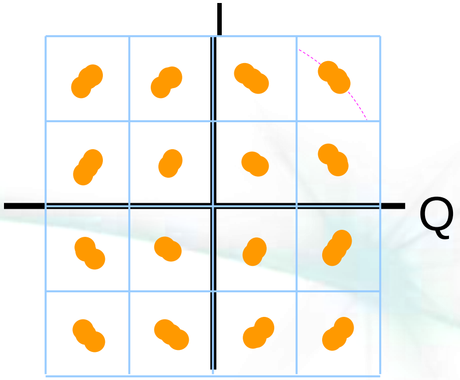
Introduction

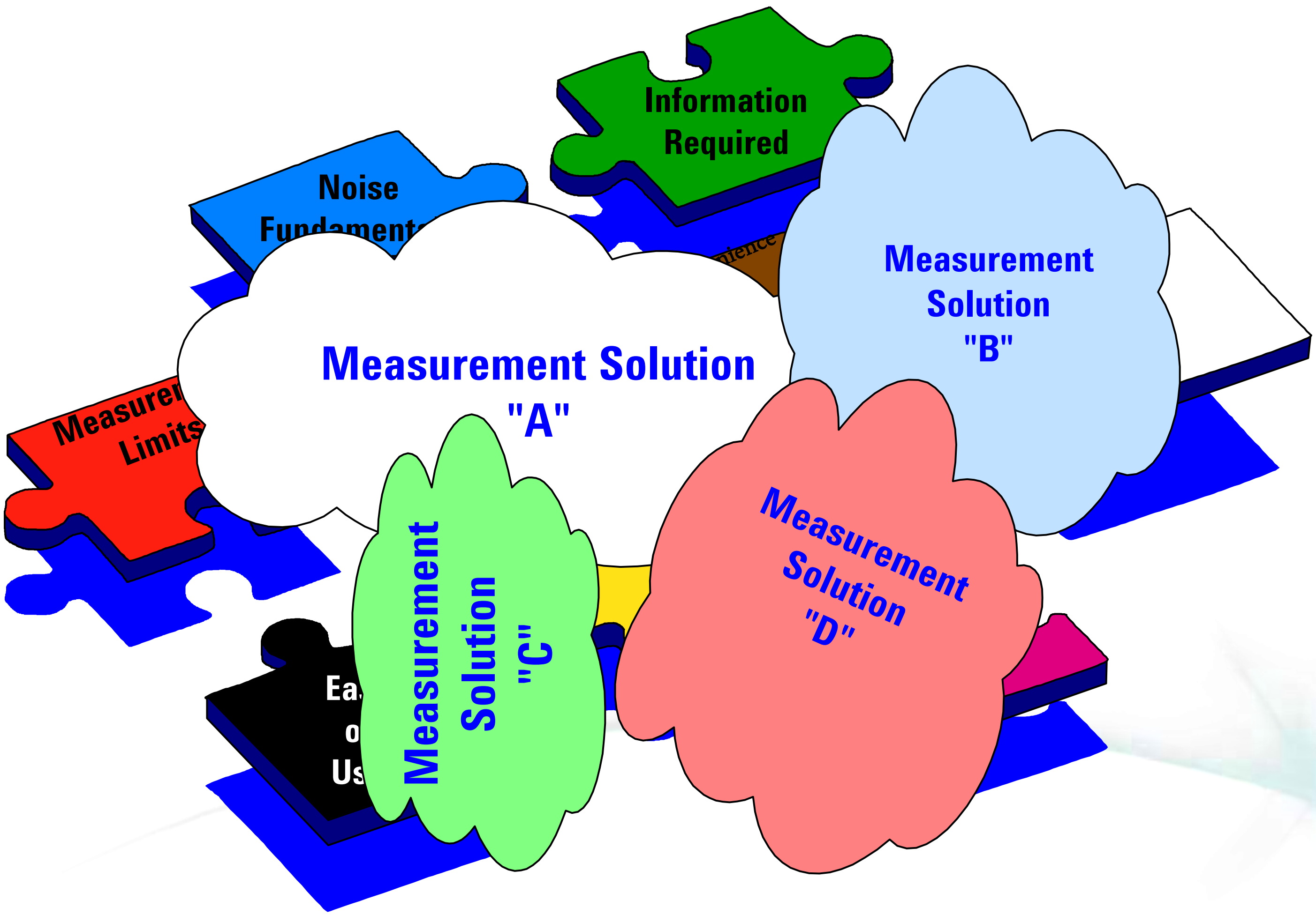
Extracting electronic signals from noise is a challenge for most electronics engineers. As engineers develop cutting edge radar and communications systems, where extreme processing is used to obtain the maximum amount of information from the signal, phase noise is the little understood nemesis limiting system performance.

Phase noise degrades the ability to process Doppler information in radar systems and degrades error vector magnitude in digitally modulated communications systems



Phase Noise

Phase Noise Measurements



Agenda

- What is phase noise?
- Phase noise measurement techniques
  - Direct phase noise measurement (with a spectrum analyzer)
  - Phase detector techniques
  - Two-channel cross correlation method
- Agilent E5500 Phase Noise Measurement System
- Comparison of Agilent Phase Noise Measurement Solutions
- Summary
- Bibliography

What is Phase Noise?

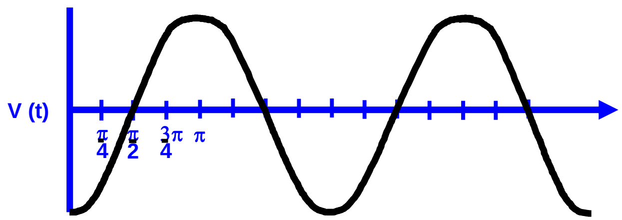
- The basic concept of phase noise centers around frequency stability, or the characteristic of an oscillator to produce the same frequency over a specified time period.
- Frequency stability can be broken into two components:
  - Long-term frequency stability—frequency variations that occur over hours, days, months, or even years
  - Short-term frequency stability—describing frequency changes that occur over a period of a few seconds, or less, duration.
- In our discussion of phase noise we will focus on short-term frequency variations in oscillators and other electronic devices like amplifiers
- Phase noise can be described by in many ways, but the most common is single sideband (SSB) phase noise, generally denoted as $\mathcal{L}(f)$
- The U.S. National Institute of Standards and Technology (NIST) defines $\mathcal{L}(f)$ as the ratio as the power density at an offset frequency from the carrier to the total power of the carrier signal.

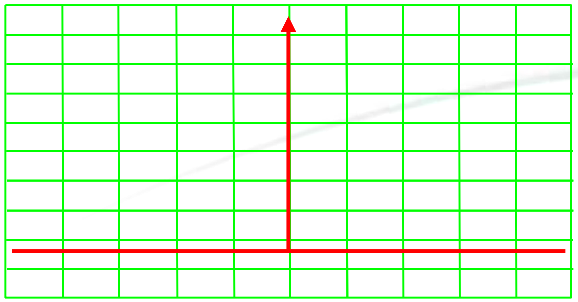
What is Phase Noise?

Ideal Signal

$$V(t) = A_o Sin(\omega_o(t))$$

Where:
A_o = nominal amplitude
ω_o = nominal frequency

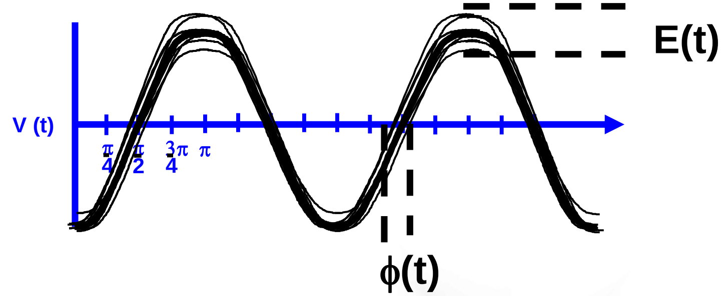


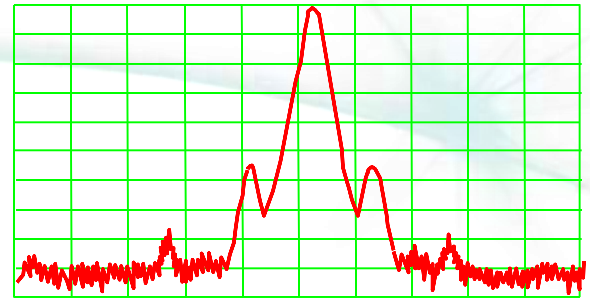


Real-World Signal

$$V(t) = (A_o + E(t))Sin(\omega_o(t) + \phi(t))$$

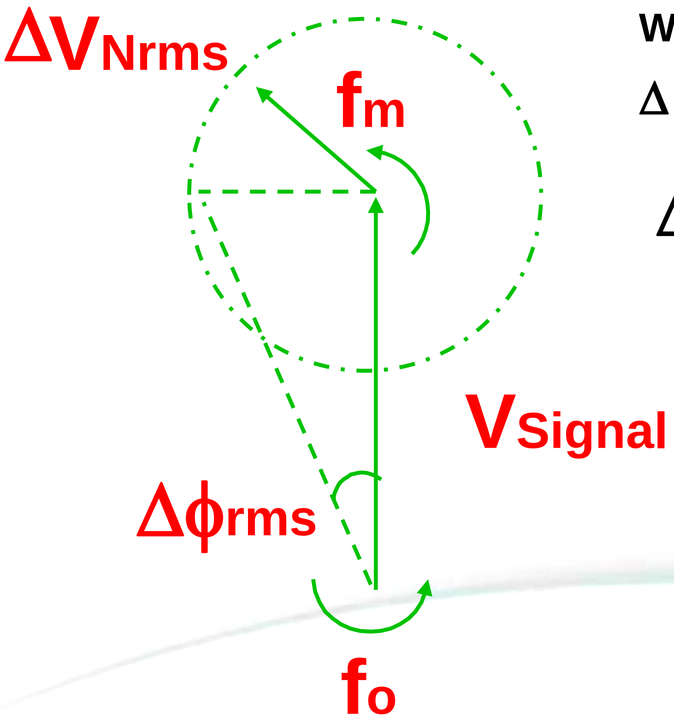
Where:
E(t) = random amplitude changes
Φ(t) = random phase changes





What is Phase Noise?

