RF Seminar

tinyPFA

MEASURING PHASE AND FREQUENCY

Content

Methods for Measuring Phase and Frequency

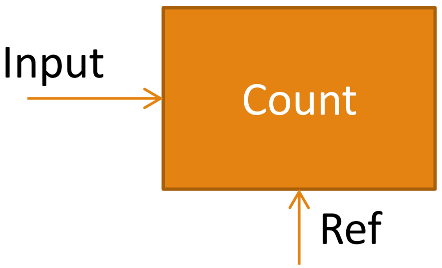
tinyPFA design and implementation

Measuring with the tinyPFA

Two typical measurement configurations

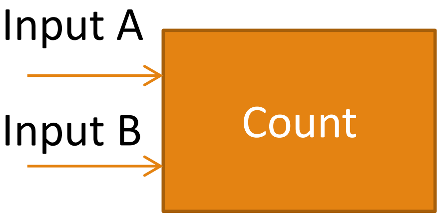
Single input channel measured against an internal or external reference

- Reference frequency fixed and often 10MHz
- Input channel frequency flexible



Two input channels measured against each other

- Input frequencies of both channels flexible but often required to be close
- Internal reference impact eliminated



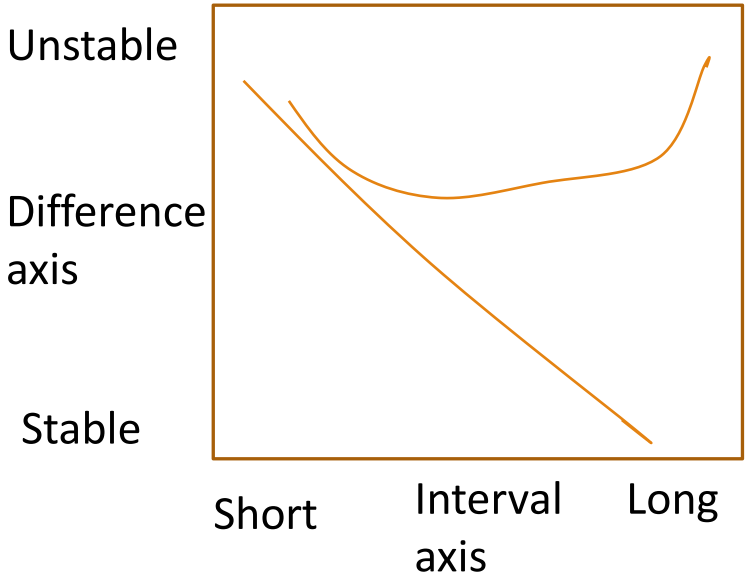
Performance: What is ADEV?

Allan Deviation (ADEV) computes the average difference of two measurements versus the interval between the two measurement and, when applied to measurements of frequency or phase of an oscillator, is a measure for stability. Often plotted in Log-Log scale of Average Difference versus Interval

ADEV number is meaningless without mentioning the interval at which it is measured

ADEV = 1e-10 @ 1 s means:

- Average 1e-10 variation
- When measured with a 1 s interval



Some methods to measure Phase and Frequency

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1:Counting pulses

2:Reciprocal counting

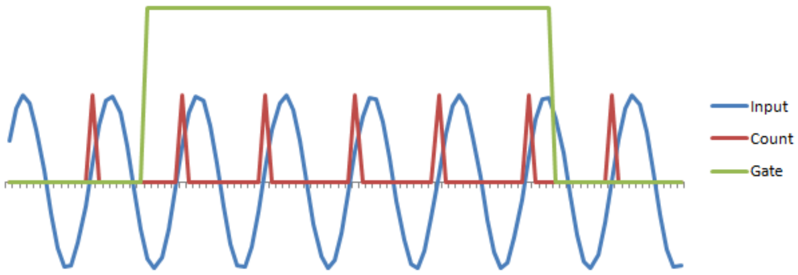
3:Adding interpolation

4:Adding linear regression

5:Dual Mixer Time Difference

6:Direct sampling with I/Q down mixing

1:Counting pulses



Detect “up” zero crossing

Count “up” during defined gate time

Frequency = count / gate time

Problems:

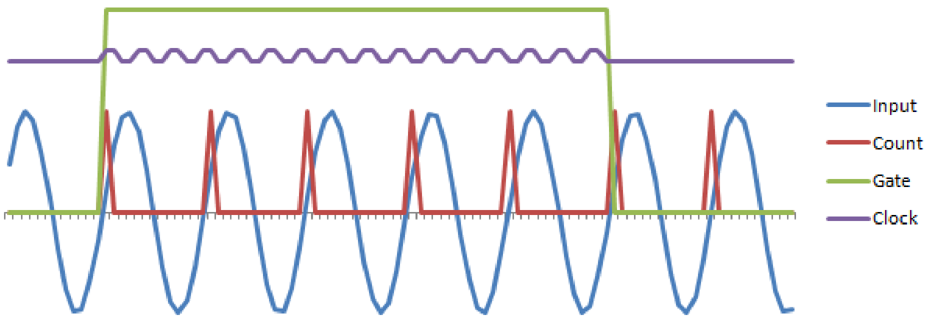
- Noise in zero crossing detection
- Accuracy limited by input frequency and gate time

Accuracy for 10MHz @ 1 s gate time 1e-7

Accuracy for 10Hz @ 1 s gate time 0.1

Example: Cheap eBay counter modules

2:Reciprocal counting



Detect “up” zero crossing

Count “up” edges during gate time

Opening and Closing of gate triggered by “up” edge

Gate time measured using high frequency clock

Frequency = count / measured gate time

No uncertainty in count

- Accuracy independent of count, only impacted by high frequency clock used to measure the gate time.

Problems:

- Noise in zero crossing detection
- Practical speed limit of high frequency clock (200MHz to 1GHz)

Accuracy @ 1s gate time 5e-8 to 1e-9

Example: Many, starting at $300

3:Adding interpolation

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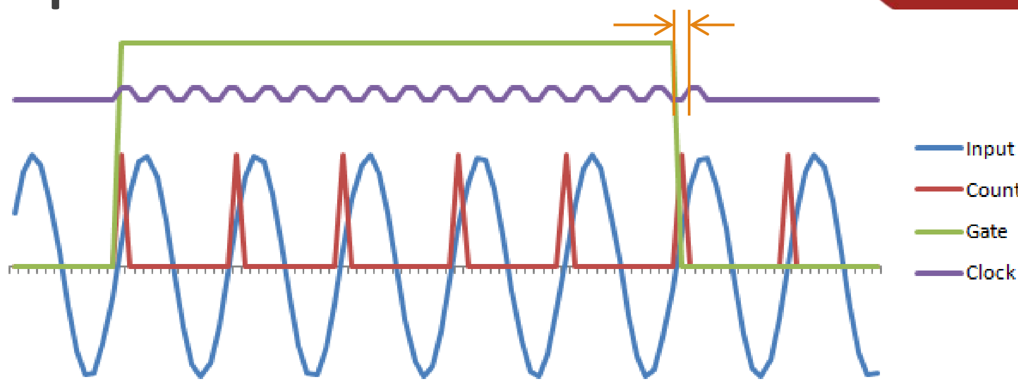


Same mechanism as reciprocal counting

Add measurement of (very short) time between closing of gate and next high speed clock pulse to increase accuracy of gate time measurement.

Problems:

- Analog interpolation temperature dependent and difficult to get gate time measurement better than 1ns
- Digital interpolation with ring counter limited by silicon/GaAs speed. Difficult to get below 15ps

Accuracy for 1s gate time 2e-10

4:Adding Linear Regression

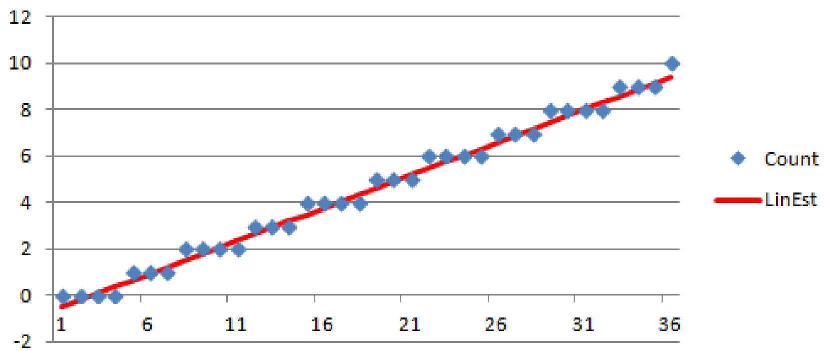
Use reciprocal counter with optional interpolation

Uses the fractional relation between input and ref

Take many measurements using smaller gate time

Typical 10000 to 100000 measurements per second

Calculate linear regression to find fraction



Accuracy improves with square root of number of measurements, factor 100 to 300

Problems:

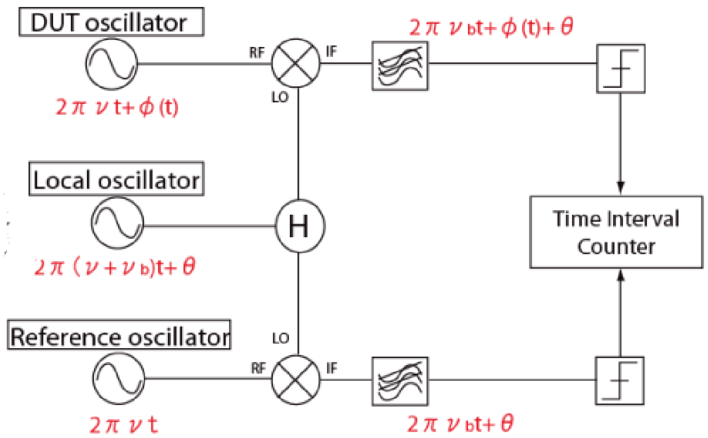
- Regression is like averaging and hides phase noise problems.
- Reaching factor 1000 improvement requires 1000000 points, FPGA for calculation speed
- No solution for noise in zero crossing detection
- Loss of accuracy when input frequency is close to harmonically related to fast reference clock

Accuracy @ 1 s gate time 1e-12

- Limited due to leakage and edge noise
- Accuracy depends on relation with fast reference clock, can degrade to 2e-10

Example: Keysight Technologies 53220A (20ps RMS single shot resolution), price $6000

5:Dual Mixer Time Difference (DMTD)



Two input mixers with same LO

Converts to much lower frequency

Time is stretched by ratio input/output

Low pass filter filters out fundamental.

