KEYSIGHT

Phase Noise and its Measurements

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Keysight Technologies

Agenda

- Phase Noise Basics
  - What is Phase Noise $\mathcal{L}(f)$?
  - Spectral Density of Phase Fluctuations $S_\phi(f)$
    - Relations between SSB PN and RMS phase deviation
  - Jitter and Phase Noise
    - Relations between Jitter and RMS phase deviation
- Phase Noise Measurements
  - Direct-Spectrum Method
  - Phase Detector Method
  - Cross-correlation of 2-Channel Measurements
- Keysight Phase Noise Measurement Solutions

What is Phase Noise?

Ideal versus real-world signals

Ideal sinusoidal signal

$$V(t) = A_o \sin(2\pi f_o t)$$

where

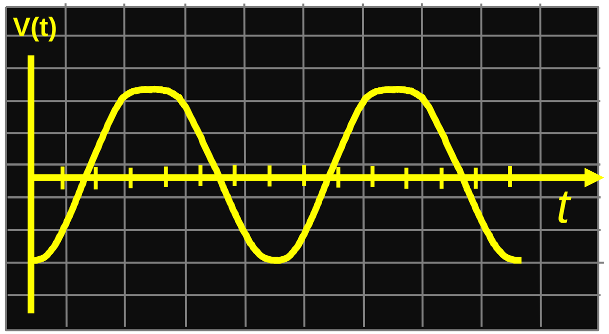
A_o = nominal amplitude
f_o = nominal frequency

Real sinusoidal signal

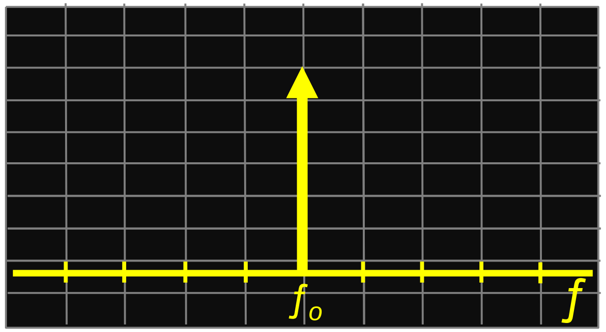
$$V(t) = [A_o + E(t)]\sin[2\pi f_o t + \phi(t)]$$

where

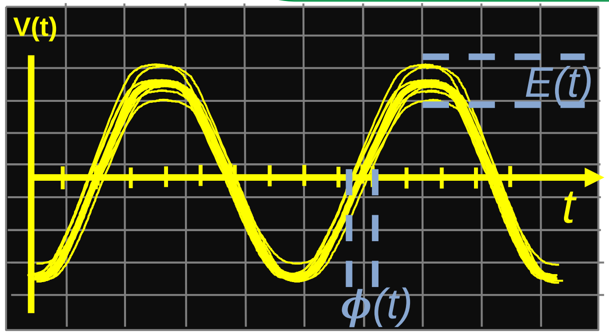
$E(t)$ = random amplitude fluctuations
$\phi(t)$ = random phase fluctuations



