The Science and Practice of Phase Noise Measurement

Dennis G. Sweeney
WA4LPR

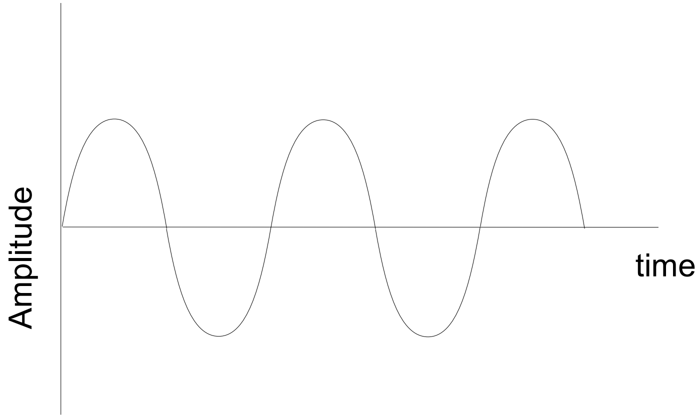
Presented for Microwave Update 2011

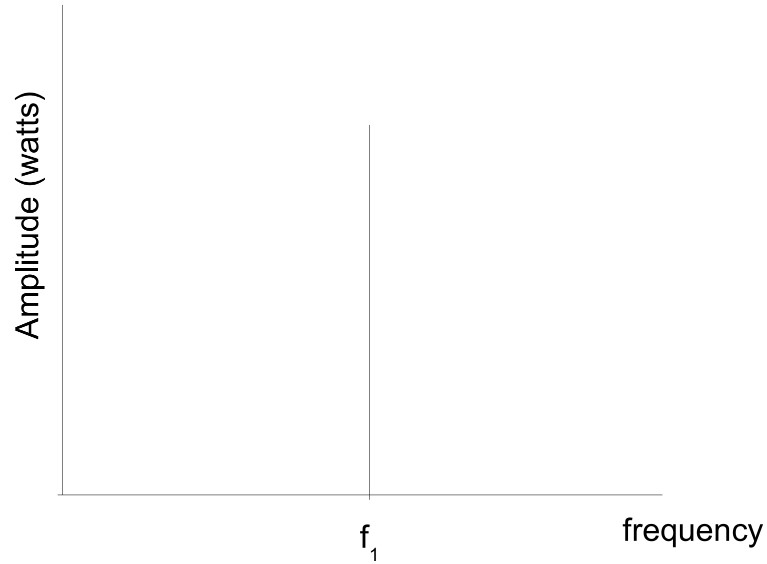
dsweeney@vt.edu

Overview

- **What is "Phase Noise"?**
  - Effects of phase noise
- **Direct Spectrum Analyser Measurement**
  - Spectrum analyser PN utility and the joys of GPIB
- **Phase Lock Quadrature System**
  - Analysis of phase detector measurement
- **Design of Phase Noise Measurement System**
  - Components and Gotcha's
- **Measurement Technique and Examples**
- **PLL Design**
- **Additional Work**

