"Phase Noise and Vibration Tolerance in Microwave Oscillators: Needs vs. State-of-the-Art "

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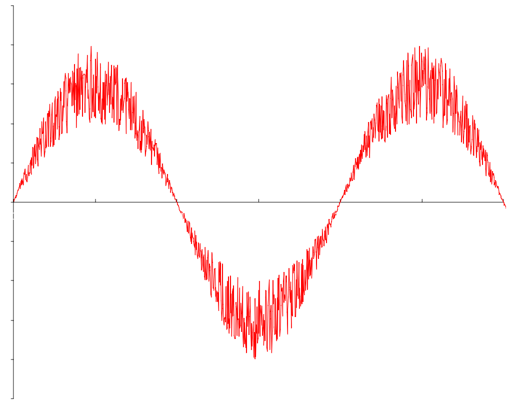
OUTLINE OF TALK

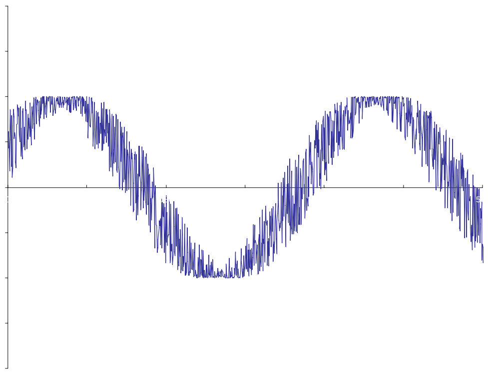
- **OSCILLATOR PM-NOISE: NOISE MEASUREMENTS and CRITERIA**
- **ASSESSMENT of BEST-IN-CLASS X-BAND OSCILLATORS**
  - Low-noise quartz oscillator, multiplied to 10 GHz
  - Optical Electronic Oscillator using fiber-delay-line resonator
  - Sapphire-loaded CSO using interferometric carrier suppression
  - High-power air-dielectric CSO using 2W drive and impedance controlled carrier suppression
  - DRO feedback oscillator
  - Optical femtosecond-comb divider & calcium reference
- **TUNABILITY and FREQUENCY SYNTHESIZERS COMPARED**
- **VIBRATION RESISTANCE STANDARDS**
  - Pitfalls in meeting standards
- **INDUSTRY and MILITARY NEEDS for SPECTRAL PURITY**
  - Stakeholders in research
  - Present beneficiaries

NOISE

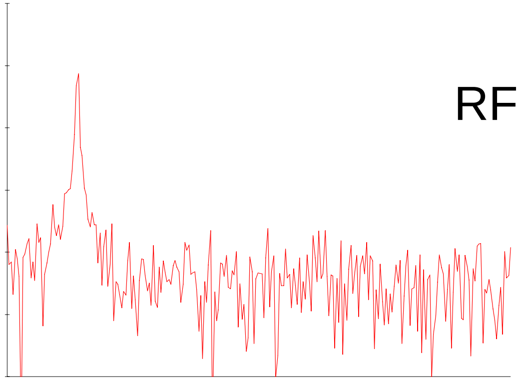
AM Noise

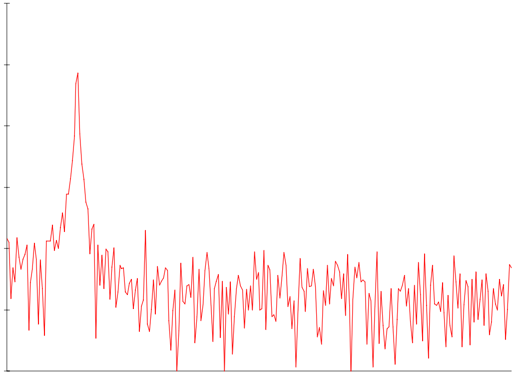
PM Noise





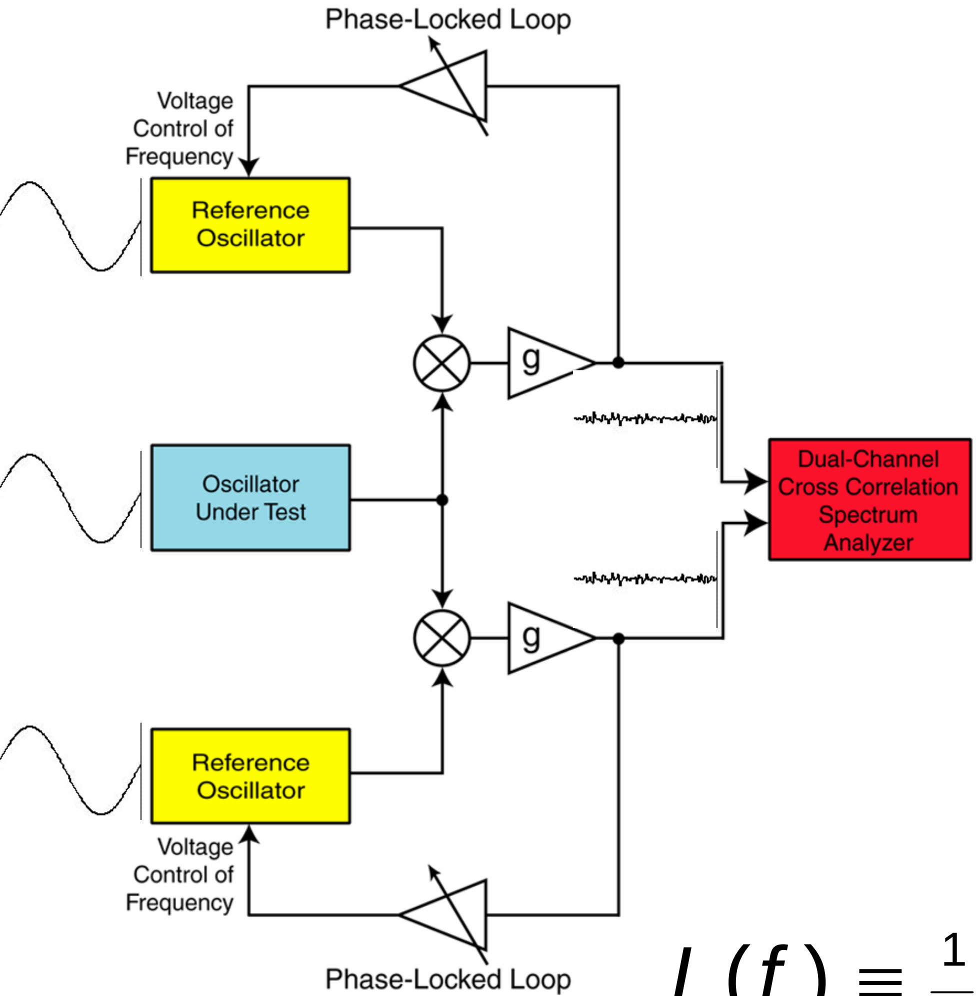
RF Spectra

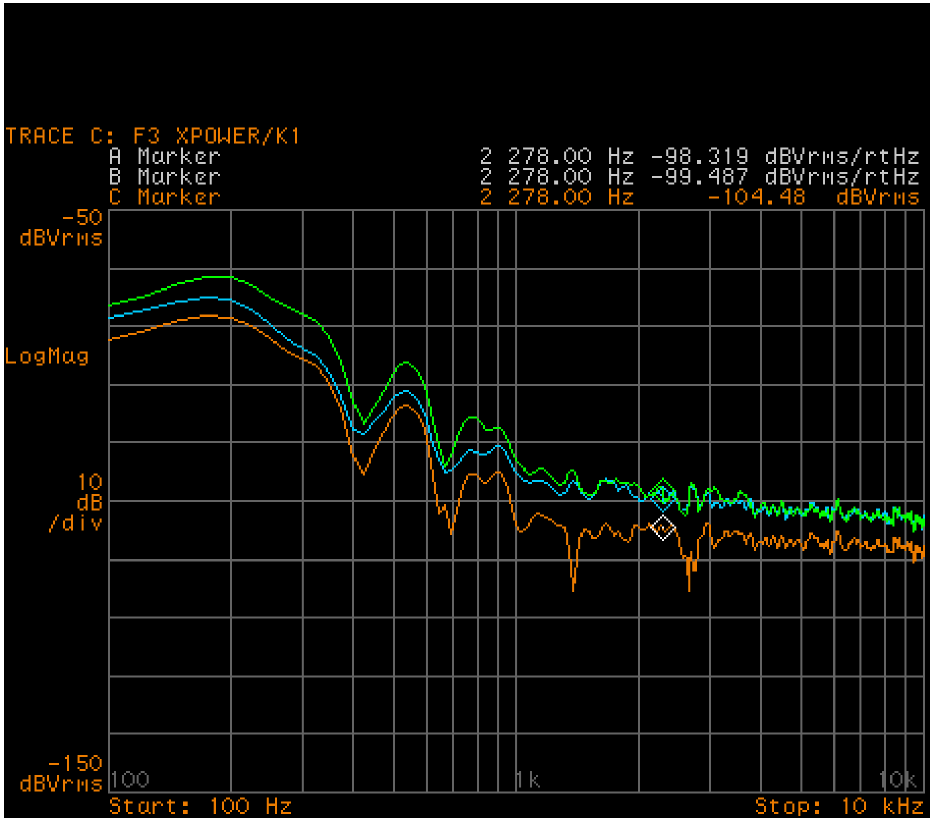




Key Functional Parameter for Oscillators is **Spectral Density of Phase Fluctuations,** $S_\phi(f)$

