Frequency Stability

Presented by: Antonio Castro
Agilent Technologies, Inc.

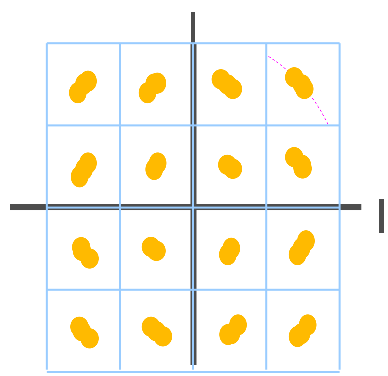
Anticipate ___Accelerate ___Achieve

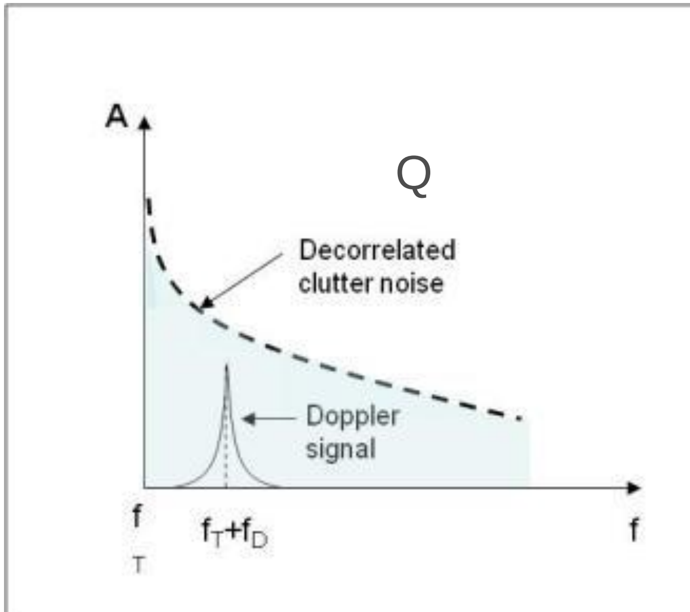
Introduction

Instabilities in the frequency or phase of a signal are caused by a number of different effects. Each type of noise process has distinct characteristics that can be measured using time domain and frequency techniques.

In many cutting edge radar and communication systems, phase noise is the characteristic that limits the system performance. In radar systems, phase noise degrades the ability to process Doppler information in radar. And, in digitally modulated communication system, phase noise degrades error vector magnitude.

Frequency
Instability
Effects

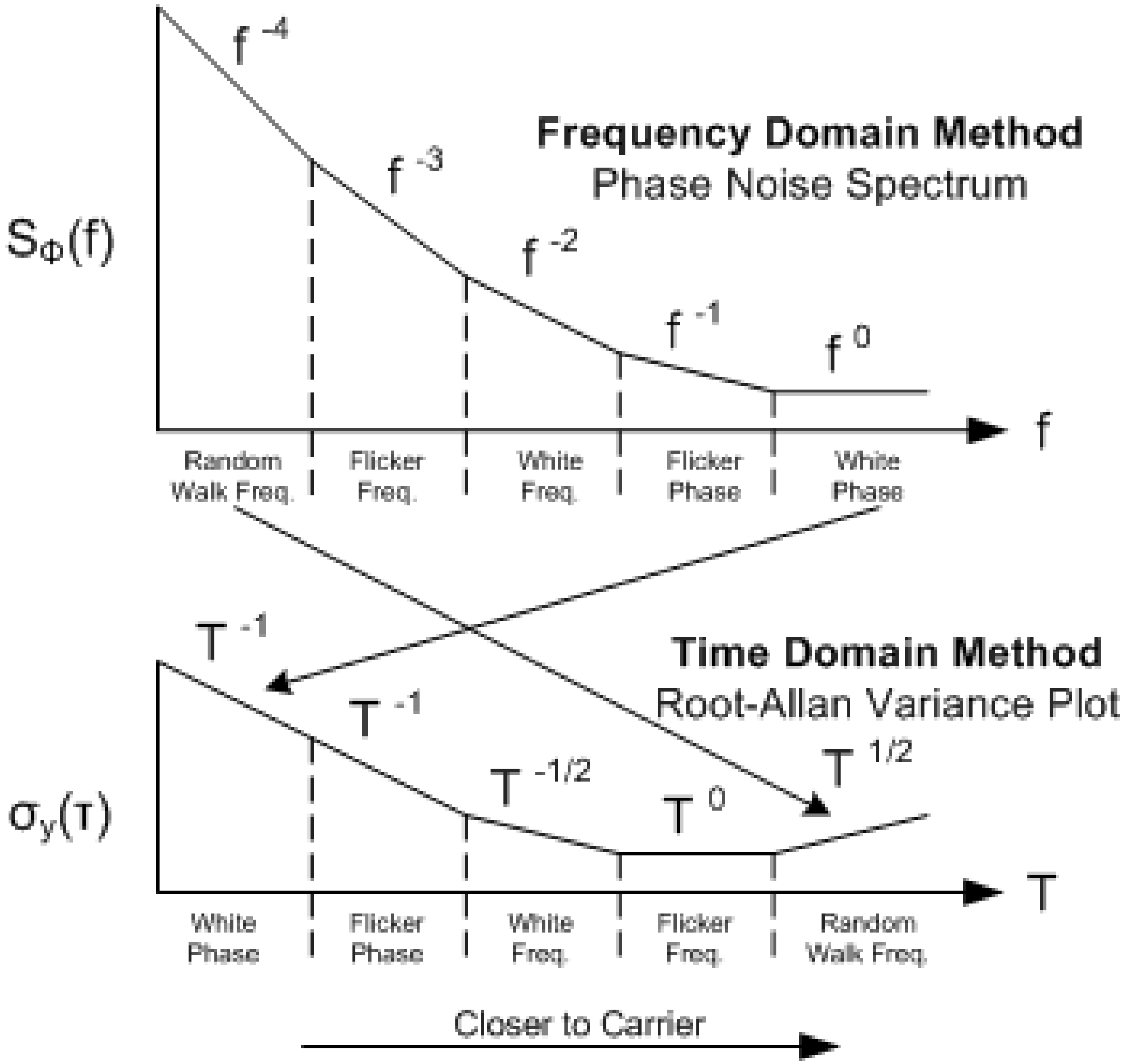




Instability in the Frequency

Random perturbations that appear as instabilities in frequency can be represented in either the frequency domain or the time domain.

- Frequency Domain
  - Frequency Offsets of a few Hz to tens of MHz
- Time Domain
  - For close-in noise (<<1 Hz)
  - Short-Term Stability



Agenda:

- Frequency-Domain Frequency Stability Analysis
  - What is Phase Noise?
  - Phase Noise Measurement Methods/Techniques
    - Direct Spectrum Method
    - Phase Detector Techniques
    - Two-Channel Cross-Correlation Method
    - µW and mm-Wave Phase Noise Techniques
- Time-Domain Frequency Stability Analysis
  - Allan Variance
  - Domain Conversion
- Atomic Frequency Reference
- Conclusion

What is Phase Noise?

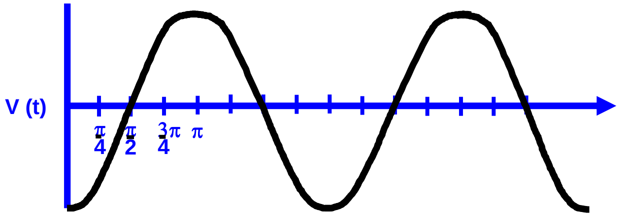
- The basic concept of phase noise centers around frequency stability, or the characteristic of an oscillator to produce the same frequency over a specified time period.
- Frequency stability can be broken into two components:
  - Long-term frequency stability—frequency variations that occur over hours, 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.

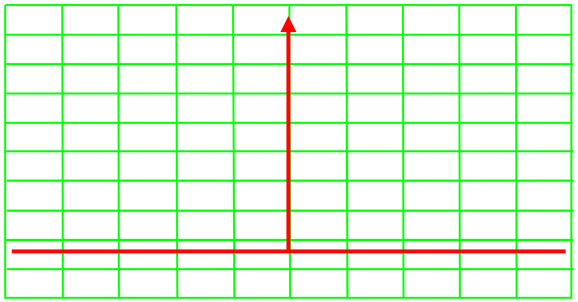
What is Phase Noise?

Ideal Signal

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

Where:
A_o = nominal amplitude
ω_o = nominal frequency

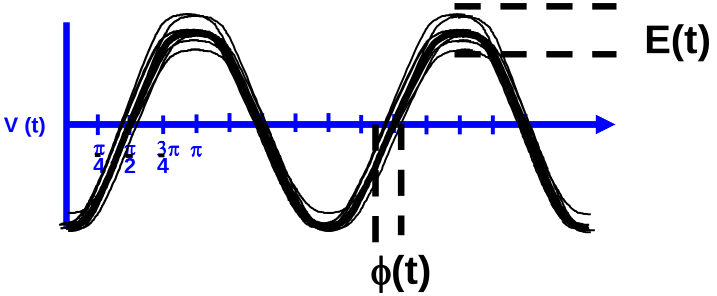


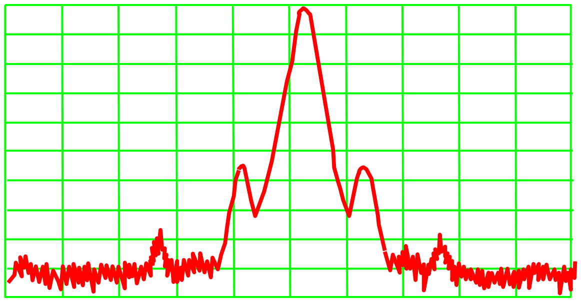


Real-World Signal

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

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





What is Phase Noise?

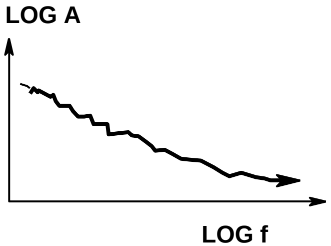
Unit of measure

- 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 BW 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

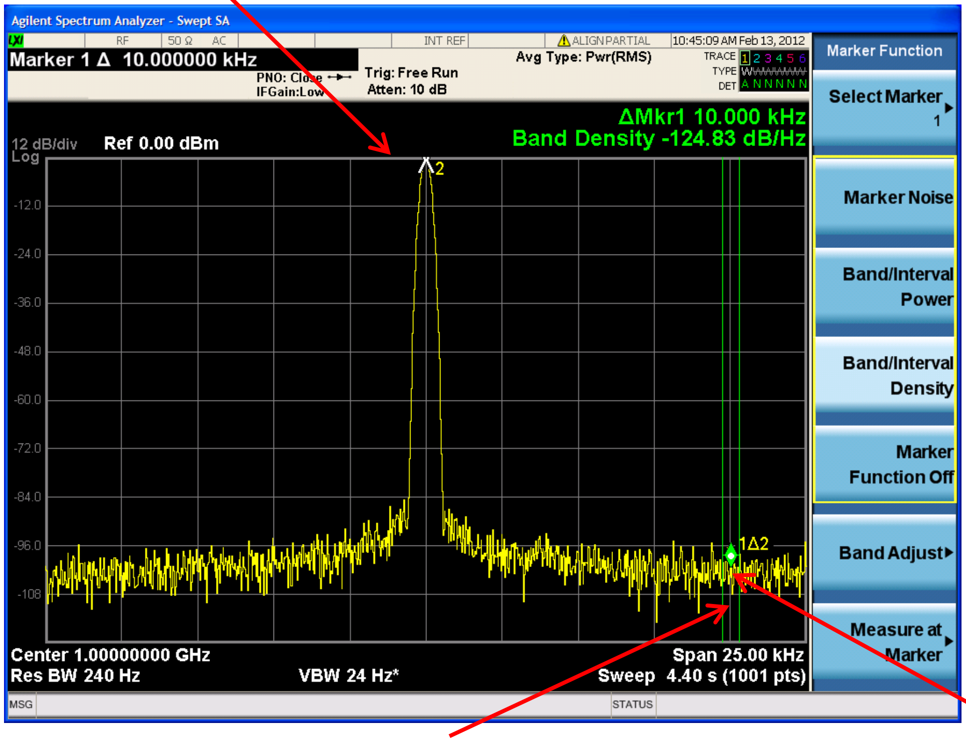
$$\mathcal{L}(f) = \frac{\text{Noise power in a 1 Hz bandwidth}}{\text{Total signal power}}$$

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

$\mathcal{L}(f)$



P_s (dBm)