Ideal Signals

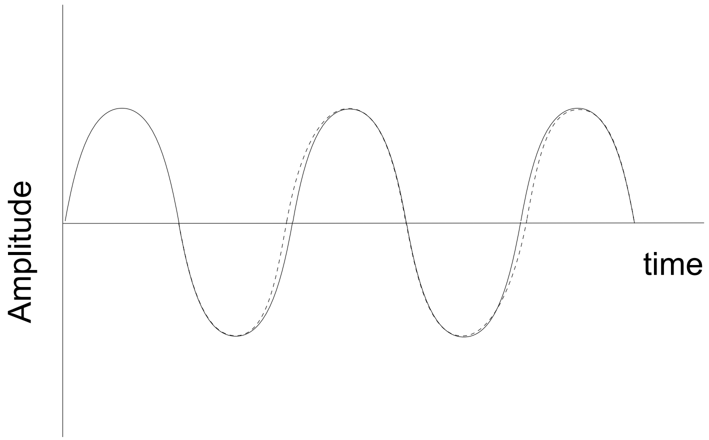


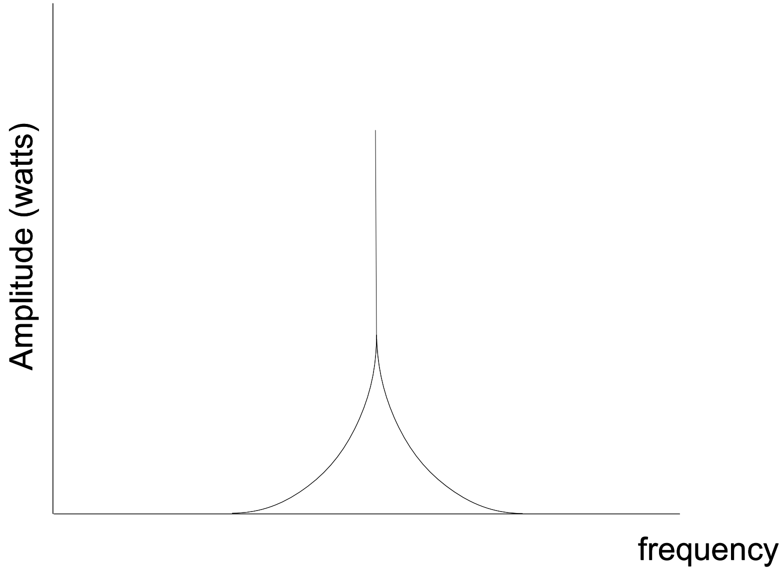


Time Domain

Frequency Domain

Signals with Phase Noise

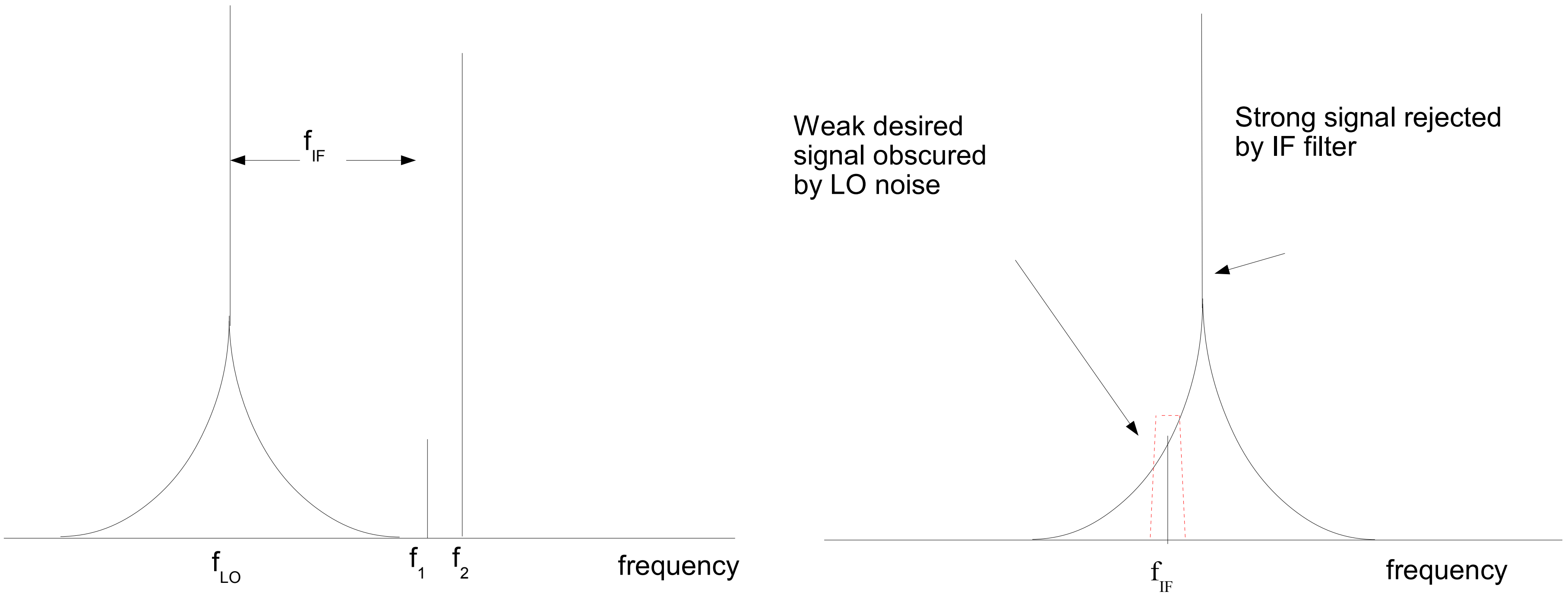




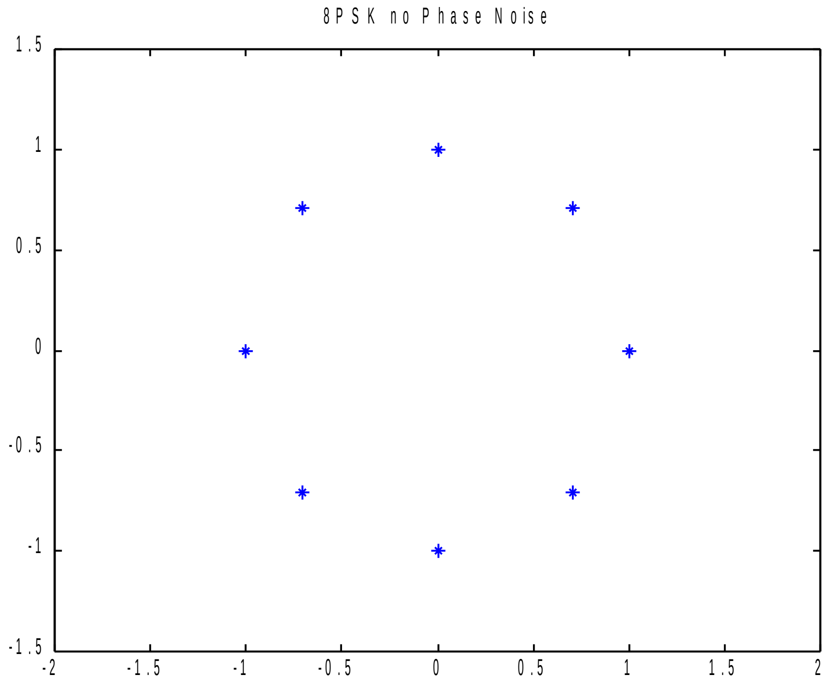
Time Domain

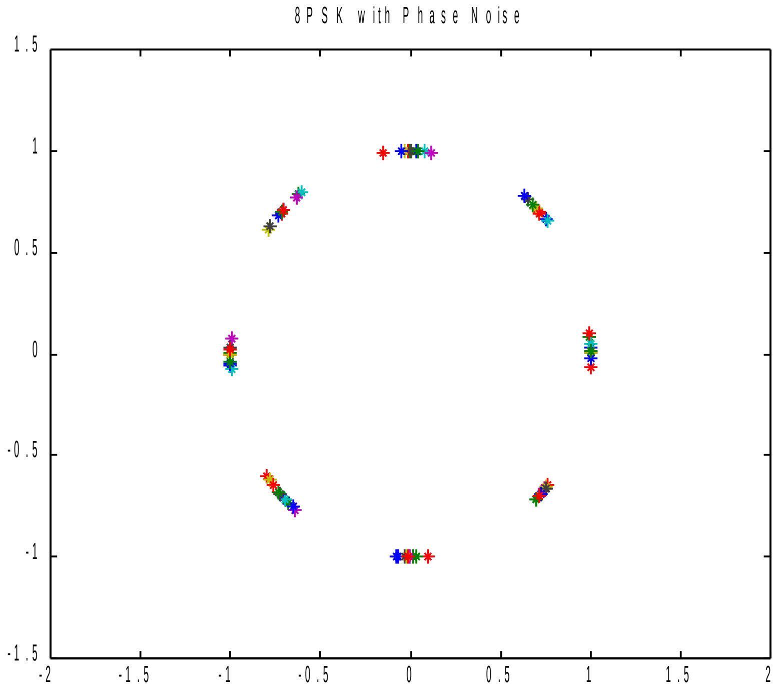
Frequency Domain

Effect of Phase Noise on Receiver Dynamic Range



Effect of Phase Noise on Digital Modulation



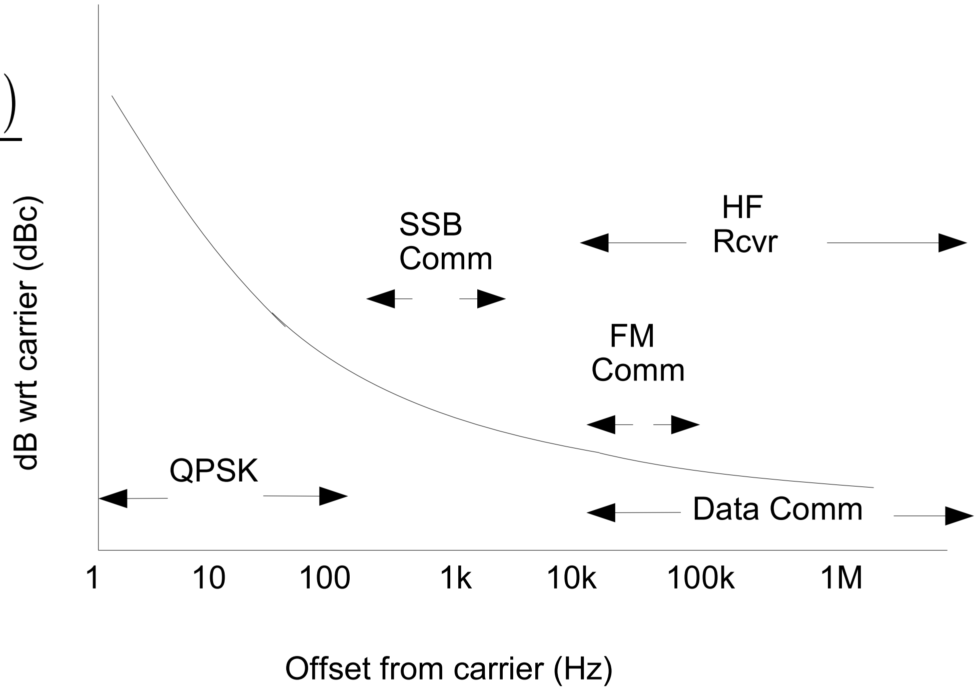


Phase Noise Spectrum

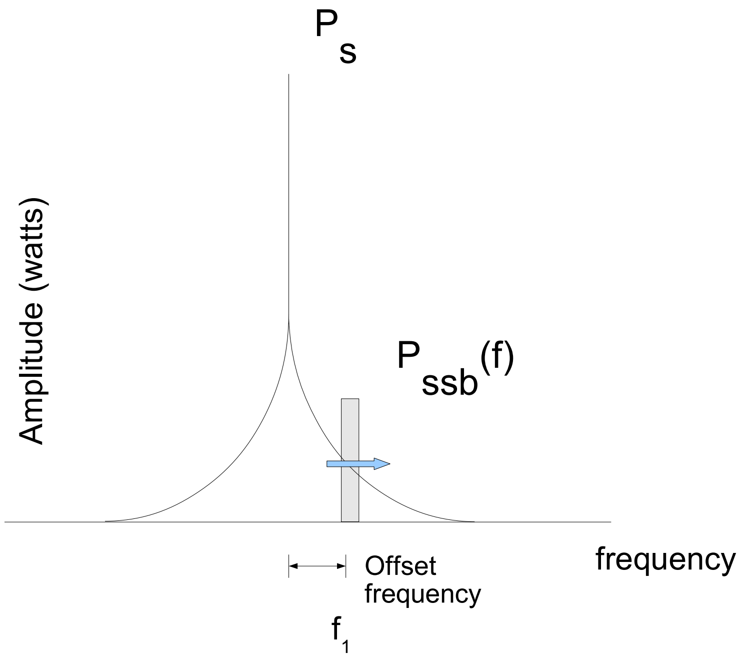
- **Phase Noise specified as a SSB level wrt to carrier (dBc)**

$$L(f) = \frac{Power\ Density(One\ sideband)}{Carrier\ power}$$

- **Graph shows typical spectrum and areas of interest**
  - Spectrum shape can be predicted from noise processes and oscillator circuit (beyond the scope of this presentation)



Direct Measurement

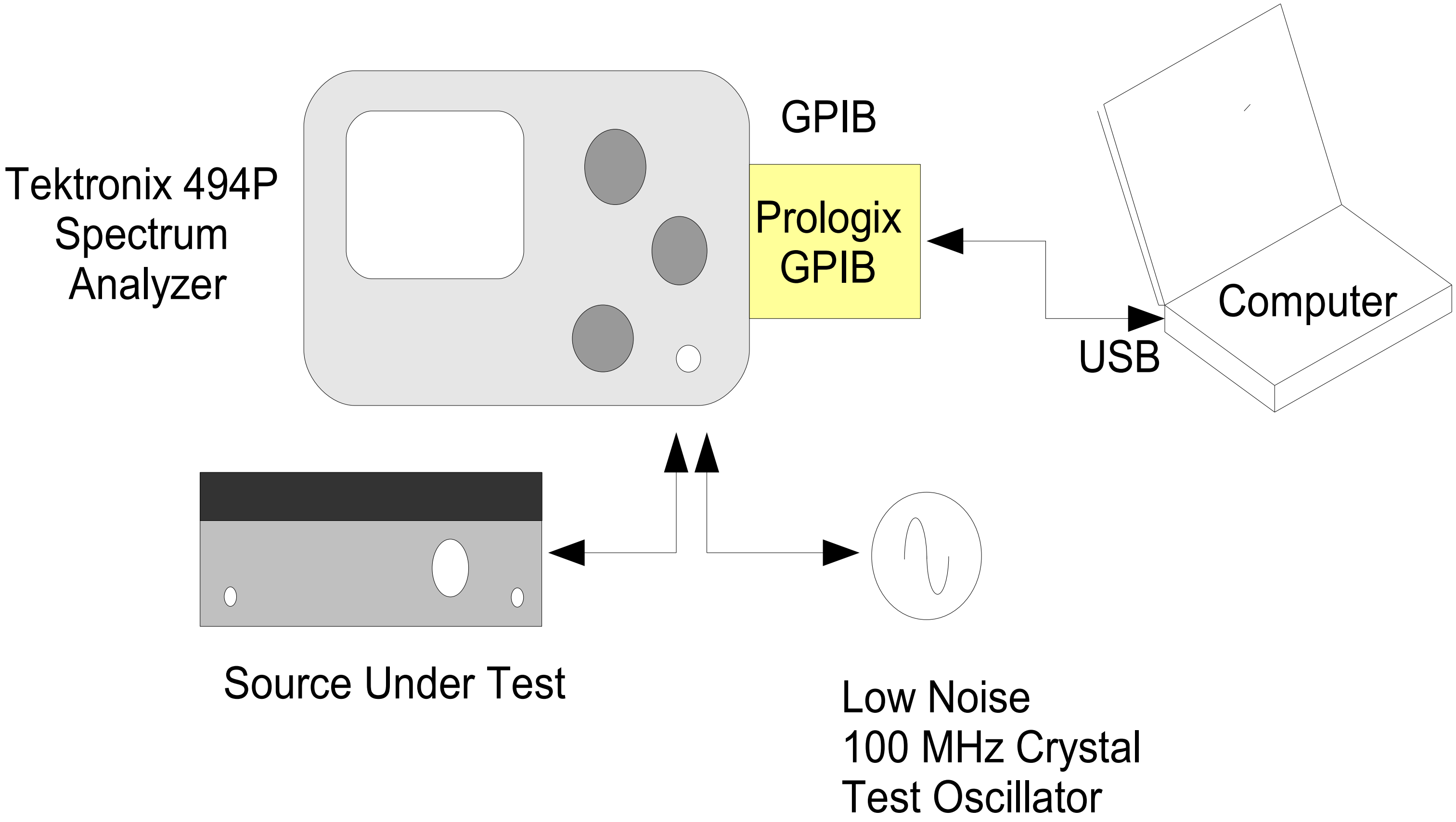


- Measure signal power P_s
- Measure sideband pwr $P_{ssb}(f)$
- Corrections
  - Bandwidth
  - Log amp w/ peak detect (+2.5 dB)
- Calculate:

$$L(f)=\frac{P_{ssb}(f)}{P_s BW} \quad \text{dBc}$$

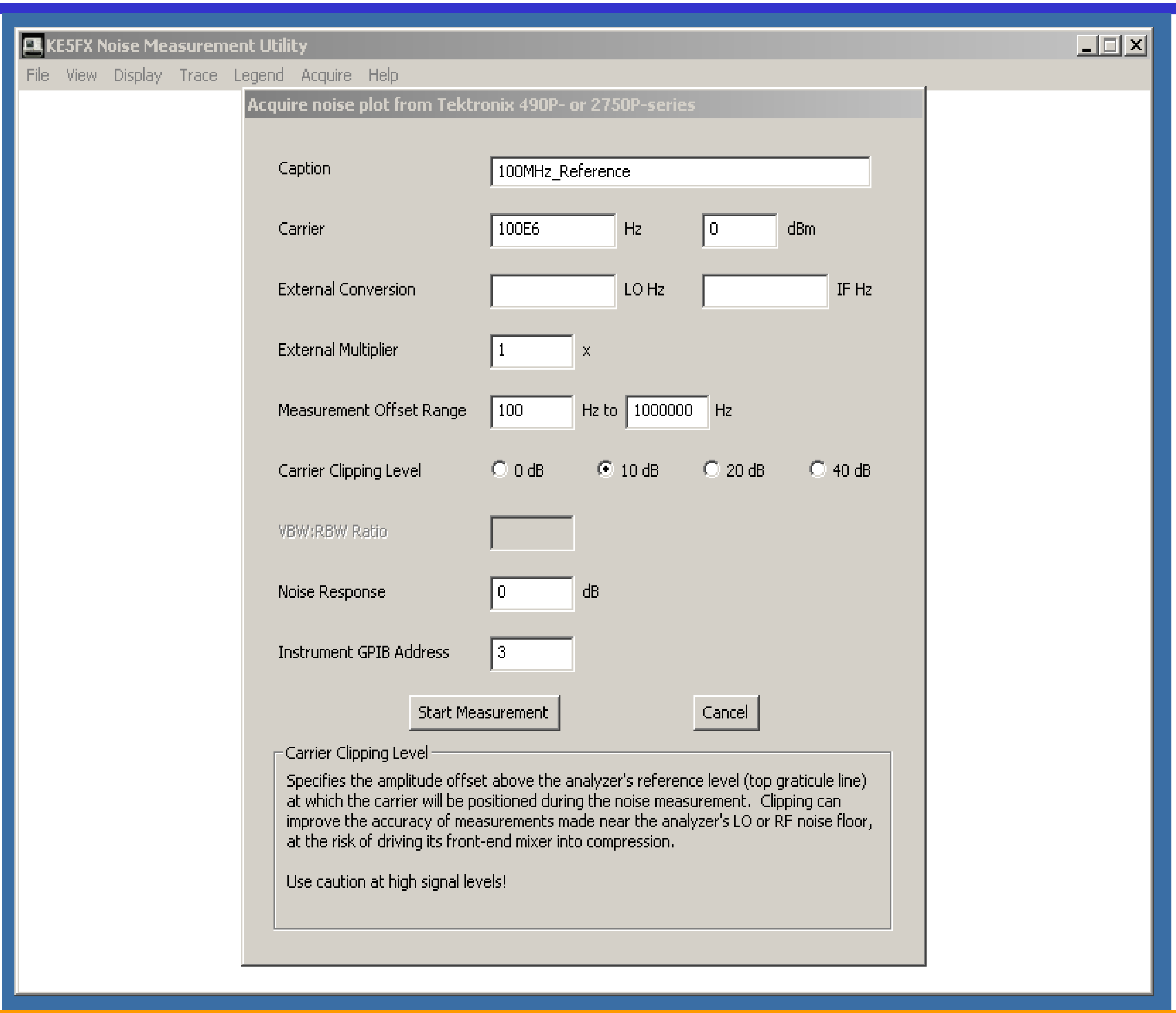
- Software automates measurement
  - John Miles' PN utility
  - www.thegleam.com/ke5fx/