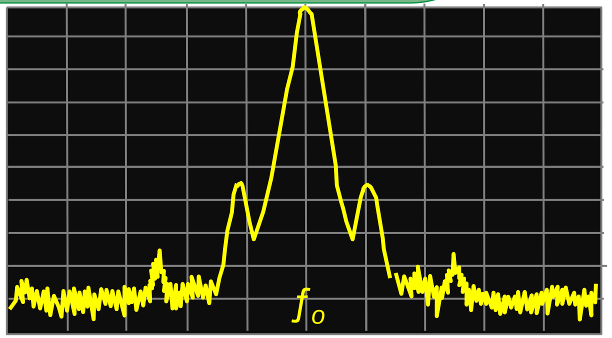
Time



Frequency



Time



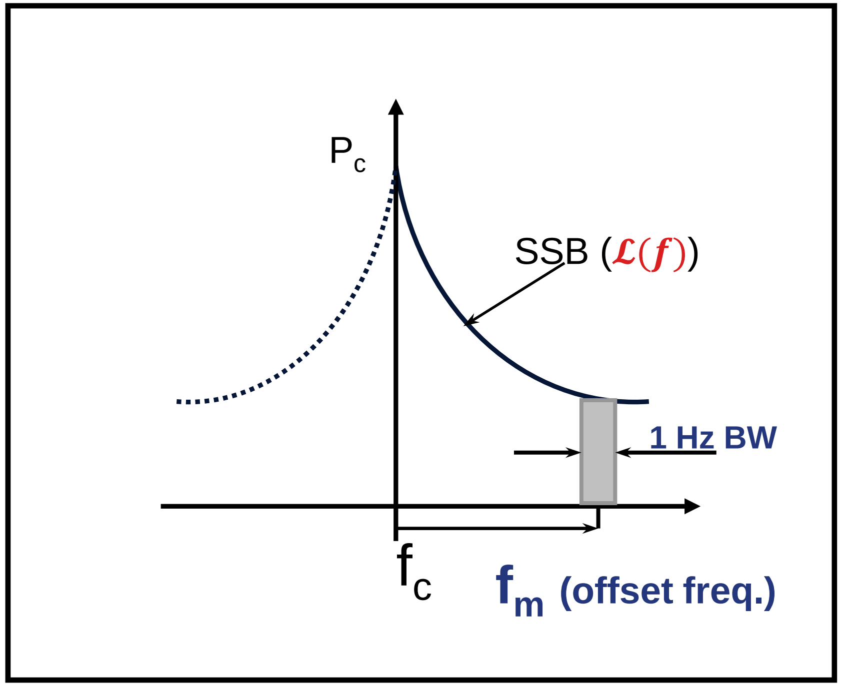
Frequency

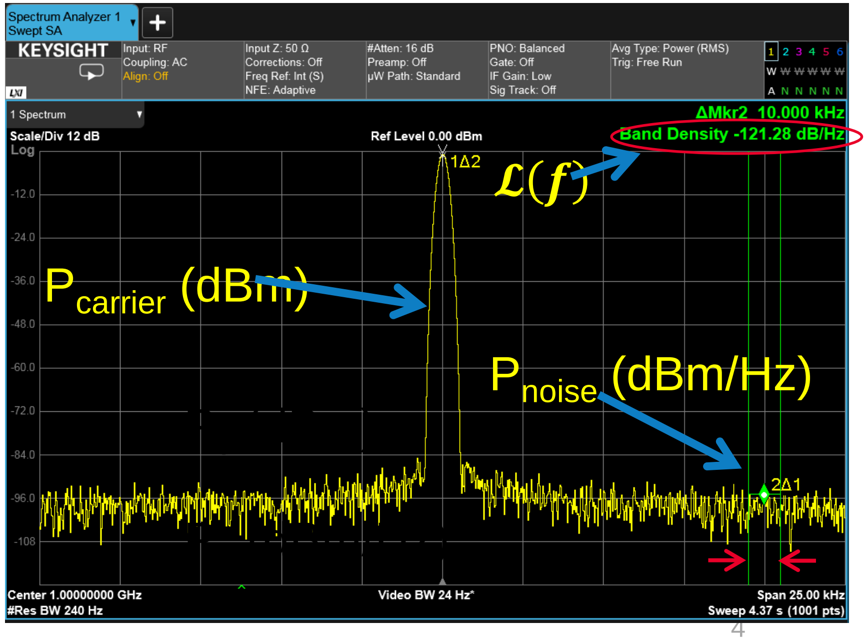
What is Phase Noise?

