Frequency Stability Measurement: Technologies, Trends, and Tricks

Presented at Microwave Update 2010
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 10-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)

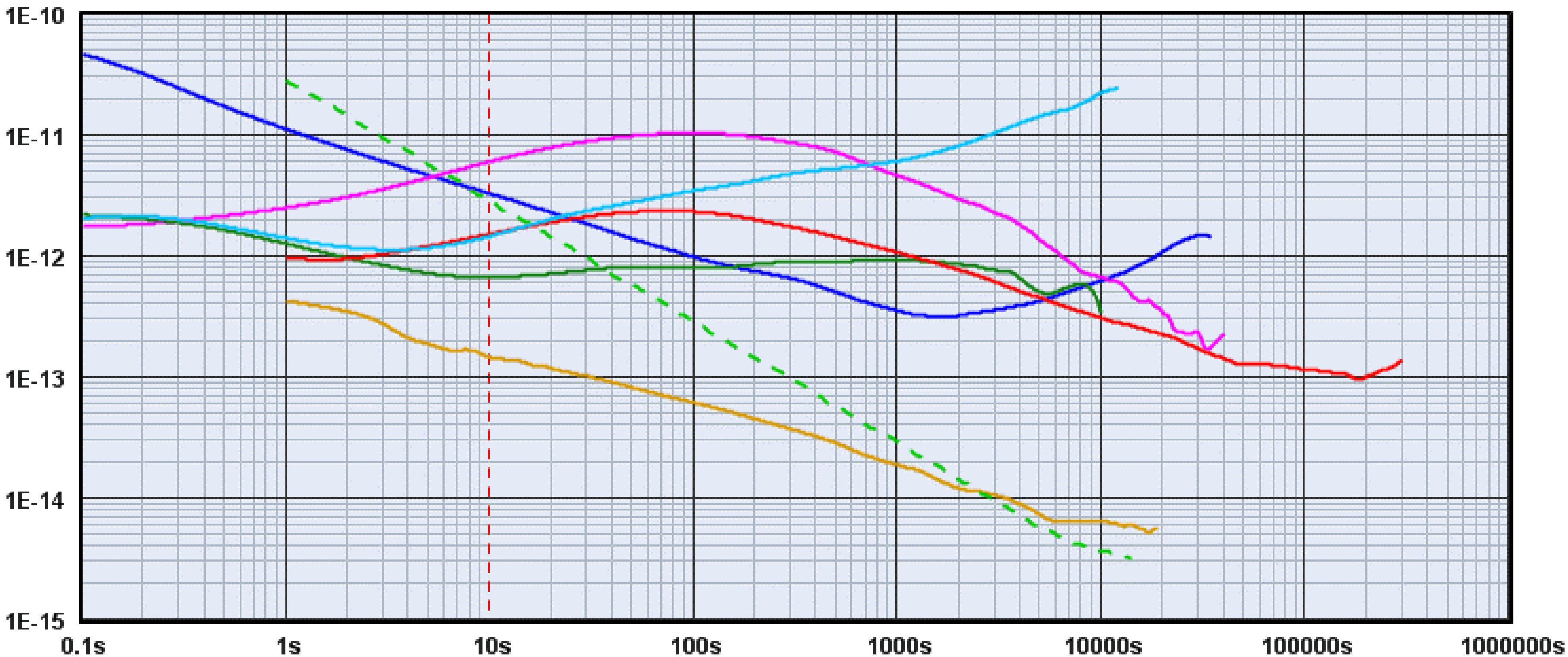
Averaging window: Per-pixel

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

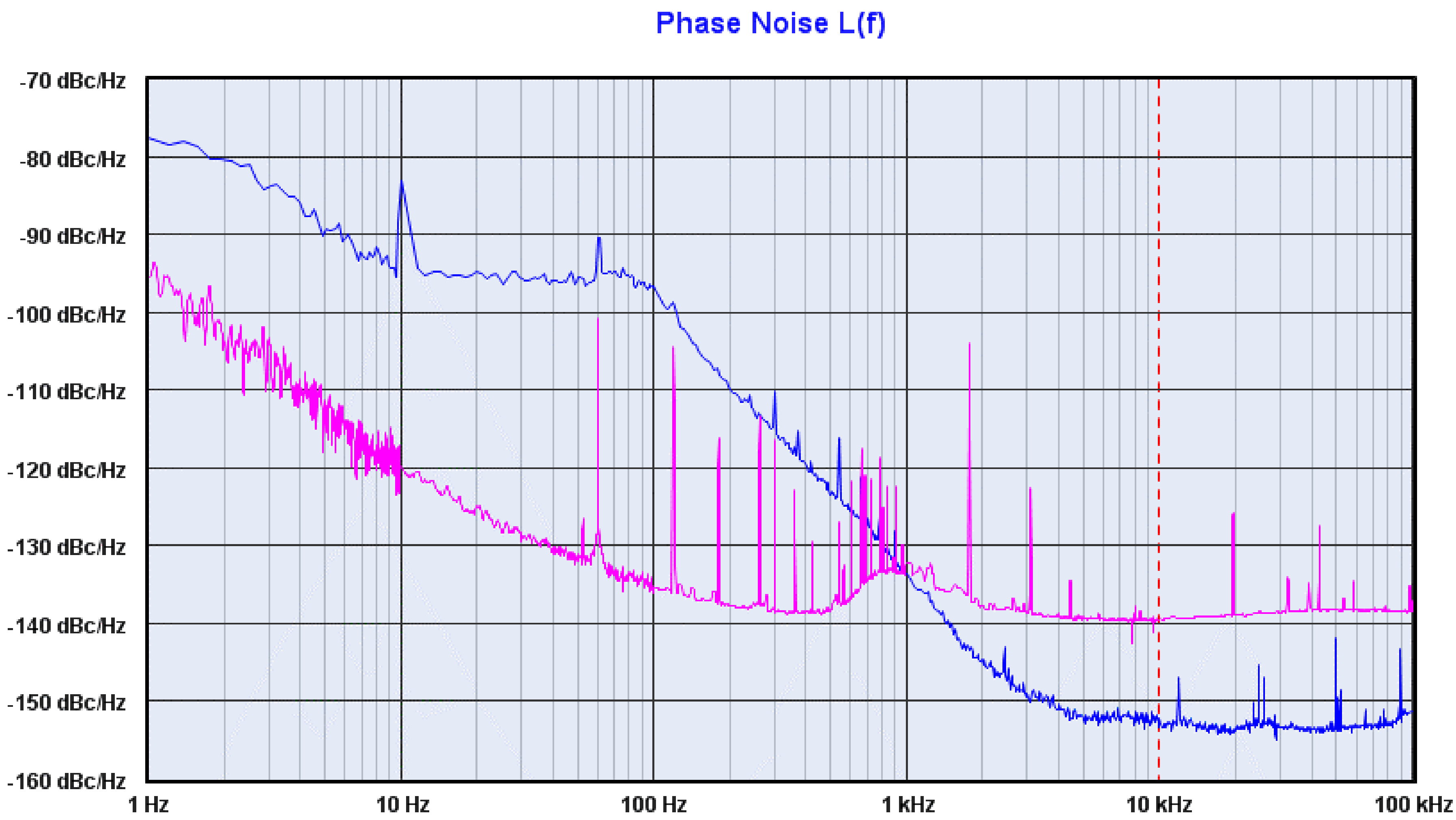
Allan Deviation



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/awkward 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 Mininum 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