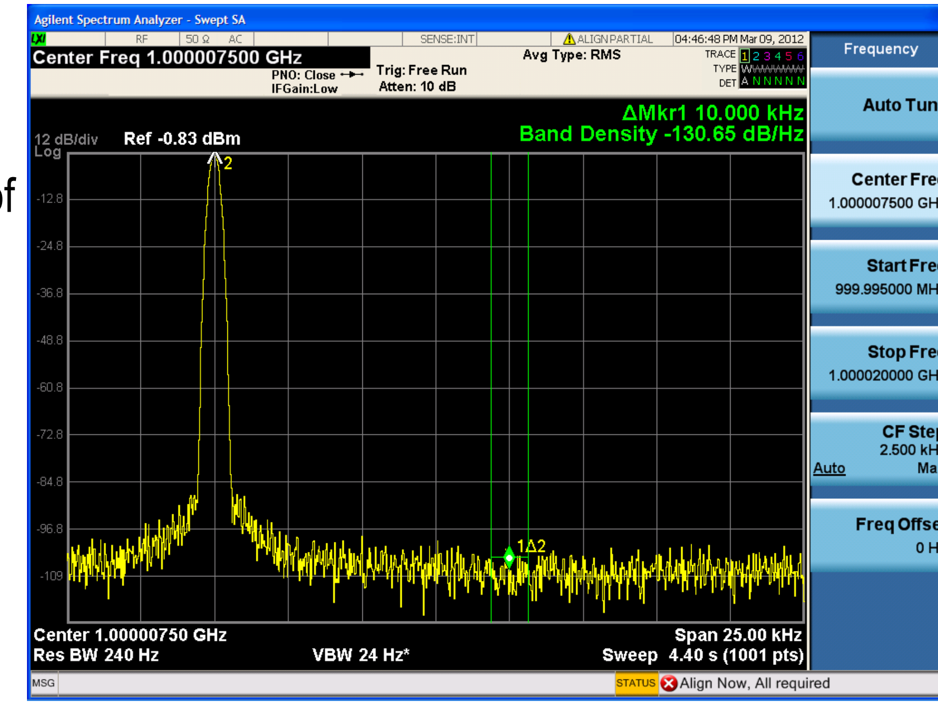


1 Hz bandwidth, generally normalizedto 1 Hz

P_n (dBm/Hz)

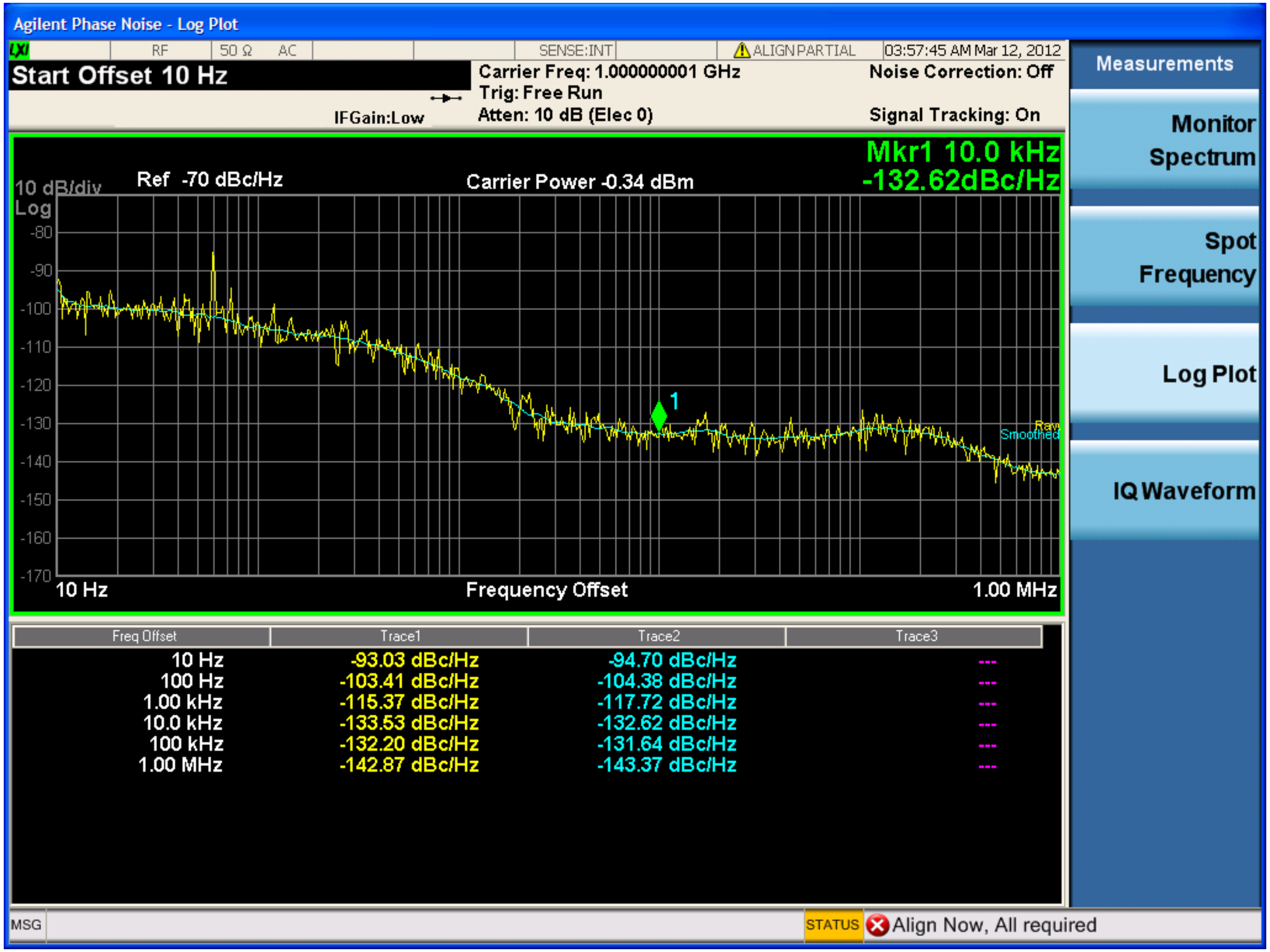
Direct Spectrum Method

- Simplest and easiest method
  - The device under test (DUT) is directly connected to the input of a spectrum analyzer
  - The analyzer is tuned to the carrier frequency
  - Directly measures the power spectral density of the oscillator in terms of L(f)
- Limitations
  - 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



The Agilent N9068A Phase Noise Measurement Application further simplifies the phase noise measurement.

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



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

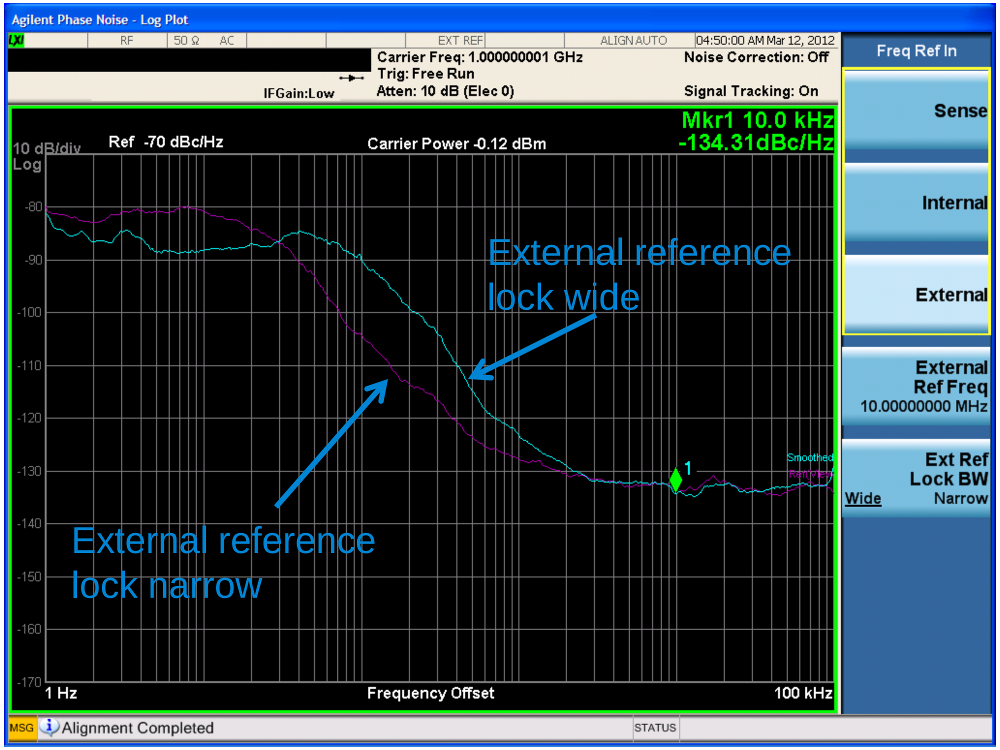
N9068A AM Noise Rejection

As mentioned previously, AM noise can degrade the accuracy of phase noise measurements.

- AM rejection can improve phase noise measurements
- AM rejection uses the I-Q processing in the PXA digital IF to remove the AM component of the noise
- AM rejection only works for offset frequencies < 1 MHz

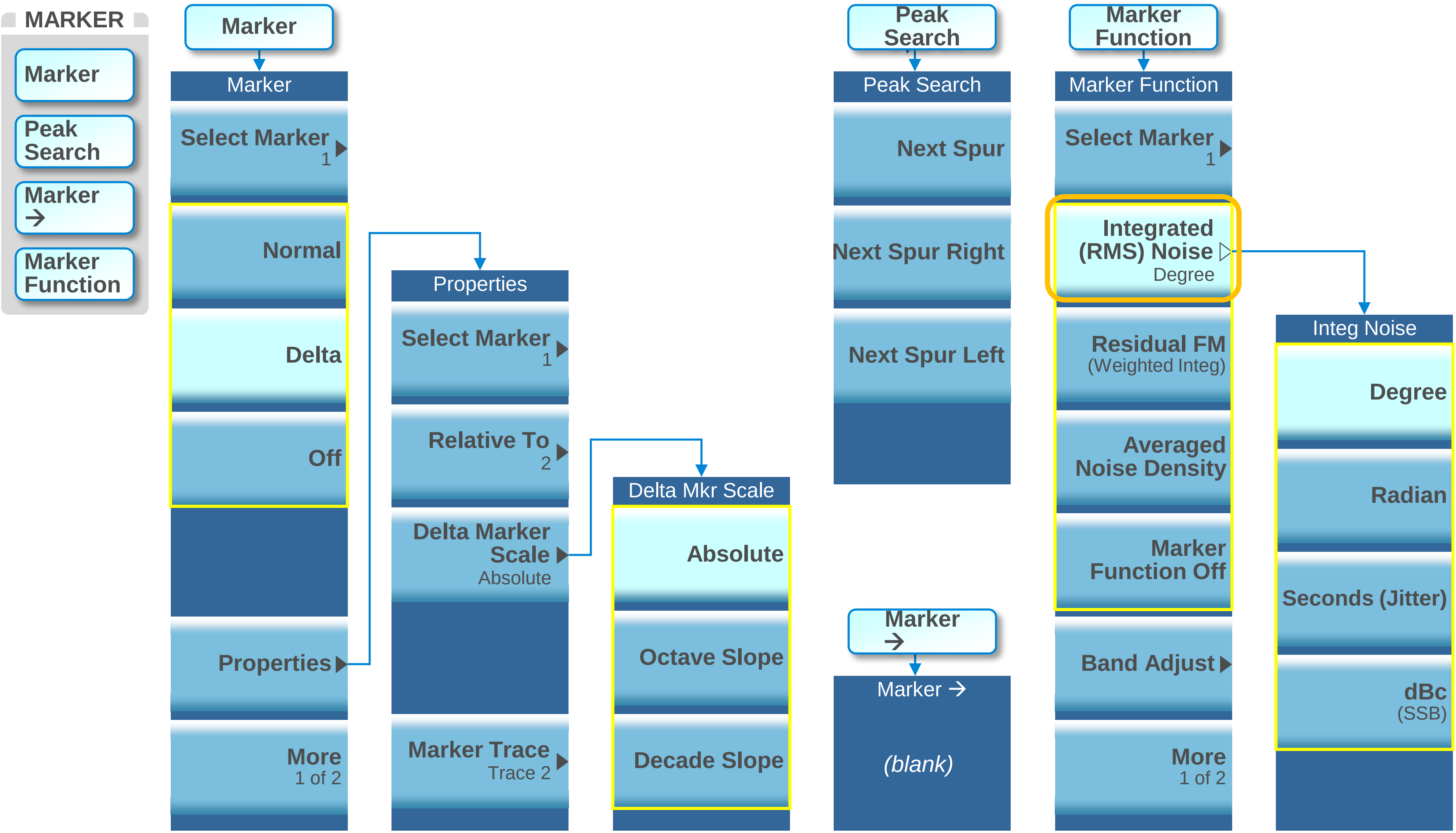
N9068A External Reference Lock Bandwidth

The quality of an external 10 MHz reference oscillator can make a big difference in phase noise measurements.



- If an external reference oscillator has better close-in phase noise than the PXA the wide locking bandwidth can be used to obtain better close-in (< 30 Hz) measurement performance.
- If higher offset frequencies are more important the narrow setting can be used.