Measure time difference of mixer outputs

Example:

- Down convert 10MHz to 1Hz gives 1e7 time stretch
- Measure time difference of mixer output using TIC with 1e-9 accuracy
- Theoretical accuracy of 1e-16

Disadvantage:

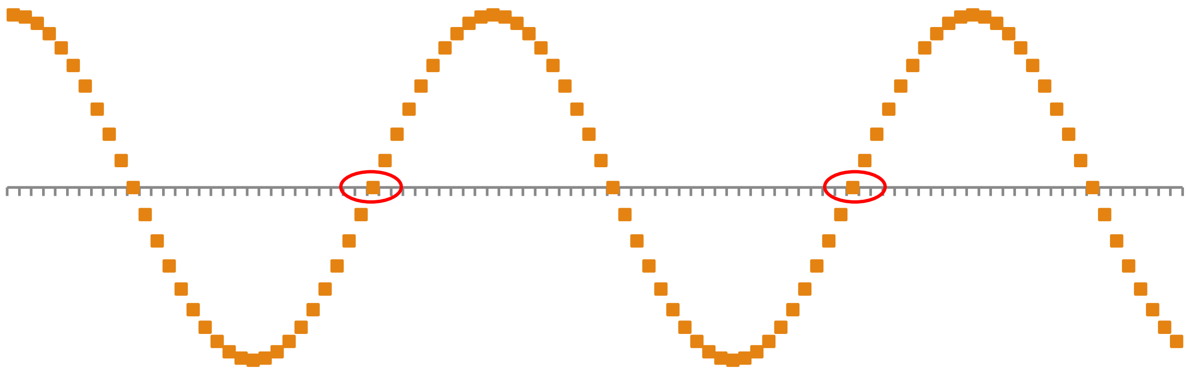
- Down conversion LO must track input frequency at fixed offset
- Still relies on detecting zero crossing

Accuracy @ 1 s gate time between 1e-13 and 1e-14

- Limited by noise, ground loops and leakage

Example: No commercial DMTD products known to me, some DIY realizations found

Making best use of available information



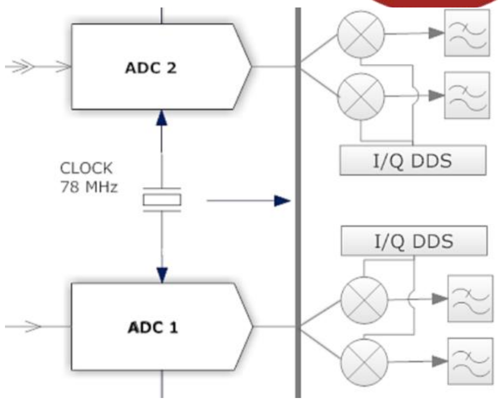
All previous approaches use zero crossing detection (samples in red circles) and ignore the rest of the input signal to determine the phase

- This approach is relevant when the input signal is directly converted to a digital signal

After filtering out the fundamental of the input signal the resulting sine wave contains much more information.

The next approaches use all the information contained in the fundamental of the input signal.

6:Direct Sampling with I/Q mixer



Use two ADC's running from same fast clock

Convert to digital domain

Digital I/Q down mix to zero Hz.

Digital LO locked to input signals.

Digital low pass filter to remove any harmonics.

Atan2(I,Q) gives phase for each input sample.

Calculate phase difference between the two inputs to eliminate sample clock

Advantages:

- More phase data per second, 1e8 instead of max 1e6 with reciprocal counter using linear regression.

Disadvantage:

- Requires very fast ADC's with sufficient amount of bits and fast DSP
- Measured phase is average over measurement time. Use decimation of factor 5 to eliminate this low pass filtering.

Accuracy @ 1 s measurement time between 1e-14 and 1e-15

- Limited due to leakage, ADC noise and bit width of ADC and processing.

Example: PhaseStation 53100A. Price: $3000 - $20000(?)

Why the tinyPFA?

During development of a GPSDO there was suspicion of short term instability.

The available counter (Picotest U6200A, 40ps resolution) was not able to measure this instability (ADEV @1 s : 1e-11)

No other second hand counter had sufficient resolution (Keysight ADEV @1 s: 3e-12)

No second hand PhaseStation available for sale

Can we build something with sufficient speed and accuracy by combining some proven technologies?

- Direct sampling very promising but ADC and FPGA too expensive
- DMTD good on stretching time but problems with noise when doing zero crossing detection.
- How about a hybrid of a DMTD and a PhaseStation?

7: tinyPFA concept: Combining DMTD and PhaseStation

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Two mixers down convert input signals

Use one LO to eliminate impact

LO locked at offset to one of the inputs

LPF to remove harmonics

Use cheap 16 bit audio stereo ADC

Rest is all in the digital domain

Same as Direct Sampling.

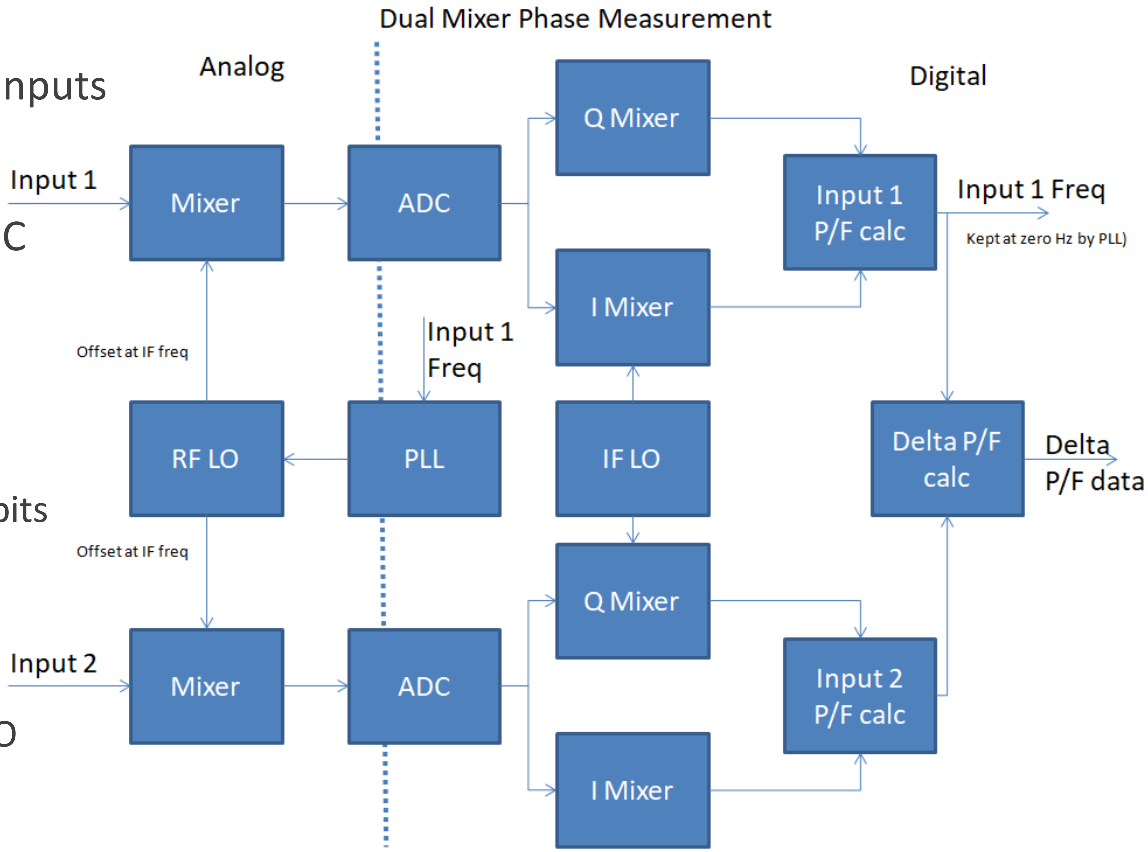
Advantage:

- Much cheaper ADC's with more bits
- Lower DSP speed required.

Disadvantage:

- Less samples
- Requires phase lock of the first LO

Lets do a simulation!

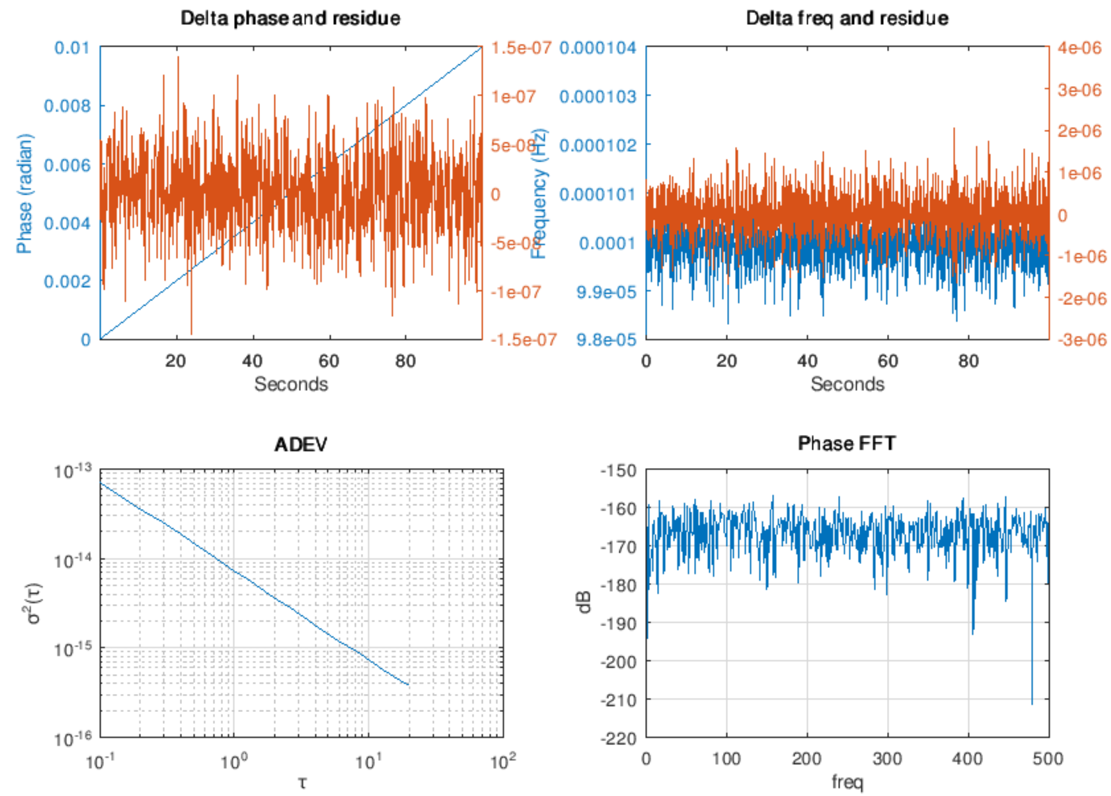


Simulating real world limitations

Limitation	How to include in simulation
There is leakage between the two inputs	Cross add input signals
Mixer introduces noise	Add noise to input signal
ADC has limits number of bits	Limit number of bits of input signal
ADC has limited sample rate	Simulation runs on same sample rate
Calculations of I/Q down mix uses integers for speed	Round all calculations to relevant number of bits, do bit true calculations

Verifying the tinyPFA design

- Simulation of the two channel sampling and I/Q down mix phase, frequency and ADEV measurement in Octave
- Calculates 10 second of measurement (1920000 samples per channel)
- Even with all real world limitations included still a very good performance
- How to implement?