Direct Phase Noise Measurement

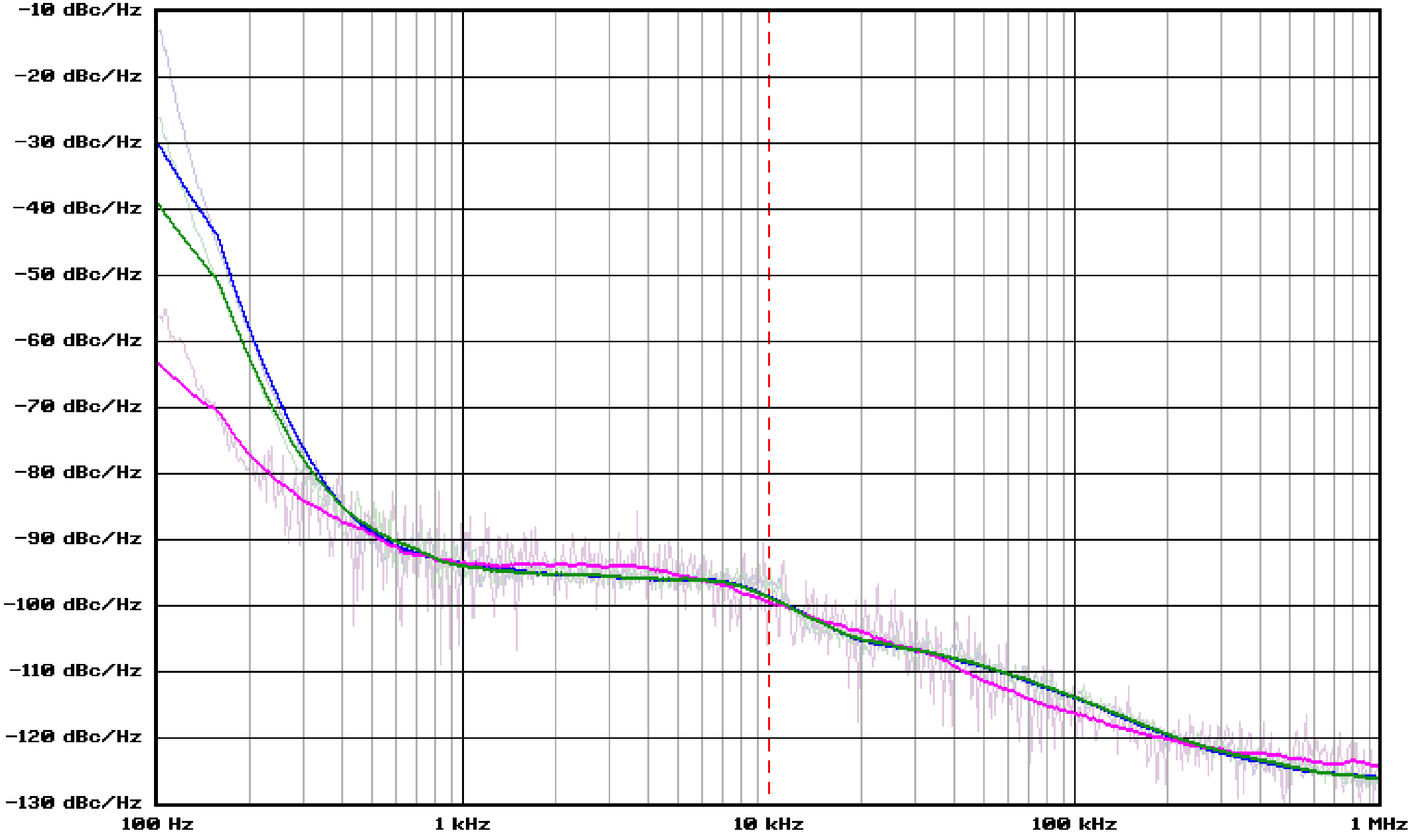


Spectrum Analyzer Set up

KE5FX PN Utility

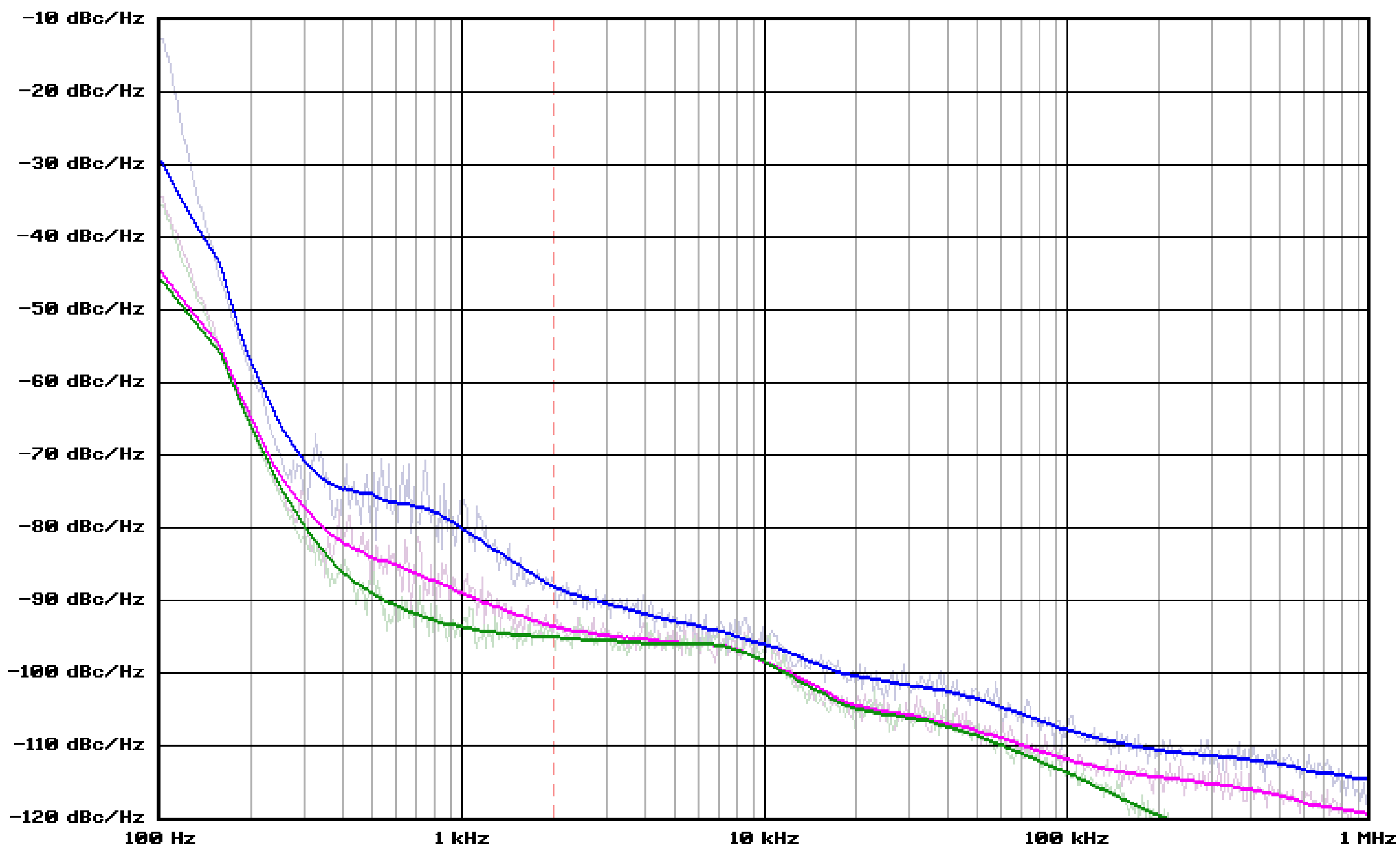


Noise Floor Measurement



Trace	Carrier Hz	Carrier dBm	dBc/Hz at 10000 Hz	RF Atten dB	Clip dB	Instrument
100MHz_Reference	100 000 000	4.00	-98.5	N/A	10	TEK 494P
Tektronix 494P PN floor	100 000 000	-22.00	-99.4	N/A		TEK 494P
100MHz_Fluke_6080	100 000 000	4.00	-98.6	N/A	10	TEK 494P

HP 8660 Phase Noise



Trace	Carrier Hz	Carrier dBm	dBc/Hz at 2000 Hz	Clip dB	Instrument
HP_8660_1500MHz	1 500 000 000	4.00	-88.1	10	TEK 494P
HP_8660_100MHz	100 000 000	4.00	-93.5	10	TEK 494P
Fluke_6080_100MHz	100 000 000	4.00	-94.9	10	TEK 494P

Limitations of Direct Method

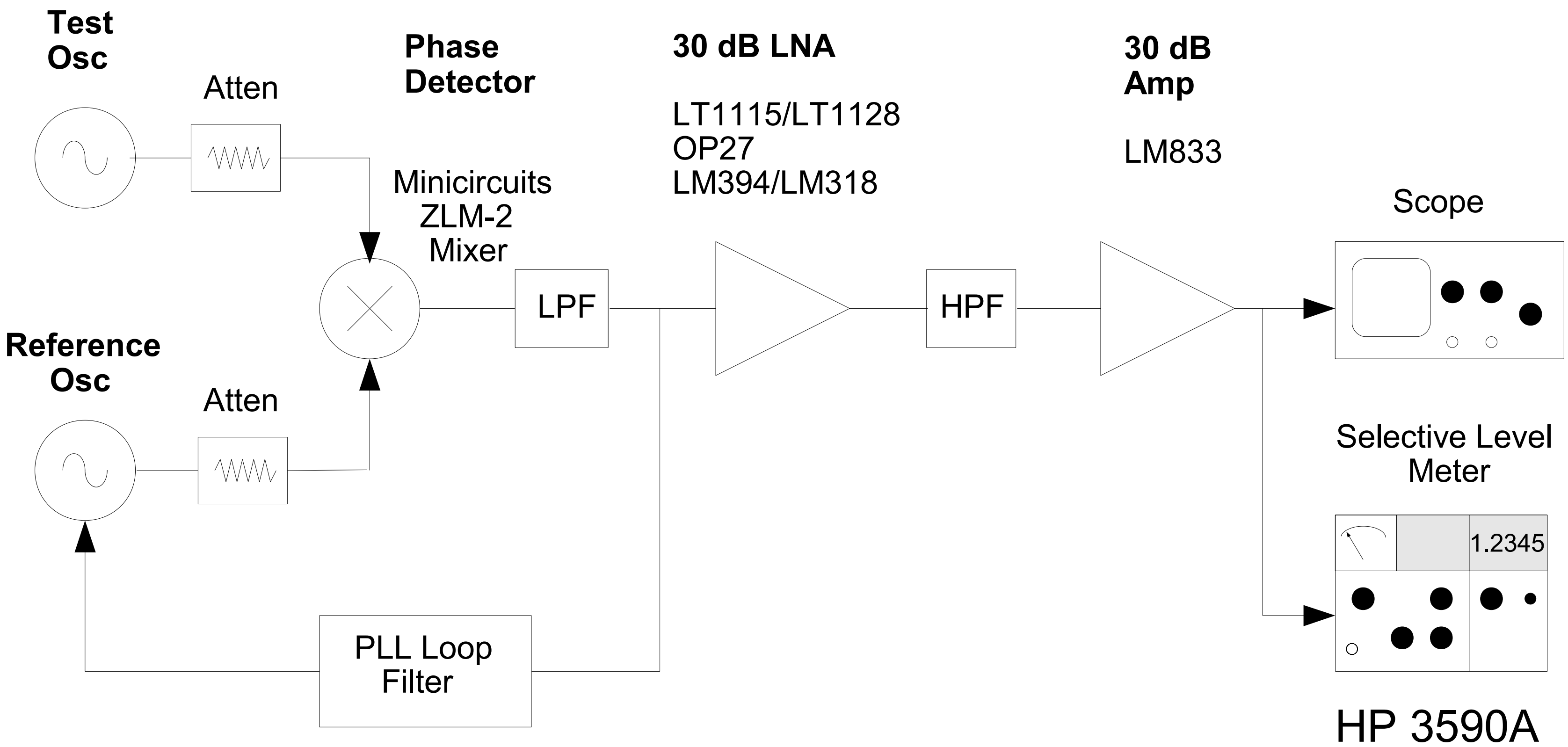
- Direct method easy and intuitive
- However:
  - Limited by spectrum analyzer (SA) dynamic rage
  - Most SA's are noisy
  - Noise floor rises by 20log(n),
    - n is mixing harmonic number
- OK for relatively noisy oscillators

- Phase detector method
  - More complex hardware and measurement technique
  - Much higher performance
  - A PLL and a wideband direct conversion receiver

Indirect PLL and Phase Detector

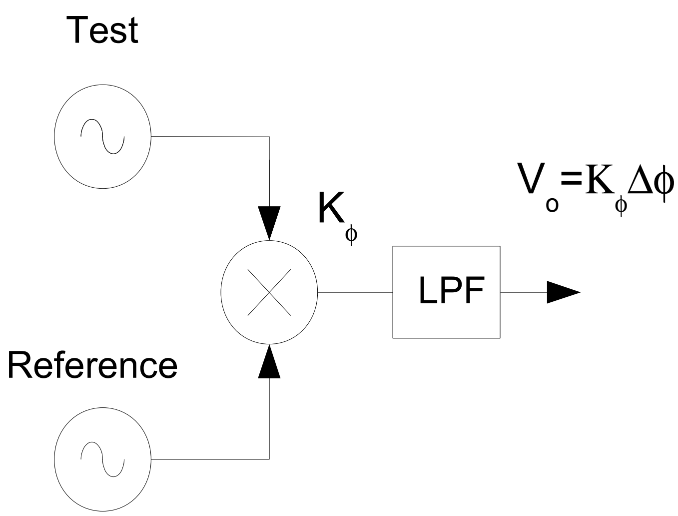
- Phase detector method
  - More complex hardware and measurement technique
  - Much higher performance
- A PLL and a wideband direct conversion receiver

PLL Based Phase Noise Measurement System



HP3590A Selective Level Meter

What Comes Out?



