PLL Synthesizer Phase Noise

$FLO := 940 \cdot 10^6$

$\omega_n := 2 \cdot \pi \cdot 3000$ Nominal loop natural frequency

$\zeta := 0.8$ Nominal loop damping factor

$F_{ref} := 10^5$ Comparison frequency at phase detector

$K_v := 2 \cdot \pi \cdot 150 \cdot 10^6$ VCO tuning sensitivity

$K_d := \frac{0.005}{2 \cdot \pi}$ Phase detector gain, A/rad

$Margin_{dB} := 4$ Margin sought compared to ideal phase detector noise floor, dB

$N_{nom} := \text{floor}\left(\frac{FLO}{F_{ref}}\right)$ $N_{nom} = 9.4 \times 10^3$

Phase Detector Noise Floor Phase detector noise floor, dBc/Hz, @ Fout

$$L_{pd}(F_{pd}, F_{in}) := -211 + 20 \cdot \log(F_{in}) - 10 \cdot \log(F_{pd}) + |Margin_{dB}|$$

$$L_{pd}(F_{ref}, FLO) - 20 \cdot \log(N_{nom}) = -157$$

$$L_{pd}(F_{ref}, FLO) = -77.537$$

Loop Parameters

$$C_1 := \left(\frac{\omega_n^2 \cdot N_{nom}}{K_d \cdot K_v}\right)^{-1} \qquad C_1 = 2.246 \times 10^{-7}$$

$$R_1 := \frac{2 \cdot \zeta}{\omega_n \cdot C_1} \qquad R_1 = 377.996$$

Phase Detector Noise Floor

$$L_{pdx} := L_{pd}(F_{ref}, FLO) \qquad L_{pdx} = -77.537$$

VCO Parameters for Leeson's Model

$F := 4 \quad k := 1.38 \cdot 10^{-23} \quad T := 290$

$Q_L := 5 \quad F_o := FLO \quad P_o := 0.001$

$$L_{vco}(f) := 10 \cdot \log\left[\frac{F \cdot k \cdot T}{2 \cdot P_o} \cdot \left[1 + \left(\frac{F_o}{2 \cdot Q_L \cdot f}\right)^2\right]\right]$$

$$R_2 := 2000 \cdot \text{floor}\left(\frac{10 \cdot R_1}{1000} + 1\right) \qquad R_2 = 8 \times 10^3$$

$$f_{corner} := \frac{8 \cdot \omega_n}{2 \cdot \pi}$$ **Corner frequency for LPF into VCO**

$$C_2 := \left(f_{corner} \cdot 2 \cdot \pi \cdot R_2\right)^{-1} \qquad C_2 = 8.289 \times 10^{-10}$$

