Frequency & Stability Measurements Using tinyPFA & TimeLab

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50 MHz and Up Group

5 Mar 2024

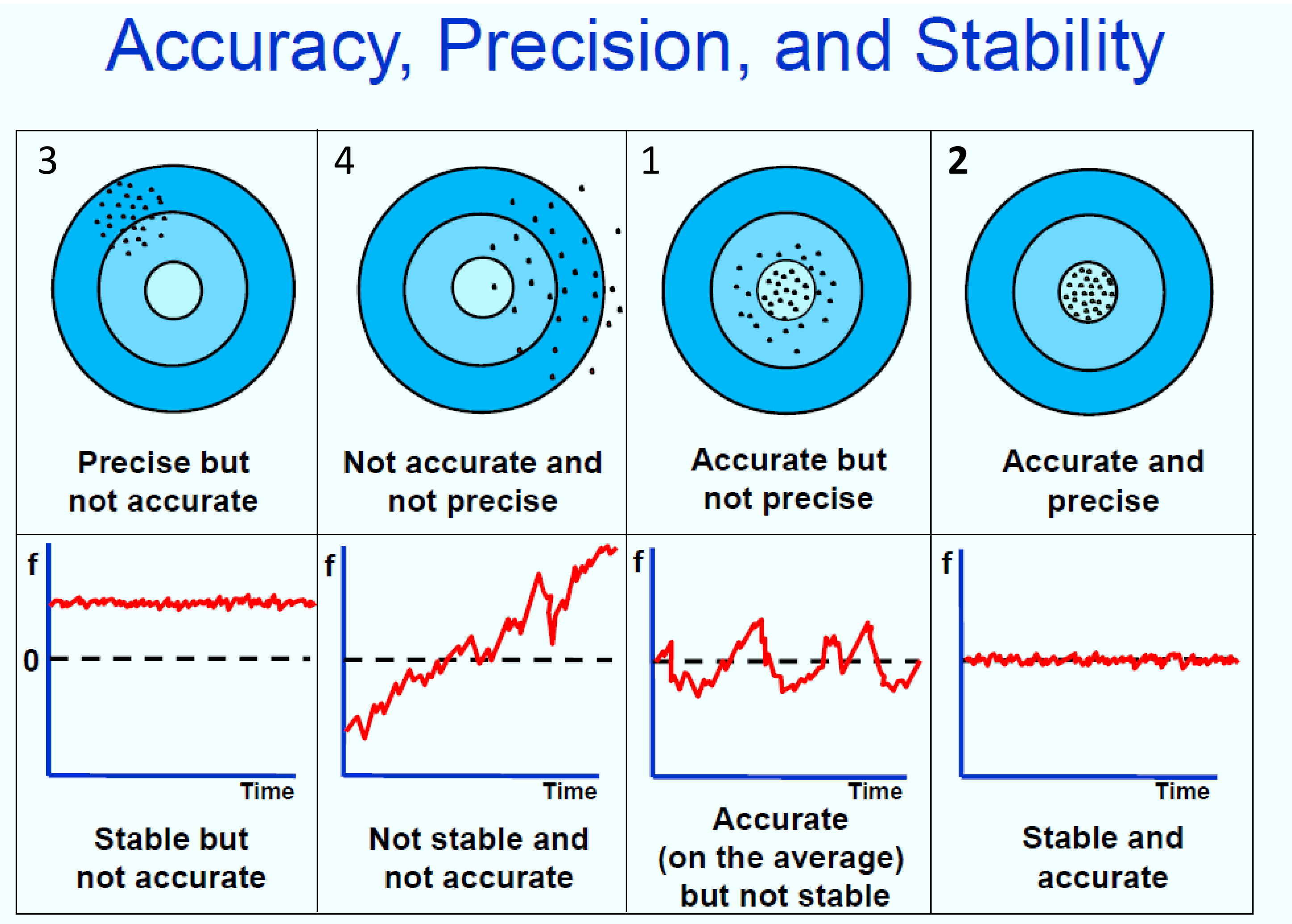
What is Frequency? (a time-nut's or fmt-nut's definition)

- Frequency is the rate of a repetitive event (in our case, a radio carrier wave)
  - Frequency of a sine wave is measured in Hz (cycles/sec) (Hz, kHz, MHz, GHz, etc)
- If T is the period of the repetitive event, then f is its reciprocal and vice versa
  - $f = 1/T$ and $T = 1/f$
- Period (one cycle) is a time interval measured in seconds (s, ms, us, ns, ps, etc)
  - Before 1960, a second was 1/86,400th of one rotation of the Earth about its axis
  - After that, was 1/31,556,925.9747th of one trip of the Earth around the Sun
  - Since 1967, is "9,192,631,770 periods of the radiation corresponding to the two hyperfine levels of the ground state of the cesium-133 atom"

Why do ***we*** care?

- One reason …
  - We can have many independent radio signals on different frequencies and they will not interfere with each other
  - We can use that big knob on our receiver to "tune in" different signals
- "Listen for me on 10368.100…"
- We will have a hard time finding each other if we don't agree on a common definition of frequency
- Our frequency is typically multiplied up from a 10 MHz reference.
- A **small error** at 10 MHz can be HUGE at our operating frequency, well outside our Rx passband
- Smaller errors make it hard to notice a weak signal while hunting with the dish
- **Still smaller errors** over the period of a WSJT (Q65) message are required for a decode

Error MHz	1 ppm 1E-6	100 ppb 1E-7	10 ppb 1E-8	1 ppb 1E-9	100 ppt 1E-10	10ppt 1E-11
10.000…	10 Hz	1 Hz	100 mHz	10 mHz	1 mHz	100 µHz
10368	10.4 kHz	1.04 kHz	104 Hz	10.4 Hz	1.04 Hz	104 mHz
122950	123 kHz	12.3 kHz	1.23 kHz	123 Hz	12.3 Hz	1.23 Hz



Off Frequency | **Can't get anything right!** | **Unstable, "Noisy"** | **What we want, BULLS EYE!**

- 1 & 2: <u>Accuracy</u> is how close we are (on average)
- 2 & 3: <u>Precision</u> is how small the deviations are from the average
- ***2**: Of course, we'd like both!*
- We can think of <u>Stability</u> as precision over time, less variation over time
  - More later on stability time scales (short-, long- term)

Accurate Frequency Calibration Methods

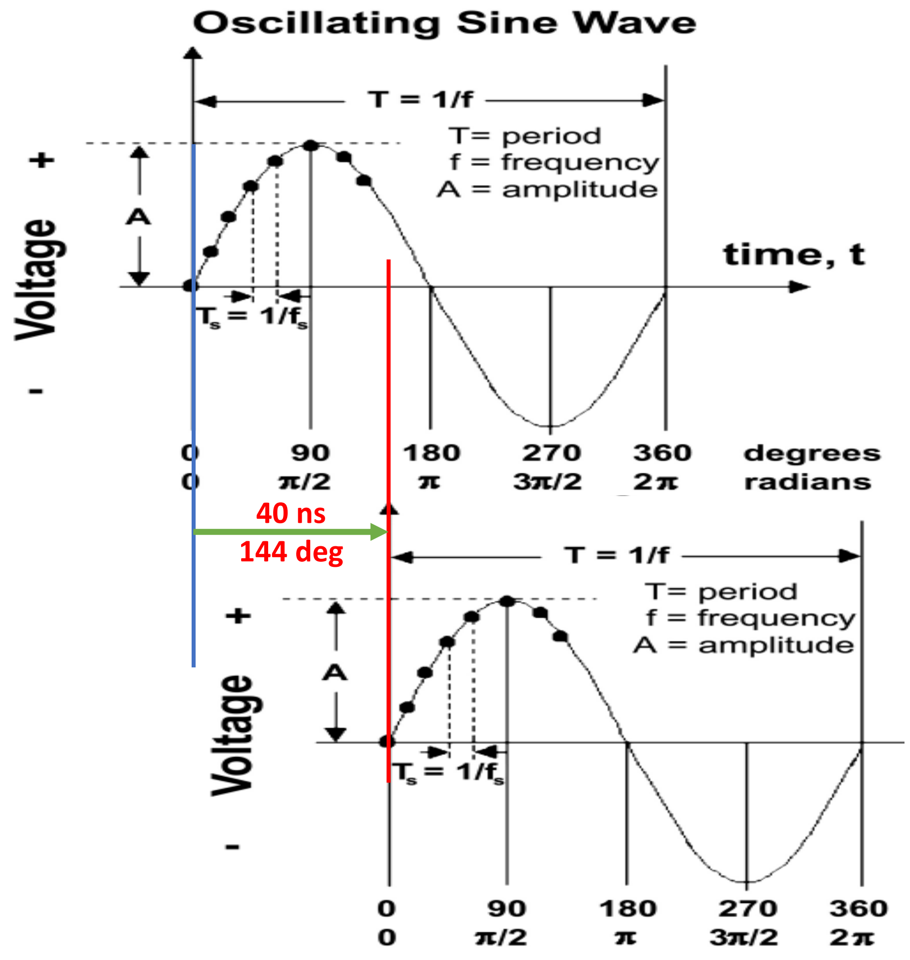
- Compare unknown frequency to an accurate frequency standard

- A frequency counter counts number of cycles of unknown frequency in one gate period
  - Frequency standard ("time base") defines gate period accuracy
  - Resolution is limited to 1 / gate period (eg, +/- 1 Hz for 1 sec gate; +/- 100 ppb at 10 MHz)
  - If we have lots of counter bits, can measure many different frequencies

- Another method uses an oscilloscope for fine calibration
  - Feed unknown frequency into CH1 of oscilloscope
  - Feed accurate standard freq into CH2 & trigger on CH2, so CH2 appears stable (~2 cycles)
  - Watch test signal (CH1) slowly slide left or right.   Measure time to slide by one cycle.
    - Frequencies must be fairly close (else cycle slip time is too fast to count/measure accurately)
  - fractional freq error = 1 / (time to slip a cycle * standard freq)
  - Example: 100 sec to slip one cycle at 10 MHz → 1E-2 * 1E-7 → 1E-9 (1 ppb at 10 MHz)
  - To calibrate unit under test, trim its frequency adjustment until waveform "stops moving"
    - If frequencies are very close, it takes a long time to slip one cycle, maybe longer than test signal is stable
    - It may drift back & forth very slowly.

What is Phase?

- **We can divide the sine wave period into units of phase**
  - One cycle = 360 degrees, or 2π radians
- Or, if we know the nominal frequency, can express phase in units of time:
  - A 10 MHz reference has 10 million cycles in a second
  - 100 nsec per cycle, 15.9 nsec per radian, 278 psec per degree
- Phase is where we are in the cycle
  - If one 10 MHz wave lags another by 40 nsec, it's 144 deg out of phase
- If one "10 MHz" (1E+7) wave is 10 mHz (1E-2) faster than another
  - Differential freq is 1E-9 (df / f_0 = 1E-2 / 1E+7)
  - "10 MHz" period = 1/10 000 000 . 00 Hz = 10 000 000 00 E-9s
  - Faster period = 1/10 000 000 . 01 Hz = 9 999 999 99 E-9s
  - The faster wave will gain 1 nsec per sec of phase
  - The faster wave will have an extra cycle every billion cycles (every 100 seconds)
  - If they started in phase, every 100 seconds they will be in phase again (phase 'wraps around' or repeats)
  - Or we can choose to 'unwrap' the phase and accumulate more and more time error (beyond 100s)
- **Phase is frequency integrated over time (sec/sec = cycles/sec * sec)**
- **Frequency is the derivative of phase vs time**



What is tinyPFA?

- **tinyPFA** is firmware developed by Eric Kaashoek, loaded into the NanoVNA-H4 hardware (~$89)
- Can measure phase & frequency DIFFERENCES to better than 1 part per trillion (1 sec averaging)
  - The A & B inputs (reference & test) should be in the range of 0 to -20 dBm and 1 to 200 MHz
  - A & B frequencies must be within about 100 Hz of each other
  - A wide and narrow FFT is provided to tune to under 100 Hz from as far apart as 37 kHz
- Uses the **DMTD** (Dual Mixer Time Difference) method (developed for measuring atomic clocks)
  - Measures differential phase vs time
  - Two mixers (reference and test inputs) with same LO (a PLL that tracks port A) are used as two phase detectors
    - The mixer (phase) outputs are changing very slowly (port A close to DC), so we can measure orders of magnitude more accurately
    - LO noise is cancelled because they have common LO
  - Original DTMDs used a TIC (time interval counter) to measure the phase difference between the mixer outputs
  - tinyPFA measures the phase using I/Q ADCs & DSP (improvement over original DMTD)
  - Outputs phase and frequency difference data to 4” LCD plot, SD flash card and/or USB port
- Can use to set frequency accurately as well as to measure frequency (in)stability and drift
- Accuracy is determined by the external reference oscillator connected to port A
- tinyPFA operating instructions are in the tinyPFA wiki at www.tinydevices.org

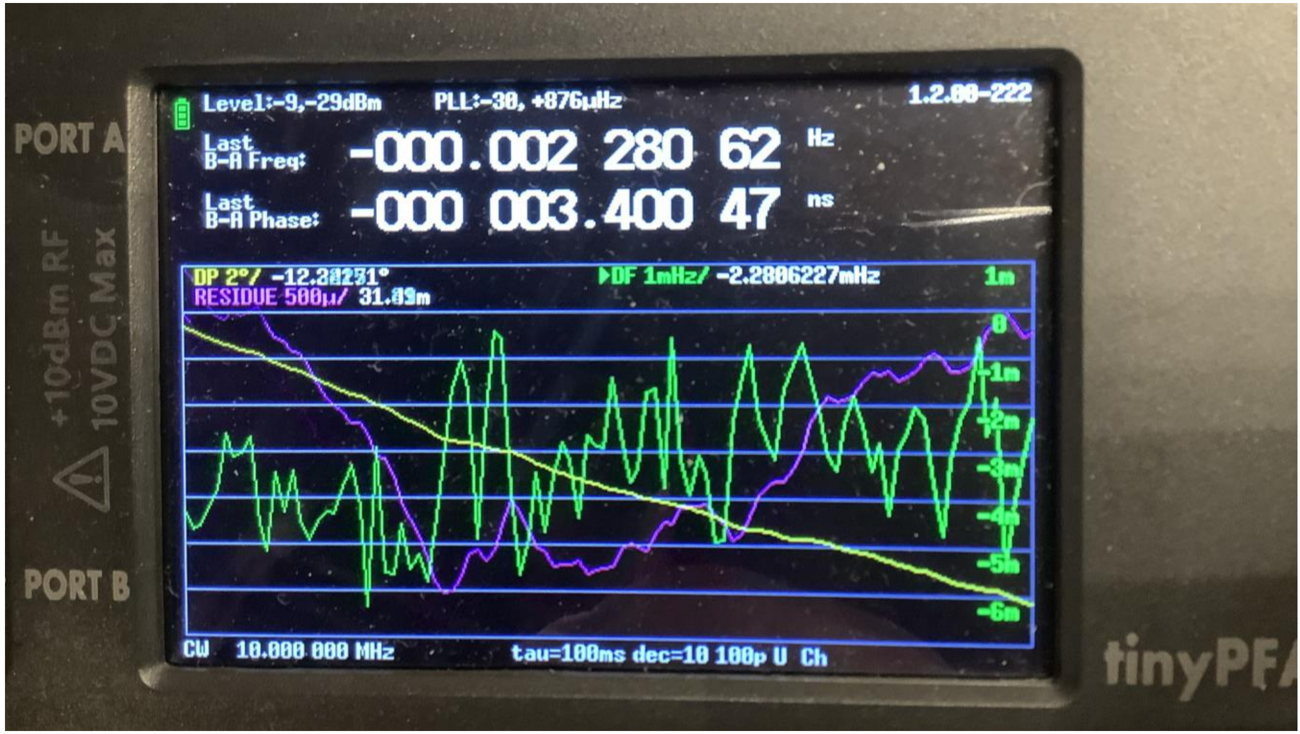
tinyPFA In Action

DUT (port B) is 4.95 milliHz below
10 MHz Rb reference (port A)

Yellow trace is phase vs time (2 deg/div);
Nearly linear slope due to the freq offset

Purple trace is phase residue after subtracting out the average slope in yellow trace; indicates frequency instability (noise/wander/drift)

Green trace is frequency vs time
(1mHz/div), derivative of phase



What is TimeLab?

