Noise - A stench to the ear, Undomesticated music, The chief product and authenticating sign of civilization

Ambrose Bierce - “The Devils Dictionary” 1907

Craig Nelson
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80303
Email: craig.nelson@boulder.nist.gov
Topics

- Introduction and Review
- Noise Types
- Measurement Methods
- Measurement Calibration
- Common Measurement Problems
- Conclusions
WEATHER MONITORING

INDUSTRY and MILITARY NEEDS for
SPECTRAL PURITY

- Navigation
- Defense & Homeland Security
- Secure Communication
- Astronomy & Geodesy

Noise Metrology

Atomic Frequency Standards & Spectroscopy
NOISE

AM Noise

PM Noise
Difficulty of using a Spectrum Analyzer

- IF bandwidth too wide
- SA internal reference too noisy
- Not enough dynamic range
  - Phase noise is often below -170 dBc
- Cannot distinguish between AM and PM noise
Single Sideband Modulation
Amplitude Modulation

Power

Frequency
Phase Modulation

Power

Frequency
Basic Model for Noisy Signal

\[ V(t) = A(1 + \alpha(t)) \cos(2\pi \nu_0 t + \phi(t)) \]

where:

- \( A \) = average amplitude
- \( \alpha(t) \) = fractional amplitude fluctuations
- \( \nu_0 \) = average frequency
- \( \phi(t) \) = phase fluctuations
Basic Definitions

\[ V(t) = A(1 + \alpha(t)) \cos(2\pi \nu_0 t + \phi(t)) \]

**phase** = \(2\pi \nu_0 t + \phi(t)\)

\[ \omega(t) = \frac{d}{dt}[\text{phase}] \]

\[ \nu(t) = \frac{1}{2\pi} \frac{d}{dt}[2\pi \nu_0 t + \phi(t)] = \nu_0 + \frac{1}{2\pi} \frac{d}{dt} \phi(t) \]

**Fractional frequency deviation**

\[ y(t) = \frac{\nu(t) - \nu_0}{\nu_0} = \frac{1}{2\pi \nu_0} \frac{d}{dt} \phi(t) \]

\[ S_y(f) = PSD[y(t)] = \frac{2}{T} |Y_T(f)|^2 \quad 0 < f < \infty \]

[\( \frac{1}{Hz} \)]
Definition of Phase Noise

\[
S_\phi(f) = PSD^1(\phi(t)) = \frac{2}{T} |\Phi_T(f)|^2 \quad 0 < f < \infty \quad [\frac{\text{rad}^2}{\text{Hz}}]
\]

Single sideband phase noise

\[
\mathcal{L}(f) \equiv \frac{1}{2} S_\phi(f) \quad [\text{dBc} / \text{Hz}]
\]

\[
S_\phi(f) = \left( \frac{v_0}{f} \right)^2 S_y(f)
\]

Definition of Amplitude Noise

\[
S_\alpha(f) = PSD^1(\alpha(t)) = \frac{2}{T} |A_T(f)|^2 \quad 0 < f < \infty \quad [\frac{1}{\text{Hz}}]
\]
Noise Types

- **Additive Noise**
  - Thermal $f^0$
  - Shot noise

- **Multiplicative Noise**
  - Flicker $f^{-1}$
  - Higher order colored noise types $f^{-2}, f^{-3}, f^{-4}, ...$
Additive Noise

Power

Frequency
Additive Noise

Frequency

Power
Since it is uncorrelated to the carrier, additive noise always appears as equal amount of AM and PM Noise.

For Amplifiers:

\[ S_\phi(f) = S_\alpha(f) = \frac{kTB}{P_l} \]

\[ NF = -174 + NF - P_l \quad @ 300K \]
Multiplicative Noise
Multiplicative Noise
Additive and Multiplicative Noise

- Power
- Additive Noise
- Multiplicative Noise
- Frequency
- Fourier Frequency
- Phase Noise
Additive and Multiplicative Noise

10 GHz, Gain=32.5dB, NF=1

Offset Frequency [Hz]

L(f) [dBc/Hz]