PLL Architecture for Loop Filter

```
-----------------------------R2----------------> VCO
       |           |                      |
      C3          R1                     C2
       |           |                      |
       |          C1                      |
       |           |                      |
     ____        ____                   ____
      _           _                      _
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$L_{vco}(10000) = -91.504$

$L_{vco}(1000) = -71.504$

$L_{vco}(30000) = -101.047$

$L_{vco}(50000) = -105.484$

$L_{vco}(75000) = -109.006$

Internal node capacitance (estimate) looking into VCO Tune Port adds to C2

$C_2 := C_2$

Want C3 to act with R1 || R2 to mimic a zero-order sample hold response for best speed performance. Also, in speed-up mode with LMX2332, loop bandwidth is doubled so this needs to be reflected in stability considerations.

$$T_{ref} := \frac{1}{F_{ref}}$$

$$R_x := R_1 \cdot R_2 \cdot \left(R_1 + R_2\right)^{-1} \qquad R_x = 360.942$$

$$C_3 := \frac{T_{ref}}{4} \cdot R_x^{-1} \qquad C_3 = 6.926 \times 10^{-9}$$

$$G_{OL}(s, N) := \frac{K_d \cdot K_v}{N \cdot s} \cdot \frac{R_2}{\left(1 + s \cdot R_2 \cdot C_2\right) \cdot \left(1 + \frac{s \cdot R_2 \cdot C_1}{1 + s \cdot R_1 \cdot C_1} + s \cdot R_2 \cdot C_3\right) - 1}$$

Examine open-loop gain function

