Frequency Stability Measurement: Technologies, Trends, and Tricks

Presented at MicroHAMS (January 2020)

John Miles, KE5FX

The importance of time

- Time is a wide-range parameter – scales of interest range from femtoseconds to years!
  - Time is also the most *precise* physical quantity we know how to measure. Almost every measurement made by engineers and physicists ultimately relies on a timebase
- When we talk about “stability”, we must specify the timescale of interest
  - Long-term stability (“Drift”) – what timescale(s)?
  - Short-term stability (“Phase noise”) – what offset(s)?
  - These look like different phenomena, but are really two aspects of the same problem: **unwanted changes in phase over time.**

Why measure long-term stability?

- Debugging a new project? Mysterious problems are sometimes obvious in the long-term time domain
  - Loop stability-margin problems
  - "Phase hits"
  - Unwanted vulnerabilities to temperature, power, vibration…anything periodic
- Comparing and tweaking clocks: OCXOs, GPS/Rb/Cs standards, and more
- Understanding and optimizing your station's behavior under different environmental conditions
- Precision timing opens new research areas to amateurs: bistatic radar, long-baseline interferometry, GPS enhancement…

Long-term stability measurement

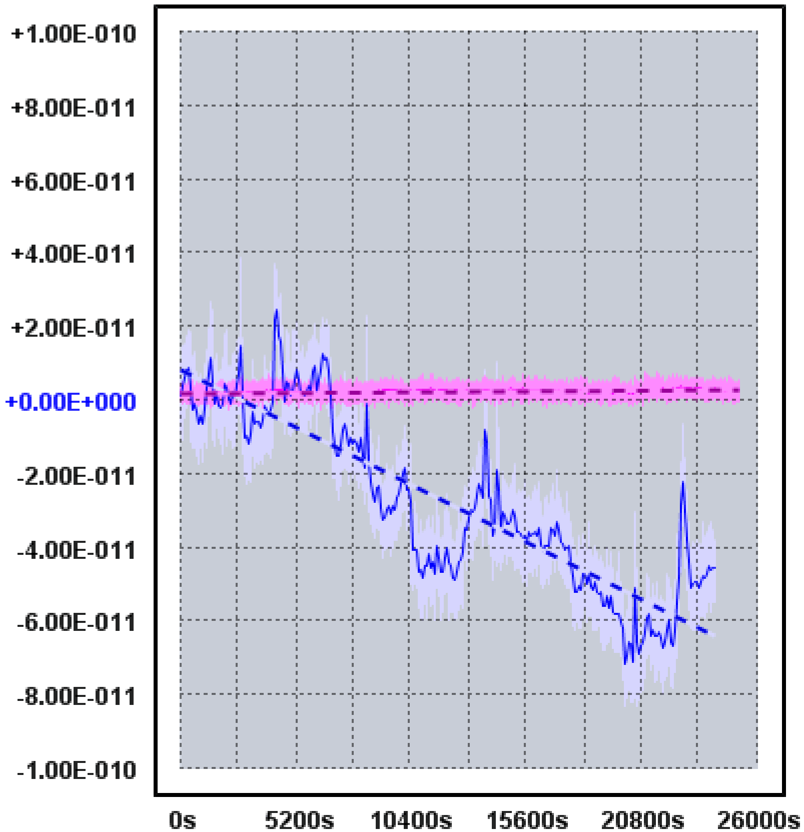
- Frequency counter
  - Like spectrum analysis for PN – ‘measurement floor’ is not great
  - Best frequency counters resolve about 11 digits/second
- Time Interval Counter (TIC)
  - Better resolution through interpolation and other techniques
  - Best TICs have single-shot resolution in the 1-ps range

Long-term stability measurement

- Direct digital test sets
  - Measures phase like a TIC, but with SDR-like "process gain"
    - Can often measure phase noise as well
  - State-of-the-art resolution is in the 1-fs (1E-15/second) range
    - 1000x better than the best counters!

Frequency Difference (Zero-based)

Averaging window: Per-pixel

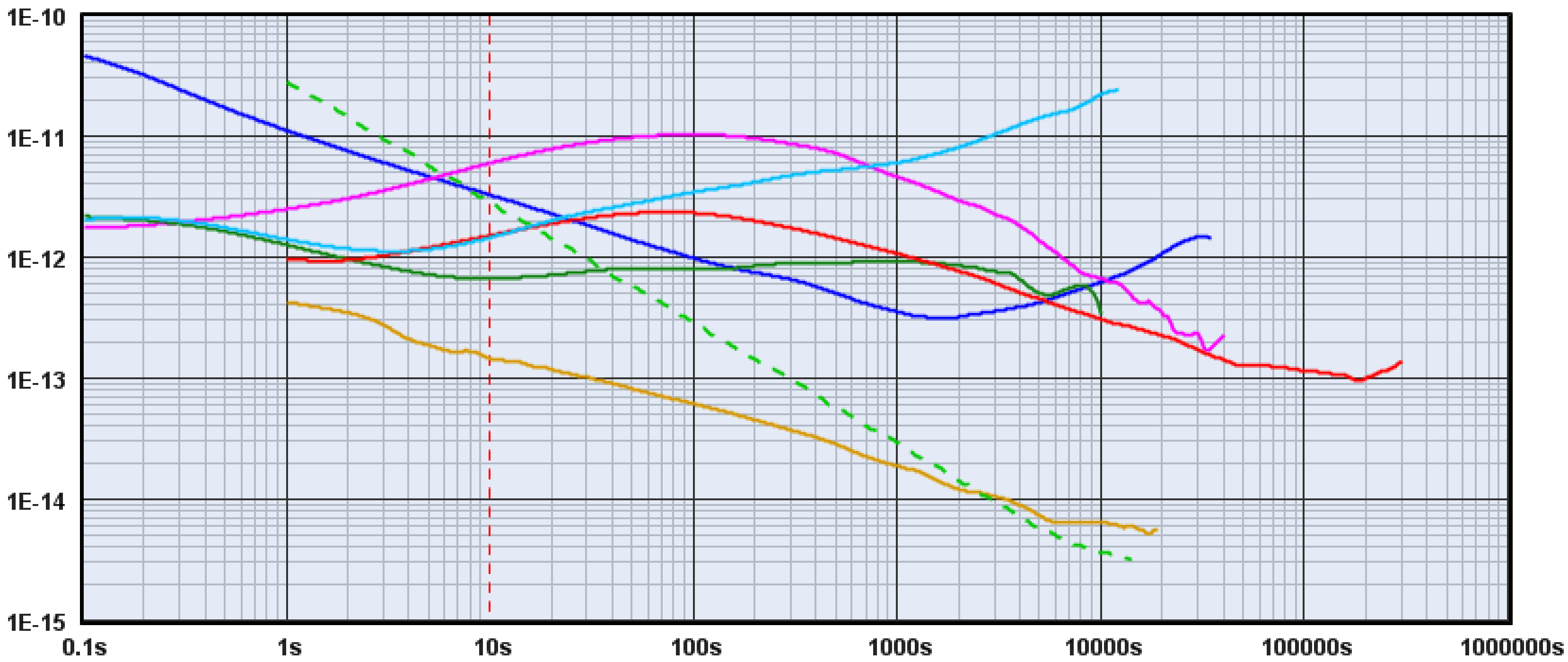


Origin	Drift (Hz/sec)	Drift (Hz/hr)
+8.25E-012	-3.01E-008	-1.08E-004
+1.85E-012	+1.94E-010	+7.00E-007

Avg Time (s)	Freq (Hz) at 24091s	Error
0 . 100	10 000 000 . 012 769 390	+1.28E-009
1	10 000 000 . 012 848 540	+1.28E-009
10	10 000 000 . 012 869 660	+1.29E-009
100	10 000 000 . 012 863 580	+1.29E-009
1 000	10 000 000 . 012 839 610	+1.28E-009
10 000	10 000 000 . 012 838 270	+1.28E-009

Trace	Notes	Input Freq	Sample Interval	Instrument
HP 10811A oscillator	5065A	10E6 Hz	0.1 s	TimePod
Oscilloquartz BVA 8607/008	HP 5065A Rb	5E6 Hz	1.0 s	TSC-5110A