$$V_1 = V_{test} \cos(\omega t + \phi_1)$$

$$V_2 = V_{ref} \sin(\omega t + \phi_2)$$

$$V_o = K[V_{test} \cos(\omega t + \phi_1)][V_{ref} \sin(\omega t + \phi_2)]$$

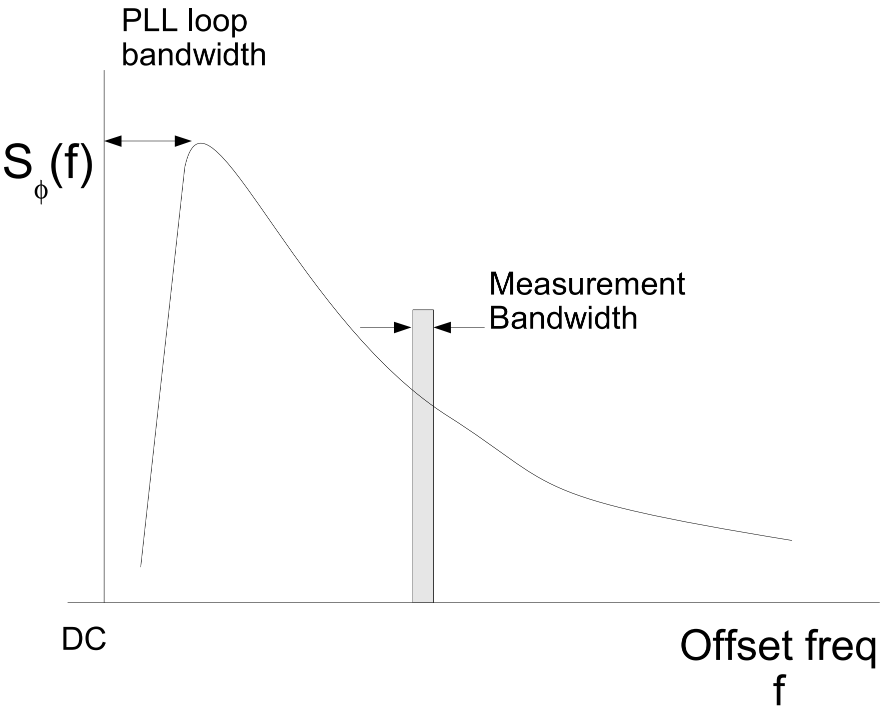
$$= K_\phi[\sin(\phi_1 - \phi_2) + \sin(2\omega t + \phi_1 + \phi_2)]$$

- PLL holds the two signals in phase quadrature

$$\boxed{V_o = K_\phi \sin(\Delta\phi) \approx \underset{\Delta_\phi \ll 1\, rad}{K_\phi \Delta\phi}}$$

- Drives $\Delta\phi$ phase error to zero inside loop bandwidth

Still isn't L(f)



$$V_{o\,rms}(f) = K_\phi \Delta\phi_{rms}(f)$$

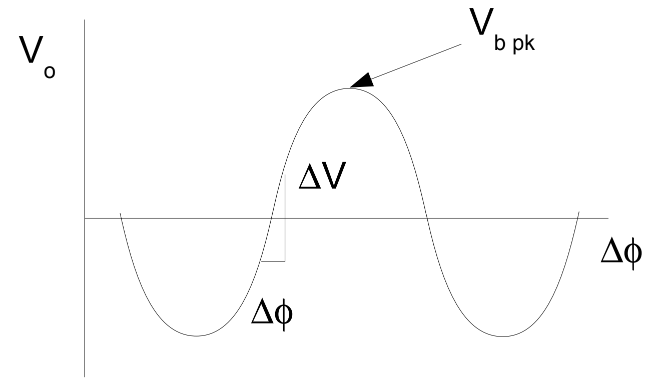
$$S_\phi(f) = \frac{\Delta\phi^2_{rms}(f)}{BW} = \frac{V^2_{o\,rms}(f)}{K^2_\phi BW} \qquad \left[\frac{rad^2}{Hz}\right]$$

$$L(f) = \frac{P_{ssb}(f)}{P_{carrier}} = \frac{S_\phi(f)}{2} \qquad \Delta\phi \ll 1\,rad$$

$$\boxed{L(f) = \frac{V^2_{o\,rms}(f)}{2K^2_\phi BW}}$$

Calibrating K_ϕ

- Offset Reference and Test Oscillators
  - Measure it directly with scope



$$K_\phi = \frac{\Delta V}{\Delta \phi}$$

  - Assume output is sinusoidal and calculate slope

$$K_\phi = \frac{dV_o}{d\Delta\phi} = \frac{d(V_{b\,pk}\sin(\Delta\phi))}{d\Delta\phi} = V_{b\,pk}\cos(\Delta\phi) = V_{b\,pk}\Big|_{\Delta\phi=0}$$

- Apply phase mod, measure sideband power
  - Van der List, Jos F. M., PA0JOZ, *Experiments with Phase-Noise Measurement*, QEX, Issue No. 188, January/February 1999,pp. 31-41.

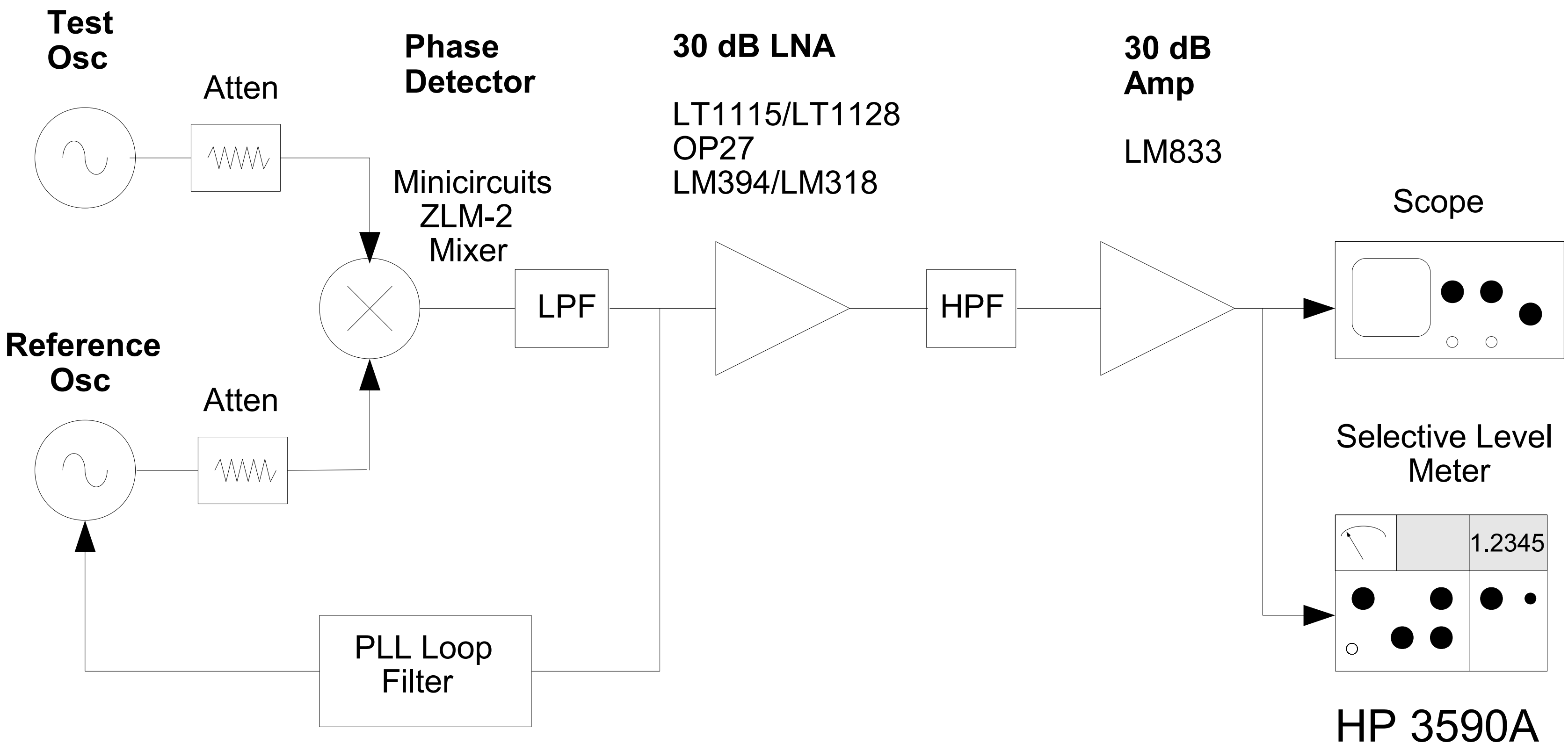
Measurement

$$L(f) = \frac{V_{orms}^2(f)}{2(K_\phi)^2 BW} = \frac{V_{orms}^2(f)}{2(\sqrt{2}V_{b\,rms})^2 BW}$$

$$\boxed{L(f) = 20\log\left(\frac{V_{o\,rms}(f)}{V_{b\,rms}}\right) - 10\log(BW) - 6 \pm Corrections}$$

- Corrections
  - Noise BW $-10\log\left(\frac{BW_n}{BW_{3\text{dB}}}\right)$
  - System Gain -60 dB
  - Log/Peak detector +2.5/+1.05 dB Log-peak / Peak-RMS
  - Contribution of test oscillator (-3 dB if oscillators are identical)

PLL Based Phase Noise Measurement System



Phase Detector

- Almost any mixer will work for the PD
  - Diode rings w/Shockley diodes are low noise
    - — *Choose high port isolation*
    - — *Run at high level*
    - — *Experiment with levels to insure linear operation*
    - — *Look at harmonic content of output*
    - — *Ports MUST be terminated to reduce intermods*
    - — *Well shielded connectorized parts desirable*

- Remember you are measuring nanovolt signals

Baseband Amplifier

- DC coupled, bandwidth 100 kHz, 60 dB
- LOW noise ($1\,\mathrm{nv}/\sqrt{(Hz)}$)
  - Phono preamp circuits (remember vinyl records?) are an excellent starting point
    - — *National AN222 LM394/LM318 (obsolete,very good)*
    - — *OP27 or LM833 (cheap, good)*
    - — *Linear Technology LT1128 (expensive, excellent)*
    - — *JFET circuit:* http://www.wenzel.com/documents/circuits.html
- Adjustable gain desirable
  - No change in operating load with change of gain
- Use low noise metal film resistors
- Shielded and battery powered
  - NiCads are a low noise power supply

Phase Locked Loop

- Simple second order PLL's OK
- Loop BW << than lowest offset frequency
  - Signal phase error driven to zero inside loop BW
- Set damping $\zeta > 1$
  - Reduces peaking around ωn
- Low noise
  - Minimize resistor ktB noise by minimizing values
  - Choose low current noise opamp
    - JFET input opamps have low current noise
    - LF353 good choice
- Add a way to sweep PLL output voltage to facilitate tuning

Spectrum Analyzers

- Selective Level Meters
  - *Calibrated tunable receiver*
  - *HP3590A (600 kHz), HP3581C (50 kHz),*
  - *HP3586A (32 MHz)*

- Low frequency spectrum analyzers
  - *HP3563A (100 kHz), HP3582A (25 kHz), HP3585A (40 MHz)*
- Dynamic Signal Analyzers (FFT based SA's)
  - *HP3561A (100 kHz)*
  - My HP3561A about $350 from eBay

Spectrum Analyzers

- Sound cards
  - eBay: UltroPro Real Time FFT Audio Spectrum Analyzer ($30)
  - Limited to 20 kHz, had difficulty calibrating
- SDR platforms

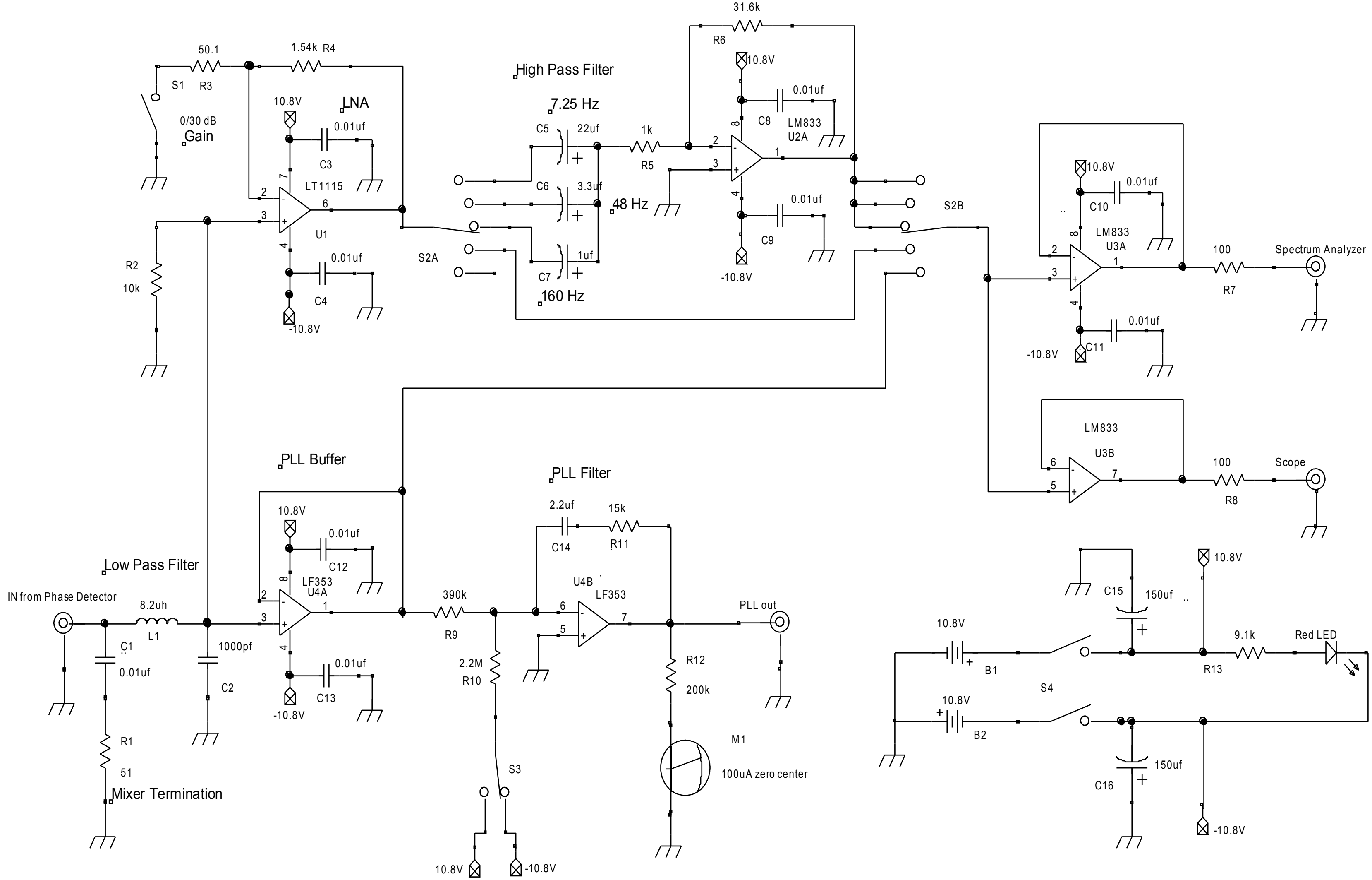
Frequency Stability Measurement: Technologies, Trends, and Tricks