$R_1 = 377.996$ $\quad C_2 = 8.289 \times 10^{-10}$

$C_1 = 2.246 \times 10^{-7}$ $\quad R_2 = 8 \times 10^{3}$

$C_3 = 6.926 \times 10^{-9}$

$ii := 0 .. 256$

$fw_{ii} := 10^{0+\frac{ii}{257} \cdot 7}$

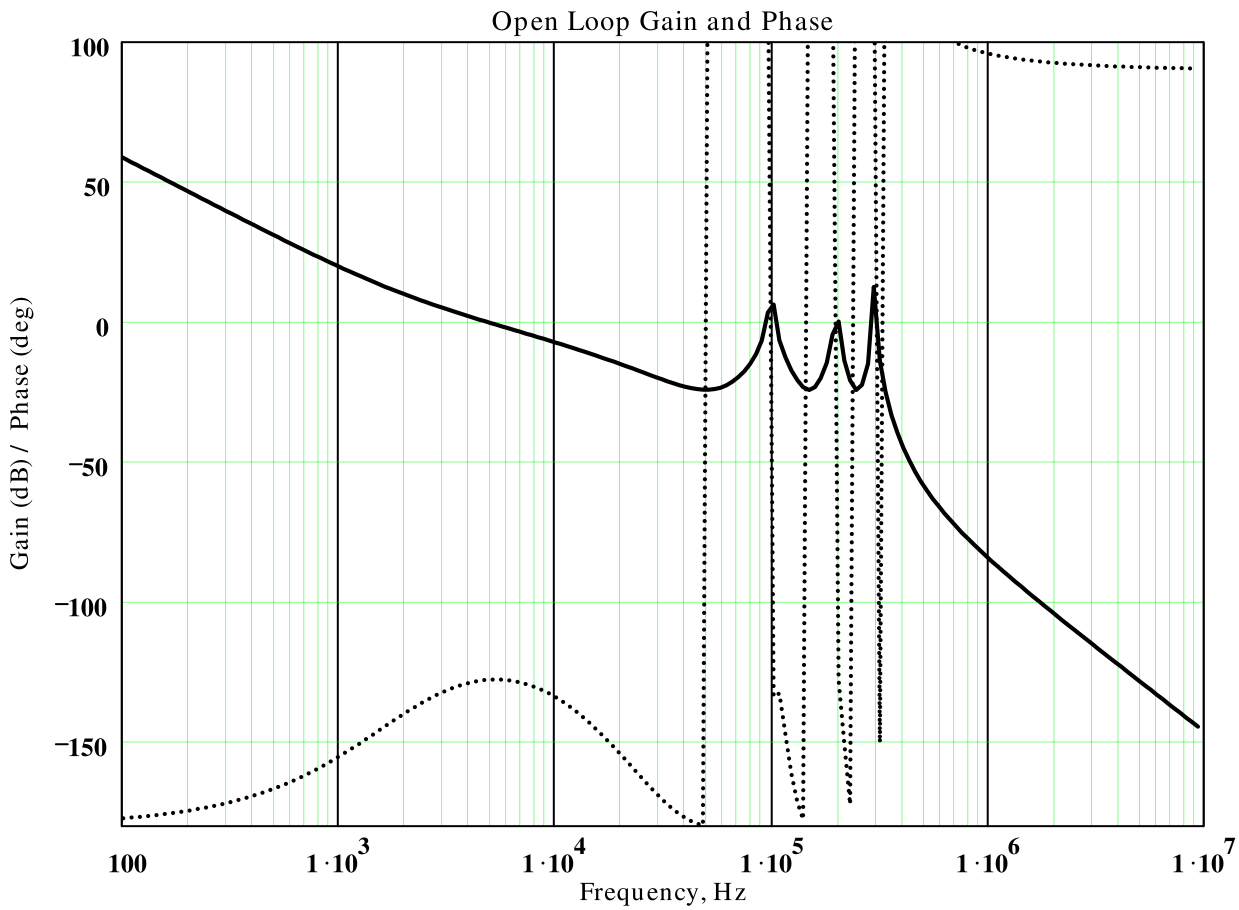
$jx := \sqrt{-1}$ $\qquad w_s := 2 \cdot \pi \cdot F_{ref}$

$sw_{ii} := jx \cdot fw_{ii} \cdot 2 \cdot \pi$ $\qquad ksum := -3 .. 3$

$GStar_{ii} := \sum_{ksum} G_{OL}(sw_{ii} + jx \cdot ksum \cdot w_s, N_{nom})$ $\qquad G_{ii} := G_{OL}(sw_{ii}, N_{nom})$

$GMag_{ii} := 10 \cdot \log\left[\left(\left|GStar_{ii}\right|\right)^2\right]$ $\qquad GAng_{ii} := \arg(GStar_{ii}) \cdot \frac{180}{\pi}$

Open-Loop Gain and Phase

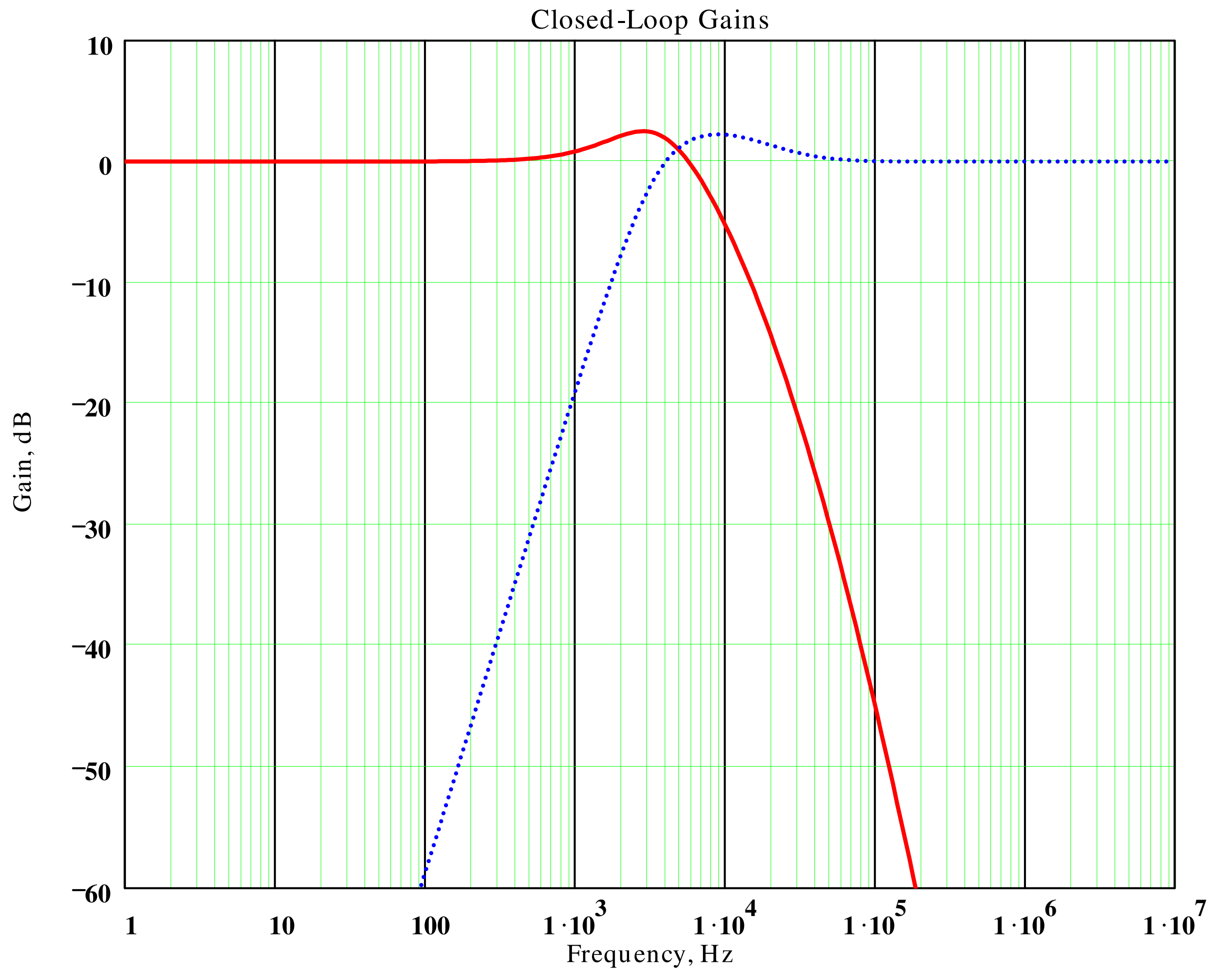


$$T1f_{ii} := \frac{G_{ii}}{1 + G_{ii}} \qquad T1dBf_{ii} := 10\cdot\log\left[\left(\left|T1f_{ii}\right|\right)^2\right]$$

$$T2f_{ii} := \frac{1}{1 + G_{ii}} \qquad T2dBf_{ii} := 10\cdot\log\left[\left(\left|T2f_{ii}\right|\right)^2\right]$$

Closed-Loop Transfer Functions

Closed-Loop Gain Functions for Stability Investigation



Predict Phase Noise Performance of PLL

External Reference Phase Noise (SSD200 10 MHz Std)

$kt := 0 .. 5$

$$F_{xo} := \begin{pmatrix} 10 \\ 100 \\ 1000 \\ 10000 \\ 10^5 \\ 10^6 \end{pmatrix} \qquad L_{xo} := \begin{pmatrix} -117 \\ -126 \\ -143 \\ -148 \\ -150 \\ -150 \end{pmatrix} \qquad FL_{xo_{kt}} := \log\left(F_{xo_{kt}}\right)$$