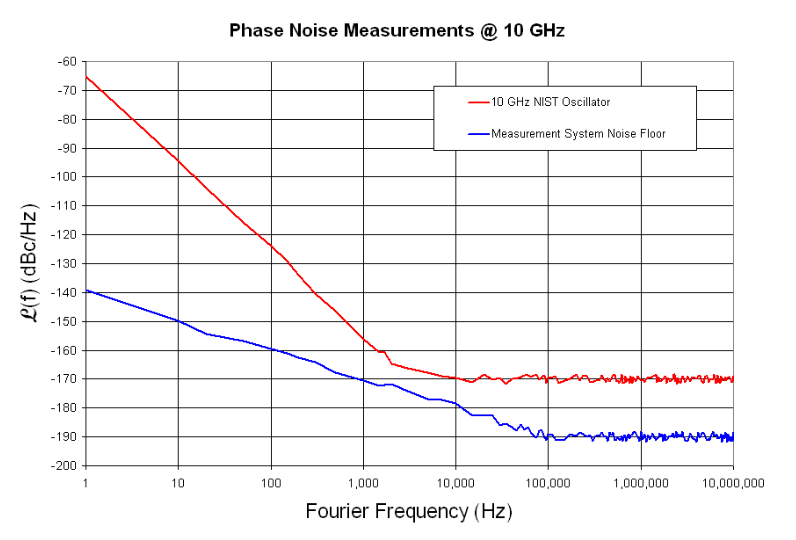
Dual-channel Cross-correlation Phase Noise Measurement

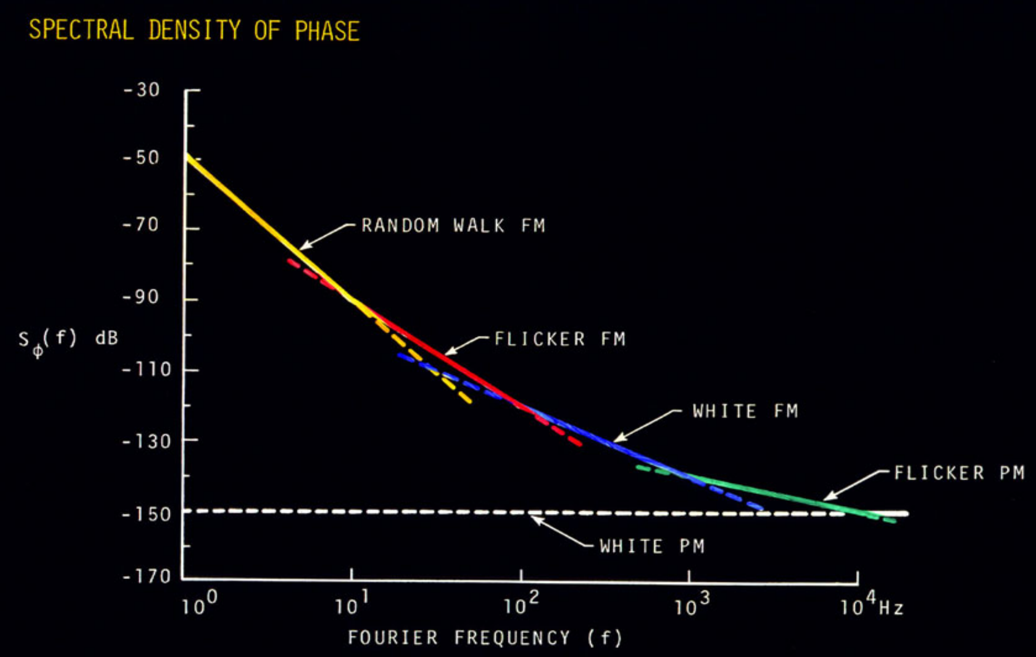




$$L(f) \equiv \frac{1}{2} S_\phi(f)$$

Physical Causes of Noise





Integrate to get jitter

- Random walk FM follows a $1/f^4$ power-law behavior. The noise indicates an environmental sensitivity. In the oscillator, this noise typifies random "bumps" in the resonance frequency. There is no mechanism for the frequency to return to a mean, or previous, frequency after a random bump.
- Flicker FM follows a $1/f^3$ power-law behavior. This noise is common in narrow frequency-determining resonator + sustaining amplifier in the oscillating loop.
- White FM follows a $1/f^2$ power-law behavior and occurs for wide frequency-determining resonator + sustaining amplifier. It is also characteristic of atomic frequency standards, in which a local oscillator is locked to an FM discriminator such as that provided by a Cs or Rb atomic resonance.
- White PM (no f-dependence) and Flicker PM (1/f) originate from late stages of amplification, frequency synthesis, frequency multiplication and division. These PM noises do not relate to an oscillator's basic resonance mechanism.

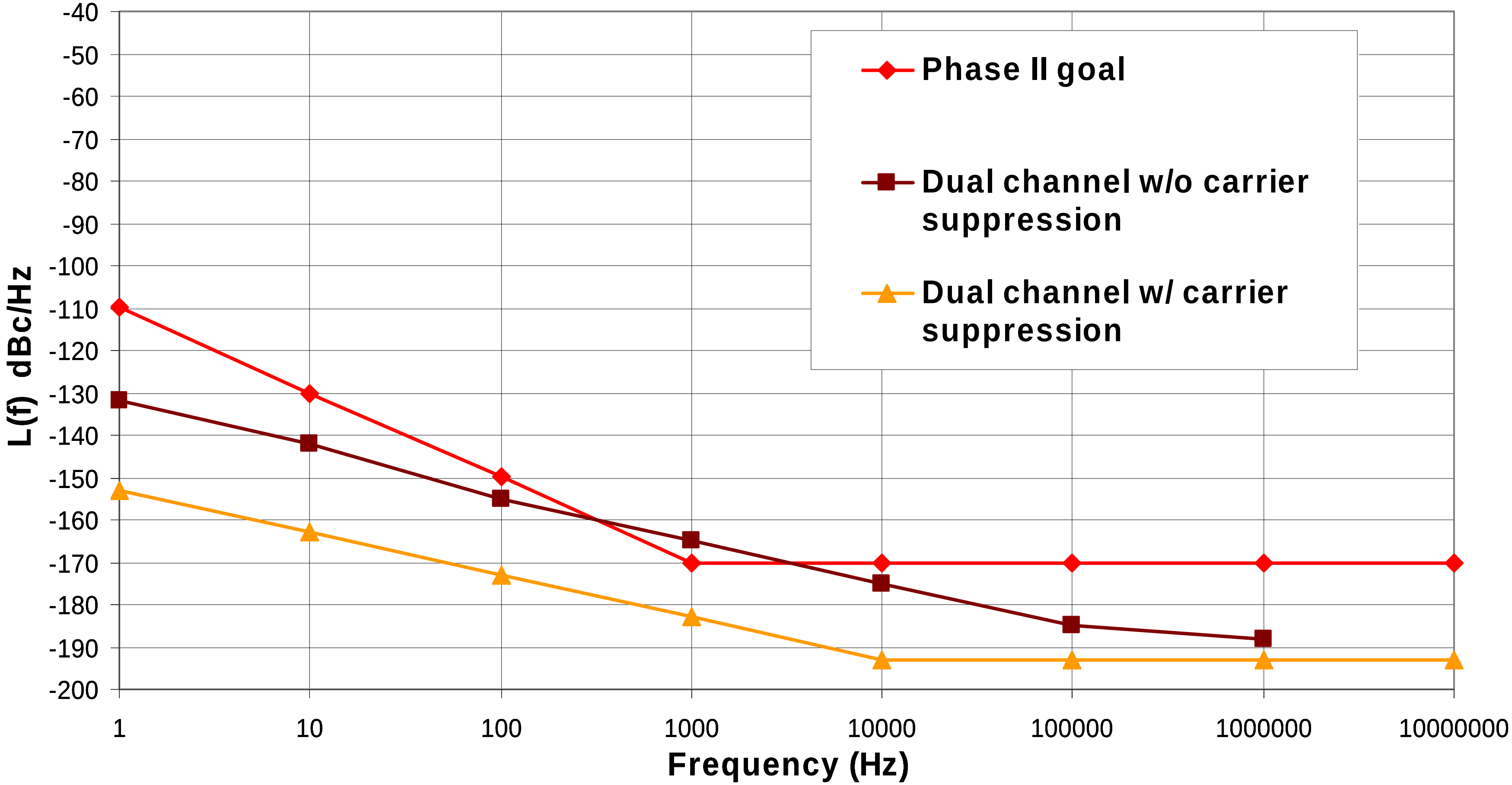
Why measure $S_\phi(f)$ when "time jitter" is the concern?