How to define phase noise and its measurements

- Phase noise is the phase fluctuation of an oscillator, produced by random noise modulation on its main carrier signal.
- In frequency domain where phase noise is simply noise sidebands or skirt around “ideal” delta function from sinusoidal oscillator, which is symmetrical in magnitude around center frequency, so we can measure a single noise sideband (SSB)
- Three elements:
  - Offset frequency (fm) from carrier frequency (fc)
  - Power spectral density, in 1 Hz BW
  - PSD relative to carrier power in dBc

$$\mathcal{L}(f) = \frac{P_{SSB}}{P_c} \left(\frac{\text{dBc}}{Hz}\right)$$





Spectral Density of Phase Fluctuations

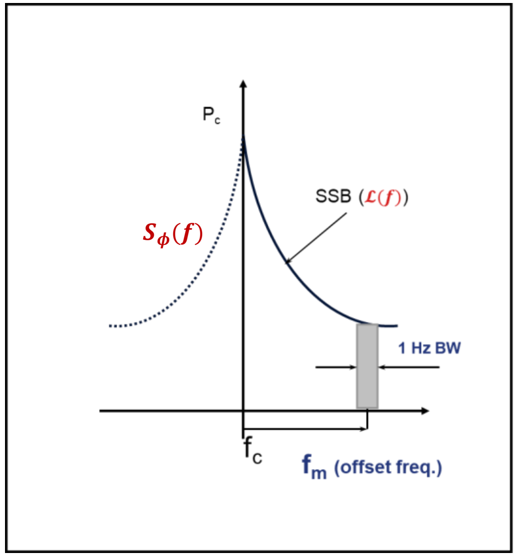
Mean-square Phase Deviation & Phase Noise

- If we can measure phase deviation ($\Delta\phi$) , we can convert mean-square phase deviation measurement (i.e., ϕ_{RMS}^2) into a spectral density by dividing by the noise bandwidth and normalizing it to 1 Hz BW:

Spectral Density of Phase Fluctuations: $S_\phi(f) = \phi_{RMS}^2(\frac{1}{BW})\ (\frac{rad^2}{Hz})$

- In case of small angle PM (where $m = \beta = \phi_{pk} \leq 0.2\ rad$), which like we mentioned above in the case of small noise modulates the carrier with small angle deviation in the phase noise situation:

$$\frac{P_{SSB}}{P_c} = (\frac{1}{2}\phi_{pk})^2 = \frac{1}{4}(\sqrt{2}\phi_{RMS})^2 = \frac{1}{2}\phi_{RMS}^2\ (rad^2)$$



$$\mathcal{L}(f) = \frac{P_{SSB}}{P_c}$$

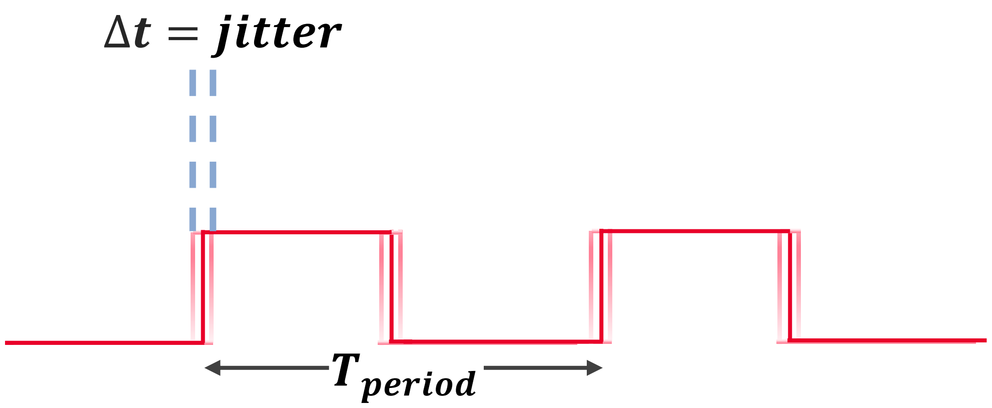
$$\mathcal{L}(f)\ (\frac{1}{Hz}) = \frac{S_\phi(f)}{2} = \frac{\phi_{RMS}^2}{2}(\frac{1}{BW})\ (\frac{rad^2}{Hz})$$

$$\phi_{RMS}\ (rad) = \sqrt{2\int_{f_{start}}^{f_{stop}} \mathcal{L}(f)df}$$

Jitter and Phase Noise

Jitter definition

- Time-domain RMS phase deviation is called jitter
- Those concerned about jitter frequently deal with clock signals, which are usually the measurements of square wave-type signals rather than sinusoids
- The following relates RMS phase deviation to jitter:



$$jitter(seconds) = \frac{\phi_{RMS}}{2\pi}[T_{period}(seconds)] = \frac{\phi_{RMS}}{2\pi f_c}$$