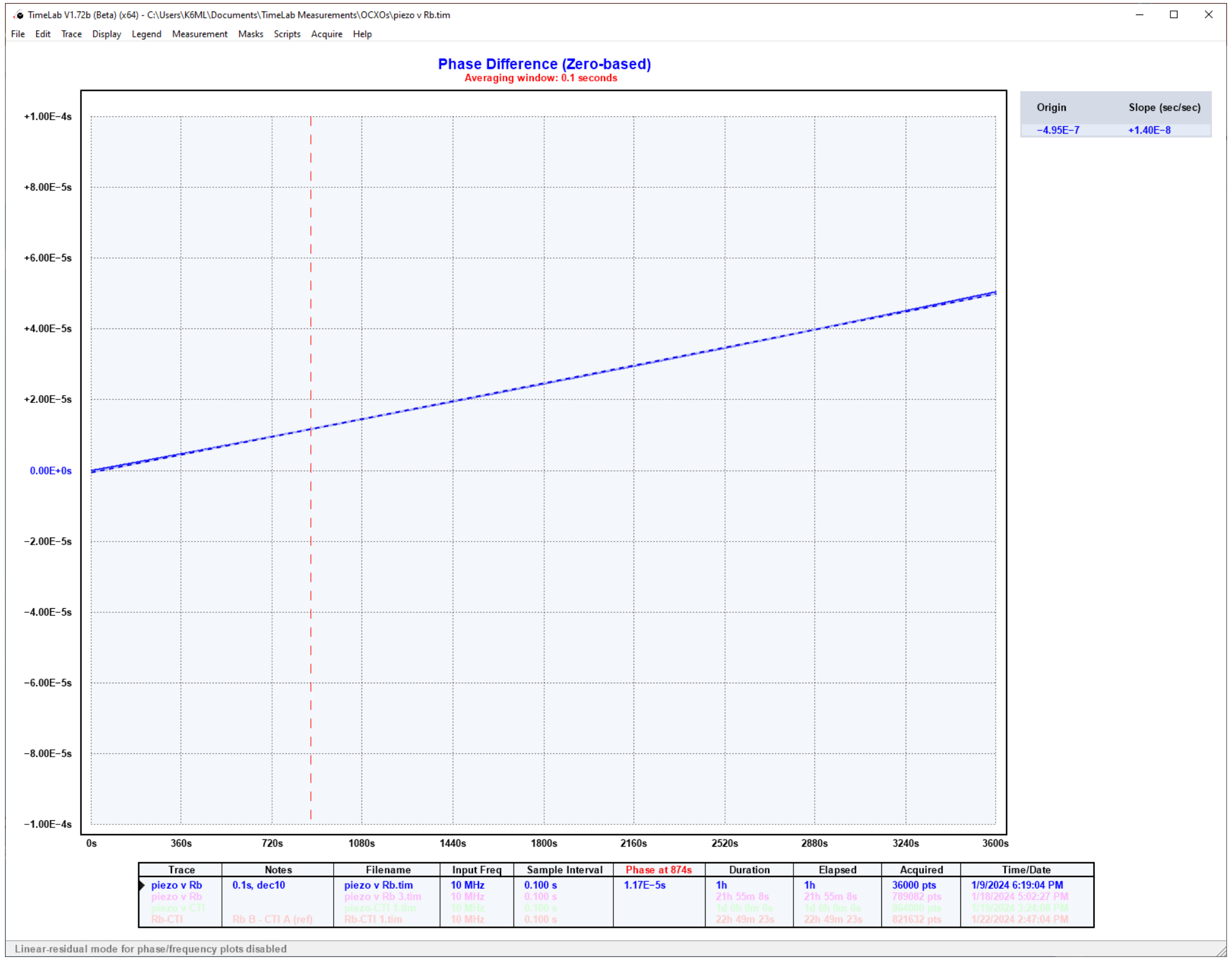
- TimeLab is a software tool written by John Miles (KE5FX)
- It accepts phase data samples from devices like tinyPFA and PhaseStation

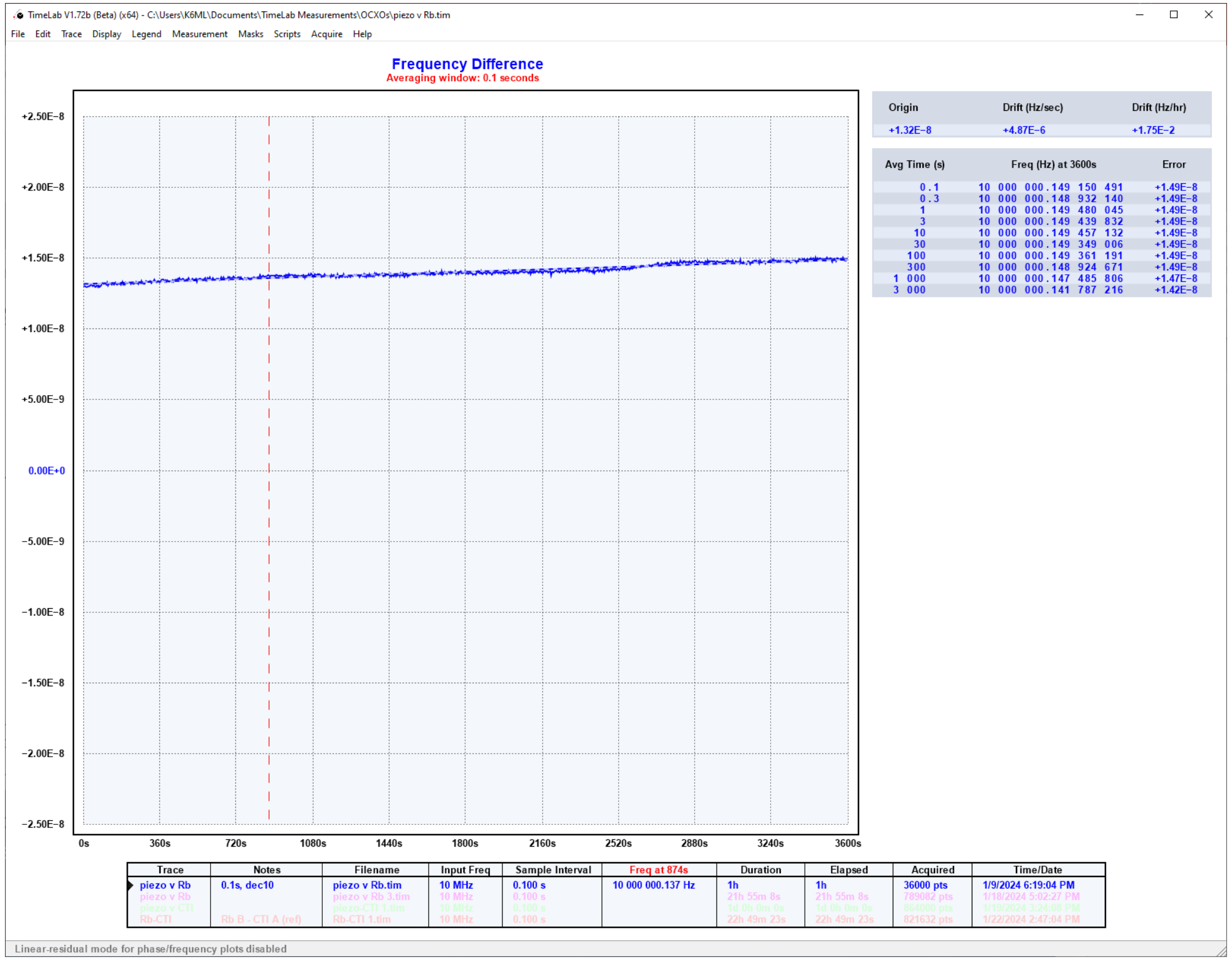
- You can use it as a nice strip chart recorder / data logger / data plotter
- It does the math to identify trends and residuals, as well as stability statistics like ADEV
- With more powerful hardware like the PhaseStation, it can also do phase noise analysis

- Runs on a Windoze PC
- TimeLab download & user's manual: www.miles.io/timelab/beta.htm
- Connecting tinyPFA to TimeLab: https://www.tinydevices.org/wiki/pmwiki.php?n=TinyPFA.TimeLab

Looking at Quartz Oscillator Phase & Frequency with tinyPFA & TimeLab

Slope of Phase vs time = Frequency vs time





Phase difference (XO – Rb std) vs time (1 hour):

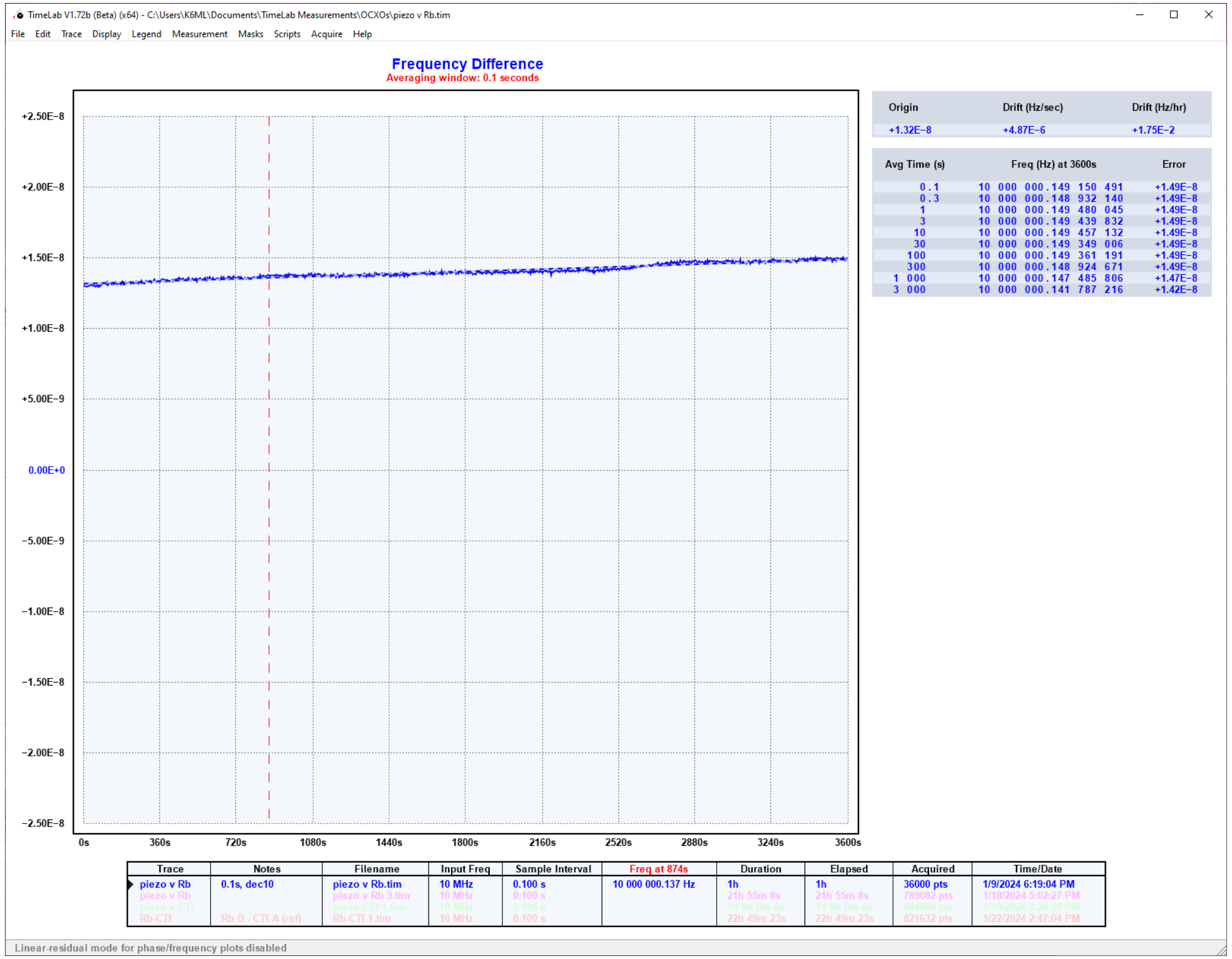
XO is tuned ~140 mHz higher than Rb standard
XO gains ~14 nsec/sec over Rb (dashed trend line slope)
Phase plot shows accumulated time error due to freq offset

Frequency difference (XO – Rb std) vs time (1 hour):

Freq difference plot is the derivative (slope) of phase plot
A linear phase trend (rising) → a constant (high) frequency offset.

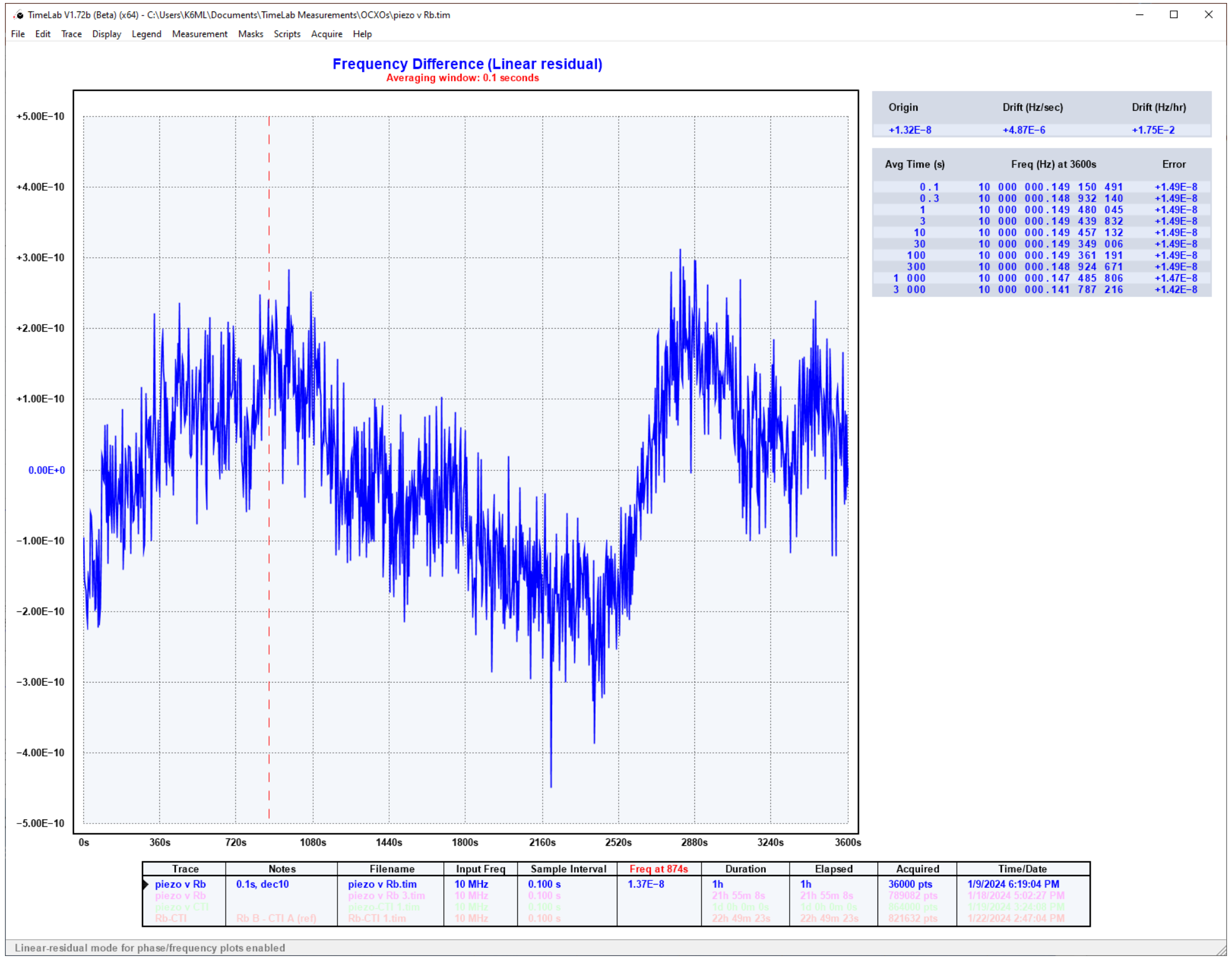
We can use this info to trim XO freq adjust to match the Rb standard
We also notice slight (~17.5 millHz/hr) warmup/aging freqeuncy drift.