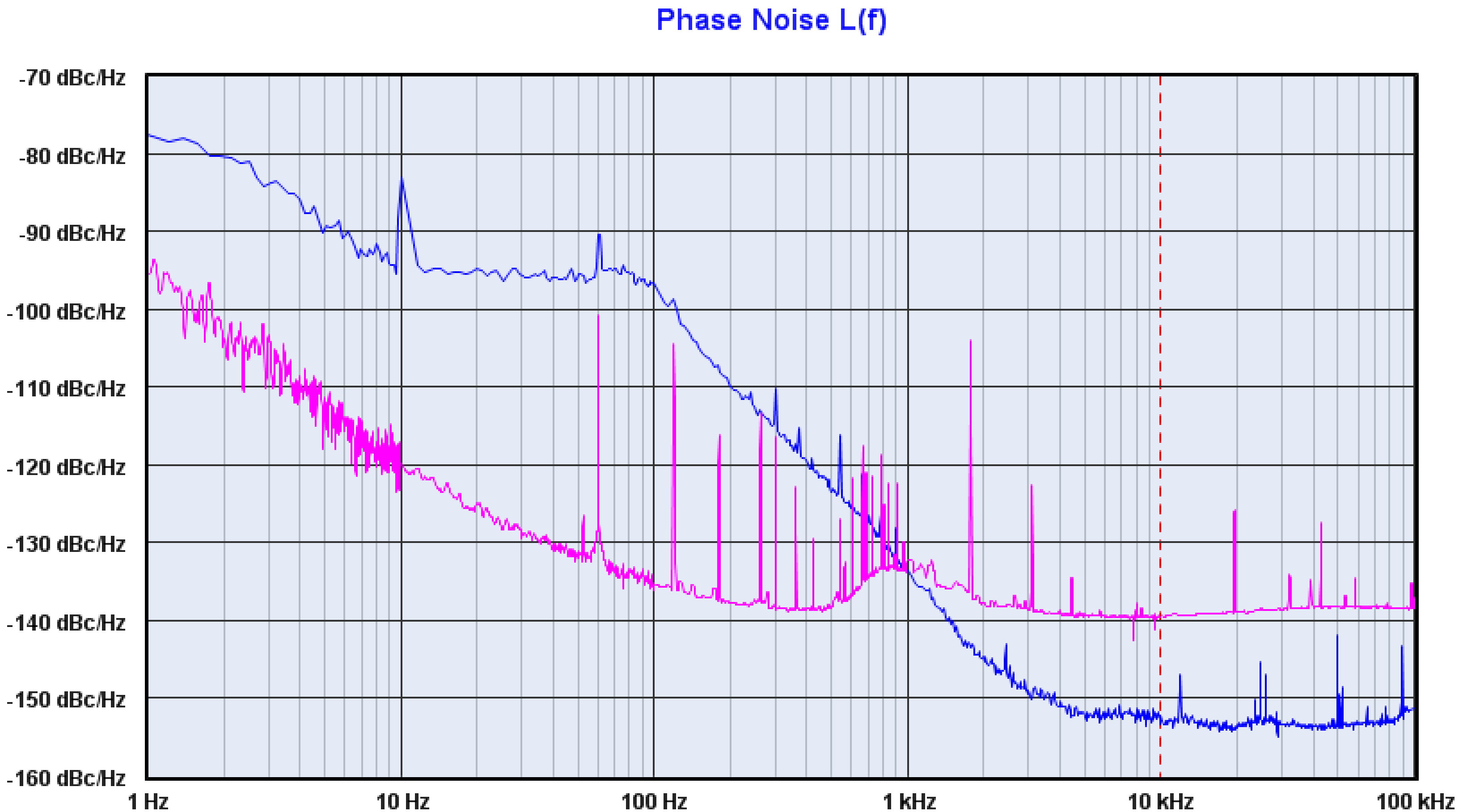
Allan Deviation



Trace	Notes	Input Freq	ADEV at 10s	Instrument
LPRO-101 Rb	HP 5065A	1.000E+007 Hz	3.3E-012	TimePod
Trimble Thunderbolt (stock)	TBolt 10811	1.000E+007 Hz	6.0E-012	TimePod
Trimble Thunderbolt (optimized)	HP 5065A	10E6 Hz	6.7E-013	TimePod
HP 5061A Cs	Hydrogen maser	5.000E+006 Hz	1.5E-012	TSC 5110A
HP 10811A oscillator	5065A	10E6 Hz	1.4E-012	TimePod
KVARZ CH1-76 passive H-maser	KVARZ CH1-75 active H-maser	5E+6 Hz	1.5E-013	TSC 5110A
HP 5370B residual floor (Broken trace)	(Via TADD-2 divider)	1.000E+007 Hz	2.9E-012	HP 5370A/B

Why measure phase noise?

- Phase noise is a common topic of discussion when serious homebrewers get together, from HF to microwave
  - PN tells you more about the health of your signal source than perhaps any other measurement
  - Historically one of the more difficult/expensive measurements to make
- Weak-signal work benefits from precise, repeatable tuning with minimal spreading on both the transmitter and receiver ends
- Excessive PN may harm Minimum Discernible Signal (MDS) level and quality
- WA1ZMS put it best: *stability determines what signals sound like.*
- Instrumentation design – the analyzer has to be cleaner than the DUT! (…or does it?)



Trace	Input Freq	dBc/Hz at 10 kHz	Instrument
HP 8642B signal generator	10000000.0 Hz	-152.7	TimePod
HP 8663A signal generator	9500000.000 Hz	-139.5	TSC 5120A

Phase noise is everywhere…

- No source or device above 0 Kelvin can avoid contributing jitter
- Multiplied references common in UHF-microwave work suffer 20*log(N) effect
  - 20*log(N) = simple consequence of jitter
    - Lag/lead time of any given edge remains constant through multiplication, but the carrier period shrinks
  - +60 dBc/Hz from 10 MHz to 10 GHz
    - Sometimes *much* worse – many PLLs divide before they multiply!
    - Even clean references can be degraded by process noise
    - Throwing money at the problem does not guarantee improvement

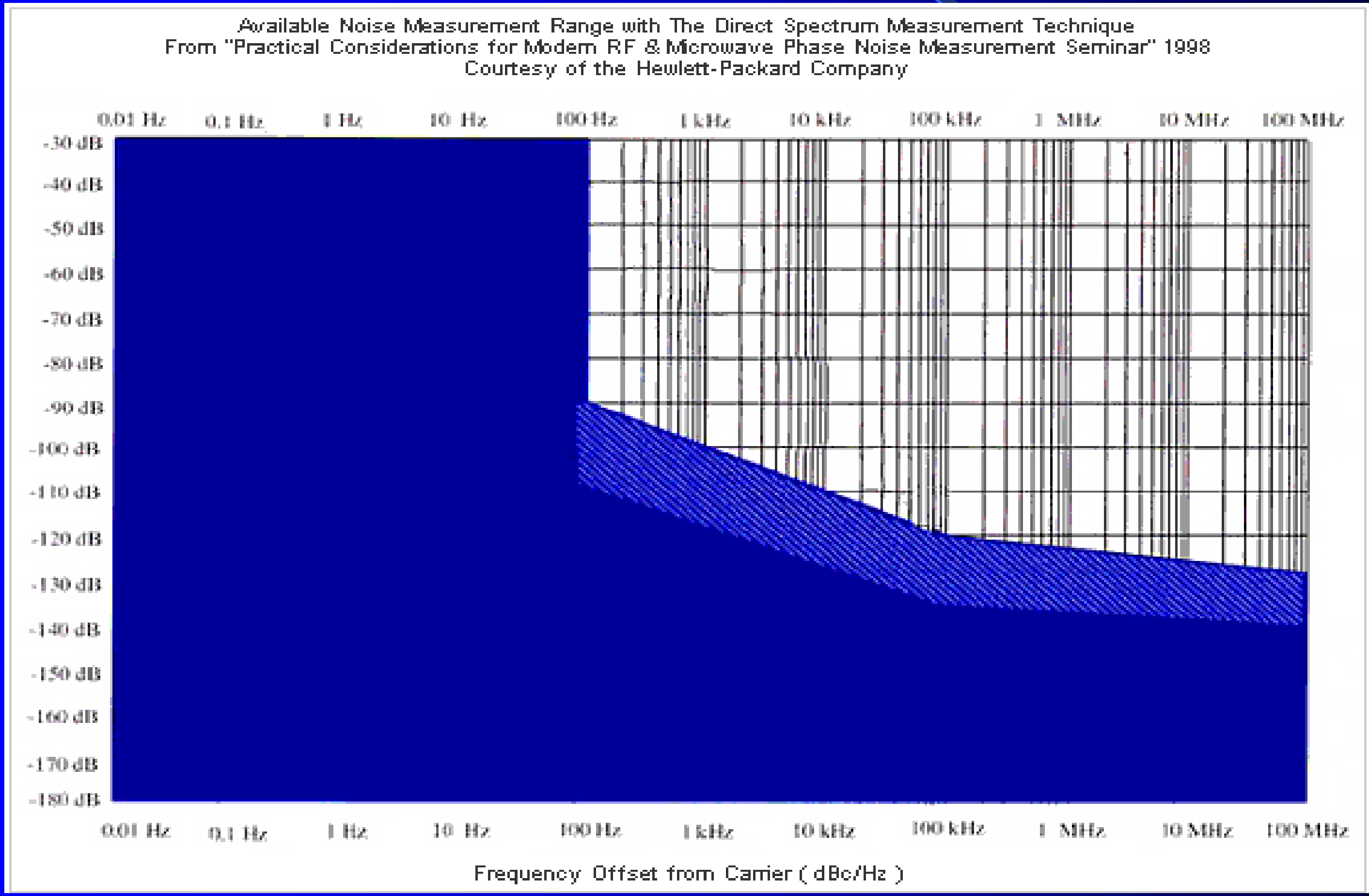
… so how do we measure it?