Using Phasor Relationships



Where

ΔV_{Nrms} = amplitude noise

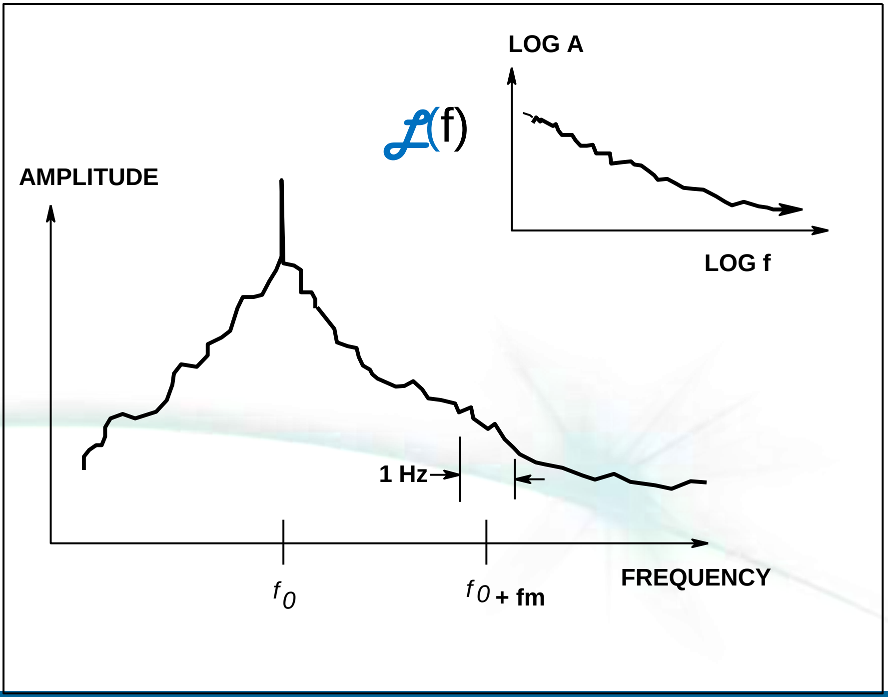
$\Delta\phi_{rms}$ = phase noise

What is Phase Noise?

Unit of measure

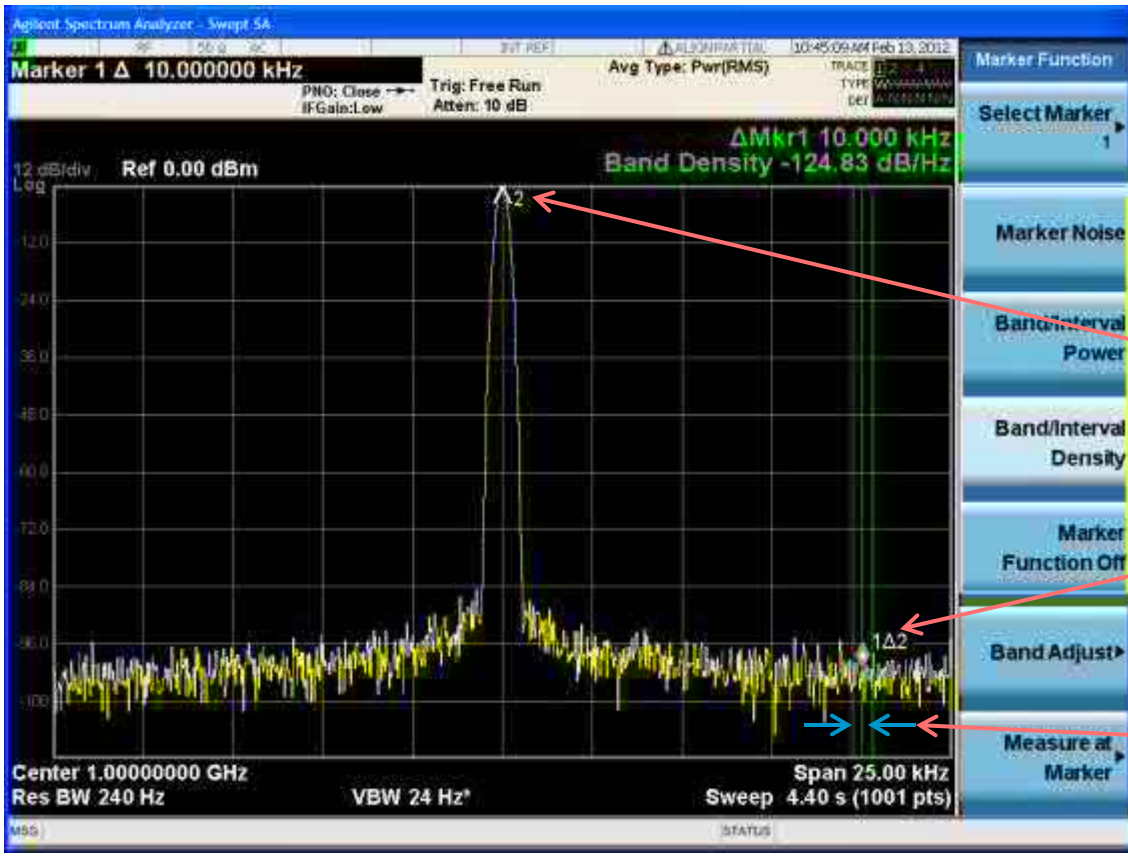
- Usually single sideband phase noise is denoted as $\mathcal{L}(f)$
- $\mathcal{L}(f)$ —*defined as single sideband power due to phase fluctuations referenced to total power*
  - In a 1 Hz bandwidth at a frequency f Hz from the carrier
  - Divided by the signal's total power
  - $\mathcal{L}(f)$ has units of dBc/Hz
  - $\mathcal{L}(f)$ is plotted using log frequency

$$L(f) = \frac{\text{Area of 1 Hz bandwidth}}{\text{Total area under the curve}}$$



Direct Phase Noise with a Spectrum Analyzer

$$\mathcal{L}(f) = \frac{\text{Noise power in a 1 Hz bandwidth}}{\text{Total signal power}}$$



$\mathcal{L}(f) = P_n$ (dBm/Hz) - P_s (dBm)

P_s (dBm)

P_n (dBm/Hz)

1 Hz bandwidth, generally normalized to 1 Hz

Thermal Noise or Johnson Noise

N_p = KTB

K = Boltzman's constant   T = Temperature (K)   B = Bandwidth (Hz)

For T = 290K

$$Np = -204\frac{dB(Watts)}{Hz} = -174\frac{dBm}{Hz}$$

Thermal Noise Limitations on Phase Noise Measurements

$$\mathcal{L}(f) = P_n \text{ (dBm/Hz)} - P_s \text{ (dBm)}$$

Total Power (kTB) = Pn (kTB) = -174 dBm/Hz
Phase Noise and AM noise equally contribute
Phase Noise Power (kTB) = -177 dBm/Hz

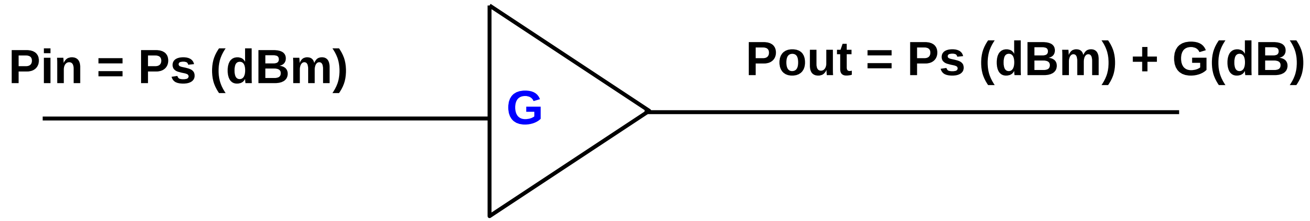
Theoretical KTB limits to phase noise measurements for low-level signals

P_s (dBm)	$\mathcal{L}(f)$ dBc/Hz
+10	-187
0	-177
-10	-167
-20	-157

Note: There are other measurement factors besides kTB limitations which can reduce the theoretical measurement limit significantly.