$F_{tcxo} := 10 \cdot 10^{6}$

$k := 1.38 \cdot 10^{-23}$ Boltzman

$T := 290$ Temperature

$L_{tcxo}(f) := \text{linterp}\left(F_{Lxo}, L_{xo}, \log(f)\right)$

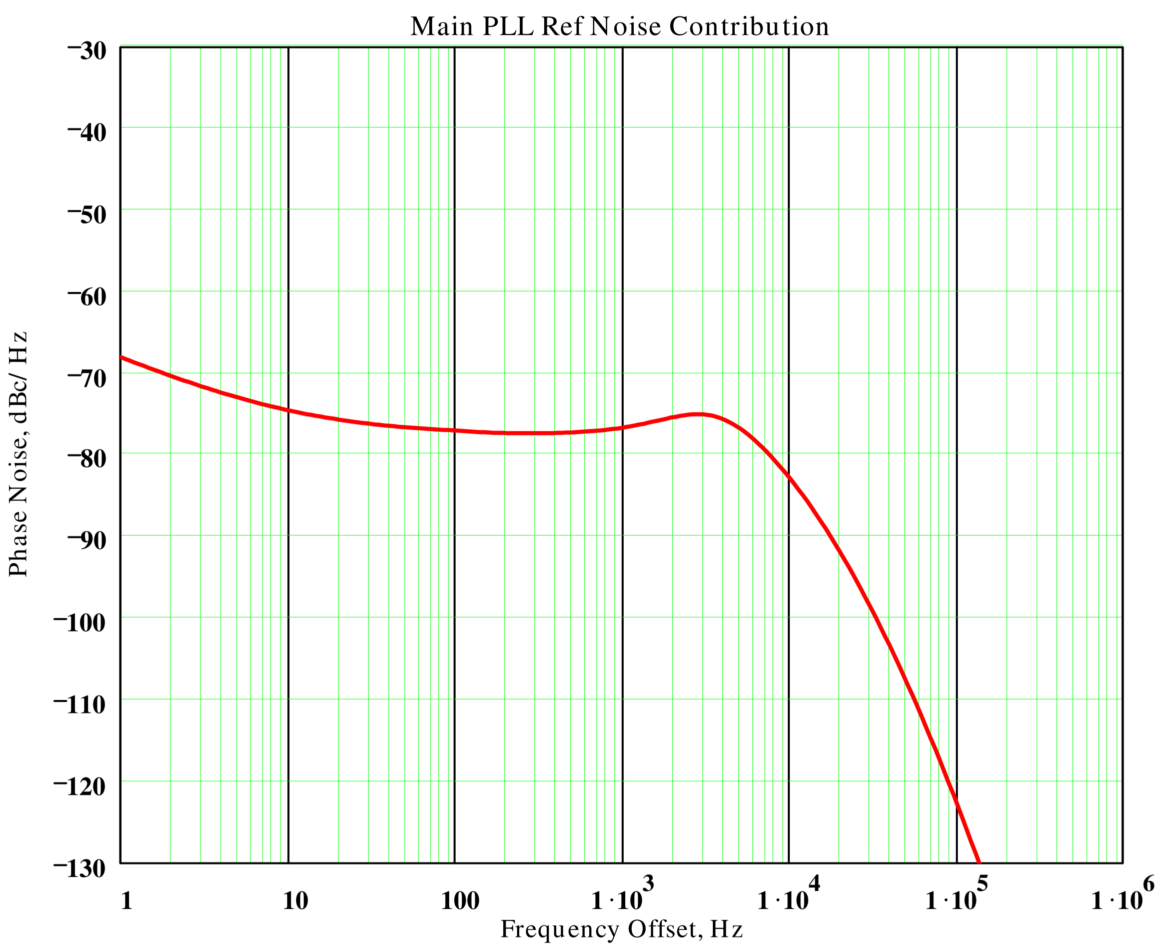
$$L_{ref_{ii}} := L_{tcxo}\left(fw_{ii}\right) - 20 \cdot \log\left(\frac{F_{tcxo}}{F_{ref}}\right) + 20 \cdot \log\left(N_{nom}\right)$$

$$L_{ref_{ii}} := 10 \cdot \log\left(10^{0.1 \cdot L_{pdx}} + 10^{0.1 \cdot L_{ref_{ii}}}\right)$$ Add noise from Phase Detector floor and Reference TCXO

$$P_{1dB_{ii}} := L_{ref_{ii}} + T_{1dBf_{ii}}$$

$$P_{1f_{ii}} := 10^{0.1 \cdot P_{1dB_{ii}}}$$

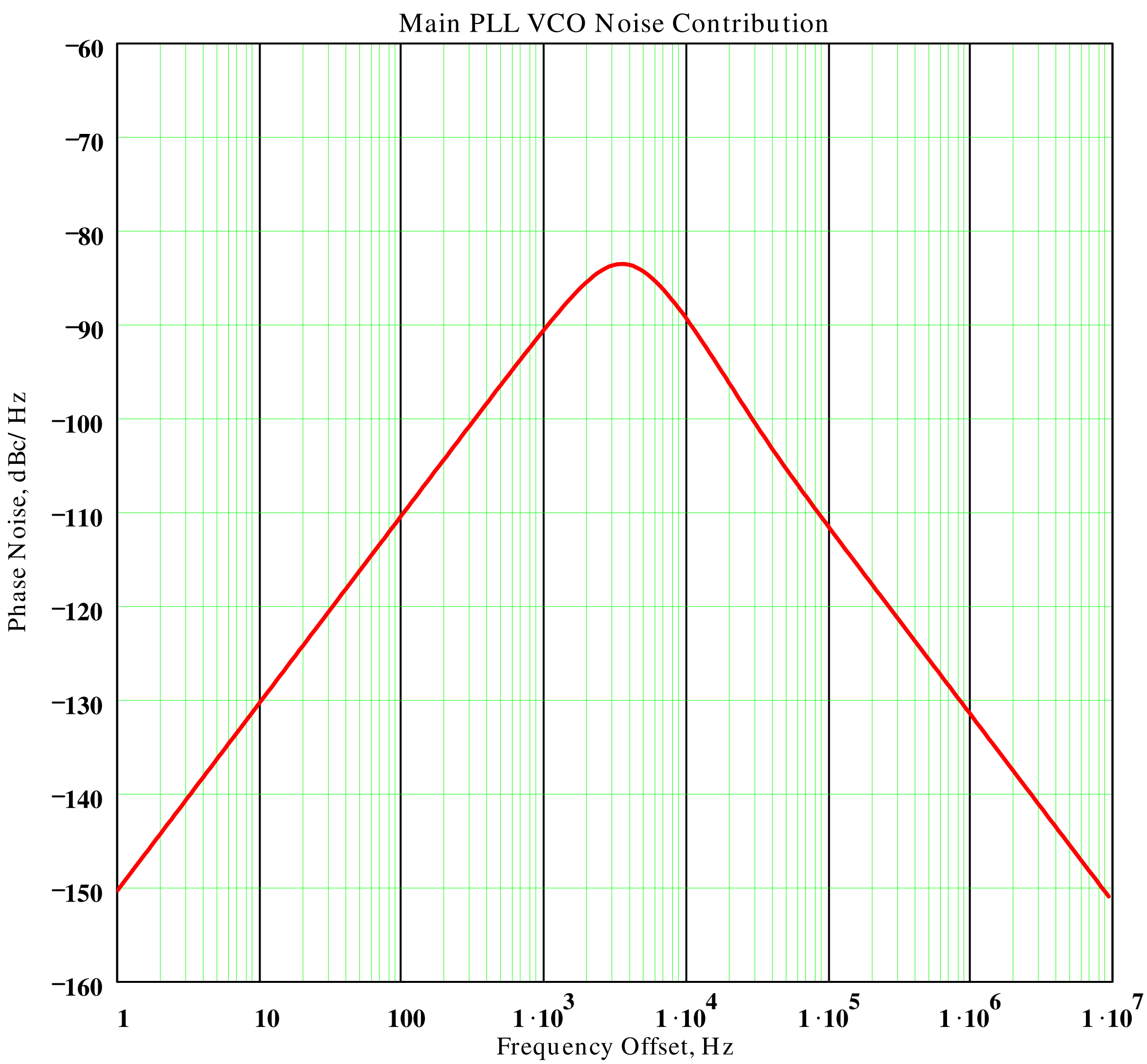
Plot of Phase Noise Spectrum Due to Reference Noise at PLL Output



$$P_{2dBf_{ii}} := L_{vco}\left(fw_{ii}\right) + T_{2dBf_{ii}}$$

$$P_{2f_{ii}} := 10^{0.1 \cdot P_{2dBf_{ii}}}$$

Phase Noise Contribution from VCO Self-Noise to PLL Output Spectrum



Compute Phase Noise Arising from R1 in PLL

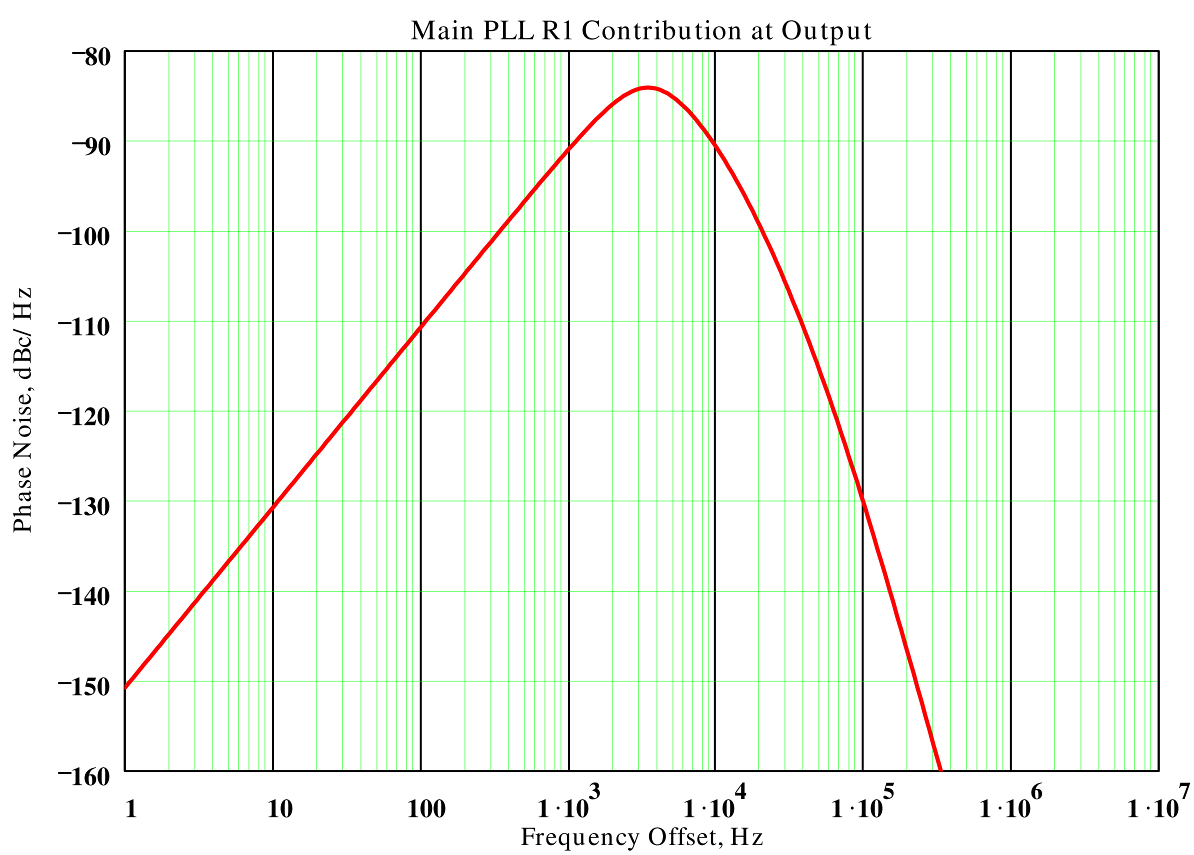
$$Y_1(s) := \frac{1}{R_2 + \frac{1}{s \cdot C_2}} \qquad Z_a(s) := \frac{1}{Y_1(s) + s \cdot C_3} \qquad Z_b(s) := R_1 + \frac{1}{s \cdot C_1}$$

$$pn_{ii} := \sqrt{4 \cdot k \cdot T \cdot R_1} \cdot \frac{Z_a(jx \cdot 2 \cdot \pi \cdot fw_{ii})}{Z_a(jx \cdot 2 \cdot \pi \cdot fw_{ii}) + Z_b(jx \cdot 2 \cdot \pi \cdot fw_{ii})} \cdot \frac{1}{1 + jx \cdot 2 \cdot \pi \cdot fw_{ii} \cdot R_2 \cdot C_2} \cdot \frac{K_v}{jx \cdot 2 \cdot \pi \cdot fw_{ii}} \cdot \frac{1}{G_{ii}} \cdot \frac{1}{\sqrt{2}}$$