From simulation to implementation

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NanoVNA-H and NanoVNA-H4 contain all required HW

Quick test on NanoVNA-H4 showed promising performance

NanoVNA-H4 MCU just fast enough for the calculations

NanoVNA-H4 HW has some limitations

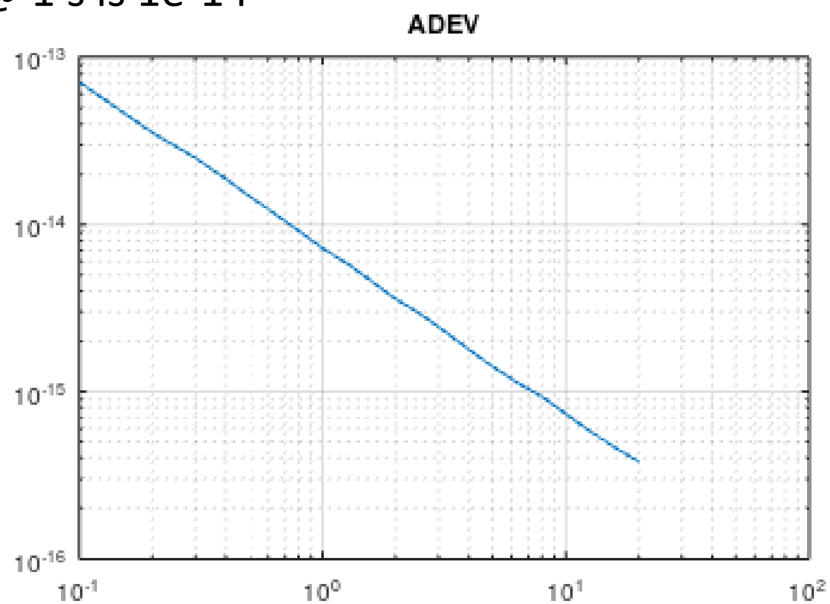
- ADC max bit rate and relevant bits
- Word length of calculations
- Temperature impact on phase due to Gilbert cell mixers

Be aware: tinyPFA SW can not run on any other member of the NanoVNA family!

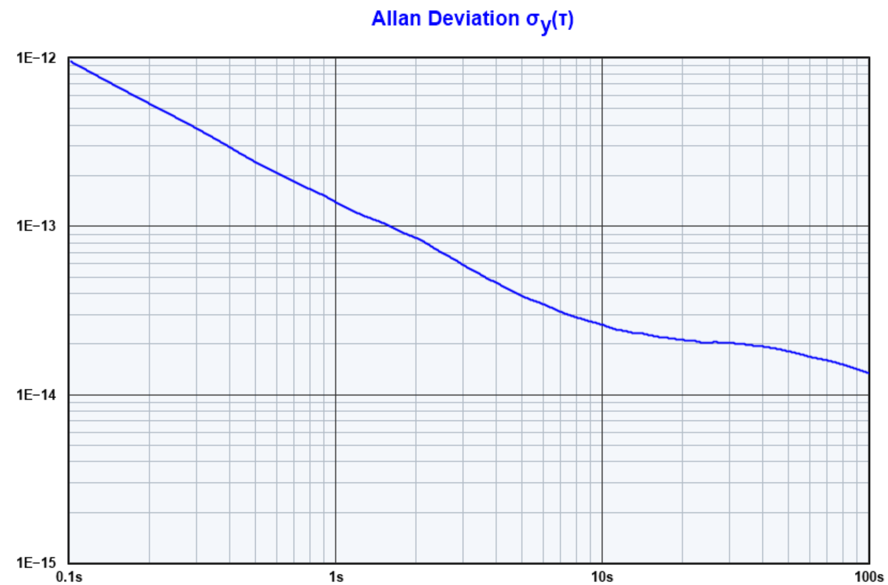
- HW incompatible: NanoVNA-F, SAA-2, LiteVNA, LibreVNA, …
- To slow: NanoVNA-H

Results of simulation vs. actual tinyPFA

Simulation phase accuracy with tau=0.1s @ 1 s is 1e-14



tinyPFA phase accuracy @ 1s is 1.5e-13



Trace	Notes	Input Freq	Sample Interval	ADEV at 1000s	Acquired	Instrument
Noise 9 degrees (Unsaved)		10 MHz	0.100 s		58611 pts	tinyPFA

tinyPFA factor 15 worse

Possible causes of difference:

- ADC does not deliver 16 relevant bits.
  - Confirmed, at 192kHz at least the last 4 bits are pure noise
- Noise levels in tinyPFA is higher

Measuring Frequency with the tinyPFA

TinyPFA can only measure Phase, calculates frequency from phase

Difference in Frequency = difference in Phase / measurement time

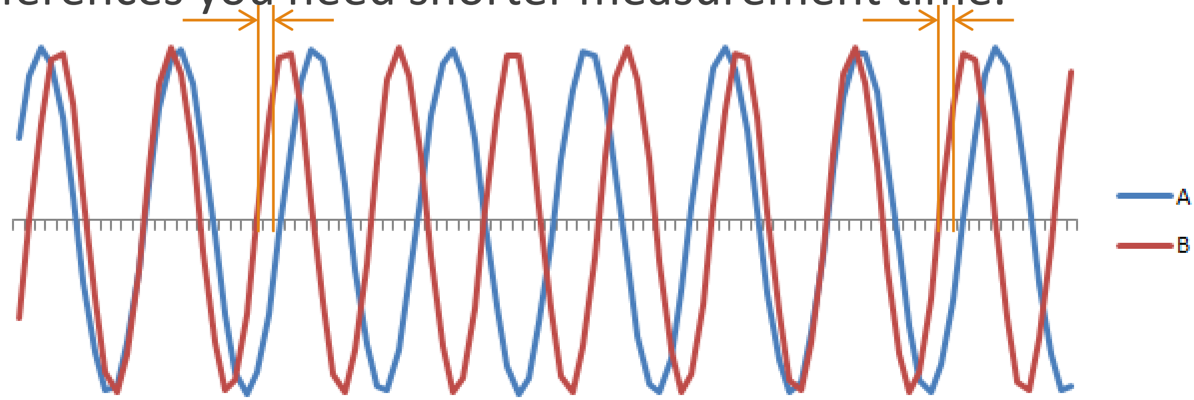
However: Phase is periodic

- 10MHz signal has 100ns period, max phase difference +/- 50 ns

When measuring phase difference you do not know how many Phase Rotations did happen (see picture below)

With 10MHz signals and measuring phase at 1 s interval the maximum frequency difference should be below 0.5 * 100ns (0.5 rotation) or 0.5 Hz difference

To see higher frequency differences you need shorter measurement time.



Measured phase the same but frequency different

Using the tinyPFA

Check input signal level and display samples

Check frequency of input using FFT

Measure single channel frequency

Check quality of input signal

Measure Phase and Frequency of two inputs

What can go wrong?

Further data analysis

Checking level of input signals

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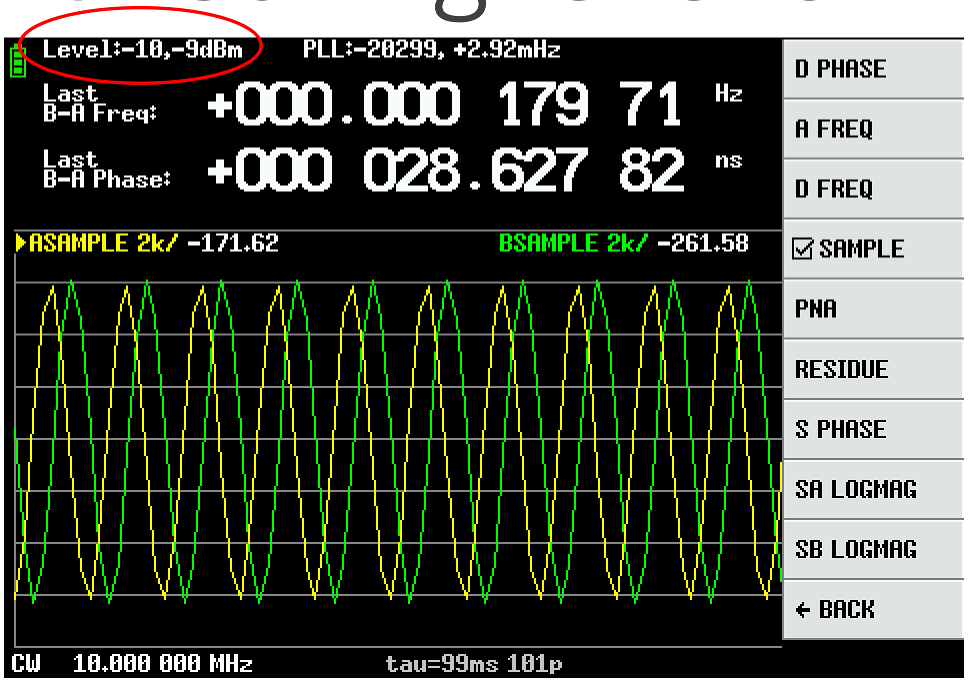