Use TimeLab to subtract out the average frequency
Look at the 'residual' to see instability and drift



Frequency difference (XO – Rb std) vs time (1 hour)

from RHS previous page



Frequency residual (XO – Rb std) vs time (1 hour):

Vertical scale now 50x more sensitive after subtracting trend

Now we can see short-term (in)stability

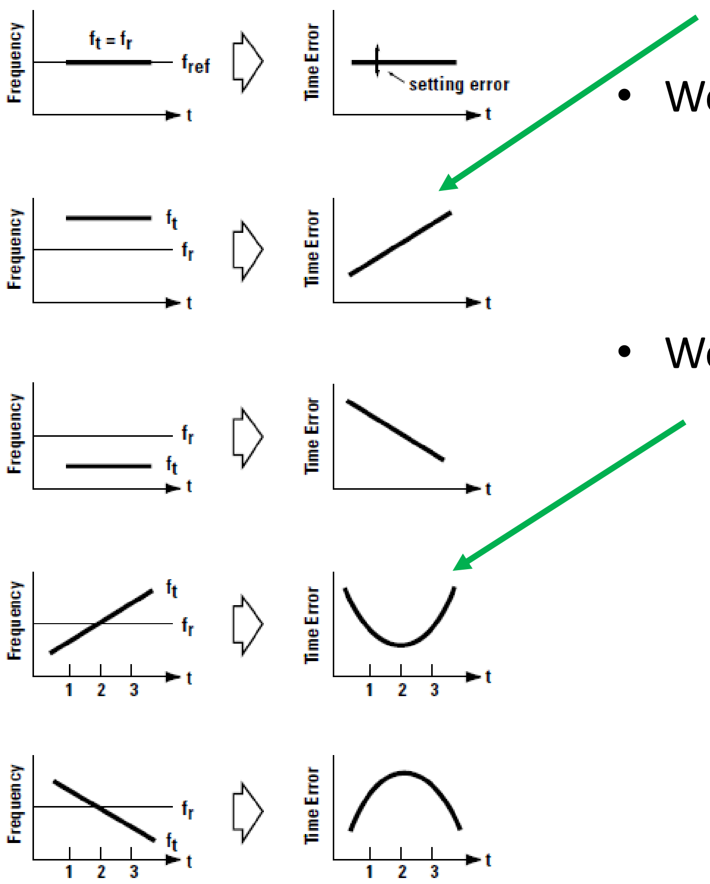
(White FM, Flicker FM and Random Walk FM noise)

Average (LPF) the freq residual to emphasize flicker and random walk noise

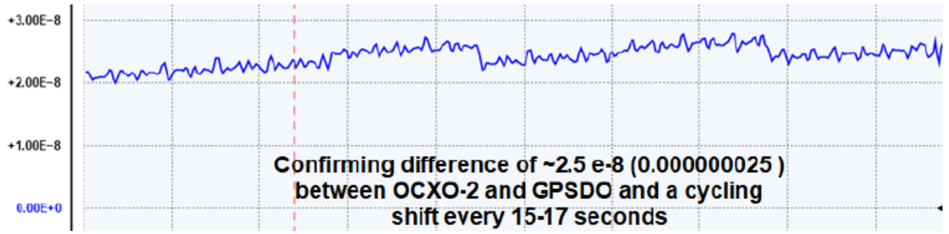
1 sec average removes most white FM noise.
Shows flicker and random walk FM noise.
About 0.5 ppB peak excursion.

100 sec average brings out the random walk FM noise.
About 0.4 ppB peak excursion.

So far …



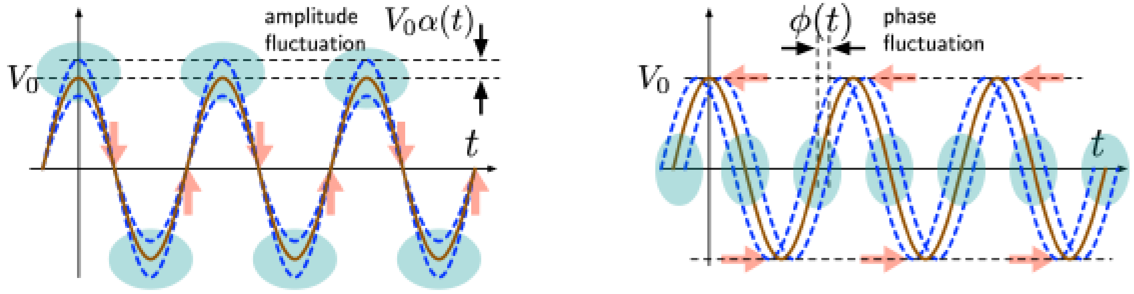
- We've seen tinyPFA can accurately set your rig's reference so that you are on frequency
  - tinyPFA measures phase vs time; tPFA or TimeLab calc freq vs time from phase data
  - f(t) = time derivative of $\phi(t)$ and $\phi(t)$ is time integral of f(t)
  - Frequency offset [high/low] -> linear phase (time error) ramp [rising/falling]
- We've mentioned that tinyPFA measurements are only as good as the reference standard
  - We are measuring port B – port A difference, so we see combined error/drift
  - To measure B, make sure A is much more stable & accurate (reference)
  - We can use the tinyPFA to compare and improve our reference standard(s)
- We're starting to see that tinyPFA can be used to characterize the stability of your ref osc
  - Linear freq drift [up/down] -> parabolic phase (time) error [upward/downward]
  - We just saw plots that show drift, PM and FM noise
  - Others have used it to study jumps in their VK3CV 122 PCB GPSDO



  - Eric built tinyPFA to measure/improve his own GPSDO design
  - Lord Kelvin: To measure is to know / understand / improve
- It's time to introduce some ways to talk about stability…

What is noise?

Clock signal $v(t) = V_0[1 + \alpha(t)] \cos[2\pi\nu_0 t + \varphi(t)]$

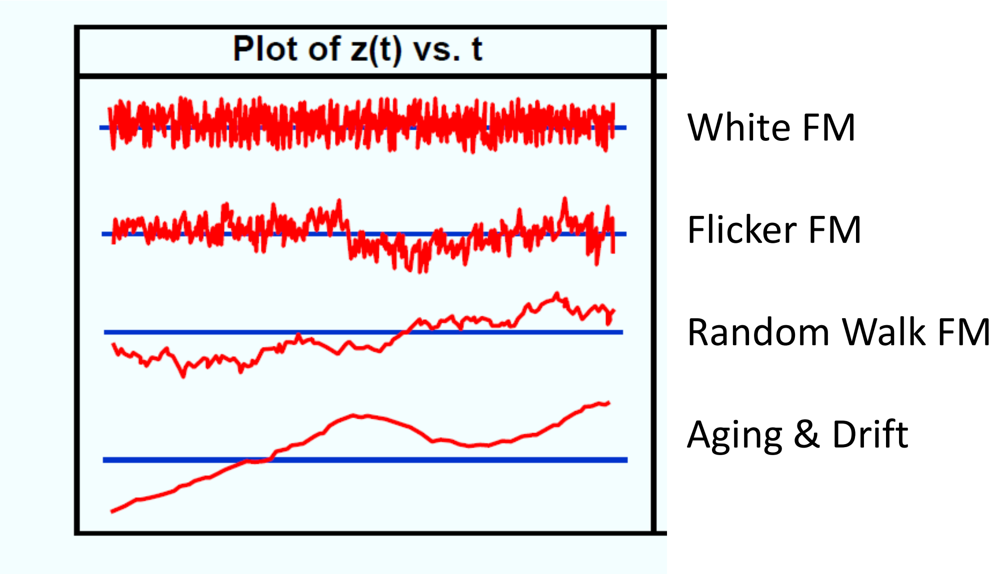


AM noise

PM noise

- Short term (in)stability is also called noise
- Fluctuations in amplitude (Not the big issue in oscillators)
- Fluctuations in phase and instantaneous frequency
- Noise is modulation by a random noise signal (various types; longer time scales)
  - "white" phase noise (thermal noise, wide & flat spectrum)
  - "flicker" phase noise
  - "white" FM noise
  - "flicker" FM noise
  - "random walk" FM noise
  - Aging & drift, frequency jumps, retrace
- Spurs (spectral spikes) are modulation by a deterministic (repeating) signal
  - Cross talk from digital and other circuits
  - Power supply noise
  - Phase detector update frequency & fractional dividers in a PLL, etc

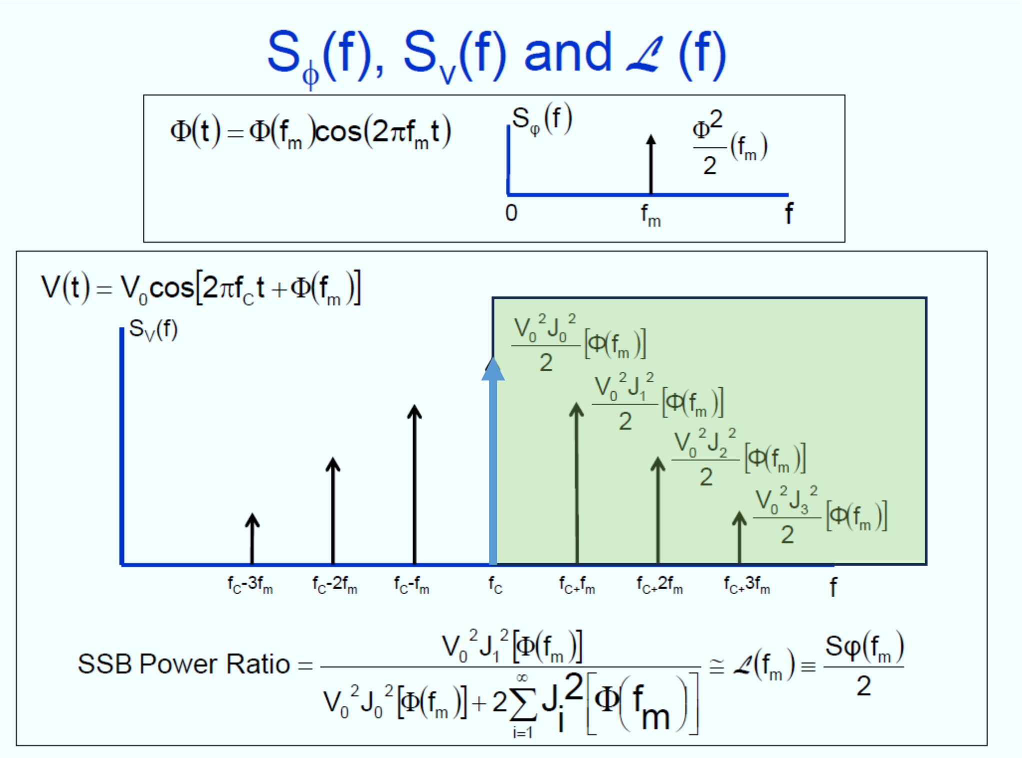
Noise in the time domain



Recall the previous examples of DMTD (tinyPFA) frequency residuals (FM noise)

Notice different time scales of fluctuations

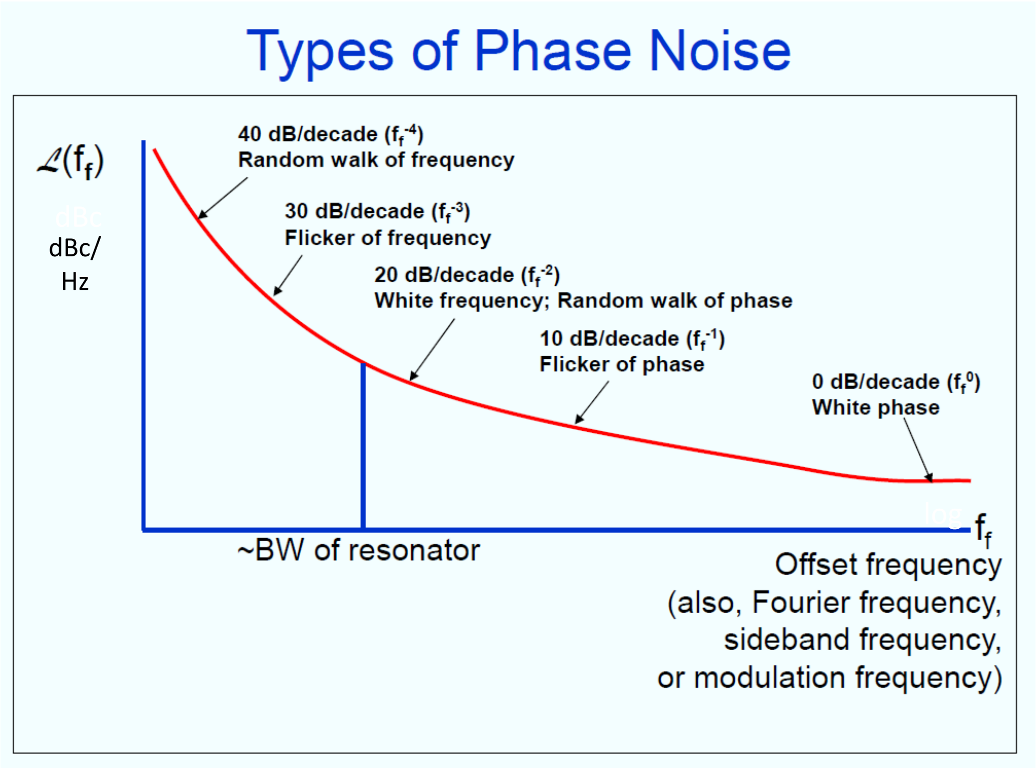
Phase Noise & Spurs as (unintentional) Phase Modulation

