



Low Noise Signal Generation and Verification Techniques

BSAC Seminar
September 10, 2013

IEEE Ultrasonics, Ferroelectrics, and
Frequency Control Society
Distinguished Lecture 2012-2013

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Consultant

The IEEE UFFC Society (from the website)



- The IEEE Ultrasonics, Ferroelectrics and Frequency Control (UFFC) Society has an international membership of approximately 2200 technologists. Our common historical origins are all traceable to the phenomenon of piezoelectricity.
- Our field of interest includes theory, technology, materials, and applications relating to:
 - The generation, transmission, and detection of ultrasonic waves.
 - Medical ultrasound and associated technologies.
 - Ferroelectric, piezoelectric, and piezo-magnetic materials.
 - Frequency generation and control, timing, and time coordination and distribution.
- For more information, including excellent Tutorials and other technical resources, please visit:

<http://www.ieee-uffc.org>

Acknowledgements



Special thanks to the IEEE UFFC Society for sponsoring this lecture.

Much of the material presented here is the result of work conducted at Westinghouse and subsequently Northrop Grumman, my previous employers of 48 years.

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Outline



- Introduction
 - Why “Low Noise”
- Noise Metrology
 - Time and Frequency Domain
 - Additive and Multiplicative
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- Low Noise Signal Generation
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 - Resonator/Oscillator Technology Comparison
 - Non-Oscillator Noise Contributors
- Noise Reduction Techniques
- Vibration-Induced Noise
- Noise Measurement Techniques
- Summary/Conclusions

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Why "Low Noise"



- Any system that sends and receives signals has a signal generator.
 - Radar
 - Electronic Warfare
 - Navigation
 - Communications
- The "information" in transmitted and received signals is in the form of carrier signal (frequency, phase, amplitude) modulation.
- The presence of "noise" on the transmitted and received signal reduces the ability of the system to accurately recover the demodulated signals (the information).
- The noise can originate in the transmitter electronics, the receiver electronics, or the external environment.

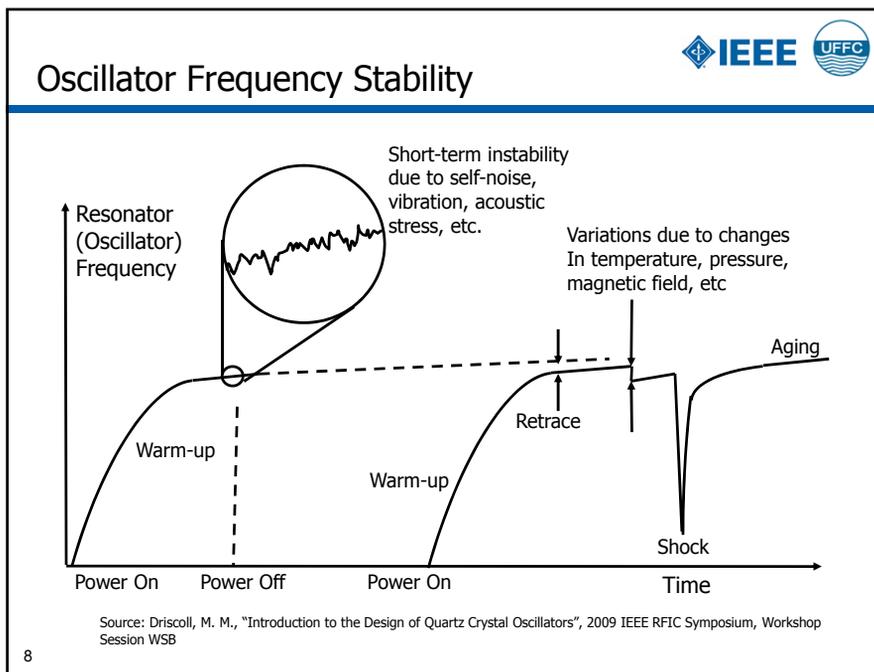
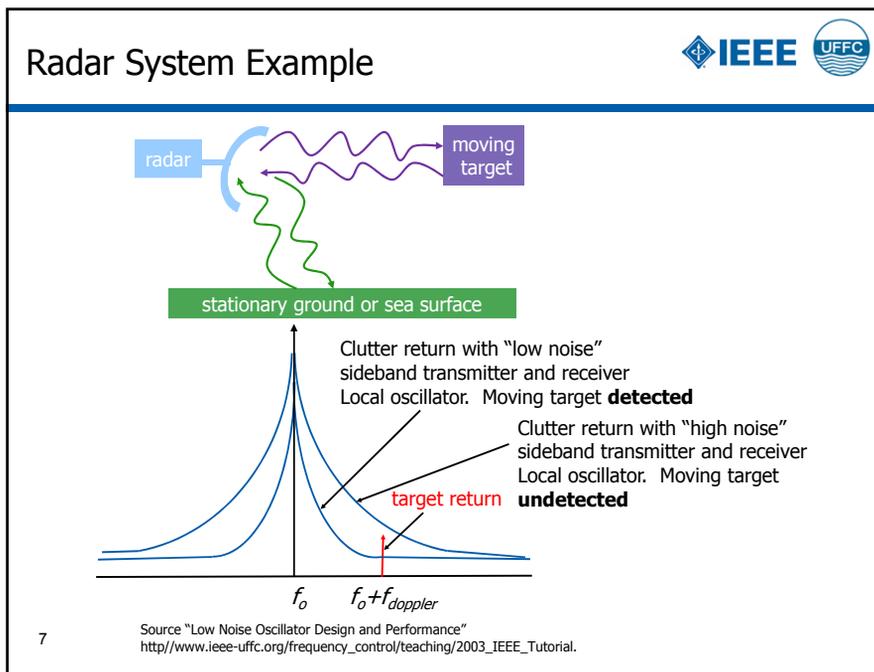
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Origins of Electrical Noise



- Noise Defined
 - Noise is a random phenomena that obscures an electrical signal.
- Sources of Noise
 - Sources of electrical noise typically occur at the "atomic" level and include:
 - shot noise
 - Johnson or thermal noise
 - partition noise
 - flicker noise or $1/f$ noise, characterized by a $1/f$ power spectrum
 - Other sources of carrier signal noise modulation include: DC supply noise acting on a RF device having gain and phase sensitivity to DC voltage, baseband noise voltage appearing across voltage-dependent, semiconductor junction capacitance, and also noise-like (i.e., random vibration) acting on sensitive components.

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Noise Metrology – Time Domain



- Time Domain: $\sigma_y(\tau)$ = The two sample deviation, or square root of the Allan Variance is the standard method of describing the short-term stability of oscillators in the time domain. It is usually denoted by $\sigma_y(\tau)$, where:

$$\sigma_y^2(\tau) = \frac{1}{2} \langle (y_{k+1} - y_k)^2 \rangle$$

- The fractional frequencies, $y = \Delta f/f$, are measured over a time interval, τ ; $y_{k+1} - y_k$ are the differences between pairs of successive measurements of y , and, ideally, $\langle \rangle$ denotes a time average of an infinite number of $(y_{k+1} - y_k)^2$. A good estimate can be obtained with a limited number, m , of measurements with $m > 100$.

Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

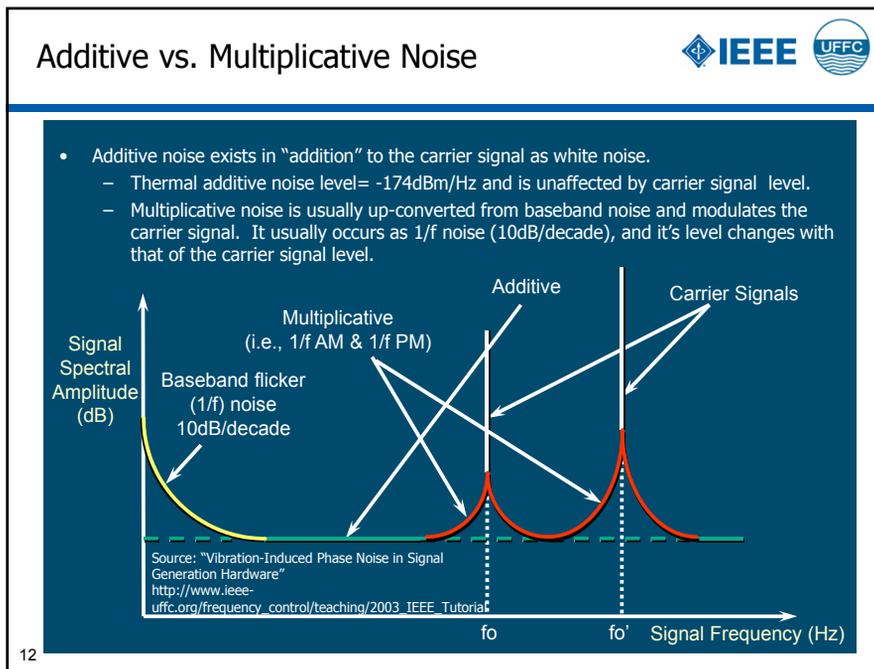
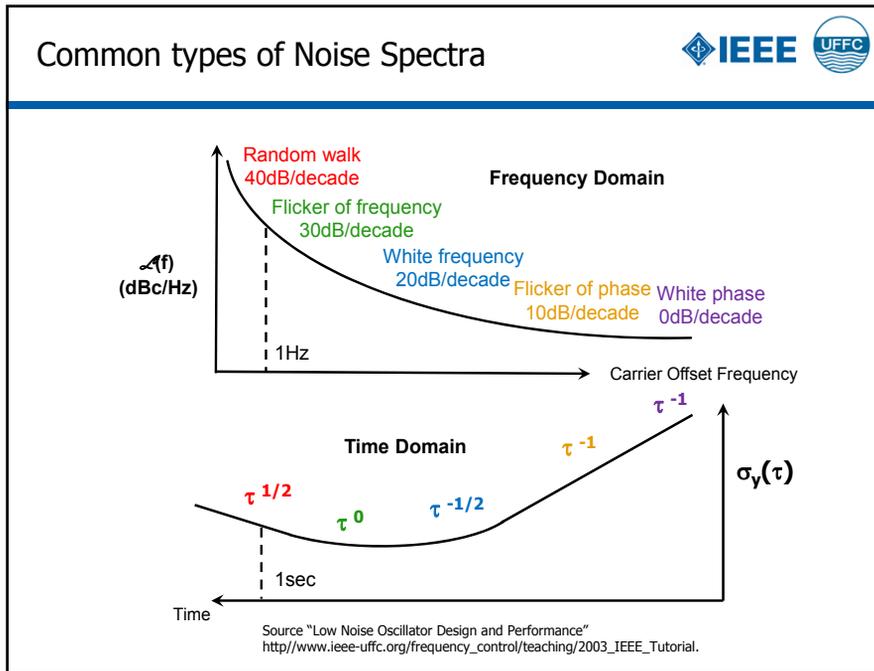
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Noise Metrology – Frequency Domain

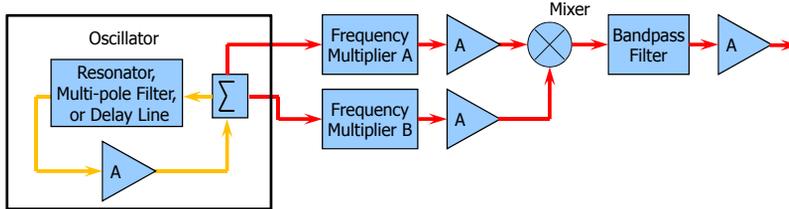


- $S_\phi(f)$ = Power Spectral Density (PSD) of the phase fluctuations. Units are rad^2/Hz .
- $S_y(f)$ = Power Spectral Density of the fractional frequency fluctuations. Units are $1/\text{Hz}$.
- $S_y(f) = (f/v_o)^2 S_\phi(f)$, v_o = carrier frequency.
- $S_a(f)$ = Power spectral Density of the fractional amplitude fluctuations. Units are $1/\text{Hz}$.
- $\mathcal{L}(f) = 10 \text{LOG}(S_\phi(f)/2)$. For small modulation indices, $\mathcal{L}(f)$ = **single sideband** phase noise-to-carrier power ratio in a 1Hz bandwidth at a offset frequency f from the carrier, expressed in units of dBc/Hz.

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Absolute vs. Residual Noise



- ➔ Absolute noise refers to noise that is due to the oscillator.
 - F**requency instabilities in the oscillator frequency control element (i.e., resonator) and **P**hase instabilities in the oscillator loop components (i.e., sustaining stage amplifier) result in signal **F**requency instability.
 - ➔ Residual noise refers to noise in non-oscillator, signal path components that modulate the signal **P**hase and **A**mplitude, but not the signal **F**requency.
- The total noise in the output signal is the sum of that due to the oscillator and that contributed by the signal path components.

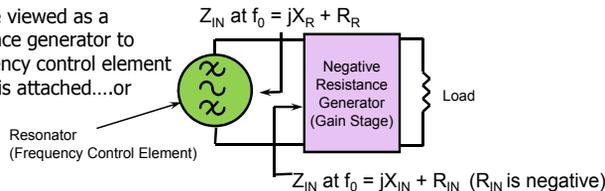
Source: "Vibration-Induced Phase Noise in Signal Generation Hardware"
http://www.ieee-uffc.org/frequency_control/teaching/Tutorial_REV_Q

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Oscillator Basics



The oscillator can be viewed as a negative resistance generator to which the frequency control element (i.e., resonator) is attached....or

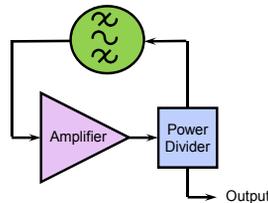


....a self-contained amplifier with the frequency control element in the positive feedback path.

