Shaky Signals – The Effects of Clock Vibration Sensitivity on High-Speed Data Transmissions

A Leading Provider of Smart, Connected and Secure Embedded Control Solutions

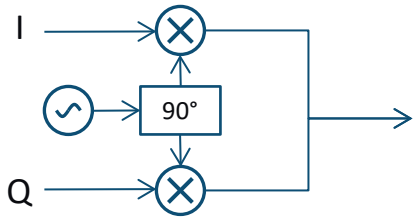
David Chandler and Daniel Boschen

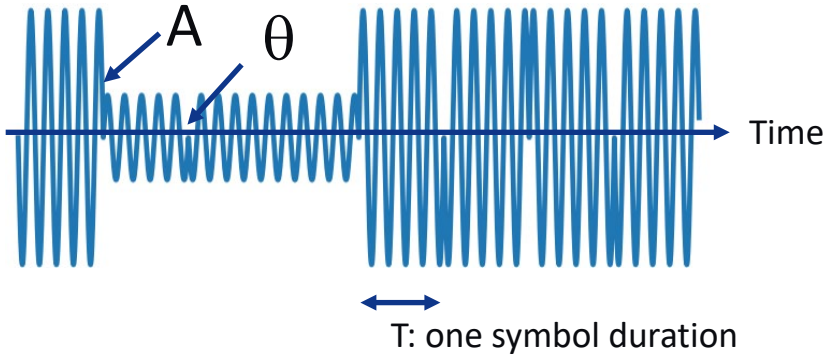
Agenda

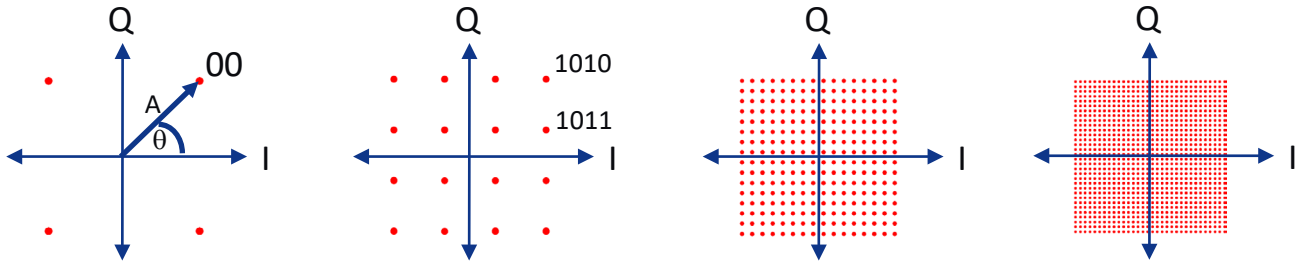
- Quadrature Amplitude Modulation (QAM)
- Orthogonal Frequency Division Multiplexing (OFDM)
- g-Sensitivity
- Practical implementation of 5G NR signal at 6.05 GHz
- Phase carrier tracking
- Impacts of g-sensitivity on Error Vector Magnitude (EVM)

Quadrature Amplitude Modulation (QAM)

The levels of "**I**" and "**Q**" at **baseband** set the **magnitude** and **phase** of an RF carrier for each of the possible M symbols to be transmitted at any given time







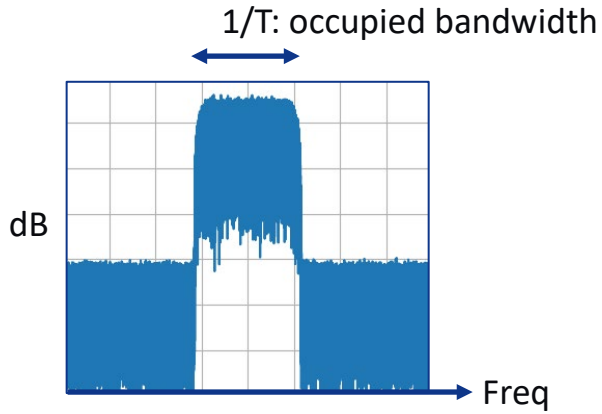
QPSK (M=4) — 2 bits/symbol

16-QAM (M=16) — 4 bits/symbol

256-QAM (M=256) — 8 bits/symbol

1024-QAM (M=1024) — 10 bits/symbol

The **Symbol Rate** 1/T sets the **RF Bandwidth**:



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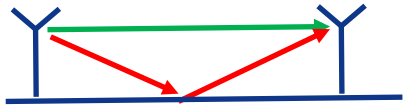
Orthogonal Frequency Division Multiplexing (OFDM)



Challenge with a single wideband QAM carrier:

Multipath fading

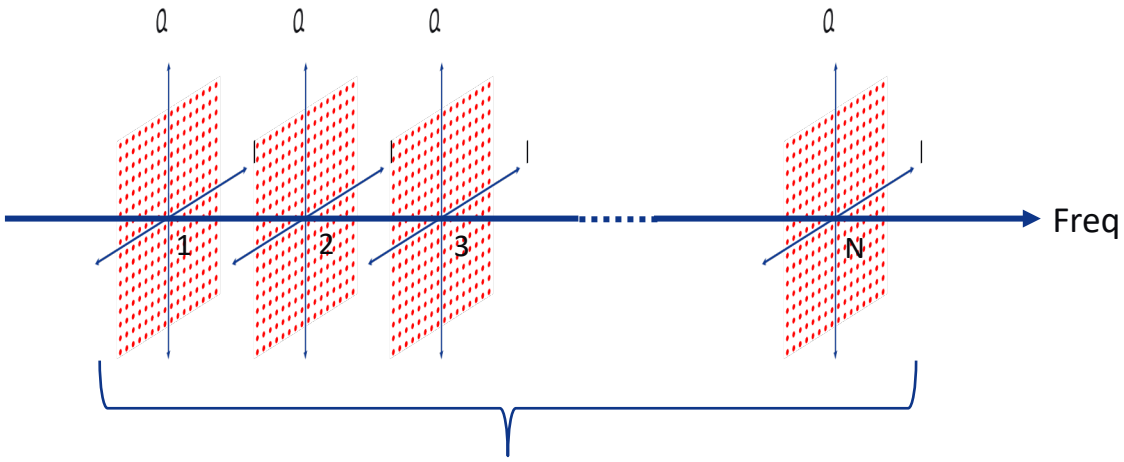
If the delay spread exceeds symbol duration T: frequency selective fading

Solution:

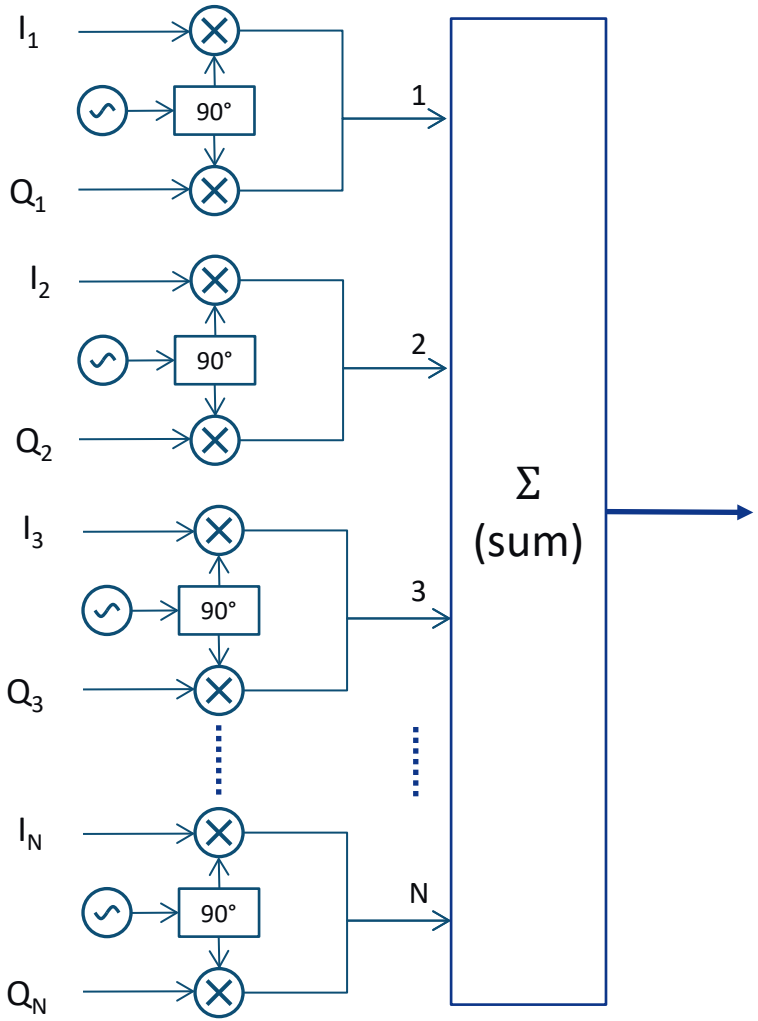
Send **multiple narrow band QAM carriers** in parallel.

OFDM

Challenge with OFDM: Phase noise



N Sub-carriers as bins of an FFT is the resulting sum in the frequency domain



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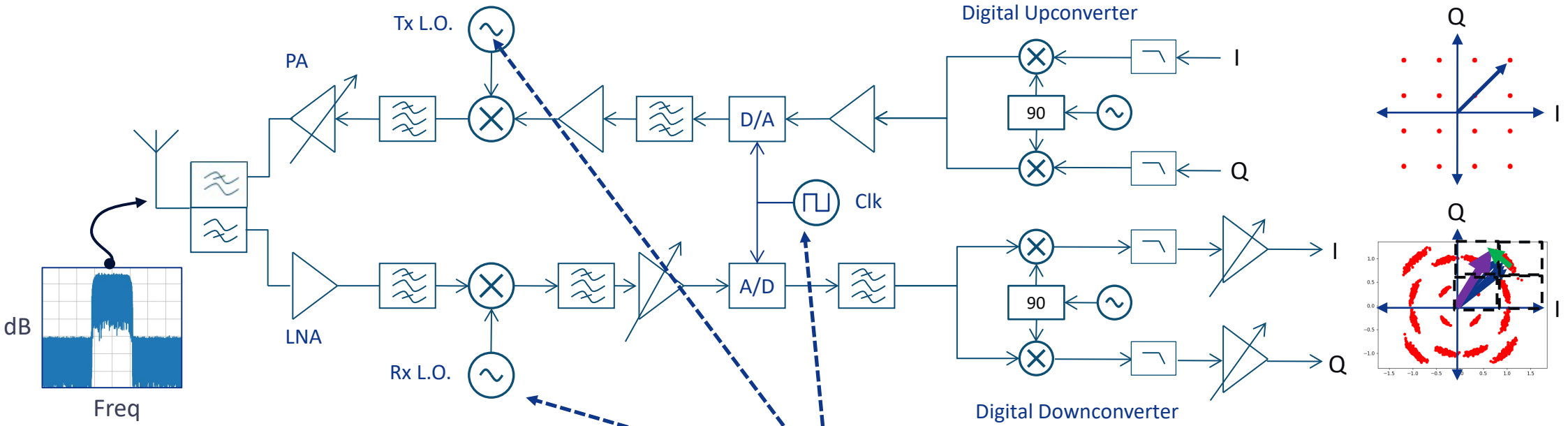
Radio Transceiver Block Diagram

(I,Q) Can be samples of Single Carrier QAM or the time domain OFDM waveform



Spectrum at microwave carrier (Frequency Domain)

Phase noise sources

IQ Constellations at baseband (Time Domain)

EVM ⇨ Bit error rate

From “DSP for Software Radio” Dan Boschen https://dsprelated.com/courses

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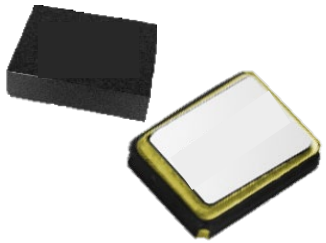
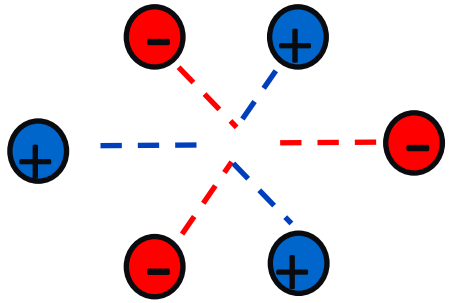
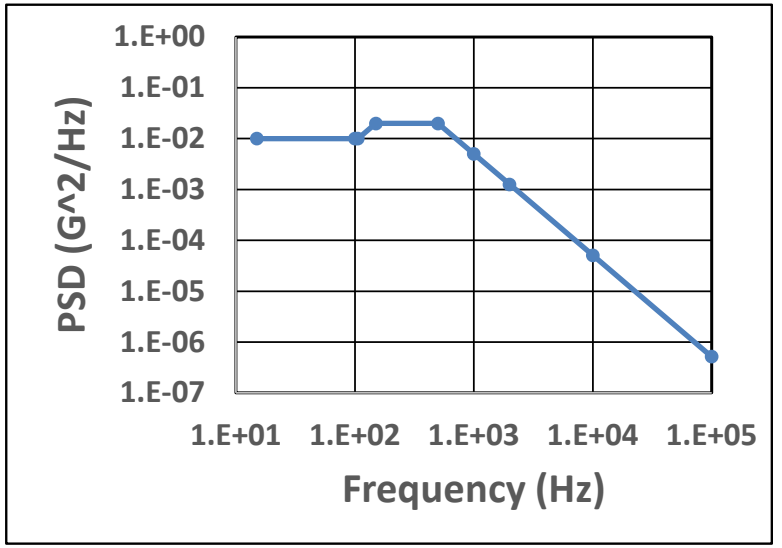
Vibration Effects on LO