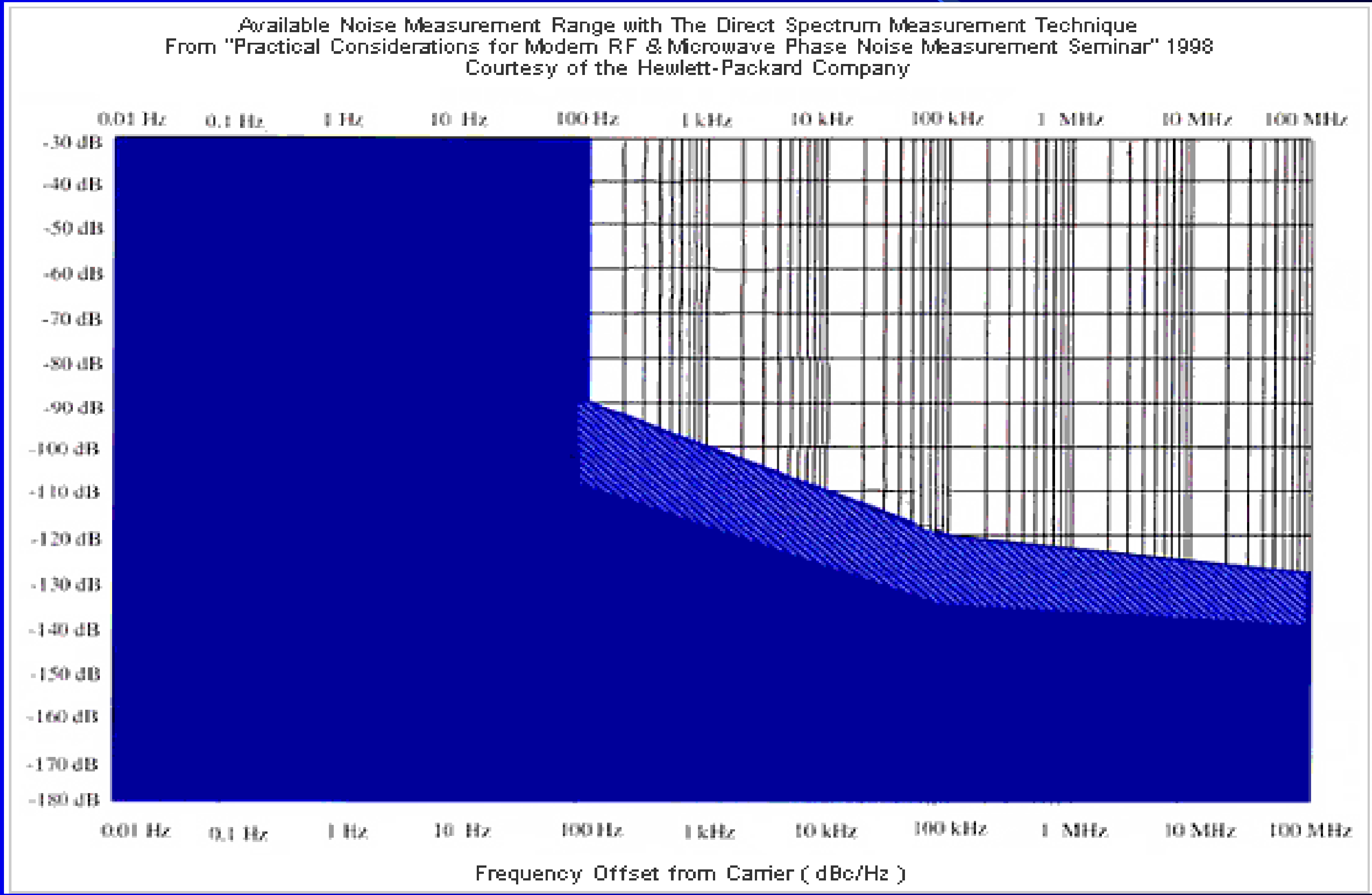
… so how do we measure it?

- 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

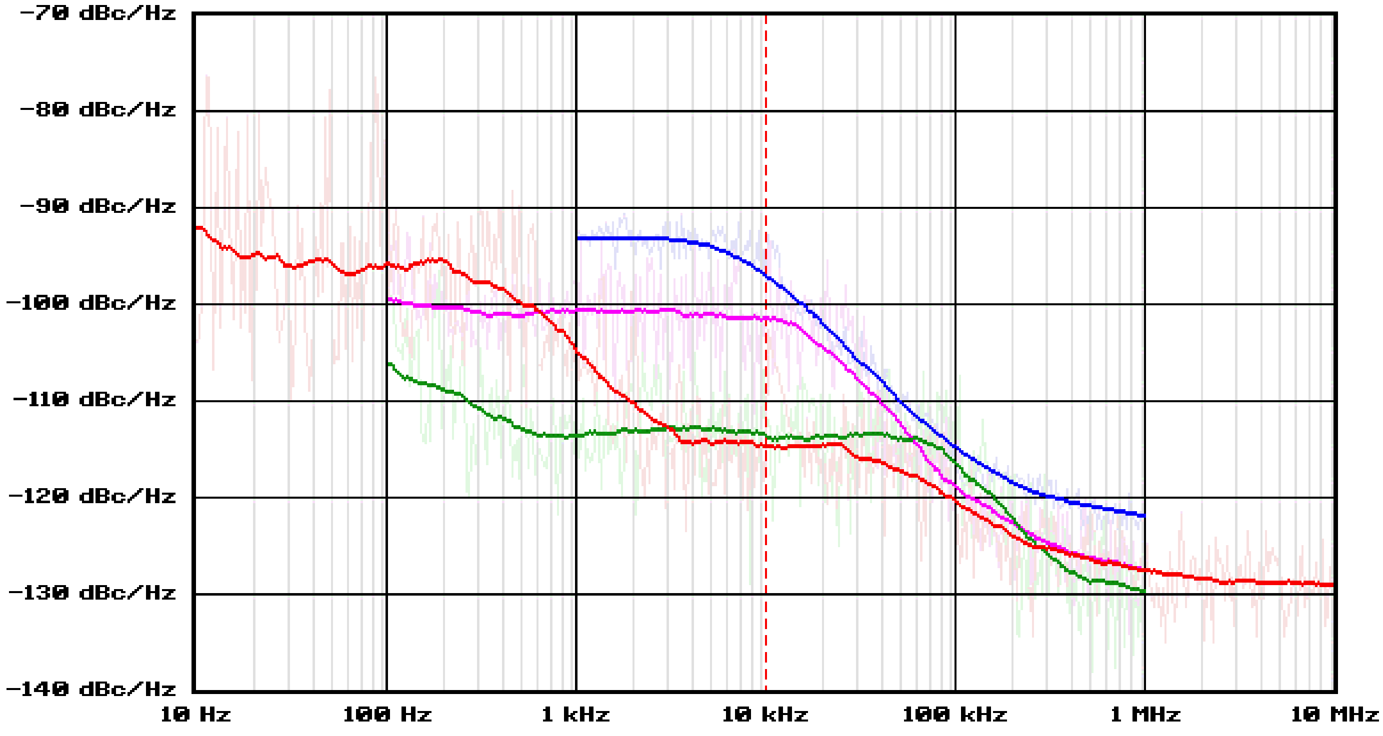
Direct spectrum analysis

- Measures composite (AM+PM) noise
- Limited by instrument's LO noise floor
- Calibration process involves a few factors…
  - 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 (ENBW) of the RBW filter
    - Usually about 0.5 dB for xtal/LC filters or 0.25 dB for FFT
- 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 from www.ke5fx.com/gpib/pn.htm
    - OEM phase-noise personality software (HP 85671A, R&S FS-K4…)

Direct spectrum analysis



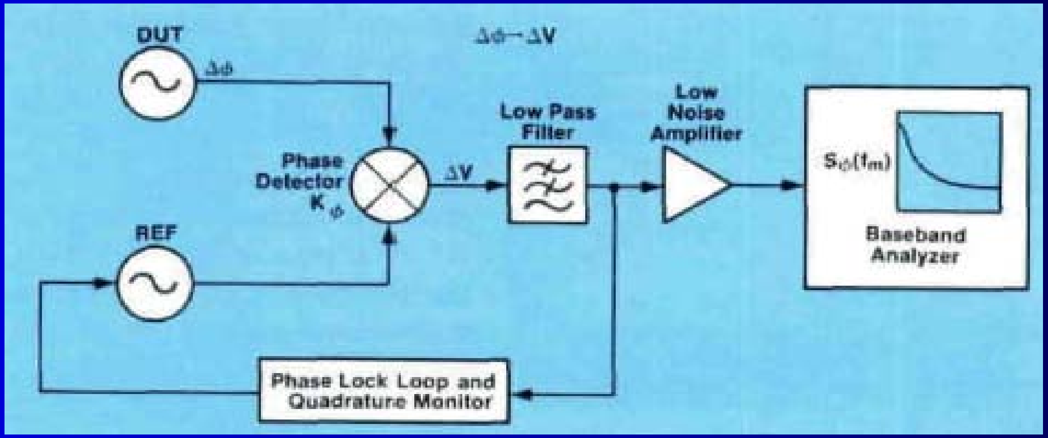
Direct spectrum analysis: some typical instrument floors