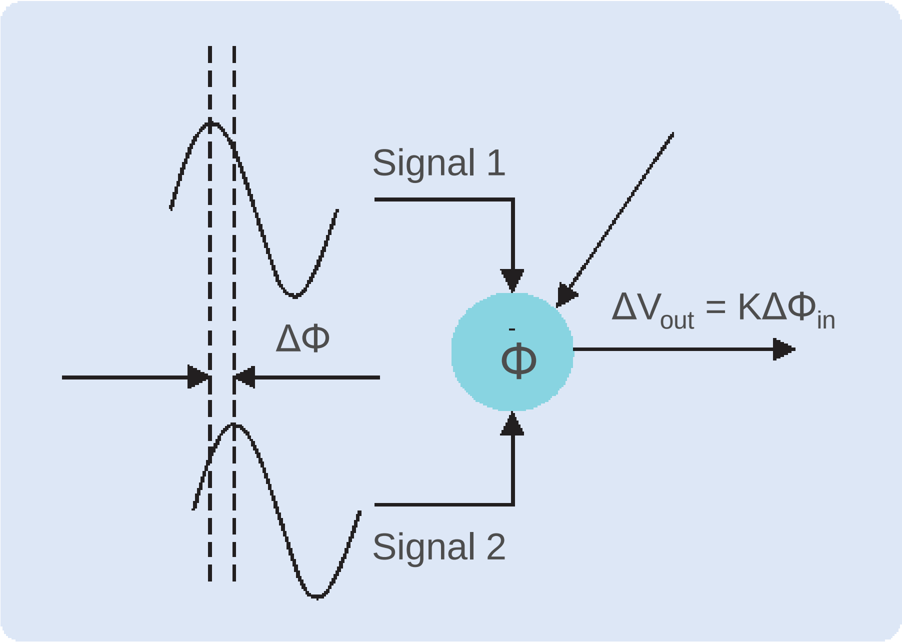
N9068A Marker Function Controls



Phase Detector Techniques

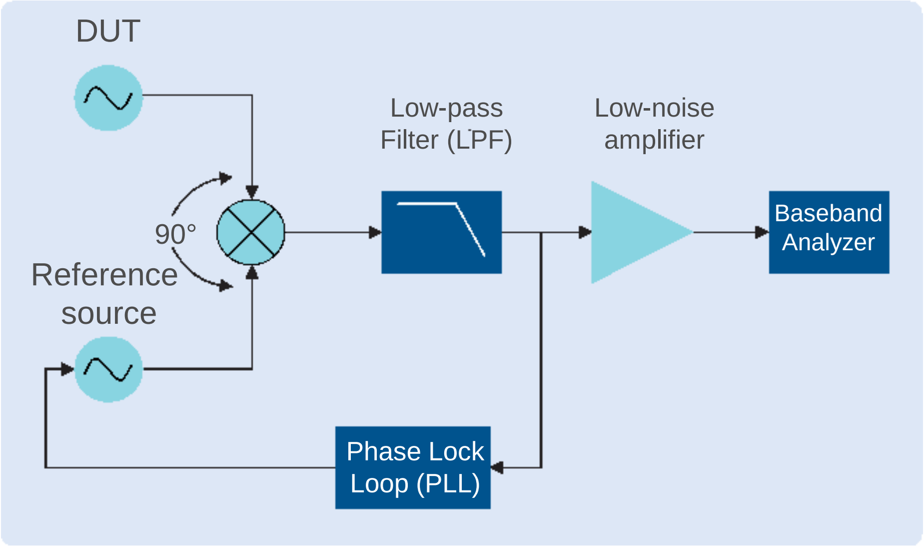
A phase detector can be used to isolate phase noise from amplitude noise. The basic concept of the phase detector forms the basis of several common phase noise measurement methods.

- 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.



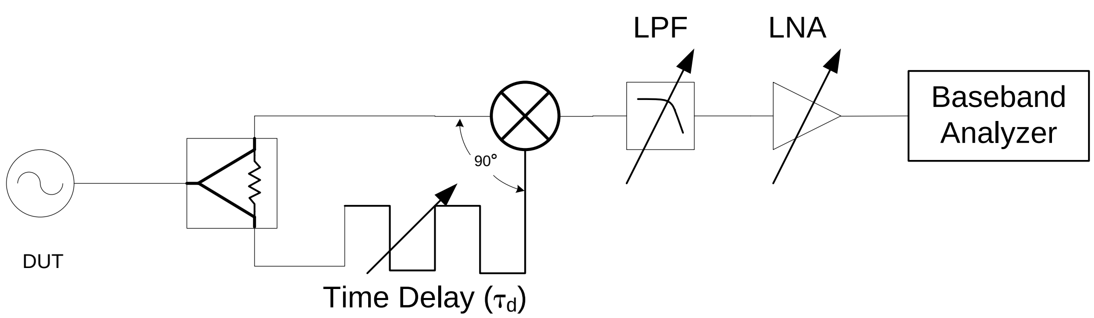
- In this method, two sources are used
  - One source is the DUT
  - The second source is a reference source that the DUT is compared to
- The reference source is controlled such that it follows the DUT at the same frequency and maintains a phase quadrature
- The mixer sum frequency, $2f_c$ is filtered 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.

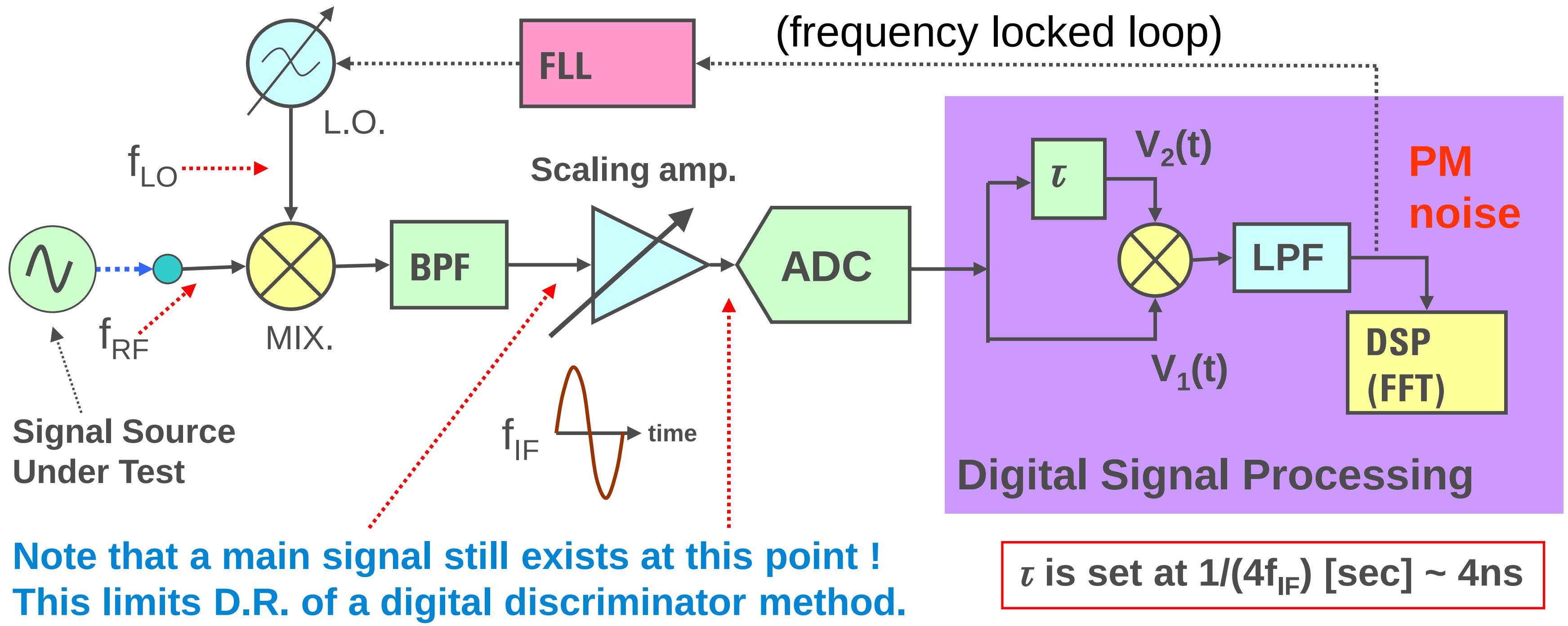


- Signal from the DUT is split into two paths
  - The signal in one path is delayed relative to the other path
  - The delay line converts frequency fluctuations into phase fluctuations
  - The delay line or phase shifter is adjusted to put the inputs to the mixer in quadrature
  - The phase detector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



- 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.