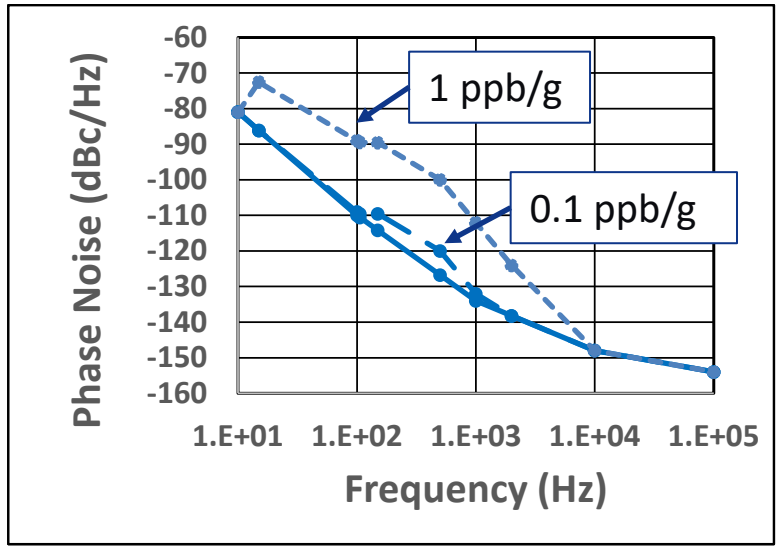
- **Local Oscillator (LO)**
  - TCXO or MEMS + synthesizer
- **LOs mechanically vibrate**
  - Q defines phase noise
- **Additional vibration modulate the resonance**
- **Net effect is increase in phase noise at vibration frequencies**
- **Different oscillators have different coupling sensitivities**
- **γ - g-sensitivity**
- **Units measured ppb/g**
- **Often not listed in specifications**

$$\mathcal{L}(f) = 20 \log \left(\frac{\bar{\gamma} \bullet \bar{A} f_0}{2f} \right), \quad where \; l\bar{A}l = [(2)(PSD)]^{1/2}$$









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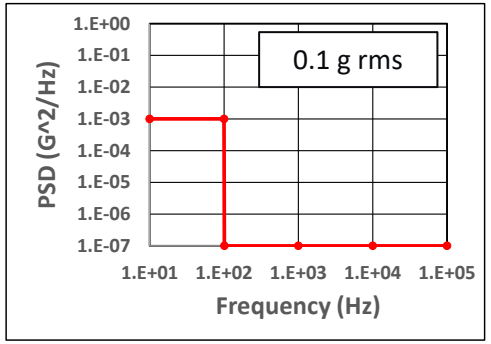
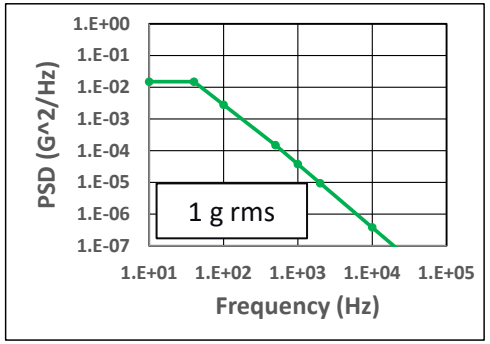
Random Vibration Profiles for Moving Vehicles

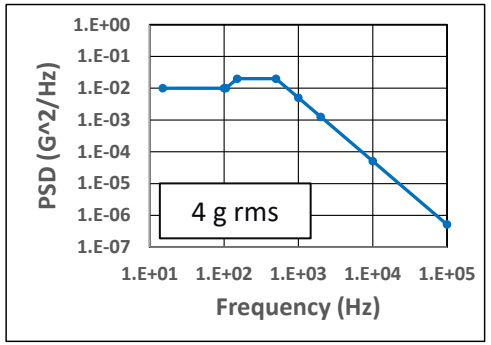
Naval Surface Vessel



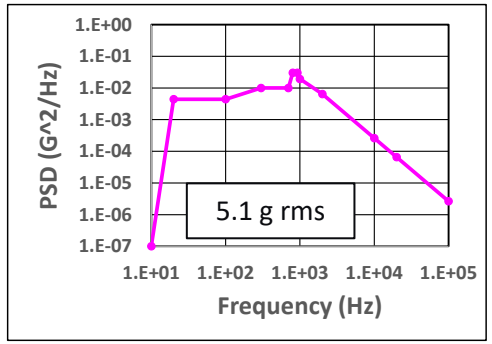
Road Vehicle



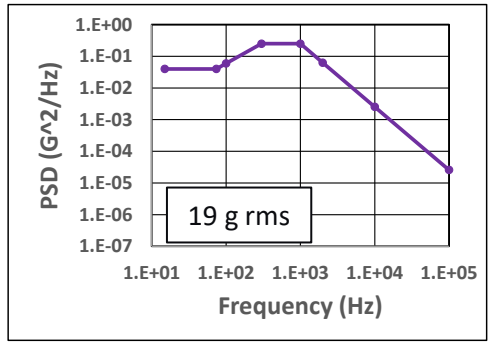
Commercial Airliner



Rocket Payload



F15 (not cockpit)



- Vibration profiles from Mil-Std-883, Falcon 9 user guide, and NASA/TM-2002-210719
- Most profiles only list vibrations out 2 kHz due to transmissibility and measurability
- Limited energy > 2 kHz– but any energy in phase noise integration region can have large effect
- Extrapolated slopes from 2 kHz out to 100 kHz
- Simulated phase noise for these profiles with a 50 MHz TCXO at 1ppb/g and 0.1ppb/g
- Does not include any isolation, resonance, or higher-level modes

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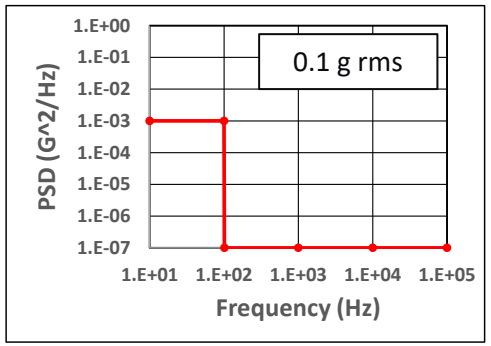
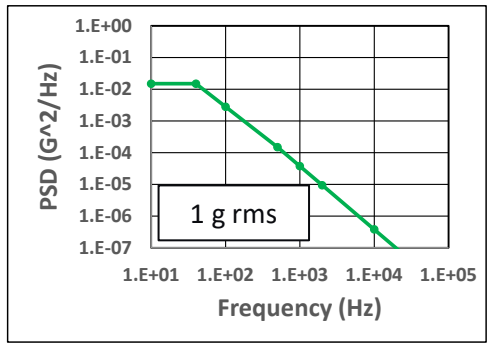
Phase Noise of TCXO at 1ppb/g and 0.1ppb/g