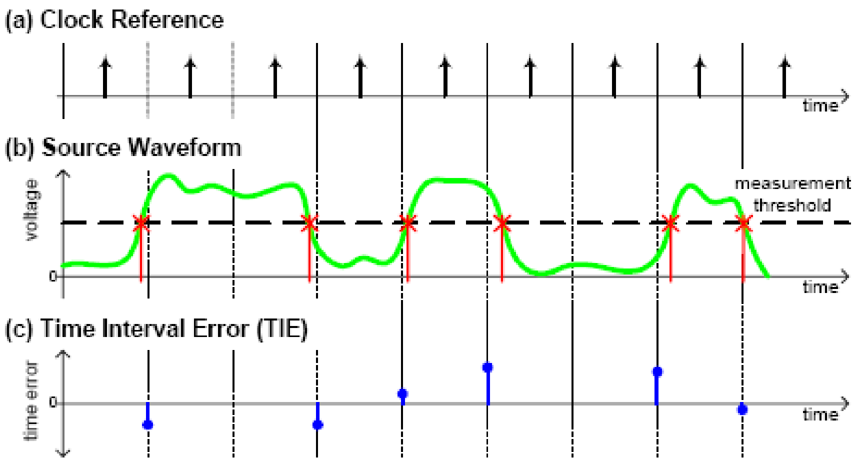
Percentage of total angular period affected by RMS phase deviation

Clock signal period (time); same as $1/f_c$

* f_c is the clock frequency and when viewed in the frequency domain, is equal to the spacing between the spectral lines

Jitter and Phase Noise

Measurement Principles Using a Real-time Oscilloscope



- A **time interval error (TIE) or Jitter** measurement on an oscilloscope will produce a time series of the absolute time error of each edge relative to the ideal clock. To convert to phase (radians), the error is simply multiplied by $2\pi f_c$ where f_c is the clock carrier frequency:

$$\varphi = 2\pi \cdot TIE(t) \cdot f_c$$

- A **Time Interval Error (TIE) trend** can be transformed to frequency domain with an FFT to give something called a **Jitter Spectrum**. Most modern oscilloscopes have this capability built in or as an option:

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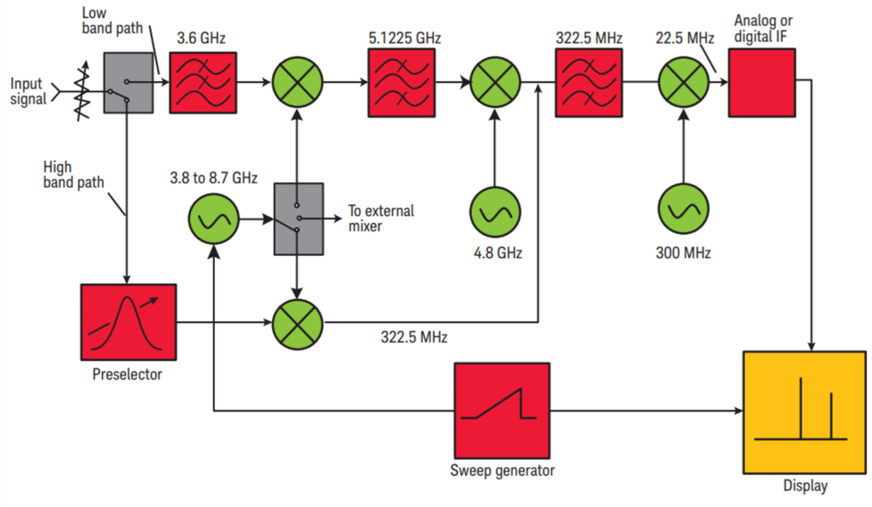
Measuring Phase Noise in Frequency Domain