- Frequency-domain narrow-band spectrum analysis identifies levels and types of noise to determine cause of noise. Not true with broadband time and tau-domain statistics.
- Time "jitter" statistics often fail to separate a mix of expected oscillator noises. Frequency spurs, discrete lines, quantization noise are problems.
- Reasonable time-domain statistics are always dependent on f_h, f_{min}, tau, trigger-threshold and unreliable for moving statistical averages.
- Discrete continuous aliasing and window aliasing confuse statistical estimates.
- $S_\phi(f)$ function maps unambiguously to most time-domain statistics, not vice-versa. Too many assumptions often prevent mapping from time domain to $S_\phi(f)$.

$$L(f) \equiv \tfrac{1}{2} S_\phi(f)$$

Best Noise Floor of Measurement Systems

COMPOSITE



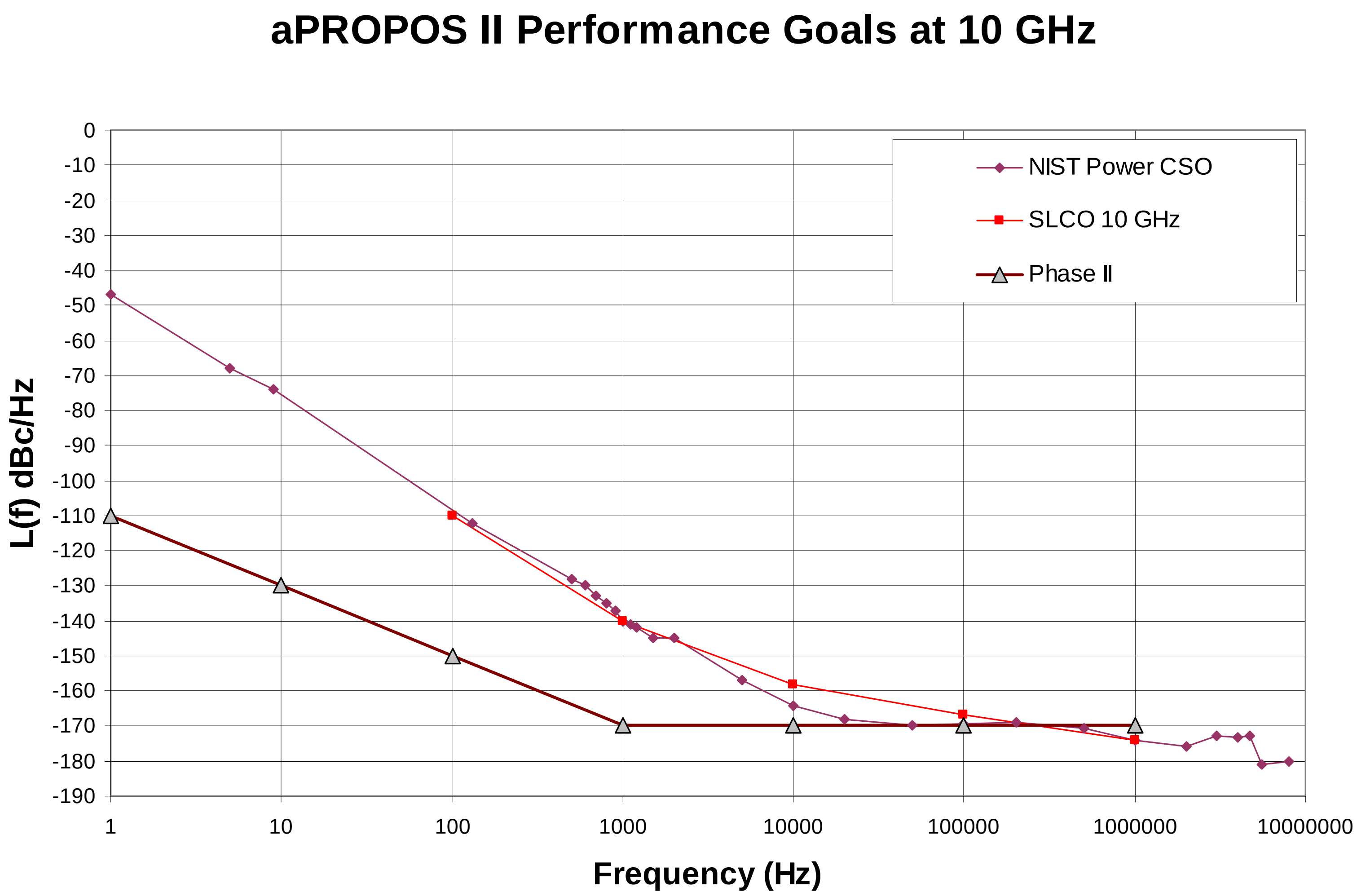
BEST-IN-CLASS X-BAND OSCILLATOR PM NOISE

- Based on measurements at NIST. Results are at an operating frequency of 10 GHz.

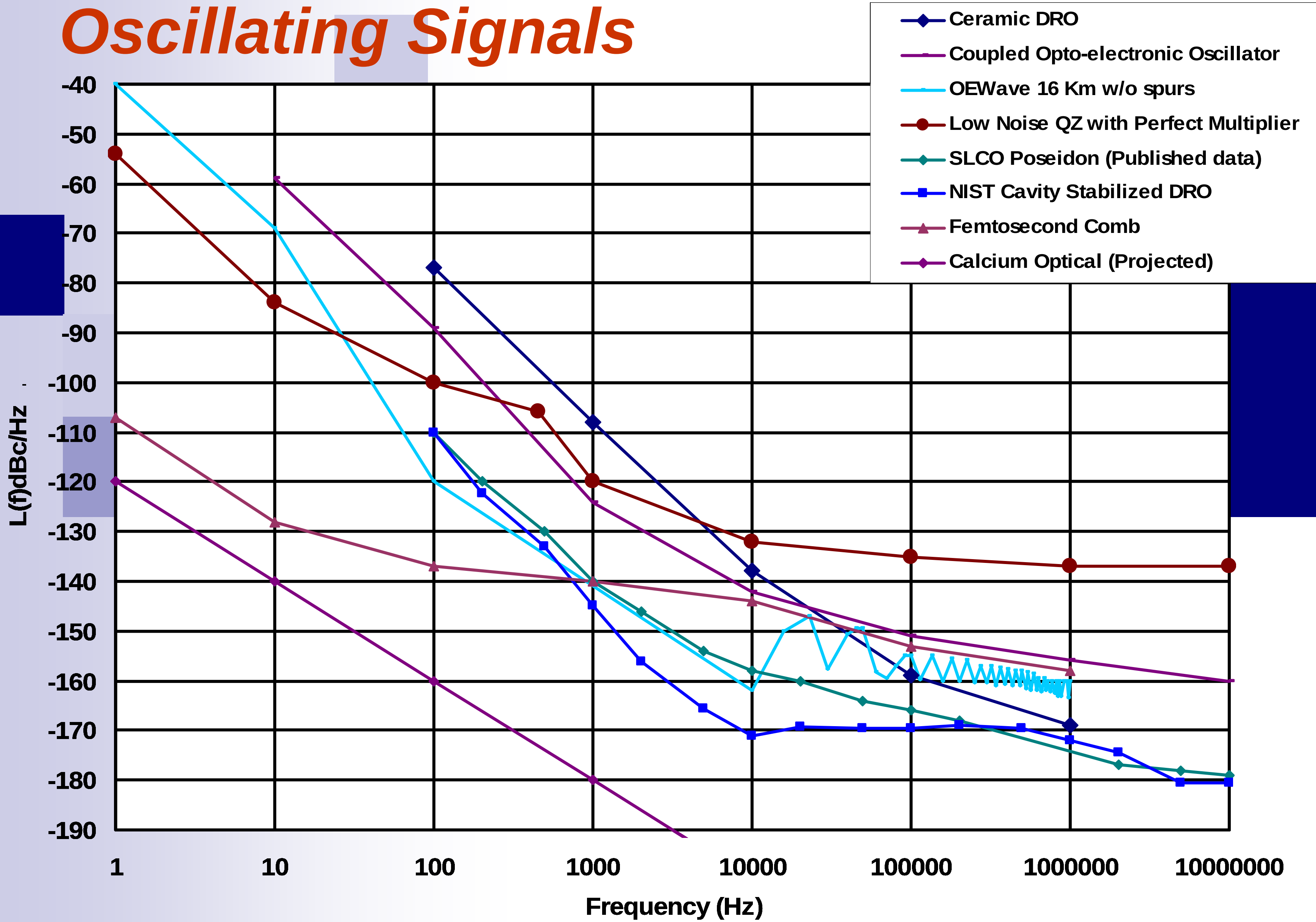
CRITERIA:

- Room-temperature operation does not require cryo-cooled augmentation
- Noise models are understood and thorough enough that PM noise of devices are consistent with their models
- Frequency selectability (the ability to fabricate to desired frequency) is simple
- Frequency range of operation is possible over at least one octave using the same set of components
- Oscillators and performance can be reproduced by other organizations or manufacturers

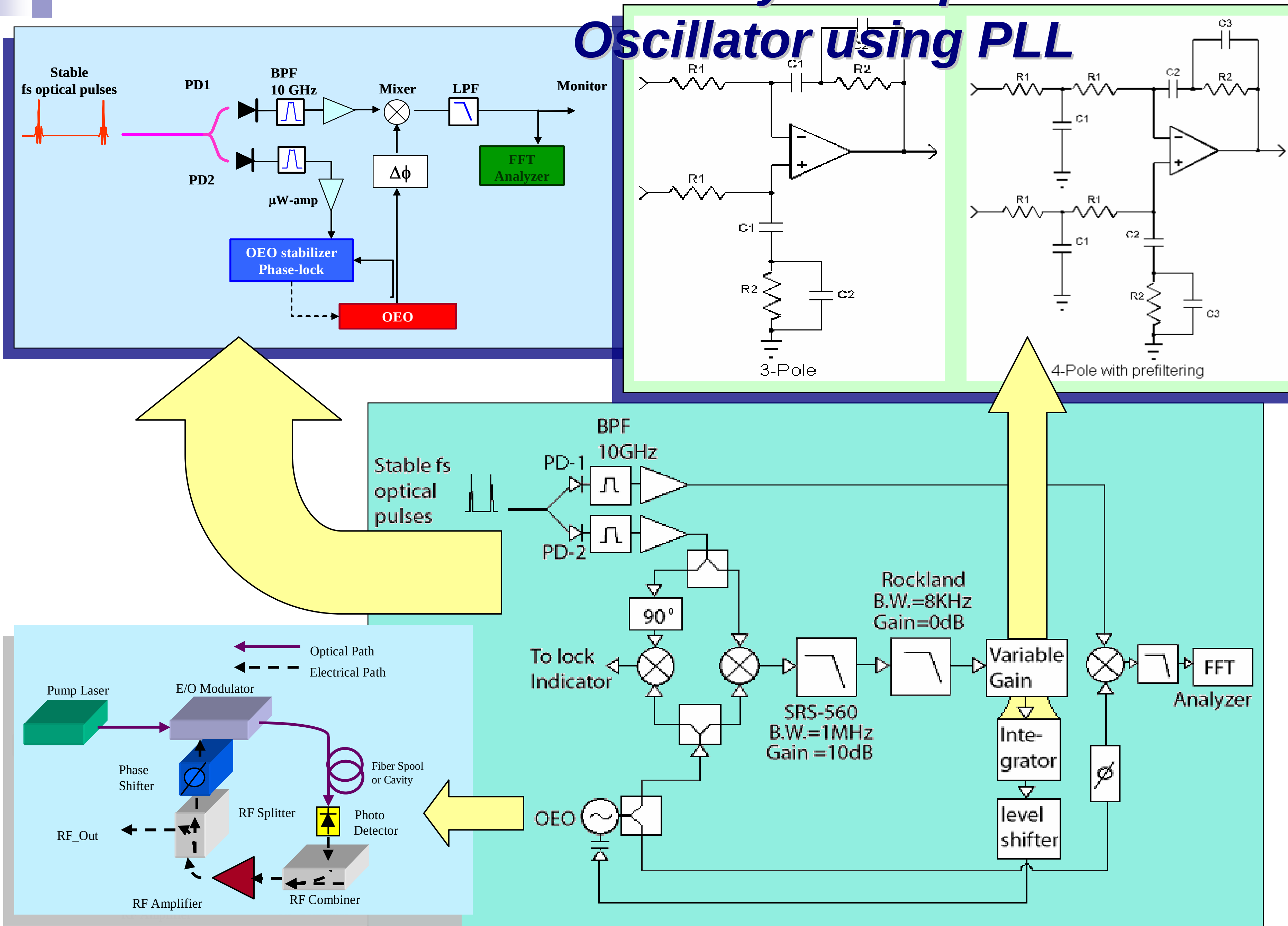
Best Reference Low-noise 10 GHz RF Oscillators vs. PM-noise Goal