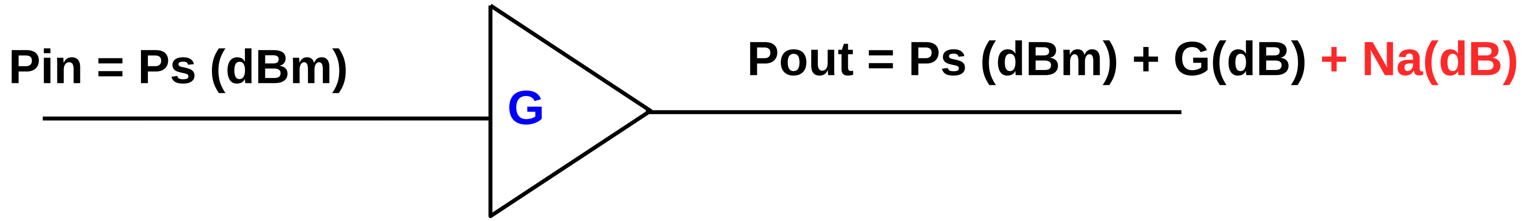
The Universal Solution to Low-Power Signals

Add an Amplifier

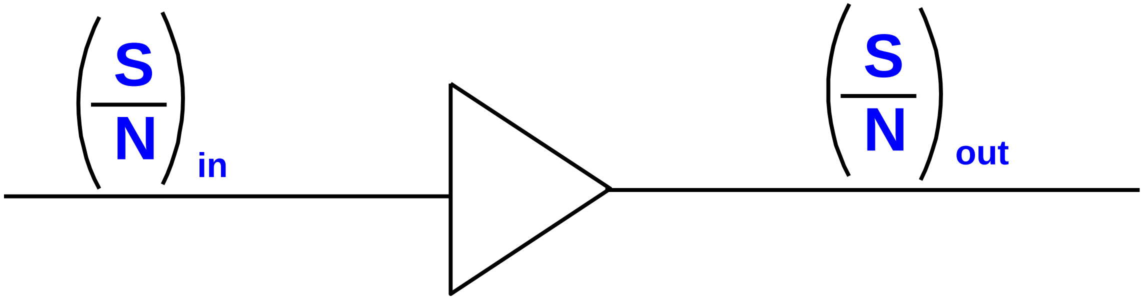


The Universal Solution to Low-Power Signals

Add an Amplifier



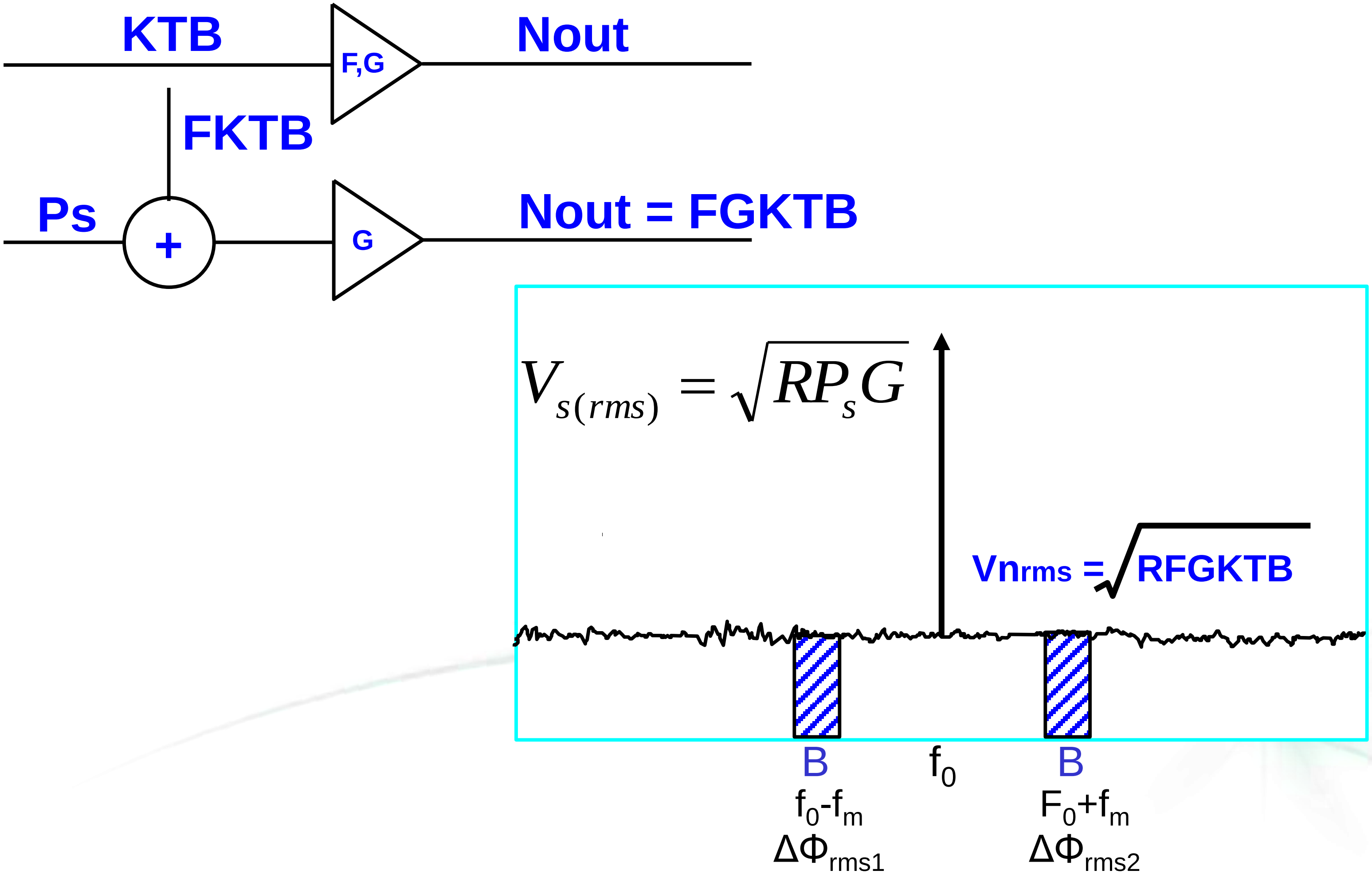
Amplifier Noise Figure



$$F = \left. \frac{(S/N)_{in}}{(S/N)_{out}} \right|_{T=290K}$$

What does noise figure have to do with phase noise?

Amplifier Noise



Phasor View of Amplifier Noise

For small $\Delta\Phi_{rms}$, where $\tan^{-1}(x) \approx x$:

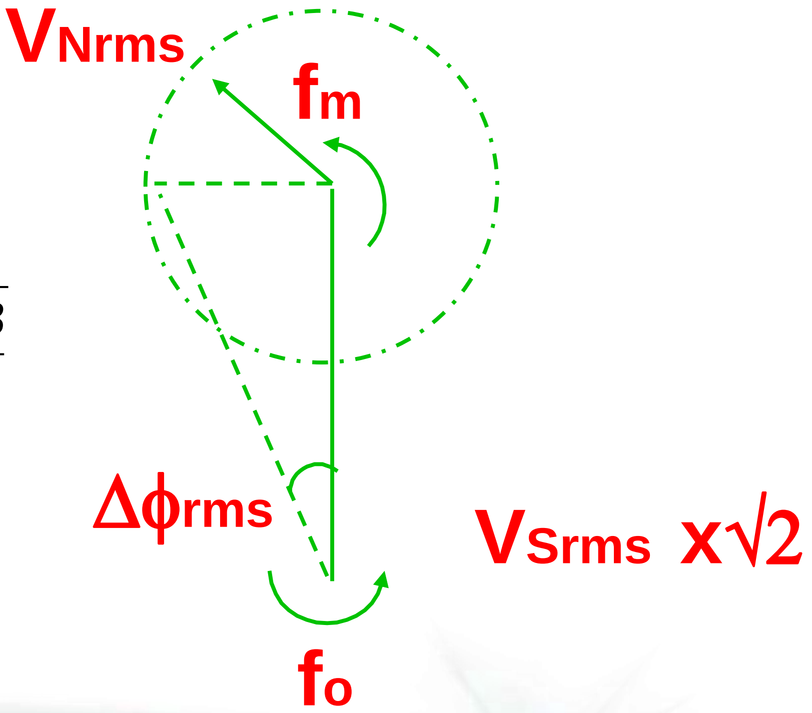
$$\Delta\Phi_{rms} = \frac{V_{Nrms}}{V_{Srms}\sqrt{2}} = \sqrt{\frac{FGkTB}{2P_sG}}$$

$$\Delta\Phi_{rms}Total = \sqrt{\Delta\Phi^2{}_{rms1} + \Delta\Phi^2{}_{rms2}} = \sqrt{\frac{FkTB}{P_S}}$$

The spectral density of phase fluctuations:

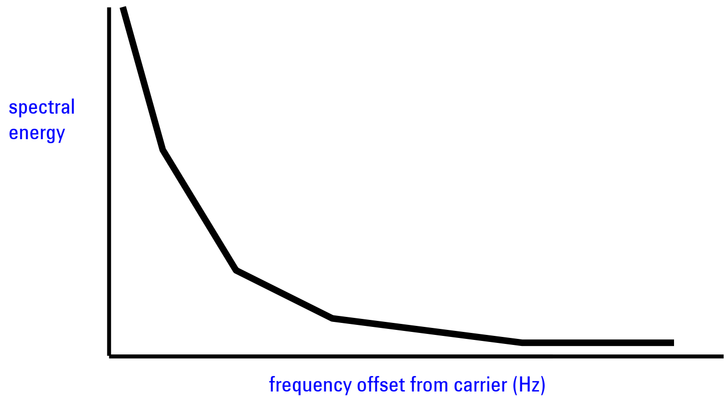
$$S_\Phi(f) = \frac{\Delta\Phi^2{}_{rms}(f)}{B} = \frac{FkT}{P_S}\left[\frac{rad^2}{Hz}\right]$$

$$L(f) = \frac{S_\Phi(f)}{2} = \frac{FkT}{2P_S}\left[\frac{rad^2}{Hz}\right]$$



Quantifying Phase Noise

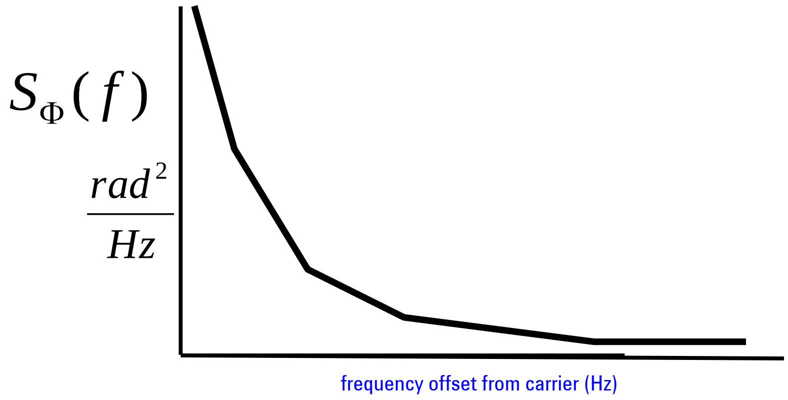
Quantifying Phase Noise in Terms of Power Spectral Density



$S_{\Phi}(f)$, Spectral density of phase fluctuations
$\mathcal{L}(f)$, Single sideband phase noise relative to total signal power
$S_{\nu}(f)$, Spectral density of frequency fluctuations
$S_{y}(f)$, Spectral density of fractional frequency fluctuations

Quantifying Phase Noise

$S_\Phi(f)$ or Spectral Density of Phase Fluctuations



Demodulate phase modulated signal with a phase detector (convert phase fluctuations to voltage fluctuations)

$\Delta v_{out} = K_\Phi \Delta\Phi_{in}$ Where: K_Φ = V/radian

Measure the voltage fluctuations on a spectrum analyzer:

$\Delta V_{rms}(f) = K_\Phi \Delta\Phi_{rms}(f)$

$$S_\Phi(f) = \frac{\Delta\Phi^2{}_{rms}(f)}{K_\Phi{}^2 B} = \frac{S_v rms(f)}{K_\Phi{}^2}\left[\frac{rad^2}{Hz}\right]$$

$Sv_{rms}(f)$ = the power spectral density of the voltage fluctuations out of the phase detector

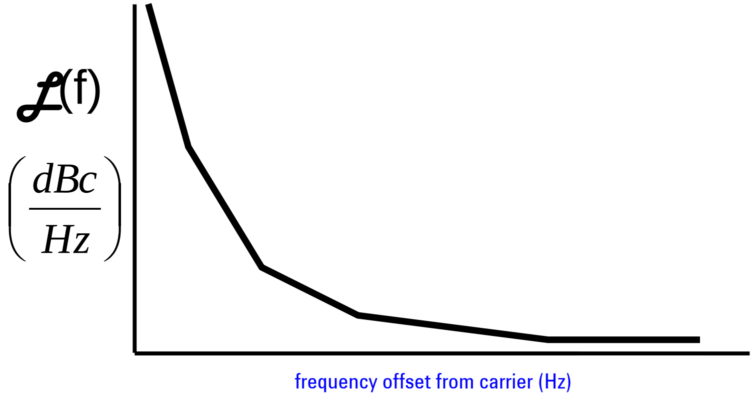
$S_\Phi(f)$ can be expressed in dB relative to 1 radian

Agilent Technologies

Quantifying Phase Noise

$\mathcal{L}(f)$, Single Sideband Phase Noise

- Due to phase fluctuations referenced to carrier power



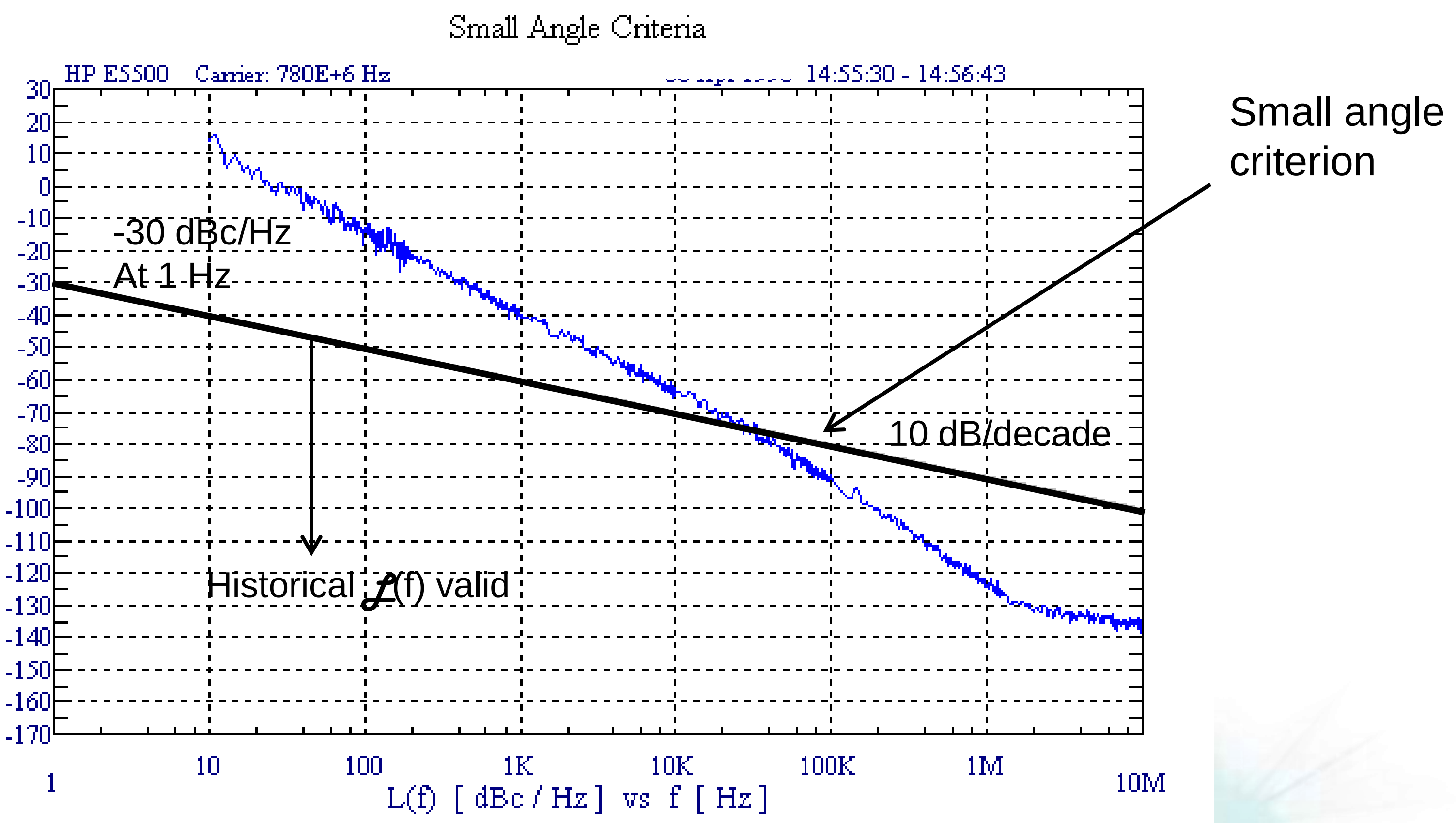
$$\mathcal{L}(f) = \frac{\text{Power density (one phase modulated sideband)}}{\text{Carrier Power}} \left(\frac{dBc}{Hz}\right)$$

$$L(f) = \frac{S_{\Phi}(f)}{2}$$

Agilent Technologies

Single Sideband Phase Noise (Region of Validity)