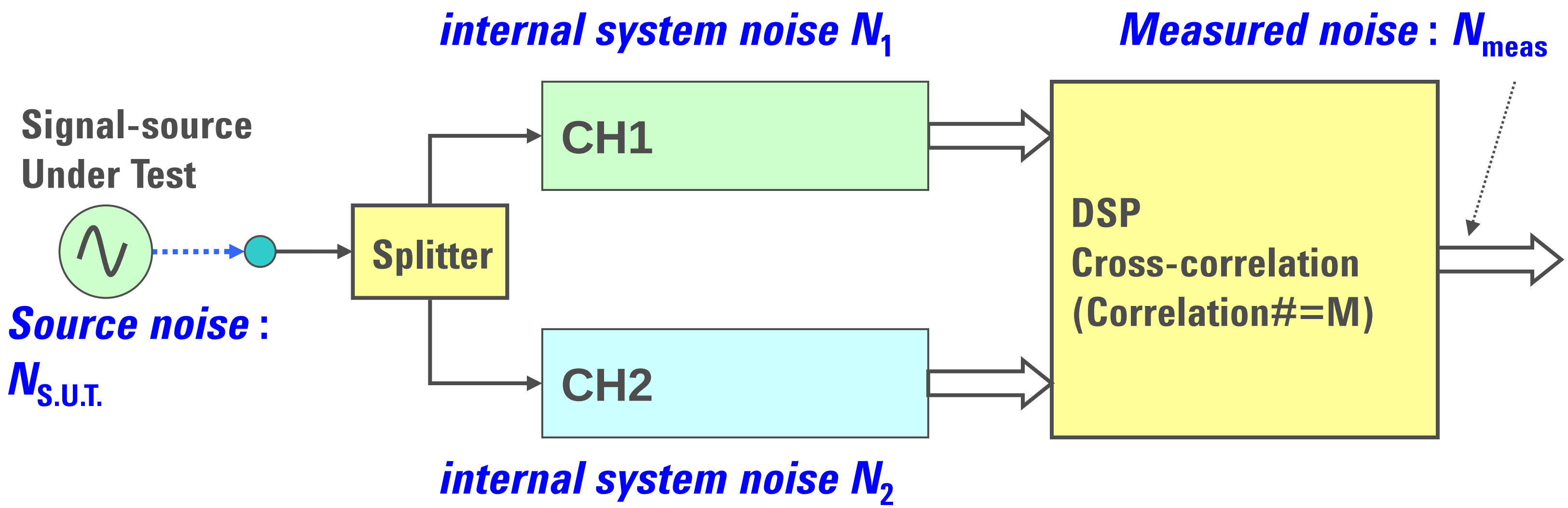
Heterodyne Digital Discriminator

- 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

Correlation technique for noise floor reduction

Two-channel Cross-Correlation Technique



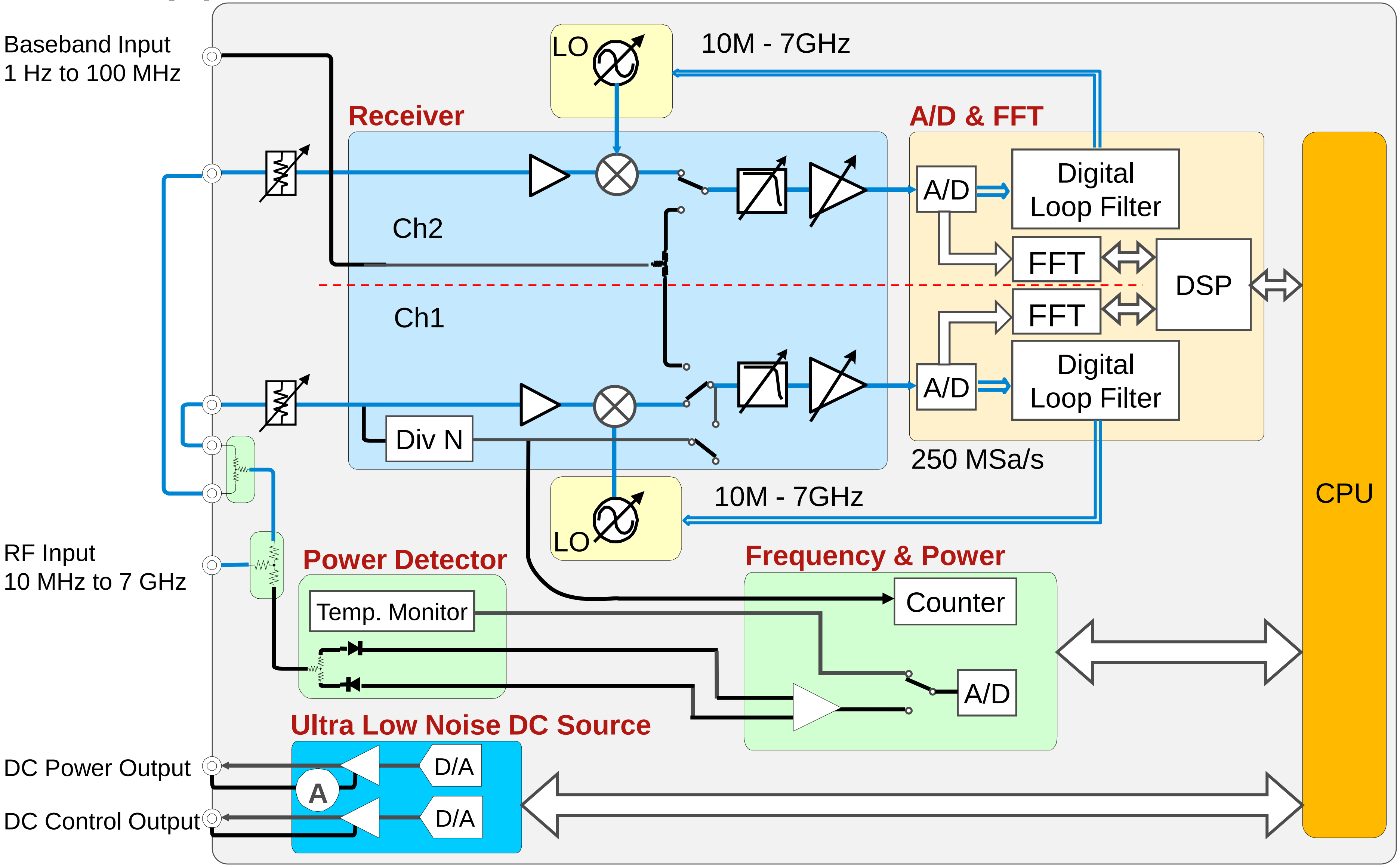
$$N_{meas} = N_{S.U.T.} + (N_1 + N_2)/\sqrt{M}$$ Assuming N_1 and N_2 are uncorrelated.

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

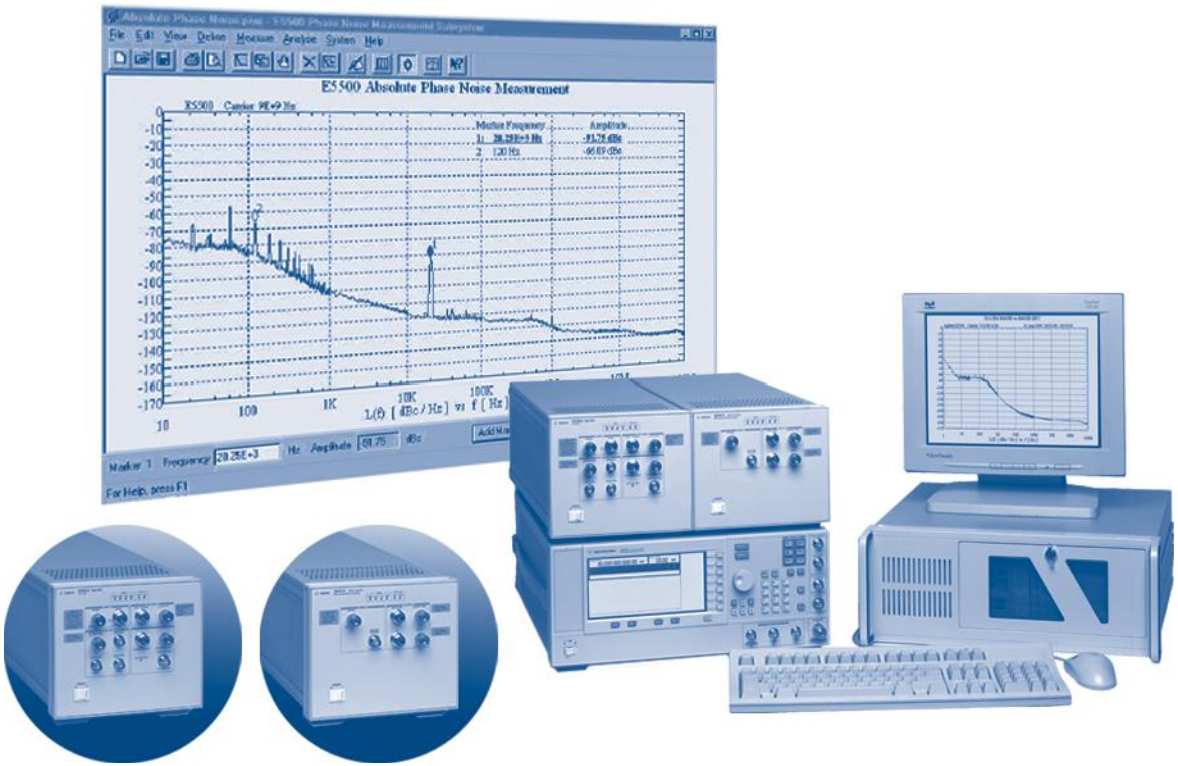
Agilent E5052B Cross Correlation

- 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
- In particular, it is well suited for free running oscillators
- Measurement speed suffers when the number of correlations becomes large, limiting close-in phase noise measurement performance.

One-step phase noise measurement



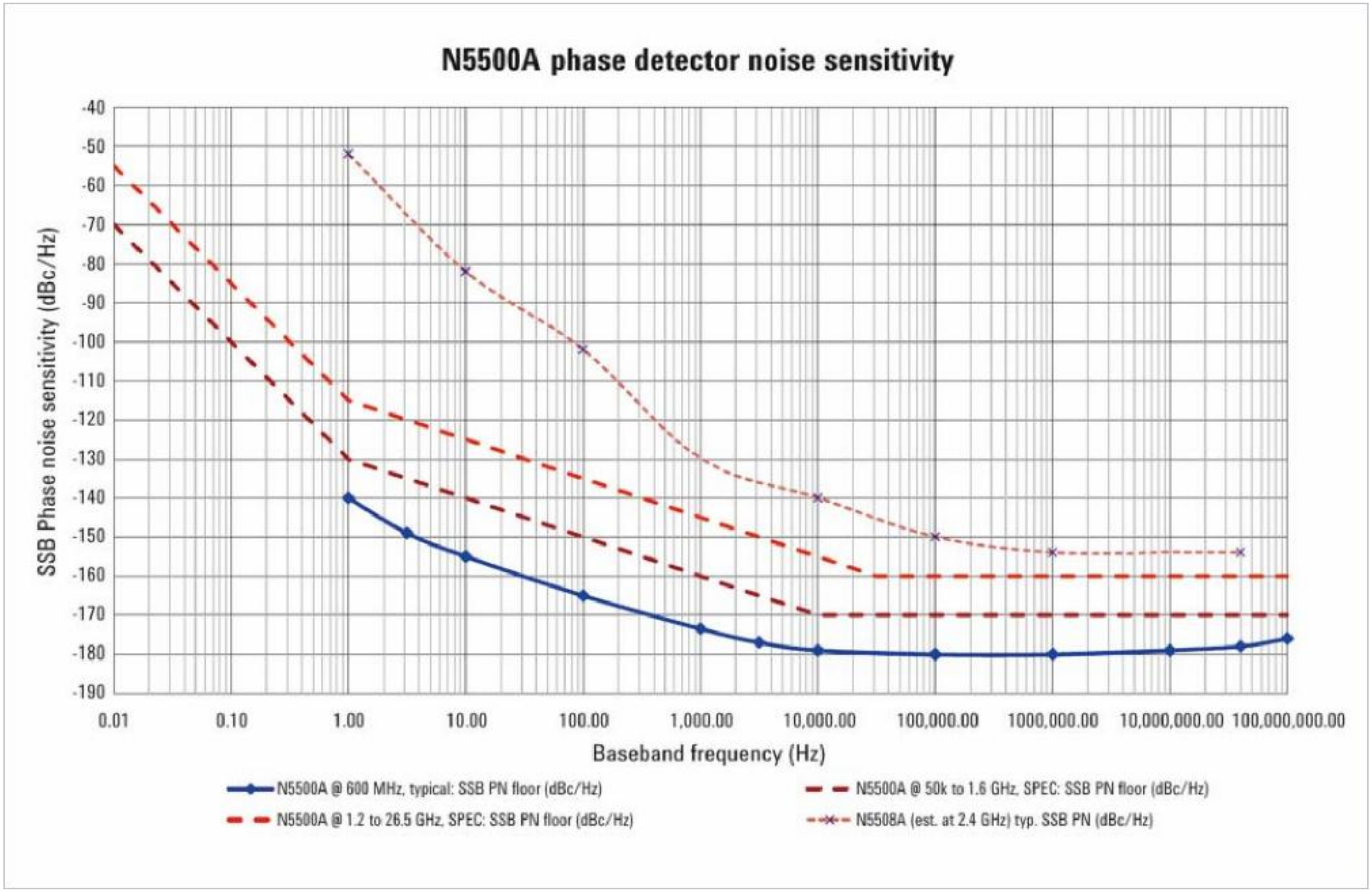
Agilent E5500 Phase Noise Measurement System



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

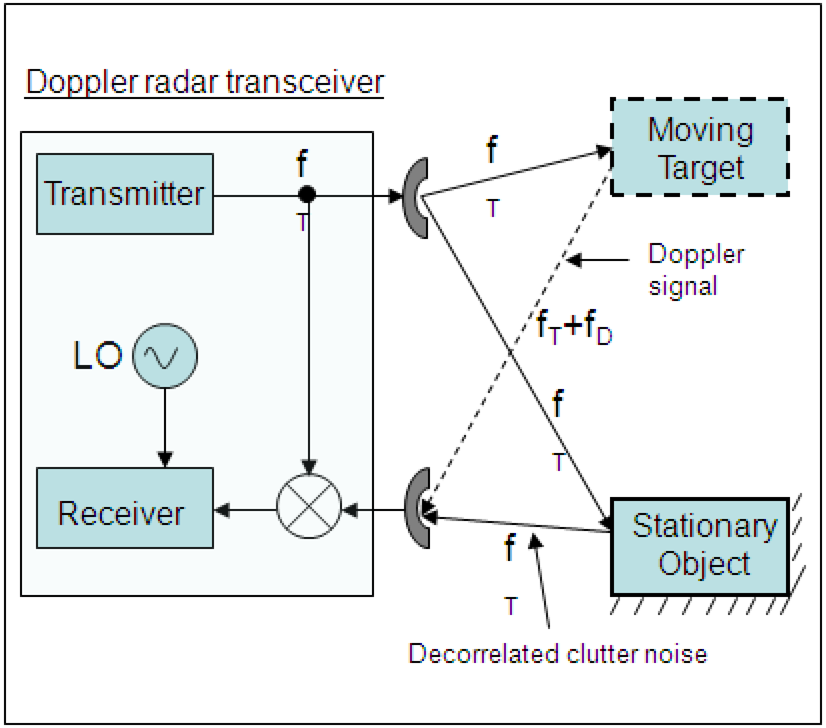


µW and mm-Wave Phase Noise Techniques – Frequency Extension Up To 110 GHz

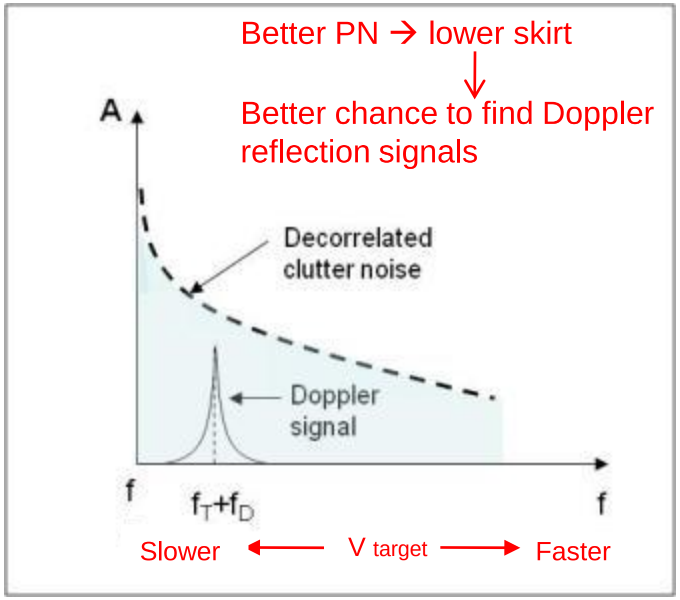
- Why is Phase Noise Important for µW and mmW?
- Microwave and mmWave Applications
- Difficulty of Phase Noise Measurement in Millimeter Freq Range
- Measurement Up To 26.5 GHz With E5053A Downconverter
- Measurement Up To 110 GHz With External Harmonics Mixers
  - Measurement Configuration
  - Measurement Example
  - Expected Phase Noise Sensitivity

Why is Phase Noise Important for uW and mmW?