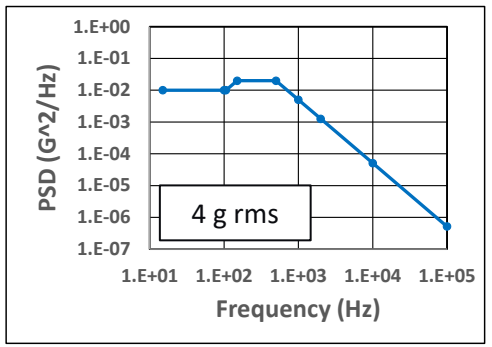
Naval Surface Vessel



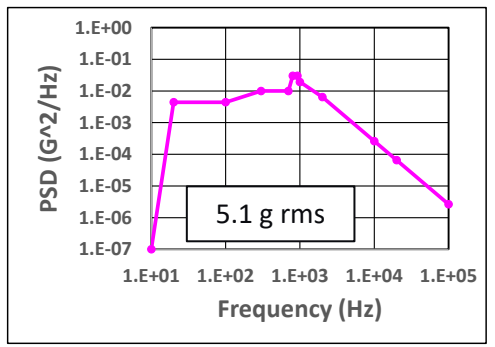
Road Vehicle



Commercial airliner



Rocket Payload



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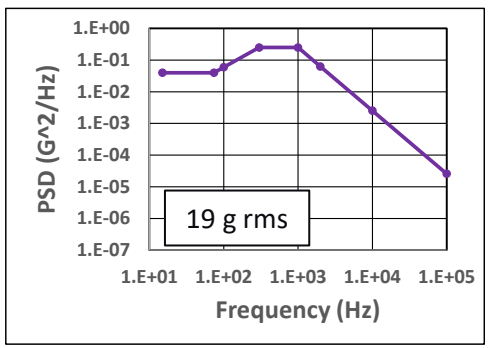

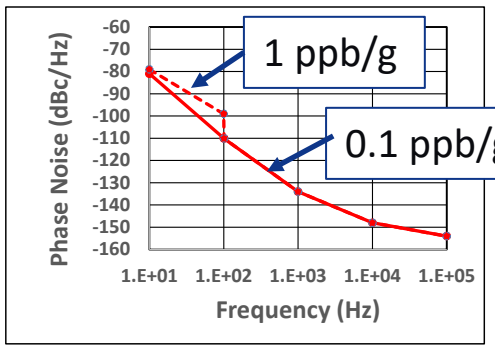

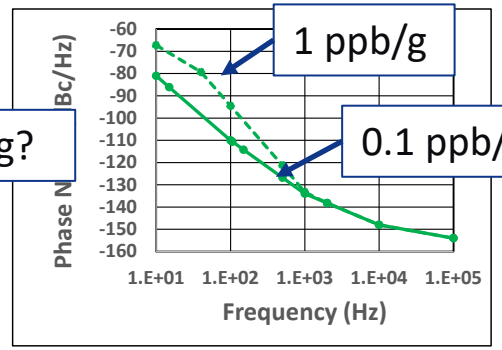

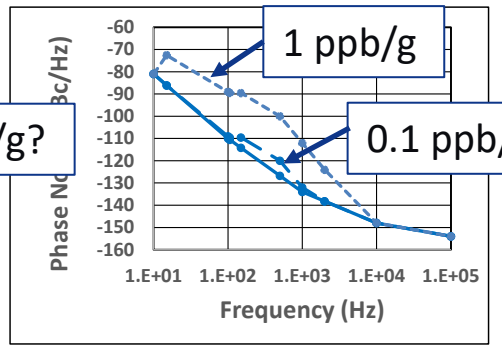

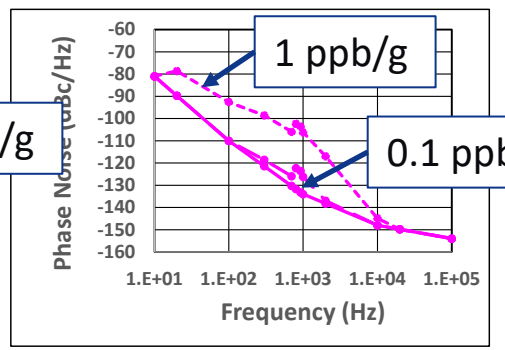

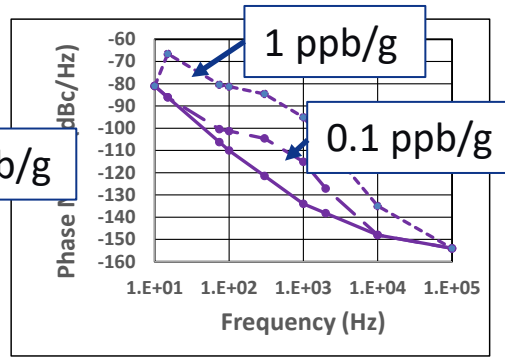

LO phase noise degradation at 50 MHz due to profiles out to 100 kHz

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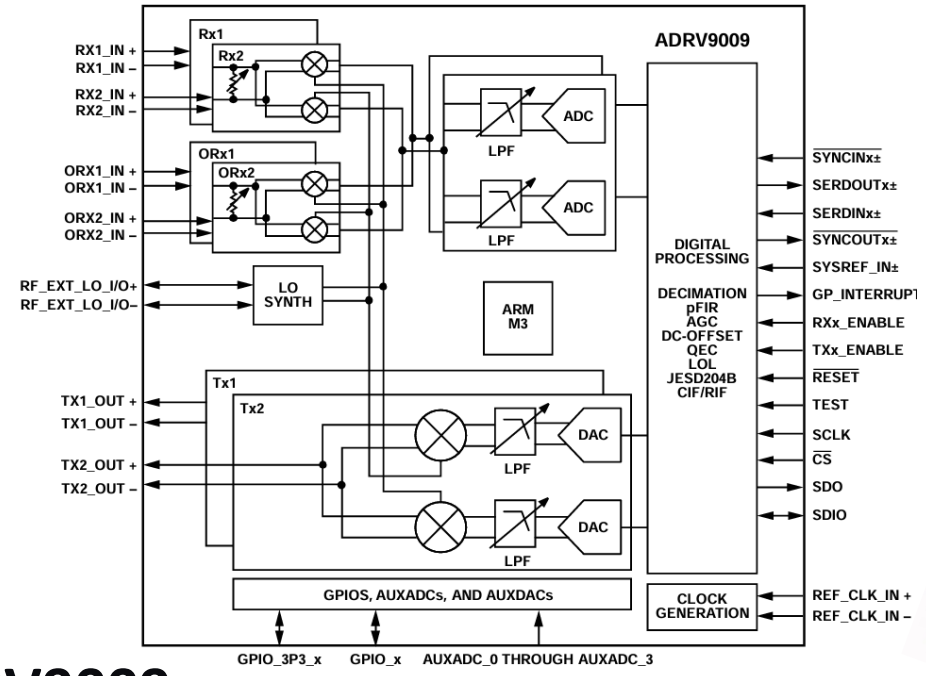
Impact at 6 GHz - Transceiver Chip Used for Simulations