Pin=-43.3dBm
Pin=-33.2dBm
Pin=-29.2dBm
Pin=-24.28
Pin=-21.22dBm, 1dB compression

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Noise Figure

• Noise figure is only a figure of merit of thermal additive noise.
• It has ZERO correlation to flicker or any other type of multiplicative noise.
• In the linear region of operation. The phase noise floor for a device can be determined from input power and noise figure as follows:

\[ S_\phi (\text{floor}) = S_\alpha (\text{floor}) = \frac{kT_0 BNF}{P_{in}} \]

\[ = -174 + NF - P_{in} \quad [dB \text{rad}^2 / Hz] \text{ or } [dB / Hz] \]

\[ L (\text{floor}) = -177 + NF - P_{in} \quad [dBc / Hz] \]
Unlike additive noise, multiplicative AM and PM are not fundamentally correlated because they up convert by different mechanisms.
High Linearity => Low Multiplicative PM Noise (Flicker) 
Separation between P1dB and IP3 is a simple indicator 
> 15 dB has potential for low flicker
Typical PM Flicker Noise for Different Semiconductor Types

-170 -160 -150 -140 -130 -120 -110 -100

SSB Phase Noise [dBc/Hz]

X-Band GaAs AMP

X-Band HBT
X-Band Schottky Mixer

L-Band BJT
HBT Amp

HF-VHF BJT
HF-UHF Schottky Mixer

Offset Frequency [Hz]

1E+0 1E+1 1E+2 1E+3 1E+4 1E+5 1E+6

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Courtesy of M. Driscoll
Noise Summary

**Additive Noise Summary**
- Noise power is uncorrelated to signal power
- AM = PM
- AM and PM noise levels vary inversely with carrier power

**Multiplicative Noise Summary**
- Noise power is correlated to signal power
- AM ≠ PM
- AM and PM noise levels are independent of carrier power
Typical Noise Types

- Passive Devices
  - Thermal $f^0$
  - Some have flicker (magnetics, carbon resistors) $f^{-1}$
  - Higher order noise may come from temperature effects $f^{-4}$

- Active Devices
  - Almost all have thermal and flicker $f^0$ and $f^{-1}$
  - Possible temperature effects $f^{-4}$

- Sources (May some or all of the higher order types)
  - White PM or Thermal $f^0$
  - Flicker PM $f^{-1}$
  - White FM $f^{-2}$
  - Flicker FM $f^{-3}$
  - Random Walk $f^{-4}$
Noise Types

- **White phase**: Thermal Noise, Shot Noise
- **Flicker phase**: Electronics, recombination-generation, traps
- **White frequency**: Resonator, integrated white phase
- **Flicker Frequency**: Resonator, integrated flicker phase
- **Random Walk**: Temperature, Shock, Vibration, Resonator

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Leeson’s Effect

Resonator

Barkhausen
Gain = 1
Phase Shift = $2\pi n$

Phase Shifter

Amplifier
Leeson’s Effect - Low Q

\[
S_\varphi(f) = \frac{FkT}{P_a} \left[ 1 + \frac{f_c}{f} + \left( \frac{f_0}{2fQ_L} \right)^2 \left( 1 + \frac{f_c}{f} \right) \right]
\]

Phase Noise

- Oscillator Noise
- Amplifier Noise

Fourier Frequency

- Half Resonator Bandwidth
- \( f_0 \)
- \( 2Q_L \)
Leeson’s Effect - High Q

\[
S_\varphi (f) = \frac{FkT}{P_a} \left[ 1 + \frac{f_c}{f} + \left( \frac{f_0}{2fQ_L} \right)^2 \left( 1 + \frac{f_c}{f} \right) \right]
\]

Amplifier Noise

Oscillator Noise

Phase Noise

Half Resonator Bandwidth

\[
\frac{f_0}{2Q_L}
\]

Fourier Frequency

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Four Sources at Different Frequencies and Similar Power

SSB Phase Noise dBc/Hz at 500 MHz

-60 -40 -20 0 dBc/Hz at 500 MHz

10 GHz DRO
500 MHz SAW
100 MHz OCXO
5 MHz OCXO

Offset Frequency [Hz]
1E+0 1E+1 1E+2 1E+3 1E+4 1E+5 1E+6 1E+7

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All Sources Normalized to 10 GHz

SSB Phase Noise [dBc/Hz]

Offset Frequency [Hz]

-180 -160 -140 -120 -100 -80 -60 -40 -20 0

1E+0 1E+1 1E+2 1E+3 1E+4 1E+5 1E+6 1E+7

10 GHz DRO
500 MHz SAW
100 MHz OCXO
5 MHz OCXO
Composite Phase Noise Synthesis

SSB Phase Noise [dBc/Hz]

Composite Phase Noise Synthesis

Offset Frequency [Hz]