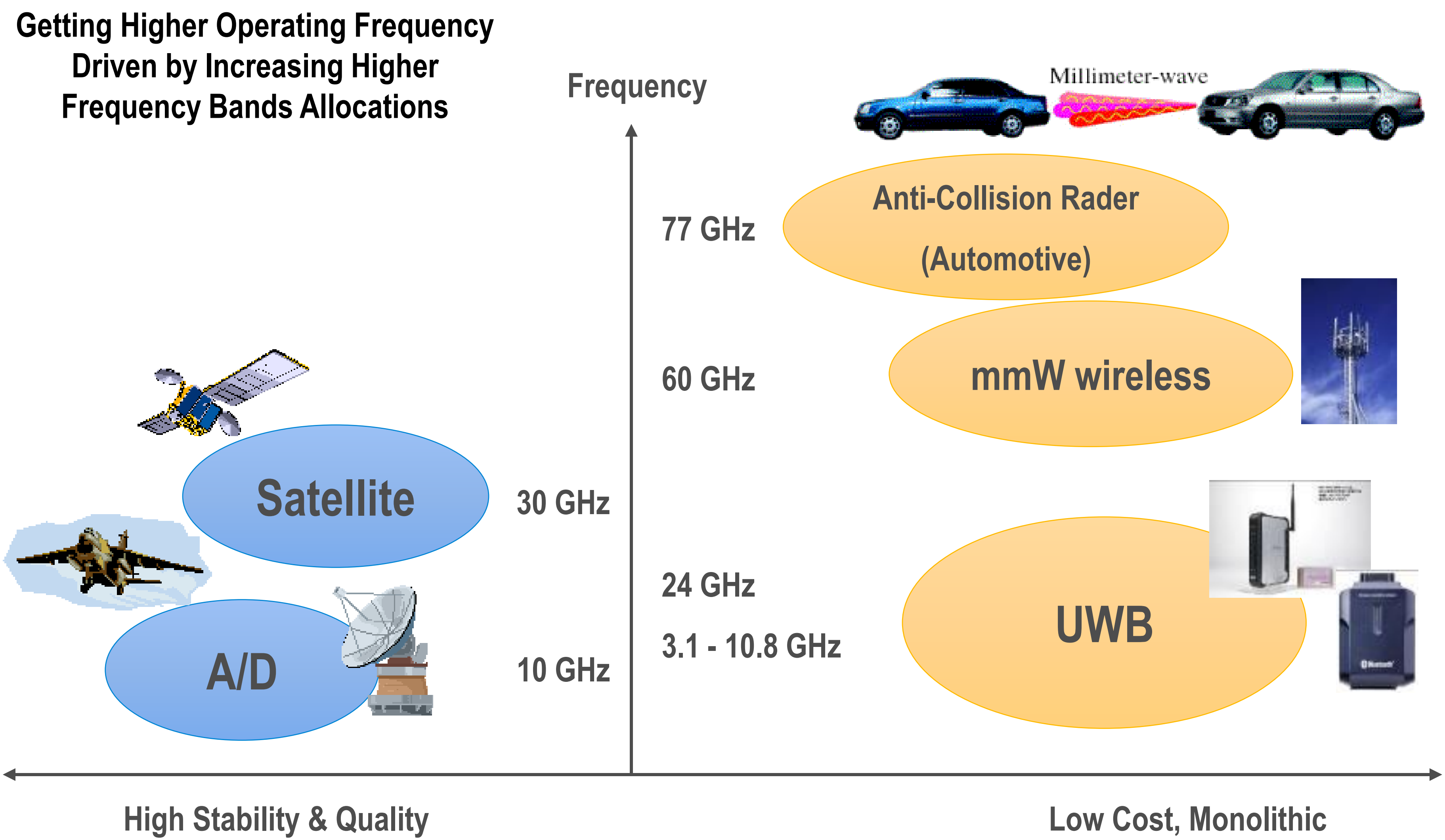
Highest performance radar transceiver designs demand the best phase noise to find moving targets, fast or slow.



Vehicle-mounted radar @ 46.7 GHz

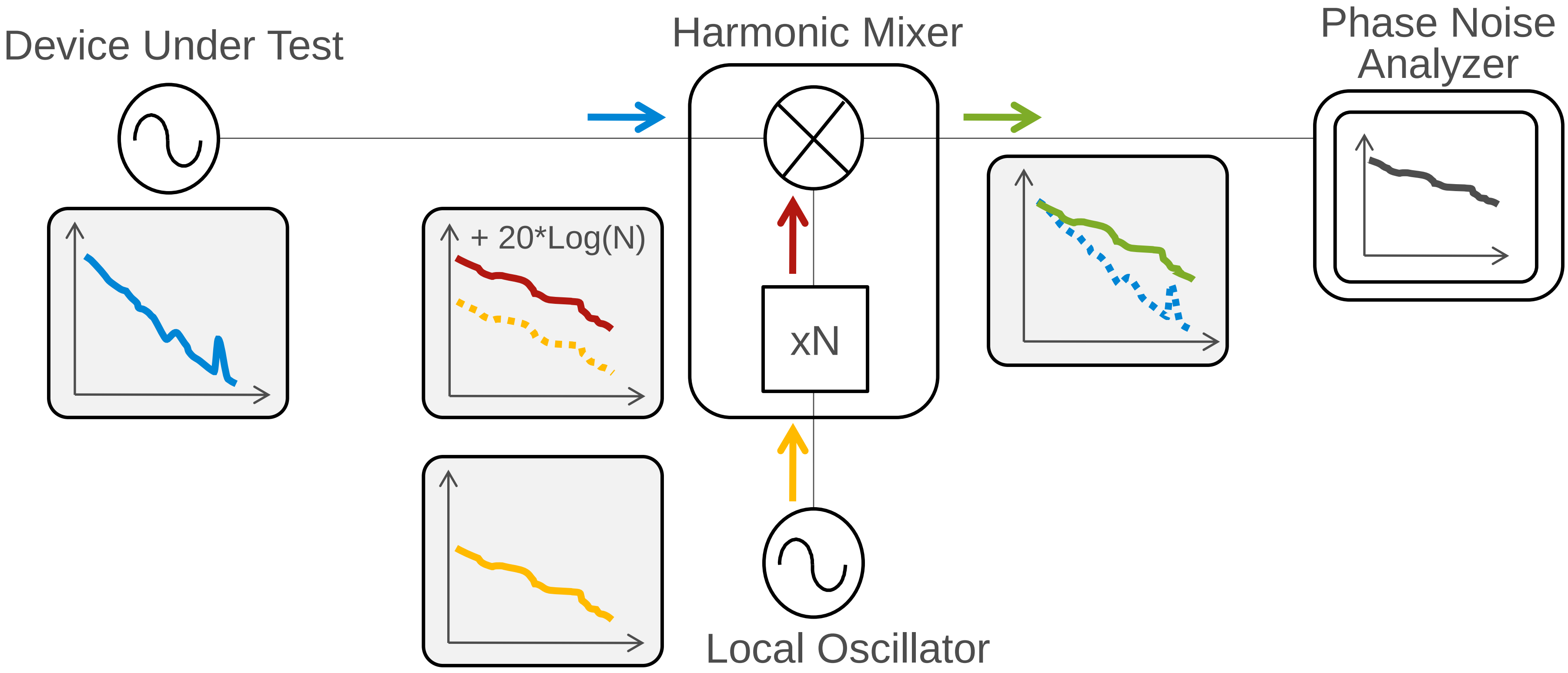


Microwave and mmWave Applications



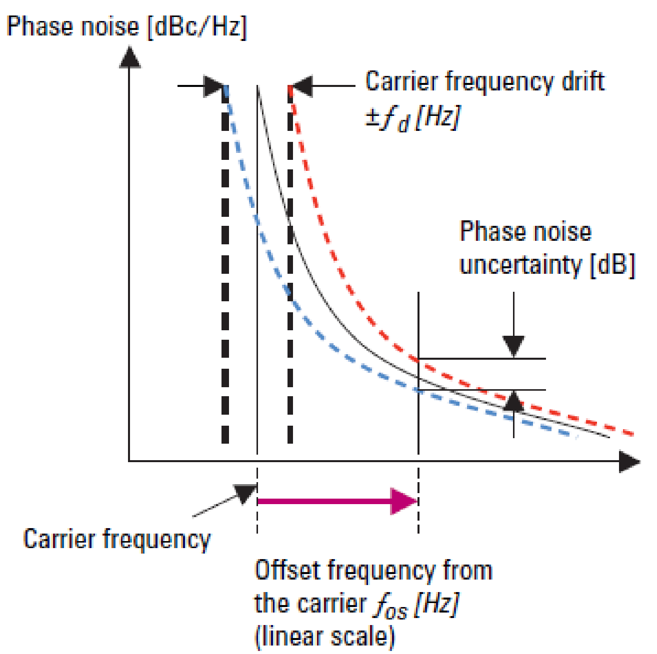
Difficulty of Phase Noise Measurement in Millimeter Freq Range

Phase noise performance of local oscillator for downconverter limits the measurement sensitivity.



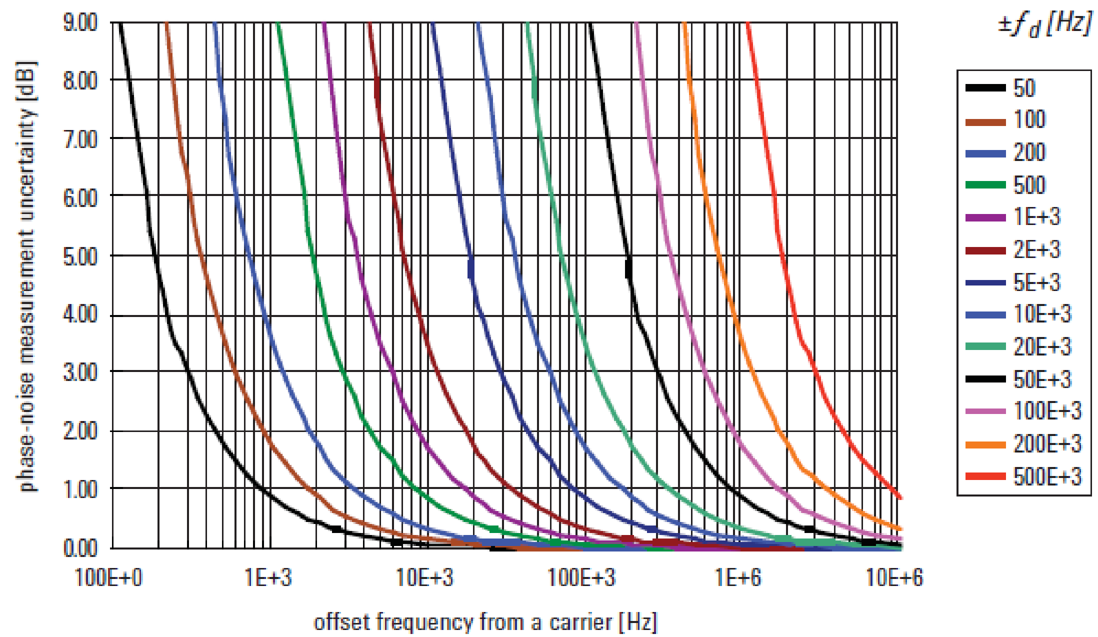
Difficulty of Phase Noise Measurement in Millimeter Freq Range

Carrier tracking is needed for accurate measurement results from close-in offset frequency.