$$P3dBf_{ii} := 10 \cdot \log\left[\left(\left|pn_{ii}\right|\right)^2\right] + T1dBf_{ii} \qquad P3f_{ii} := 10^{0.1 \cdot P3dBf_{ii}}$$

$$R_1 = 377.996 \qquad R_2 = 8 \times 10^3 \qquad \frac{K_v}{2 \cdot \pi} = 1.5 \times 10^8$$

Phase Noise Contribution at PLL Output Due to R1



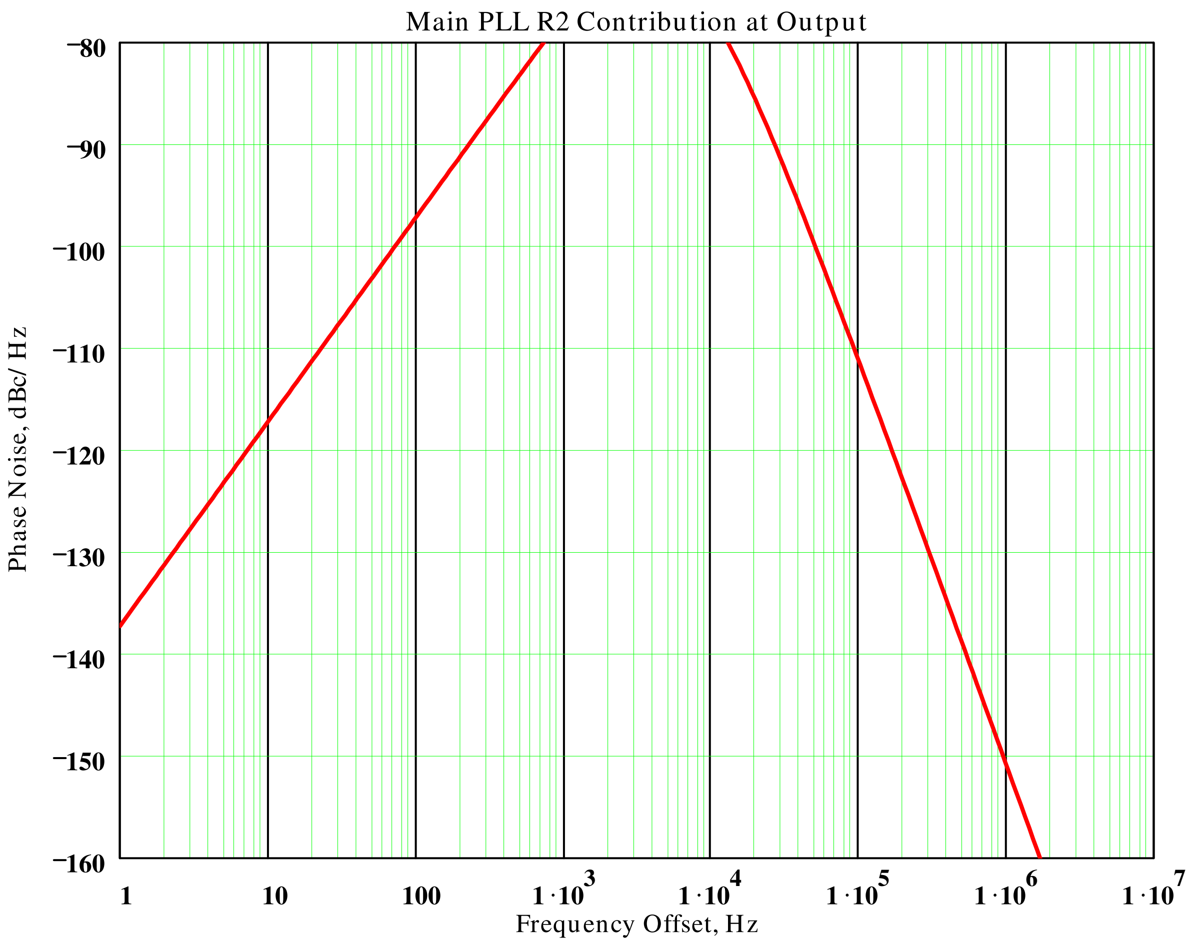
Compute Phase Noise Arising from R2 in Loop Filter

$$Z_x(s) := \left(\frac{1}{R_1 + \frac{1}{s \cdot C_1}} + s \cdot C_3 \right)^{-1}$$

$$pn2_{ii} := \sqrt{4 \cdot k \cdot T \cdot R_2} \cdot \frac{\left(jx \cdot 2 \cdot \pi \cdot fw_{ii} \cdot C_2 \right)^{-1}}{\left(jx \cdot 2 \cdot \pi \cdot fw_{ii} \cdot C_2 \right)^{-1} + R_2 + Z_x\left(jx \cdot 2 \cdot \pi \cdot fw_{ii} \right)} \cdot \frac{K_v}{jx \cdot 2 \cdot \pi \cdot fw_{ii}} \cdot \frac{1}{G_{ii}} \cdot \frac{1}{\sqrt{2}}$$

$$P_{4dBf_{ii}} := 10 \cdot \log\left[\left(\left| pn2_{ii} \right| \right)^2 \right] + T_{1dBf_{ii}} \qquad P_{4f_{ii}} := 10^{0.1 \cdot P_{4dBf_{ii}}}$$

Phase Noise Contribution at PLL Output Due to R2



$$PSDx_{ii} := \mathbf{10} \cdot \log\left(P1_{f_{ii}} + P2_{f_{ii}} + P3_{f_{ii}} + P4_{f_{ii}}\right)$$

$\text{linterp}(fw, PSDx, \mathbf{500}) = \mathbf{-76.221}$