10 GHz DRO

500 MHz SAW

100 MHz OCXO

5 MHz OCXO

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Effects of Frequency Manipulation on Phase Noise

Translation or Mixing

\[ S_A^\phi(f) + S_B^\phi(f) + S_M^\phi(f) \]

- Residual Noise
- AM to PM Conversion
- Noise Folding

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Frequency Multiplication

\[ v_2(t) = \cos[N(\omega t + \varphi(t))] \]

\[ \omega_2 = N \omega \]

\[ S_{\phi_2}(f) = \frac{2}{T} \left| N \Phi_{1,T}(f) \right|^2 = N^2 S_{\phi}(f) \]
Phase Noise

Divider Noise Floor

20LogN dB

Phase Noise

Frequency Division

Fourier Frequency

Ideal Response

Typical Response

Oscillator Response

\[ v_2(t) = \cos(\omega t + \phi(t)) \]

\[ N = \frac{\omega}{\omega_0} \]

\[ \left| \frac{S_{\phi^2}(f)}{N} \right|^2 = \frac{2}{T} \left| \frac{\Phi_f(f)}{T} \right|^2 \]

\[ \frac{\omega}{\omega_0} = \frac{N}{2} \]

\[ \frac{1}{\omega + \phi(t)} \]

\[ (\omega t + \phi(t)) \]
Extracting Noise

Two noisy signals

\[ V_1(t) = A_1(1 + \alpha_1(t))\cos(\omega t + \varphi_1(t)) \]
\[ V_2(t) = A_2(1 + \alpha_2(t))\cos(\omega t + \varphi_2(t)) \]

Multiply them together

\[ V_1(t) \cdot V_2(t) = \left[ \frac{A_1A_2(1 + \alpha_1(t) + \alpha_2(t) + \alpha_1\alpha_2(t))}{2} \right] \cdot \left\{ \cos[(\omega_1 + \omega_2)t + \varphi_1(t) + \varphi_2(t)] + \cos[(\omega_1 - \omega_2)t + \varphi_1(t) - \varphi_2(t)] \right\} \]
Pha se Noise

Set $\omega = \omega_1 = \omega_2$

$$V_1(t) \cdot V_2(t) = \frac{A_1A_2(1 + \alpha_1(t) + \alpha_2(t) + \alpha_1\alpha_2(t))}{1 + \alpha_1(t) + \alpha_2(t) + 2\alpha_1\alpha_2(t)} \cdot \cos\left[\phi_1(t) - \phi_2(t) + \phi_3\right] + \cos\left[\phi_1(t) - \phi_2(t)\right]$$

When $\phi_3 = 90^\circ$ 

$$\sin x \equiv x, \quad \cos(x + 90) \equiv x$$

$$h_{LPF} * \left[ V_1(t) \cdot V_2(t) \right] \equiv k_d \left[ \phi_1(t) - \phi_2(t) \right] \quad \text{when} \quad \omega_1 = \omega_2 \land \phi_3 = 90^\circ$$
Amplitude Noise

\[ \alpha_1 = \alpha_2 \]

\[ V_1(t) = V_2(t) = A_1[1 + \alpha_1(t)]\cos[\omega t + \varphi(t)] = A_2[1 + \alpha_2(t)]\cos[\omega_2 t + \varphi_2(t)] \]

\[
\left[ \frac{A^2 (1 + 2\alpha(t) + \alpha^2(t))}{2} \right] \cos[\phi_3]
\]

When \( \phi_3 = 0^\circ \) and \( \cos(0) = 1 \)

Remove DC term and neglect higher order term

\[
\left[ \frac{A^2}{2} + A^2 \alpha(t) + \frac{A^2 \alpha^2}{2}(t) \right]
\]

\[ h_{LPF} \ast [V^2(t)] \equiv \frac{A^2}{2} + k_a \alpha(t) \quad \text{when} \quad \phi_3 = 0^\circ \]
Phase Noise Measurement Types

- Homodyne or Residual – Single source
  - Noise Floor
  - Any two port device
- Heterodyne - Two source measurement
- Frequency Discriminator
  - Delay Line
  - Cavity Resonator
- Digital Measurement Systems
Two Oscillator Measurement

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Phase noise of source cancels

\[
S_{\phi_{\text{NoiseFloor}}}(f) = \frac{[\Delta \phi_R]^2(f) - [\Delta \phi_R]^2(f)}{K_d^2(f) \cdot BW} + \frac{PSD[V_{\text{rms}_\text{system}}(f)]}{K_d^2(f)}
\]
Phase noise of source cancels