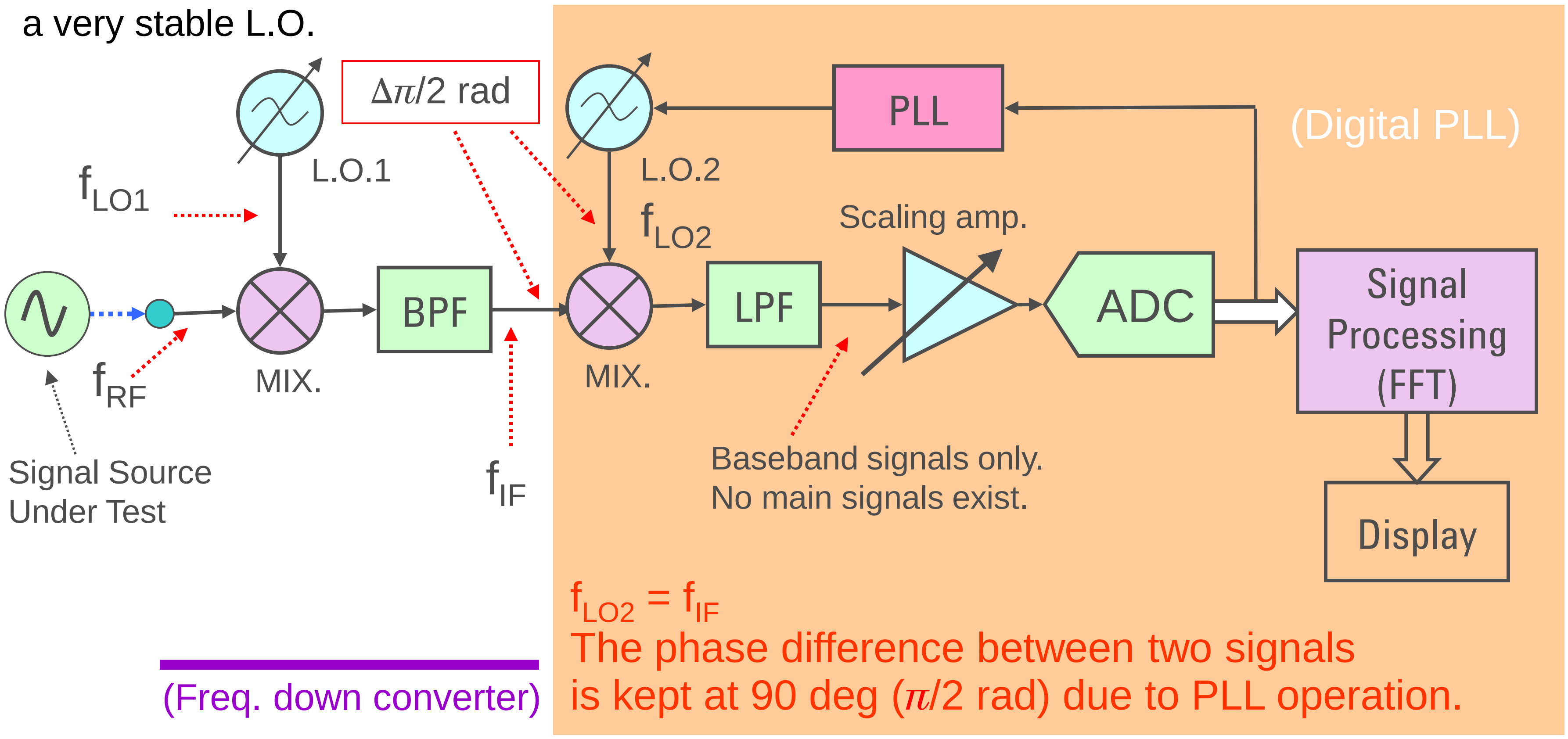
uncertainty: $20 * Log_{10}\left(\frac{f_{os}+f_d}{f_{os}-f_d}\right)$

assuming that – *20 dB/dec of slope*



Measurement Up To 26.5 GHz
With E5052B + E5053A Downconverter

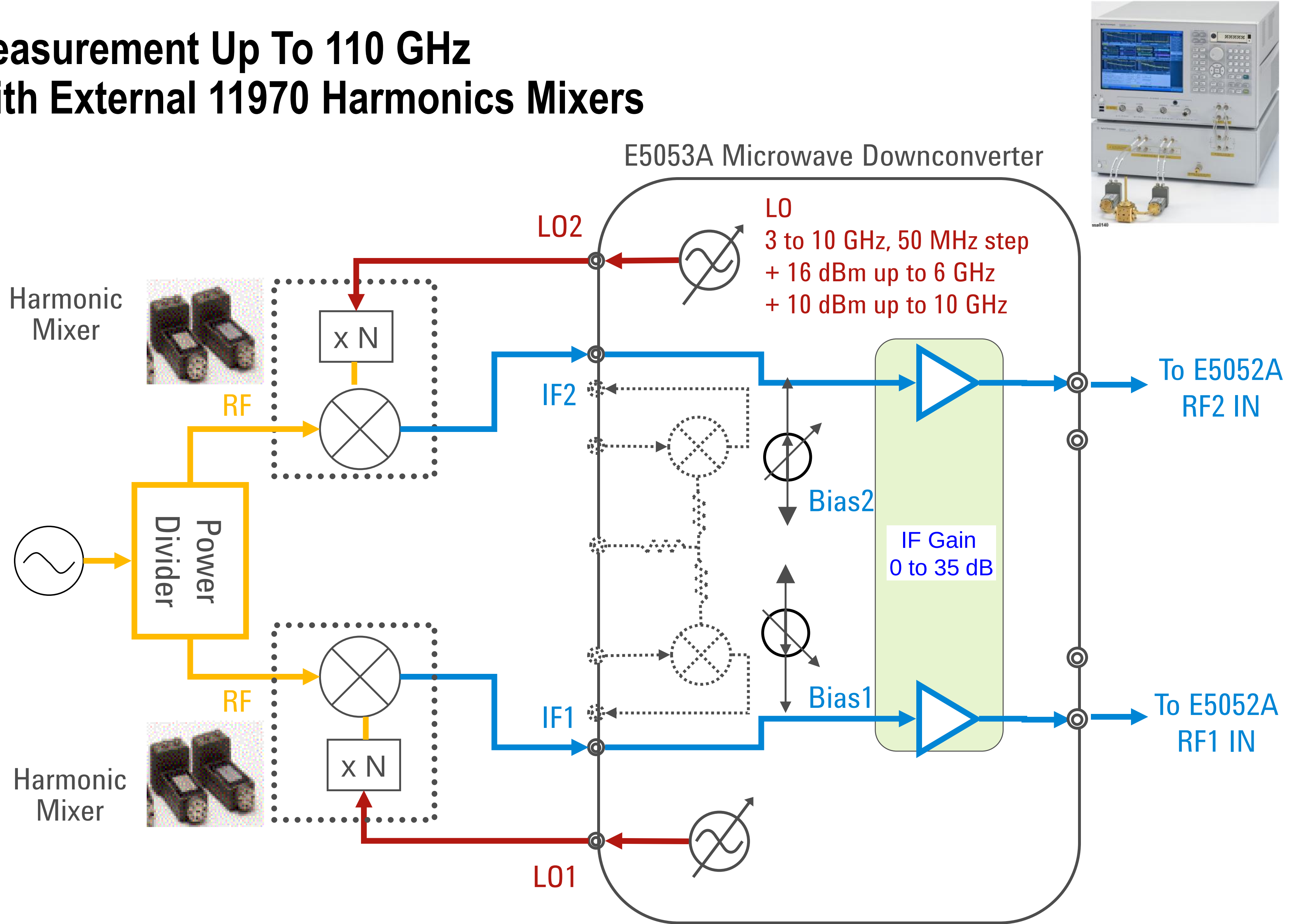
Basic theory of PLL method (Heterodyne conversion)



$f_{LO2} = f_{IF}$

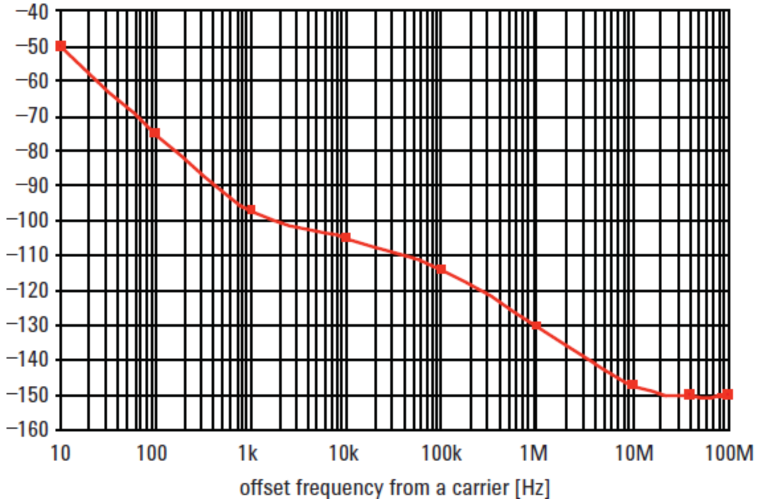
The phase difference between two signals is kept at 90 deg ($\pi/2$ rad) due to PLL operation.

Measurement Up To 110 GHz
With External 11970 Harmonics Mixers

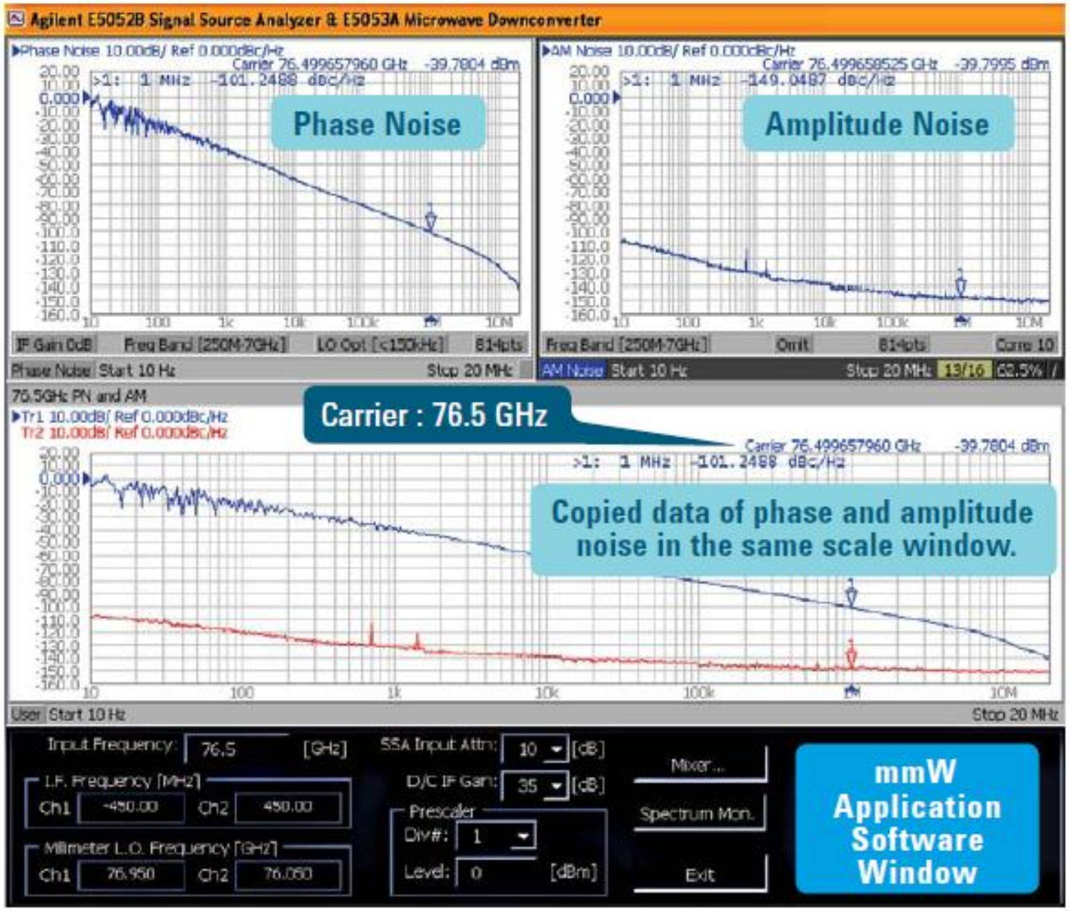


77 GHz Measurement Example

Phase Noise Floor at 77 GHz (Nominal)



Offset Freq [dBc/Hz]	SSB PN Floor [dBc/Hz]
100	-73
1k	-97
10k	-108
100k	-112
1M	-128
10M	-138
100M	-141



Phase Noise Sensitivity

Harmonic Mixer

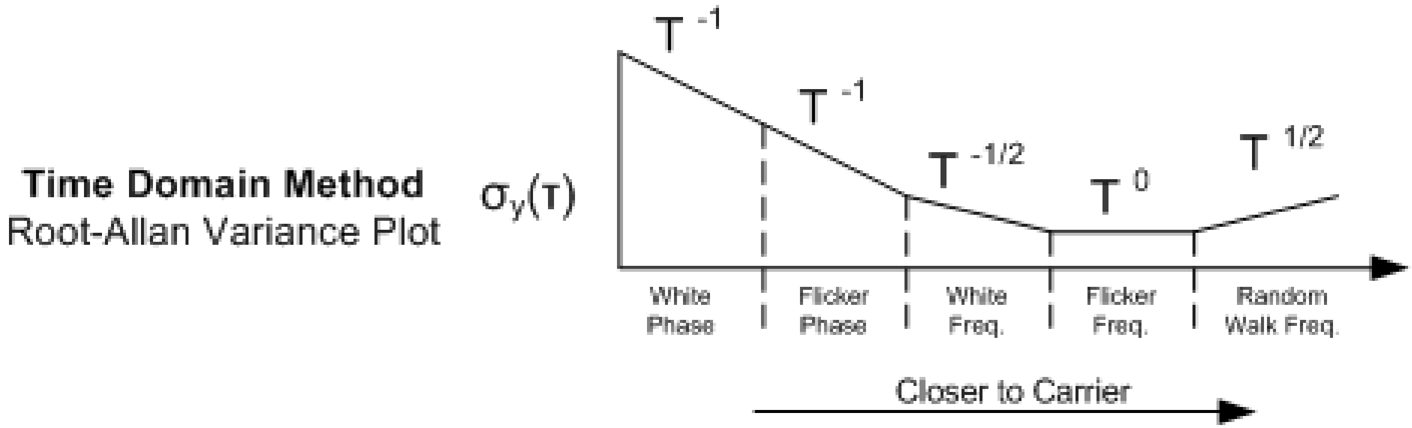
Mixer model	Frequency band	N
11970A	26.5 to 40 GHz	8
11970Q	33 to 50 GHz	10
11970U	40 to 60 GHz	10
11970V	50 to 75 GHz	14
11970W	75 to 110 GHz	18