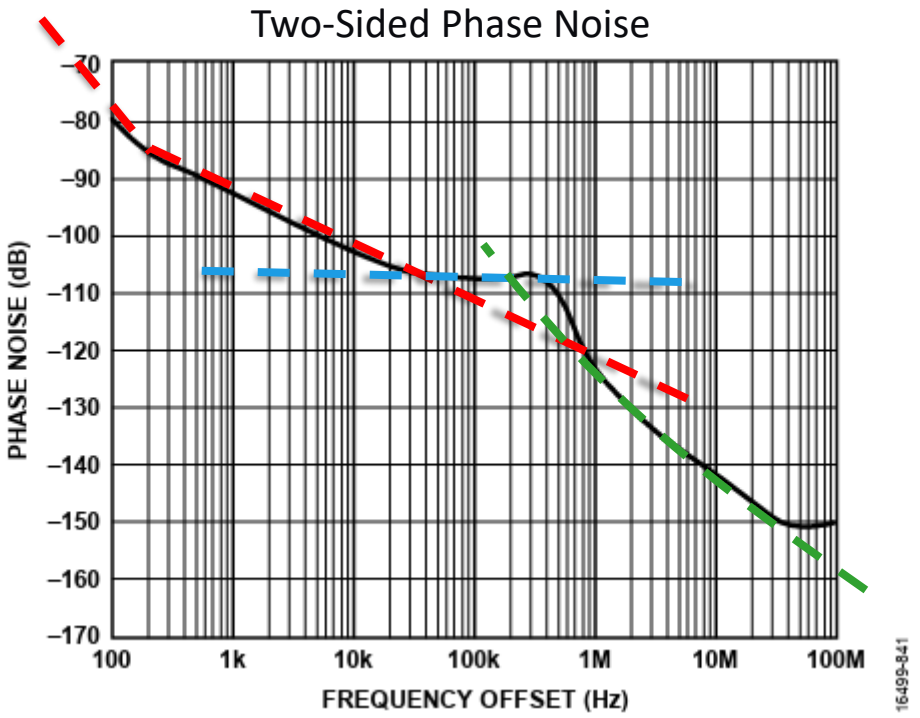
XO ref + 20Log(N) < 200 Hz and PLL 1/f noise > 200 Hz

PLL flat noise: PN1Hz+10Log(F_{PFD})+20Log(N)

uW VCO Phase Noise

FUNCTIONAL BLOCK DIAGRAM





ADRV9009

50 MHz TCXO for reference clock

Std-g– 1 ppb/g

Low-g – 0.1 ppb/g – TX-709

15 kHz OFDM channel

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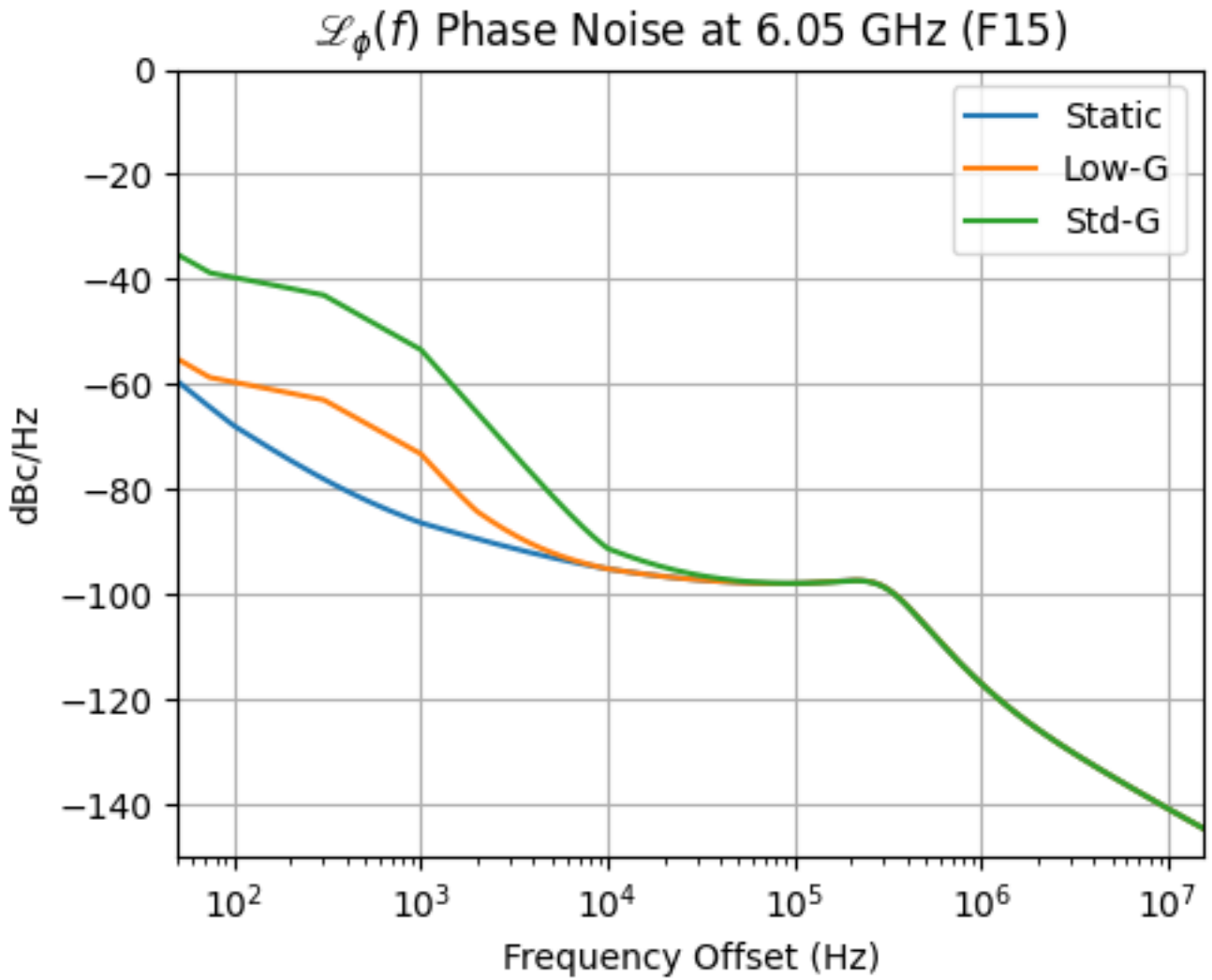
Resulting uW Phase Noise