$\text{linterp}(fw, PSDx, \mathbf{1000}) = \mathbf{-73.883}$

$\text{linterp}(fw, PSDx, \mathbf{2000}) = \mathbf{-70.388}$

$\text{linterp}(fw, PSDx, \mathbf{3000}) = \mathbf{-69.057}$

$\text{linterp}(fw, PSDx, \mathbf{4000}) = \mathbf{-69.168}$

$\text{linterp}(fw, PSDx, \mathbf{5000}) = \mathbf{-69.991}$

$\text{linterp}(fw, PSDx, \mathbf{7000}) = \mathbf{-72.256}$

$\text{linterp}(fw, PSDx, \mathbf{10000}) = \mathbf{-75.622}$

$\text{linterp}(fw, PSDx, \mathbf{15000}) = \mathbf{-80.347}$

$\text{linterp}(fw, PSDx, \mathbf{18750}) = \mathbf{-83.3}$

$\text{linterp}(fw, PSDx, \mathbf{20000}) = \mathbf{-84.195}$

$\text{linterp}(fw, PSDx, \mathbf{31250}) = \mathbf{-90.756}$

$\text{linterp}(fw, PSDx, \mathbf{43500}) = \mathbf{-95.85}$

$\text{linterp}(fw, PSDx, \mathbf{50000}) = \mathbf{-97.999}$

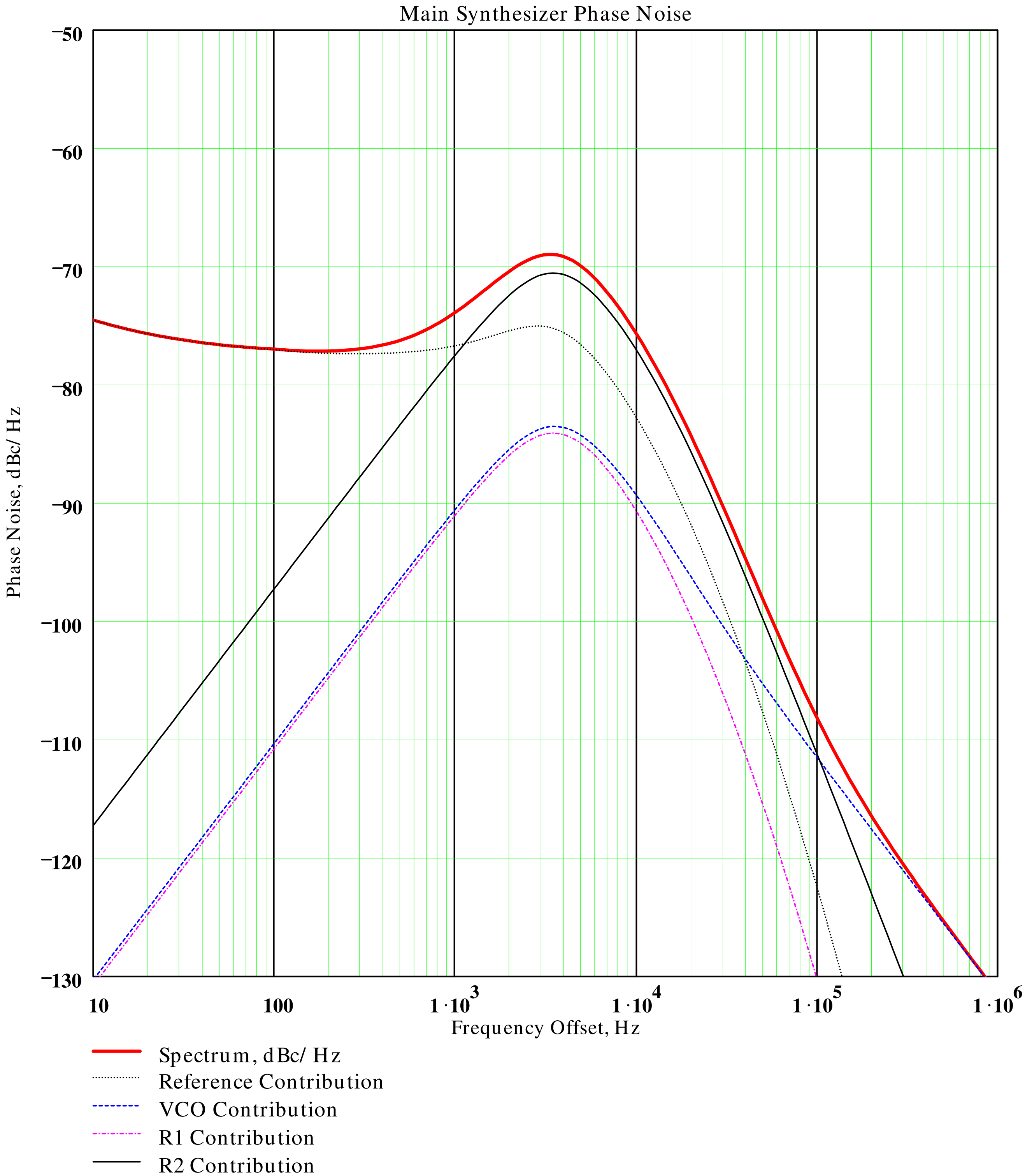
$\text{linterp}(fw, PSDx, \mathbf{75000}) = \mathbf{-104.094}$

$\text{linterp}(fw, PSDx, \mathbf{100000}) = \mathbf{-108.102}$

$\text{linterp}(fw, PSDx, \mathbf{200000}) = \mathbf{-116.397}$

$\text{linterp}(fw, PSDx, \mathbf{1000000}) = \mathbf{-131.45}$

Composite Phase Noise Output Spectrum for Output



$ku := 0..200$

$Fx_{ku} := 1 \cdot 10^{6 \cdot \frac{ku}{200}}$ $\quad S_{out_{ku}} := \text{linterp}\left(fw, PSDx, Fx_{ku}\right)$ $\quad LogFx_{ku} := \log\left(Fx_{ku}\right)$

Integrated Phase Noise Out to FH Offset:

$F_H := 312 \cdot 10^3$

$$PhaseNoise\left(F_L\right) := \left| \begin{array}{l} df \leftarrow \frac{\left(F_H - F_L\right)}{11} \\ N \leftarrow \frac{180}{\pi} \cdot \sqrt{2 \cdot \sum_{ix=0}^{10} \int_{F_L + ix \cdot df}^{F_L + (ix+1) \cdot df} 10^{0.1 \cdot \text{linterp}\left(LogFx, S_{out}, \log(fx)\right)} dfx} \end{array} \right.$$

$PhaseNoise(5000) = 1.668$ degrees rms

Phase Change Over Time

$$PhaseAccumulation(\tau) := \left| \begin{array}{l} df \leftarrow \frac{2000 \cdot 10^3}{11} \\ N \leftarrow \frac{180}{\pi} \cdot \sqrt{8 \cdot \sum_{ix=0}^{10} \int_{\frac{1}{2 \cdot \tau} + ix \cdot df}^{\frac{1}{2 \cdot \tau} + (ix+1) \cdot df} 10^{0.1 \cdot \text{linterp}\left(LogFx, S_{out}, \log(fx)\right)} \cdot \sin(\pi \cdot fx \cdot \tau)^2 \, dfx} \end{array} \right.$$

$PhaseAccumulation\left(3.2 \cdot 10^{-6} \cdot 3\right) = 0.237$ degrees rms

$Dat_{ku,1} := S_{out_{ku}}$ $\quad Dat_{ku,0} := Fx_{ku}$

Residual FM

$$\text{ResidualFM}\left(F_L, F_H\right) := \left| \begin{array}{l} df \leftarrow \dfrac{\left(F_H - F_L\right)}{11} \\ N \leftarrow \sqrt{2 \cdot \displaystyle\sum_{ix=0}^{10} \int_{F_L + ix \cdot df}^{F_L + (ix+1) \cdot df} fx^2 \cdot 10^{0.1 \cdot \text{linterp}\left(\text{LogFx}, S_{out}, \log(fx)\right)} \, dfx} \end{array} \right.$$

$\text{ResidualFM}(100, 100000) = 387.024$ Hertz rms