	A band		U band		V band			W band	
	26.5 to 40 GHz		40 to 60 GHz		50 to 75 GHz			75 to 110 GHz	
Offset Freq	34GHz	40GHz	42GHz	60GHz	60GHz	66GHz	75GHz	77GHz	110GHz
1 kHz	-106	-104	-104	-100	-100	-99	-98	-97	-94
10 kHz	-117	-114	-115	-111	-111	-110	-109	-108	-105
100 kHz	-119	-119	-117	-115	-115	-114	-113	-112	-109
1 MHz	-136	-135	-133	-131	-131	-130	-129	-128	-125
10 MHz	-145	-144	-144	-140	-140	-139	-138	-138	-135
100 MHz	-148	-147	-147	-143	-143	-142	-141	-141	-138

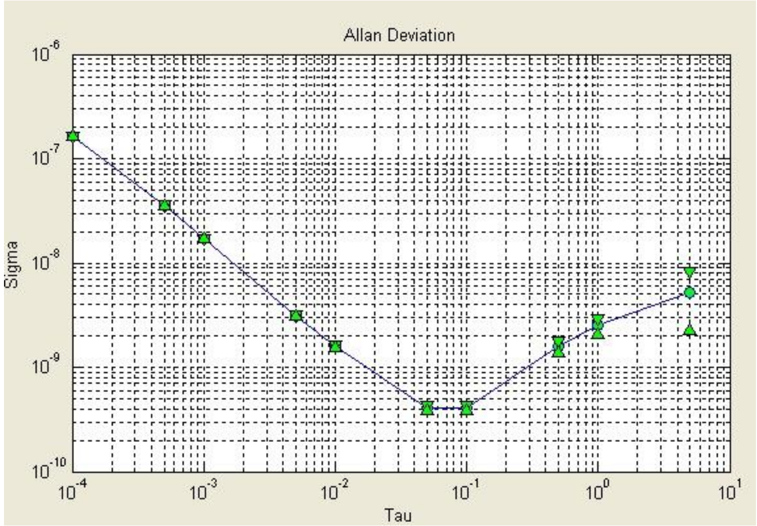
Start Freq: 1 Hz, Correlation 1

Time-Domain Stability Analysis

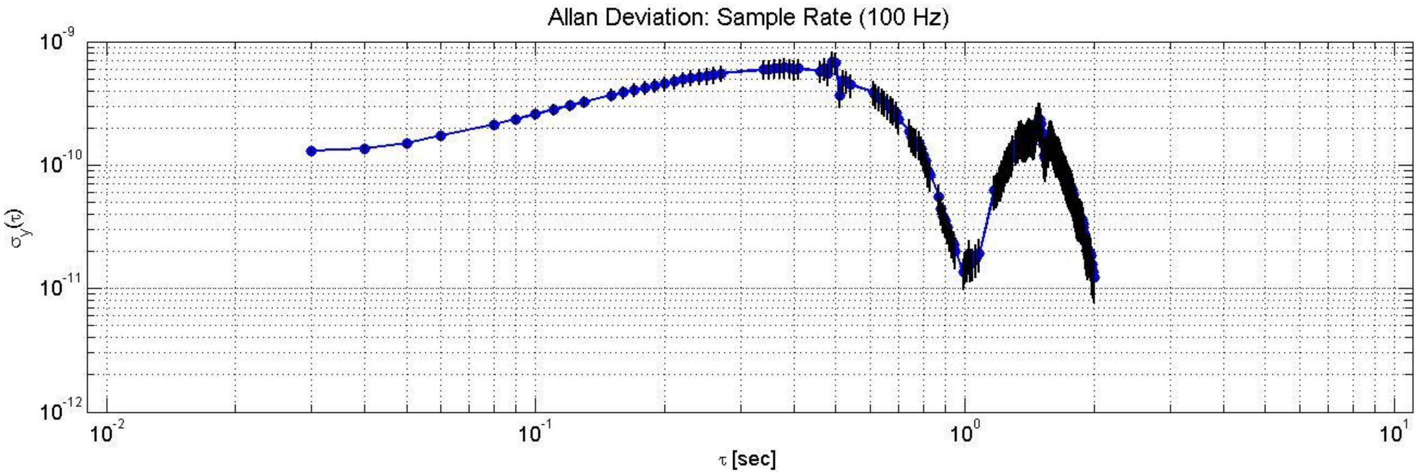
- In the time-domain, the stability of a signal is based on the statistics of its phase or frequency fluctuations as a function of time.
- Commonly a variance is used to facilitate this analysis.
  - Variance is a second-moment measurement of the phase or frequency fluctuations.
  - Common variances for frequency stability analysis include:
    - Allan => Most common but has relative poor confidence
    - Modified Allan => Used to distinguish White and Flicker Noise (PM)



Agilent 53230A Frequency Counter for Stability Analysis Using Allan Variance

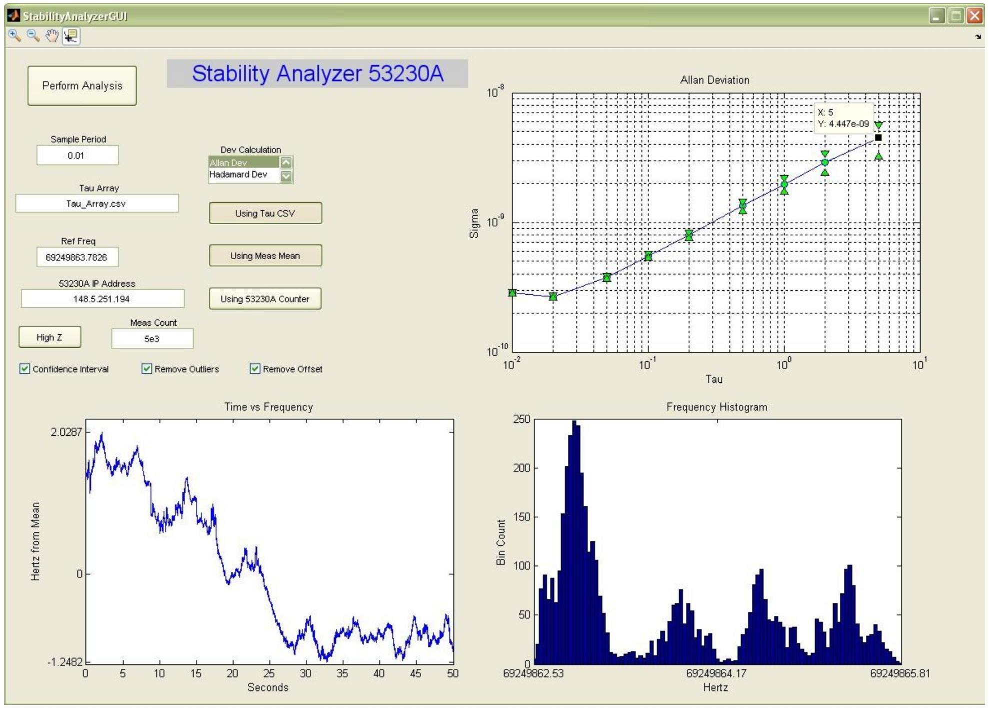


- 53230A Performance
  - Single shot resolution of 20 ps
  - Gap-free or Zero-Dead Time Capability
    - Fast:1 MSa/s
    - Slow: 1 Sample per 1000 seconds
    - This allows it to capture any noise process of interest
- With these features allow the 53230A to make frequency stability analysis in time domain



Stability Analyzer 53230A (2.0)

- The Stability Analyzer 53230A (2.0) is a free Matlab program that allows analysis of the stability of clocks, oscillators, and other signal sources using frequency measurements.
- The program uploads either frequency measurements from Agilent's 53230A universal counter or stored measurements on a CSV file.
- The program provides with a choice of two stability calculations, Allan deviation or Hadamard deviation.
- The outputs are three plots:
  - Allan or Hadamard variance
    - with optional confidence intervals
  - Frequency vs. time plot
  - Histogram frequency plot
- Program available at MatLab Central:
  - http://www.mathworks.com/matlabcentral/
  - Search Stability Analyzer 53230A



Local Oscillator (LO) Stability

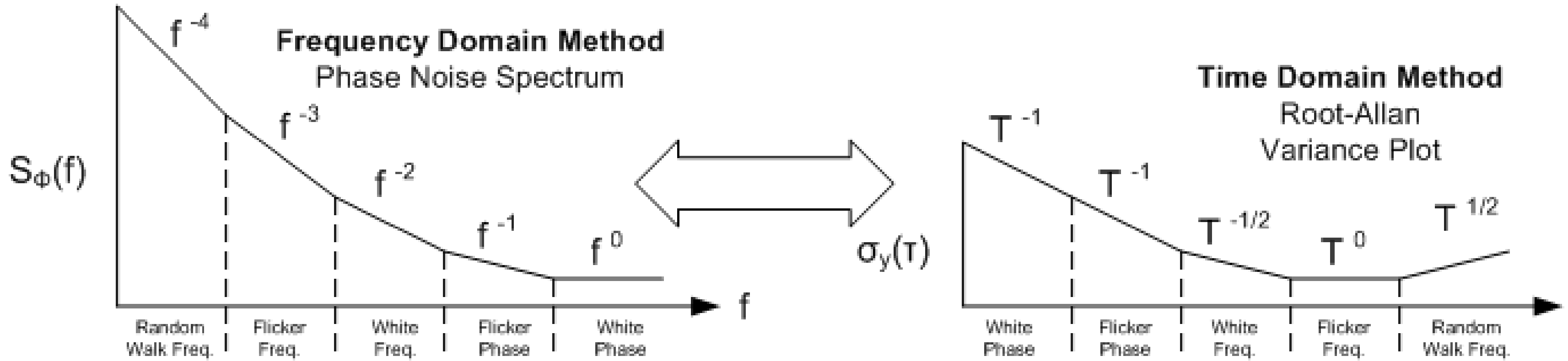
- A local oscillator (LO) is the heart of modern radar, electronic warfare or communication system. LOs produce carrier signals for transmitters and reference signals for receivers. With more data being squeezed into small bandwidths and the continuous need to resolve targets accurately in crowded areas, ensuring an LO has high stability and spectral quality is a critical part of modern transmitter and receiver design.

- To verify stability and spectral quality, instruments like signal analyzers provide a great wide-area view of the noise and spectral content around the LO carrier signal. Where they fall short is providing a clear picture of the phase noise close to the carrier. Modern frequency counters can pick up where instruments like signal analyzers leave off.
- In the past, to fully characterize noise <10 Hz from the carrier a complex measurement setup like the heterodyne method or a phase noise analyzer was needed. Today, with modern counters we can get < 1 Hz. To look really close to the carrier, we need to capture a large set of data to spot any gradual changes caused by low frequency noise.

Frequency Stability – Domain Conversion

- Conversions between the time and frequency domains can be made with numerical integration of their fundamental relationship, or with an approximation method based on a power law spectral model for the noise processes involved.

- The general conversion from time to frequency domain is not unique because white and flicker phase noise have the same Allan variance dependence on τ.



Frequency Stability – Domain Conversion (Continued)

- The time domain frequency stability is related to the spectral density of the fractional frequency fluctuations by

$$\sigma^2(\tau) = \int_0^{\infty} S_y \cdot |H(f)|^2 \cdot df$$

where $|H(f)|^2$ is the transfer function of the time domain sampling function. For the two-sample Allan time domain stability, the transfer function is given by

$$|H(f)|^2 = 2\left[\frac{sin^4(\pi\tau f)}{(\pi\tau f)^2}\right]$$

- Hence, the Allan variance can be found from the frequency domain by

$$\sigma_y^2(\tau) = 2\int_0^{f_h} S_y(f)\,\frac{sin^4(\pi\tau f)}{(\pi\tau f)^2}\,df$$

- And, the expression for the modified Allan variance is

$$Mod\sigma_y^2(\tau) = \frac{2}{N^4\pi^2\tau_0^2}\int_0^{f_h} S_y(f)\,\frac{sin^6(\pi\tau f)}{f^2 sin^2(\pi\tau_0 f)}\,df$$

Power Law Domain Conversions

- Domain conversion can be made for power law noise models using the following expression and defined terms:

$$\sigma_y^2(\tau) = h_{-2}\frac{(2\pi)^2}{6}\tau + h_{-1}2\ln 2 + h_0\frac{1}{2\tau} + h_1\frac{1.038 + 3\ln(2\pi f_h\tau)}{2\pi^2\tau^2} + h_2\frac{3f_h}{(2\pi)^2\tau^2}$$

where the h_α terms represent the level of the various power law nioses.