Direct-Spectrum Method

- As mentioned earlier, we use spectrum analyzer to measure the SSB PN:

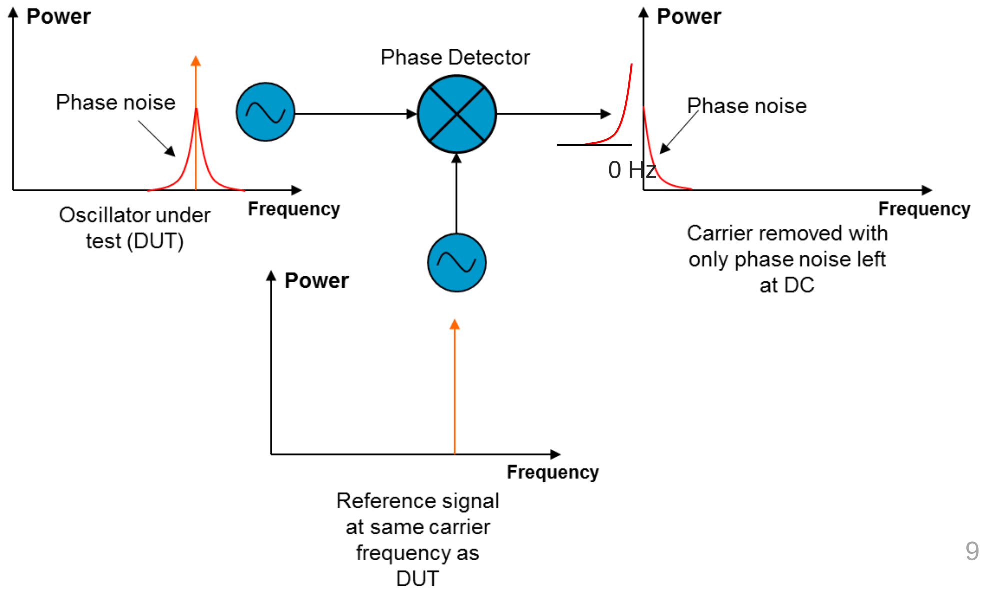
$$\mathcal{L}(f) = \frac{P_{SSB}}{P_c}\ \left(\frac{\text{dBc}}{Hz}\right)$$

- It is far less sensitive than carrier-removal method because of spectrum analyzer's limitations.
  - *Can not separate AM Noise*
  - *Has LO PN, preamp noise, ADC noise, etc.*



Phase Detector Method
（Carrier-removal method ）

- Has increased sensitivity obtained by nulling carrier & then amplifying & measuring phase noise of resulting baseband signal with high-gain, low noise figure amplifiers
- It uses a phase detector to convert phase fluctuation into voltage of noise. We are measuring $S_\phi(f) = \phi_{RMS}^2\left(\frac{1}{BW}\right)\ \left(\frac{rad^2}{Hz}\right)$