Signal level impact noise floor, best performance between -10 dBm and 0 dBm

Signal on A (-10 dBm, yellow) and B channel (-9 dBm, green)

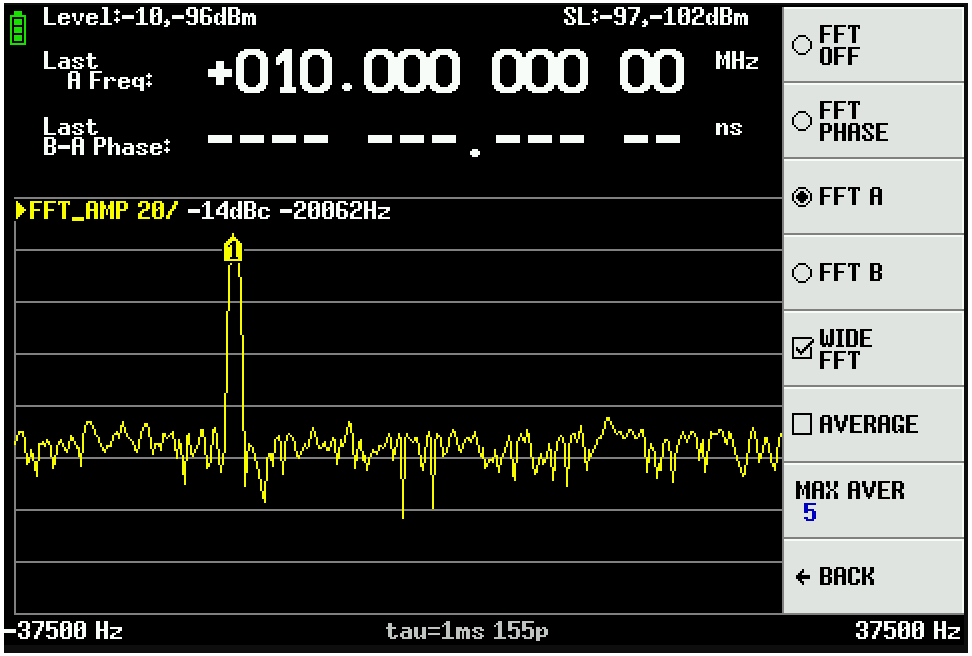
Internal AGC ensures ADC uses full range for inputs over the full -50 dBm to 0 dBm range

AGC not adapting in sample display mode!!!!

DISPLAY/FORMAT/SAMPLE option useful to check input signals

Demo:Switch between -10dBm and -30dBm

Checking frequency of inputs using FFT



Marker displays frequency difference with reference frequency

Wide span helps to "find" signal

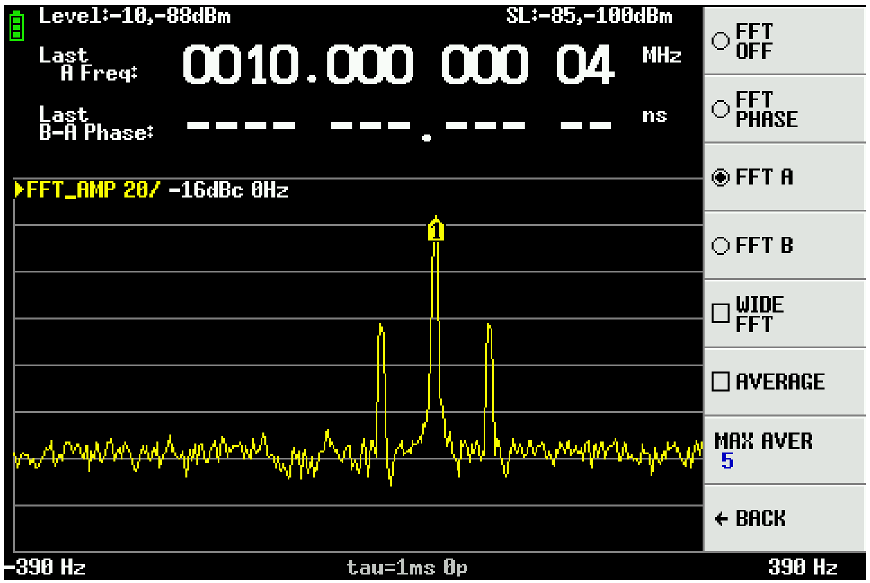
Watch out for mirrors as analog mixers in nanoVNA-H4 do not have mirror suppression (IF=48kHz above signal, mirror @ +96kHz

FFT resolution 187Hz, determined by FFT length (512) and sample rate (192kHz)

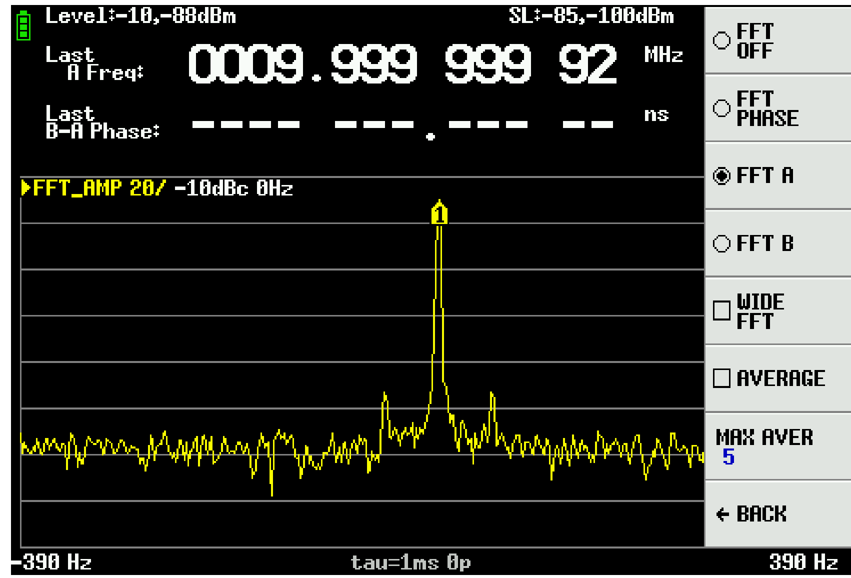
Use the wide FFT to bring the frequency error below 200 Hz

Demo: Signal at 10.01MHz, preset 2

Checking quality of input signals



AM modulation 1% @ 50Hz



Phase modulation 0.01 degree @ 50Hz

Display potential close in spurs

Span limited to +/- 390Hz

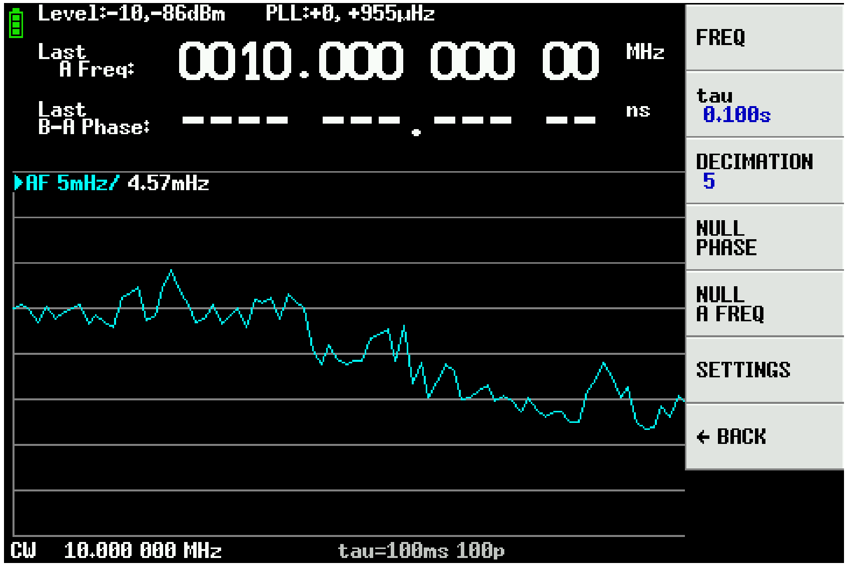
FFT resolution 2Hz, determined by tau (0.001s) and FFT length (512)

- Set tau=0.01s for +/- 39Hz span.

Good to detect low frequency Amplitude or Phase modulation

Demo: Very small phase modulation, preset 2

Measuring single channel frequency



Single channel input displays frequency using the internal reference. Accuracy better than 1e-9,

Frequency range +/- 500Hz

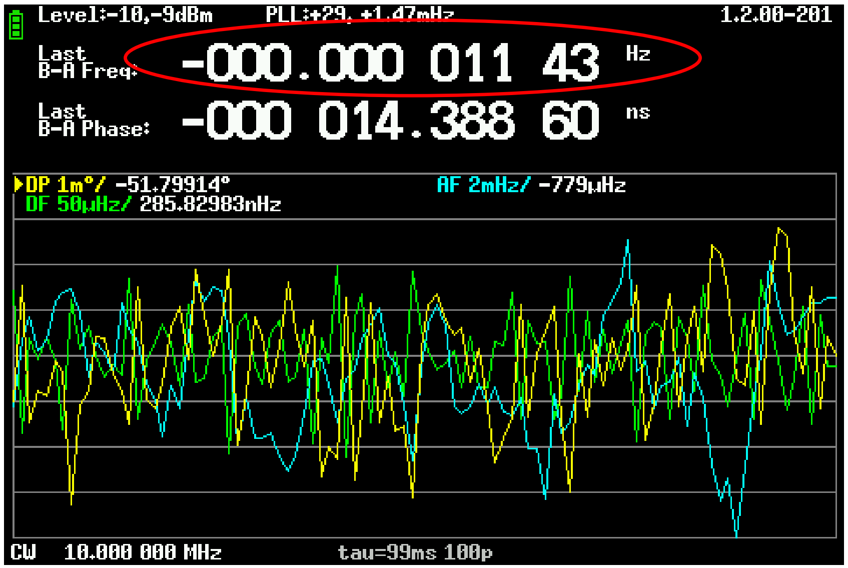
Select correct frequency and calibrate internal reference with NULL A FREQ

Reset calibration with NULL A FREQ without A channel input

Now ready for differential frequency/phase measurements!