Conditions for start-up: $X_R = -X_{IN}$, $R_R + R_{IN} < 0$ at f_0
 Steady State: $X_R = -X_{IN}$, $R_R + R_{IN} = 0$ at f_0

Conditions for start-up: Loop gain > 1 at f_0
 Loop phase shift = $2N\pi$ radians at f_0

Steady State: Loop gain = 1 at f_0
 Loop phase shift = $2N\pi$ radians at f_0



Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

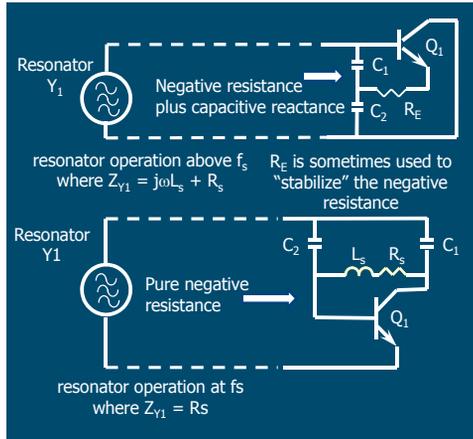
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Discrete Component vs. Modular Amplifier Sustaining Stage Oscillators



Discrete transistor:

- ☺ Low Cost.
- ☺ Component value change flexibility and reasonably good efficiency (DC power consumption).
- ☺ Ability to make use of resonator selectivity to reduce output signal additive phase noise (i.e., signal extraction through the resonator).
- ☹ For low noise, transistors with high f_t should be used. The circuit is then susceptible to high frequency instability due to layout parasitics and lossless resonator out-of-band impedance.
- ☹ Difficulty in predicting or measuring 1/f AM and PM noise using 50 ohm test equipment because the actual sustaining stage-to-resonator circuit interface impedances are not usually 50 ohms.



Source: M. Driscoll, "Introduction to Quartz Crystal Oscillators", Workshop WSB, 2009 IEEE International Microwave Symposium (RFIC portion)".

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Discrete Component vs. Modular Amplifier Sustaining Stage Oscillators

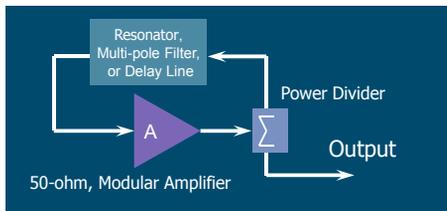


Modular Amplifier:

- ☺ Easily characterized using 50 ohm test equipment (s-parameters, AM and PM noise, etc).
- ☺ Availability of unconditionally stable amplifiers eliminates the possibility of parasitic oscillations.
- ☺ Amplifiers are available that exhibit relatively low 1/f AM and PM noise.

Modular Amplifier (cont.):

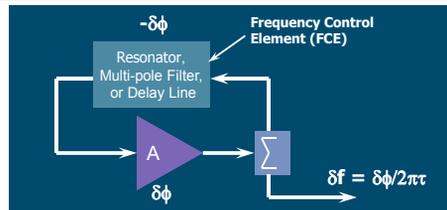
- ☺ Certain models maintain low noise performance when operated in gain compression, thereby eliminating a requirement for separate ALC/AGC circuitry in the oscillator.
- ☺ Amplifier use allows a building block approach to be used for all of the oscillator functional sub-circuits: amplifier, resonator, resonator tuning circuit, resonator mode selection filter, etc.
- ☺ Relatively low cost amplifiers (plastic, COTS, HBT darlington pair configuration) are now available with multi-decade bandwidths operating from HF to microwave frequencies.
- ☹ Relatively poor efficiency and not amenable to design modification.
- ☹ Compromise between additive (KTBF) noise and resonator drive level.



Oscillators", Workshop WSB, 2009 IEEE International Microwave Symposium (RFIC portion)".

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Oscillator PM-to-FM Noise Conversion (the Leeson Effect)

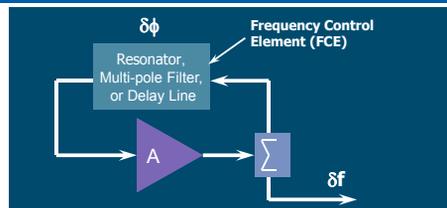


- If a phase perturbation, $\delta\phi$ occurs in an oscillator component (i.e., sustaining stage amplifier phase noise), the oscillator signal frequency must change in order to maintain necessary conditions for oscillation ($2n\pi$ radians loop phase shift).
- The amount of signal frequency change caused by the phase perturbation is related to the oscillator loop phase vs. frequency (i.e., resonator group delay or loaded Q). The larger the delay (or loaded Q), the smaller the resultant frequency change.
- This conversion results in 20dB/decade signal spectral degradation at carrier offset frequencies within $f=1/2\pi\tau$ where τ is the loop group delay ($1/2\pi\tau =$ half-bandwidth for a single resonator).

Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

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Resonator Short-term Frequency Instability (self-noise)

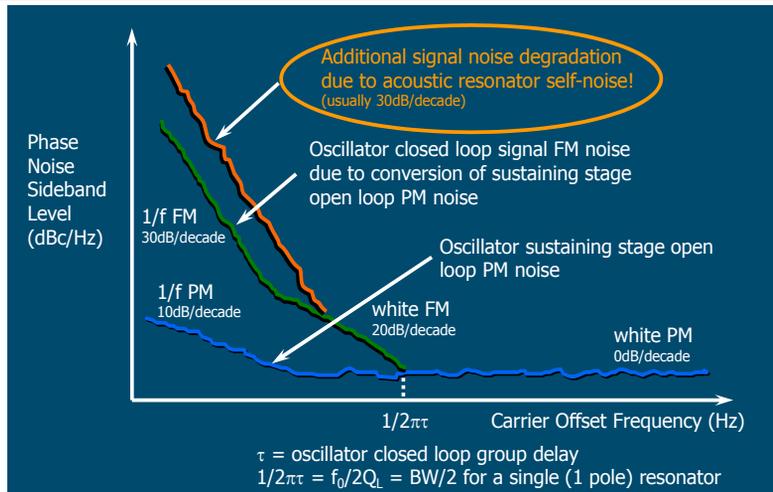


- Some resonators, notably including acoustic resonators, exhibit short-term instability in the form of resonant impedance fluctuations. In many cases, the FM noise of the oscillator output signal due to this instability can exceed that due to the open-loop phase fluctuations (noise) of the non-resonator portion of the oscillator circuitry.
- The dominant portion of this instability usually occurs as flicker-of-frequency noise.
- Other factors affecting oscillator output signal frequency stability include environmental stress and aging.

Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

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PM-to-FM Noise Conversion in an Oscillator



Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

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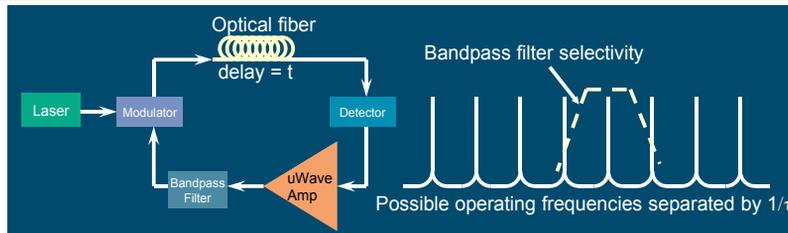
Quartz BAW, SAW, and STW Oscillators



- ☺ Very high Q
Q-frequency product = 10^{13}
- ☺ Controllable (selectable) frequency temperature coefficient
- ☺ Excellent long-term and short-term frequency stability
- ☺ Relatively low cost
- ☺ Moderately small volume
- ☺ Well defined, mature technology
- ☺ FM (self) noise that often exceeds effects of sustaining stage amplifier 1/f PM noise
- ☺ Unit-to-unit FM noise level variation, high cost and low yield of very low noise resonators
- ☺ BAW resonator maximum dissipation limitations: 1-2 mW for AT-cut, 3-6 mW for SC-cut. Much lower drive must be used to achieve good long-term frequency stability.
- ☺ Unit-to-unit variation in vibration sensitivity
- ☺ FOM (Q) decreases with increasing frequency

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The Opto-Electronic Oscillator (OEO)



- Other refinements include use of a second, shorter length optical fiber for selection (in-phase reinforcement) of a specific frequency signal and use of carrier suppression for additional noise reduction.
- Another version uses a tiny optical resonator in place of the delay line.

Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

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Whispering Gallery Mode, Sapphire Dielectric Resonators



- Dielectric loss in sapphire is very low at room temperature and rapidly decreases with decreasing temperature.
- High-order "whispering gallery" mode ring and solid cylindrical resonators have been built that exhibit unloaded Q values, at X-band, of 200,000 at room temperature and 5 to 10million at liquid nitrogen temperature.
- This ultra-high resonator Q results in oscillators whose X-band output signal spectra are currently superior to that attainable using any other resonator technology.
- The lowest noise wgm Sapphire DROs employ carrier nulling and baseband noise detection and feedback to minimize the effects of sustaining stage, open-loop $1/f$ PM noise.

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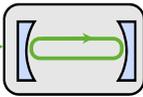
Optical Frequency Combs: Microwave Generation via Optical Frequency Division




Main system components

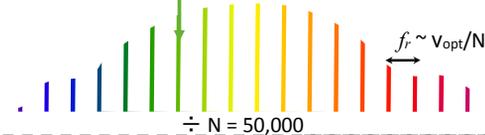
CW LASER

$\nu_{opt} = 500 \text{ THz}$
 $\Delta\nu < 1 \text{ Hz}$



1. Ultrastable CW Laser Oscillator

- CW laser stabilized to well-isolated & vibrationally-insensitive optical cavity
- Optical cavity is the timing/frequency reference for entire system



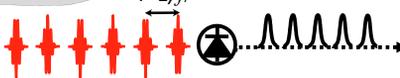
$f_r \sim \nu_{opt}/N$

$\div N = 50,000$

2. Optical Frequency Divider

- Femtosecond laser frequency comb stabilized to CW laser
- Phase coherent division from optical to microwave
- Reduction of phase noise power by N^2

microwave signal:
any harmonic of f_r
 $\Delta f/f < 10^{-15}$ @ 1s
 $S_{\mu wave}(f) = S_{opt}(f)/N^2$



$T = 1/f_r$

3. Opto-Electronic Conversion

- High-speed photodiode detects stable optical pulse train
- Provides electronic output
- Stringent demands on power handling and linearity

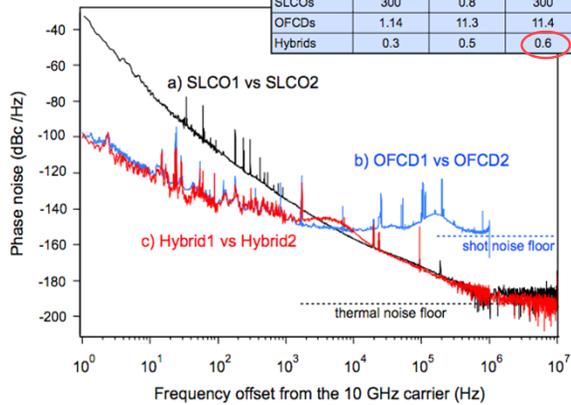
23 S. Diddams et al, IEEE JSTQE, 9, 1072 (2003); A. Bartels, et al, *Opt. Lett.* 30, 667 (2005);
J. McFerran, et al. *Electron. Lett.* 41, 36 (2005); T. Fortier, et al. *Nat. Photon.* 5, 425 (2011).
Slide provided by Scott Diddams, NIST, Time and Frequency Division.


Time & Frequency Division
scott.diddams@nist.gov

Measured Phase Noise of Optical Comb-Derived, 10GHz Signal




INTEGRATED JITTER			
	1Hz - 1 MHz (fs)	1MHz - 5GHz (fs)	total (fs)
SLCOs	300	0.8	300
OFCDs	1.14	11.3	11.4
Hybrids	0.3	0.5	0.6



a) SLCO1 vs SLCO2
b) OFCD1 vs OFCD2
c) Hybrid1 vs Hybrid2

shot noise floor
thermal noise floor

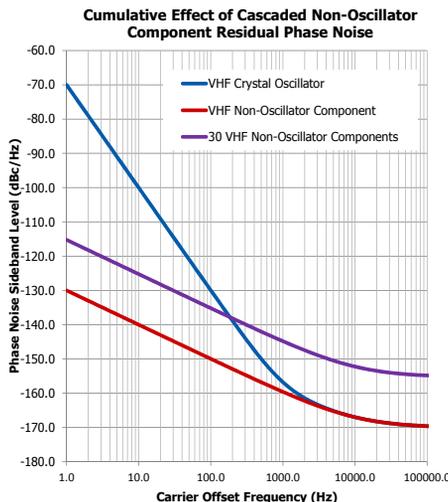
24 T.M. Fortier et al., *Applied Physics Letters* (2012)


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scott.diddams@nist.gov

Non-Oscillator Noise Contributors

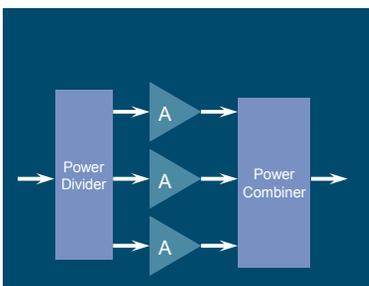


- In many Transmitters and Receivers, the Oscillator(s) signal path necessarily includes literally hundreds of “residual noise” contributors. These can include amplifiers, mixers, filters, frequency multipliers and dividers, switches, waveform generators, and indirect (PLL) and direct frequency synthesis circuitry.
- The net residual noise added by these signal path components is usually the main contributor to the final output signal white noise level.
- In addition, the net, near-carrier noise contribution of these components can also have a significant degrading effect at moderate carrier offset frequencies.