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

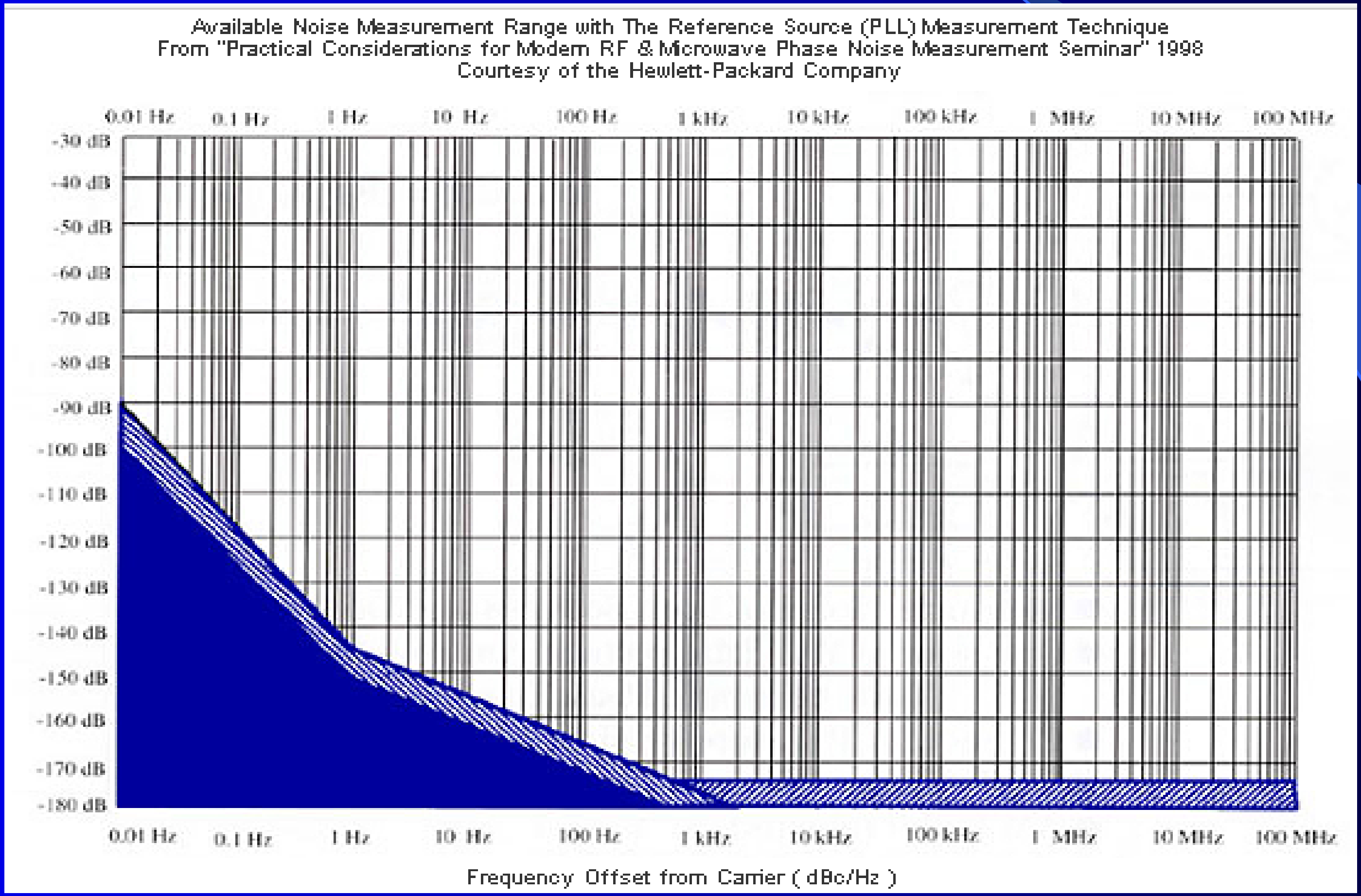
- Downconvert signal from DUT to 0 Hz ("baseband")
  - Simple PLL with mixer as phase detector
  - Commonly-cited references
    - HP Product Note 11729B-1
    - www.wenzel.com/documents/measuringphasenoise.htm



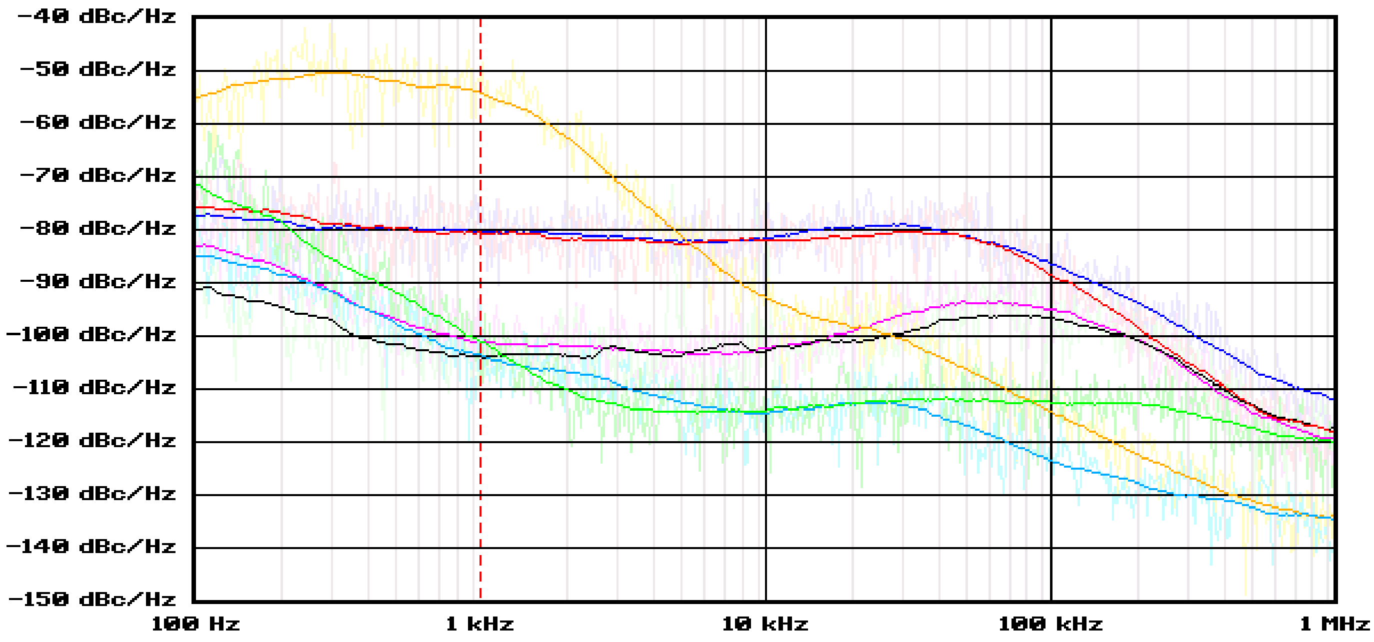
Indirect PN analysis: Phase Detector method

- 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 PN, HP 3047A, HP 3048A, Agilent E5500…