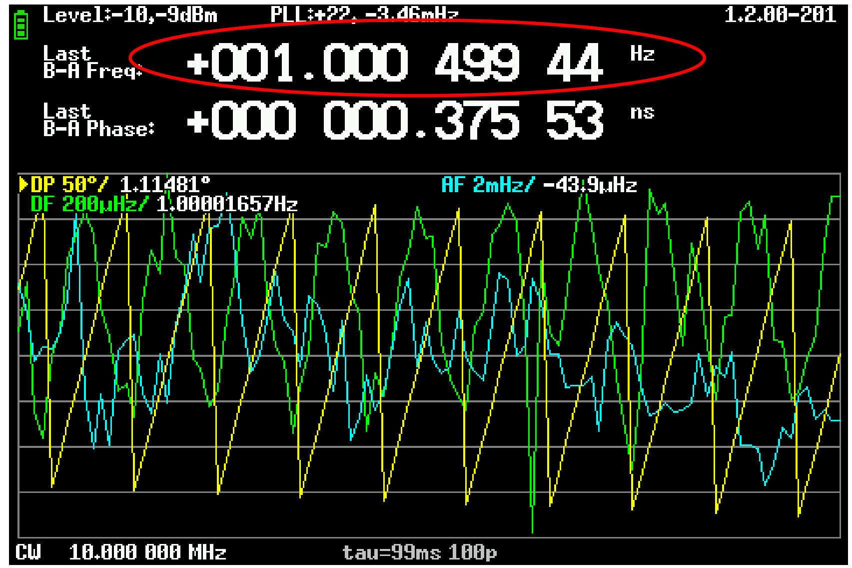
Demo: Preset 1, 4, blue trace, remove Null A Freq

Measuring Phase and Frequency difference between A and B channels



0 Hz A-B difference

Enable SCROLL TRACE, AUTO SCALE and tau=0.1 s



1 Hz A-B difference shows phase rotation and frequency pulling

DP = B - A Delta Phase, DF = B – A Delta Frequency, AF = A channel frequency difference with internal reference, RESIDUE = Linear residue of delta Phase

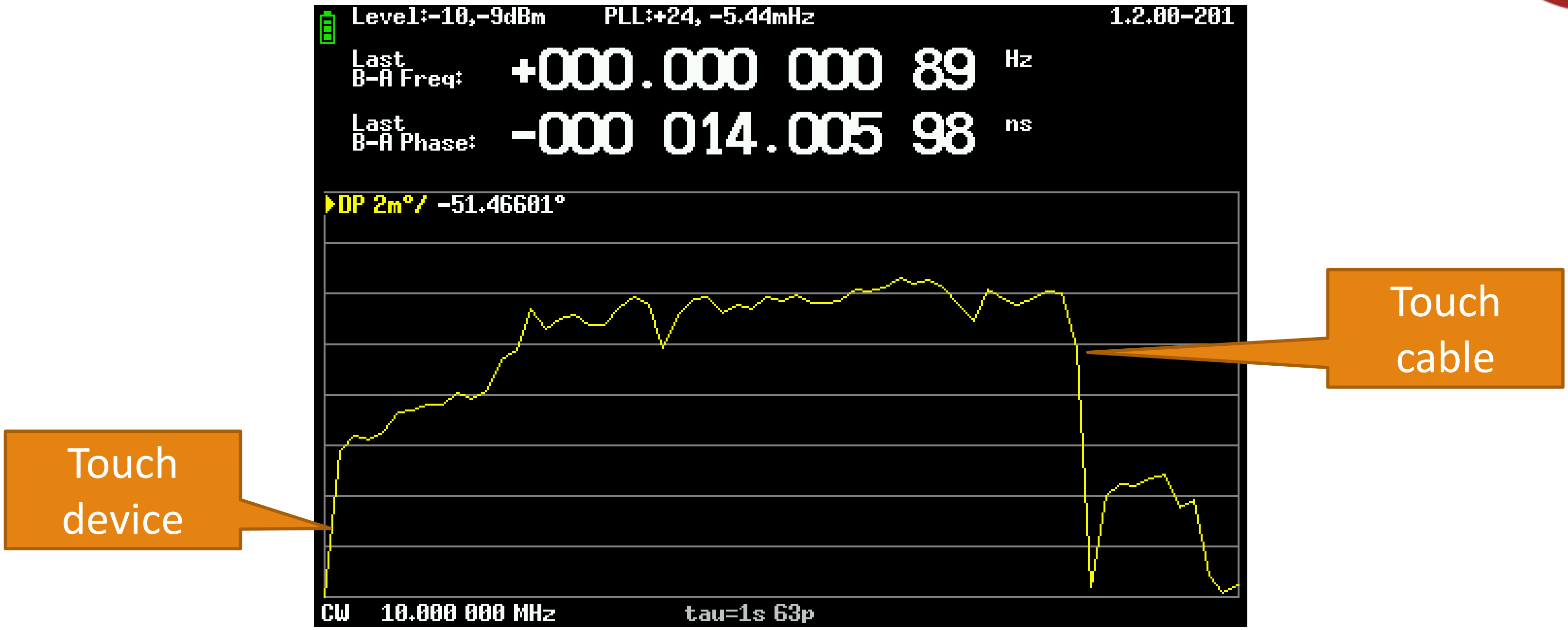
PLL keeps internal reference locked to A channel frequency to minimize pulling

Maximum delta Frequency independent of tau (maximum difference +/- 200 Hz)

Large frequency difference A-B shows pulling due to limited isolation (80dB) between inputs.

Demo: Preset 4, all traces

Factors influencing measurements



Tau=1 s gives 0.0005 ns RMS phase noise

Temperature and mechanical movement impacts phase

Many cables not phase stable

Torque of SMA connectors

Any non-shielded close by oscillator will be visible

Analyzing measurements

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Log via USB to programs like TimeLab

- Minimum tau = 2 ms
- tinyPFA freezes when USB buffer full
- Displays RED numbers when data lost
- Logs wrapped phase as -0.5 .. +0.5
- Use scaling and unwrapping in TimeLab
- Optional phase unwrap and scaling avoids having to know the measured frequency