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Noise Reduction techniques Use of Multiple Devices

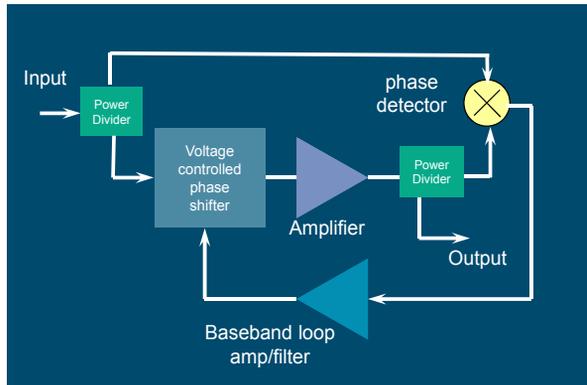


- Individual device (amplifier) noise is un-correlated.
- Net effect is a $10\log(N)$ decrease in flicker-of-phase noise.
- Additive (KTBF) white noise is not reduced because signal level at each amplifier is reduced by the input power divider.

Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

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Noise Reduction Techniques - Noise Detection and Reduction via Baseband Feedback

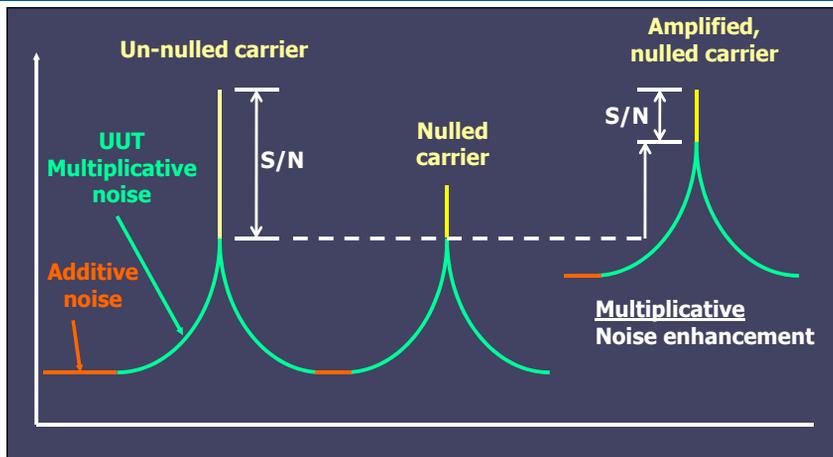


- Wide-band noise feedback used to reduce amplifier phase noise.
- Noise reduction is limited to noise of the phase detector and loop amplifier.

Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

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Noise Enhancement (carrier nulling), Amplification, and Reduction



Noise reduction is normally accomplished via carrier-nulled, RF signal feed-forward or baseband detection with feedback techniques

Source "Low Noise Oscillator Design and Performance"
http://www.ieee-uffc.org/frequency_control/teaching/2003_IEEE_Tutorial.

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Vibration-Induced Noise



- Vibration usually constitutes the primary environmental stress affecting oscillator signal short-term frequency stability (phase noise).
- Resonator sensitivity to vibration is usually the primary contributor to the noise degradation.
- High Q mechanical resonances in the resonator and/or non-resonator circuitry and enclosures can cause severe signal spectral degradation under vibration.
- Frequency Control Element (i.e., resonator) and/or oscillator sensitivity to vibration is normally expressed on a fractional frequency basis and denoted as Γ , in units of $1/g$ ($\delta f/f_0$ per g).

Source: "Vibration-Induced Phase Noise in Signal Generation Hardware"
http://www.ieee-uffc.org/frequency_control/teaching/Tutorial_REV_Q

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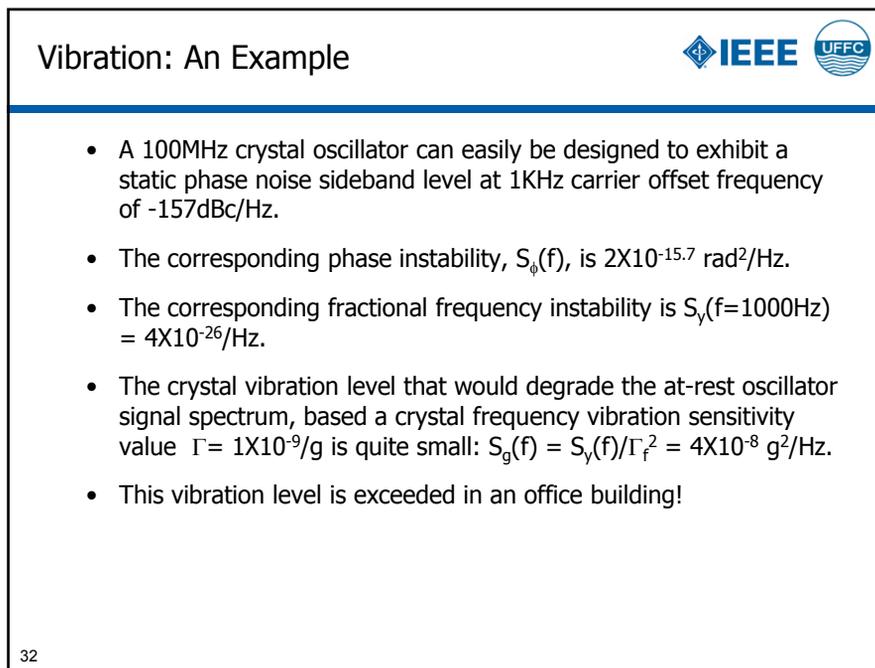
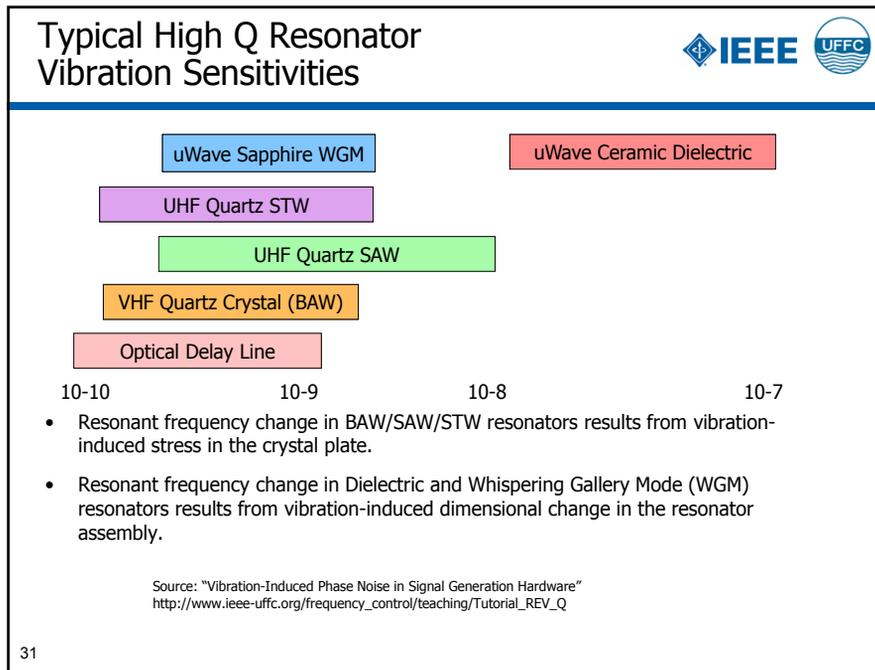
Vibration-Induced Noise (cont.)