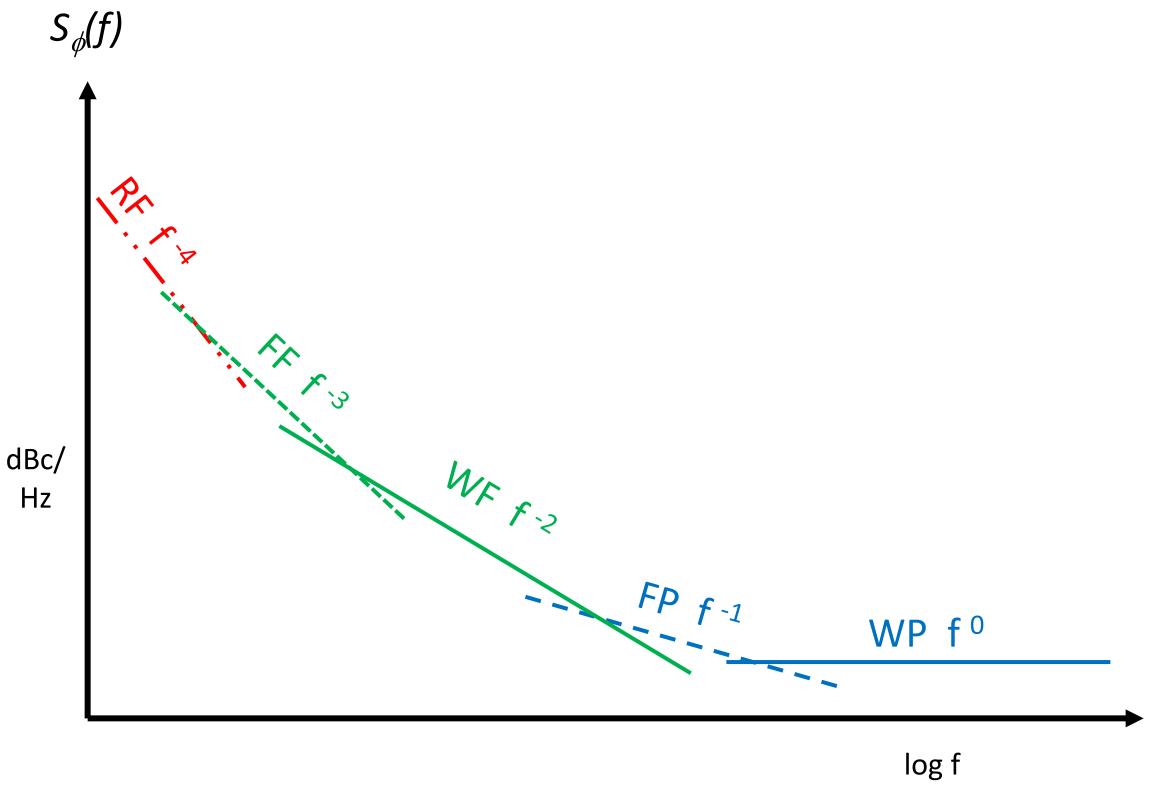


- If the modulation time signal is deterministic…
- Power spectrum is discrete sideband spurs at harmonics of the modulation (can be stronger than carrier!)
- Symmetric about the **carrier**, so IEEE defines SSB spectrum (carrier & above)

- If the modulation time signal is random noise…
- Power spectrum is broad sidebands, slope depends on the noise type *(see next slide)*

Noise Power Spectrum (frequency domain)





Oscillator data sheets and PLL simulators provide $\mathcal{L}$(f) tables or plots.

PN power spectrum can be measured using a spectrum analyzer, or better still, a phase noise analyzer (like PhaseStation).

$$S_\phi(f) = b_{wp} f^{-4} + b_{wp} f^{-3} + b_{wp} f^{-2} + b_{wp} f^{-1} + b_{wp} f^{0}$$

Phase Noise Power = random walk FM + flicker FM + white FM + flicker phase + white phase

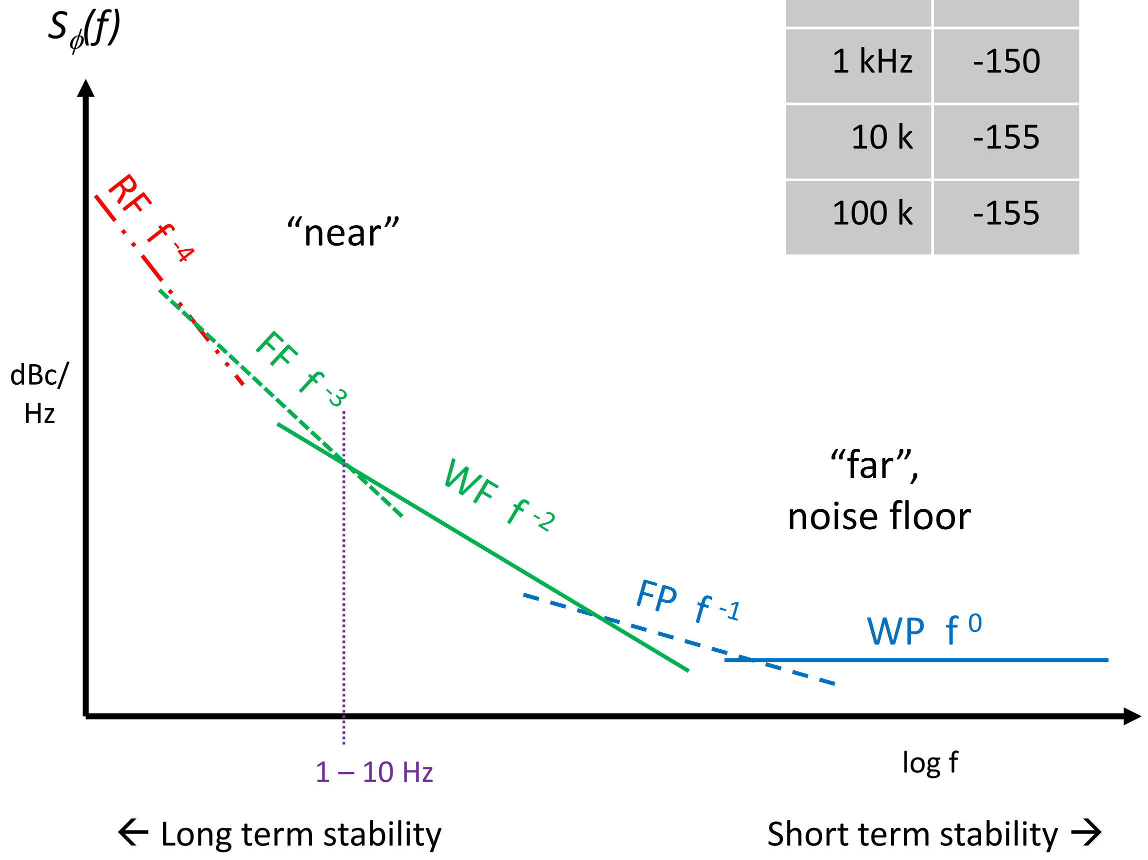
The weights (b_{xx}) vary with device type and model, some may be swamped by others

Noise Power Spectrum (XO)

eBay 10 MHz OCXO

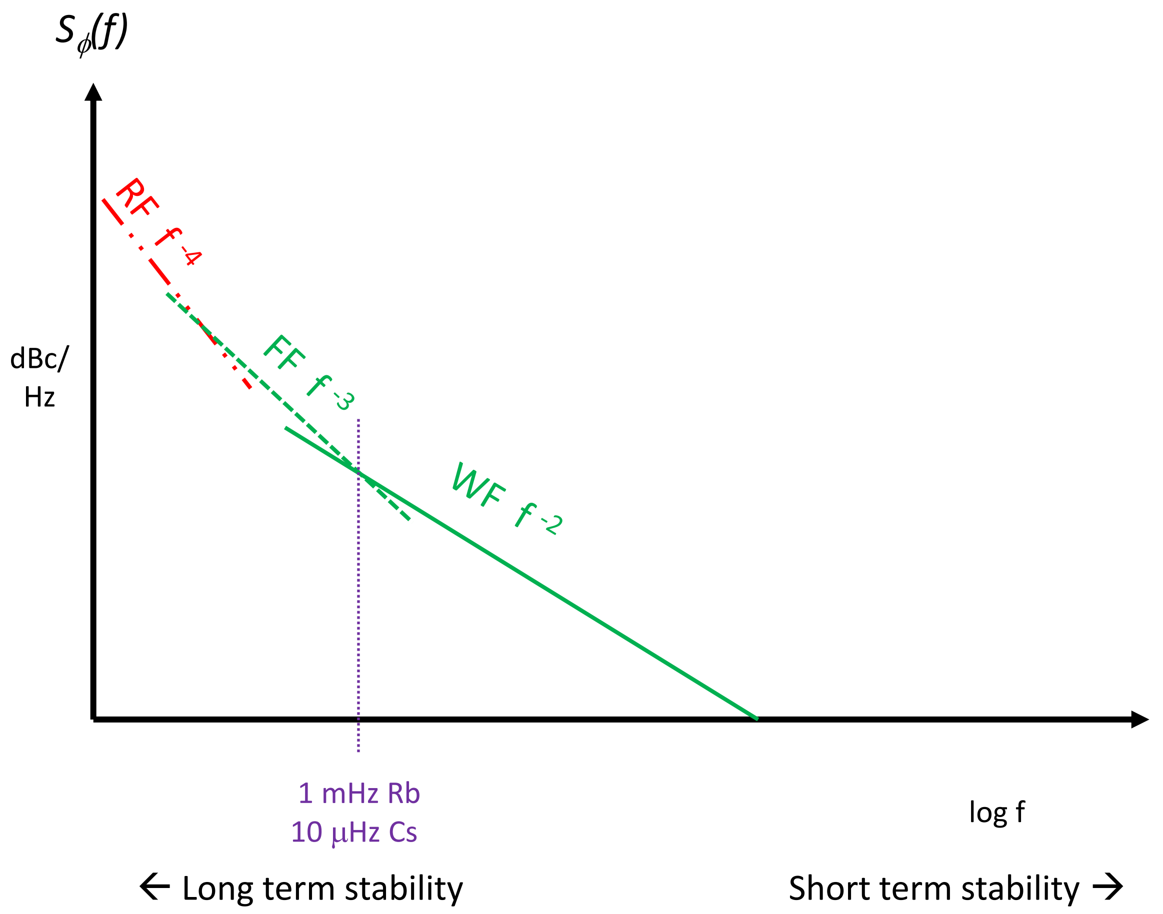
Carrier Offset	8663 dBc
1 Hz	-95
10 Hz	-130
100 Hz	-140
1 kHz	-150
10 k	-155
100 k	-155

- Quartz oscillators may show all five noise components, plus (even longer term) aging and drift
- FP (flicker phase noise) may not be very visible
- FF/WF corner freq is usually in 1-10 Hz range
- SC cut OCXO better than AT cut TCXO
- Is OCXO accurate enough for frequency control
  - Can it hold calibration for a contest weekend?
  - Can it handle temp swings?
- Is OCXO stable enough for MFSK digital modes (WSJT)?
  - Stable long enough to decode Q65 -60, -120, 300?
  - Stable over temp swings?



Noise Power Spectrum (Atomic clocks)

- Atomic clocks show the three FM components
  - Rb has some long term aging/drift, but not much
  - Cs has essentially no aging and drift
- FF/WF corner freq is on the order of
  - 1 mHz for Rb
  - 10 μHz for Cs
- These oscillators tend to be
  - more power hungry
  - more expensive
- DMTD and ADEV was invented for this space



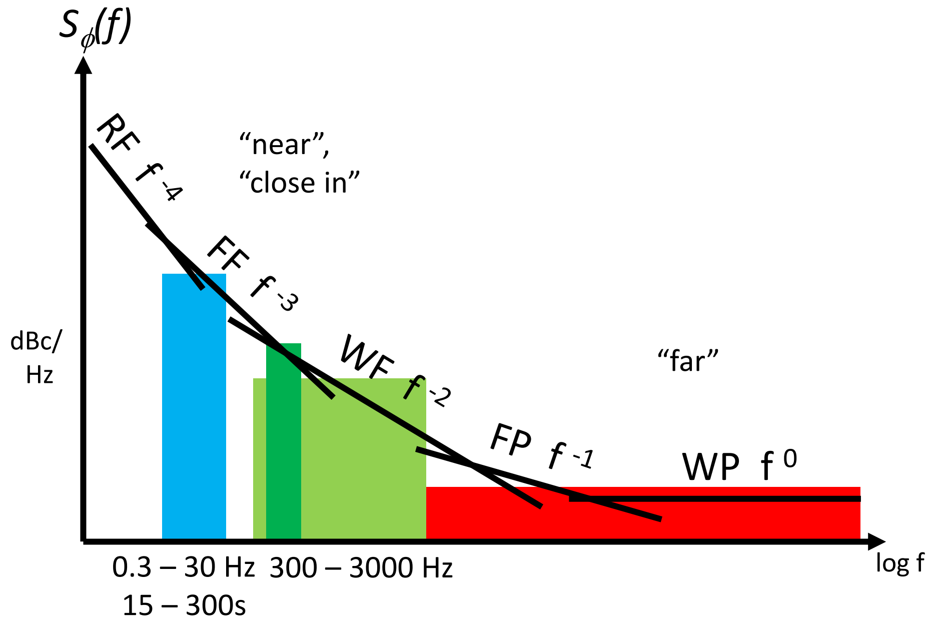
Why do ***we*** care? Effects of PN, Stability

IPN is PN (dBc/Hz) integrated over channel (or symbol) bandwidth (Hz)

- PN power under the curve
- Note log f scale…

  as we move to the right, many more Hz per step

- IPN (f) ~ jitter (t)



In channel IPN

MFSK (WSJT)

symbols are 'smeared' and/or 'wander' over the message period, decoding fails

Higher sensitivity requires narrow symbols and close spacing which moves us "closer in"

In channel IPN

(CW, SSB)

competes with the signal

reduces SNR and intelligibility

Off channel IPN ***(& spurs)***

Wasted Tx power

Tx interferes with others

Rx 'hears' off channel interference (reciprocal mixing of that beacon 300 kHz up the band), masks desired signal

Many decades of f… adds up

Spurs bring in stronger interference, waste more power

Another reason to care:

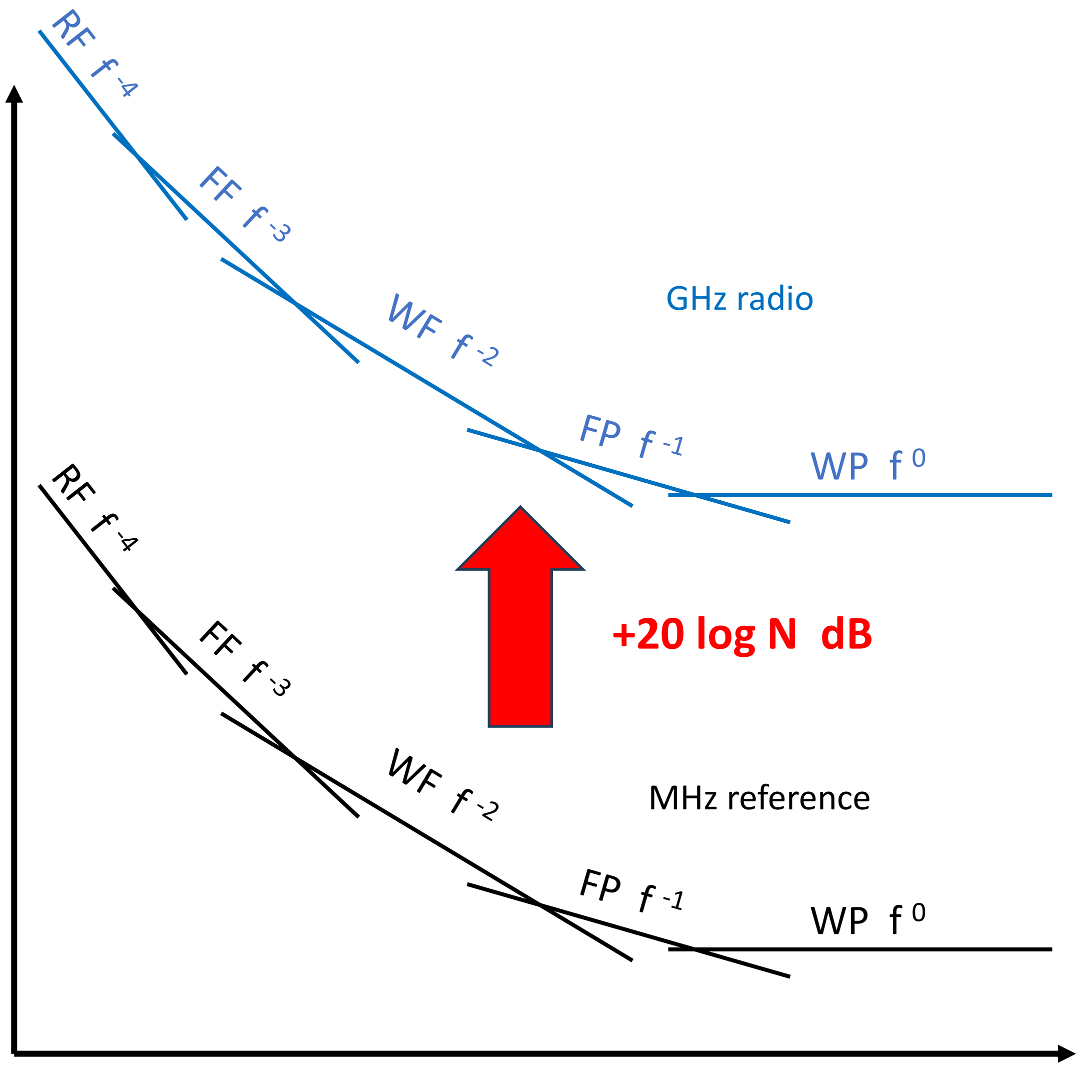
Frequency Multiplication

- In a typical radio, we use a HF frequency reference and multiply it up to get the operating frequency
- When we multiply frequency by ***N***, phase noise & spurs increase by ***20 log(N) dB !***

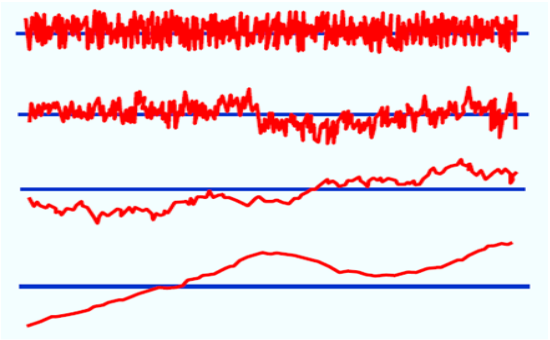
(at same offset frequencies)

  - 10M -> 1296M : **+42 dB**
  - 10M -> 10368M : **+60 dB**
  - 10M -> 122950M : **+82 dB**

- Divide by N is a happier story ☺



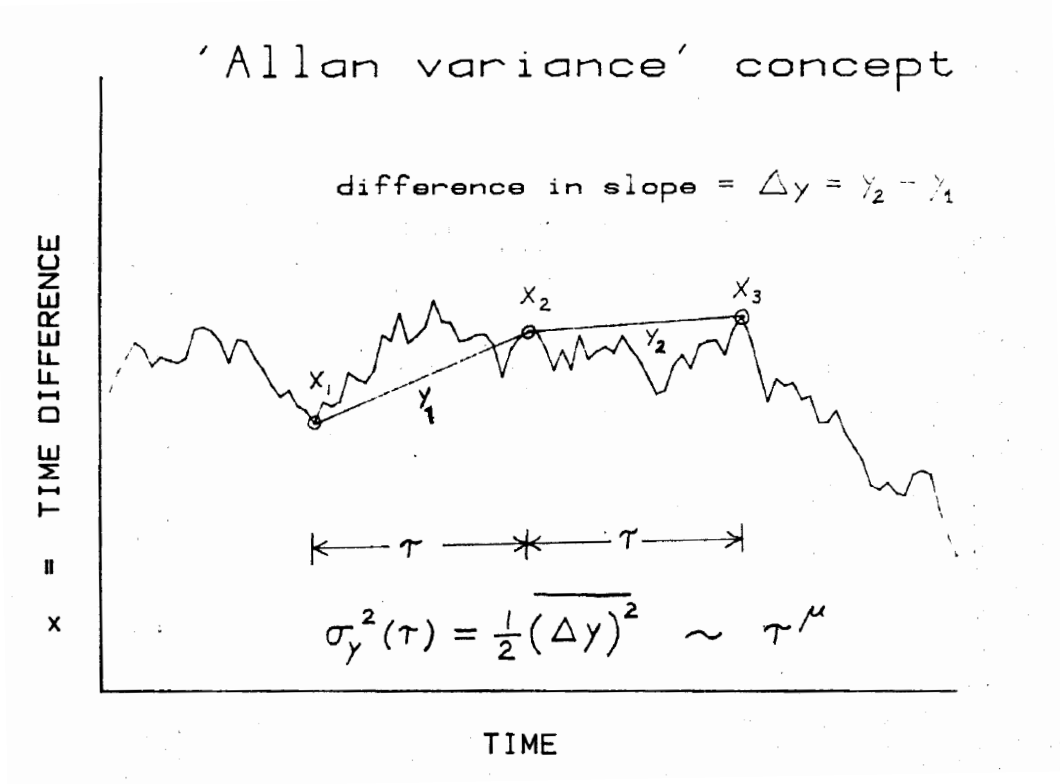
Time Domain Statistics: Allan Variance



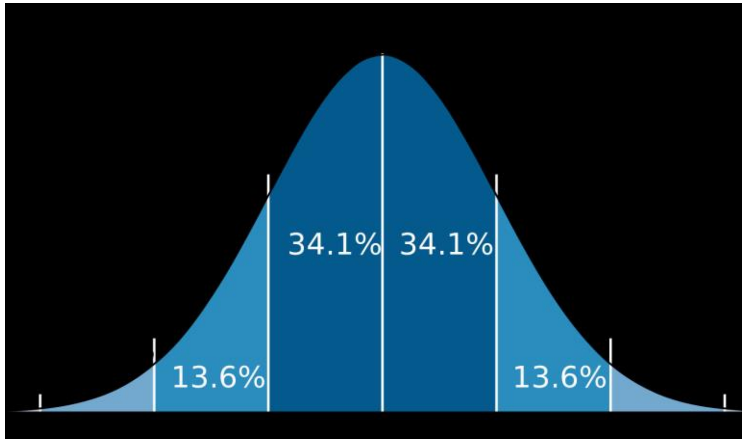
- David Allan developed a statistical measure the stability of an oscillator's fractional frequency over time
- N samples of **x = phase (time) difference**
- N-1 samples of **y = differential frequency = df / f_0**
- $\mathbf{y_n} = (x_{n+1} - x_n) / \tau = \mathbf{\Delta x_n / \tau}$ (first difference)
- $\mathbf{y_{n+1}} = (x_{n+2} - x_{n+1}) / \tau = \mathbf{\Delta x_{n+1} / \tau}$ (first difference)
- Clock instability from period τ to **next** period τ :
- N-2 samples of $\mathbf{\Delta y_n} = (y_{n+1} - y_n) = \mathbf{(\Delta x_n - \Delta x_{n+1}) / \tau}$

  $= \mathbf{\Delta^2 x_n / \tau}$ (second difference)
- The **2-sample variance** is

  the **sum** of the **squares** of the **second differences**, **divided by N-2**
- Divide that by 2 (to match classical variance of white freq noise)
- And call it **AVAR** or $\boldsymbol{\sigma_y^2(\tau)}$
- Popular (among time-nuts) as a measure of long term accuracy/stability



Time Domain Stats: Allan Deviation



For white FM noise,
68% of the time, we expect to be within 1 ADEV
95% of the time, we expect to be within 2 ADEVs
99.7% of the time, we expect to be within 3 ADEVs

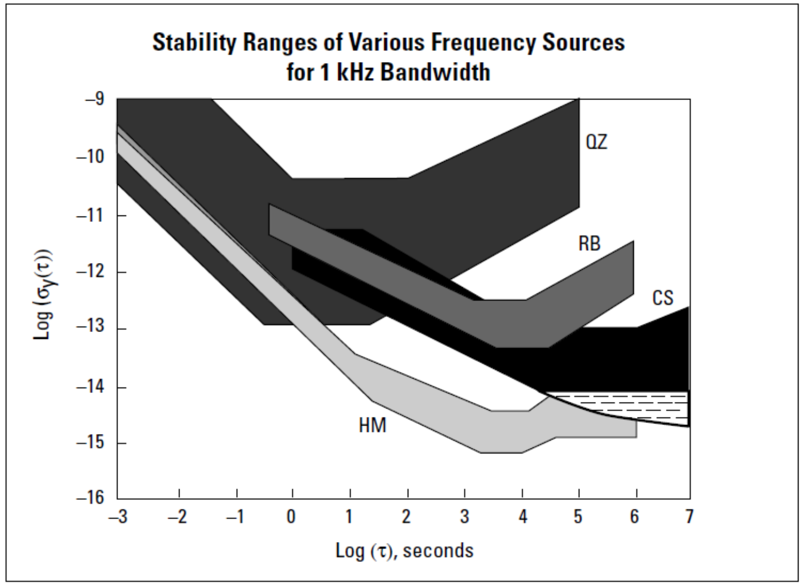
- **ADEV** (Allan Deviation), $\sigma_y(\tau)$, is the **square root of AVAR**
  - **68% of the time, we expect to be within one ADEV** (for white FM)
  - 95% of the time, we expect to be within two ADEVs (for white FM)
  - 99.7% of the time, we expect to be within three ADEVs (for white FM
- It's a measure of fractional frequency stability vs averaging time
- Popular (among time-nuts) as a measure of long term accuracy/stability

QZ: quartz   RB: Rubidium   CS: Cesium   HM: Hydrogen Maser

ADEV Plots: log $\sigma_y(\tau)$ vs log τ

In an ADEV plot, log $\sigma_y(\tau)$ vs log τ, the data slopes identify the noise type

MDEV (Modified ADEV) developed to separate the flicker and white PN



0 = 1s, 2 ~ 2m, 4 ~ 3h, 5 ~ 1d, 6 ~ 2wk, 7 ~ 4 mo

Noise Type	ADEV Slope	MDEV Slope
Freq drift	+1	+1
Random Walk Freq	+0.5	+0.5
Flicker Freq	0	0
White Freq	-0.5	-0.5
Flicker Phase	-1	-1
White Phase	-1	-1.5

Notice that different types of oscillators have different high stability regions in τ

PN(f) → ADEV(τ)

Phase Noise Power Spectrum $S\phi(f) = b_{-4} f^{-4} + b_{-3} f^{-3} + b_{-2} f^{-2} + b_{-1} f^{-1} + b_4 f^{0}$

- They are related, but "It's complicated"
- Convert PN power $S\phi(f)$ -> FF power $S_y(f)$
  - *multiplies by f^2, 'rotates' slopes CCW*

αf^2

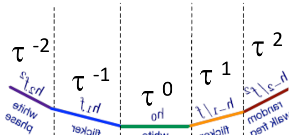
$h_n = b_{n-2} / (2\pi f_0)^2$

h_n *are small due to* $1/f^2$

- Identify noise type regions
  - 'corner freq' breakpoints, avg powers

Frac Freq Power Spectrum $S_y(f) = h_{-2} f^{-2} + h_{-1} f^{-1} + h_0 f^{0} + h_1 f^{1} + h_2 f^{2}$

$f \Leftrightarrow t$ "mirror"



- Transform from freq to time domain
  - 'mirrors' about the power axis (t = 1/2πf)

average over τ τ^{-1}

- Time-average over various τ (integrating LPF)
  - 1/τ * area rotates a click CW

AVAR $\sigma_y^2(\tau) = (0.076 f_H h_2 + 0.17 h_1)\, \tau^{-2} + 0.5 h_0\, \tau^{-1} + 1.4 h_{-1} + 6.6 h_{-2}\, \tau^{1} + 0.5 D_y^2\, \tau^2$

ADEV = sqrt (AVAR), so $\tau^{-1}, \tau^{-1/2}, \tau^0, \tau^{1/2}, \tau^1$

- xDEV = sqrt(xVAR)
  - τ exponents divided by 2

MVAR $= 0.038 h_2\, \tau^{-3} + 0.086 h_1\, \tau^{-2} + 0.25 h_0\, \tau^{-1} + 0.94 h_{-1} + 5.4 h_{-2}\, \tau^{1} + 0.5 D_y^2\, \tau^2$

MDEV = sqrt (MVAR), so $\tau^{-3/2}, \tau^{-1}, \tau^{-1/2}, \tau^0, \tau^{1/2}, \tau^1$

- The reverse (ADEV -> PN) is even more complicated (not always possible)

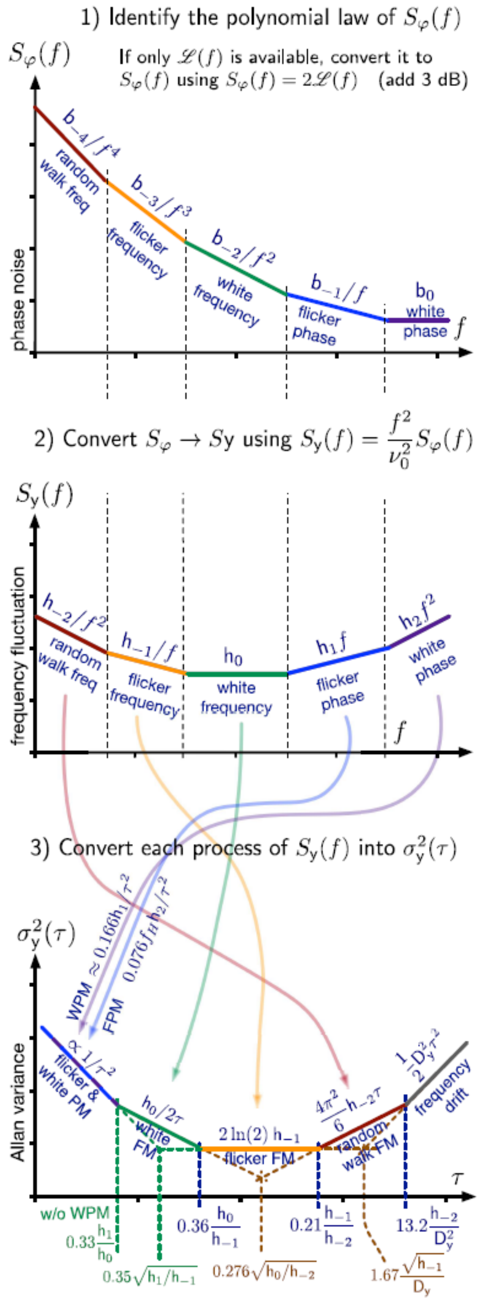
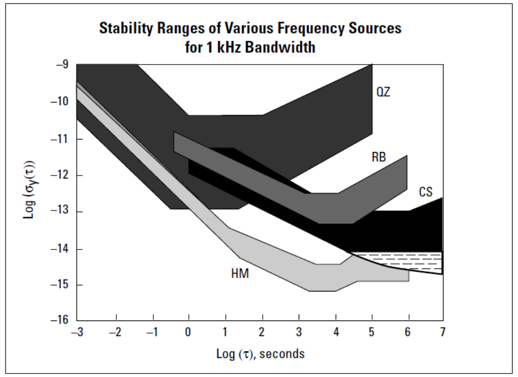


Fig. 11: Conversion from phase noise to Allan variance. The colors of the straight line approximation recall the frequency, from reddish (low) to bluish (high).