Indirect PN analysis: Phase Detector method



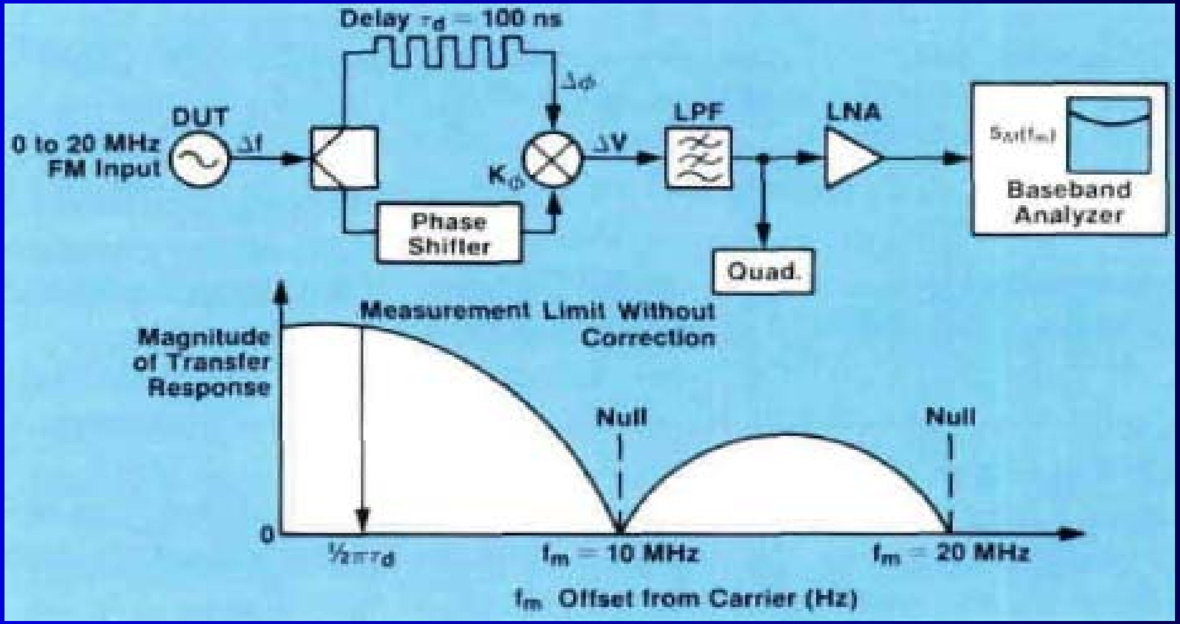
Phase Detector method: some typical measurements



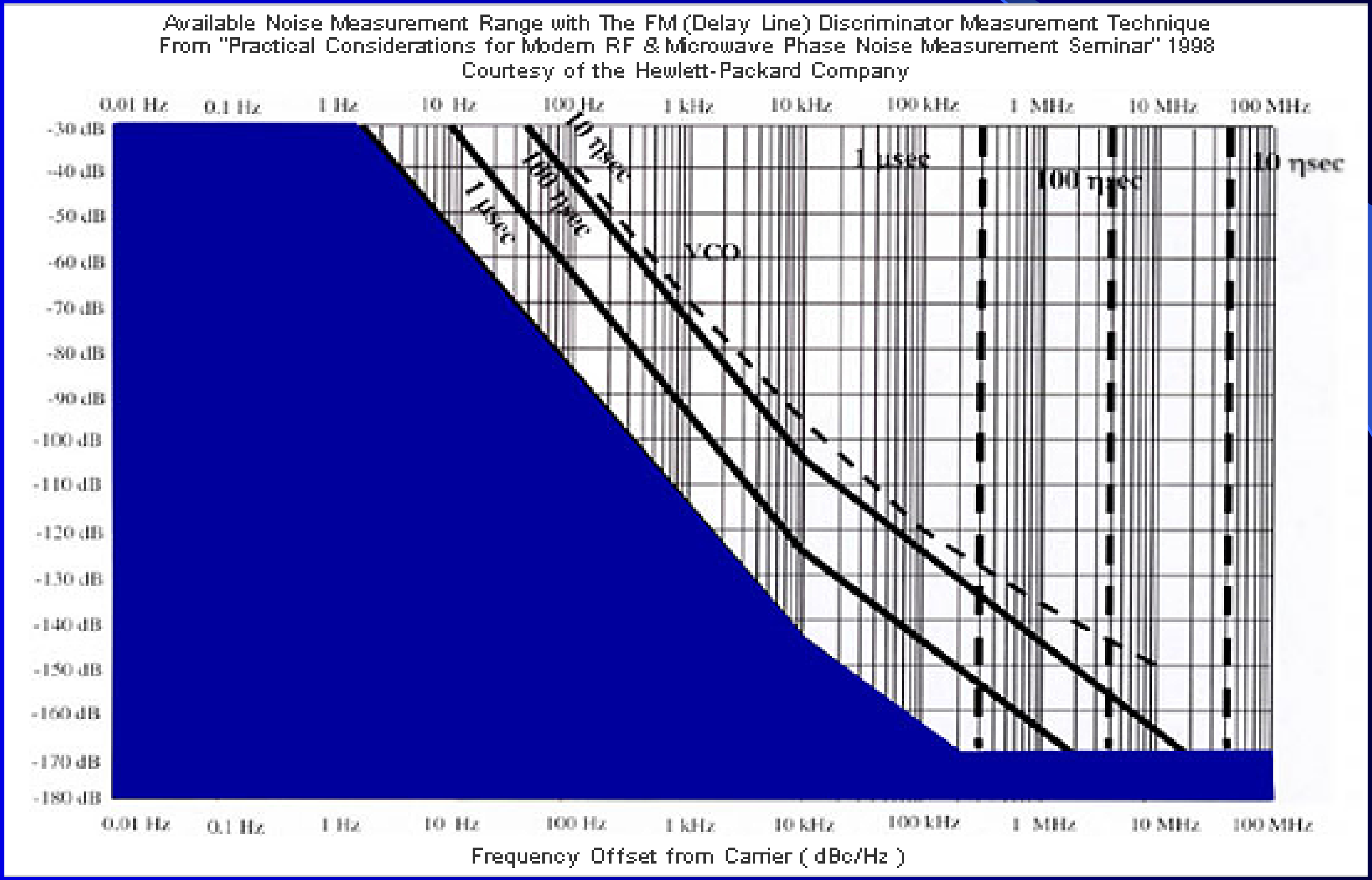
Trace	Carrier Hz	dBc/Hz at 1000 Hz
10 MHz ref (HP 8566B OCXO via MC100EL16), 80 kHz LBW	8 000 000 000	-80.4
100 MHz ref (Bliley OCXO), 200 kHz LBW	8 000 000 000	-101.0
80 MHz ref (Wenzel ULN OCXO), 200 kHz LBW	7 680 000 000	-104.0
ADF4112-based PLL, 100 MHz ref (Bliley OCXO), 46 kHz LBW	8 000 000 000	-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