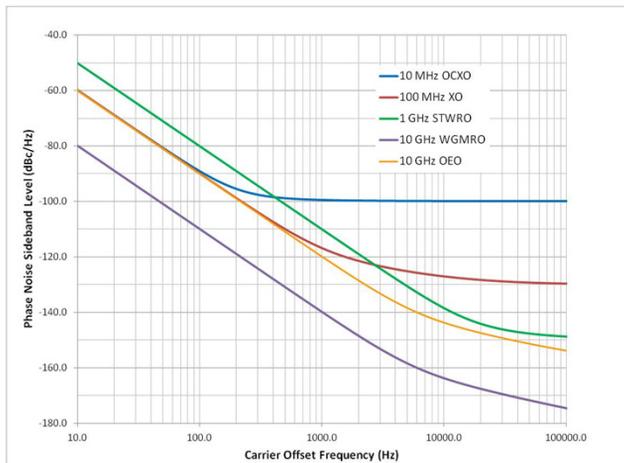
- Vibration in oscillators induces FREQUENCY modulation; in non-oscillator circuitry it induces PHASE modulation.
- For most platforms, vibration occurs and is characterized as a random excitation defined by a measured or calculated power spectral density denoted $S_g(f)$ in units of g^2/Hz .
- Vibration-sensitive, non-oscillator components typically include (especially narrow bandwidth) filters, coaxial cables, (especially bayonet and blind-mate) connectors, and inadequately constrained printed wiring boards and enclosure covers.
- Mechanical nonlinearities (hitting, scraping, etc.) can result in noise degradation at frequencies well in excess of the maximum vibration input frequency.
- Mechanical resonances amplify the input vibration PSD by Q^2 !

Source: "Vibration-Induced Phase Noise in Signal Generation Hardware"
http://www.ieee-uffc.org/frequency_control/teaching/Tutorial_REV_Q

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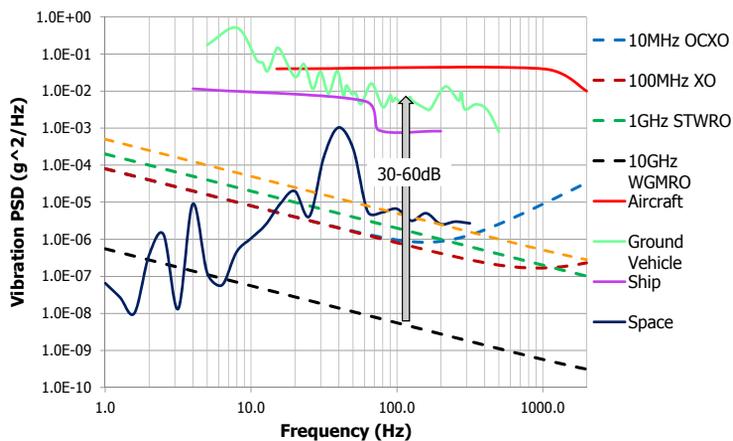
Near-Carrier, Static Phase Noise PSDs for Various Oscillator Technologies, all referred to 10GHz



The STATIC phase noise performance of lowest noise signals is degraded by correspondingly lower levels of vibration.

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Vibration PSDs that would degrade Oscillator Static Phase Noise vs Platform Vibration



J. B. Donovan, "Vibration Isolation of Acceleration-Sensitive Devices", Proceedings of the 2011 IEEE International Frequency Control Symposium, May, 2011

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Methods for Reducing Vibration-Induced, Crystal Oscillator Phase Noise

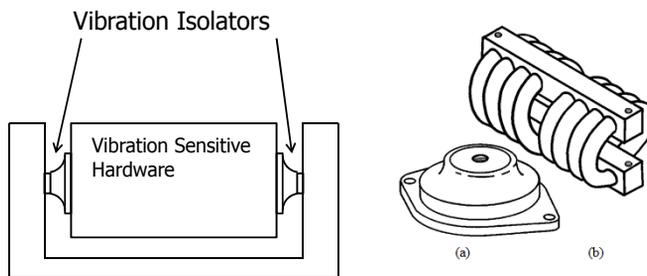


Least Costly	Use of mechanical vibration isolation
↓	Use of multiple, unmatched oppositely-oriented resonators. Reduction of resonator vibration sensitivity via resonator design (geometry, mounting, mass loading, etc.).
Most Costly	Cancellation via feedback of accelerometer-sensed signals to the oscillator frequency tuning circuitry.

Source: "Vibration-Induced Phase Noise in Signal Generation Hardware"
http://www.ieee-uffc.org/frequency_control/teaching/Tutorial_REV_Q

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Mechanical Isolation

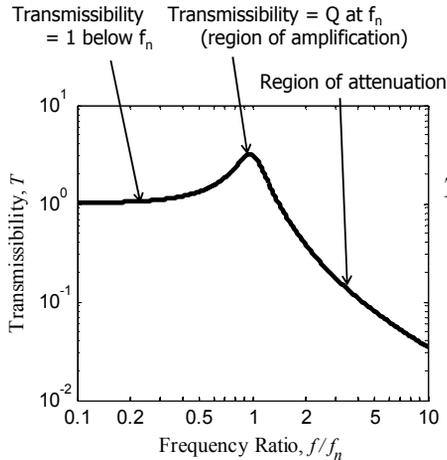


Typical vibration isolators for used with acceleration sensitive devices. The resilient element is often (a) an elastomer or (b) wire rope.