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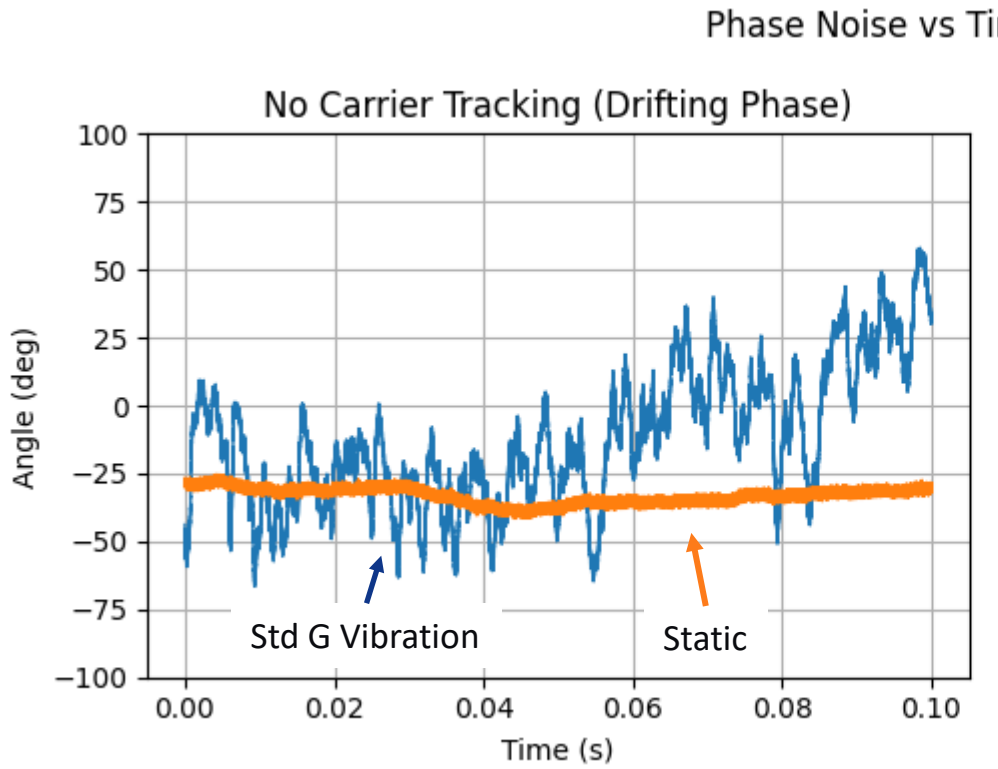
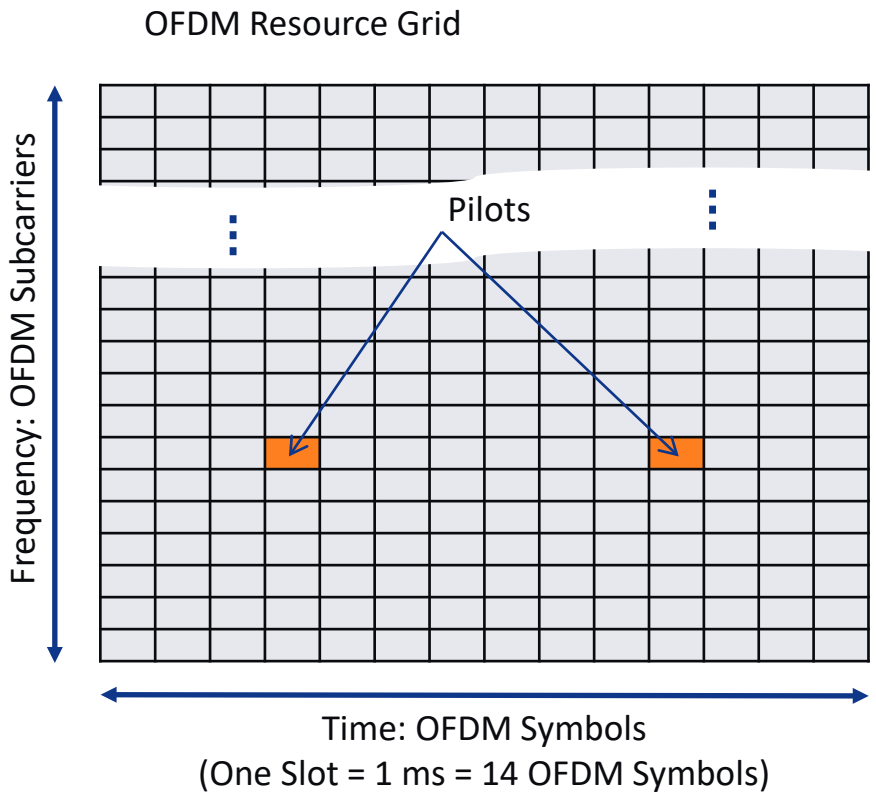
Carrier Phase Tracking