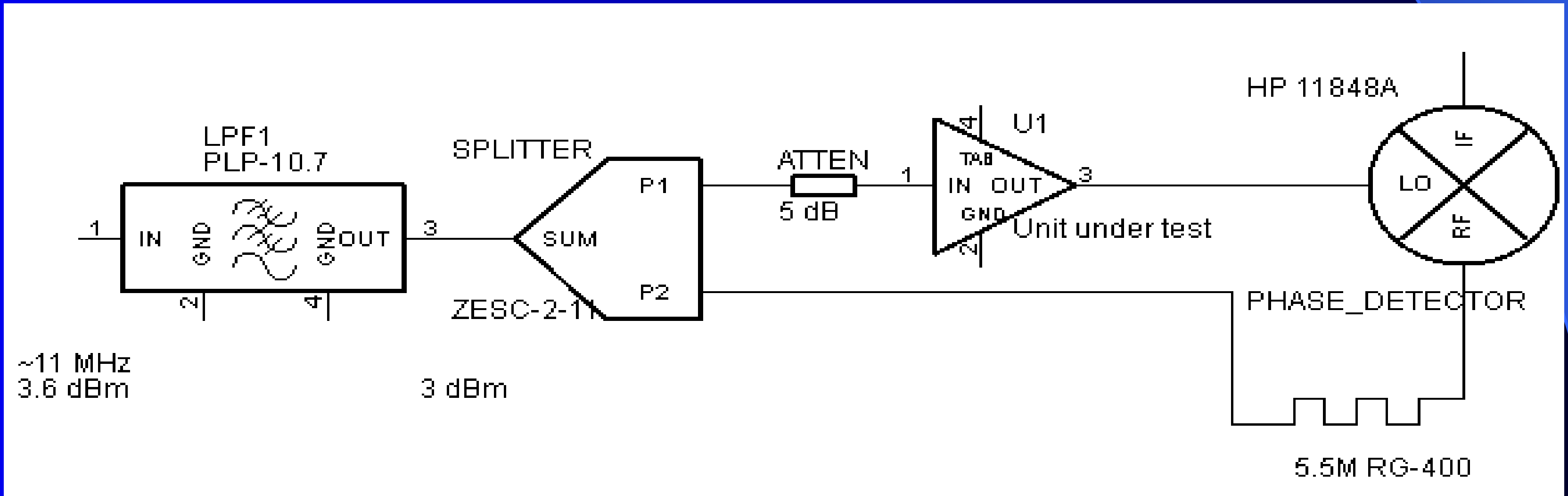


Indirect PN analysis: Frequency Discriminator method

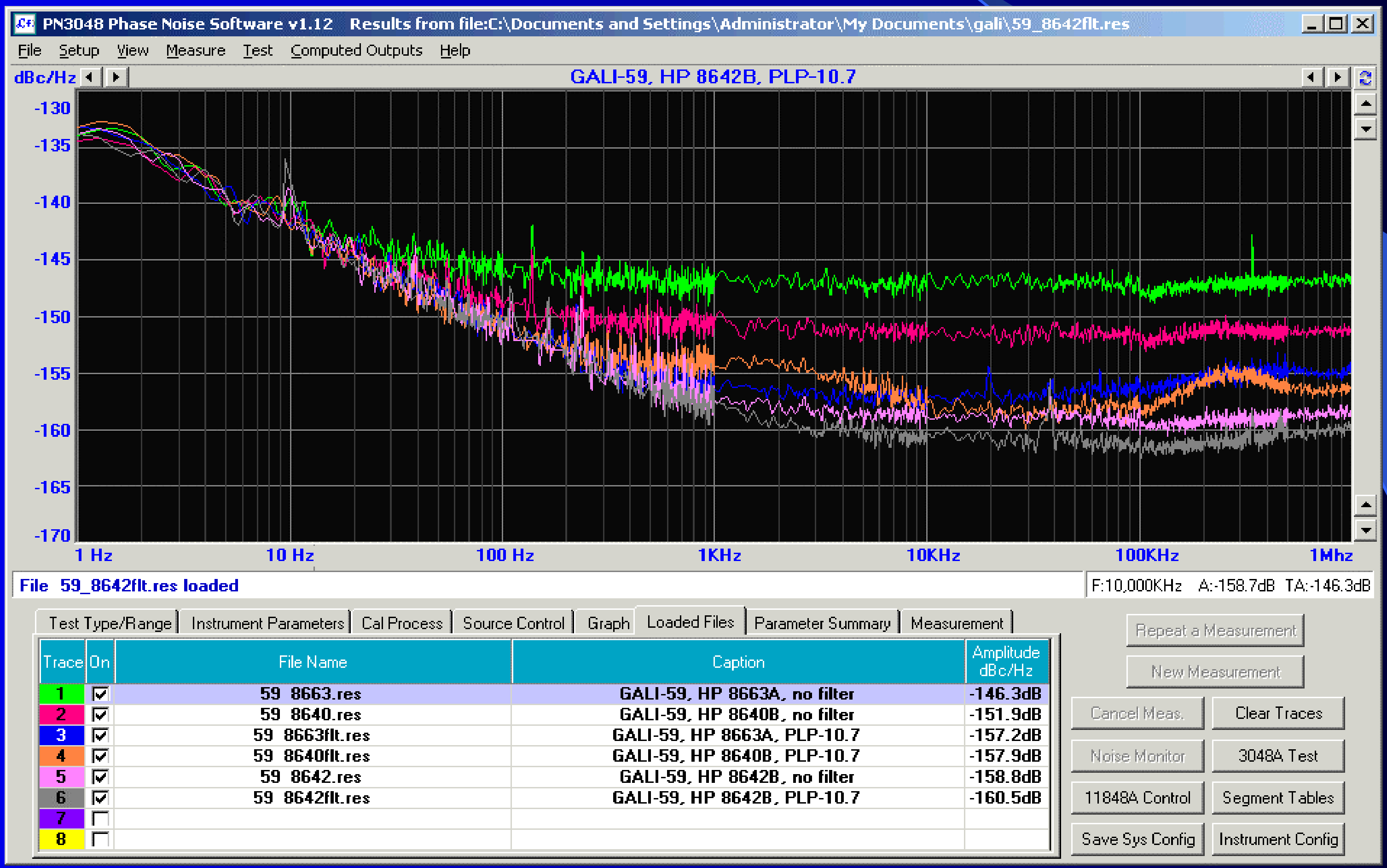


Indirect PN analysis: Two-port residual measurements

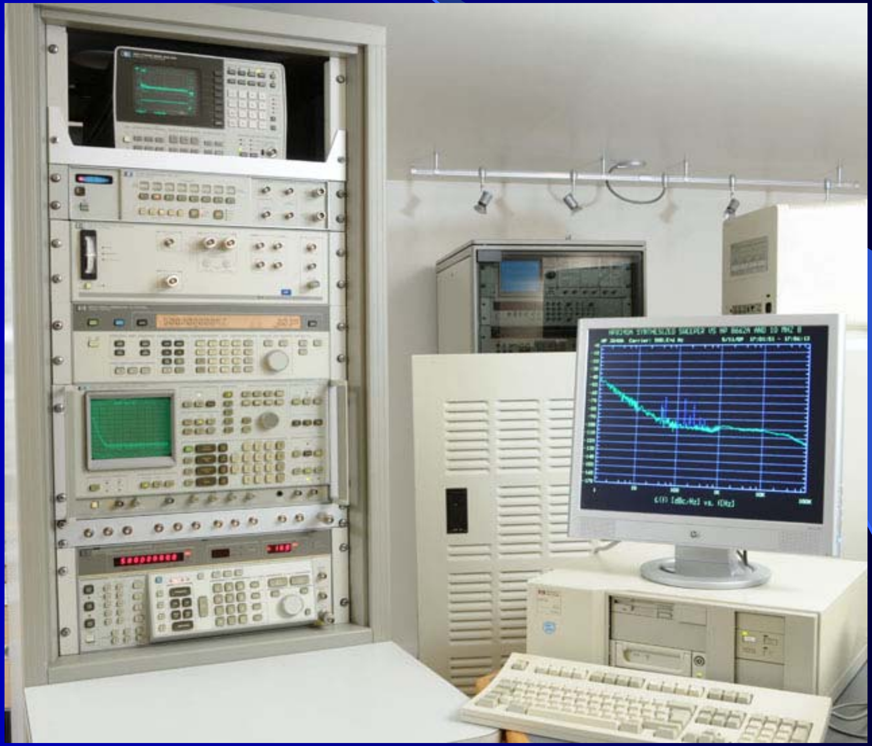
- Useful variation on discriminator measurement
- Replaces delay line with DUT
- Must drive splitter with a clean signal source or its broadband noise will decorrelate and fold…



Indirect PN analysis: Two-port residual measurements



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



See www.hpmemory.org/news/3048/hp3048_01.htm

Great collection of HP app notes on indirect PN measurement!