10 GHz Low-noise Microwave Oscillating Signals

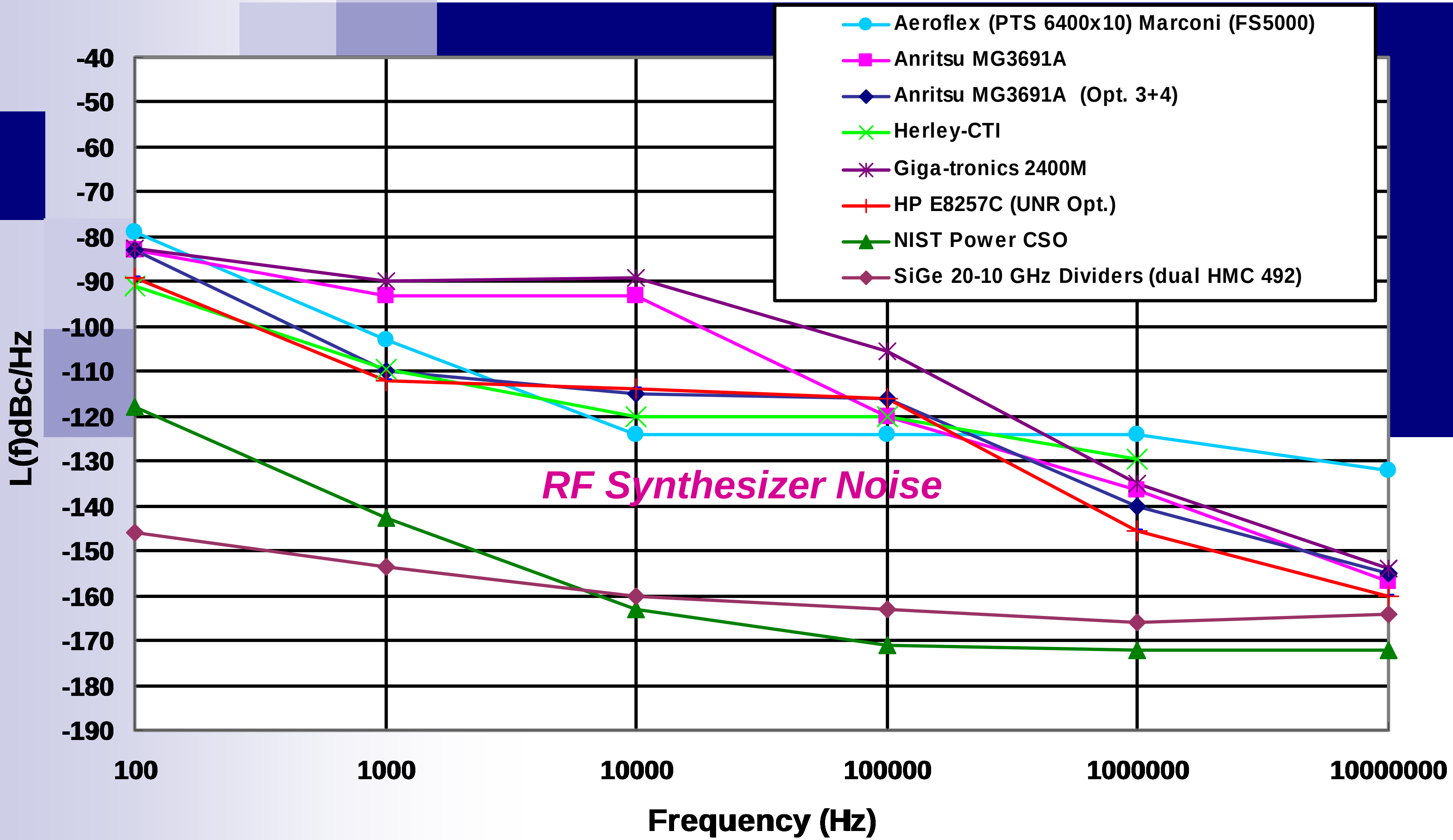


Hybrid Optical Oscillator using PLL



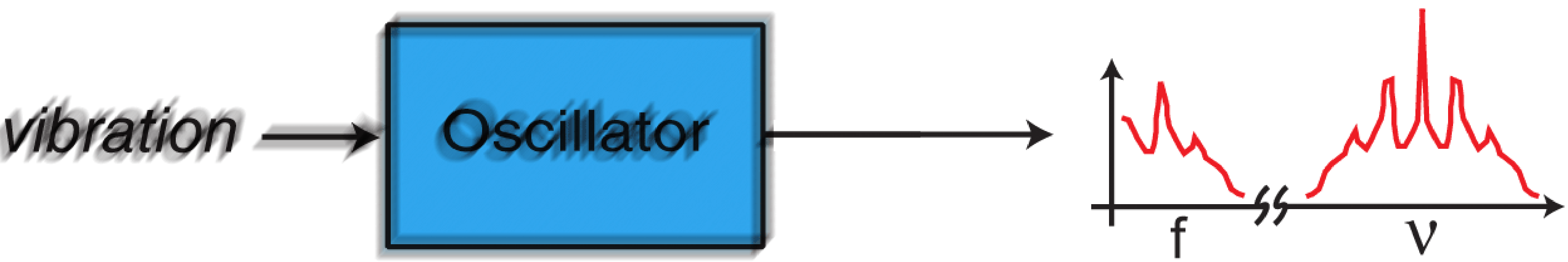
TUNABILITY: FREQUENCY SYNTHESIZERS COMPARED

10 GHz Frequency Synthesizers



VIBRATION RESISTANCE STANDARDS

Vibration induces phase fluctuations



Oscillator Under Vibration

Vibration resistance of oscillators and other components has always been important to DOD and civil applications. New requirements for (1) lower jitter, (2) higher (microwave) frequencies, (3) harsher operating environments, has made this importance more urgent.

Unfortunately, needed vibration resistance is somewhat obscured by the way the existing requirements are written.

One must use the following procedure:

Locate an original source document, usually called the "Standard," that says that the oscillator, synthesizer, etc., must meet <u>all</u> of its specifications in the environment of operation.

→

Locate the specific document that outlines two things: (1) the frequency and range of operation and the corresponding noise requirement and (2) the environment of operation having to do with vibration and acceleration.

→

From these, we can compute the signal's required vibration and acceleration resistance.

For example:

Source document MIL-STD-188-181A 31 March 1997 is an INTEROPERABILITY STANDARD for the DOD that states, among other things:

"***5.2.5 Frequency generation.*** *The frequency generation system shall provide long-term plus short-term frequency accuracy within ±1 ppm across the full range of environmental conditions outlined in the terminal specification. The root-mean-square value of the phase noise shall not exceed 10 degrees over the specified frequency range in a bandwidth of 10 Hz to 15 kHz.*"

Many frequencies, primarily in the UHF band up to 1 GHz, are required in this particular Standard. All of the frequencies must comply with 5.2.5.

Looking elsewhere, the "full range of environmental conditions" in 5.25 includes the environment's vibration profile as shown below.

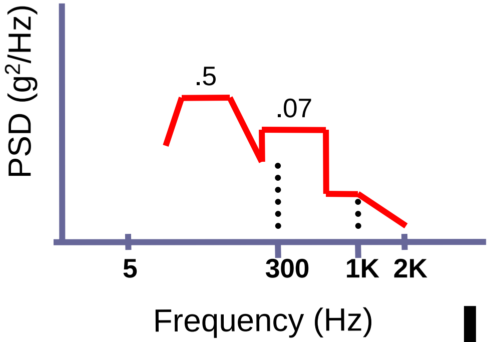


Figure 1: Vibration profile of the operating environment.

Not at all obvious, the signal's vibration resistance turns out to be a very hard spec. to meet, requiring <5 e (-12)/g at many offset frequencies.

For example:
Source document MIL-STD-188-181A 31 March 1997 is an INTEROPERABILITY STANDARD for the DOD that states, among other things:
*"**5.2.5 Frequency generation.** The frequency generation system shall provide long-term plus short-term frequency accuracy within ±1 ppm across the full range of environmental conditions outlined in the terminal specification. The root-mean-square value of the phase noise shall not exceed 10 degrees over the specified frequency range in a bandwidth of 10 Hz to 15 kHz."*

Since no oscillator can meet the specification in the vibrating environment that is specified, then the vibration levels are measured that could be tolerated from the best-choice oscillator while just meeting the 10-degree phase requirement.

When this is done, a search is started to identify at least one location within the given "environmental conditions" (aircraft, Humvee, etc.) that is quiet enough for the oscillator to meet phase requirements.

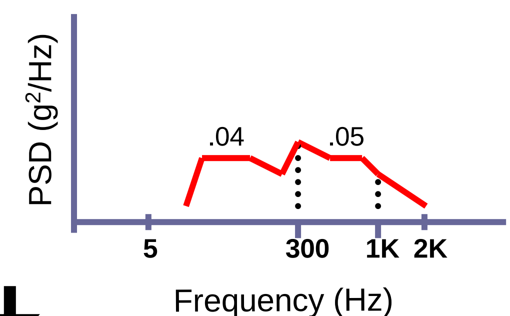


Figure 2: Vibration profile of best oscillator that actually meets phase noise requirement.

This practice is speculative and extremely risky because usually there is no such convenient location.

DEPARTMENT OF DEFENSE STANDARDS

Here is a partial list of Mil-spec Standards that specify vibration profiles as part of the “full range of environmental conditions” for electronic and mechanical components (“frequency generator” limits performance):

- MIL-STD-810F
- MIL-STD-188-181A
- MIL-STD-202
- MIL-STD-331
- MIL-STD-167

CIVIL STANDARDS

Here is a partial list of Civil Standards that specify vibration profiles as part of the “full range of environmental conditions”:

- RTCA/DO-160
- ASTM D 999, D 3580, D 4728
- ISTA Series 1 and 2
- Various SAE, IEC 68-2-6, IEC 68-2-27, IEC 68-2-29, IEC 68-2-34
- Various Telcordia standards

Example:

DEPARTMENT OF DEFENSE STANDARDS

Case of **MIL-STD-810C**

MIL-STD-810C defines a typical jet aircraft vibration environment. The test breaks down into Method 514.2, Category b.2 and is extrapolated for >2 kHz**.** The purpose of these tests is to determine the performance characteristics of airborne equipment in environmental conditions representative of those which may be encountered in airborne operation of the equipment.

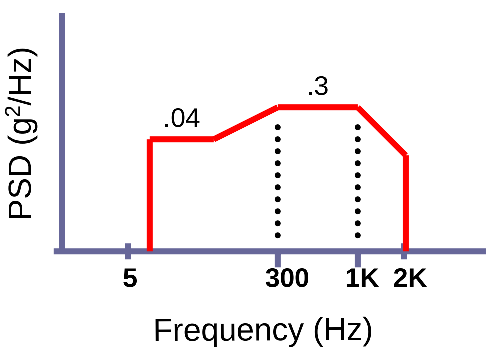


Figure 3: MIL-STD-810F vibration profile.

Example:

DEPARTMENT OF DEFENSE STANDARDS

Case of **MIL-STD-810C**

MIL-STD-810F defines a series of minimum standard environmental test conditions and applicable test procedures for all airborne equipment. The purpose of these tests is to determine the performance characteristics of airborne equipment in environmental conditions representative of those which may be encountered in airborne operation of the equipment.

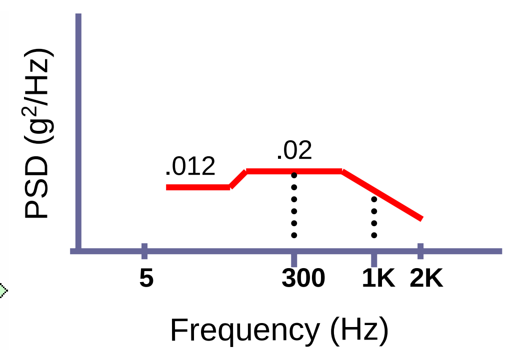


Figure 4: RTCA/DO160E vibration profile.

Example: CIVIL AVIATION ELECTRONICS STANDARD

Case of **RTCA/DO-160D/E**

RTCA/DO160E is published by RTCA, Inc., a global organization comprised of government and industry representatives, which develops standards to assure the safety and reliability of all Airborne Electronics (Avionics). Manufacturers of aircraft electronic equipment selling their products in the United States, Europe, and around the globe must meet RTCA requirements, including RTCA/DO-160E. The European Organization for Civil Aviation Electronics (EUROCAE) works jointly with RTCA in the development of standards, and publishes an identical document, EUROCAE/ED-14D.