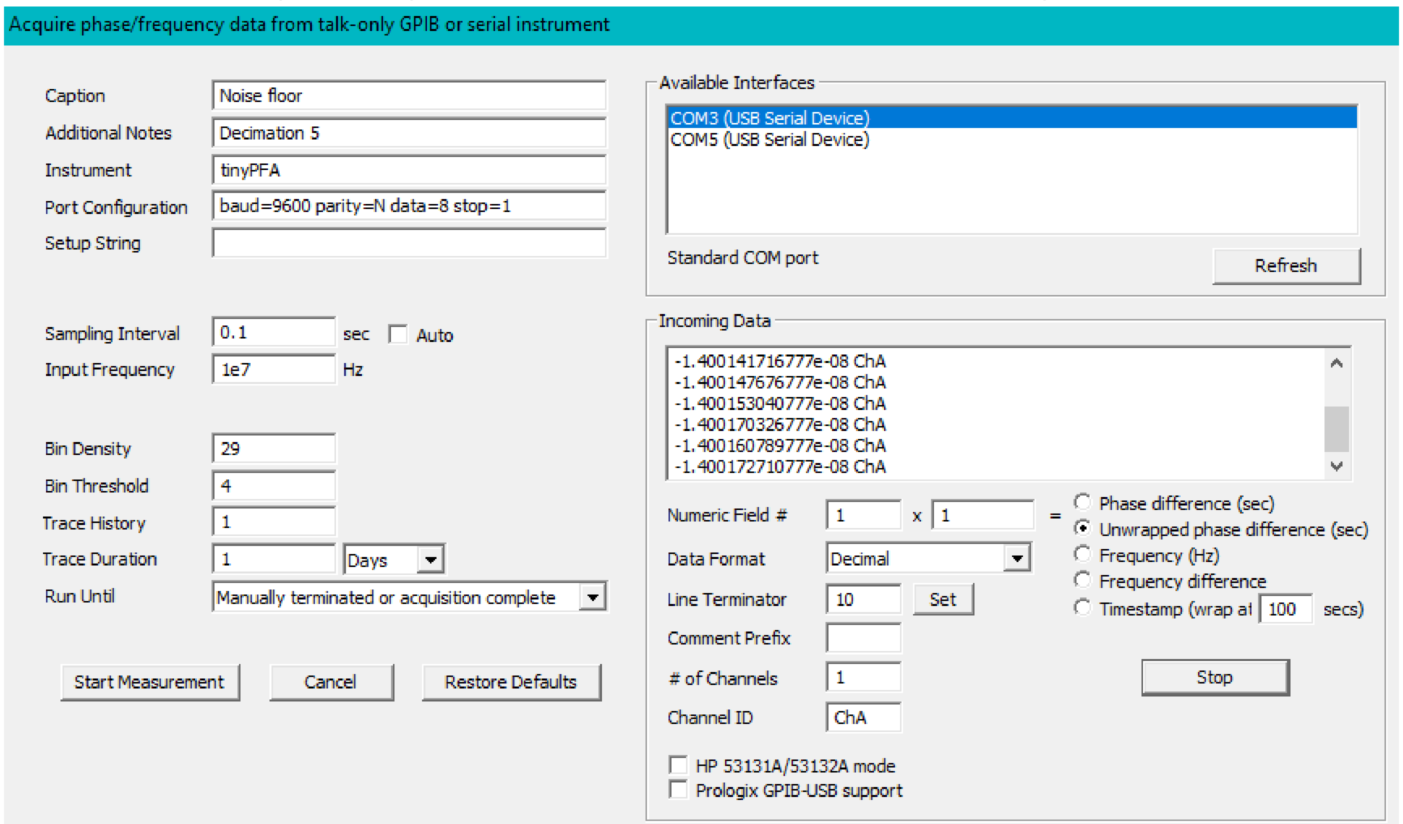
Log to internal SD card

- Minimum tau = 0.1 s

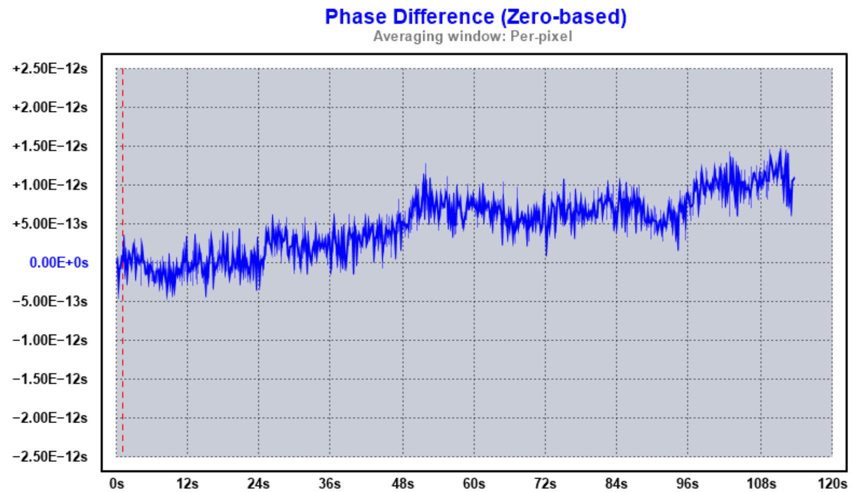
TimeLab interface settings

tinyPFA: USB LOG and UNWRAP enabled

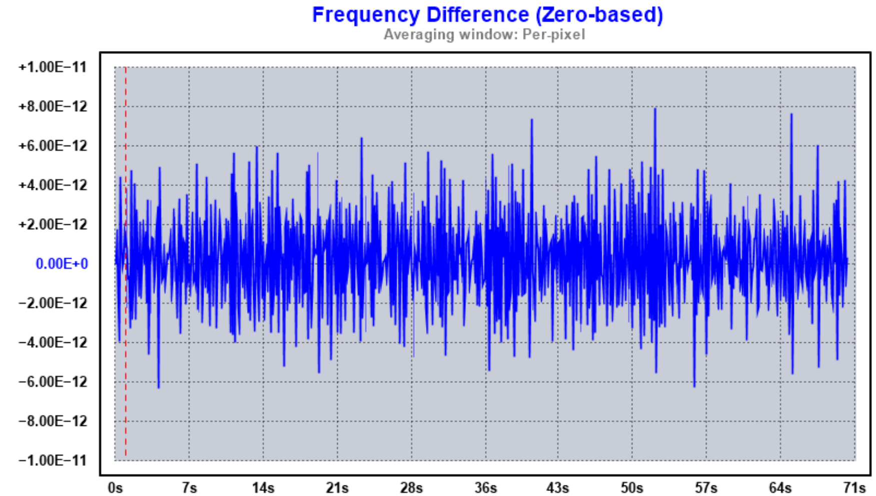
TimeLab acquire phase data from talk only serial instrument



Important TimeLab views



Trace	Notes	Input Freq	Sample Interval	Phase at 1s	Acquired	Instrument
Noise floor (Unsaved)	Decimation 5	10 MHz	0.100 s	−1.40E−8s	1138 pts	tinyPFA

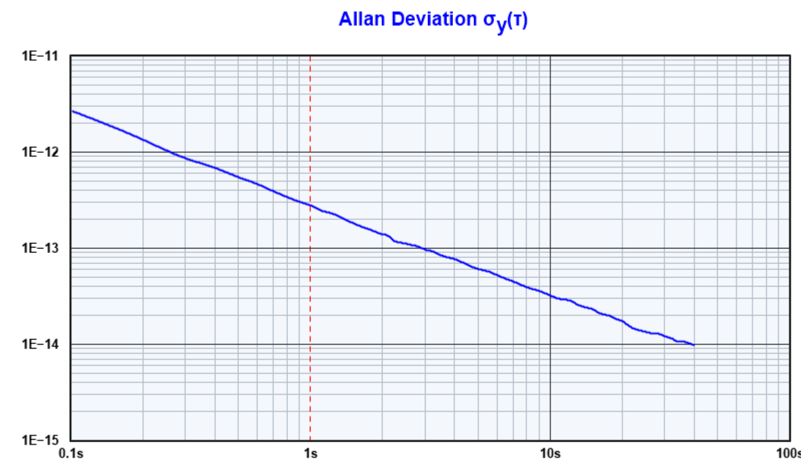


Trace	Notes	Input Freq	Sample Interval	Freq at 1s	Acquired	Instrument
Noise floor (Unsaved)	Decimation 5	10 MHz	0.100 s	10 000 000 Hz	703 pts	tinyPFA

Phase difference: No Jumps and only slow Drift

Frequency difference: Must look like noise

ADEV: Straight line



Trace	Notes	Input Freq	Sample Interval	ADEV at 1s	Acquired	Instrument
Noise floor (Unsaved)	Decimation 5	10 MHz	0.100 s	2.80E−13	1703 pts	tinyPFA

Impact of tau and decimation

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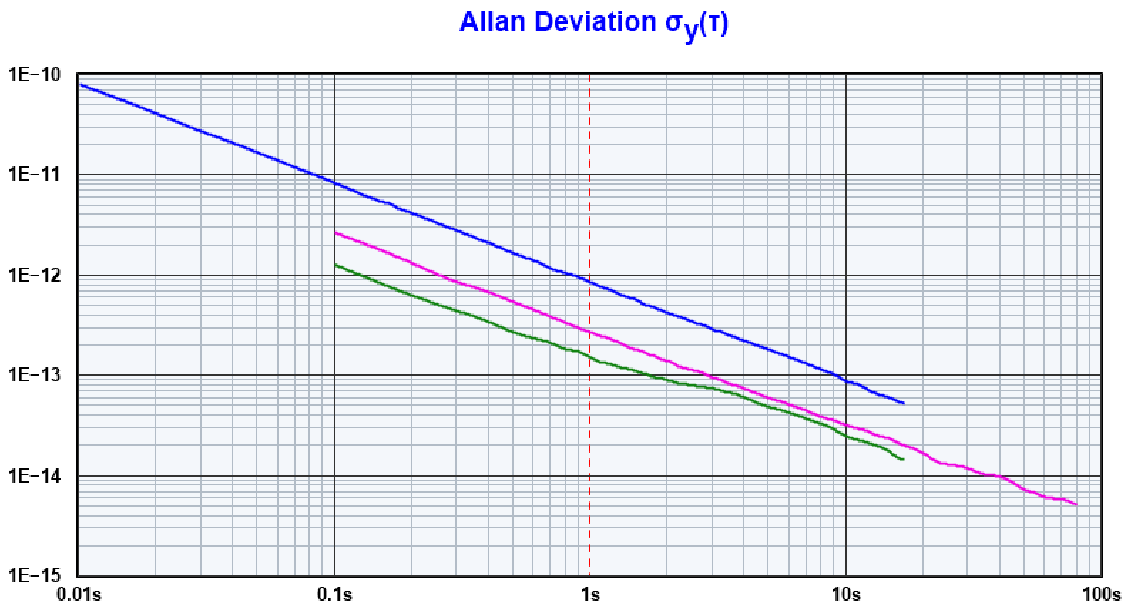
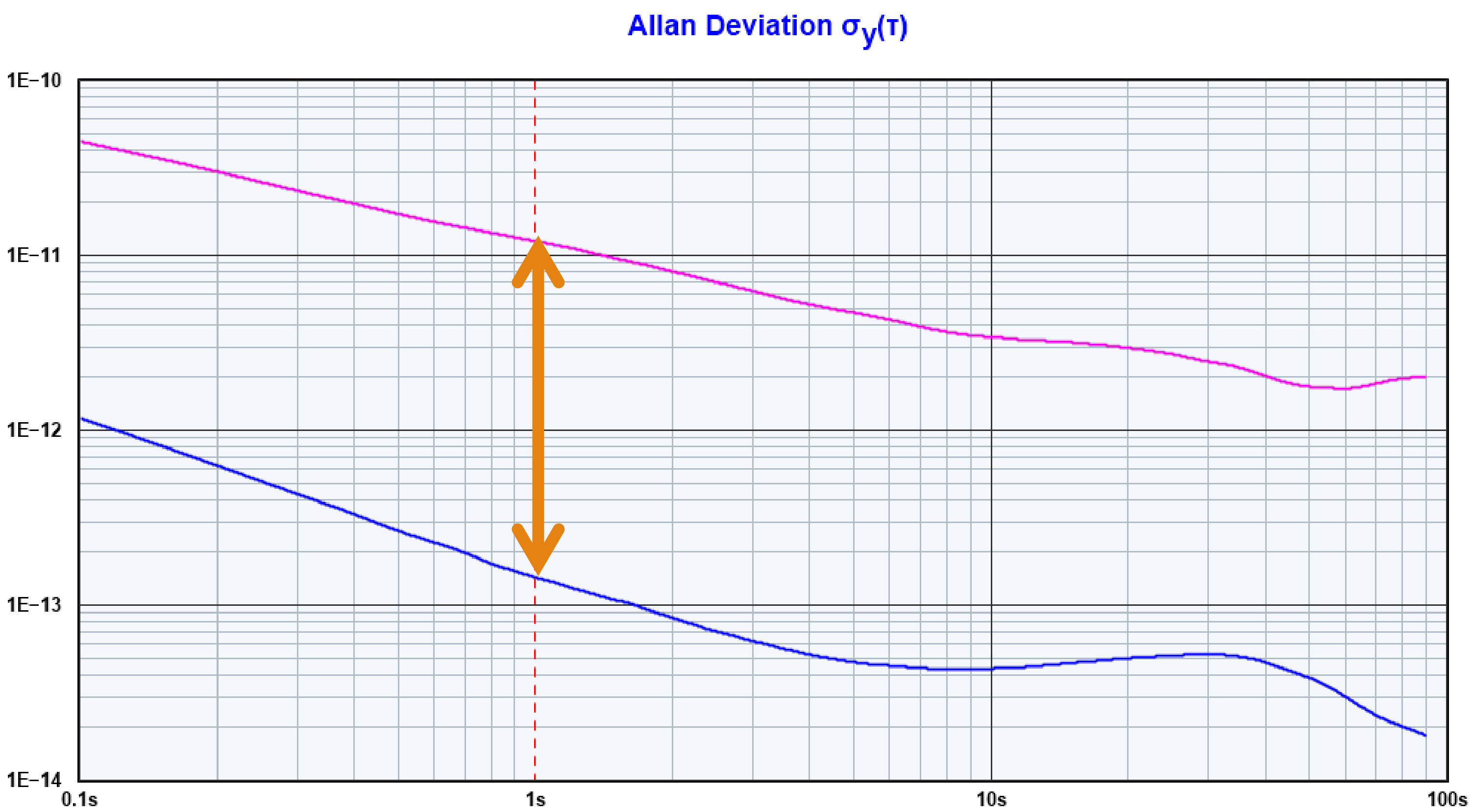