Presented at Microwave Update 2010

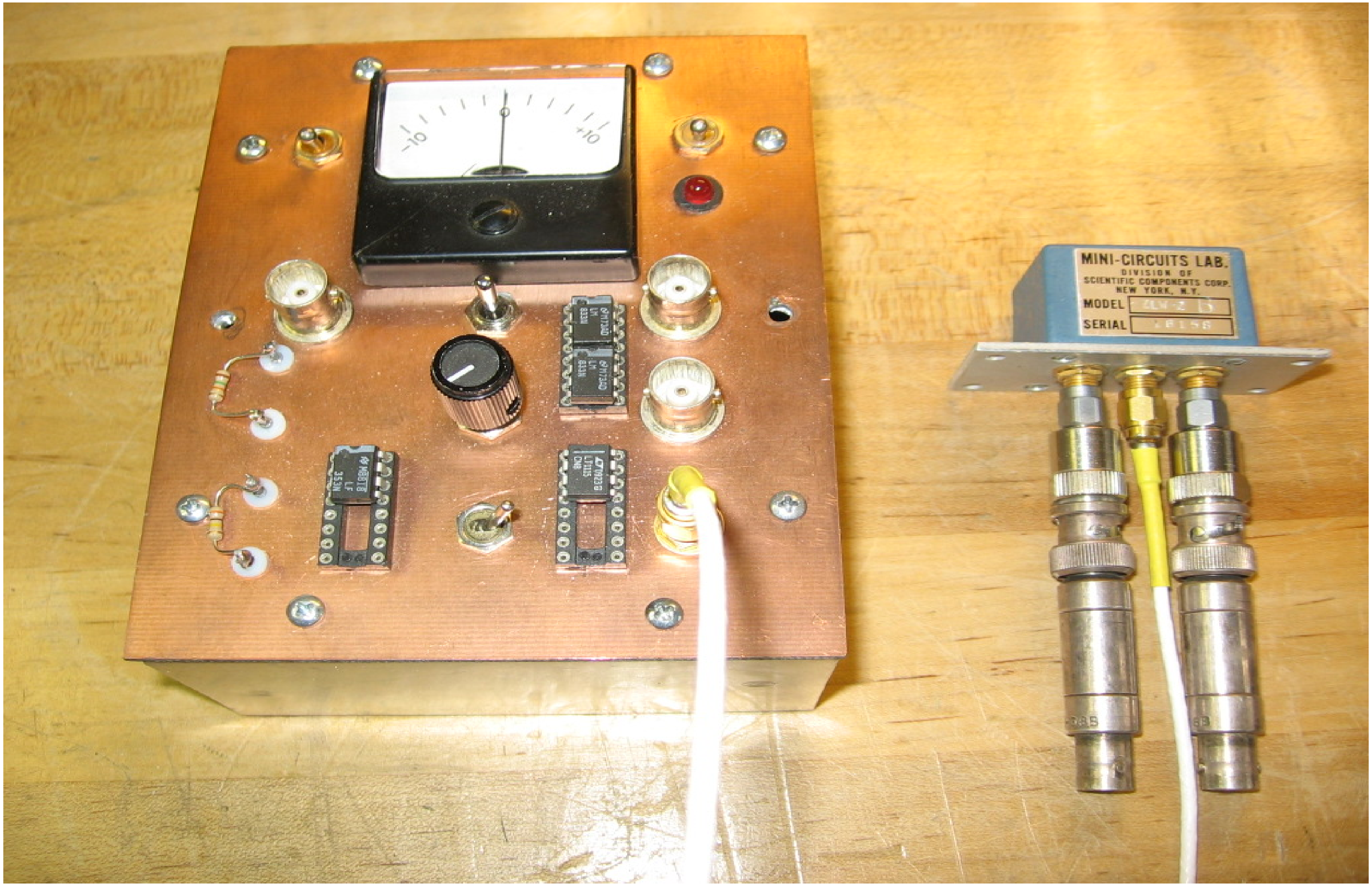
John Miles, KE5FX

- USB sampling scope
  - Velleman pcsgu250
  - Scope/FFT SA/function generator
  - About $200 on the street
- Analog Filter bank
  - QEX, January/February 1999.

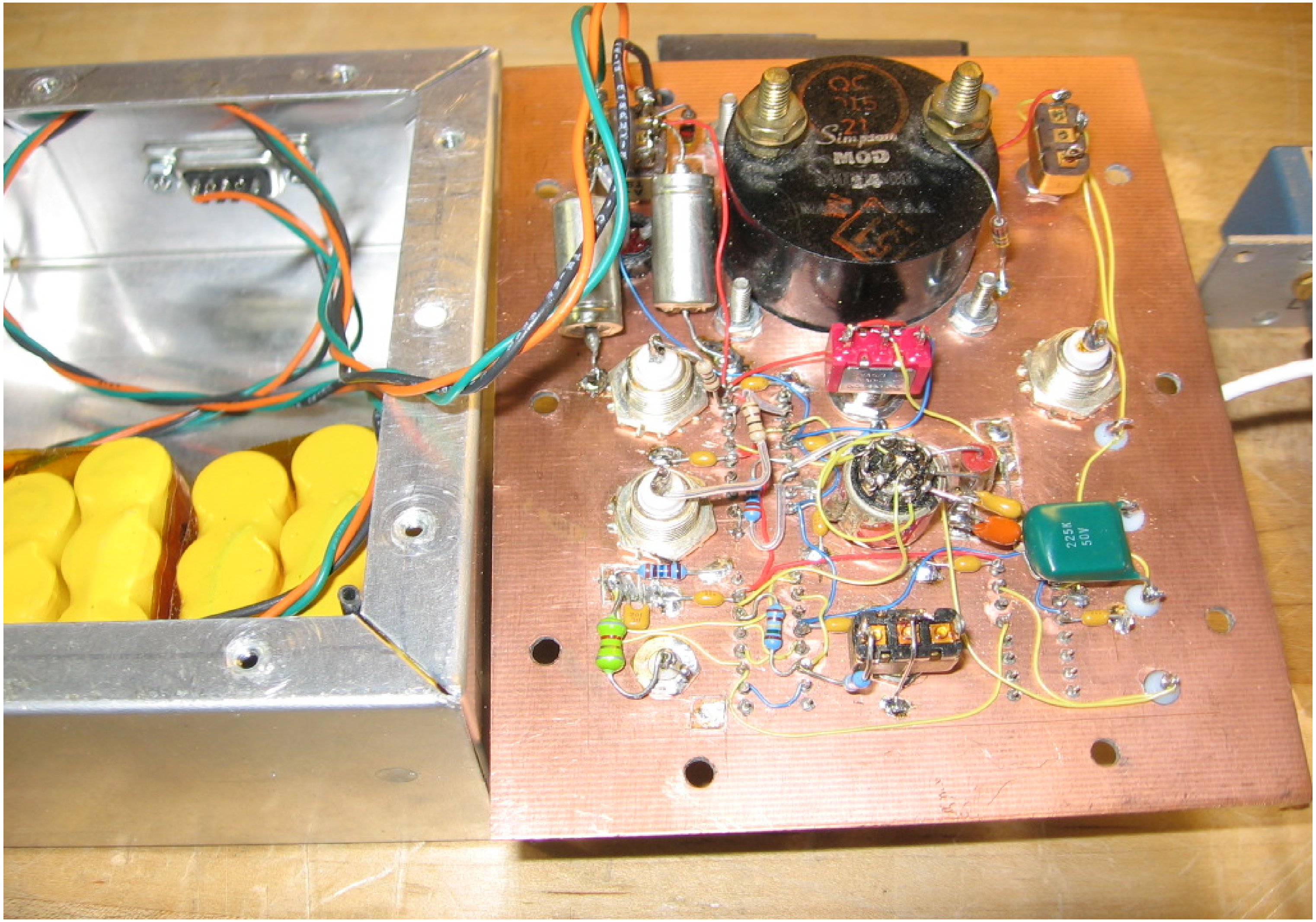
Phase Noise Box Schematic



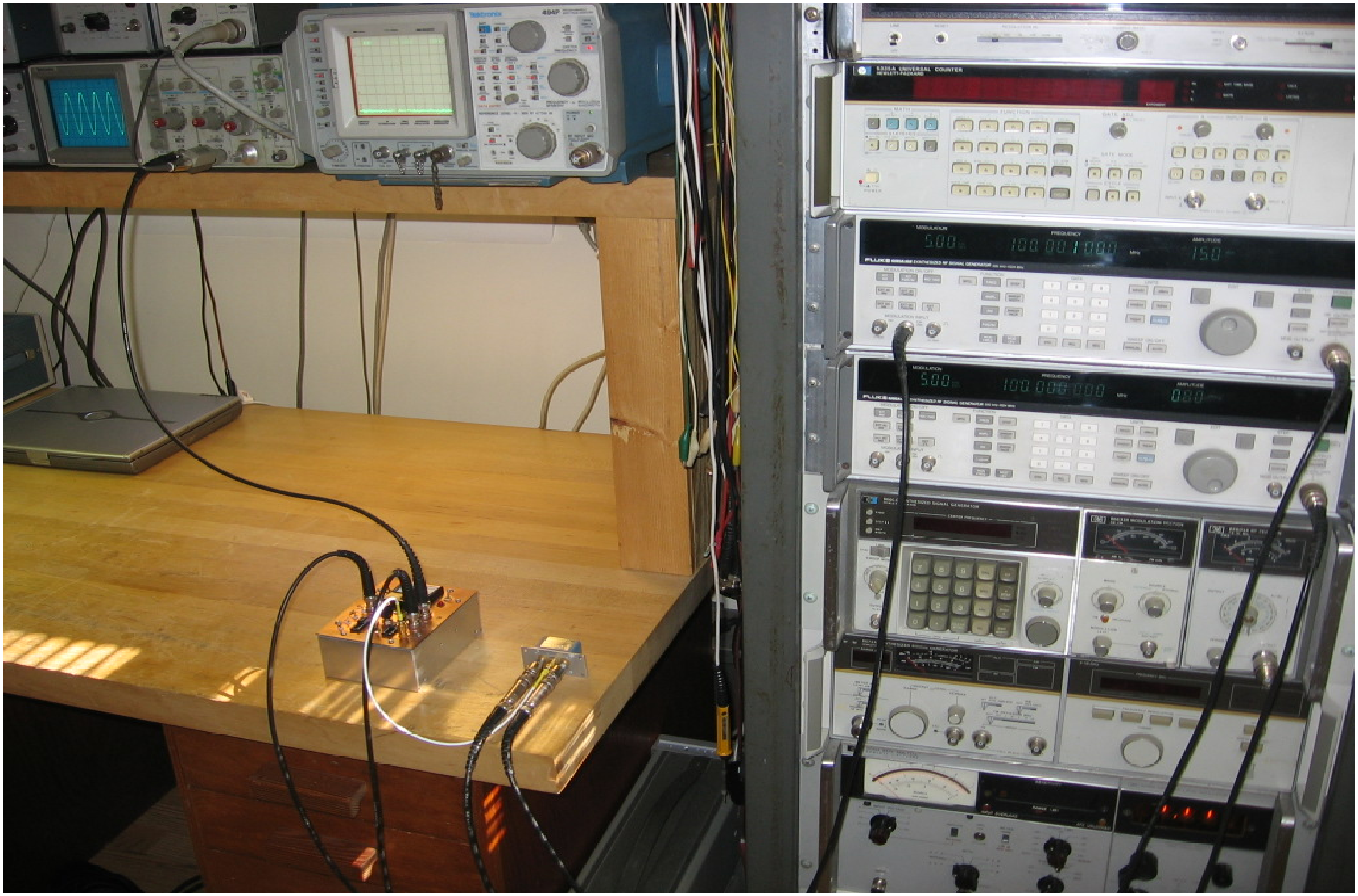
Phase Noise "Box"