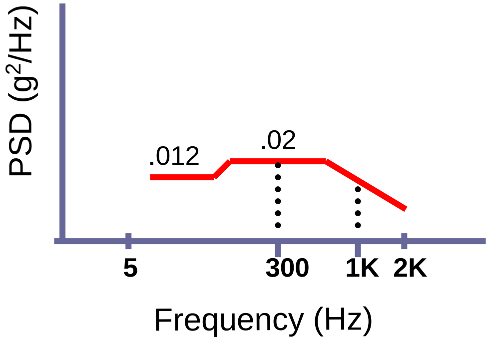
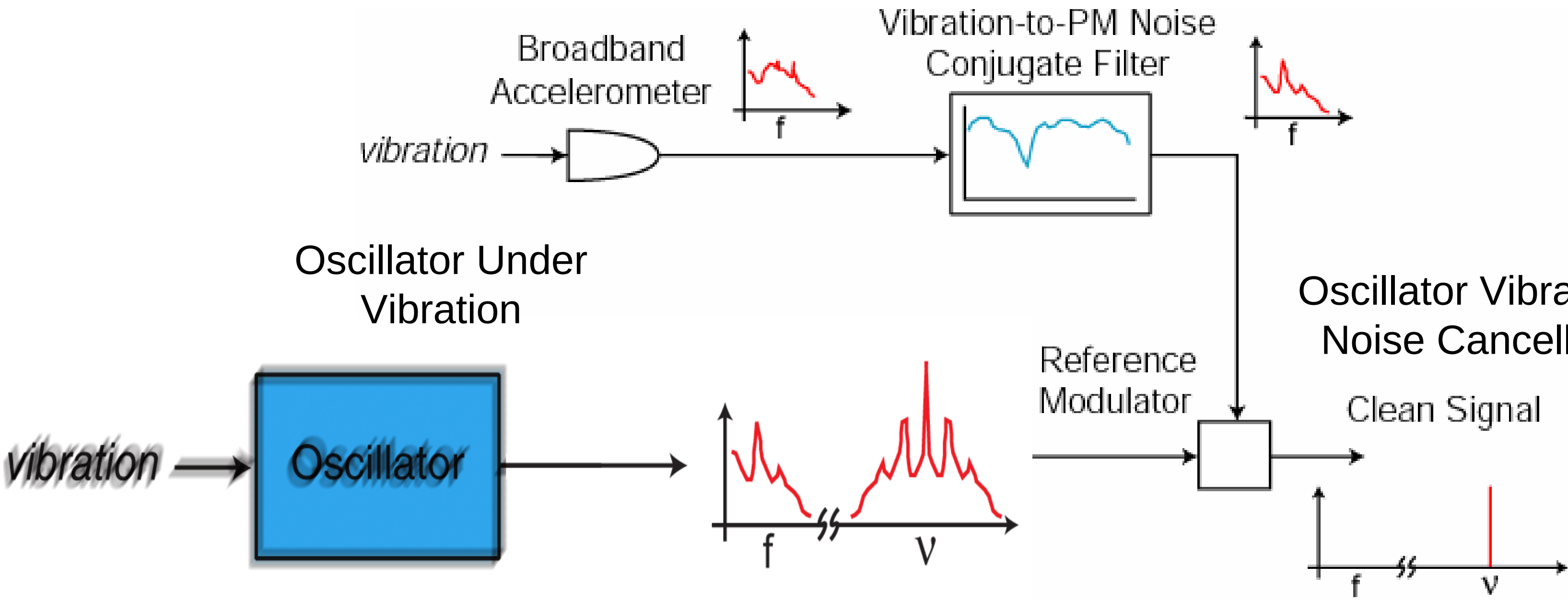


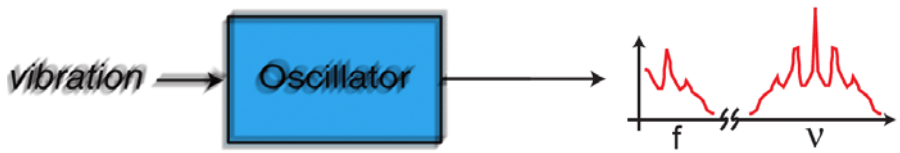
Figure 4: RTCA/DO160E vibration profile.

NIST Active Vibration Cancellation



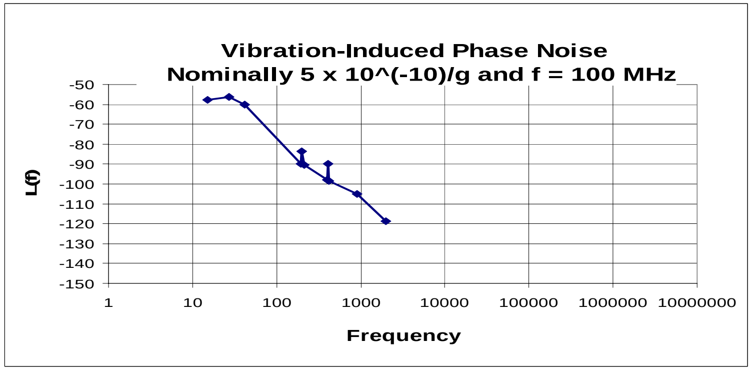
CONCEPT: While oscillator is under vibration, an estimate of a complex-conjugate (same amplitude, opposite phase) signal can be generated from accelerometer signals and used to modulate the oscillator's output phase in such a way as to suppress or cancel the induced sidebands. One-axis cancellation is shown for simplicity.

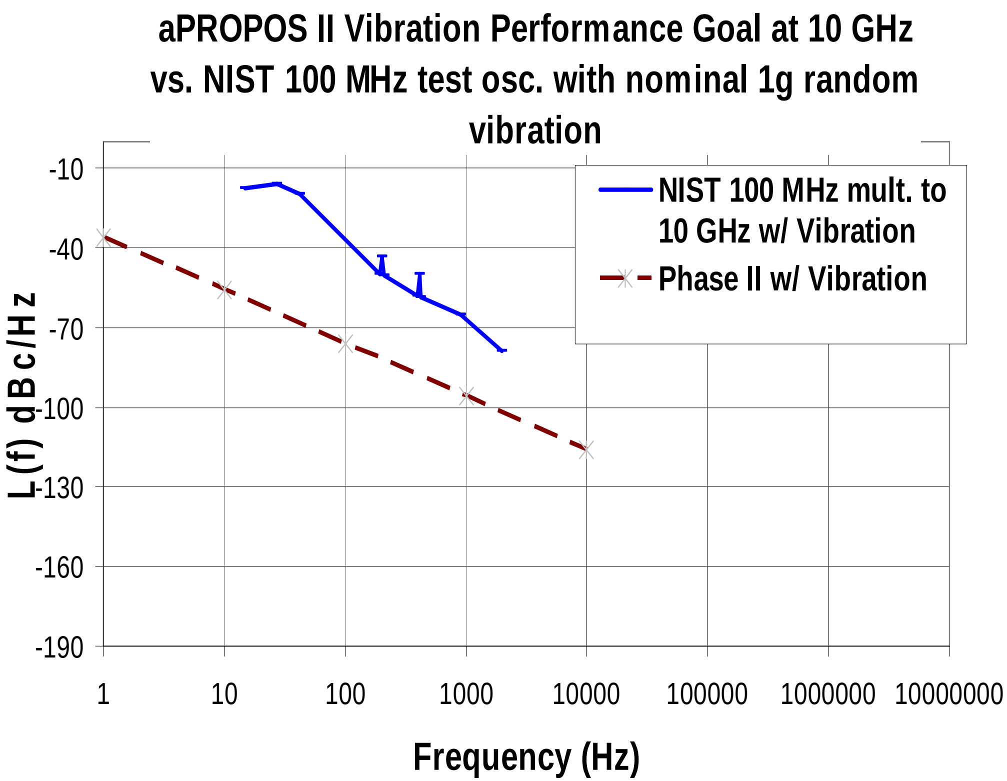
NIST Characterizations of Oscillator Vibration Sensitivity, and PM noise vs. Vibration Profile.



Oscillator Under Vibration

Vibration causes modulation sidebands





Noise measurement with vibration controller and amplifier, actuator, adaptor, power converter.

INDUSTRY and MILITARY NEEDS for SPECTRAL PURITY

- Secure signaling and protocols,
- Radio surveillance,
- Broadband telecommunications,
- Instrumentation needing low jitter and/or high-sync applications,
- Geodesy,
- Conventional and imaging radar,
- Digital logic,
- High-speed signal processing,
- Photonics,
- On-chip atomic clock development,
- Spectrum usage and management,
- Weather monitoring and Doppler imaging,
- Programmed beam antennae and lobe steering.