- Direct spectrum analysis
  – Simply tune a spectrum analyzer to the USB half of the carrier
- Indirect (baseband) spectrum analysis
  – Phase detector method
  – Frequency discriminator method
  – Two-port device measurements
- Direct digital analysis
  – Recover and measure phase variations with DSP techniques

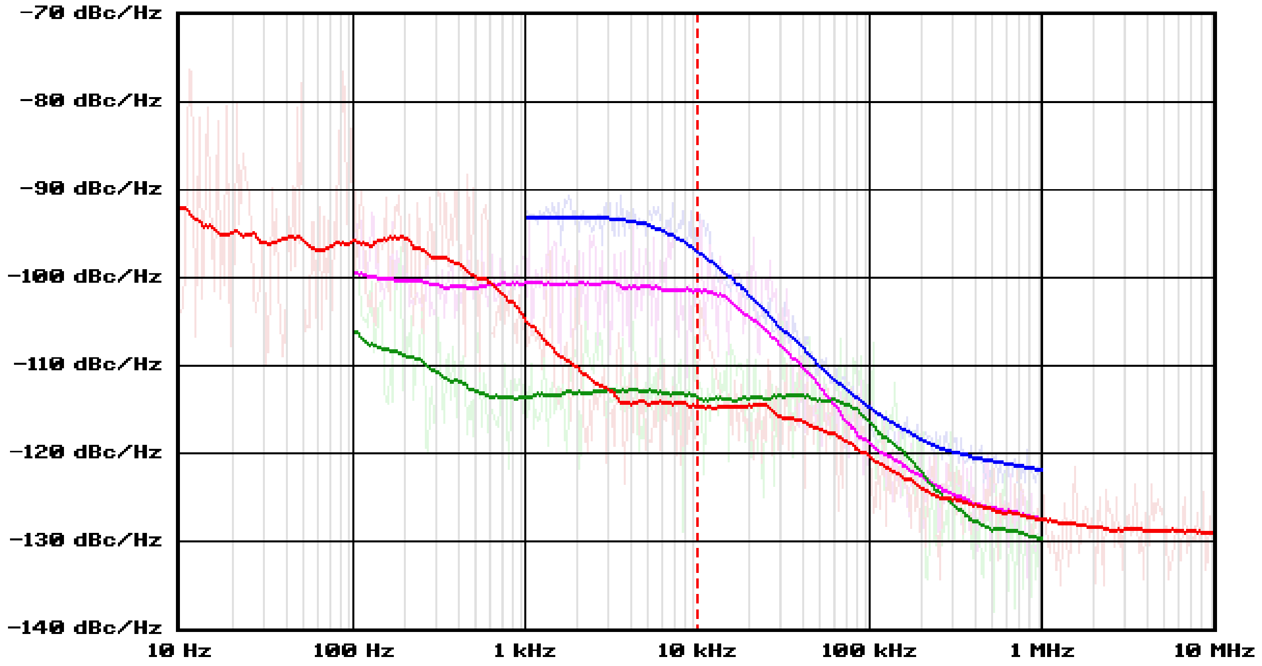
Direct spectrum analysis

- Measures composite (AM+PM) noise
- Limited by instrument's LO noise floor
- Calibration process involves a few factors (see AN 1303)…
  - Subtract carrier level if not 0 dBm
  - Subtract 10*log(resolution BW) to normalize to 1 Hz BW
  - Add 2.5 dB to account for averaging power in "dB space"
  - Subtract equivalent noise bandwidth of the RBW filter
    - Usually < 1 dB difference depending on type
- Spot measurements are often supported by dBm/Hz markers
  - Note difference between dBm/Hz and dBc/Hz – use reference-level offset to avoid confusion
  - Better to use software!
    - PN.EXE from www.ke5fx.com/gpib/pn.htm
    - OEM phase-noise personality software (HP 85671A, R&S FS-K4…)

Direct spectrum analysis



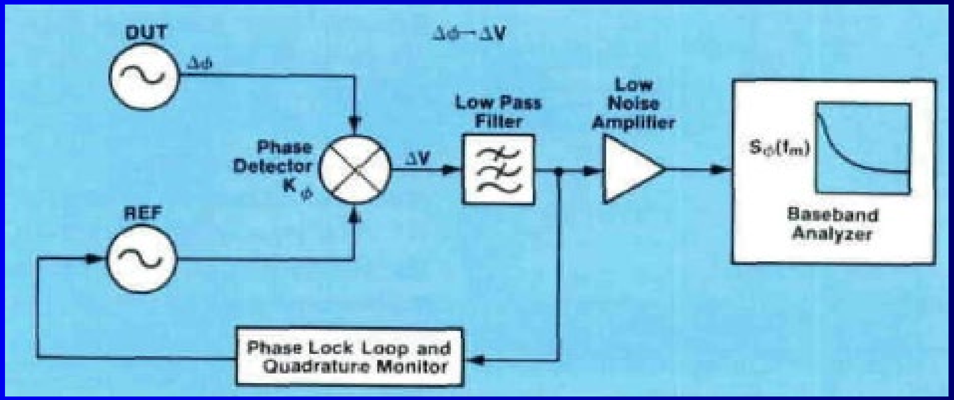
Direct spectrum analysis: some typical instrument floors



Trace	Carrier Hz	Carrier dBm	dBc/Hz at 10000 Hz	Sweep
Tektronix 492P	100 000 000	-10.00	-97.1	62s
HP 8566B	100 000 000	-20.30	-101.4	125 sec
HP 8568A	20 000 000	-10.00	-113.6	93 sec
HP 8560E	300 000 000	-10.00	-114.6	27s

Indirect PN analysis: Phase Detector method

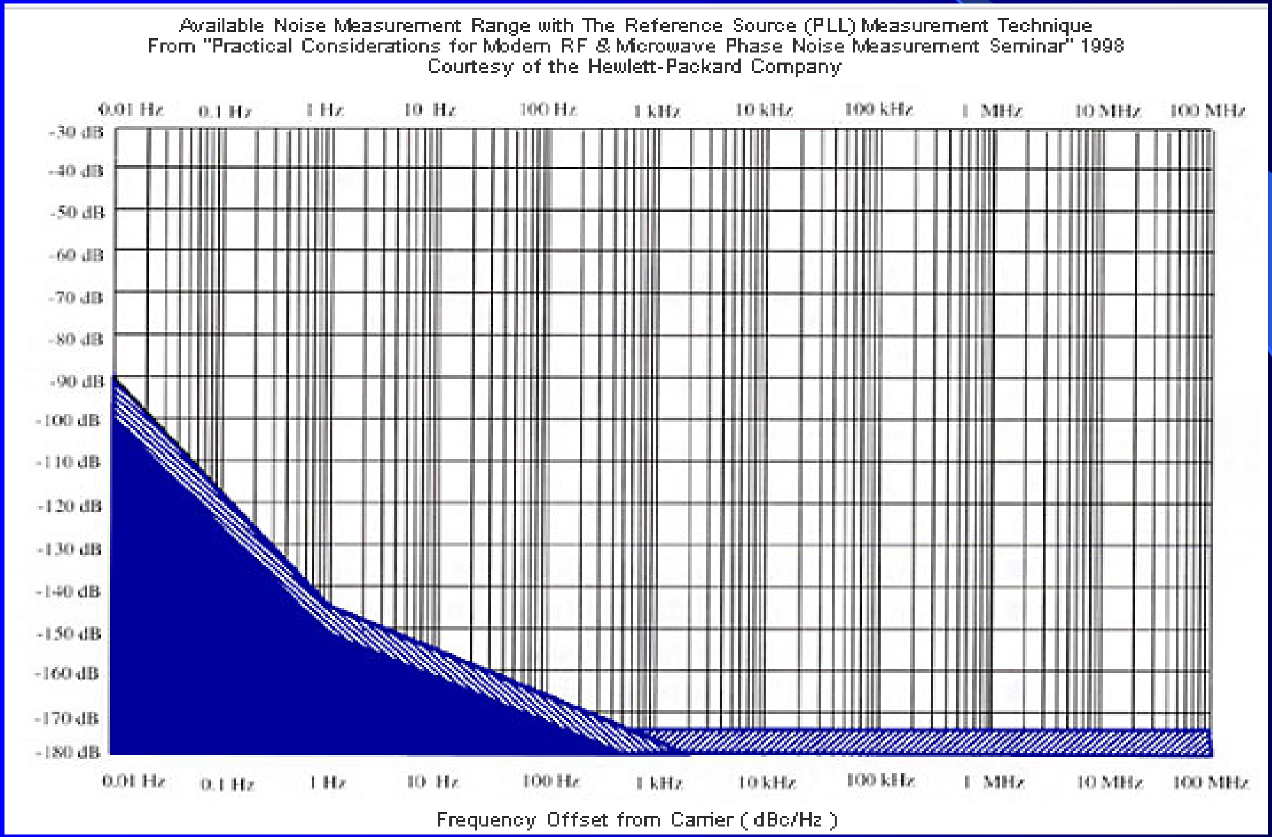
- Downconvert signal from DUT to 0 Hz ("baseband")
  - Simple PLL with mixer as phase detector
  - Commonly-cited references
    - HP Product Note 11729B-1
    - www.wenzel.com/documents/measuringphasenoise.htm