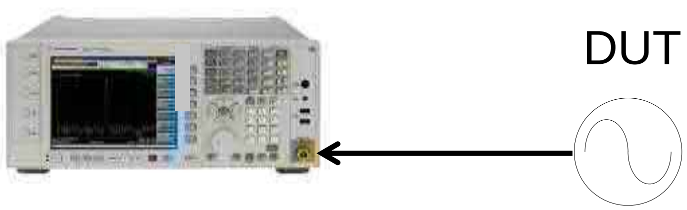
$$L(f) = \frac{S_{\Phi}(f)}{2}$$

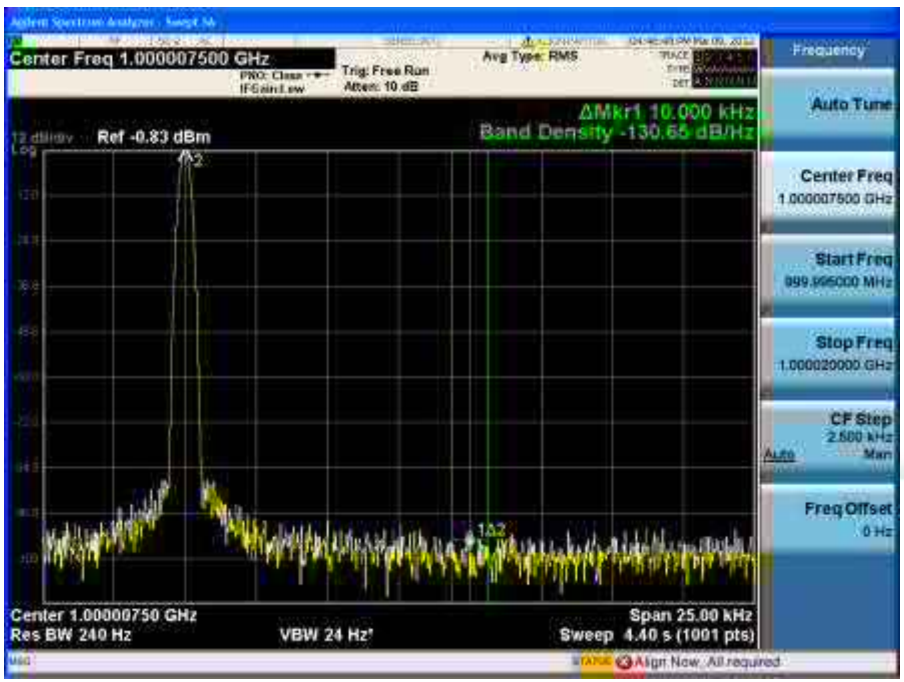


Agenda

- What is phase noise?
- Phase noise measurement techniques
  - Direct phase noise measurement (with a spectrum analyzer)
  - Phase detector techniques
  - Two-channel cross correlation method
- Agilent E5500 Phase Noise Measurement System
- Comparison of Agilent Phase Noise Measurement Solutions
- Summary
- Bibliography

Direct Spectrum Method





- Oldest phase noise measurement method
- Simplest and easiest method of phase noise measurement
  - The device under test (DUT) is directly connected to the input of a spectrum analyzer
  - The analyzer is tuned to the carrier frequency
  - Directly measure the power spectral density of the oscillator in terms of $\mathcal{L}(f)$

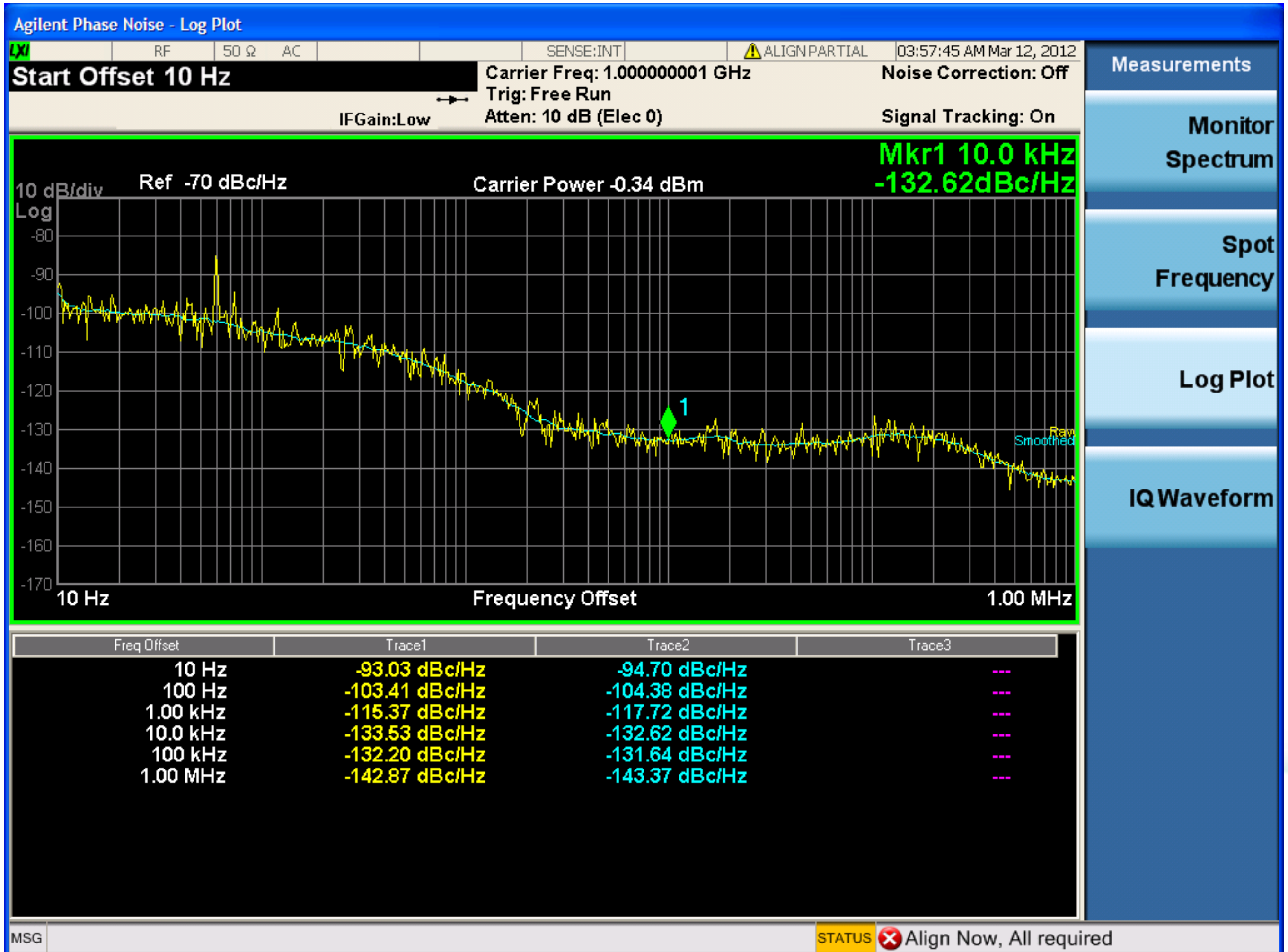
Phase noise measurement personalities further simplify the measurement

Limitations of the Direct Spectrum Method

The following factors limit the accuracy of direct spectrum phase noise measurements:

- IF (RBW) filter bandwidth, verses noise bandwidth
- IF filter type and shape factor
- Local oscillator stability—residual FM
- Local oscillator stability—noise sidebands
- Analyzer's detector response to noise—peak detector introduces error
- Analyzer's log amplifiers response to noise
- Noise floor of the analyzer

Agilent N9068A Phase Noise Measurement Application for PXA, MXA, and EXA

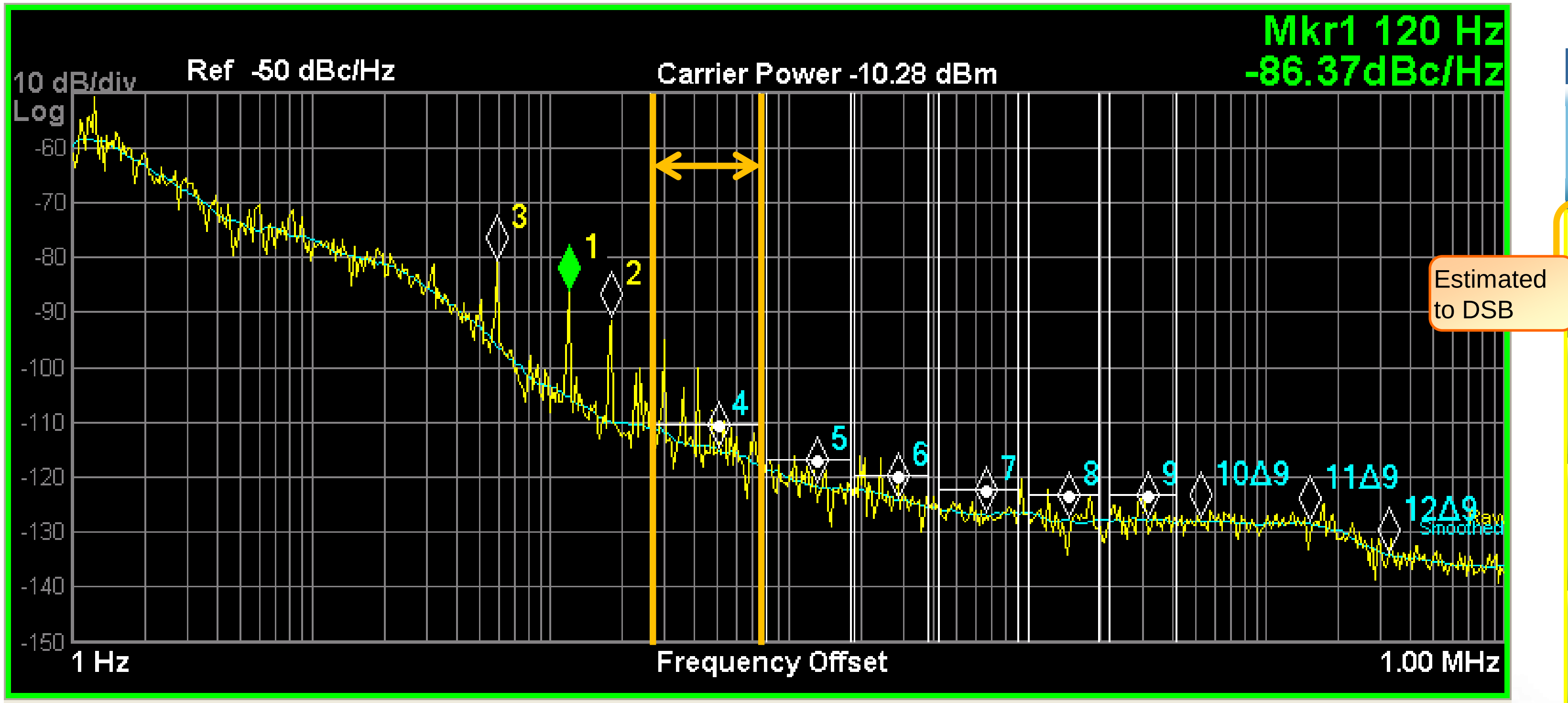


- N9068A provides a simple one-button PN measurement
- Can:
  - Monitor a spectrum
  - Spot measurement verses time at a single frequency
  - Log plot, as shown here