Trace	Notes	Input Freq	Sample Interval	ADEV at 1s	Acquired	Instrument
Noise floor (Unsaved)	Decimation 5	10 MHz	0.010 s	8.59E−13	7031 pts	tinyPFA
Noise floor (Unsaved)	Decimation 5	10 MHz	0.100 s	2.74E−13	3413 pts	tinyPFA
Noise floor (Unsaved)	Decimation 1	10 MHz	0.100 s	1.54E−13	681 pts	tinyPFA

- Factor 10 increase in tau reduces ADEV with sqrt(10)
- Factor 10 increase in decimation increases ADEV with sqrt(10)
- Set decimation to 5 to avoid hiding phase problems with period 1/tau
- Set tau factor 10 lower than shortest period of what you want to observe

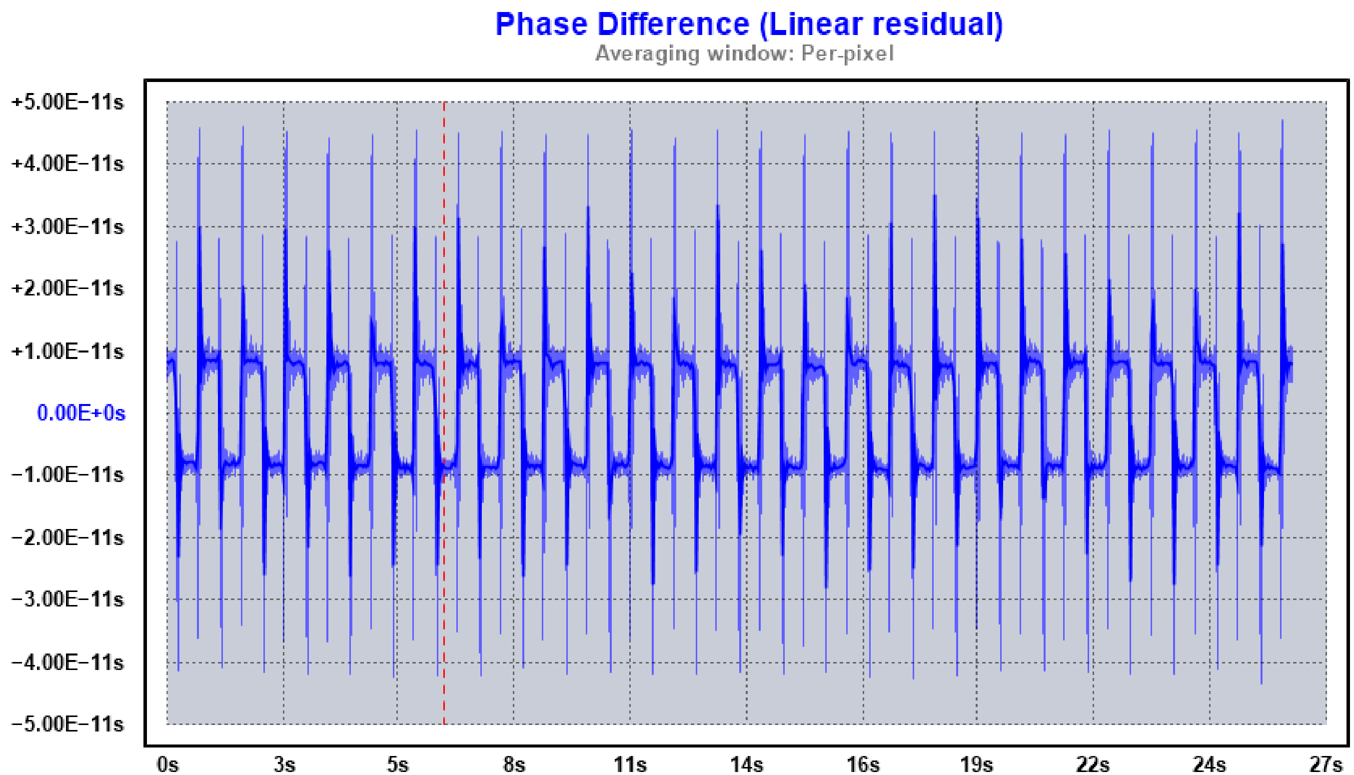
tinyPFA vs Picotest U6200A



Trace	Notes	Input Freq	Sample Interval	ADEV at 1s	Acquired	Instrument
Noise floor (Unsaved)	Decimation 1	10 MHz	0.100 s	1.45E−13	3695 pts	tinyPFA
Noise floor (Unsaved)		10 MHz	0.100 s	1.22E−11	3621 pts	PICOTEST U6200A

Almost factor 100 accuracy improvement with same measurement speed

Visualizing phase stability problem



Trace	Notes	Input Freq	Sample Interval	Phase at 6s	Acquired	Instrument
Output vs input of BG7TBL (Unsaved)		10 MHz	0.002 s	−4.04E−8s	13113 pts	tinyDMTD

- Measures the phase of the output of a clock distribution amplifier with internal reference versus the selected external reference input
- Phase jumping caused by leakage from internal reference when in external reference mode

Measuring reference oscillators

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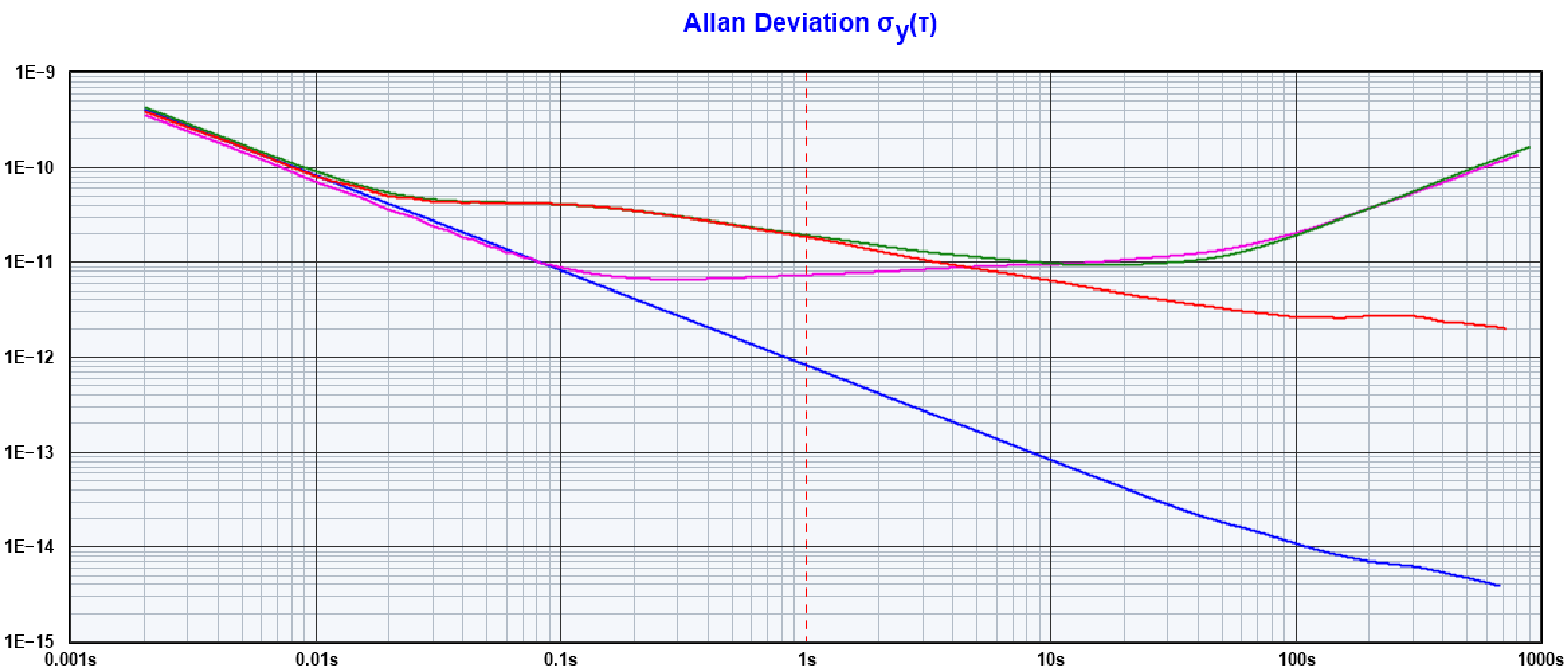

Trace	Notes	Input Freq	Sample Interval	ADEV at 1s	Acquired	Instrument
Noise Floor		10 MHz	0.002 s	8.44E−13	1417202 pts	tinyDMTD
OCXO vs DOCXO		10 MHz	0.002 s	7.50E−12	1626356 pts	tinyDMTD
OCXO vs Rb		10 MHz	0.002 s	1.97E−11	1800000 pts	tinyDMTD
DOCXO vs Rb		10 MHz	0.002 s	1.89E−11	1506034 pts	tinyDMTD

OCXO and DOCXO have the best short term stability below 1 s

Rb and DOCXO have the best stability above 1 s (OCXO was still drifting)

Blue trace is the noise floor of the tinyPFA

Long term Phase Stability

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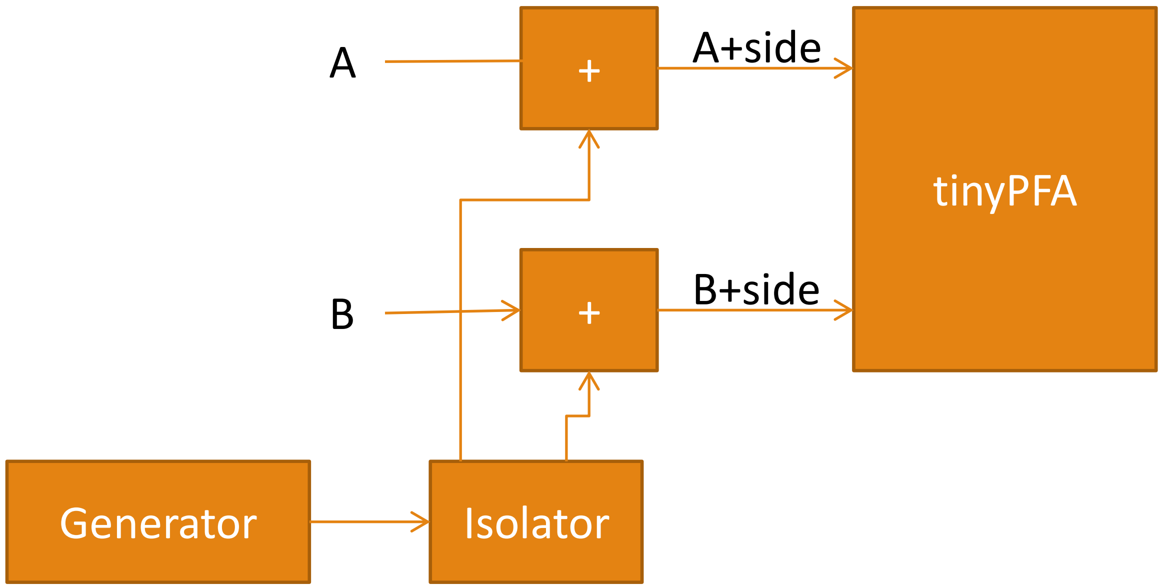
Use phase stable cables