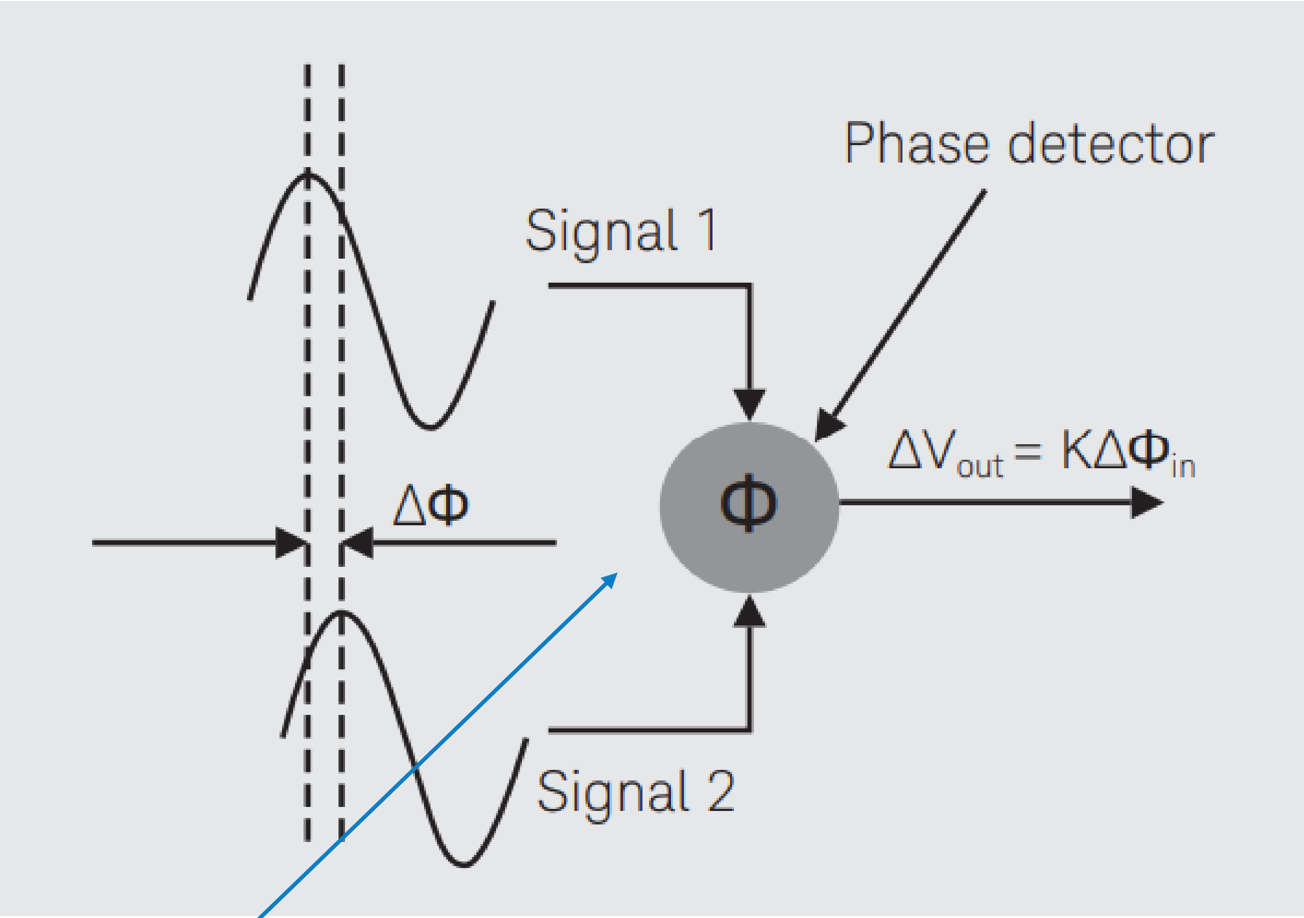
Phase Detector Techniques

Carrier-removal method

- Phase detector takes two input signals & compares phase
  - Output of phase detector is DC voltage proportional to delta phase of input signals ($\Delta\phi$)
  - Constant of proportionality, K, has units of volts per radian (V/rad) & must be measured
  - When we got the $\Delta\phi(\mathrm{t})$, we FFT it to get

$$S_\phi(f) = \phi^2_{RMS}\left(\frac{1}{BW}\right)\left(\frac{rad^2}{Hz}\right) \text{ and } \mathcal{L}(f)\left(\frac{1}{Hz}\right) = \frac{S_\phi(f)}{2}$$