J. B. Donovan, "Vibration Isolation of Acceleration-Sensitive Devices", Proceedings of the 2011 IEEE International Frequency Control Symposium, May, 2011

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Isolation System Transmissibility



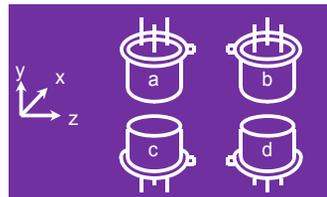
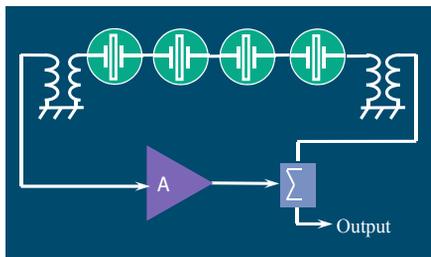
$$T = \sqrt{\frac{1 + \left(\frac{f}{f_n Q}\right)^2}{\left[1 - \left(\frac{f}{f_n}\right)^2\right]^2 + \left(\frac{f}{f_n Q}\right)^2}}$$

NOTE: Input vibration power spectral density (g^2/Hz) is multiplied by T^2

J. B. Donovan, "Vibration Isolation of Acceleration-Sensitive Devices", Proceedings of the 2011 IEEE International Frequency Control Symposium, May, 2011

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"Poor Mans" Method for Reducing Quartz Crystal Phase Noise and Vibration Sensitivity



- The use of multiple crystals "acts" like a crystal capable of N times higher drive level. Higher amplifier input drive results in lower KTBf (noise floor) level.
- The self noise of each crystal is un-correlated. The result is N times lower near-carrier, flicker-of-frequency noise.
- Mounting the crystals in opposing orientations provides partial cancellation of vibration sensitivity. Crystals can be mounted "right side up and upside down" within the crystal enclosure.

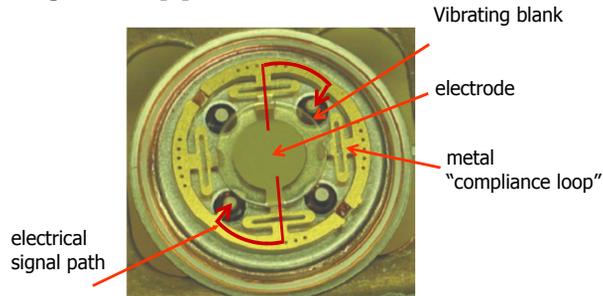
Source: "Vibration-Induced Phase Noise in Signal Generation Hardware"
http://www.ieee-uffc.org/frequency_control/teaching/Tutorial_REV_Q

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An Example of Vibration Sensitivity Reduction via Resonator Design



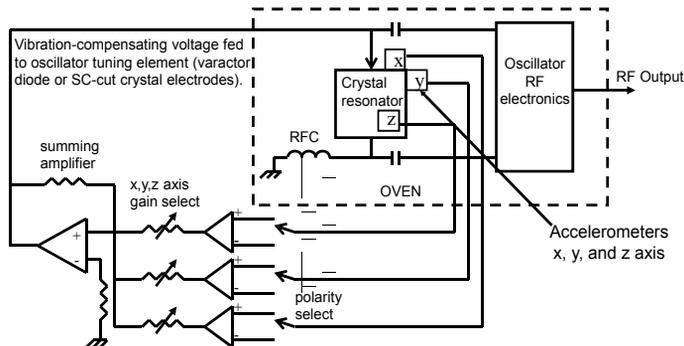
- Low stress, QRM (Quad Relief Mounting) crystal resonator mounting scheme [1]



[1] R. B. Haskell, J. E. Buchanan, B. B. Desai, D. Stevens (Vectron International), Y. Kim (U.S. Army Communications-Electronics RDEC), "Acceleration Sensitivity Measurements of Quad Relief Mount Langasite Resonators", Proc. 2008 IEEE Int'l Freq. Contr. Symp., May, 2008, pp. 237-239.

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Cancellation of Vibration-Induced Frequency Change via Electrical Feedback



- Vibration produces a voltage from the accelerometers that is appropriately amplified and fed back to the oscillator frequency tune control element.
- Tuning can be via use of varactor diodes in series with the resonator or, in the case of an SC-cut crystal, can be applied directly across the crystal electrodes.
- Vibration sensitivity reduction factors of more than 10:1 out to several hundred Hz have been demonstrated in commercially available, 10MHz crystal oscillators.

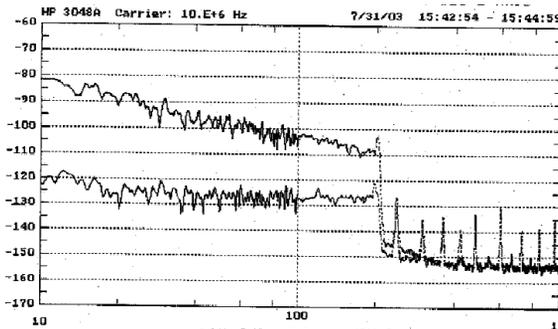
"R. Filler, and V. Rosati", Proceedings of the 25th Annual Frequency Control Symposium May, 1981, pp117-121.

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Performance Improvement in a Frequency Electronics, Inc. 10MHz Crystal Oscillator with Electronic Vibration Cancellation



Measured Results: Input = 0.08g²/Hz, 10Hz-200Hz



Frequency (Hz)	Standard Performance DUT (upper curve)	Low g-sensitivity DUT (lower curve)
10	4X10 ⁻¹⁰ /g	5X10 ⁻¹² /g
100	4X10 ⁻¹⁰ /g	2X10 ⁻¹¹ /g
200	3X10 ⁻¹⁰ /g	4X10 ⁻¹¹ /g

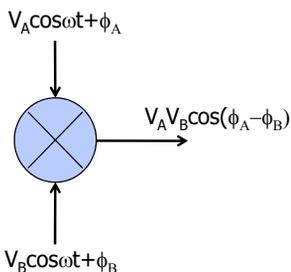
Courtesy of Frequency Electronics, Inc.
<http://www.freqelec.com>

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Phase Noise Measurement Techniques



- Most analog, phase noise measurement equipment down-converts the UUT carrier signal to baseband using a second, identical frequency signal. This removes the RF carrier signal and increases the ability of the test equipment to measure the noise.
- The UUT carrier signal is down-converted by applying identical RF signals to a phase detector (usually a double-balanced mixer) operated in quadrature.



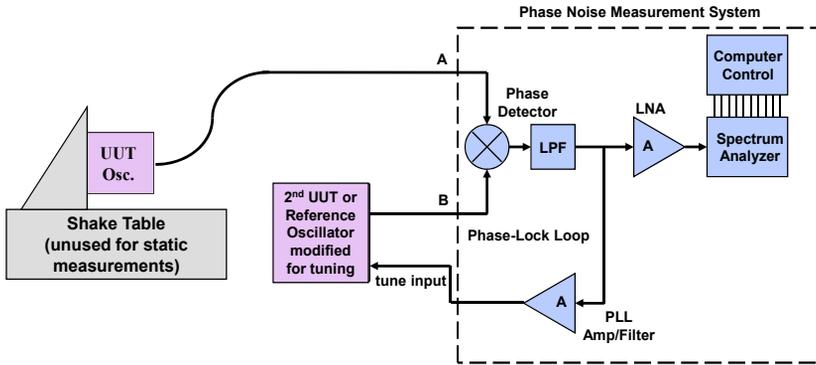
- When $\phi_A - \phi_B = \pm 90^\circ$, the detector is maximally sensitive to the phase perturbations in both of the RF input signals and minimally sensitive to the amplitude perturbations.
- The mixer also produces the sum frequency, which is removed using a low pass filter.