The Search For a Good Reference



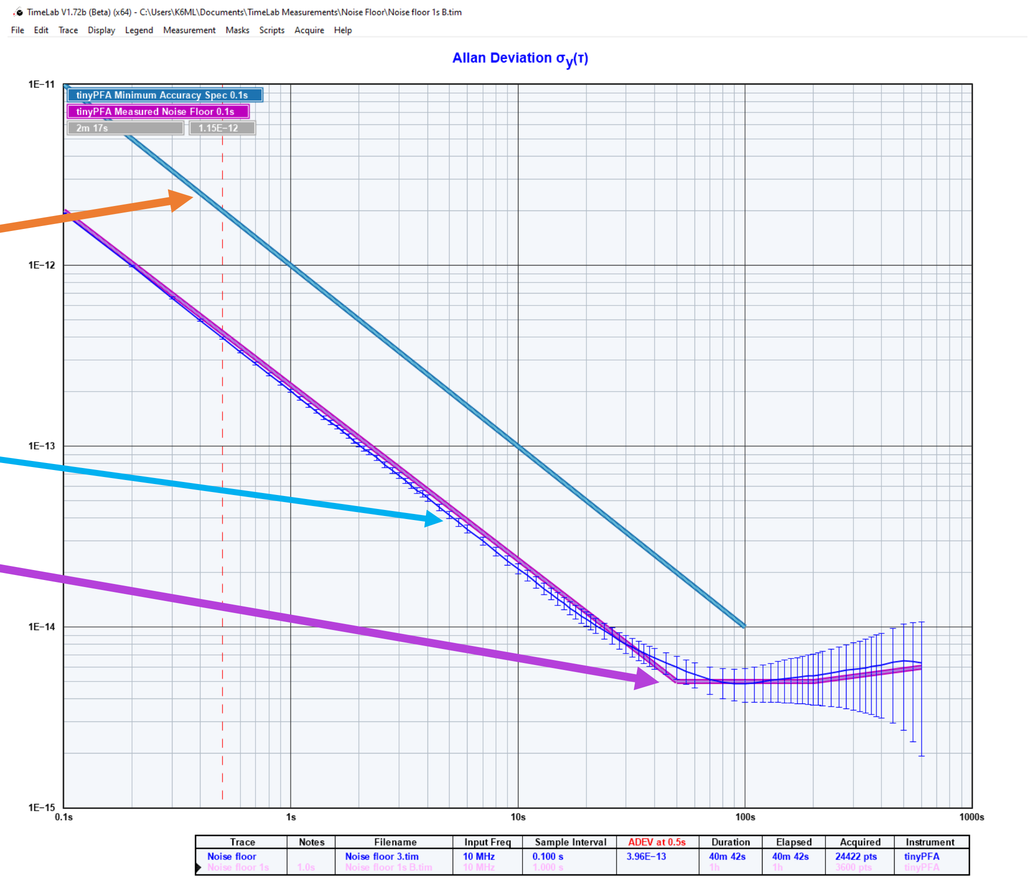
- We saw earlier that no one source type is best over all τ
- We also saw that the overall performance differs for different sources
- Also, individual devices of the same type may perform better or worse

- I'm searching for the best reference(s) to use on my bench and in my radio
  - On the bench, accuracy and stability outweigh size, power, warmup time, temp stability, etc
  - In the field I want "good enough" stability and accuracy
    - "Good enough" depends on the frequency and the mode (SSB, CW, Q65, QRSS) of operation
    - Stability time frames are: over a message, over a rover stop, over a contest weekend
    - Size, weight, power consumption, wider temp range, etc get count for more than in the lab

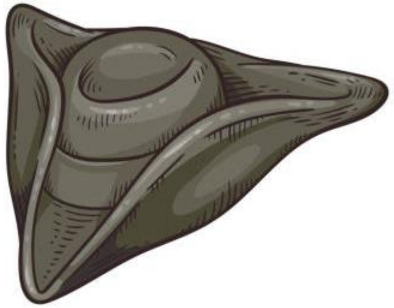
- Let's prepare for the search …

tinyPFA Noise Floor (Time Domain Accuracy)

- Don’t use an instrument without knowing its accuracy limit
- tinyPFA accuracy is spec’d as better than 1E-12 divided by τ
- Feed the same source into both ports to measure the internal noise floor of the tinyPFA; this is the accuracy limit
- Expect white noise (τ slope = -1 on log-log), with intercept below 1E-12 at τ = 1s (light blue mask line)
- Result (dark blue, with error bars) is
  - about 5x better than spec: 2E-12 at 1s
  - τ slope = -1 to about 8E-15 where noise floor flattens out
- Made a new mask (purple) for ‘my measured noise floor’
  - Good enough for testing a 122 GHz Q65-300 reference
  - Everything I will show you is a decade or more above that mask



BTW, this ADEV plot took ~40 min to acquire (~24k samples @ 10/sec), but end of plot is τ ~ 10 min (not enough data points)
Also note the confidence drops near end of plot (error bars increase)
Much higher confidence up to about t ~ 1 min…
the last decade of τ on (any) ADEV plot is less accurate than the shorter τ decades



Tri-cornered Hat Statistics

$$\sigma_{ab}^2 = \sigma_a^2 + \sigma_b^2$$

$$\sigma_{ac}^2 = \sigma_a^2 + \sigma_c^2$$

$$\sigma_{bc}^2 = \sigma_b^2 + \sigma_c^2$$

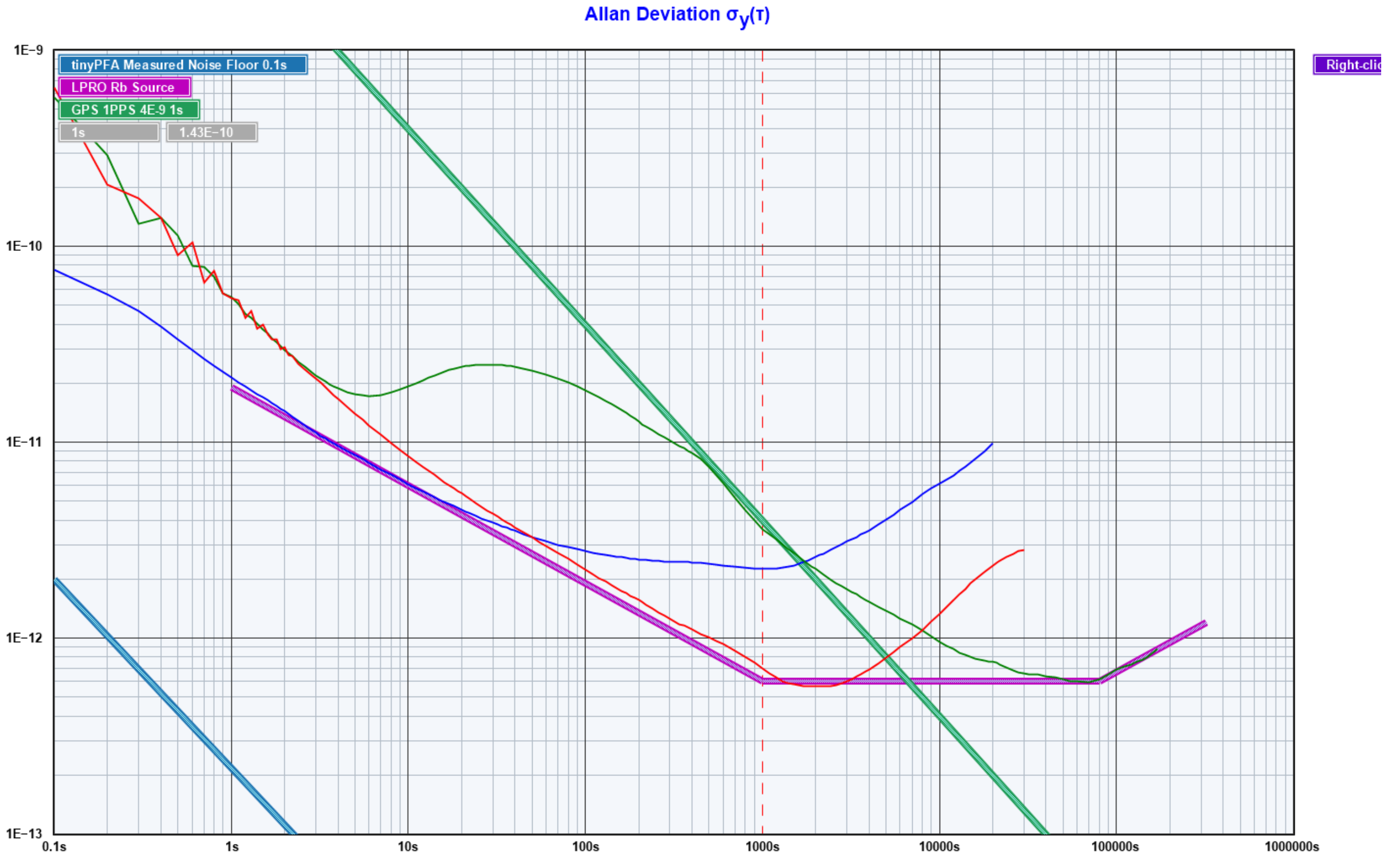
- Each of our measurements is the difference between two devices
- Compare $\sigma_{y_{ab}}^2(\tau)$, $\sigma_{y_{ac}}^2(\tau)$, $\sigma_{y_{bc}}^2(\tau)$ plots for the 3 pairings of 3 devices (a, b, c)
- If measurements are independent, we can extract the stability of each device:

$$\sigma_a^2 = \frac{1}{2}\left(\sigma_{ab}^2 + \sigma_{ac}^2 - \sigma_{bc}^2\right),$$

- If we only have two devices (one plot), we make these rough approximations:
- ADEV = $\sigma_y(\tau) = \text{sqrt}\left(\sigma_{y_A}^2(\tau) + \sigma_{y_B}^2(\tau)\right)$
  - ADEV = $\sigma_{y_A}^2(\tau)$ when $\sigma_{y_A}^2(\tau) \gg \sigma_{y_B}^2(\tau)$
  - ADEV = $\sqrt{2}\,\sigma_{y_A}^2(\tau)$ when $\sigma_{y_A}^2(\tau) = \sigma_{y_B}^2(\tau)$
  - ADEV = $\sigma_{y_B}^2(\tau)$ when $\sigma_{y_A}^2(\tau) \ll \sigma_{y_B}^2(\tau)$

Searching For a Good Rb Source

- The red trace compares two 10 MHz Rubidium sources that I found at All-Phone (Lucent, LPRO), Rb2 - Rb
- The blue trace compares a CTI OCXO with the first Rb source
- The green trace compares a GPSDO with the first Rb source
- The blue mask is the tinyPFA noise floor.
- The green mask is the GPSDO jitter limit (more on this later).
- The purple mask matches the LPRO datasheet spec, which runs from τ = 1s to τ = 100s; the rest is my inference from the measurements.
  - The τ = -0.5 slope from 1s to 1000s is white FM noise
  - The flicker FM floor is ~ 6E-13
  - Random walk FM starts at about 1 day (below 10K sec)
- The first unit (Rb) is better than the second (Rb2)
  - Rb2 is has more WFM noise below τ ~ 10s
  - Rb2 starts random walk FM above τ ~ 5000s
- The purple mask is a composite mask for the better Rb source, from the LPRO Rb datasheet and my measurements.

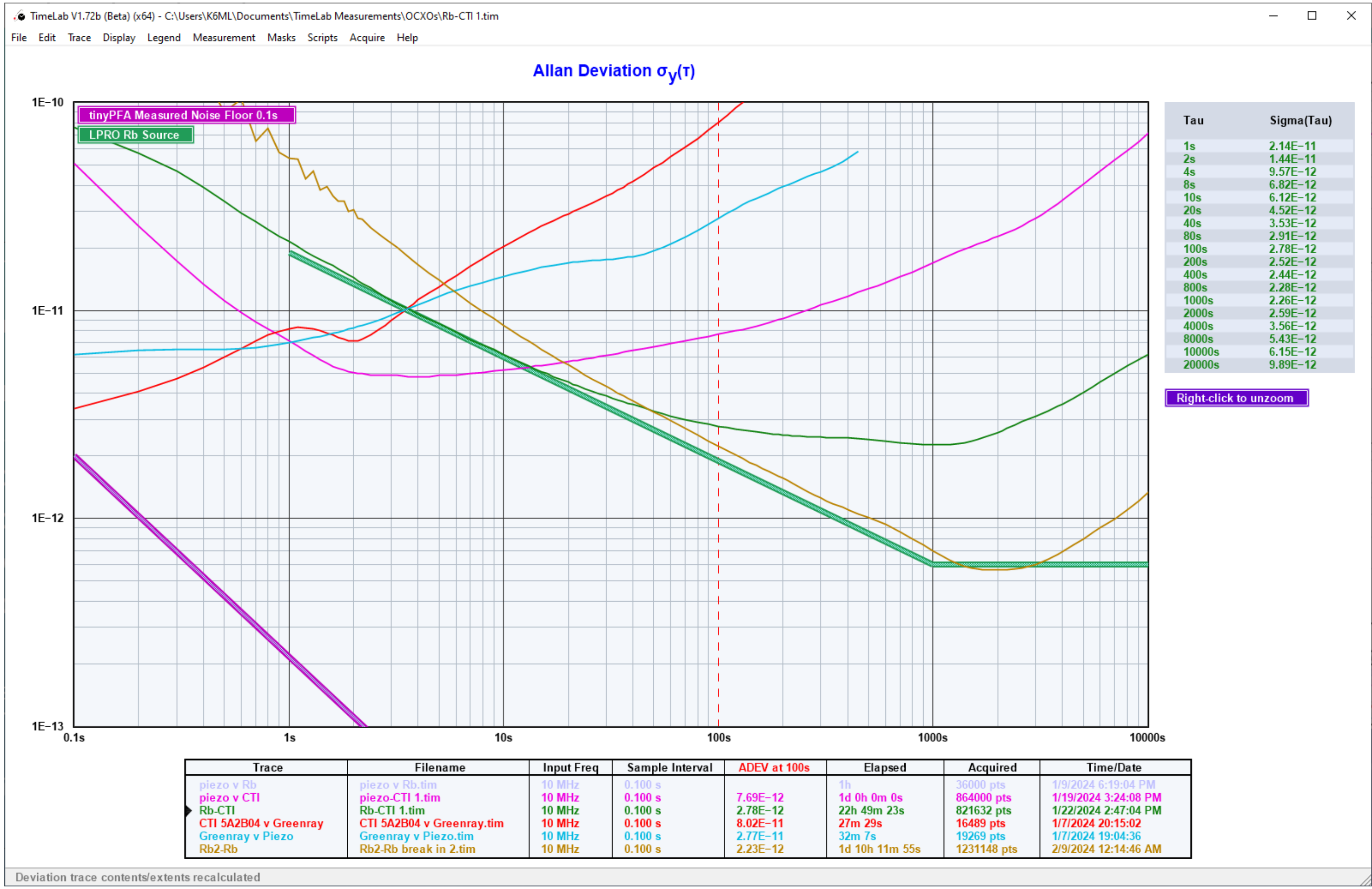


Trace	Notes	Filename	Input Freq	Sample Interval	ADEV at 1000s	Elapsed	Acquired	Time/Date
Rb-CTI	Rb B - CTI A (ref)	Rb-CTI 1.tim	10 MHz	0.100 s	2.26E-12	22h 49m 23s	821632 pts	1/22/2024 2:47:04
TM4313 - CTI	TM4313 - CTI N ant	TM4313 - CTI n.tim	10 MHz	0.100 s		20h 15m 7s	729067 pts	2/29/2024 1:58:11
TM4313-Rb	GOSDO B - Rb A (ref)	TM4313-Rb 2.tim	10 MHz	0.100 s	3.61E-12	8d 0h 0m 0s	6912000 pts	1/28/2024 12:53:45
TM4313 - Rb	TM4313 - Rb N ant	TM4313 - Rb n.tim	10 MHz	0.100 s		23h 50m 39s	858388 pts	3/1/2024 11:10:42
Rb2-Rb	Rb#2 B - Rb A (ref)	Rb2-Rb break in 2.tim	10 MHz	0.100 s	7.01E-13	1d 10h 11m 55s	1231148 pts	2/9/2024 12:14:46

