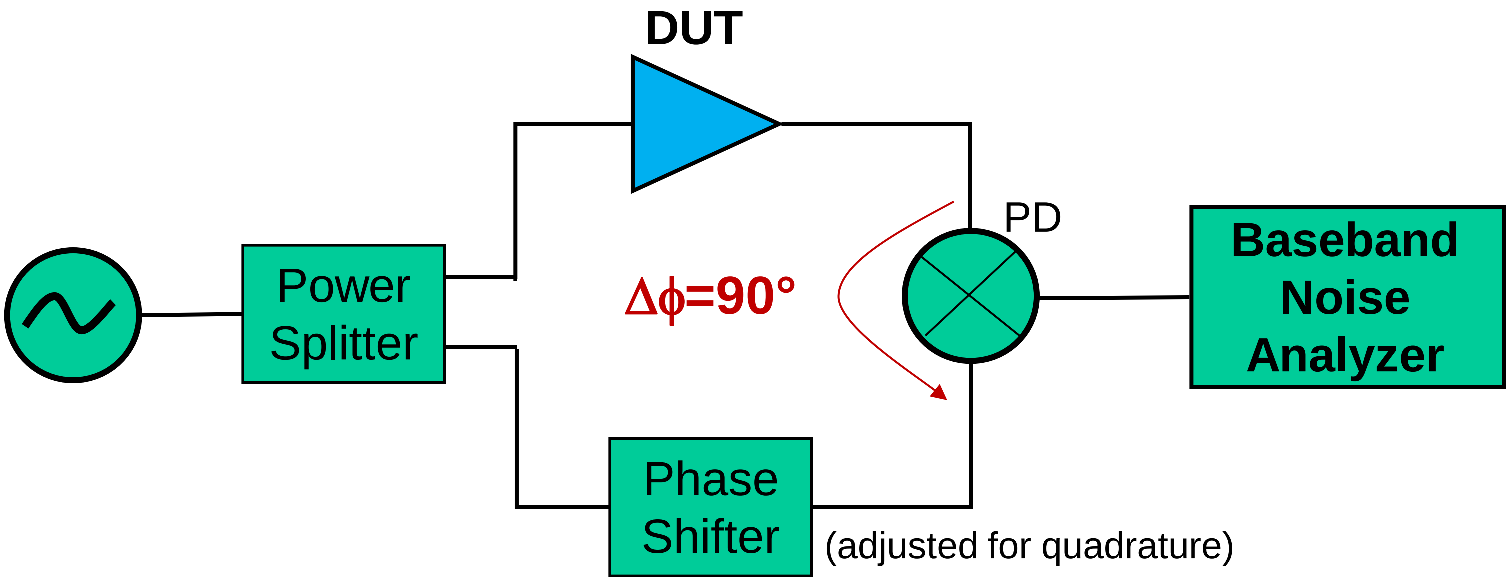
Delay Line Discriminator



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

Additive Phase Noise Measurement

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

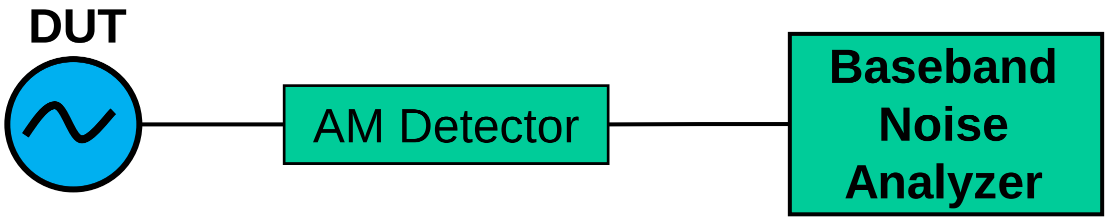


AM Noise Measurement

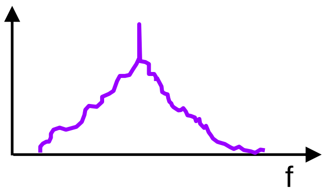
- Recall the expression of a real-world sine wave:

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

- 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
- A signal generator with a known AM modulation index can be used to calibrate the measurement system



Summary



- Phase noise is unintentional phase modulation on a signal
- Residual parameters can be calculated from phase noise data – Integrated Phase Noise, Residual PM, Residual FM, and Jitter
- Absolute Phase Noise can be measured using several methods – each with its own strengths and weaknesses
  - Direct Spectrum Analyzer
  - Phase Detector, Phase Detector + Cross-Correlation
  - Delay Line Discriminator
- Additive Phase Noise is measured using a power splitter, phase shifter, and baseband noise analyzer
- AM Noise is measured using an external diode detector along with a baseband noise analyzer

Thank You!

ROHDE&SCHWARZ