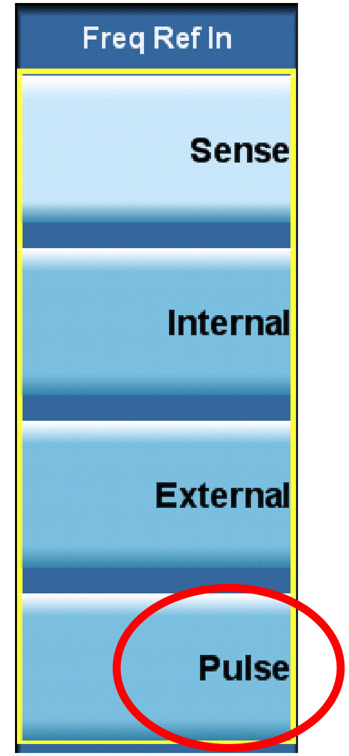
Noise Type	**$\sigma^2_y(\tau)$**	**$S_y(f)$**	where
Rand. Walk (FM)	$A \cdot f^2 \cdot S_y(f) \cdot \tau^1$	$A^{-1} \cdot \tau^{-1} \cdot \sigma^2_y(\tau) \cdot f^{-2}$	$A=4\pi^2/6$
Flicker (FM)	$B \cdot f^1 \cdot S_y(f) \cdot \tau^0$	$B^{-1} \cdot \tau^0 \cdot \sigma^2_y(\tau) \cdot f^{-1}$	$B=2 \cdot \ln 2$
White (FM)	$C \cdot f^0 \cdot S_y(f) \cdot \tau^{-1}$	$C^{-1} \cdot \tau^1 \cdot \sigma^2_y(\tau) \cdot f^0$	$C=1/2$
Flicker (PM)	$D \cdot f^{-1} \cdot S_y(f) \cdot \tau^{-2}$	$D^{-1} \cdot \tau^2 \cdot \sigma^2_y(\tau) \cdot f^1$	$D=1.038+3 \cdot \ln(2\pi f_h \tau_0)/4\pi^2$
White (PM)	$E \cdot f^{-2} \cdot S_y(f) \cdot \tau^{-2}$	$E^{-1} \cdot \tau^2 \cdot \sigma^2_y(\tau) \cdot f^2$	$E=3\ f_h/4\pi^2$

- f_h is the upper cutoff frequency of the measuring system in Hz and τ_0 is the measurement time. These factors only apply to white and flicker PM noise.

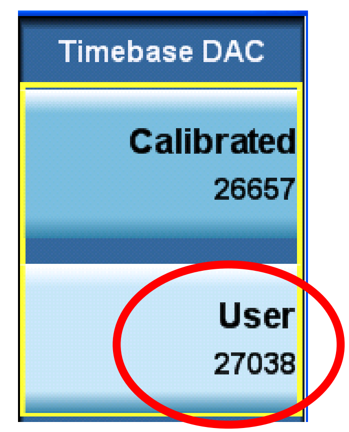
Atomic Frequency Reference

- The Atomic Frequency Reference (AFR) is a cesium-based atomic clock that PXA/MXA/EXA can use to discipline (adjust) the Internal 10 MHz Reference and effectively increasing the frequency accuracy.
- The AFR allows users to make more sensitive frequency reading measurements.
- Great alternative to a Primary Reference Standard which many labs and manufacturing facilities do not have.
- Model Number: J7203A

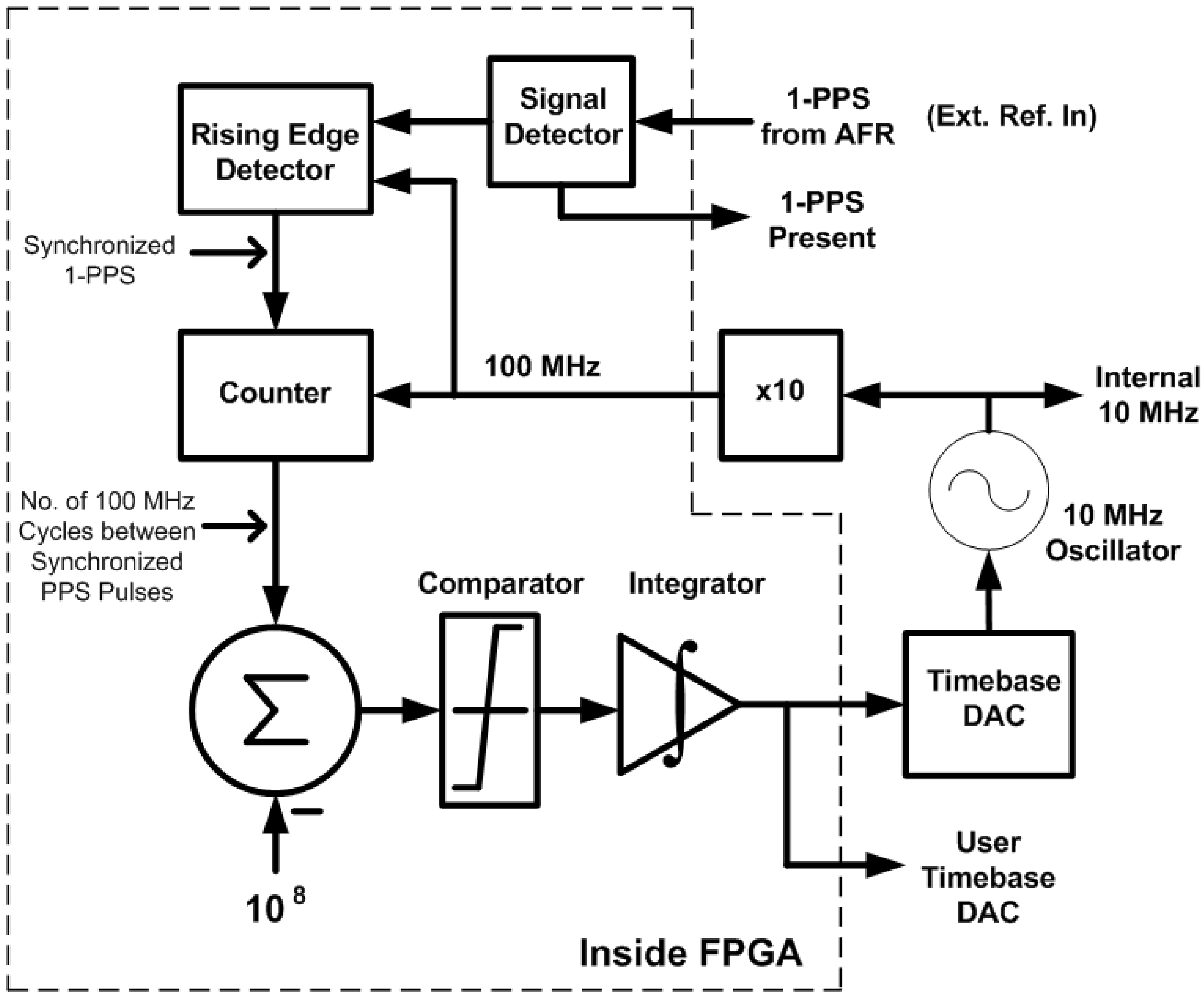
Interfacing with the AFR



- Now, a Pulse choice is under Freq Ref In
- The AFR is engaged if:
  - Instrument is in Pulse or Sense mode
- If Instrument is set to Pulse and AFR is removed, an error message appears: "Ref missing or out of range; Pulse"
- If Instrument is set to Sense and AFR is removed, the Instrument switches to Internal
- When the AFR is engaged, the User Timebase DAC is adjusted automatically and the user can't adjust it



AFR Interfacing with Signal Analyzer



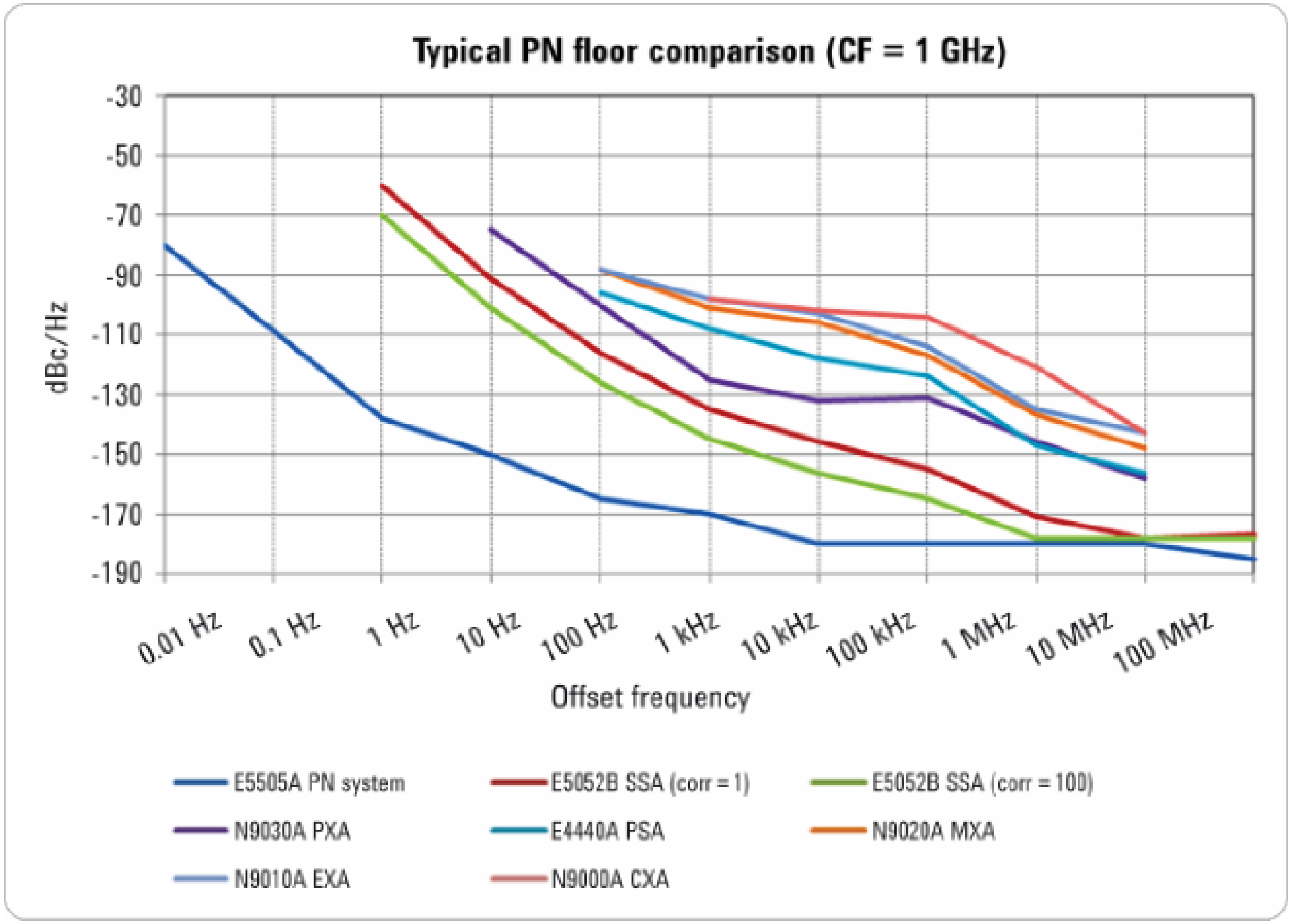
Summary

- Frequency instability is an important parameter that needs to be characterized in modern radar, analog communications, and digital systems.
- The analysis can be done in the frequency or time domains.
  - In the frequency-domain, there are several methods to measure phase noise. These techniques have advantages and disadvantages related to complexity, performance, and price.
    - Agilent's solutions are summarized on the following slide.
  - In the time-domain, modern counters are used to measure variance to characterize the statistics of a signal phase or frequency fluctuations as a function of time
    - Agilent's solution is the 53230A Frequency Counter with
      - Single Shot Resolution of 20-ps and Gap-Free capability.
  - Also, domain conversion of the instability analysis is possible with numerical integration or power law noise model approximation.
- The Atomic Frequency Reference, J7203A, effectively increases the stability of the internal reference of X-series signal analyzers.
  - Higher accuracy of frequency readout

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 measureing 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



Questions?