Interior of Phase Noise Box



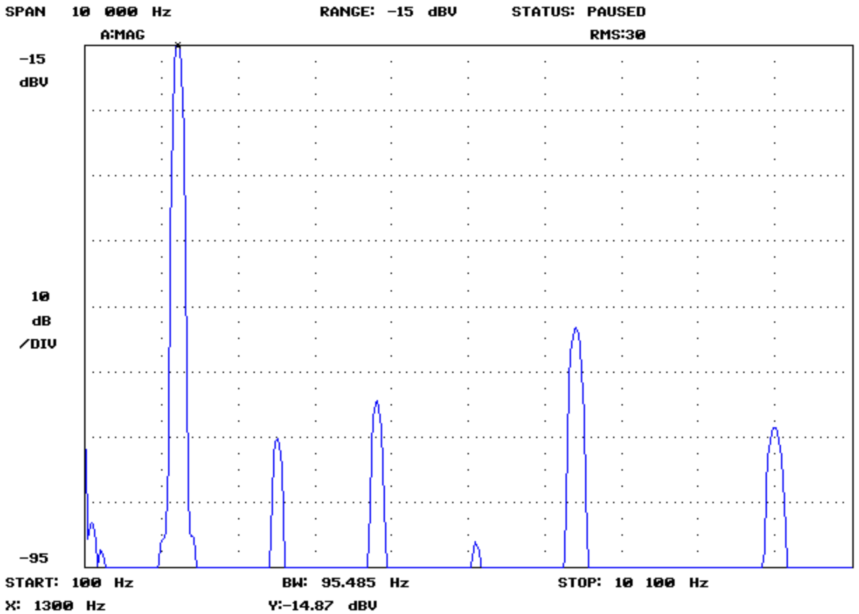
PLL Phase Noise Measurement

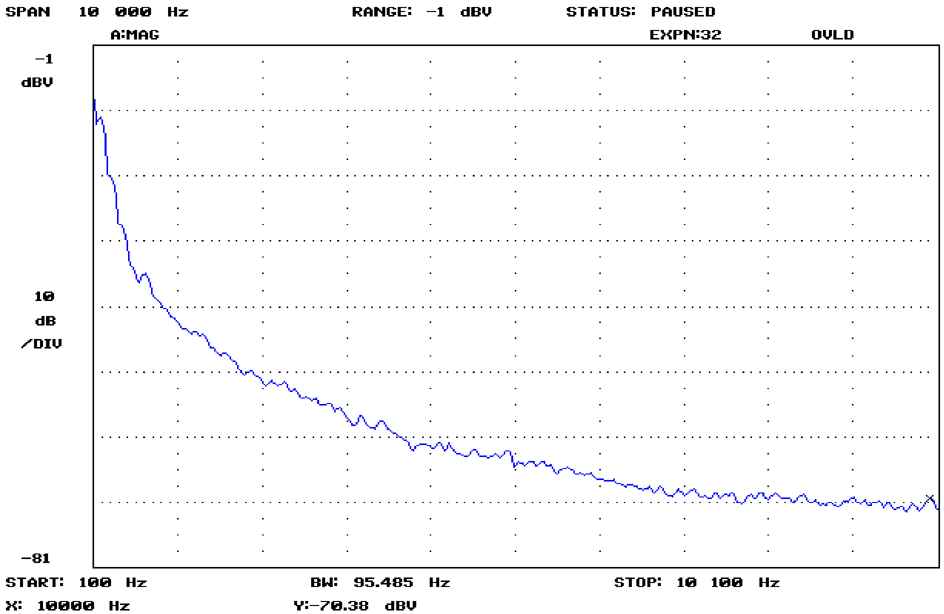


Measurement Technique

- Set gain to 0 dB
- Offset reference and test oscillator
  - Measure and record amplitude of beat note
  - Check for linear operation
  - If linear, measured peak voltage is $K\varphi$
    - — Note calculation set up to use rms voltage
- Phase lock reference and test oscillator
  - Choose 30 dB or 60 dB and desired high pass frequency
  - Measure and record noise voltage at desired offset frequency
  - Record measurement BW
- Calculate L(f)
  - Correct for measurement BW, system gain, and detector type

HP3156A Measurement





- Phase detector calibration
  - Marker: 1300 Hz -14.87 dBV
  - Worst case harmonic is over -40 dB
  - 0 dB gain, BW 95.485 hz
- Phase noise measure
  - Marker: 10,000 Hz -70.83 dBV
  - 32 averages
  - 60 dB of additional gain

Calculation

$$L(f) = 20\log\left(\frac{V_{o\,rms}(f)}{V_{b\,rms}}\right) - 10\log(BW) - 6 \pm Corrections$$

$$L(f) = -70.83\,dBV - (-14.87\,dBV) - 10\log(95.485\,Hz) - 6 - 60 - 3$$

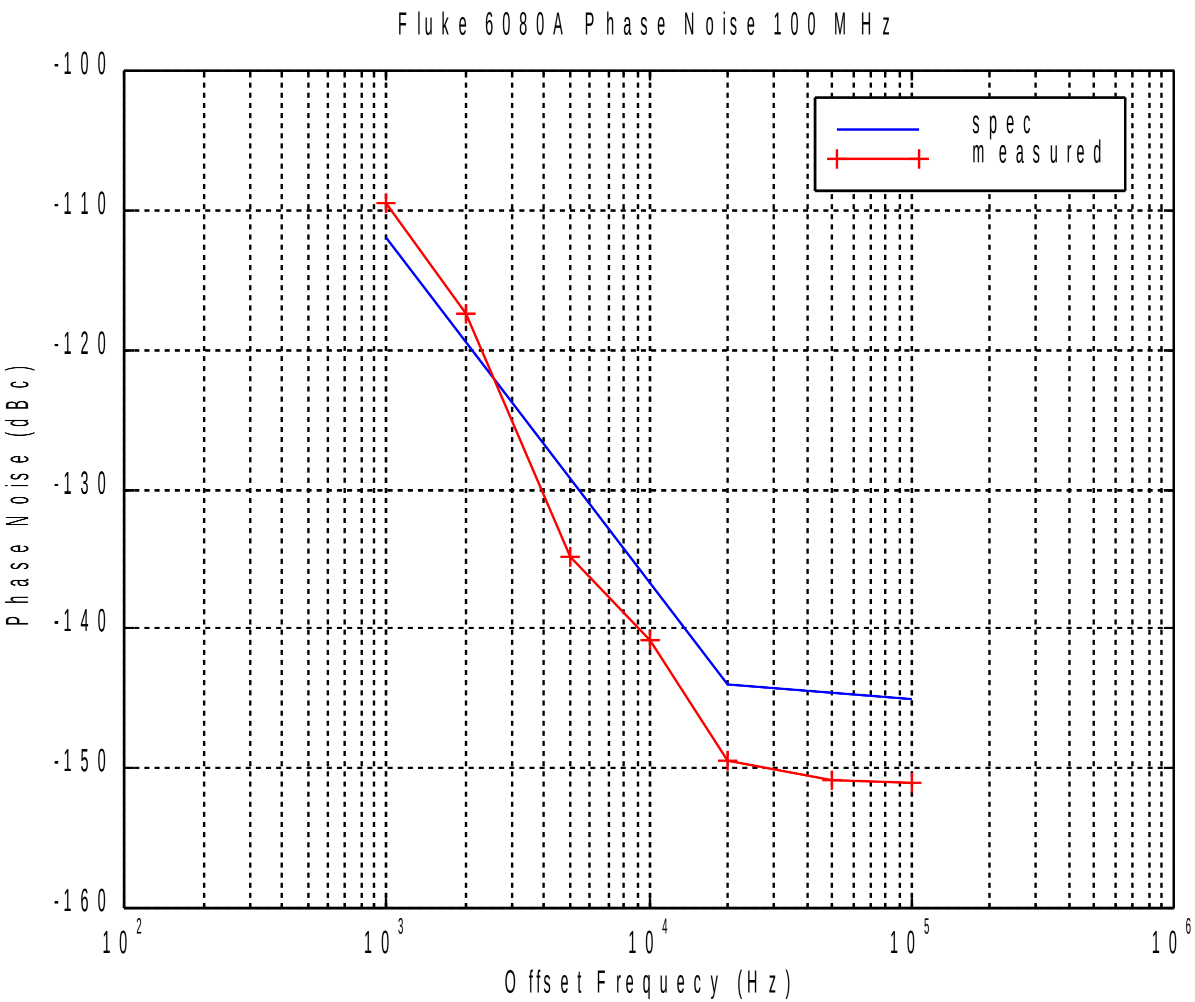
$$L(f) = -144.76\,dBc$$

- Corrections
  - -60 dB for the additional gain used during the noise measurement
  - -3 dB the test and reference oscillators identical
  - HP3561A does a RMS average, no detector correction needed
  - Averaging reduces uncertainty to ~0.5 dB

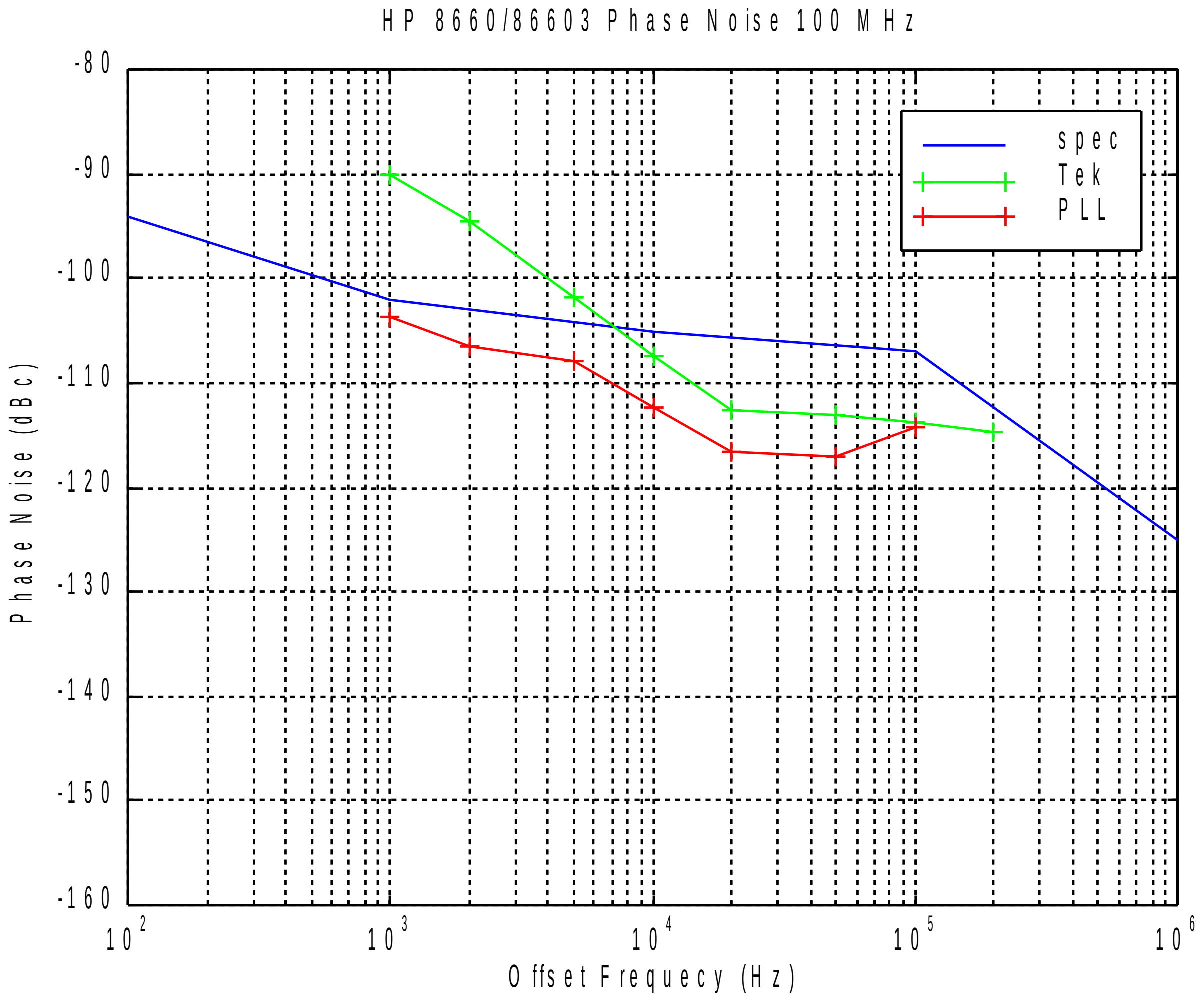
Vellemen pcsgu250

- Work in progress
  - Vellemen pcsgu250
    USB sampling oscilloscope/spectrum analyzer
  - http://www.vellemanusa.com/
- Setup
  - Set window type to “Flat Top”
  - Set display to “RMS average”
  - Determine BW by subtracting $dBV/\sqrt{(Hz)}$ from dBV
- Unresolved problem
  - Doesn't appear to give proper BW
  - The Vellemen and the HP3561 disagree by about 10 dB
  - Reference level agree