Future Microwave Oscillator Requirements

NIST

Future system needs
- Small size, light weight
- Similar or improved phase noise
- Lower vibration sensitivity
- Fiber optic reference distribution
- Low cost – large quantities

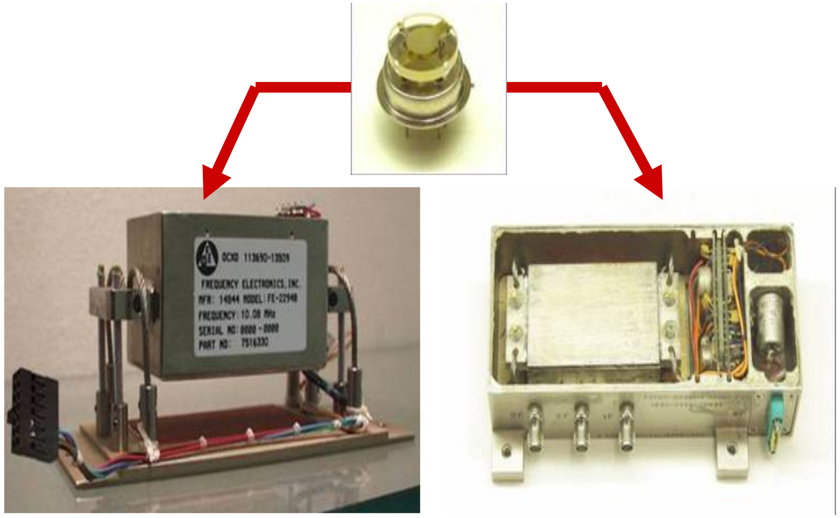
- Vibration Sensitivity: < 1 x 10^{-12} per g
  - Eliminate or reduce the need for vibration isolation
  - Mitigate effects of correlated vibration in distributed architectures
  - Use in higher vibration environments: aircraft, UAV, UCAV, missiles
- Operating Temperature: 0 – 70 ºC
- Warm-up time: < 1 minute
- Power Dissipation
  - Near term - conventional architectures: < 20W
  - Longer term – distributed architectures: < 5W
- Size/Weight
  - Near term: < 50 - 200 cu in, < 15 pounds
  - Longer term: < 5 - 10 cu in, < 0.5 pounds
- Cost
  - Typical applications: < $10,000
- Frequency
  - X-band - near term for LO generation and low cost alternatives using current architectures
  - ≥ 30 GHz - longer term for DDS and A/D clocks providing direct RF signal generation and direct RF sampling
- Phase Noise
  - Below best of current technology for low cost alternatives using current architectures
  - Longer term - use distributed architectures to achieve effective phase noise performance unachievable from single sources
  - Interfering signals from jammers, co-site interference or multi-function applications are driving force for low phase noise in digital beam forming systems

Mike Yeomans, Raytheon, NIST Workshop on Future Oscillator Needs

Qz Low G-sensitivity Clocks

The Way Forward

Summary: Clocks for Challenging Environments

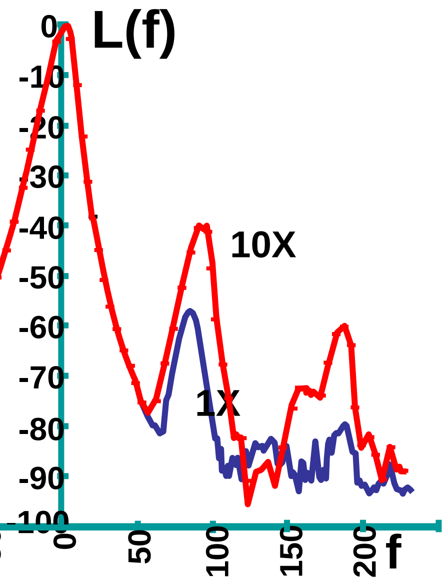


- **Further work is required to reduce size, cost and improve performance**
- **Acceleration sensitivities of parts in E-13/g need to be achieved:**
  - –Improving resonator cross-axis coupling
  - –Improving broad-band compensation (DC to 2 KHz) by enhancing the gain and phase tracking in the compensation circuitry
- **A Chip Quartz Clock**
  - –Meets demanding DoD environments
  - –Very low power consumption
  - –Low-g (E-12/g to E-13/g)
  - –Affordable

Martin Bloch, Frequency Electronics,
NIST Workshop on Future Oscillator Needs

Vibration-Induced Sidebands After Frequency Multiplication

Each frequency multiplication by 10 increases the sidebands by 20 dB.



Vibration Isolation: Limitations

Poor at low frequencies

- Adds size, weight and cost
- Ineffective for acoustic noise

John Vig, US Army Communications-Electronics Research, NIST Workshop on Future Oscillator Needs

Atomic Standard Acceleration Effects

In Rb cell standards, high acceleration can cause Δf due to light shift, power shift, and servo effects:

- Location of molten Rb in the Rb lamp can shift
- Mechanical changes can deflect light beam
- Mechanical changes can cause rf power changes

In Cs beam standards, high acceleration can cause Δf due to changes in the atomic trajectory with respect to the tube & microwave cavity structures:

- Vibration modulates the amplitude of the detected signal.
  Worst when $f_{vib} = f_{mod}$.
- Beam to cavity position change causes cavity phase shift
  effects
- Velocity distribution of Cs atoms can change
- Rocking effect can cause Δf even when $f_{vib} < f_{mod}$

In H-masers, cavity deformation causes Δf due to cavity pulling effect

GPS Clock Requirements

NIST

- Performance Drivers
  - Carrier tracking drives phase noise requirement
  - Cost, size, weight, power (handheld is the long pole)
  - Direct Military Signal Acquisition drives long-term drift requirement
  - Signal reacquisition after Standby periods (with no tracking) drives medium-term requirement
- Field Environment:
  - Temperature changes
  - Acceleration
  - Vibration
  - Shock
  - Power supply voltage variations

Quantitative Considerations

Tony Abbott, The Aerospace Corporation, NIST Workshop on Future Oscillator Needs

- Allan Deviation (Tau = 1 sec.)
  - 2.3 x 10^{-12} allows navigation filter to estimate clock phase and frequency with only a 1 dB loss in anti-jam performance relative to a perfect clock
- Phase Noise
  - Frequency white noise for long coherent integration periods

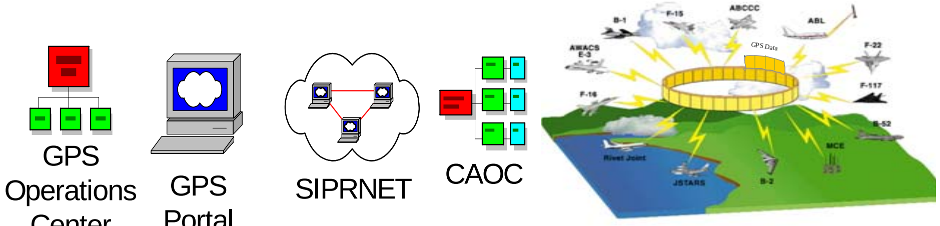
The "Impossible" Dream

Give me an oscillator that:

- Only consumes milliwatts of power (battery)
- Builds up less than one millisecond of error during one year
- Has no phase noise
- Is insensitive to environment
- Costs less

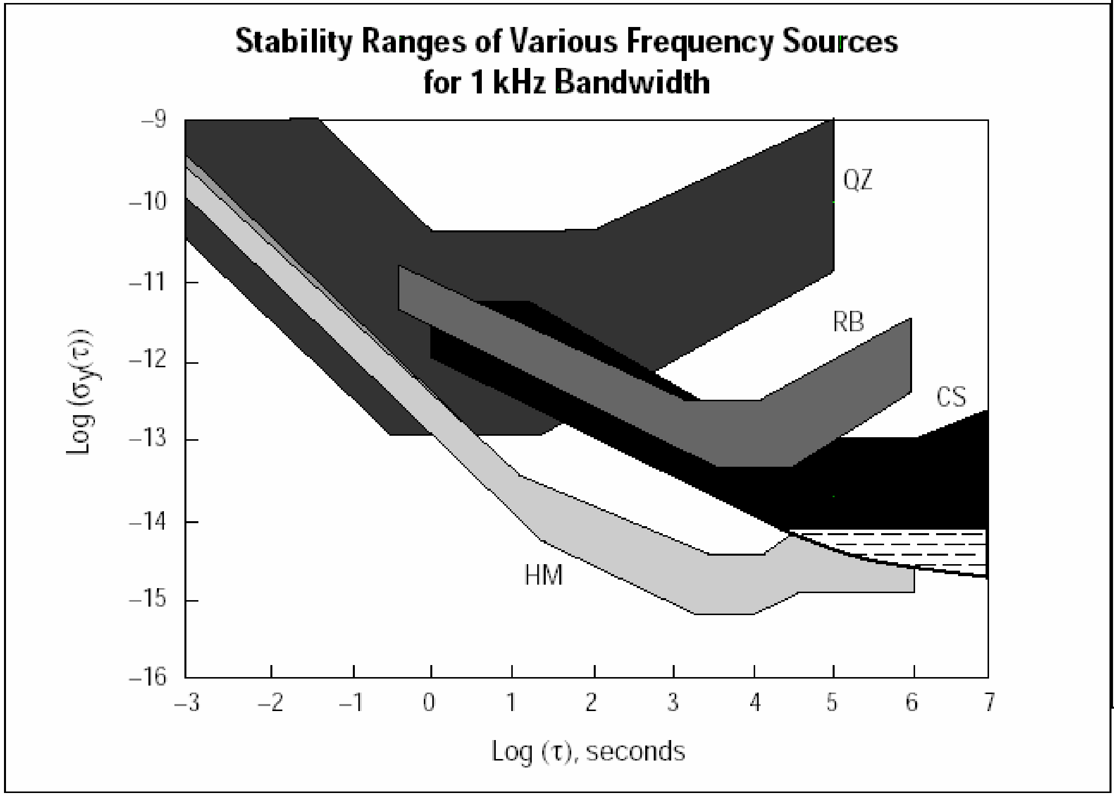
Network Centric View of GPS Operations

NIST



Global Information Grid allows GPS Information Services to be provided directly to the Warfighter from the GPS Operations Center