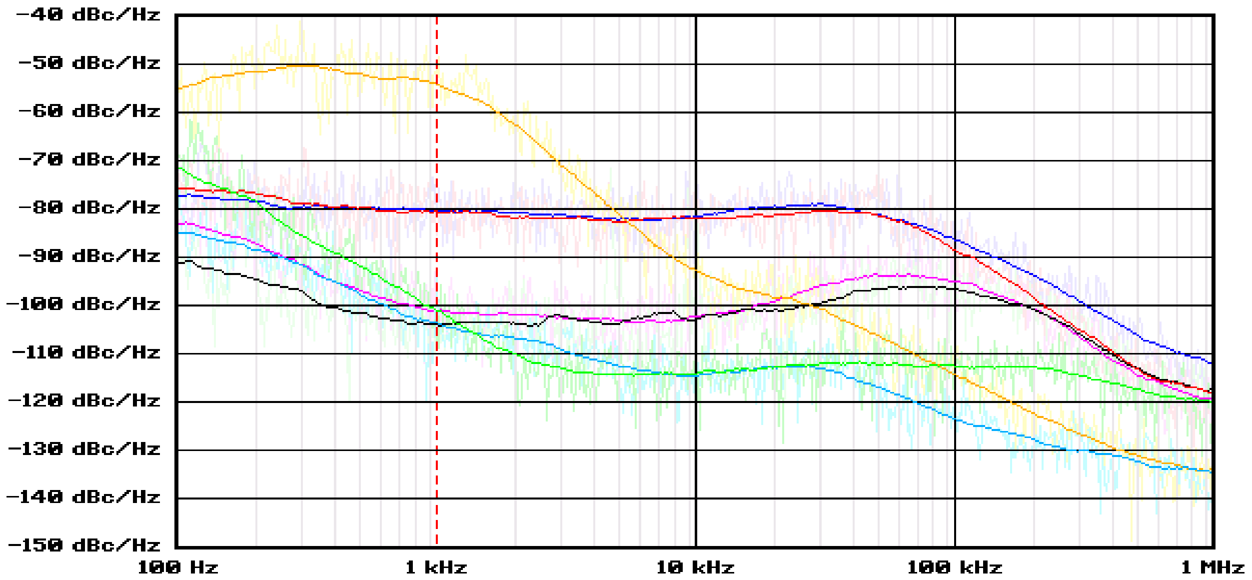
Indirect PN analysis: Phase Detector method

- Requires a reference at the same frequency as the DUT
- Injection locking can be a problem – need isolation amps
- Lots of options, with manuals the size of phone books
- Calibration process is much more detailed…
  - All factors in direct spectrum analysis apply here as well
  - Plus the need to account for the test set's response
    - Mixer's sensitivity when used as phase detector (volts per radian)
    - Post-mixer LNA gain, if any
    - 6 dB to convert folded DSB baseband to L(f)
    - Effect of PLL, if its bandwidth overlaps desired measurement range
- Only a masochist would attempt indirect PN measurements without software support!
    - KE5FX GPIB Toolkit (PN.EXE), HP 3047A, HP 3048A, Agilent E5500…

Indirect PN analysis: Phase Detector method



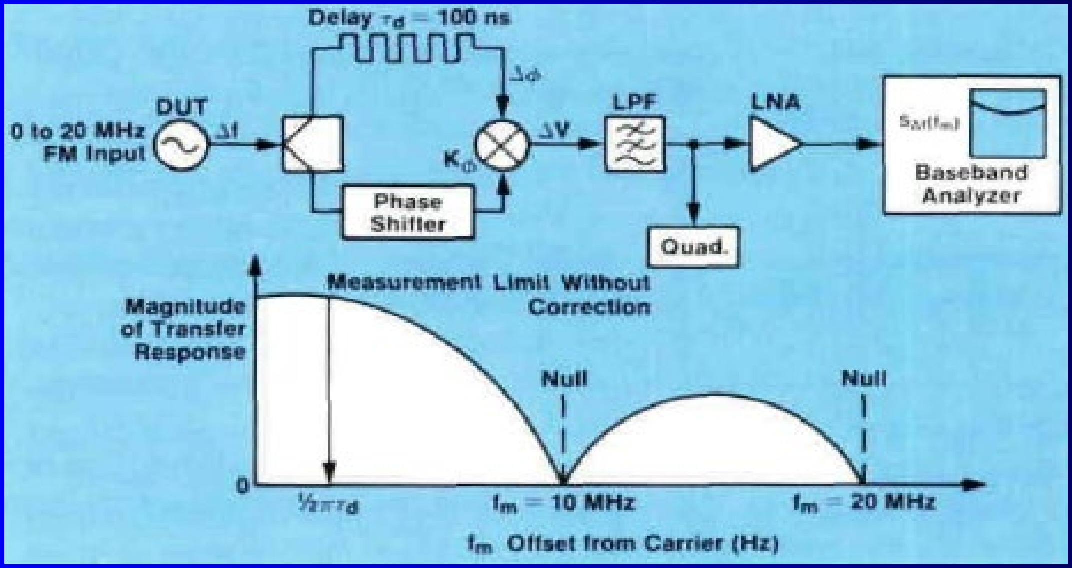
Phase Detector method: some typical measurements



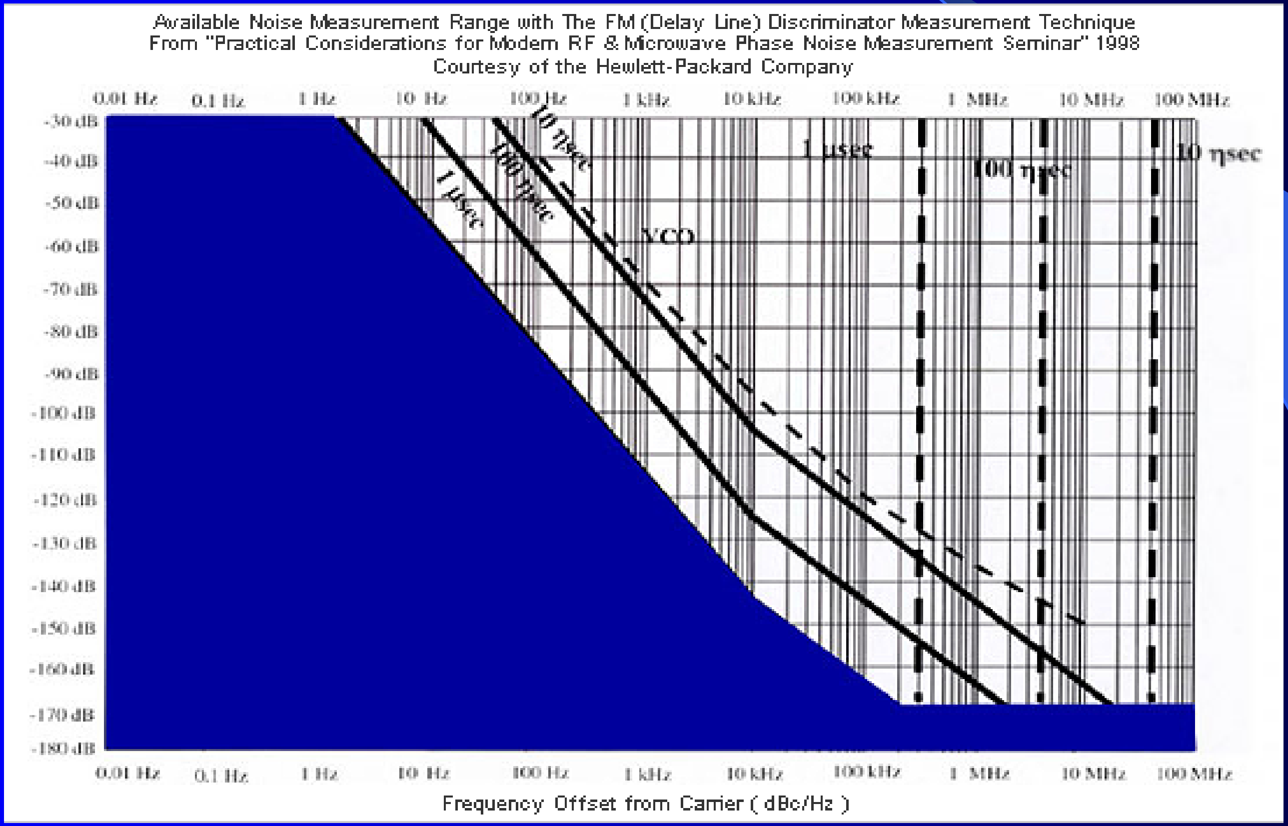
Trace	Carrier Hz	dBc/Hz at 1000 Hz
10 MHz ref (HP 8566B OCXO via MC100EL16), 80 kHz LBW	8 000 000 000	-80.4
100 MHz ref (Bliley OCXO), 200 kHz LBW	8 000 000 000	-101.0
80 MHz ref (Wenzel ULN OCXO), 200 kHz LBW	7 680 000 000	-104.0
ADF4112-based PLL, 100 MHz ref (Bliley OCXO), 46 kHz LBW	8 000 000 000	-80.7
Stellex YIG synthesizer with ext 10 MHz ref	9 000 000 000	-54.5
Frequency West brick, 100 MHz from Bliley OCXO	8 000 000 000	-103.7
KE5FX comb generator, 1 GHz from HP 8662A x8	8 000 000 000	-101.1