Basic Type-II PLL Parameters

Phase error at phase detector (radians) output due to a frequency step change

$$\theta_{pd}(t,\omega_n,\zeta,F_{step}) := \frac{2\cdot\pi\cdot F_{step}}{\omega_n}\cdot\frac{e^{-\zeta\cdot\omega_n\cdot t}}{\sqrt{\left|1-\zeta^2\right|}}\cdot \text{if}\left(\zeta \ge 1, \sinh\left(\omega_n\cdot\sqrt{\zeta^2-1}\cdot t\right), \sin\left(\omega_n\cdot\sqrt{1-\zeta^2}\cdot t\right)\right)$$

Peak phase error for a frequency-step input occurs for

$$T_{fstep}(\omega_n,\zeta) := \frac{1}{\omega_n\cdot\sqrt{1-\zeta^2}}\cdot \text{atan2}\left(\zeta,\sqrt{1-\zeta^2}\right)$$

3 dB Closed-Loop Bandwidth, Hz

$$BW_{3dBClosed}(\omega_n,\zeta) := \frac{\omega_n}{2\cdot\pi}\cdot\sqrt{1+2\cdot\zeta^2+2\cdot\sqrt{\zeta^4+\zeta^2+0.5}}$$

0 dB Open-Loop Band Bandwidth, Hz

$$BW_{0dBOpen}(\omega_n,\zeta) := \frac{\omega_n}{2\cdot\pi}\cdot\sqrt{2\cdot\zeta^2+\sqrt{4\cdot\zeta^4+1}}$$

System Phase Margin

$$PhaseMargin(\omega_n,\zeta) := \text{atan}\left(2\cdot\frac{BW_{0dBOpen}(\omega_n,\zeta)\cdot 2\cdot\pi}{\omega_n}\right)$$

Peak Frequency Overshoot with Frequency Step Input

$$\omega_{error}(t,\omega_n,\zeta,\Delta F) := 2\cdot\pi\cdot\Delta F\cdot e^{-\zeta\cdot\omega_n\cdot t}\cdot\left(\cos\left(\sqrt{1-\zeta^2}\cdot\omega_n\cdot t\right)-\frac{\zeta}{\sqrt{1-\zeta^2}}\cdot\sin\left(\sqrt{1-\zeta^2}\cdot\omega_n\cdot t\right)\right)$$