Homebrewing a quadrature PLL

- Simple type-2 PLL with DBM and opamp
  - http://www.wenzel.com/documents/measuringphasenoise.htm
  - Several other references at end of this slide deck
- Can measure two sources with a microwave mixer
- Can also use a downconverter for a single microwave source, with a stable HF reference on the other port
  - HP 11729B/C block diagram is a good example of this technique
- 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 analyzers offer some advantages, though…

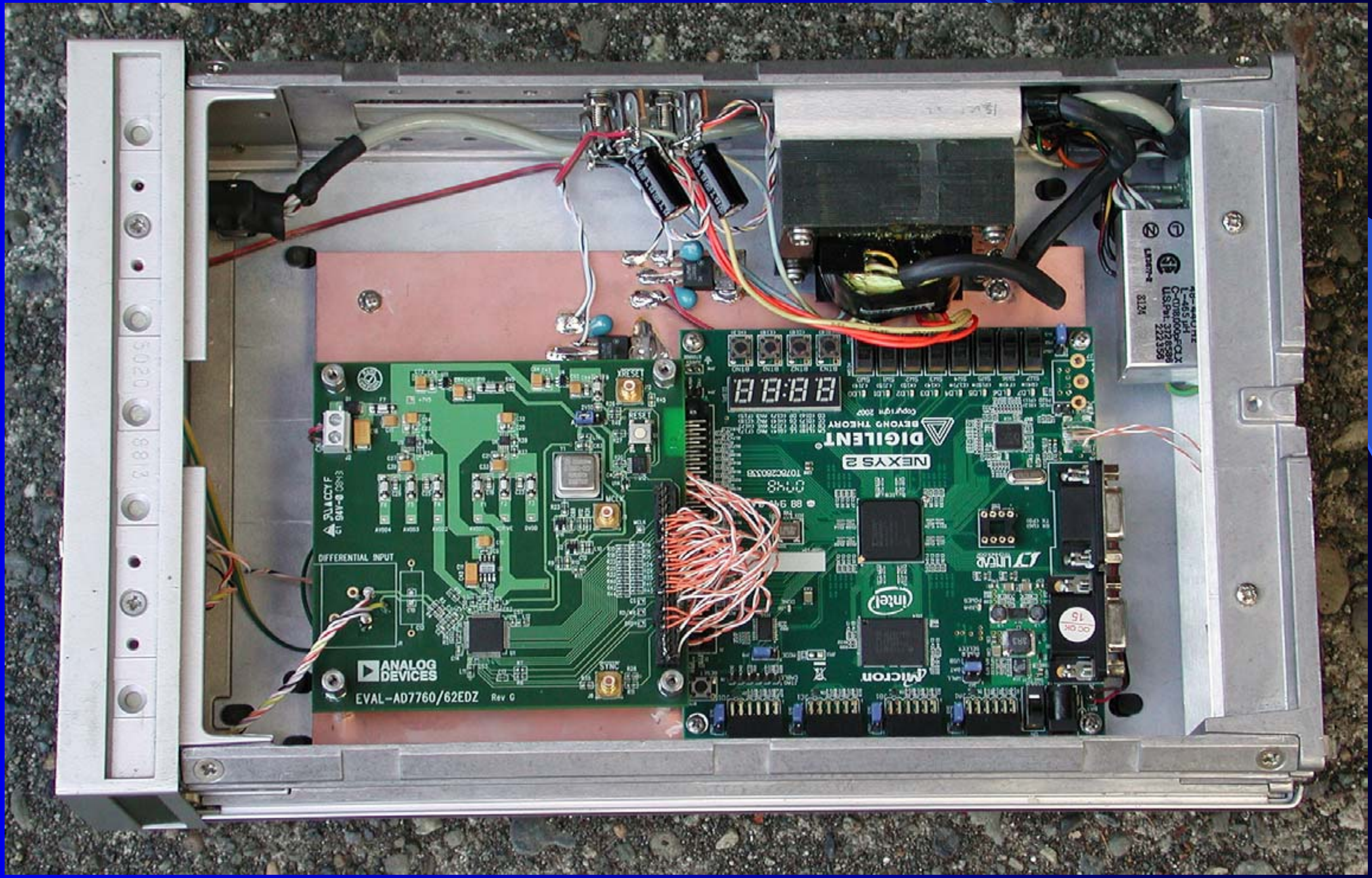
Baseband analysis for indirect measurements

- Advantages of popular surplus FFT analyzers
  - Faster ‘sweeps’ with FFT versus conventional RF analyzers
  - Resolves noise at offsets down to 1 Hz or better
    - Not too important at RF/microwave but can be good for HF work
- 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 doesn’t work with popular baseband analyzers like HP 3561A, 3562A

Baseband analysis: alternatives to older surplus gear

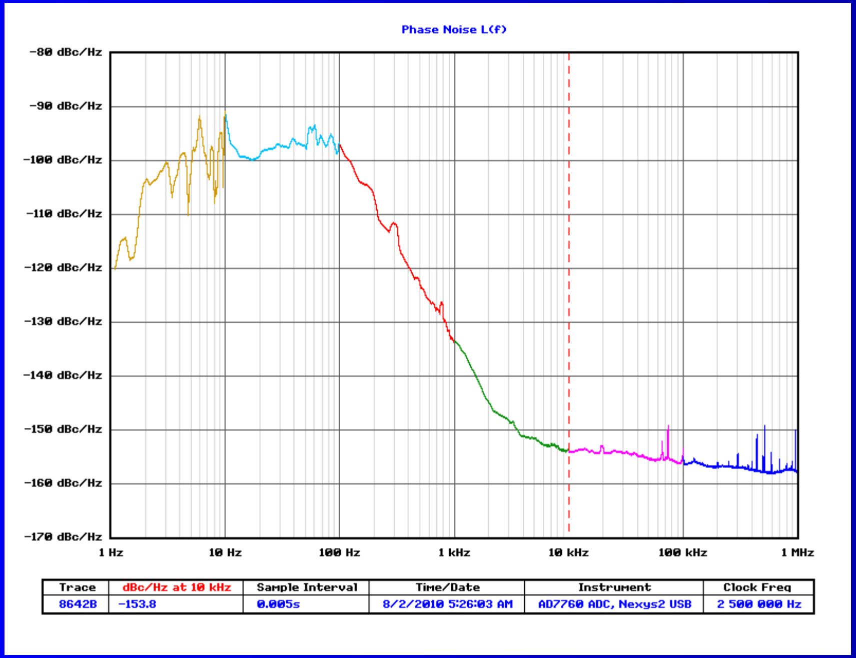
- Software-defined radio hardware with good LF response
  - RFSPACE SDR-IQ supported by TimeLab
    - www.ke5fx.com/timelab/readme.htm
    - $500 retail, 14-bit ADC, can ‘see’ from ~100 Hz-30 MHz
- PC sound cards
  - Planned support in TimeLab
  - Range similar to SDR-IQ, but with widely varying performance
- Homebrew data-acquisition hardware
  - Analog Devices EVAL-AD7760 boards are about $150 each
    - 100+ dB dynamic range at 2.5 MSPS
    - Overall highest performance LF-to-MF ADC I’m aware of
    - Need a very fast PC to perform realtime analysis at full rate!