Indirect PN analysis: Frequency Discriminator method

- Instead of a separate reference….
  - Delay line converts df to dphi, then mixer converts dphi to dv
  - See HP 3048A manuals, HP Product Note 11729C-2

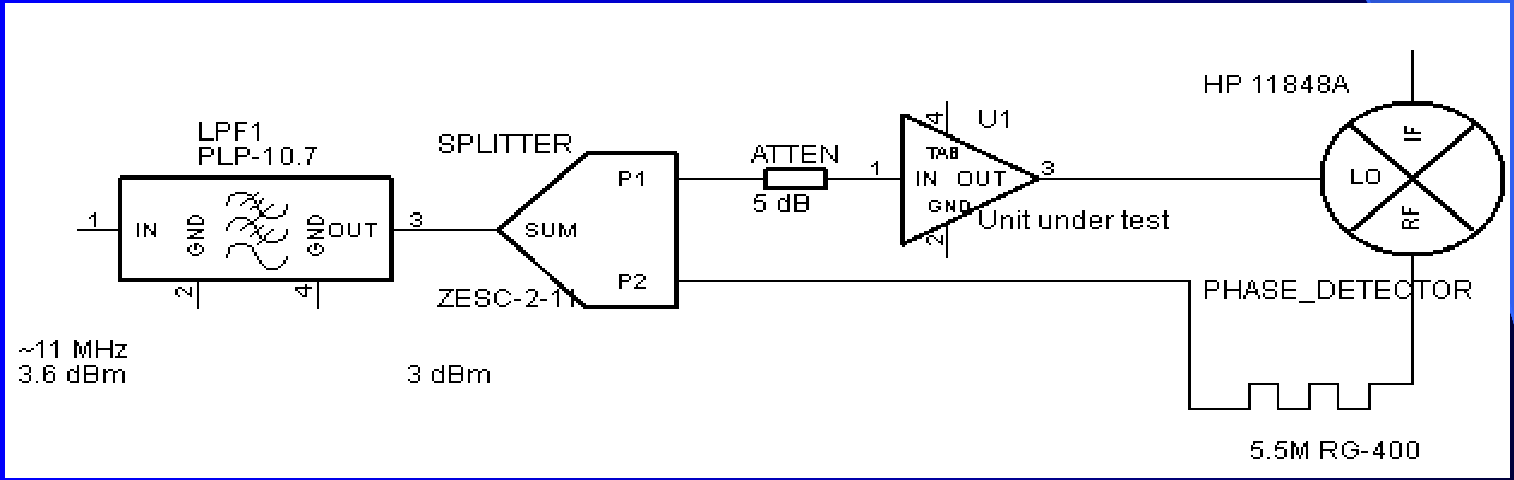


Indirect PN analysis: Frequency Discriminator method

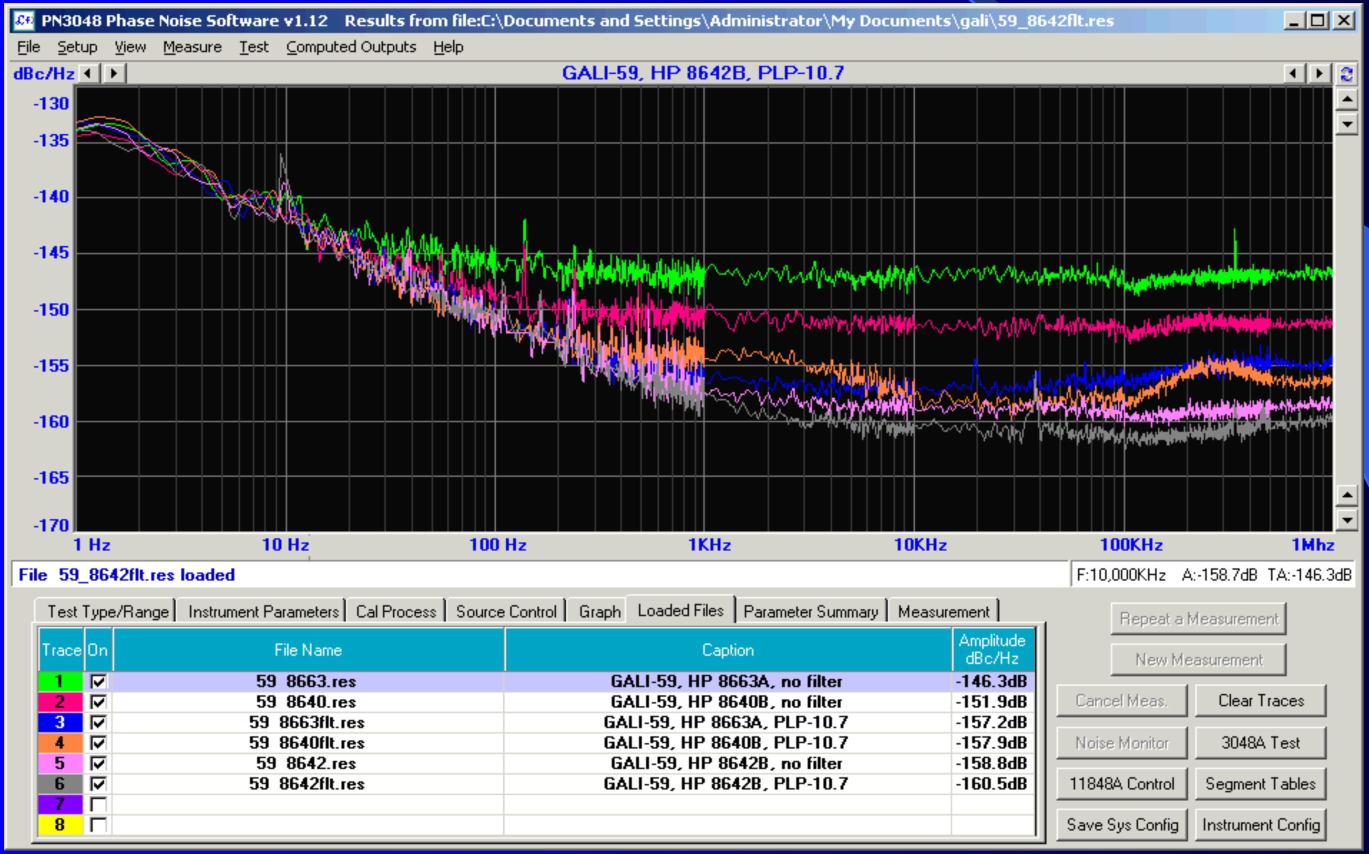


Indirect PN analysis: Two-port residual measurements

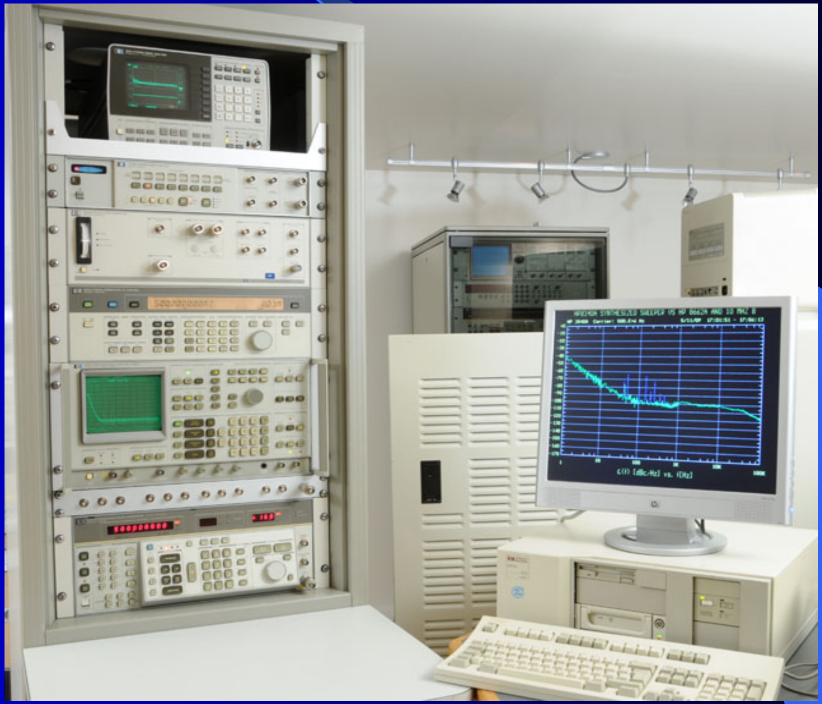
- Useful variation on discriminator measurement
- Replaces delay line with DUT
- Must drive splitter with a clean signal source or its broadband noise will decorrelate and fold…