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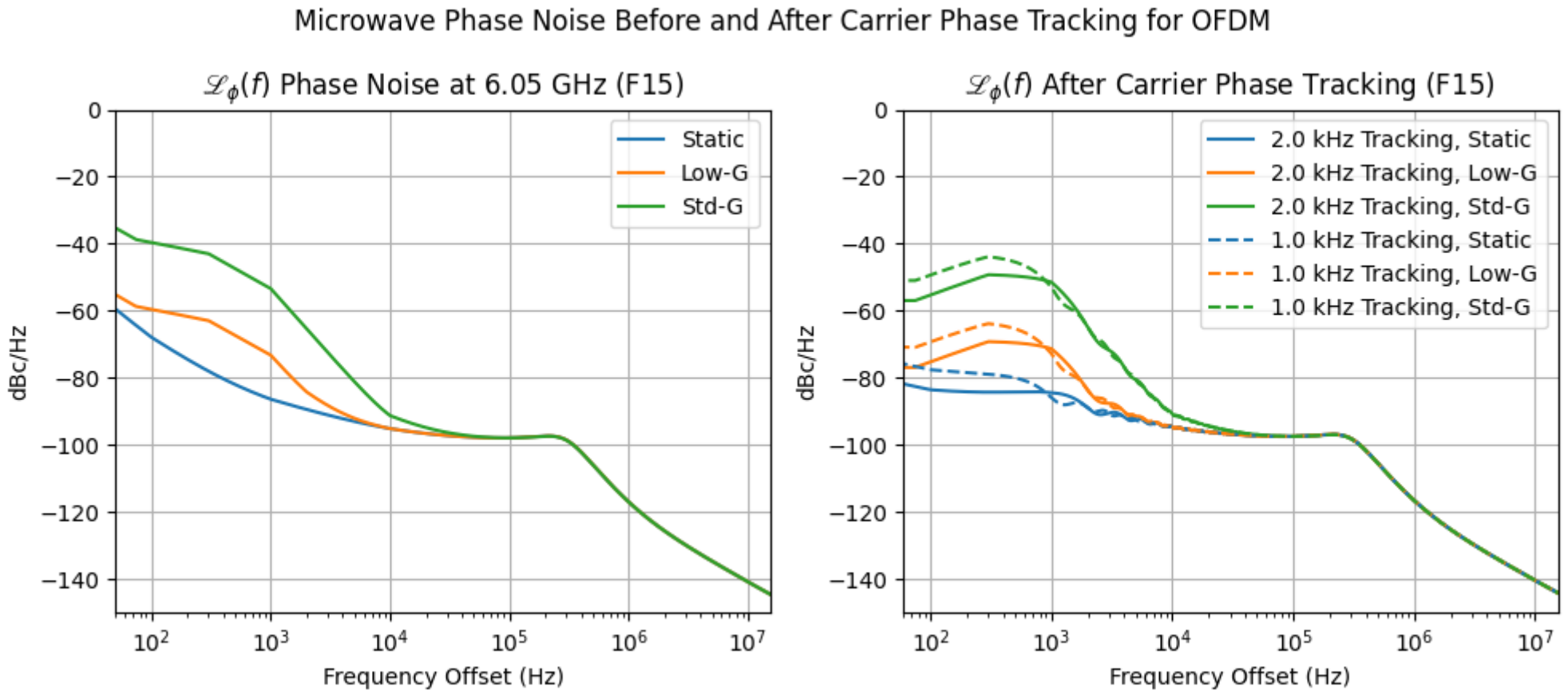
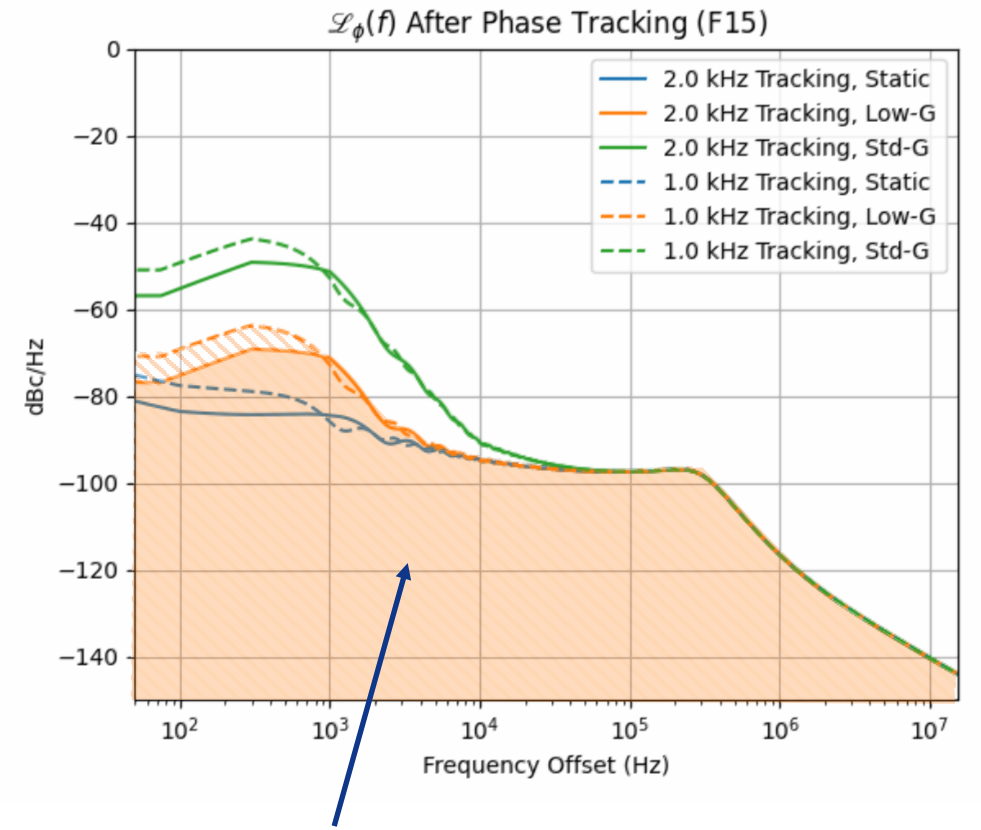
Impact of Phase Carrier Tracking on uW Phase Noise



Phase Noise after Carrier Tracking Impact on Constellation Diagrams



The total integrated noise power under this curve is the EVM squared.

5G NR EVM Requirements

256 QAM: 3.5%, 1024 QAM: 2.5%

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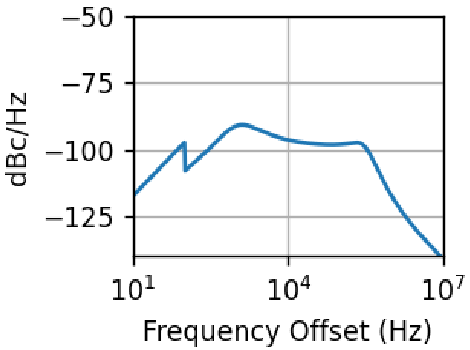
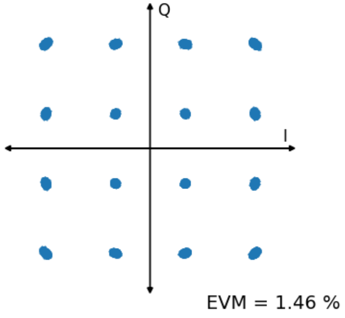
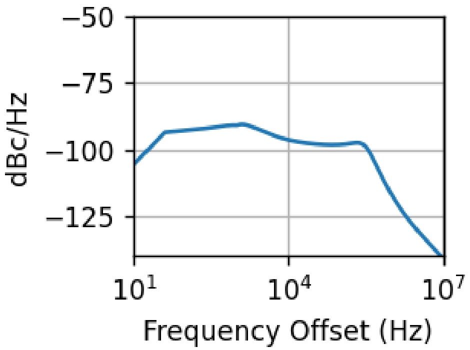
Phase Noise and EVM for Std-g TCXO