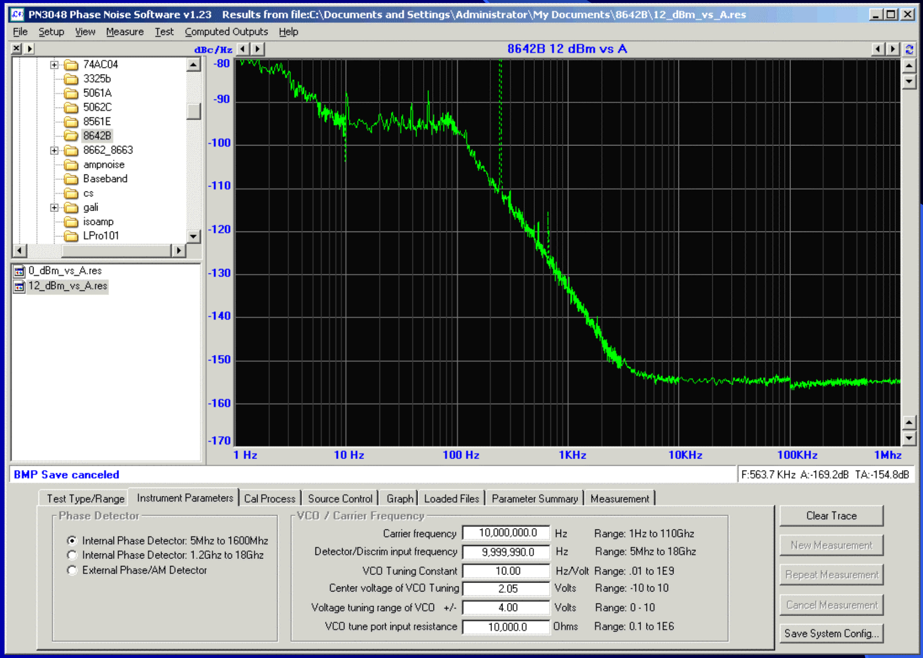
EVAL-AD7760 as baseband analyzer



EVAL-AD7760 as baseband analyzer

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

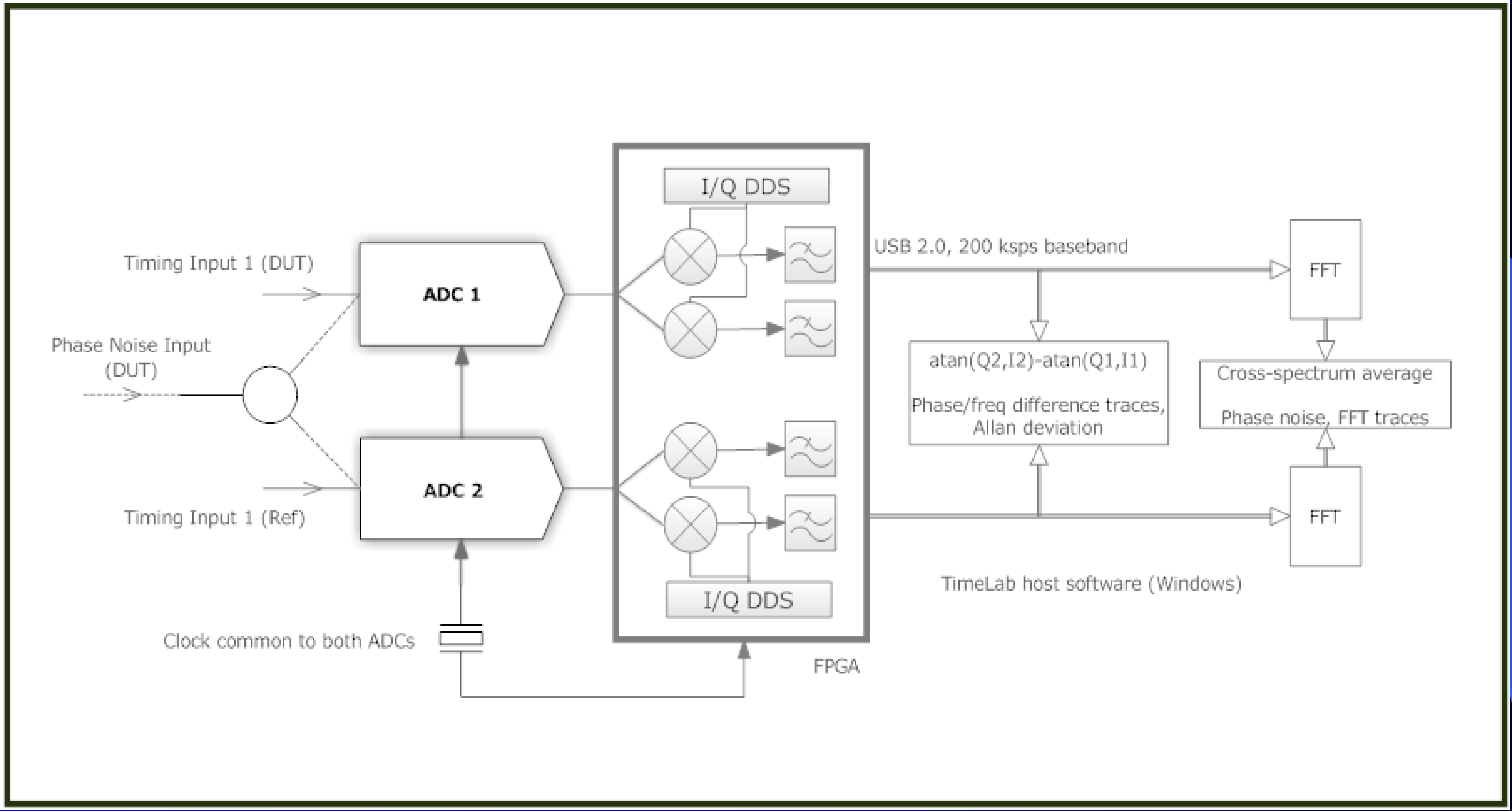




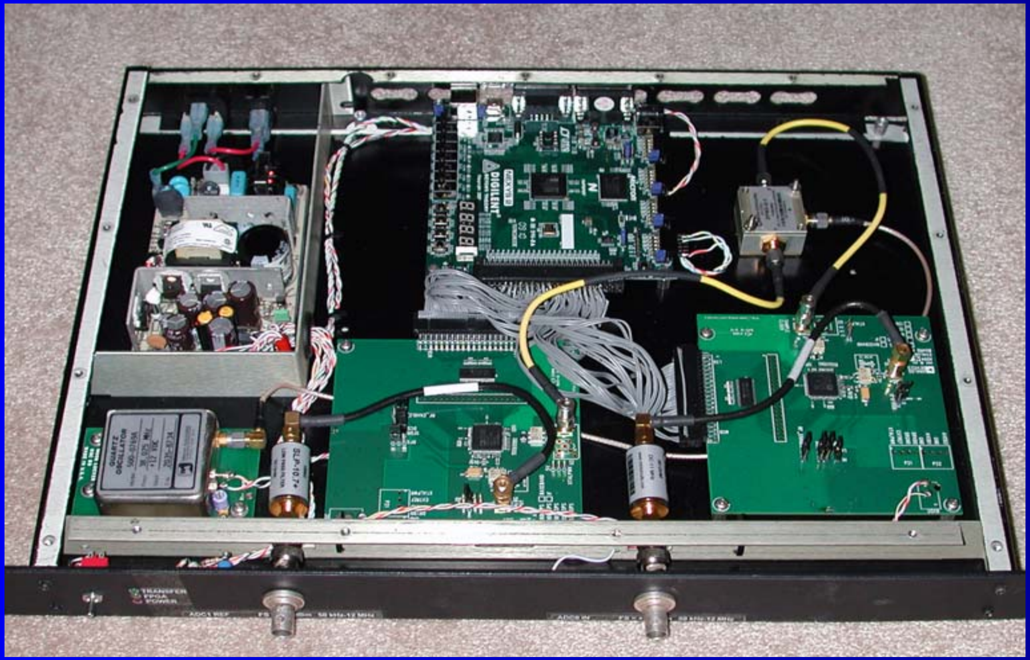
Build a direct digital analyzer instead?

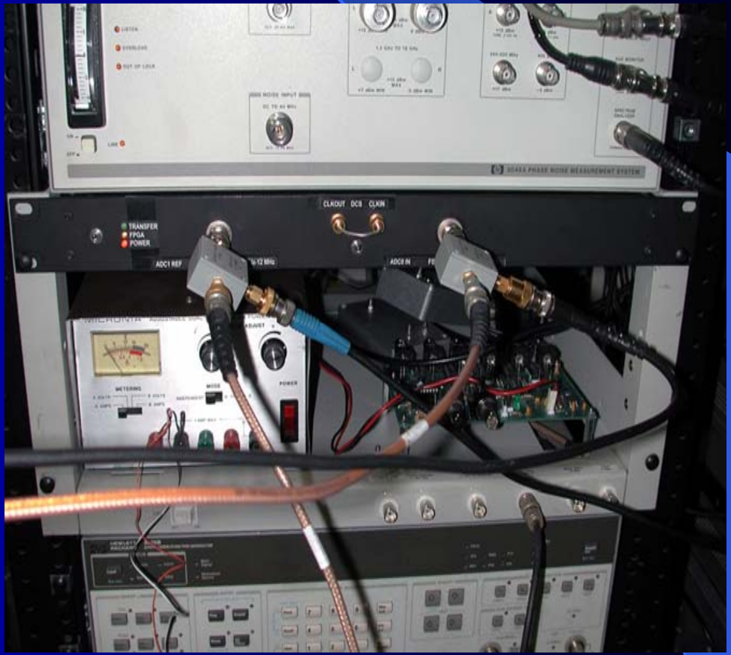
- State of the art performance of commercial gear is better than most users will need
  - Symmetricom TSC 5120A: about $25,000
    - ADEV floor near 3E-15/s (“3 fs”), BW=0.5 Hz
    - PN floor near –175 dBc/Hz
  - Agilent E5052B: about $90,000
    - PN floor near –180 dBc/Hz
  - A phase-noise analyzer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