Indirect PN analysis:
Two-port residual measurements



Typical indirect PN analysis gear: HP 11729B/C, HP 3048A



HP 3048A software (VB6): http://www.ke5fx.com/PN3048.htm

Homebrewing a quadrature PLL

– Simple type-2 PLL with DBM and opamp
  - http://www.wenzel.com/documents/measuringphasenoise.htm
  - Several other references at http://www.ke5fx.com/stability.htm

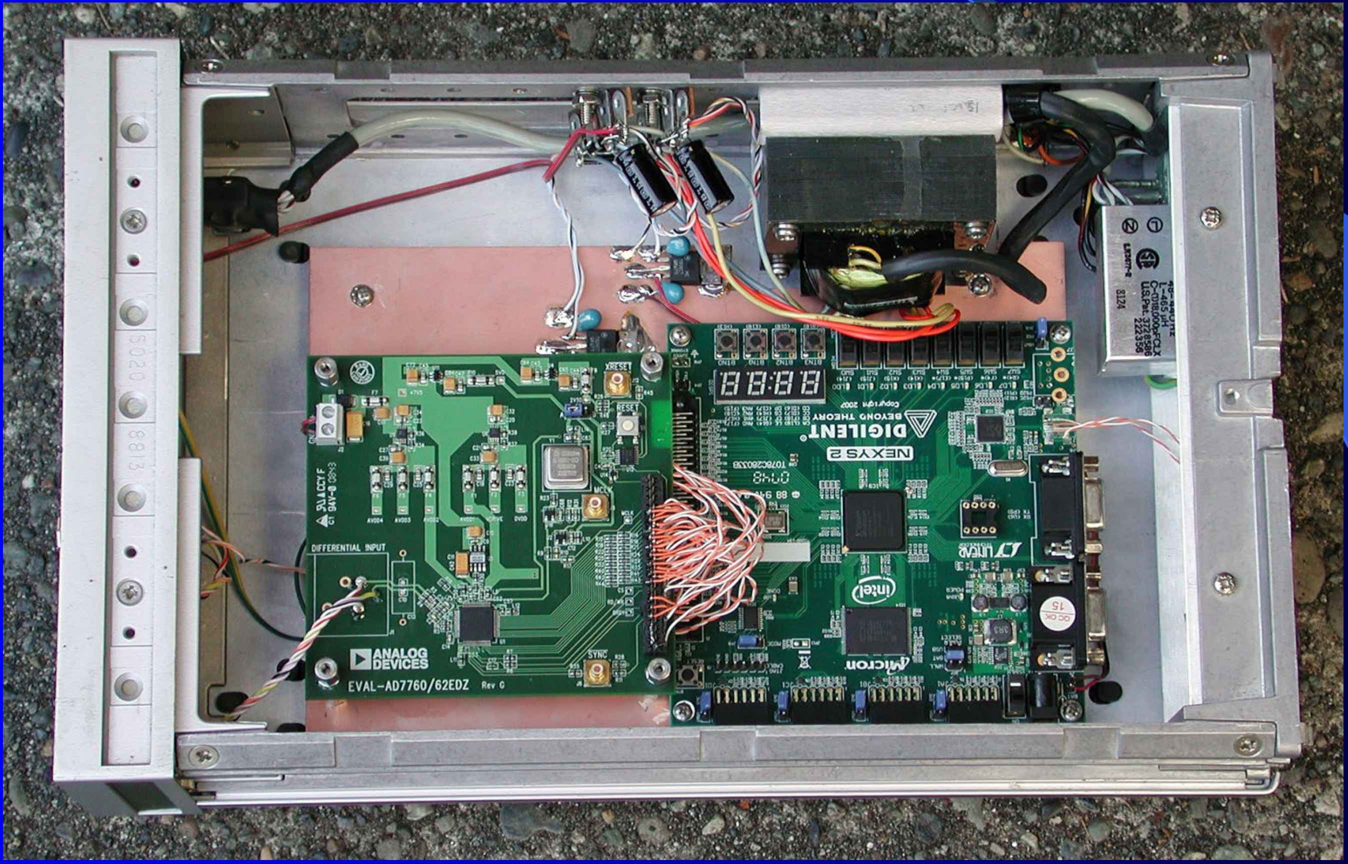
– As with the commercial 3048A and E5500 packages, almost any spectrum analyzer can be used
  - Quadrature-PLL measurements with RF analyzers are supported by PN.EXE
  - See last FAQ entry at http://www.ke5fx.com/gpib/faq.htm

Baseband analysis for indirect measurements

- Advantages of popular surplus FFT analyzers
  - Faster ‘sweeps’ with FFT versus conventional RF analyzers
  - Resolves noise at offsets down to 1 Hz or better

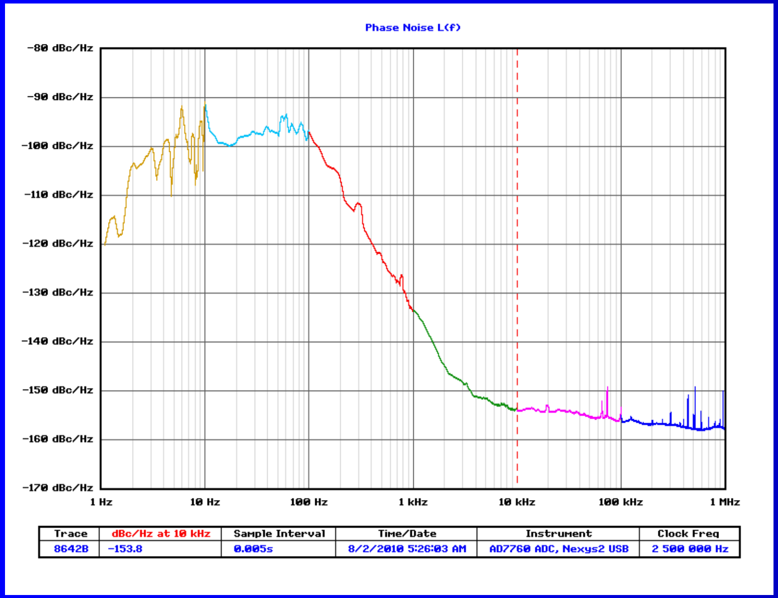
- Disadvantages versus RF spectrum analyzers
  - Less dynamic range
    - Common to overdrive the front-end mixer in an RF analyzer for improved range, but ADCs don’t tolerate this
    - High-amplitude LF content has to be high-pass filtered to avoid swamping the broadband response
    - HP 3048A hardware+software switches filters for you, but it complicates homebrew solutions
  - Less third-party software support
    - PN.EXE doesn’t work with popular baseband analyzers like HP 3561A, HP 3562A, HP 89440A series