Avoid temperature changes

Or use Side Channel to eliminate temperature impact

Side channel setup

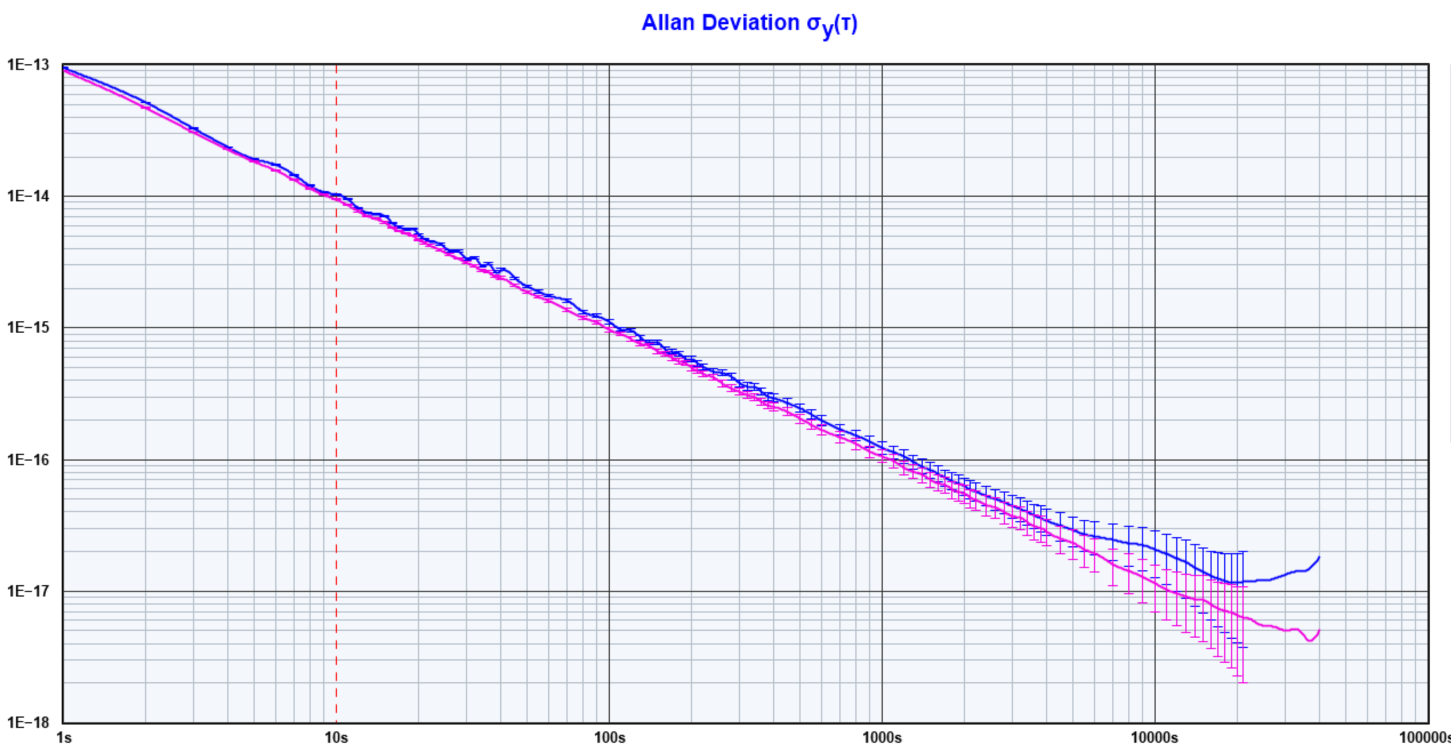


Generator set to A freq + 8 kHz

Isolator has minimum 80dB isolation and outputs -15 dBm

Use resistive combiner (6 dB loss) to add side channels with input signals

Long term noise floor with side channel



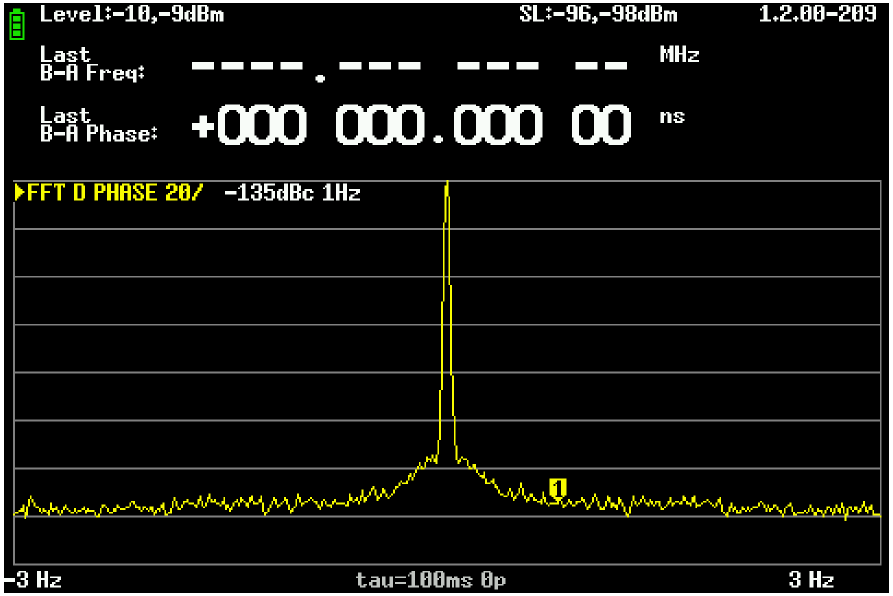
Tau	Sigma(Tau)
1s	9.08E−14
2s	4.72E−14
4s	2.28E−14
8s	1.15E−14
10s	9.47E−15
20s	4.67E−15
40s	2.41E−15
80s	1.21E−15
100s	9.70E−16
200s	4.94E−16
400s	2.53E−16
800s	1.32E−16
1000s	1.06E−16
2000s	5.53E−17
4000s	2.84E−17
8000s	1.43E−17
10000s	1.15E−17
20000s	6.57E−18
40000s	5.21E−18

Trace	Notes	Input Freq	Sample Interval	ADEV at 10s	Duration	Elapsed	Acquired	Instrument
GPSDO 10MHz 2x30dB att -7.5dBm A and to B 2x10dB att tau=1		10 MHz	1 s	1.04E−14	1d 0h 0m 0s	1d 0h 0m 0s	86400 pts	TinyDMDT
Rubidium 2 10MHz 2x30dB att -7.5dBm A and to B 2x10dB att tau=1		10 MHz	1 s	9.47E−15	1d 0h 0m 0s	1d 0h 0m 0s	86400 pts	TinyDMDT

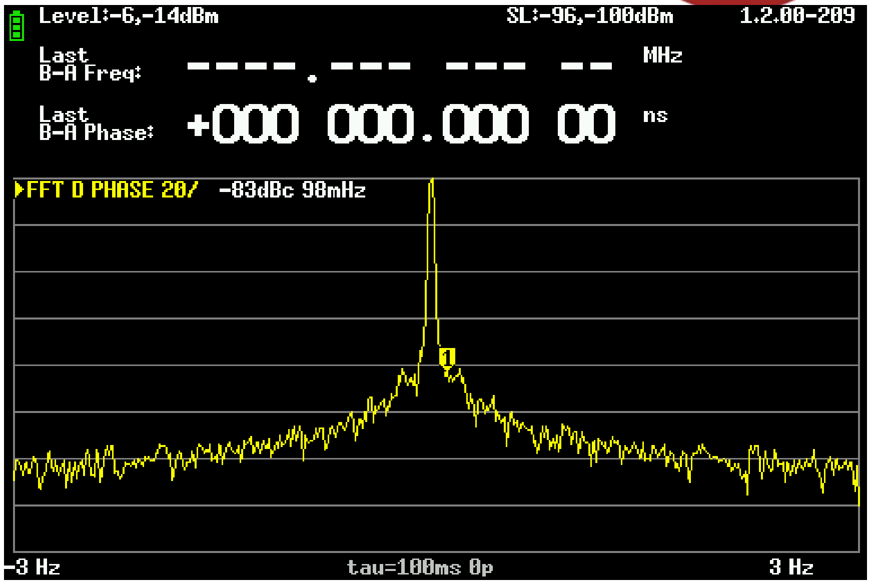
ADEV drops 1/tau down to below 1e-16

Good enough to measure Cesium clocks.

How about phase noise measurement?



Close in (1 Hz) phase noise floor is about -135dBc



Measuring good OCXO against excellent DOCXO

Using the FFT display it is possible to show the close in phase noise of an incoming signal against an internal or external reference by setting tau to 100 ms

The phase noise of the internal reference (TCXO) is limited but eliminated when using an external reference

- -60dBc @ 0.1 Hz offset
- -80dBc @ 1 Hz offset

The internal noise floor at -135dBc is too high to measure phase noise of good clocks beyond 10Hz offset.

Next steps

SW:

Improve FFT UI logic

HW:

Investigate optimized HW platform

- Different mixers to reduce noise and temperature impact
- Increased accuracy with better ADC
- Integrated side channel

Don't expect anything soon.

More info

Wiki: https://www.tinydevices.org

Support forum: https://tinydevices.org/forum/

Firmware repository: http://athome.kaashoek.com/tinyPFA/DFU/

YouTube playlist(see note): https://www.youtube.com/playlist?list=PL5ZELMM2xseNmCdrnXSOD1CY_8GKQpsyU

Note: Most video's use older FW, new FW may have different behavior

Questions

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