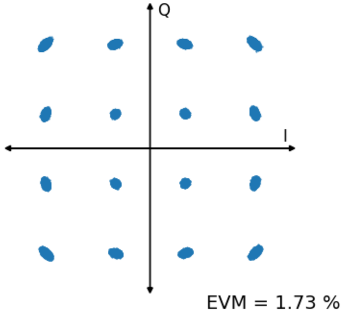
Naval Surface Vessel



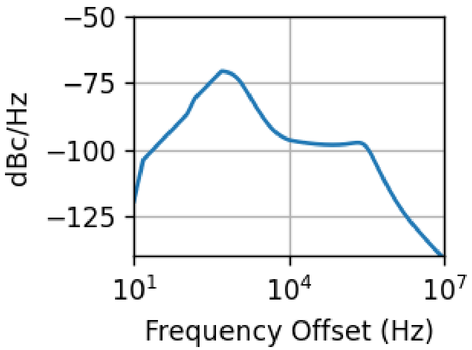


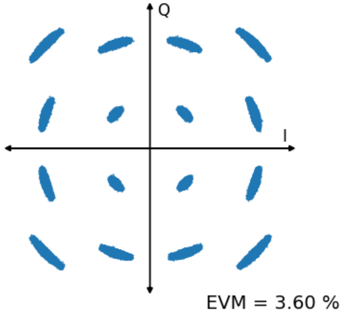
Road Vehicle



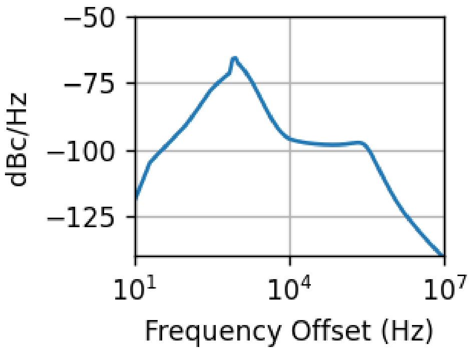


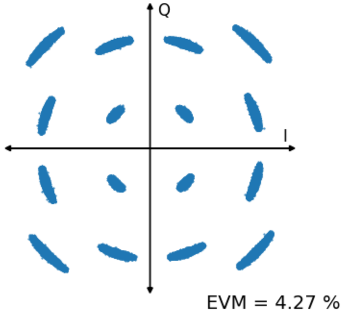
Commercial Airliner



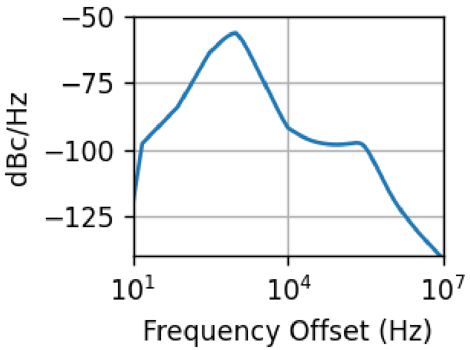


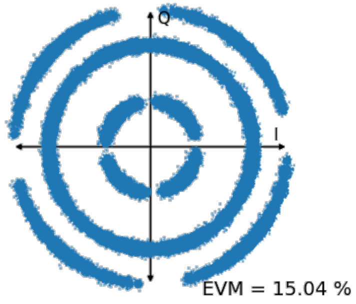
Rocket Payload





F15 (not cockpit)





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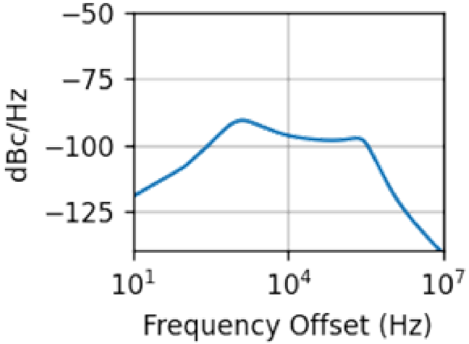
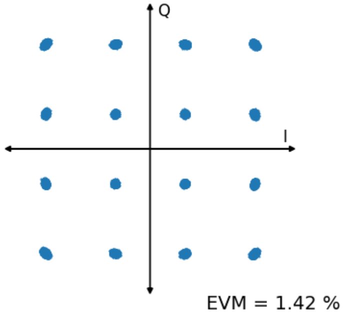
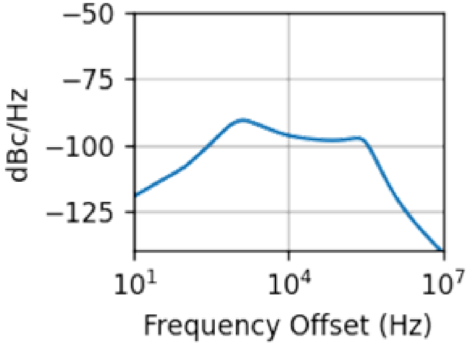
Phase Noise and EVM for Low-g TCXO

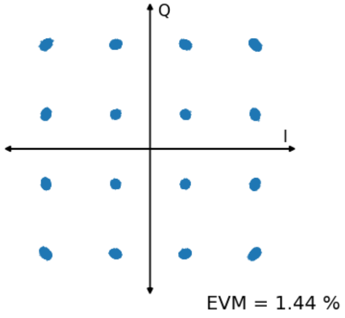
Naval Surface Vessel



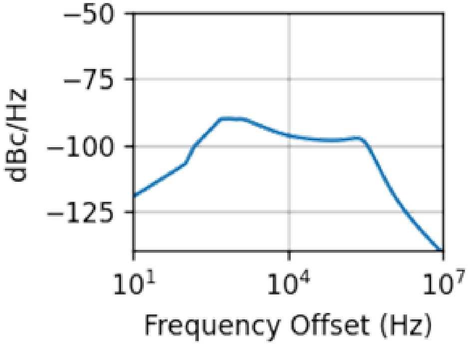


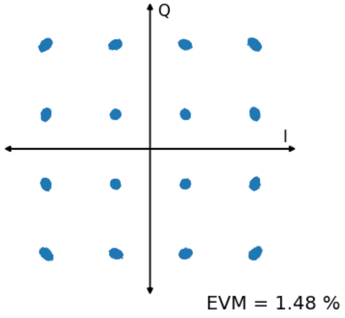
Road Vehicle



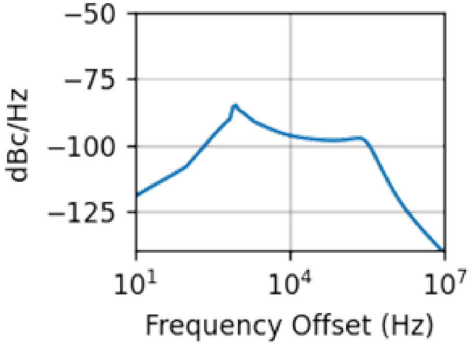


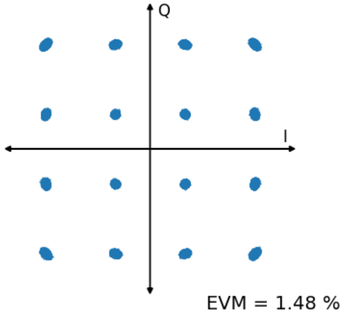
Commercial Airliner



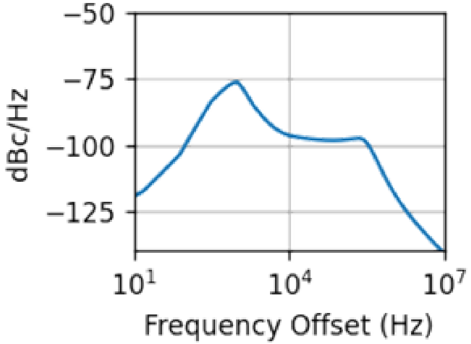


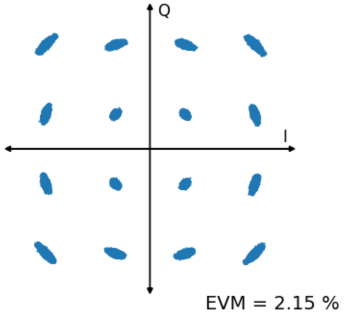
Rocket Payload





F15 (not cockpit)





Summary

- Phase noise degradation due to vibration is most prevalent in the 10 Hz - 2 kHz range
- Low energy vibration past 2 kHz still affects phase noise
- Correctly choosing the correct phase carrier tracking can mitigate most significant effects for 5G and other similar architectures using QAM and OFDM
- Low g oscillators can effectively mitigate the EVM degradation in almost all cases
- EVM levels will only be more challenging at 4096 QAM and higher
- LO phase noise is only one source of EVM
- Not mentioned – Doppler issues (and time dilation in the rocket case) could start to have more significant impacts

Thank You!