Fluke 6080 Phase Noise

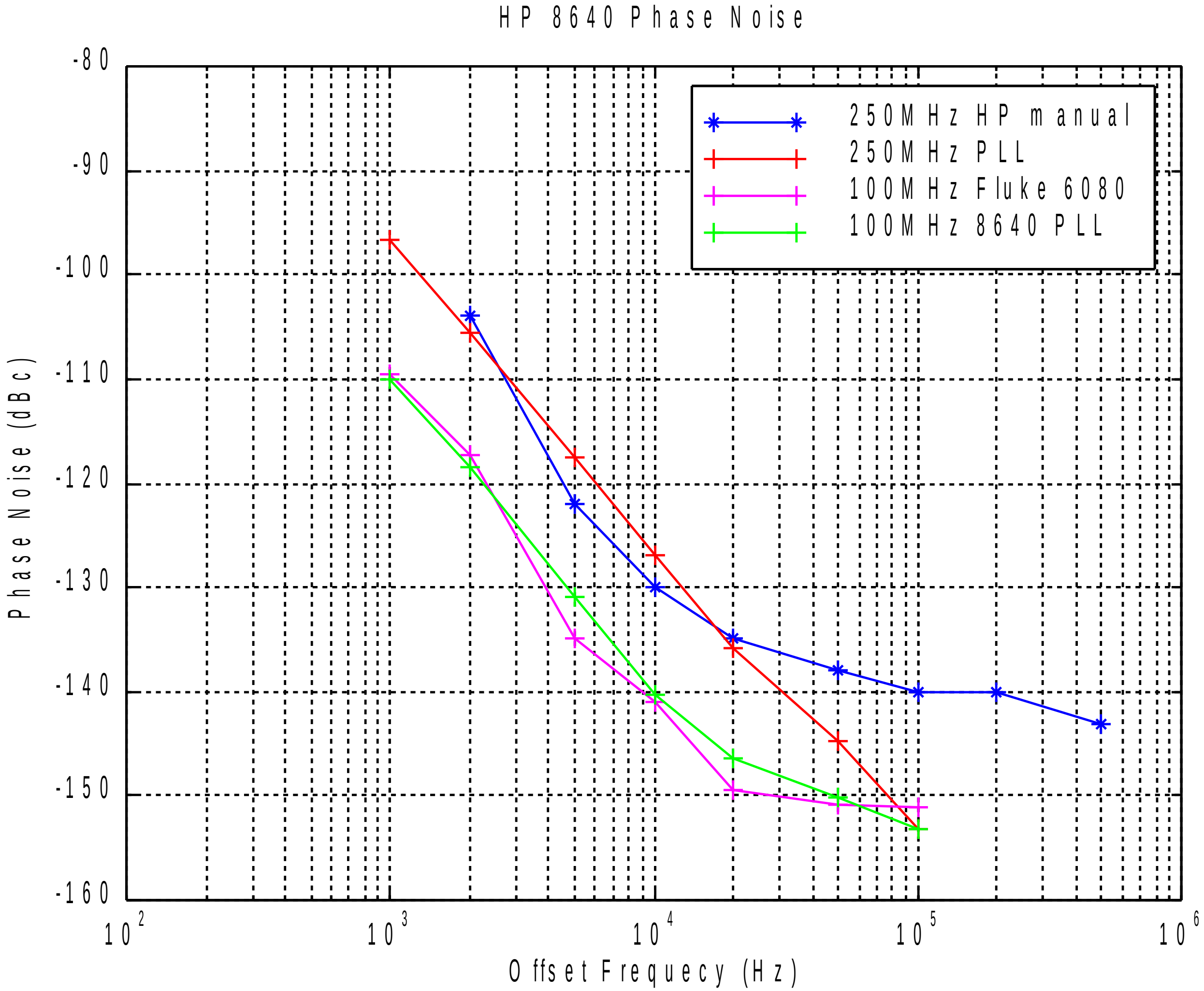


HP8660/86603 Phase Noise

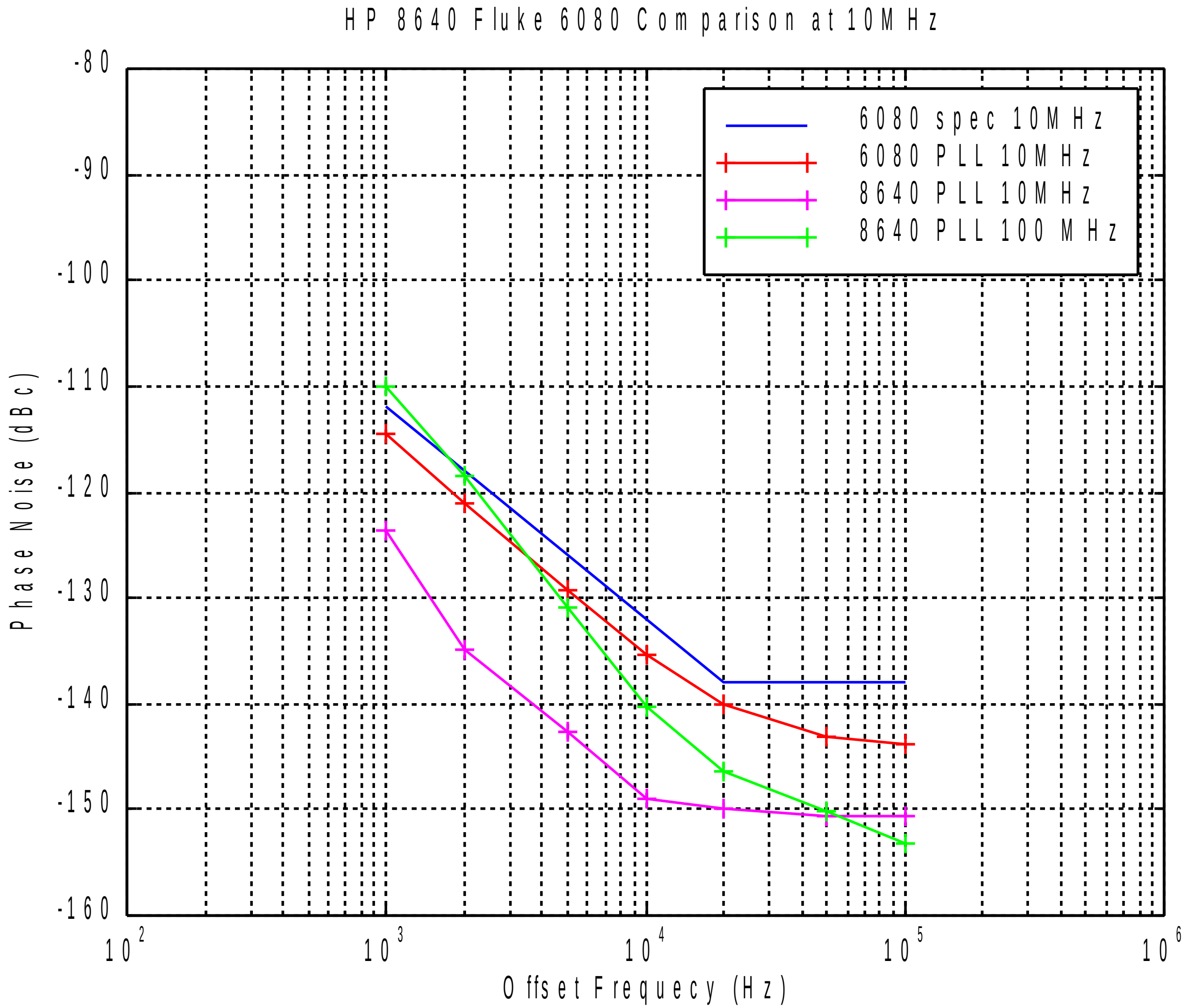


A Couple of Venerable HP8640's

HP8640 Phase Noise



HP8640 – Fluke 6080 Comparison at 10 MHz



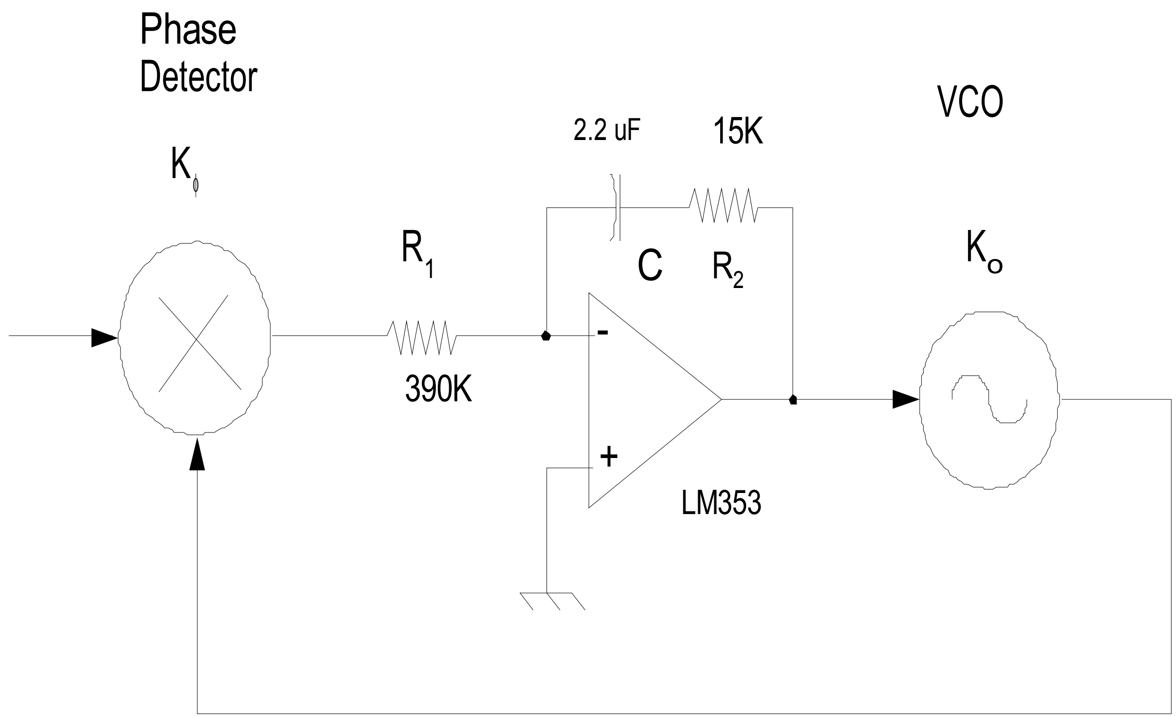
Gotcha's

- Very sensitive measurement!
  - Millivolts/microvolts after 60 dB of gain!
  - Shielding and power supply noise critical
- Phase detector linearity
  - Cal measurement must be sinusoidal
  - Good termination required
- Cal and measurement conditions must be identical
- Good Isolation between source and phase detector
  - Injection locking results in artificially optimistic results
- Did is mention shielding? Signal generators are cheating

Future Work

- Improve consistency
  - Tek 494 and PLL not always consistent
  - Calibration
  - Velleman BW
- Verify noise floor
  - Sometimes get noise floor greater than measured noise!
  - Warren Walls from USNO provided a new technique
- Improve LNA
  - LT1115 not compensated for unity gain, test OP27 or LT1128
- Have more fun
  - My wife tells me to get a life, but nerd engineer and proud of it!

Appendix I: Phase Noise PLL



2^{nd} Order PLL w/Active Lag-Lead Filter

$$K_o = 5000 \quad Hz/V \qquad K_\phi = 0.25 \quad V/rad \qquad V_{brms} = -14.87\, dBV$$

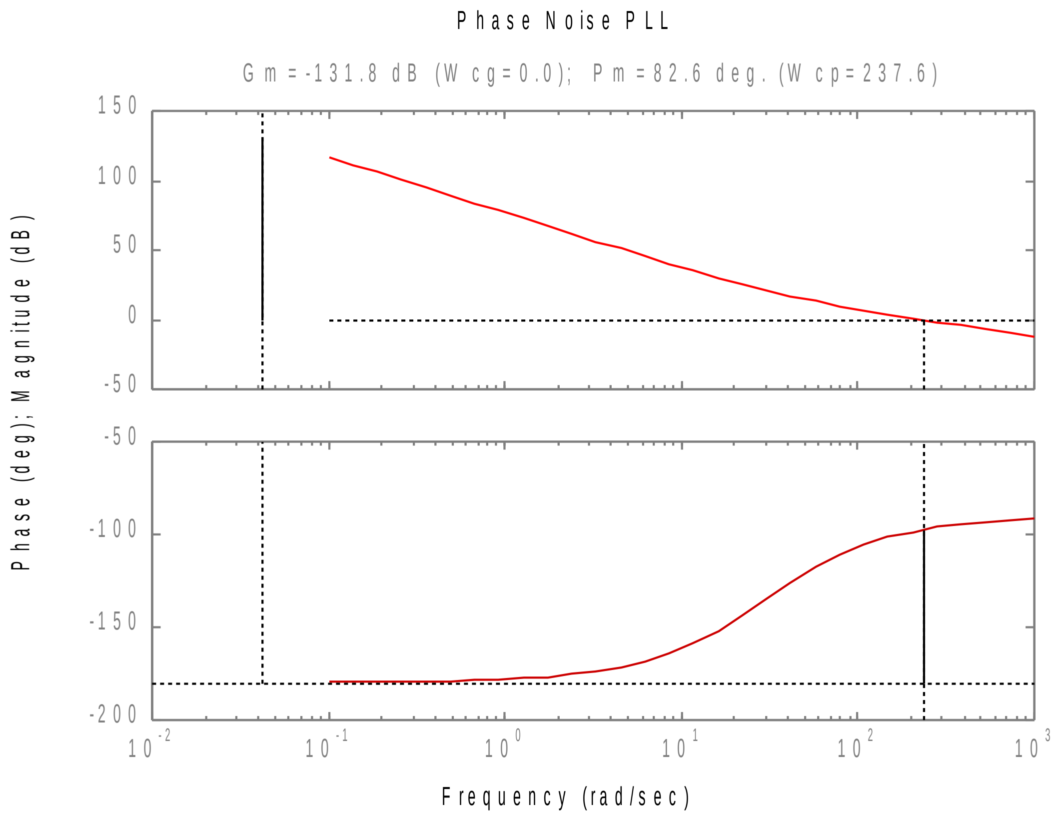
$$K = K_o K_\phi = (2\pi)(5000)(0.25) = 7854$$

$$\omega_n = \sqrt{\frac{K}{R_1 C}} = \sqrt{\frac{7854}{(390\text{K})(2.2\mu f)}} = 95.7\, rad/sec = 15.2\text{Hz}$$