Searching For a Good OCXO

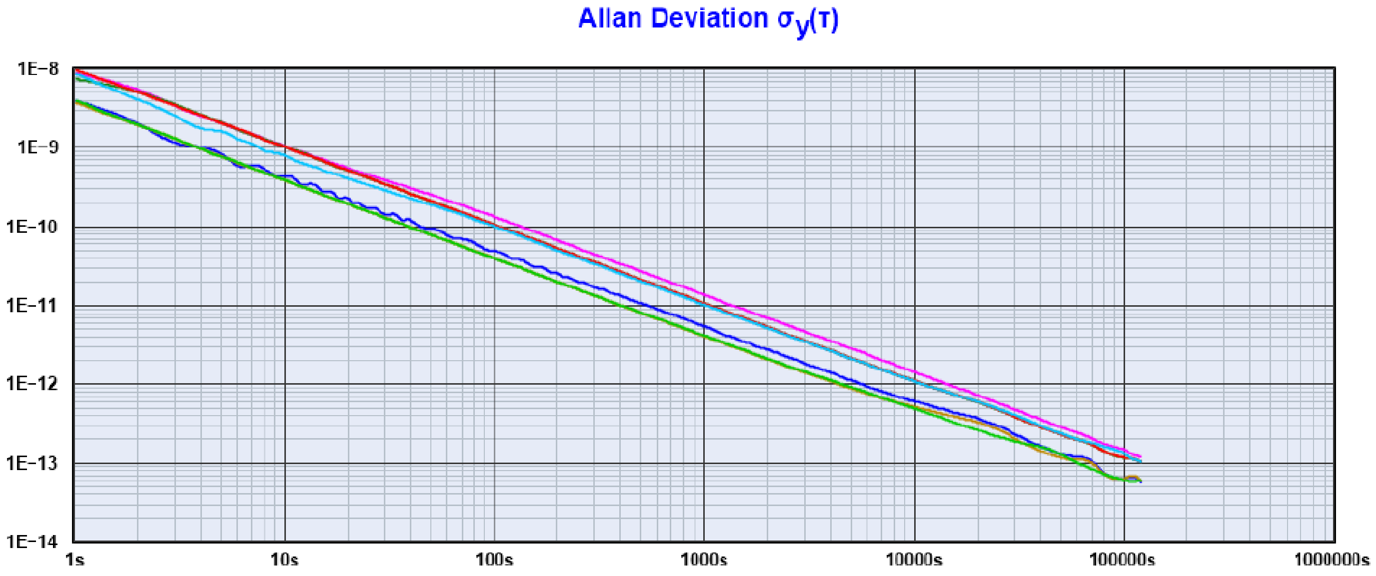
- The purple, red and blue traces compare three pairs of three 10 MHz OCXOs from my junkbox (Piezo, CTI, Greenray)
- I've also compared the CTI with my better Rb source (green)
- I've also compared two RB sources (brown)
- The green mask is the composite mask for the better Rb unit (was purple on previous slide)
- The purple mask is the tinyPFA noise floor
- Based on tri-corner, etc, the CTI unit seems best of the lot

  ~ 3.6E-12 at 0.1s
  < 5E-12 at 1s
  ~ 3.5E-12 at 10s
  < 3E-12 at 100s
  ~ 2E-12 at 1000s (~17m)
  ~ 7E-12 at 10000s (~2.8h)
  Overall, below 4E-12 from 0.1s to 5000s.
- XOs get more stable with age, so a few weeks of burn-in helps a lot.
- Thermal isolation and/or a more stable temp environment helps, too.



GPS System

- **The DoD was kind enough to launch dozens of GPS satellites that are high stability, accurate references**
- The GPS system is based on accurate time; propagation time from known positions is used to determine range to multiple satellites
- The satellites have two or more atomic (Rb?) each and all are syntonized (zero freq offset) and synchronized (zero time offset) against primary time standards on the ground on a regular basis
- GPS receivers calculate the location based on the satellites in view and also produce an accurate timing pulse (often 1 PPS, sometimes a higher frequency) and position and time messages
- The GPS system transfers the accuracy of the primary standards on the ground to the satellites



Trace	Notes	Sample Interval	Acquired	Instrument
LEA-M8F	vs HP 5071A	1 s	510244 pts	multi-TICC
NEO-M8N	vs HP 5071A	1 s	510244 pts	multi-TICC
NEO-M8P	vs HP 5071A	1 s	510244 pts	multi-TICC
NEO-M8T	vs HP 5071A	1 s	510244 pts	multi-TICC
NEO-M9N	vs HP 5071A	1 s	510244 pts	multi-TICC
ZED-F9P	vs HP 5071A	1 s	510244 pts	multi-TICC
ZED-F9T	vs HP 5071A	1 s	510244 pts	multi-TICC

Figure 2: Allan Deviation of all seven u-blox receivers.

- **We can use a GPS Rx to transfer (most of) that accuracy back to our QTH on Earth**
- Some accuracy is lost due propagation variations thru the ionosphere, some more in the Rx.
- Dual frequency GPS Rx can identify & factor out some of the ionospheric errors for better transfer accuracy.
- **GPS Rx time pulses have tens of nsec of jitter**, mostly white PN (thus the $\tau = -1$ slope).
  - We saw an example of this jitter limit in the Rb tests two slides ago.

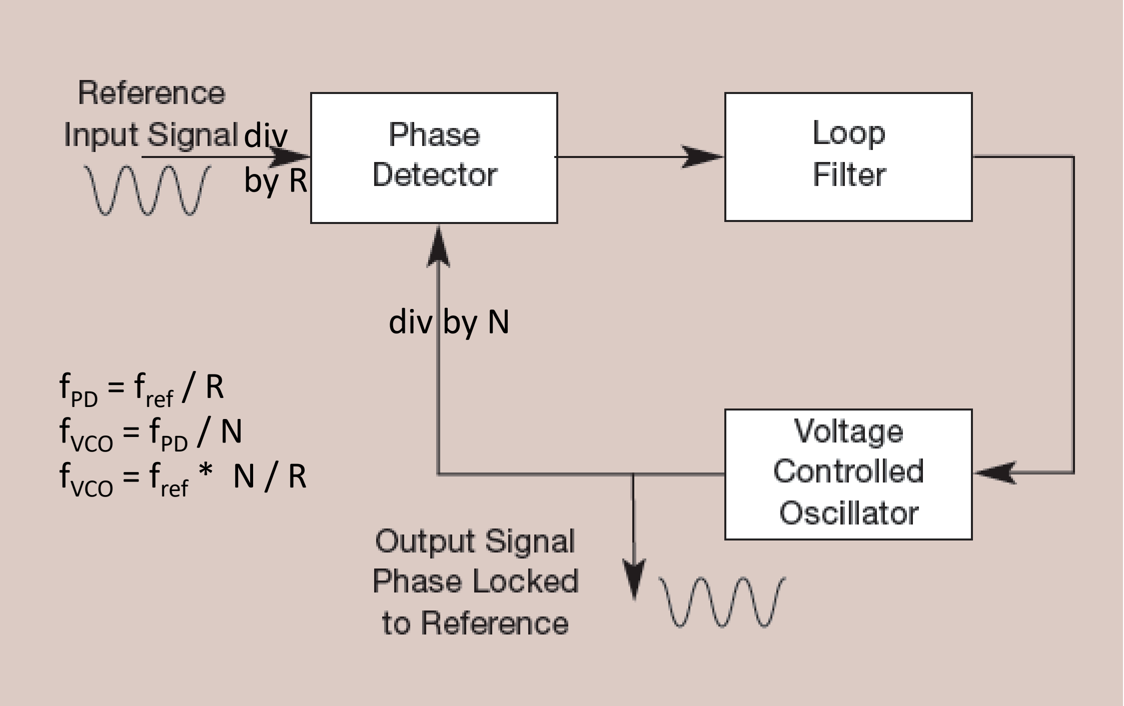
Phase Locked Loops

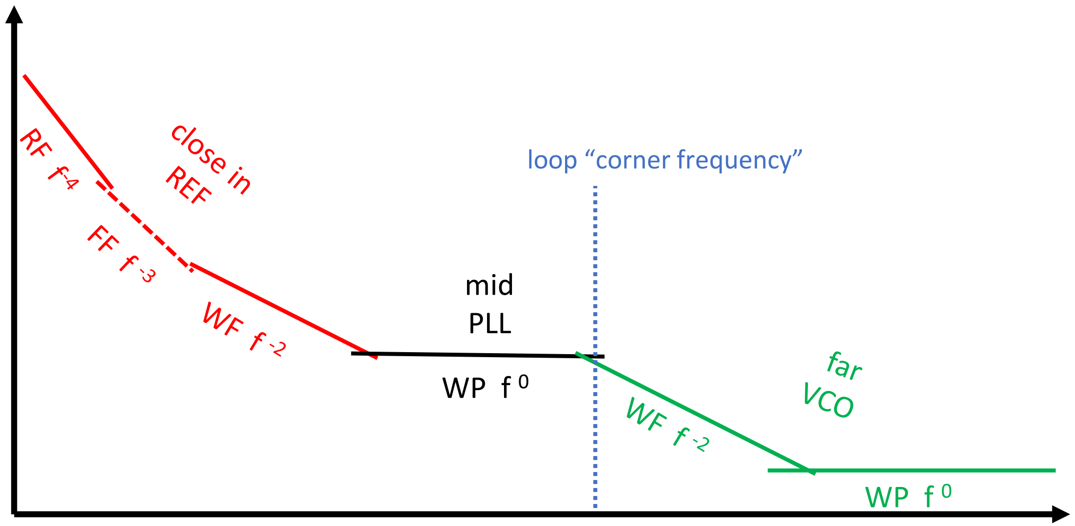
- A well designed PLL gives the best of two oscillators
  - A phase detector compares a higher frequency voltage controller oscillator (VCO) to a lower frequency reference oscillator.
  - Either or both oscillators may be frequency divided prior to the phase comparator.
  - A loop filter (typ 2nd order LPF) filters the PD output to develop the VCO control voltage.
  - The "loop dynamics" are determined by the loop filter
    - Bandwidth (f domain) / Settling Time (t domain): Below the 'corner frequency', the reference oscillator PN/stability dominates the output. Above, the VCO dominates.
    - Phase Margin (f domain) / Damping (t domain): Controls the transition near the corner frequency; we may see more instability if too low.

- Jitter Cleaner PLL
  - We can 'clean up' a reference's far PN by choosing a VC(X)O with lower PN.
- Disciplined Oscillator
  - We can 'discipline' (stabilize) a VCO by choosing a reference with better close in PN / better long tern stability.

- Frequency Multiplier (fixed M/N ratio PLL)
- Frequency Synthesizer (tunable M/N ratio PLL)

- The PLL chip can add noise (and spurs)
  - typically shows up in the 'mid-band pedestal'
- $PN_{tot} = PN_{ref}$ (close in) + PN_{PLL} (mid) +

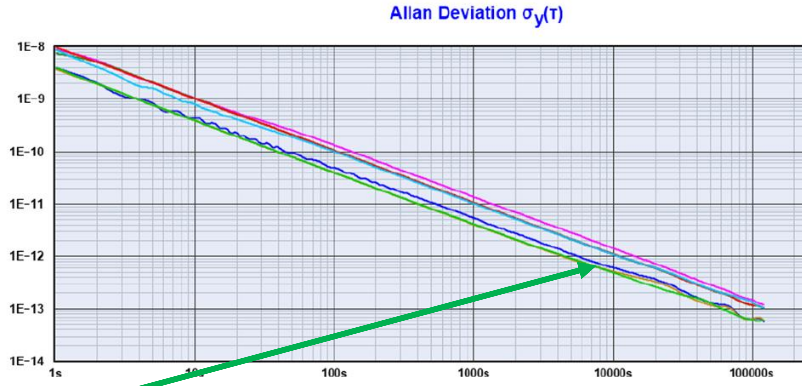




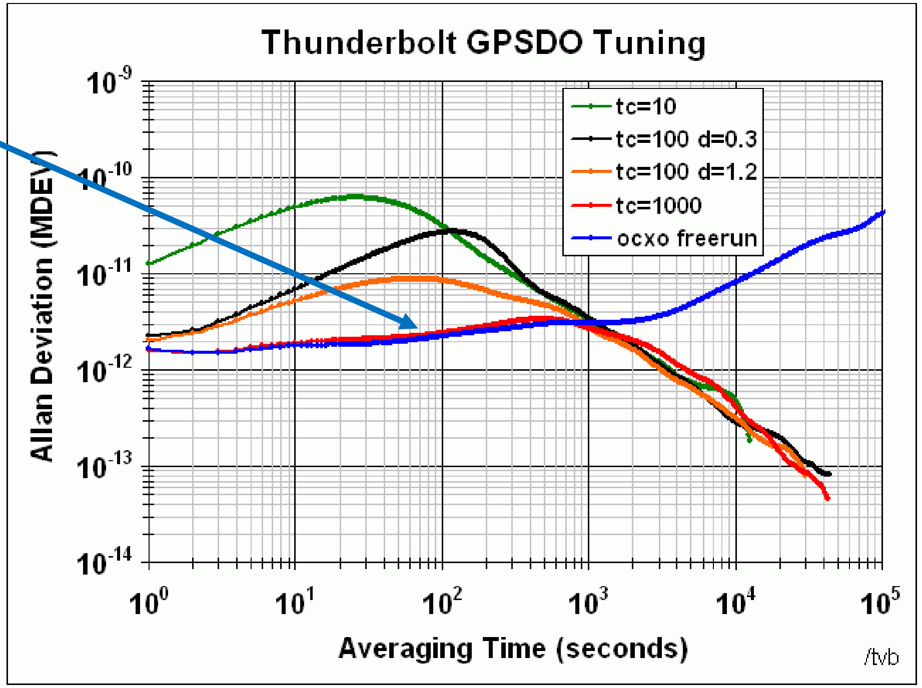
GPS Disciplined Oscillators (GPSDO)

- Use GPS as the PLL reference
- Clean up GPS propagation & Rx noise / jitter
- Combine accuracy & long term stability of GPS with good phase noise & short term stability of VCXO
  - Get the loop dynamics right (tc = 1000s in this case)
- Transfers GPS accuracy & long term stability to VCXO oscillator

GPS reference stability (better above τ ~1000s)



Blue trace = VC(X)O stability (better below τ ~ 1000s)



Tuning the Leo Bodnar Mini GPSDO

uBLOX MAX-M8Q GPS Rx (includes a TCXO)