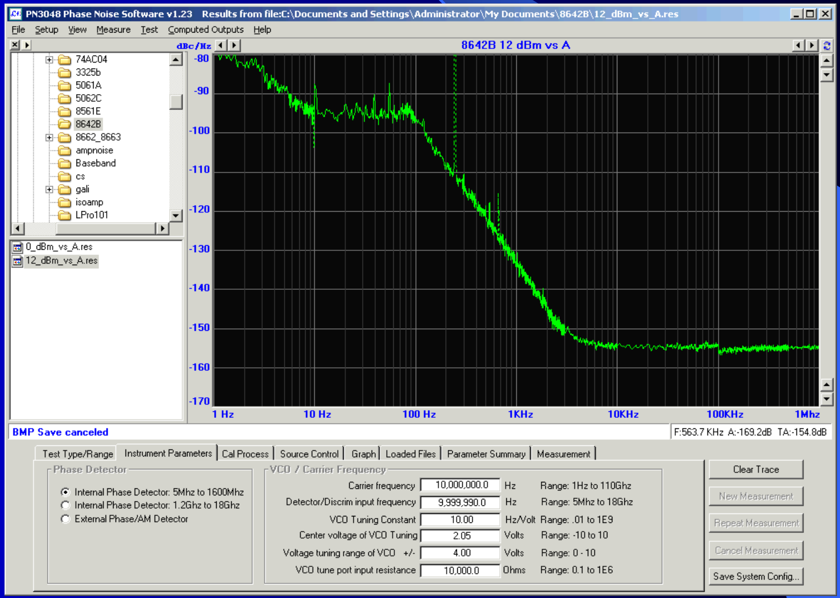
EVAL-AD7760 as baseband analyzer



EVAL-AD7760 as baseband analyzer

EVAL-AD7760 as baseband analyzer: HP 8642B measured via 11729C



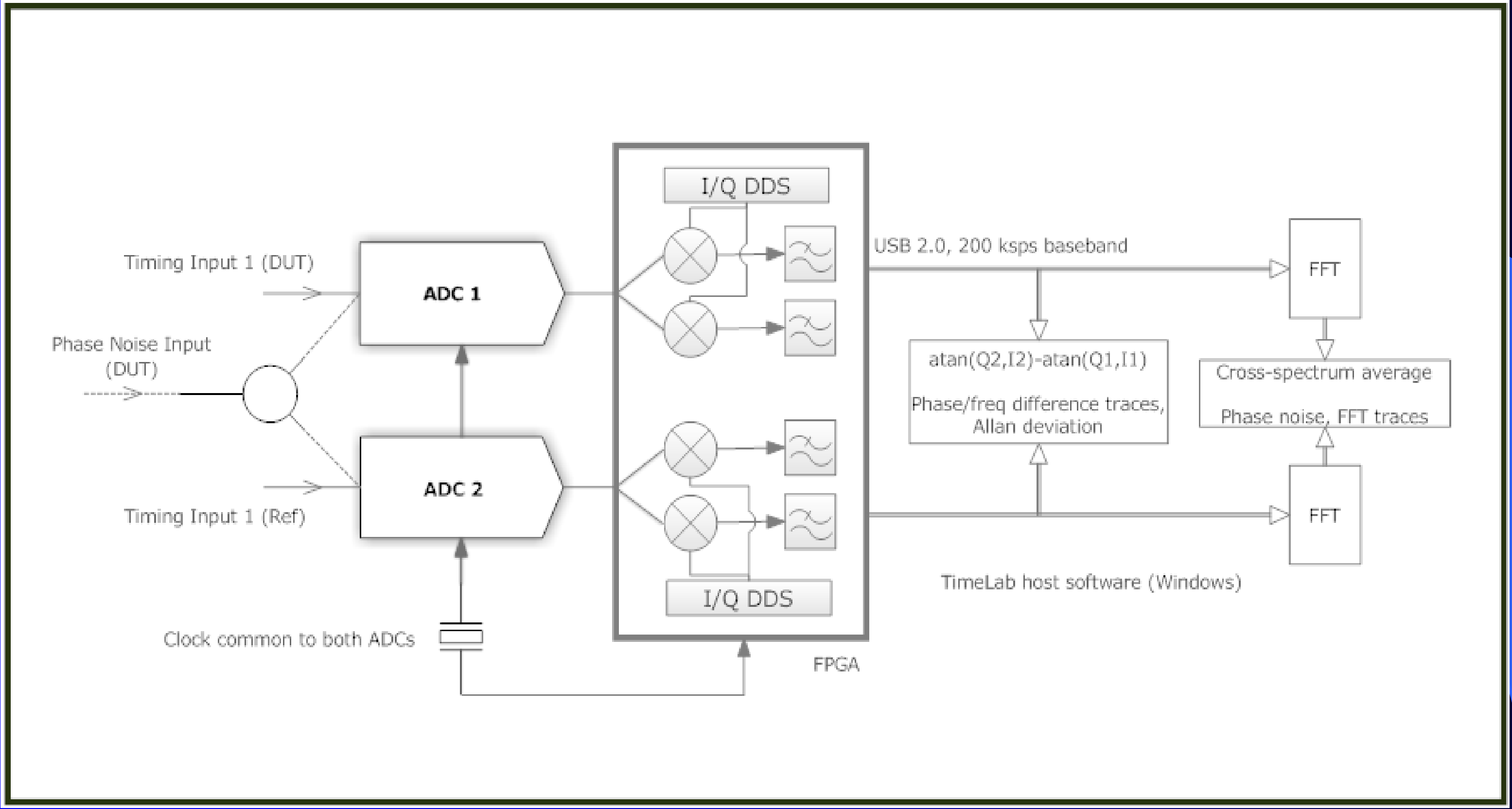


Build a direct digital analyzer instead?

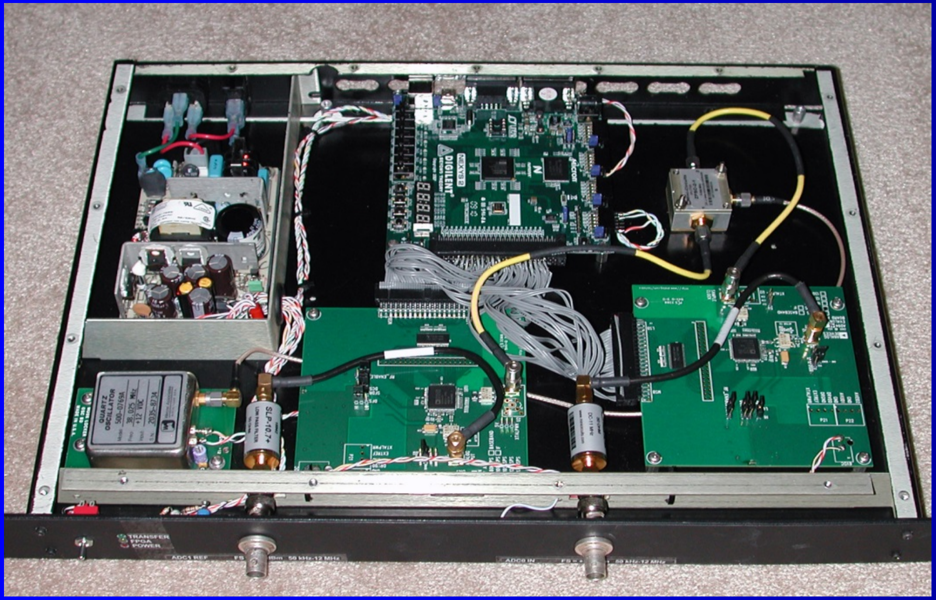
- State of the art performance of commercial gear is better than most users will need
  - Symmetricom TSC 5120A: about $25,000
    - ADEV floor near 3E-15/s (“3 fs”), BW=0.5 Hz
    - PN floor near –175 dBc/Hz
  - Agilent E5052B: about $90,000
    - PN floor near –180 dBc/Hz
  - A phase-noise analyzer with 10-15 dB worse performance would still be extremely useful

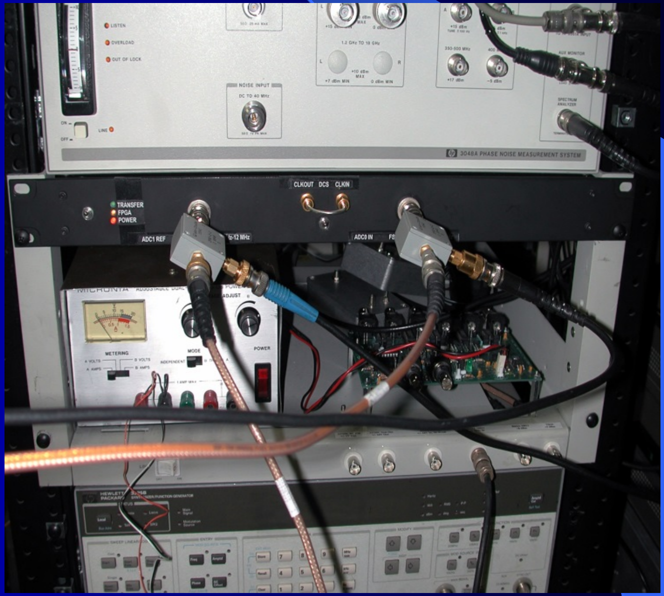
- ADC eval boards to the rescue again…
  - 2x AD9446100LVDS/PCBZ-ND ($220 each)
    - 100 MSPS x16 bit, jitter = 60 fs RMS
  - Nexys2 FPGA trainer ($129)
    - Spartan3E FPGA with 1.2M equiv gates
    - USB 2.0 high-speed interface, 30+ MB/sec
  - Surplus Wenzel 38.025 MHz OCXO from eBay used for initial experiments ($25)