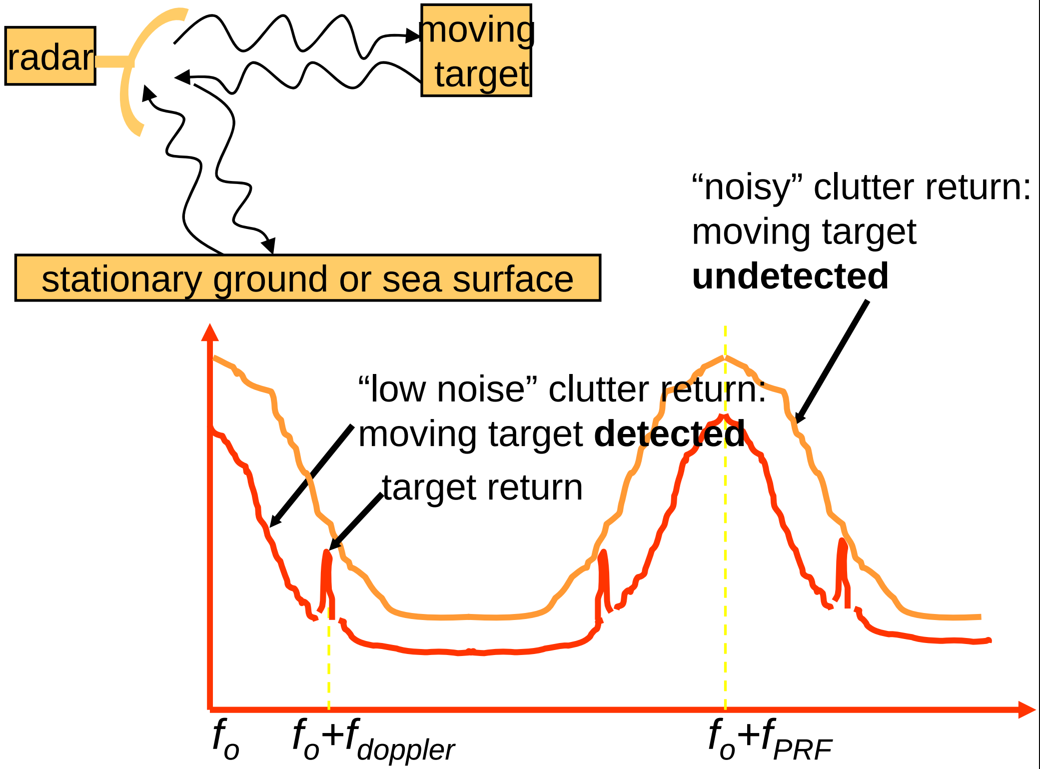
Clock Allan Variance and Desired Phase Stability



GPS Ultra-Stable Oscillator Requirements

- Requirements
  - Low phase noise
    - Needed to provide high quality phase tracking
  - Short term stability
    - 1-100 secs is the critical stability region for UTC operation
  - Man-portable : Low power, Small size
  - Platforms: High vibration, High-dynamic stress

Alison Brown, Navsys Corp., NIST Workshop on Future Oscillator Needs



Effect of Phase Noise on RADAR Performance

Michael Driscoll, Northrop Grumman, NIST Workshop on Future Oscillator Needs

Insufficient vibration resistance is the primary problem…

- Improvements must to be made for all components
- Areas of development:
  - Components and architectures with lower 1/f PM noise
  - Reduced vibration sensitivity of non-oscillator hardware
  - Reduce vibration transmission of packaging
    - structure design
    - vibration isolation
    - applied damping materials
    - vibration absorbers
    - active control/cancellation systems
  - Northrop Grumman is developing a standard test procedure for verification of vibration sensitivity
    - for use by vendors

Radar Oscillator Desired Requirement Hypothesis

NIST

- ✓ **Digital radars parallel 100s of oscillators to obtain extremely high clutter rejection with ordinary high-quality parts**
- ✓ **Provided Precision Oscillator Requirement Hypothesis:**
  1. **Case 1: Single Precision oscillator with distribution network**
  2. **Case 2: Many high quality oscillators phase locked to 10 MHz Reference and of fairly small size and low cost**
- ✓ **Showed how phase noise relates to radar merit through a set of radar parameters**

Summary of High Performance Radar Requirements

Assumption: Digital S to X-Band Radar has about 300 subarrays

Case 1: Single precision oscillator after distribution to many frequency synthesizers

Phase noise floor = -175 dBc/Hz

Phase noise at 500 Hz = -145 dBc/Hz

Case 2. 300 distributed precision oscillators at each frequency synthesizer

Phase noise floor = -150 dBc/Hz

Phase noise at 500 Hz = -120 dBc/Hz

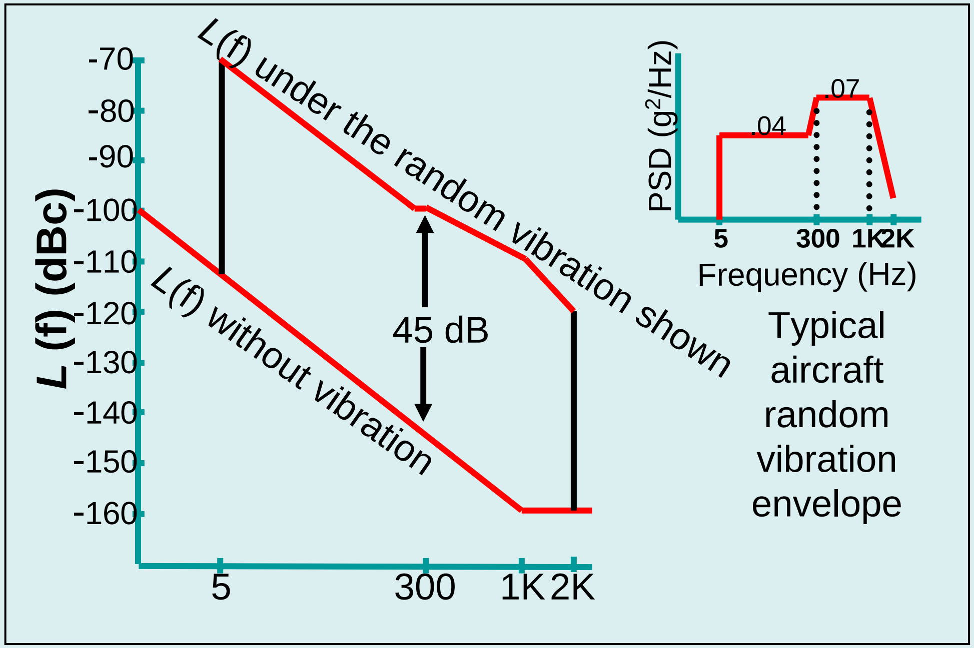
All phase locked to 10 MHz reference below 100 Hz bandwidth

Small and low cost

Ben Cantrell, Naval Research Lab, NIST Workshop on Future Oscillator Needs

When Does Vibration Affect Frequency Difference Of Arrival (FDOA)?

Random-Vibration-Induced Phase Noise



Summary

- Vibration affects FDOA when independent clocks are used on the receivers
  - Lack of suitable communications channels
  - When communications between receivers needs to be minimized to prevent detection
- Vibration is an issue in the case of a tactical target location system
- The effect is large enough to be of significance

- Vibration induced phase noise is more important than static phase noise for an aircraft FDOA geolocation system
  - Typical jet aircraft vibration levels and standard acceleration sensitivity produces induced phase noise 40 dB above static levels
  - Geolocation system engineers are specifying reference oscillator
  - performance based on static phase noise levels
- Simple analysis demonstrates that vibration induced phase noise can inhibit performance above levels desired in future geolocation systems
- Geolocation system engineers must account for vibration induced errors in the detailed system error budget for their specific algorithms and configurations

Sam Stein, Timing Solutions Corporation, NIST Workshop on Future Oscillator Needs

The End

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All 10 GHz Frequency Synthesizers