Si5328 Jitter Cleaner PLL w/ ext TCXO as VCO

Si5328 digital PLL has a "BW" tuning parameter:

2 (1.2 Hz)

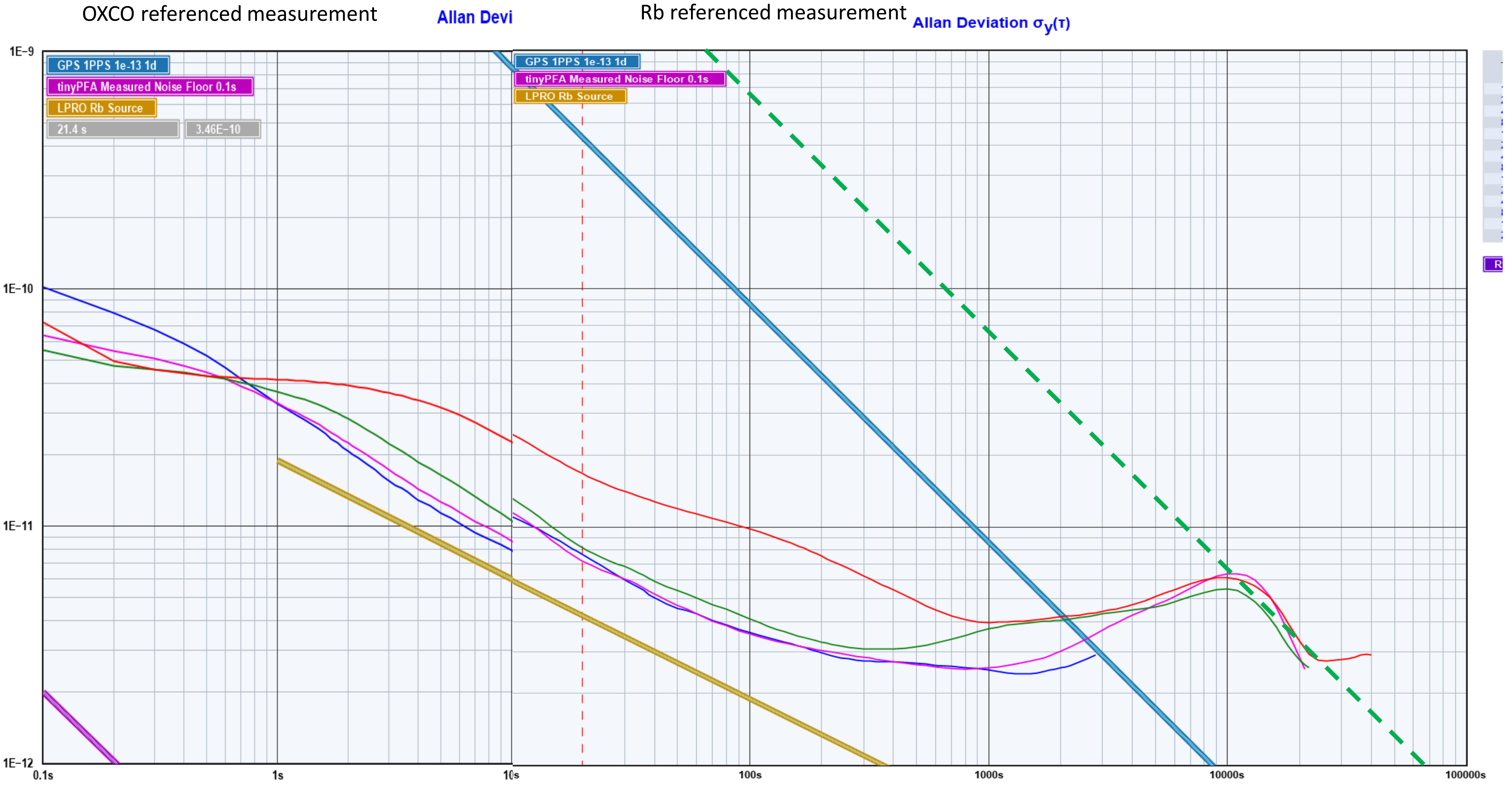
3 (0.56 Hz)

4 (0.28 Hz)

6 (0.07 Hz)

3 seems best overall

not sure… maybe τ ~ .3 ?

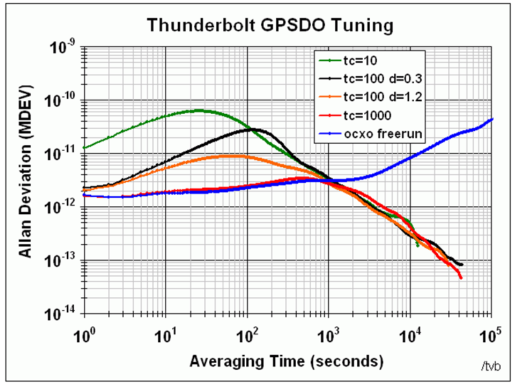


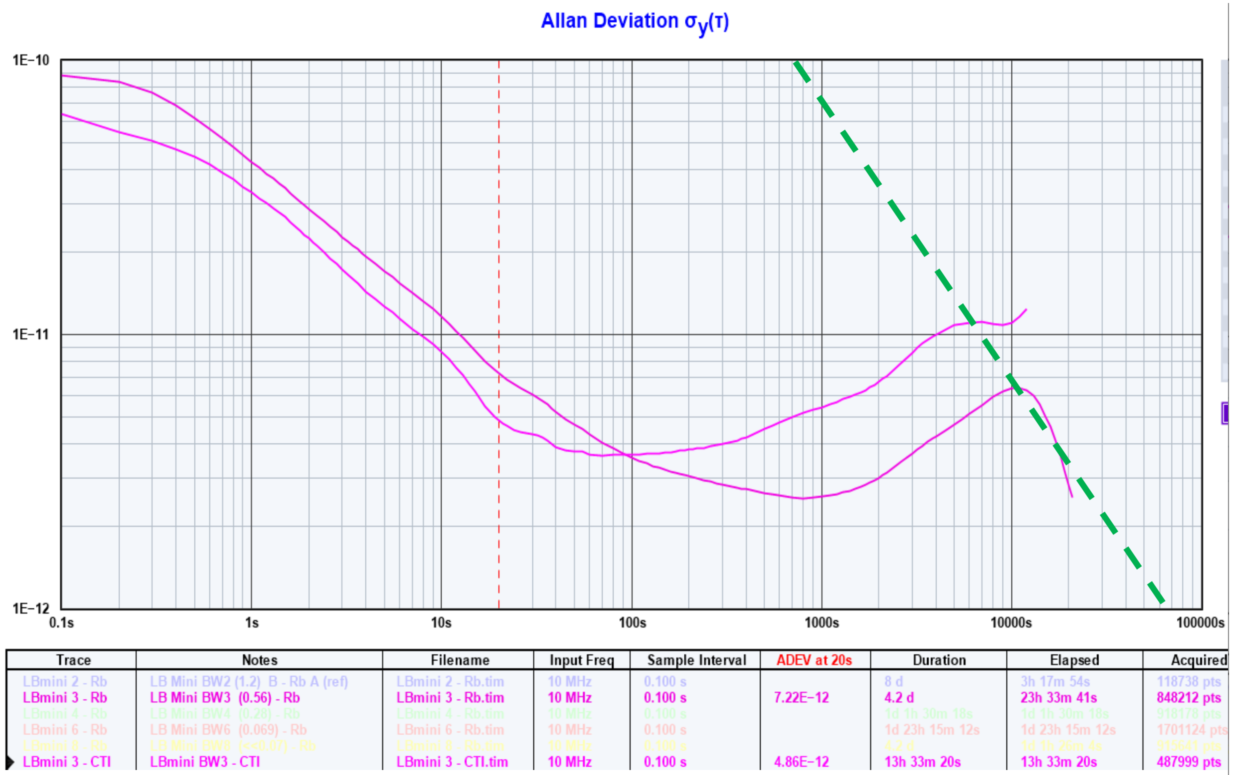
Trace	Notes	Filename	Input Freq
LBmini 2 - CTI	LBmini BW2 - CTI	LBmini 2 - CTI.tim	10 MHz
LBmini 3 - CTI	LBmini BW3 - CTI	LBmini 3 - CTI.tim	10 MHz
LBmini 4 - CTI	LBmini BW4 - CTI	LBmini 4 - CTI.tim	10 MHz
LBmini 6 - CTI	LBmini BW6 - CTI	LBmini 6 - CTI.tim	10 MHz

race	Notes	Filename	Input Freq	Sample Interval	ADEV at 20s	Duration	Elapsed	Acquired
i 2 - Rb	LB Mini BW2 (1.2) B - Rb A (ref)	LBmini 2 - Rb.tim	10 MHz	0.100 s	7.68E−12	8 d	3h 17m 54s	118738 pts
i 3 - Rb	LB Mini BW3 (0.56) - Rb	LBmini 3 - Rb.tim	10 MHz	0.100 s	7.22E−12	4.2 d	23h 33m 41s	848212 pts
i 4 - Rb	LB Mini BW4 (0.28) - Rb	LBmini 4 - Rb.tim	10 MHz	0.100 s	8.20E−12	1d 1h 30m 18s	1d 1h 30m 18s	918178 pts
i 6 - Rb	LB Mini BW6 (0.069) - Rb	LBmini 6 - Rb.tim	10 MHz	0.100 s	1.68E−11	1d 23h 15m 12s	1d 23h 15m 12s	1701124 pts

Comparing LB Mini & TM4313 (eBay) GPSDOs

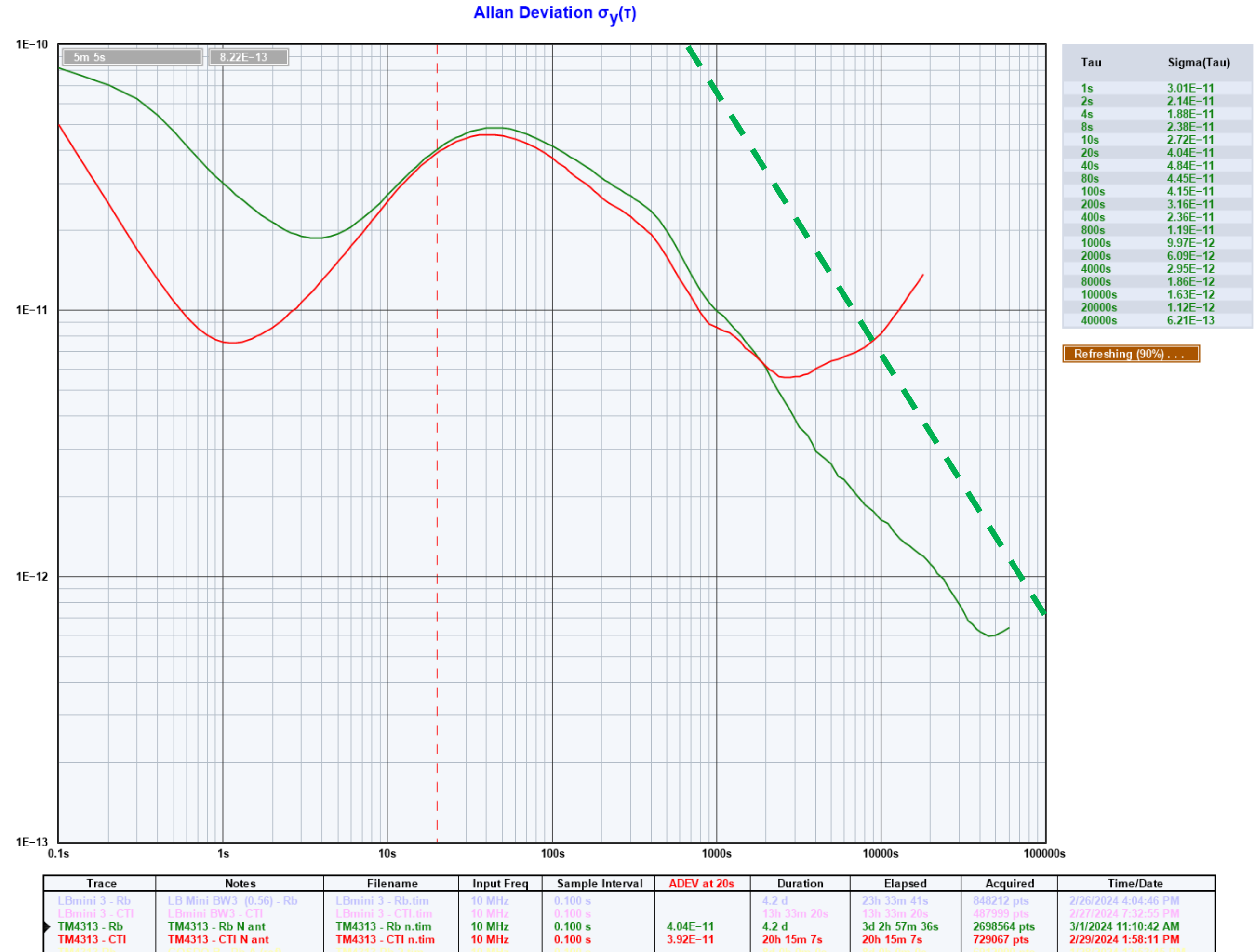
TM4313 probably has better VCXO,
but no way found to tune loop;
loop seems mistuned, overdisciplined
(bump in midrange, 1s < τ < 1000s)





Optimized LB Mini, BW = 3 (0.56 Hz)
Does better in midrange, but more
Rx jitter (3E-12 at 20 ksec)

TM4313, less Rx jitter
(3E-12 at 4 ksec, 1E-12 at 20 ksec)



Conclusion

- Frequency calibration can be done with counter, scope or tinyPFA; all require a good reference
- tinyPFA is an affordable tool for mid to long term stability measurements of HF/VHF reference sources
  - We need a reference standard at same nominal freq as device under test
  - TimeLab displays & crunches tinyPFA measurements, reveals stability and trends
- Phase noise (short term stability) is done with a spectrum analyzer or PN analyzer (lower noise floor)
- We can convert / compare between the PN and xDEV domains
- We can use the tools to measure and select better references and PLLs for our radios
  - Far PN: interferes with Rx, wastes Tx power
  - Audio band PN: distorts Rx/Tx, raises Rx noise floor
  - Close in PN / mid term stability: impacts digital modes
  - tinyPFA and a good SA are 'good enough' for our purposes, although a PhaseStation (or clone) would be nicer!

Thank You!

References for time-nuts, fmt-nuts & PN nuts

welcome to the rabbit hole ☺

- www.tinydevices.org   tinyPFA homepage
- www.miles.io/timelab/beta.htm   TimeLab download & user's manual
- http://www.ke5fx.com/   a treasure trove of tools, measurements and education
- http://www.ke5fx.com/stability.htm   lists many excellent papers and websites, including
  - John Vig on Oscillators http://www.umbc.edu/photonics/Menyuk/Phase-Noise/Vig-tutorial_8.5.2.2.pdf
  - Enrico Rubiola's Chart of Phase Noise and Two-Sample Variances is Rosetta Stone of time & freq meas
    - Even more at https://rubiola.org/
  - www.wriley.com *(WJ Riley explains xDEV, DMTD design & schematics)*
  - http://www.leapsecond.com/
  - https://www.febo.com/
  - https://www.nist.gov/pml/time-and-frequency-division publications and time & freq A to Z
    - Including early papers by David Allan on AVAR, etc and DMTD
    - Also tutorial collections of landmark papers, WJ Riley report
  - HP AN 1289   The Science of Timekeeping
  - The time-nuts mailing list