N9068A Marker Functions

- Spurious Search:
  - Next spur, next spur right, and next spur left
- Band Marker Functions:
  - RMS integrated phase deviation in degrees
  - RMS integrated phase deviation in radians
  - RMS integrated jitter in seconds
  - RMS integrated phase noise in dBc per marker bandwidth Hz
  - Residual FM (frequency weighted integrated) in Hz
  - RMS averaged phase noise density in dBc/Hz
- Delta Marker Scales:
  - Absolute (+ Δx Hz)
  - Octave slope (x $\Delta 2^x$ Hz)
  - Decade slope (x $\Delta 10^x$ Hz)

N9068A Band Marker Functions
RMS *integrated* phase deviation in degree



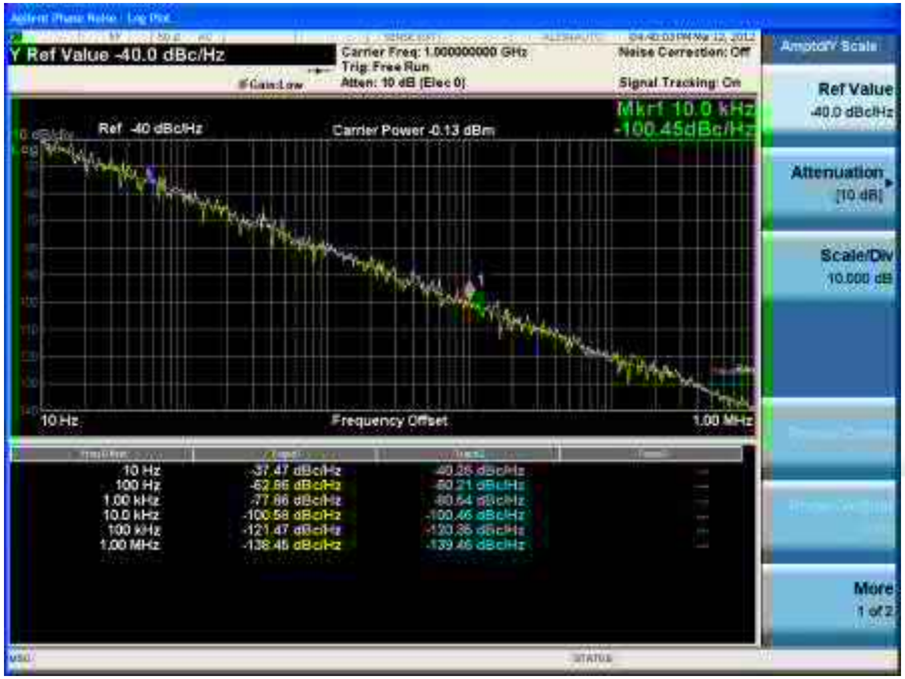
MKR	MODE	TRC	X	Y	FUNCTION	FUNCTION WIDTH	FUNCTION VALUE
1	N	1	120 Hz	-86.37dBc/Hz			
2	N	1	182 Hz	-91.26dBc/Hz			
3	N	1	60.3 Hz	-80.86dBc/Hz			
4	N	2	513 Hz	-115.05 dBc/Hz	Integ Noise	500 Hz	3.445 mDeg
5	N	2	1.32 kHz	-121.39 dBc/Hz	Integ Noise	1.00 kHz	40.53 µRad
6	N	2	2.88 kHz	-124.17 dBc/Hz	Integ Noise	2.00 kHz	3.468 fs
7	N	2	6.76 kHz	-126.79 dBc/Hz	Integ Noise	5.00 kHz	-89.40 dBc
8	N	2	15.1 kHz	-127.69 dBc/Hz	Residual FM	10.0 kHz	1.070 Hz
9	N	2	32.4 kHz	-127.76 dBc/Hz	Average	20.0 kHz	-127.9 dBc/Hz
10	Δ9	2	(Δ) 21.34400000 kHz	(Δ) -0.06dB			
11	Δ9	2	(Δ) 2.259 octaves	(Δ) -0.20dB/oct.			
12	Δ9	2	(Δ) 1.01 decades	(Δ) -6.23dB/dec.			

Marker Function

Marker Function
- Select Marker ▶ 1
- Integrated (RMS) Noise ▷ Degree
- Residual FM (Weighted Integ)
- Averaged Noise Density
- Marker Function Off
- Band Adjust ▶
- More 1 of 2

Calibrated Phase Noise
(Note: can be used with any test method)

Occasionally, it is desirable to have a calibrated phase noise signal that can be used to verify the performance of a measurement setup. Here a calibrated phase noise is generated with a constant slope of -20 dB/decade, by creating an FM signal modulated with uniform noise.



- Set up an Agilent PSG signal generator for FM modulation, by selecting:
  - FM path 1
  - FM on
  - FM deviation, as specified on next slide
  - FM waveform to noise, uniform
- Ensure that noise of the PSG in FM off is at least 10 dB less than the desired calibrated noise at a desired offset frequency, to ensure accuracy.

Calibrated Phase Noise—Cont'd

FM Noise Deviation	Offset 1 Hz	10 Hz	100 Hz	1 kHz	10 kHz	100 kHz
5 Hz	-60	-80	-100	-120	-140	-160
16 Hz	-50	-70	-90	-110	-130	-150
50 Hz	-40	-60	-80	-100	-120	-140
158 Hz	-30	-50	-70	-90	-110	-130
500 Hz	-20	-40	-60	-80	-100	-120
1.58 kHz	-10	-30	-50	-70	-90	-110
5 kHz	0	-20	-40	-60	-80	-100
15.8 kHz	10	-10	-30	-50	-70	-90
50 kHz	20	0	-20	-40	-60	-80

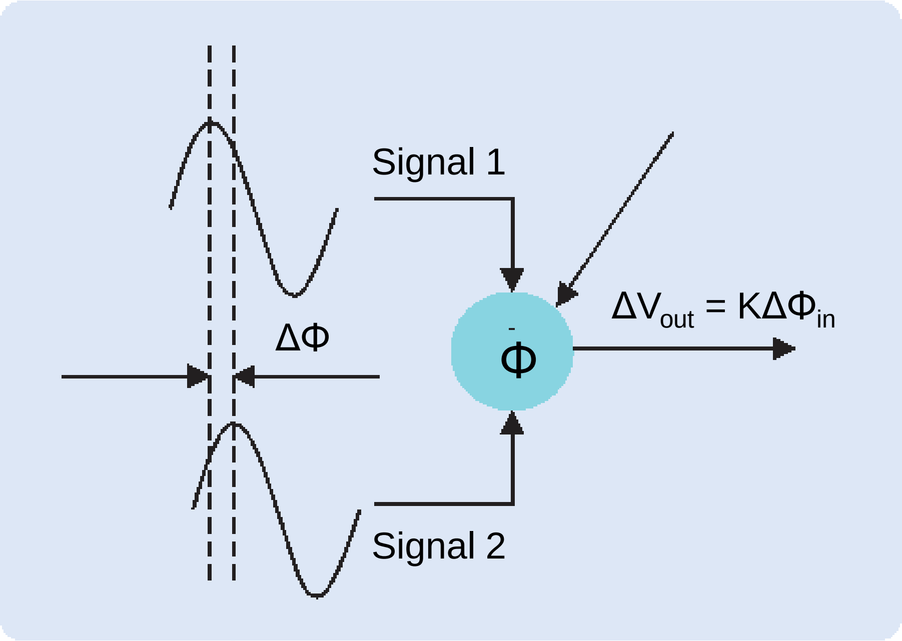
Note: For the example on the previous slide, an FM deviation of 500 Hz was selected to produce a calibrated phase noise of -100 dBc/Hz at a 10 kHz offset.