Two devices are needed if they have a long delay

Two devices are needed if they change the frequency
System Calibration

- Static Phase shift (PM)
- Kd or Beat Frequency Method (PM)
- Modulation
  - Single Sideband (AM/PM)
  - Phase Modulation (PM)
  - Frequency Modulation (PM)
  - Amplitude Modulation (AM)
- Noise Standards (AM/PM)
Static Phase Shift

- A known phase shift is introduced, and the corresponding voltage change measured.
- Adjustable phase shifter (mechanical or electrical)
  - Switched delay lines
  - Programmable phase shift in a synthesizer

\[ K_d = \frac{\text{Voltage Change}}{\text{Phase Shift}} \left[ \frac{V}{\text{rad}} \right] \]
\[ S_\phi(f) = \frac{\text{PSD}[V_{rms}(f)]}{K_d^2} \]

Remember:
\[ \mathcal{L}(f) = \frac{1}{2} S_\phi(f) \quad [\text{dBc} / \text{Hz}] \]
Two Oscillator Beat Frequency Calibration
Calculating Mixer Sensitivity $K_d$

Period $T$

Make sure both positive and negative slopes are equal in magnitude and symmetric

$K_d (v / rad) = \frac{Slope(v / s) \cdot T(s)}{2\pi (rad)}$

Typically 0.3 to 0.4 V/rad for a saturated double balanced Schottky diode mixer
Singl  e Sourc  e Kd Calibration

Power Meter

50Ω

LPF

Substitution Source

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Mixer Sensitivity

- Frequency
- RF and LO power
- Mixer termination at all three ports
- Cable lengths

Calibration conditions must replicate the measurement conditions as closely as possible
Possible Errors Using $K_d$ Calibration

- Determines gain only at a single frequency
- Noise is suppressed inside PLL bandwidth
- Requires open loop PLL or substitution source
- Beat configuration does NOT match actual measurement configuration
- Injection Locking
SSB Calibration Method

![Diagram of SSB Calibration Method](image-url)
Generates equal amounts of AM and PM Noise
Phase and amplitude modulation is detected at ½ the SSB ratio

\[ S_\phi(f_c) \equiv S_\alpha(f_c) \equiv \frac{P_{v_0+f_c}}{2P_{v_0}} \equiv \frac{P_{v_0-f_c}}{2P_{v_0}} \]

A SSB tone at n dB below the carrier creates phase and amplitude noise with

\[ S_\phi(f_{cal}) = n - 3dB \quad \text{or} \quad L(f_{cal}) = n - 6dB \]

\[ S_\alpha(f_{cal}) = n - 3dB \]
Additive Noise Calibration Method
AM/PM Modulator

- Can be adjusted for pure PM or AM modulation
- Extremely flat frequency response
- Calibrates $K_d(f)$ with system locked
- Can be used to find true quadrature for minimizing AM leakage
MAXIMIZE detected AM signal
By adjusting phase shifter

\[ S_\alpha(f_c) \cong \frac{P_{V_0-f_c} + P_{V_0+f_c}}{P_{V_0}} \]
Monitor Port MINIMIZE detected AM signal
Diode Detector By adjusting phase shifter

\[ S_\phi(f_c) \equiv \frac{P_{V_0-f_c} + P_{V_0+f_c}}{P_{V_0}} \]
Tips for Measuring Gain vs. Fourier Frequency using Swept Modulation

- Measure power spectrum not PSD
- Use flattop windows for FFT
- Only small number of averages required
- 3-5 points per decade
- Create gain curve with cubic spline or linear curve
- Make sure tone does not saturate IF amplifiers
Calibration Curve at X-band

Gain : 23.1

Fourier Frequency (Hz)
Phase Noise of X-band Synthesizer

![Phase Noise Graph](image)
Tips for Measuring Noise

- Measure Power Spectral Density in Vrms/√Hz
- Use Hanning window
- Confidence interval depends on number of averages
- Confidence interval depends also on resolution and video bandwidth for swept analyzers
- Measure system noise floor.
Noise Floor Reduction Techniques

- Cross-Correlation
- Carrier Suppression
Cross-correlation PM Noise System for Two Port Measurements

\[ \text{Noise}_{\text{Crosscorrelated}} = \text{Noise}_{\text{Correlated}_{1,2}} + \frac{\text{Noise}_{\text{Uncorrelated}_{1}} + \text{Noise}_{\text{Uncorrelated}_{2}}}{\sqrt{N_{\text{Averages}}}} \]
Correlated Noise Measurements