- Phase detectors also tend to suppress AM noise

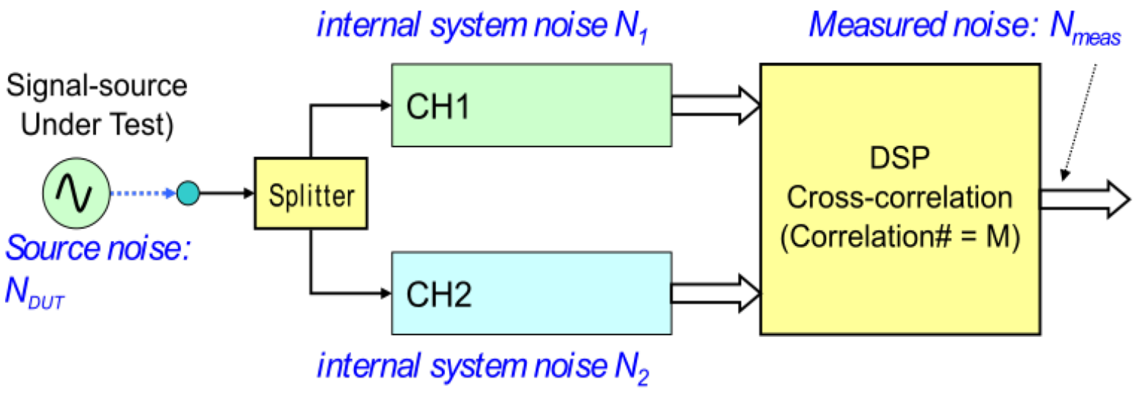


$\Delta\phi$ *to Voltage Converter (phase detector)*

Cross-Correlation Technique

- We can use two phase detectors to further improve phase noise floor (i.e., sensitivity)
- Two channels are uncorrelated so remove noise from references & system components through computational process.
- DUT signal is common to both channels so is perfectly correlated in both channels & kept as measurement result
- The two-channel cross-correlation technique achieves superior measurement sensitivity without requiring exceptional performance of the hardware components.
- However, the measurement speed suffers when increasing the number of computational correlations.

Two-Channel Cross-Correlation Technique:



$$N_{meas} = N_{DUT} + (N_1 + N_2) / \sqrt{M}$$ 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

DUT noises through each channel are coherent and are not affected by the cross-correlation, whereas the internal noises generated by each channel are incoherent and are diminished by the cross-correlation operation at the rate of $M^{1/2}$ (M being the number of correlations). This can be expressed as:

$$N_{meas} = N_{DUT} + (N_1 + N_2) / \sqrt{M}$$

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Keysight Phase Noise Solution Portfolio

Building on 35 years of phase noise experience, Keysight solutions provide excellent performance and are economically tailored to fit your needs.

Performance

N5511A Phase Noise Test System (PNTS)

Fast and flexible noise measurement at the limit of physics (kT = -177 dBm/Hz)

- Absolute / residual / AM / baseband / pulse / transient
- 50 kHz to 3.0 / 26.5 / 40 GHz
- 0.01 Hz to 160 MHz offset frequency
- Cross correlation
- E5500 replacement (100% code compatible)
- External mixer support for mmWave measurements

Legacy SSA (E5052B) + Downconverter (E5053A)

Feb'24 Release

E505xA Signal Source Analyzer (SSA-X)

Everything you need for signal source analysis

- Absolute / residual / 2-port VNA (S-parameters) / AM / baseband / pulse / transient / SA / Clock jitter
- 1 MHz to 8 / 26.5 / 44 / 54 GHz
- >54 GHz with external mixers (sub-THz)
- 1 mHz to > 1 GHz offset frequency
- Cross correlation

X-series Signal Analyzers

N9068 Phase Noise Measurement Application

- Absolute / residual / AM / baseband / pulse / transient
- Frequency range, offset range and performance depends on X-series model

PNA/PNA-X Network Analyzers

S9303xxB Phase Noise Application

- Absolute / residual / AM / baseband / pulse / transient
- 10 MHz to 70 / 125 GHz
- 0.1 Hz to 10 MHz offset frequency

Infinium / MXR / UXR Oscilloscopes

D90x0JITA Jitter, Vertical and Phase Noise Analysis

- Absolute / residual / AM / baseband / pulse / transient
- Frequency range, offset range and performance depends on oscilloscope model
- Cross correlation
- Best for measurements on digital signals, such as clocks

Ease of Use

www.keysight.com/find/phasenoise

Thank you