Agenda

- What is phase noise?
- Phase noise measurement techniques
  - Direct phase noise measurement (with a spectrum analyzer)
  - Phase detector techniques
  - Two-channel cross correlation method
- Agilent E5500 Phase Noise Measurement System
- Comparison of Agilent Phase Noise Measurement Solutions
- Summary
- Bibliography

Phase Detector Techniques

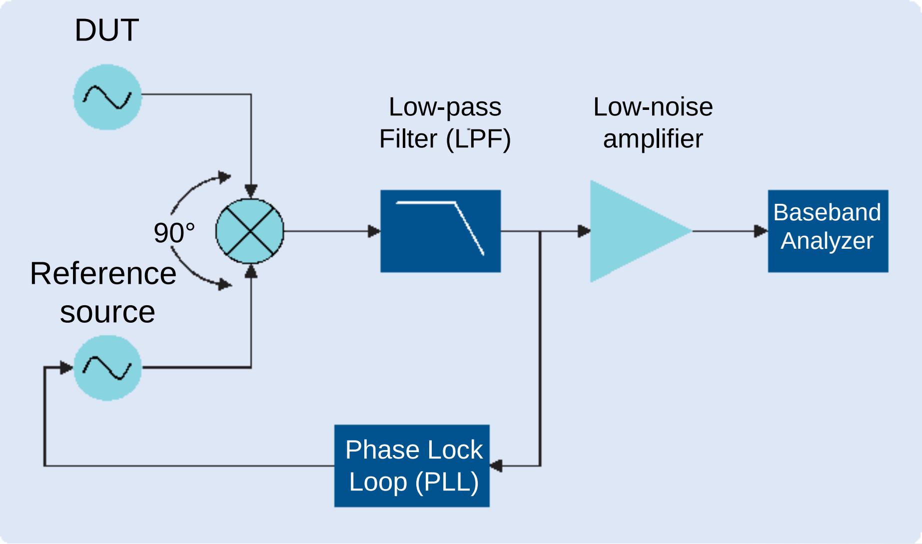
A phase detector can be used to isolate phase noise from amplitude noise. The basic concept of the phase detector forms the basis of several common phase noise measurement methods.



- The phase detector converts phase difference between its two inputs into a voltage
- When the phase difference between the two inputs is 90° (quadrature), the phase detector output will be 0 Volts.
- Any phase fluctuations around the quadrature point will result in a voltage fluctuation at the output of the phase detector
- The phase detector output can then be digitized and processed to obtain the phase noise information desired.

Reference Source / PLL Method

The reference source / phase lock loop (PLL) method is an adaptation of the phase detector technique, where a double balanced mixer is used as a phase detector.



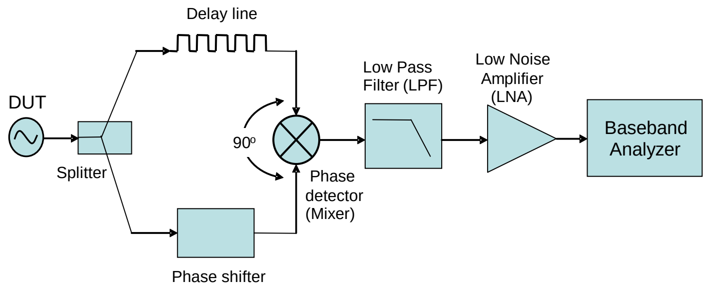
- In this method, two sources are used
  - One source is the DUT
  - The second source is a reference source that the DUT is compared to
- The reference source is controlled such that it follows the DUT at the same frequency and maintains a phase quadrature
- The mixer sum frequency, $2f_c$ is filtered off with the low-pass filter and the mixer difference frequency is 0 Hz, with an average voltage of 0 Volts
- Riding on the DC output of the mixer are AC voltage fluctuations proportional to the combined phase noise contributions of the two sources.

Note: The phase noise of the reference must be negligible, when compared to the DUT.

- Offers the best sensitivity and widest offset coverage
- Insensitive to AM and can track drifting DUTs
- Requires a clean electronically tunable reference.

Frequency Discriminator Method

The frequency discriminator method is another adaptation of the phase detector technique, where the reference source has been eliminated and the DUT signal is compared with a time delayed version of itself.

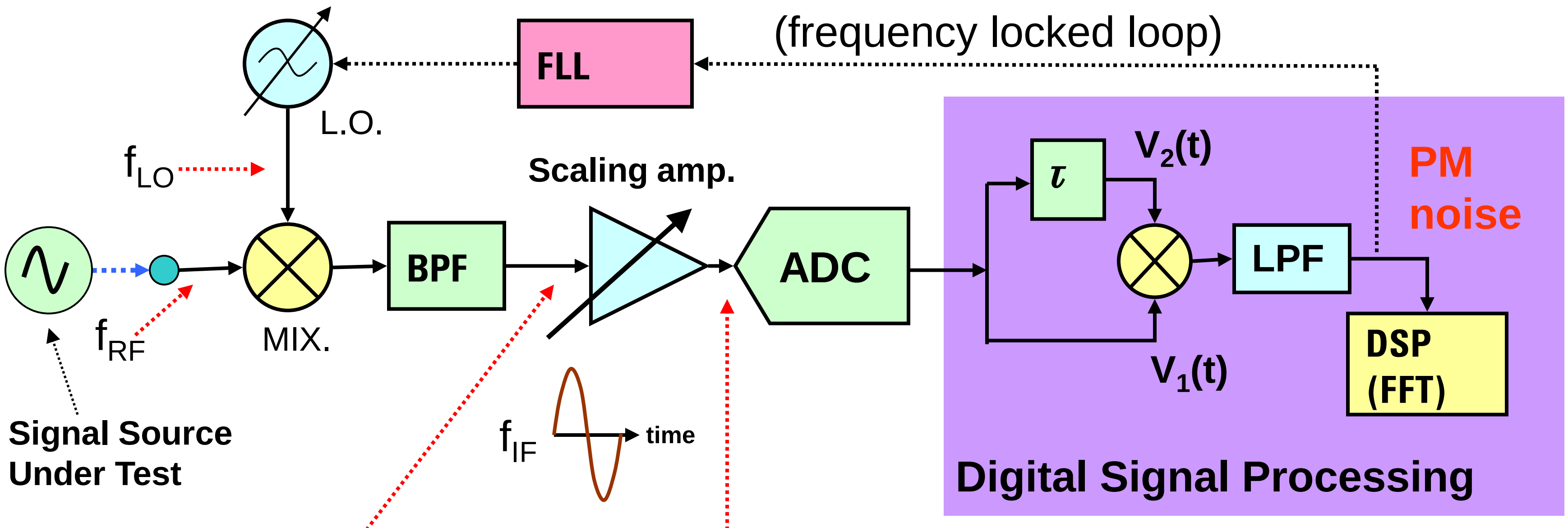


- Signal from the DUT is split into two paths
  - The signal in one path is delayed relative to the other path
  - The delay line converts frequency fluctuations into phase fluctuations
  - The delay line or phase shifter is adjusted to put the inputs to the mixer in quadrature
  - The phase detector converts phase fluctuations into voltage fluctuations which are analyzed on the baseband analyzer

Frequency Discriminator Method

- The analog delay-line discriminator degrades measurement sensitivity, at close-in offset frequencies
- Is a very useful method when the DUT is a noisy source that has high-level low-rate phase noise or high close-in spurious sideband conditions which can limit performance of the phase detector PLL technique.
- Longer delay lines can improve sensitivity, the added insertion loss of the longer delay can degrade signal to noise ratio and measurement sensitivity
- Longer delay lines also limit the maximum offset frequency that can be measured.
- This is the best method for free-running sources, such as LC and cavity oscillators.

Heterodyne Digital Discriminator
(A modification of the analog delay line discriminator)



Note that a main signal still exists at this point !
This limits D.R. of a digital discriminator method.

τ is set at $1/(4f_{IF})$ [sec] ~ 4ns

- DUT signal is down converted to an IF frequency by a mixer and a frequency locked LO.
- The IF signal is amplified and then digitized by an A to D converter
- In DSP, the signal is split and a delayed version of the signal is compared with a non delayed version in a mixer. The delay is set to ensure quadrature.
- The mixer output is filtered to remove the sum component, leaving the baseband component which is processed for phase noise.

Heterodyne Digital Discriminator

- Can measure unstable sources and oscillators
- Wider phase noise measurement range than the PLL method
- Dynamic range is limited by the LNA and ADC
- Provides very fast and accurate AM noise measurements by setting the delay time to zero
- Performance is improved by cross correlation in the Agilent E5052B.