Voltage Noise (dBV/rtHz)

Channel 1
Channel 2
Cross Spectrum

-140
-150
-160
-170
-180
-200

1E+6 1E+7

Frequency (Hz)

Voltage Noise (dBV/rtHz)

1E+6 1E+7

100,000 Ave : 35 min

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Cross-correlation Oscillator PM Measurements

\[
S_{\phi}(f)_{\text{Cross}_{1,2}} = S_{\phi}(f)_{\text{DUT}} + \frac{S_{\phi}(f)_{\text{Ref}_1} + S_{\phi}(f)_{\text{Ref}_2} + S_{\phi}(f)_{\text{System}_1} + S_{\phi}(f)_{\text{System}_2}}{\sqrt{N_{\text{Averages}}}}
\]
Cross-correlation Oscillator PM Measurements

Three oscillator cross-spectrum measurement

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AM Measurements*

\[ v(t) = k_{\alpha} P(t) \]

or

Diode Power Detector

In-phase non-saturated Mixer

\[ k_{\alpha} P_0 = \frac{\Delta v}{\Delta P/P_0} \]

\[ v(t) = k_{\alpha} P_0 (1 + \alpha(t))^2 \cong k_{\alpha} P_0 (1 + 2\alpha(t) + \alpha^2(t)) \]

\[ S_{\alpha}(f) = \frac{S_{\text{Vrms}}(f)}{4k_{\alpha}^2 P_0^2} \]

*The Measurement of AM noise of Oscillators – Rubiola2005
Cross-correlation Source AM Measurements

\[ S_{\alpha}(f)_{CrossAB} = S_{\alpha}(f)_{DUT} + \frac{S_{System_1}(f) + S_{System_2}(f)}{\sqrt{2N_{Ave}}} \]

\[ S_{\alpha}(f)_{CrossAB} = \frac{S_{v_{AB}}(f)}{4k^2_{\alpha_A} P_A^2 k^2_{\alpha_B} P_B^2} \]

\[ S_{\alpha}(f)_{CrossAB} = \frac{S_{v_{AB}}(f)}{K_a} \quad , \quad K_a = 4k^2_{\alpha_A} P_A^2 k^2_{\alpha_B} P_B^2 \]

*The Measurement of AM noise of Oscillators – Rubiola2005*
Two-port AM Measurements

\[ S_{\alpha}(f)_{\text{Cross}_{1,2}} = S_{\alpha}(f)_{\text{DUT}} + S_{\alpha}(f)_{\text{REF}} + \frac{S_{\alpha}(f)_{\text{SystemA}} + S_{\alpha}(f)_{\text{SystemB}}}{\sqrt{2N_{\text{Averages}}}} \]

Reference AM noise must be less than DUT noise

Saturation can help in reducing AM Source noise
Digital Measurement Systems

- Carrier frequencies are sampled directly with A/D converters and phase information is extracted mathematically.
- No phase lock required
- Signals can be of different frequencies.
- Limited frequency range 1 - 400 MHz.
- Fourier Range of 1 mHz to 1 MHz.
- Limited sensitivity
Integral PM and AM Noise Standards

- Low noise signal source
- Two outputs with extremely low differential AM and PM noise
- Calibrated noise source
- Greatly simplifies AM and PM measurements
- Generates a calibrated level of equal AM and PM noise
Block Diagram of NIST PM/AM Noise Standard

- **Signal**
- **White Noise**
- **Bandpass**
- **Splitter**
- **Summer**
- **Phase Shifter**
- **Reference**
- **Modulated**

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Added Noise Appears as Equal Amounts of AM and PM

\[ S_a(f) = S_\phi(f) = \frac{PSDV_n(v_0 - f) + PSDV_n(v_0 + f)}{2V_0^2} \]

While

\[ \int_0^{\infty} S_\phi(f) \ll 0.1 \]
Basic Carrier Suppression Technique (Interferometric)
Basic Carrier Suppression Technique (Interferometric)
Delay Line Measurement Systems

\[ S_\varphi(f) = \frac{S_v(f)}{k_d^2 |H(jf)|^2} \]

\[ |H(jf)|^2 = 4\sin^2(\pi f \tau_d) \]
Delay Line Transfer Function

\[ |H(jf)|^2 = 4\sin^2(\pi f \tau) \]