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In-Oscillator Measurement of Oscillator Static and Vibration-Induced (Absolute) Phase Noise



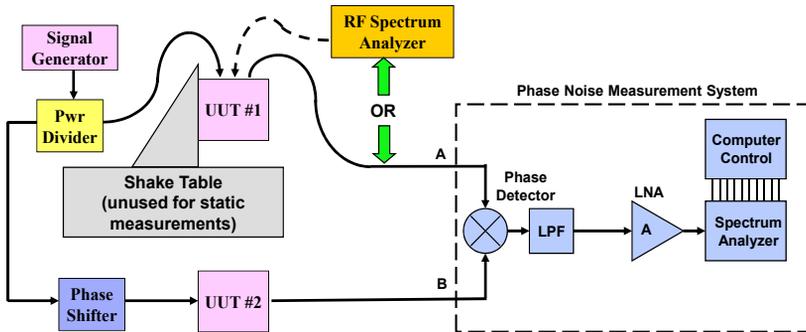
- The UUT oscillator is phase-locked to a reference oscillator having equal or better phase noise.
- Most measurement equipment measures the PLL closed loop response and appropriately modifies the output data accordingly.



Source: "Vibration-Induced Phase Noise in Signal Generation Hardware"
http://www.ieee-uffc.org/frequency_control/teaching/Tutorial_REV_Q

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Measurement of Non-Oscillator Component Static and Vibration-Induced Residual Phase Noise



- If the UUT is a relatively broadband component with low group delay, a second UUT may not be required.
- A second, UUT is required if it (the UUT) is a frequency translation device.
- For vibration sensitivity measurements, the vibration input may be a PSD profile, sine, or swept-sine.

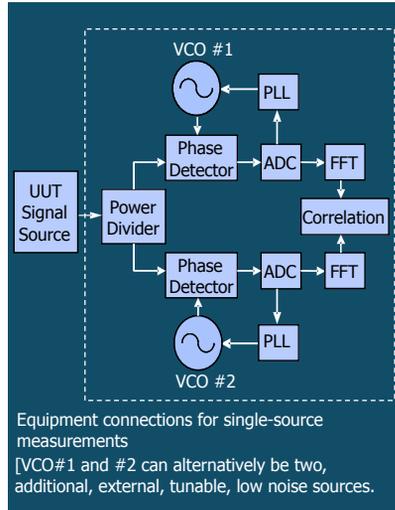
Source: "Vibration-Induced Phase Noise in Signal Generation Hardware"
http://www.ieee-uffc.org/frequency_control/teaching/Tutorial_REV_Q

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Cross-Correlation Phase Noise Test Sets (Absolute Phase Noise Measurements)



- Cross-correlation Phase Noise Measurement Systems allow significant increase in dynamic range. Un-correlated noise (i.e., noise in the VCOs and phase detectors) is suppressed.
- The test sets usually allow the use of user supplied low noise VCOs (i.e., VCXOs).
- Examples of available test sets include:
 - Agilent E5052A
 - Rohde & Schwarz® FSUP Signal Source Analyzer
 - Wenzel BP-1000-CC
 - Holzworth HA7062A



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Allan Deviation Test Sets (courtesy Sam Stein and Symmetricom)



- Direct Digital Phase Measurement Systems
 - Sample the RF waveform directly
 - Compute phase difference between device under test and reference using the arctangent function
 - Require no user calibration for the measurement
- Analog Phase Measurement Systems
 - Utilize an analog transducer to produce an output proportional to phase
 - Sample the transducer output in order for further processing
 - Require the user to calibrate the transducer for each measurement setup



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Phase Noise Measurement Guidelines



- Use maximum obtainable detector sensitivity. Don't un-necessarily attenuate under test signal levels.
- Use low noise DC supplies. Be aware of voltage regulator noise. Shield UUT power supply lines. Float DC supplies.
- Avoid use of bayonet type coaxial cable above 100MHz. Use threaded connectors.
- Shield UUT assemblies not housed in metal enclosures.
- Be aware of sources of interference from nearby equipment.
- Minimize environmental stress (temperature, vibration, acoustic, etc.)

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Factors Affecting Noise Measurement Accuracy



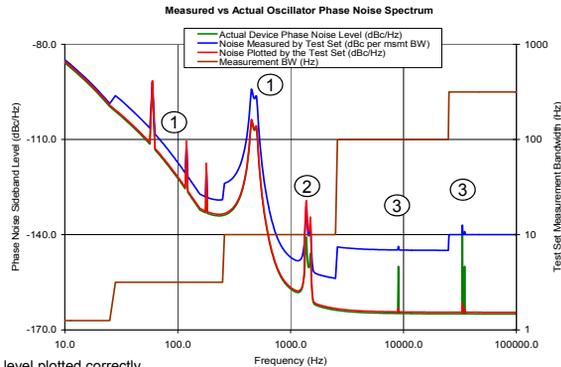
- On some test sets, inaccurate (non-measurement) of the effects of closed loop response for locked oscillators.
- Non-negligible contribution of test set self-noise (detector, LNA).
- Non-negligible contribution of bench-top vibration, acoustic noise.
- For residual (non-oscillator) measurements, use of a signal generator having unacceptably high PM noise (and AM noise), AM-to-PM conversion in the UUT(s), and unequal bridge arm delay.
- For phase noise under vibration measurements:
 - Unanticipated non-linearity (hitting or scraping of parts).
 - Vibration due to acoustic noise.
 - Vibration sensitivity of cables to and from the shake table.
- **Test set measurement bandwidth** (see next slide).

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Actual vs. Measured vs. Plotted Noise Spectra



- Most phase noise test sets PLOT phase noise on a per Hz bandwidth basis, but DO NOT MEASURE the noise in a 1Hz bandwidth, especially at higher carrier offset frequencies where the measurement times (especially taking averages) would become excessive.



- ① Noise level plotted correctly.
- ② Noise level plotted incorrectly. Due to the rapid noise level change, this noise peak was interpreted as a "zero BW discrete signal, and no bandwidth-related, level correction was made.
- ③ Noise level plotted incorrectly. Due to the large measurement bandwidth, the discrete spurious sideband was masked by the white noise level.

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Summary/Conclusions



- New technologies and techniques are being developed that result in signal generation circuitry exhibiting extremely low noise levels.
- In complex, multifunction signal generators, the effect of non-oscillator, signal path residual noise must be included and accurately modeled and minimized.
- The spectral degrading effects of vibration remain a difficult problem limiting system performance, especially for low noise oscillators housed in moving platforms.
- Automated phase noise measurement equipment dynamic range has also improved, but measurement results can be inaccurately characterized by issues such as measurement bandwidth and software used to discriminate between narrow noise peaks and discrete spurious signals.

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