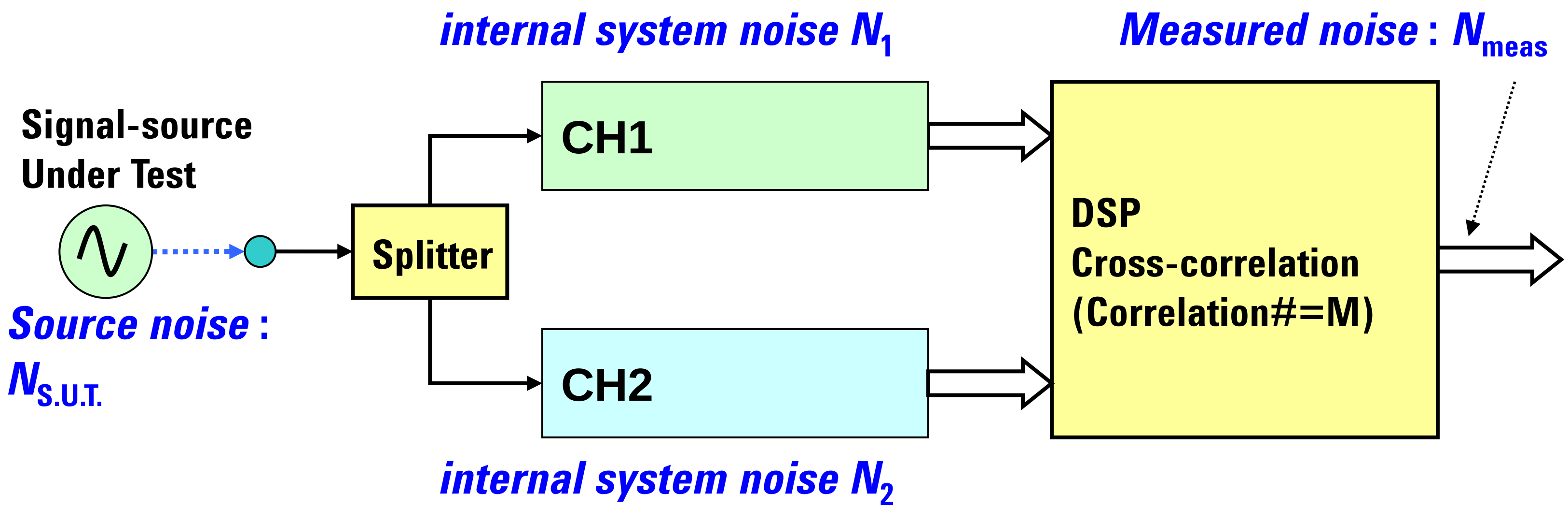
Agilent E5052B, Signal Source Analyzer

Agenda

- What is phase noise?
- Phase noise measurement techniques
  - Direct phase noise measurement (with a spectrum analyzer)
  - Phase detector techniques
  - Two-channel cross correlation method
- Agilent E5500 Phase Noise Measurement System
- Comparison of Agilent Phase Noise Measurement Solutions
- Summary
- Bibliography

Correlation technique for noise floor reduction

Two-channel Cross-Correlation Technique



$$N_{meas} = N_{S.U.T.} + (N_1 + N_2)/\sqrt{M}$$ Assuming N_1 and N_2 are uncorrelated.

M (number of correlation)	10	100	1,000	10,000
Noise reduction on (N_1+N_2)	-5dB	-10dB	-15dB	-20dB

Agilent E5052B Cross Correlation

- The Agilent E5052B incorporates
  - A two-channel cross-correlation measurement system to reduce measurement noise
  - Can be configured as:
    - Two-channel normal phase noise PLL system
    - Two-channel Heterodyne Digital Discriminator system
- Provides excellent phase noise measurement performance for many classes of sources and oscillators
- Is particularly well suited for free running oscillators
- Measurement speed suffers when the number of correlations becomes large, limiting close-in phase noise measurement performance.

Agenda

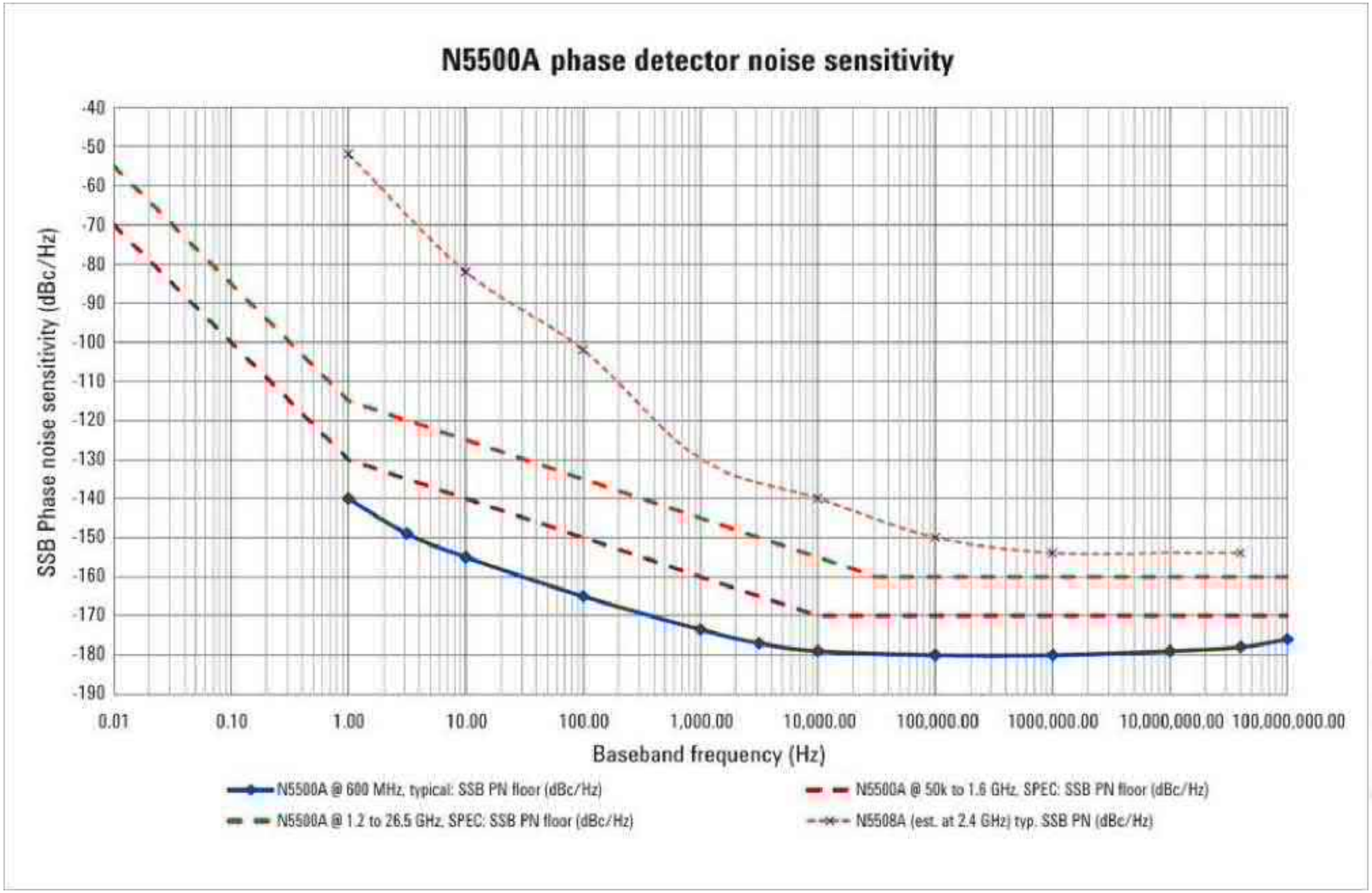
- What is phase noise?
- Phase noise measurement techniques
  - Direct phase noise measurement (with a spectrum analyzer)
  - Phase detector techniques
  - Two-channel cross correlation method
- Agilent E5500 Phase Noise Measurement System
- Comparison of Agilent Phase Noise Measurement Solutions
- Summary
- Bibliography

Agilent E5500 Phase Noise Measurement System

Agilent E5500 Phase Noise Measurement System

- The E5500 system can be configured as:
  - A phase detector system
  - A reference source/PLL system
  - A frequency discriminator system
  - For residual phase noise measurements
  - For pulsed phase noise measurements
- System is complex, but allows the most measurement flexibility and best overall system performance

Agilent E5500 Phase Detector Sensitivity



Agenda

- What is phase noise?
- Phase noise measurement techniques
  - Direct phase noise measurement (with a spectrum analyzer)
  - Phase detector techniques
  - Two-channel cross correlation method
- Agilent E5500 Phase Noise Measurement System
- Comparison of Agilent Phase Noise Measurement Solutions
- Summary
- Bibliography

Comparison of Agilent Phase Noise Solutions

Agilent PN Solution	PN Measurement Technique	Advantages	Disadvantages
N9068 PN measurement App for X-Series	Direct Spectrum Measurement	• Easy operation • Quick check of phase-locked signals • Instrument is not dedicated to phase noise can be used for general purpose also.	• Difficult to measure close-in PN of quiet signal sources like crystal oscillators • Cannot measure PN of drifty signal sources, such as free-running VCOs.
E5500 PN Measurement system	Phase detector (reference source / PLL)	• Applicable to broad offset range • Can measure very low PN at close-in offsets with a good LO • Measure PN for pulsed carriers as well as CW • Can separate PN from AM noise.	• PN noise is limited by LO noise • Complicated set up and calibration required.
E5500 PN Measurement system	Phase detector (analog delay-line discriminator)	• Can measure very low PN at far-out offset frequencies • Suitable for measuring relatively dirty sources, like YIG oscillators	• Not applicable to close-in PN measurements due to gain degradation by discriminator • Complicated set up and calibration required • Difficult to obtain the right delay line at an arbitrary frequency.
E5052B Signal Source Analyzer	PLL method and heterodyne digital discriminator with two-channel cross-correlation	• Easy operation, setup, and cal. • Measure very low PN at broad offsets • Cross-correlation improves PN sensitivity • Can separate AM and PN noise	• Long measurement time for extremely low PN at close-in offset frequencies.

Phase Noise Comparison of Agilent Solutions