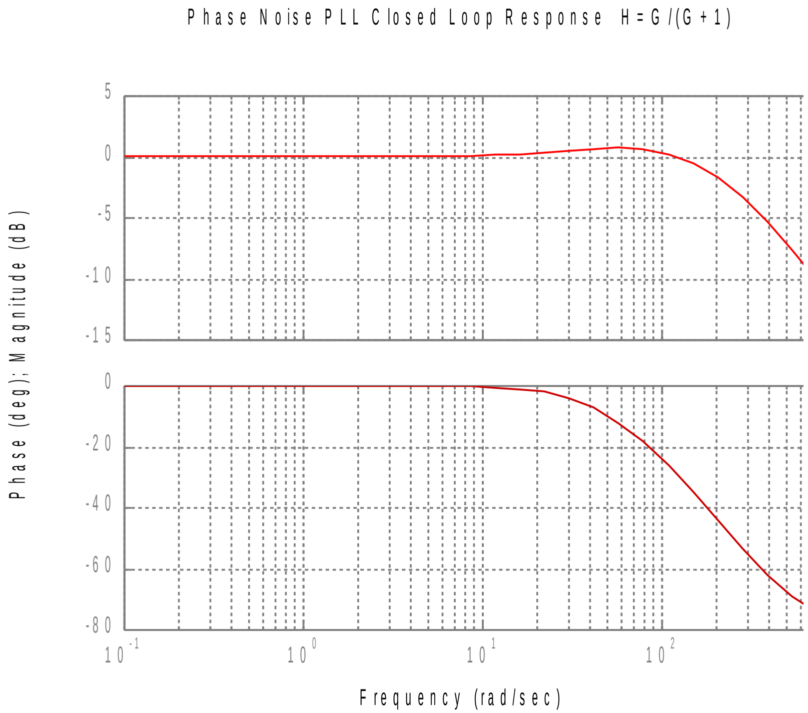
$$\zeta = \frac{\tau_2}{2}\omega_n = \frac{(C_1)(R_2)}{2}\omega_n = \frac{(2.2\mu f)(15\text{k})}{2}(95.7) = 1.58$$

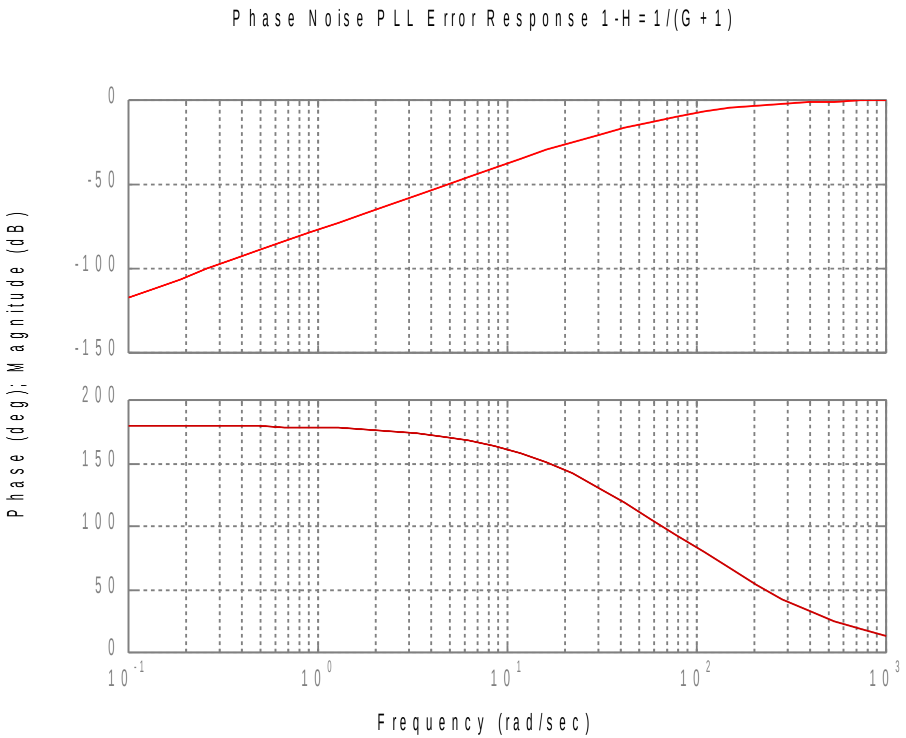
$$BW_{3\text{dB}} = \omega_n \sqrt{\left(2\zeta^2 + 1 + \sqrt{\left(2\zeta^2+1\right)^2 + 1}\right)} = 303.4\, rad = 48.3\, Hz$$

Phase Noise PLL Bode Plot



PLL Closed Loop Response



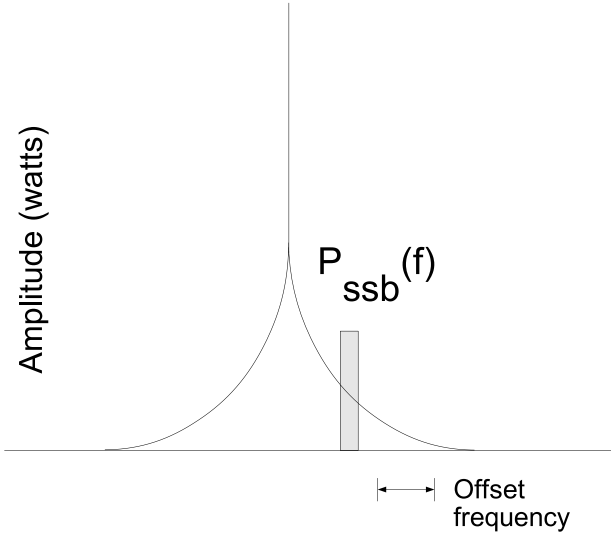


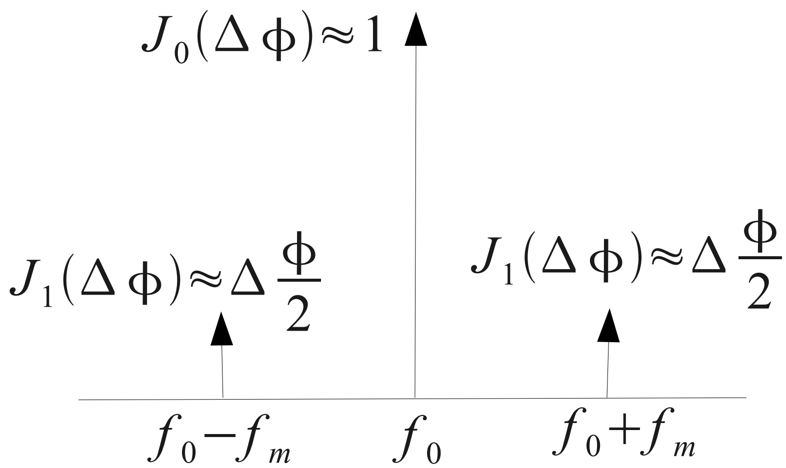
$$BW_{\text{3dB}} \approx 300\, rad/sec = 47.75\, Hz$$

Appendix II: Derivation of L(f) from S$_\phi$ (f)

- Consider a narrow BW (1 Hz) filter at the offset frequency
- Phase noise power is relatively constant in the BW so treat it as a single tone
- Now apply phase modulation theory to estimate side band power levels
- Zeroth and first order Bessel functions predict carrier and 1st sideband levels respectively
- At low phase deviations,

$$J_0(\Delta\phi) \approx 1 \qquad J_1(\Delta\phi) \approx \Delta\frac{\phi}{2}$$





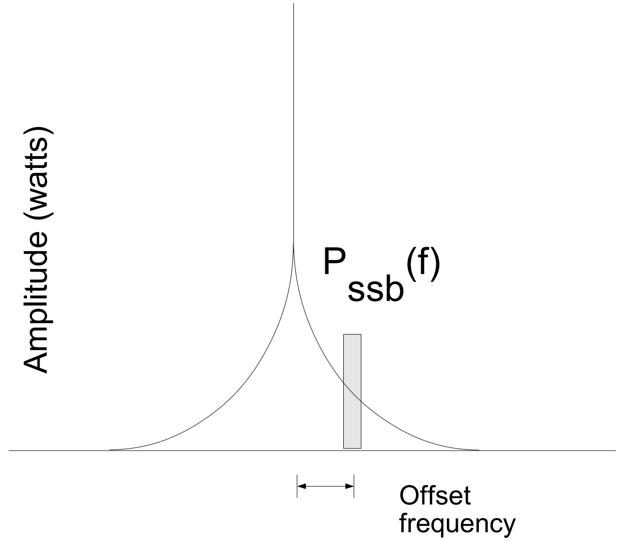
Appendix II:
Derivation of SΦ (f) and L(f)

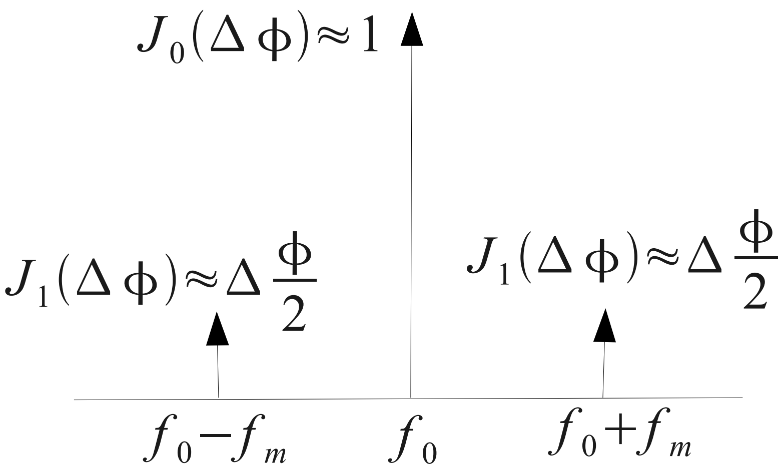
$$\frac{V_{ssb\,peak}(f)}{V_{carrier}} = \frac{J_1(\Delta\phi(f))}{J_0(\Delta\phi(f))} \approx \frac{\Delta\phi_{peak}(f)}{2}$$

$$L(f) = \frac{P_{ssb}(f)}{P_{carrier}} = \frac{V_{ssb}^2(f)}{V_{carrier}^2} = \frac{\Delta\phi_{peak}^2(f)}{4}$$

$$L(f) = \frac{P_{ssb}(f)}{P_{carrier}} = \frac{[\sqrt{(2)}\Delta\phi_{rms}(f)]^2}{4}$$

$$\boxed{L(f) = \frac{P_{ssb}(f)}{P_{carrier}} = \frac{S\phi(f)}{2} = \frac{\Delta\phi_{rms}^2(f)}{2}}$$





Bibliography

- Websites
  - http://www.febo.com/time-freq/index.html
  - http://www.ke5fx.com/stability.htm (large archive of app notes)
  - http://www.wenzel.com/library1.htm
- Application Notes
  - HP AN 270-2 Spectrum analyzer measurement
  - HP PN Seminar: Everything you ever wanted to know!
  - HP Notes by Dieter Scherer
    - The "Art" of Phase Noise Measurement
    - Low Noise Source Design and Test
    - Generation of Low Phase Noise Microwave Signals
- Books

  - William F. Egan, *Phase-Lock Basics,* John Wiley, 1998
  - R. P. Robbins, *Phase Noise in Sources,* IEE Telecom Series 9, 1984

Bibliography

- QEX

  - Pontius, Bruce E., N0ADL, *Measurement of Signal-Source Phase Noise with Low-Cost Equipment*, QEX, Issue No. 188, May/June 1998,pp. 38-49.
  - Van der List, Jos F. M., PA0JOZ, *Experiments with Phase-Noise Measurement*, QEX, Issue No. 188, January/February 1999,pp. 31-41.
  - Karlsen, Kjell, LA2NI, A Method of Measuring Phase Noise in Oscillators, QEX, November 2004, pp 54.