Prototype direct digital phase noise/timing analyzer

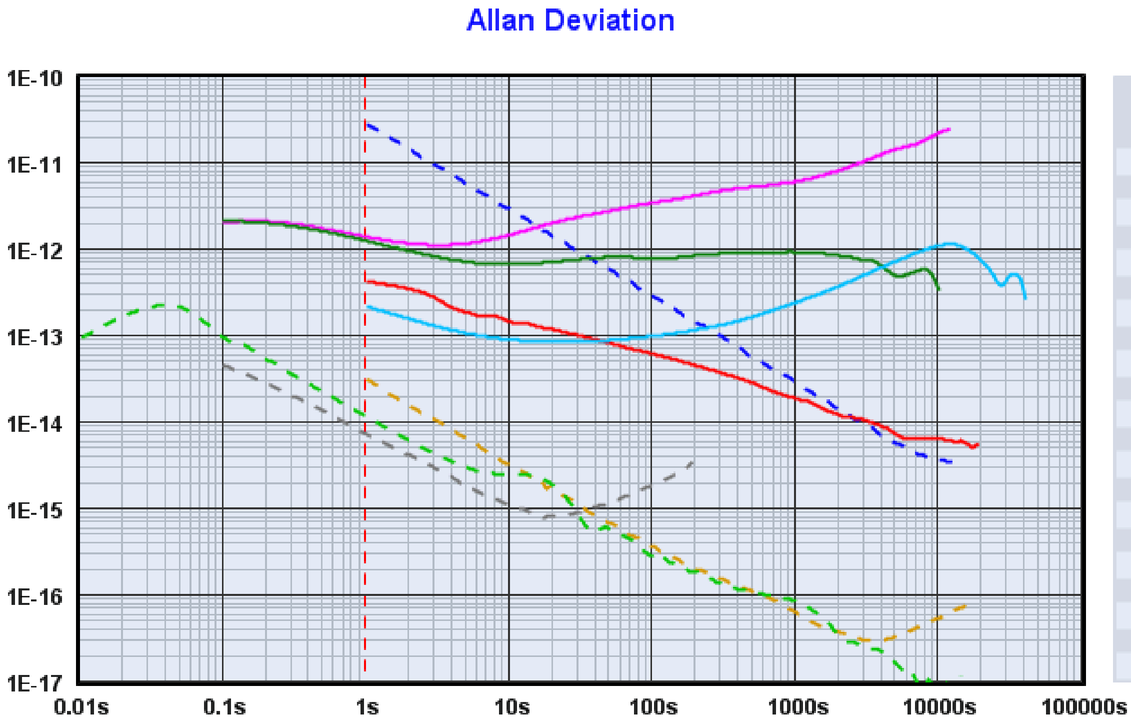


Prototype direct digital phase noise/timing analyzer





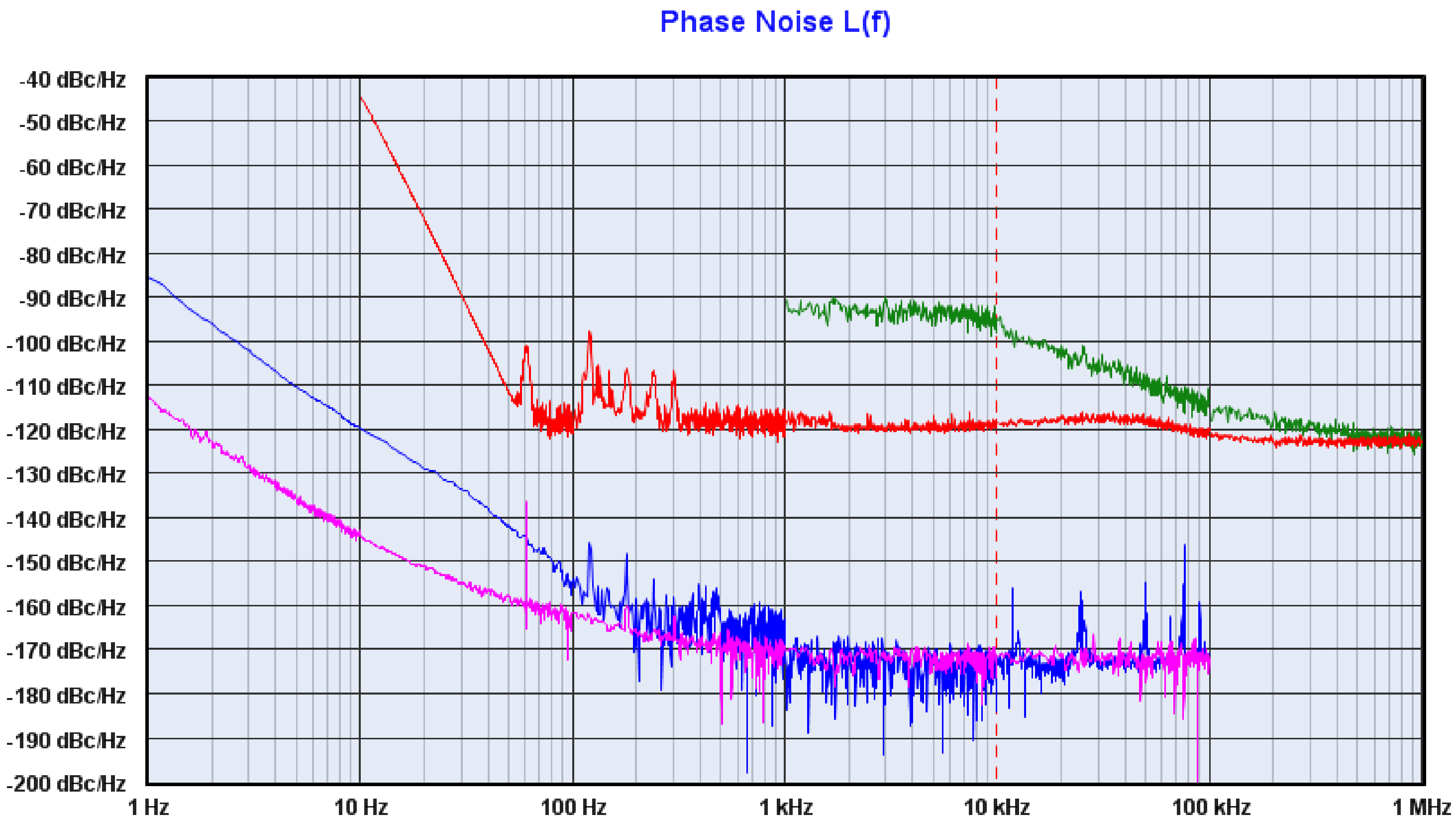
Timing performance shootout



Tau	Sigma(Tau)
0.005s	4.87E-014
0.01s	9.51E-014
0.02s	1.72E-013
0.04s	2.32E-013
0.05s	2.18E-013
0.1s	9.70E-014
0.2s	5.32E-014
0.4s	2.82E-014
0.5s	2.28E-014
1s	1.18E-014
2s	6.22E-015
4s	3.52E-015
5s	3.04E-015
10s	2.56E-015
20s	1.90E-015
40s	5.59E-016
50s	6.04E-016
100s	3.02E-016
200s	1.94E-016
400s	1.19E-016
500s	1.10E-016

Trace	Notes	Input Freq	ADEV at 1s	Instrument
Residual floor (Broken trace)	10811 via TADD-2 divider	1.000E+007 Hz	2.7E-011	HP 5370A/B
HP 10811A oscillator	5065A	10E6 Hz	1.4E-012	TimePod
Trimble Thunderbolt (optimized)	HP 5065A	10E6 Hz	1.3E-012	TimePod
KVARZ CH1-76 passive H-maser	KVARZ CH1-75 active H-maser	5E+6 Hz	4.2E-013	TSC 5110A
Oscilloquartz BVA 8607/008	KVARZ CH1-75 active H-maser	5E6 Hz	2.2E-013	TSC-5110A
Residual floor (Broken trace)	10811 w/splitter	10E6 Hz	3.2E-014	TSC 5110A
Residual floor (Broken trace)	10811 w/splitter	9999999.7 Hz	1.2E-014	TimePod
Residual floor (Broken trace)	10811 w/splitter	10E6 Hz	7.5E-015	TSC 5120A

Phase noise performance shootout



Trace	Input Freq	Ref Freq	dBc/Hz at 10 kHz	Instrument
Wenzel ULN OCXO	4999999.676 Hz	4999999.676 Hz	-173.6	TimePod
Wenzel ULN OCXO	5000000.000 Hz	10E6 Hz	-171.3	TSC 5120A
Tektronix 492P	100000000 Hz		-95.8	TEK 492P
HP3585A PN floor	10000000 Hz		-118.6	HP3585A/B

Commercial efforts

2011 TimePod 5330A
2012 Microsemi 3120A
2019 PhaseStation 53100A

http://www.miles.io/PhaseStation_53100A_user_manual.pdf

http://jackson-labs.com/index.php/products/phasestation_signal_source_analyzer

http://www.ke5fx.com/stability.htm

Collection of useful links for phase noise and timing metrology, updated frequently

Special thanks to Marc Mislanghe for contributing photos and artwork for this presentation, and to Keysight Technologies and http://www.hparchive.com for their support in making the material available!