System sensitivity is proportional to \( \tau_d \)
Long delays reduce sensitivity due to insertion loss
Transfer Function has nulls at \( n/\tau_d \)
System sensitivity is proportional to $\tau_d$
Long delays reduce sensitivity due to insertion loss
Transfer Function has nulls at $n/\tau_d$
## Single and Dual Source Measurements

<table>
<thead>
<tr>
<th>Direct Frequency Comparison (Delay Line)</th>
<th>Direct Phase Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages:</strong></td>
<td><strong>Advantages:</strong></td>
</tr>
<tr>
<td>Doesn’t require reference source</td>
<td>Lowest noise floor</td>
</tr>
<tr>
<td>No PLL effects</td>
<td>Noise scales as $f^{-1}$ near carrier</td>
</tr>
<tr>
<td>Simple basic calibration</td>
<td>Noise floor easy to determine</td>
</tr>
<tr>
<td></td>
<td>Very wide band performance</td>
</tr>
<tr>
<td></td>
<td>Can be used for residual measurement</td>
</tr>
<tr>
<td><strong>Disadvantages:</strong></td>
<td><strong>Disadvantages:</strong></td>
</tr>
<tr>
<td>Noise floor scales as $f^{-3}$ near carrier</td>
<td>Requires reference of comparable quality</td>
</tr>
<tr>
<td>Noise floor harder to determine</td>
<td>Requires PLL to maintain phase lock between sources</td>
</tr>
<tr>
<td>Multiple delay lines required to cover different measurement conditions</td>
<td>Calibration needed for measuring inside PLL loop bandwidth</td>
</tr>
<tr>
<td>Not wideband – Frequency response has nulls</td>
<td></td>
</tr>
<tr>
<td>Not useful for residual measurements</td>
<td></td>
</tr>
<tr>
<td>Long delays have higher insertion loss</td>
<td></td>
</tr>
</tbody>
</table>
Optical Encoded Delay Line Measurement

~0.2 dB/km insertion loss vs 1 dB/m
Comparison of Noise Floors

Typical Noise Floors @ 10 GHz

-120
-130
-140
-150
-160
-170
-180
-190
-200

SSB Phase Noise [dBc/Hz]

1E+0 1E+1 1E+2 1E+3 1E+4 1E+5 1E+6

Offset Frequency [Hz]

Single Mixer
Correlated Mixer
Correlated Photonic Delayline
Correlated Interferometer (Rubiola)
Measurement Problems

- Mechanical Instabilities
- Phase locked loop effects
- IF Gain Flatness
- Delay effects
- RBW effects
- AM Leakage
- FM Port noise
- Ground Loops
Phase Locked Loop Effects

![Graph of Phase Noise vs Offset Frequency](image)
IF Gain Reduction in Presence of Noise Floor

Phase Noise (dBc/Hz)

Fourier Frequency (Hz)

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Delay Mismatch in Residual Measurements

Transfer function of delay line

Offset Frequency [Hz]

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Insufficient Resolution Bandwidth

Phase Noise

Frequency [Hz]

$L(f)$ [dBc/Hz]

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AM to PM Leakage in Mixer

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AM to PM Leakage in Mixer

Residual Measurement

Absolute Measurement

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FM Port (PLL) Noise

Phase Noise

\[ S_\phi(f) = \left( \frac{\nu_0}{f} \right)^2 \]

\[ S_y(f) = \left( \frac{K_\nu}{f} \right)^2 \text{PSD}(V_{rms}) \]

\( f^{-2} \text{ slope} \)

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K_\nu \text{ is VCO sensitivity in Hz/V}
Ground Loops and EMI

Noise floor at X-Band

$L(f) [\text{dBc/Hz}]$

Frequency [Hz]

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Ground Loops and EMI

- Power devices from batteries
- Shielding – Faraday and magnetic
- DC Blocks
- Replace IF Gain with RF gain (Interferometric)
- Isolate or remove computer connections
- Plug in AC power all at same place
- EMI filtered power strips/ Ferrite Cores
- Ground lifting plugs (dangerous)
- Isolation transformers (dangerous)
Conclusions

- Great care must be taken when calibrating the mixer sensitivity.
- Calibrating Kd versus Fourier can be achieved by utilizing a modulation technique.
- For ultra-low noise floors cross-correlation or carrier-suppression techniques can be used.
References