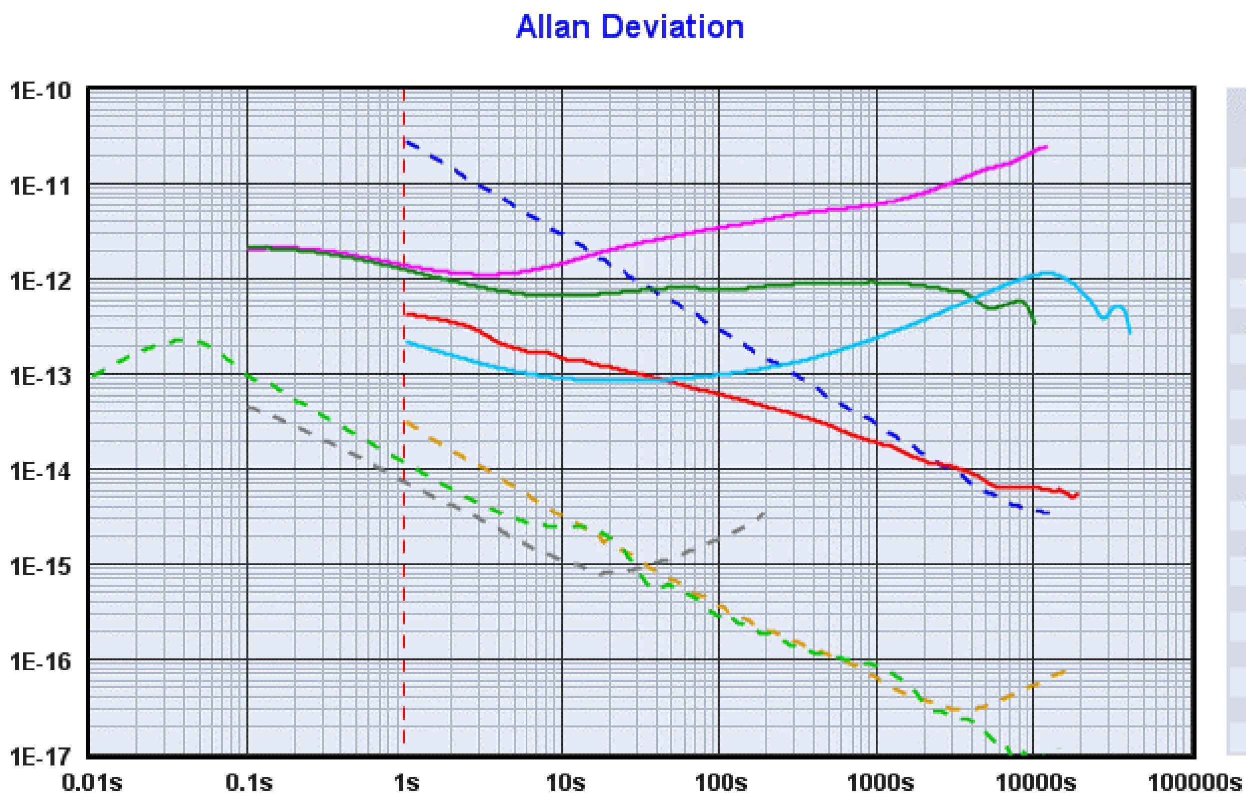


Prototype direct digital phase noise/timing analyzer





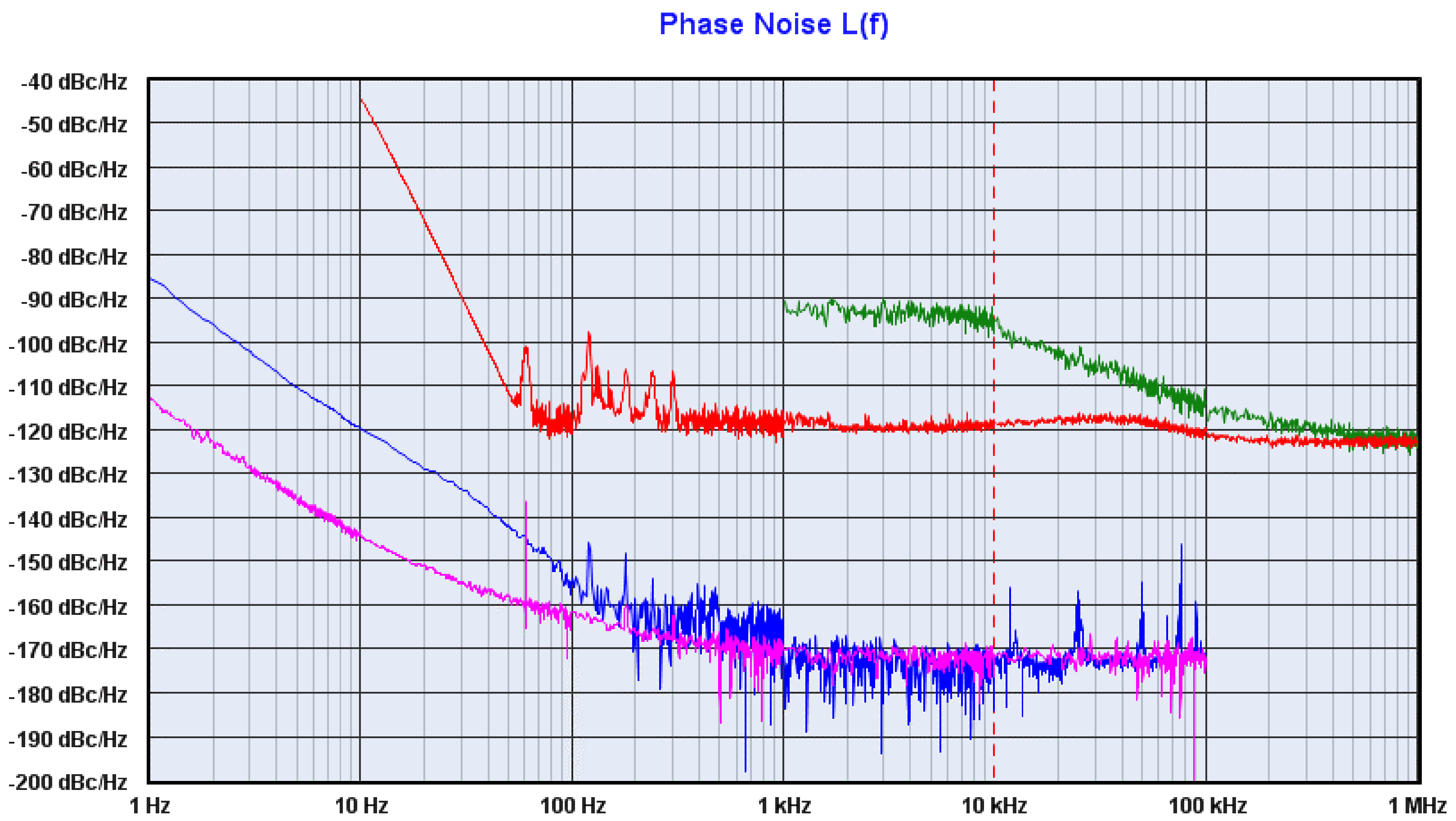
Timing performance shootout



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

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

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

Special thanks to Marc Mislanghe of http://www.hpmemory.org for contributing photos and artwork for this presentation, and to Agilent Technologies for their support in making the material available.