TDEV – Then and Now

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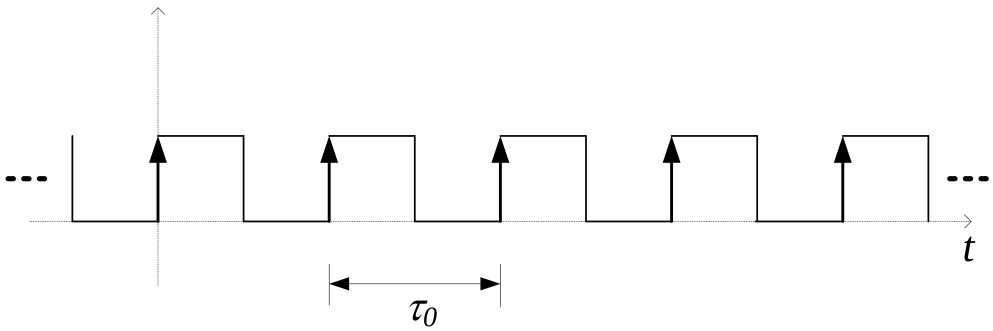
Presentation Outline

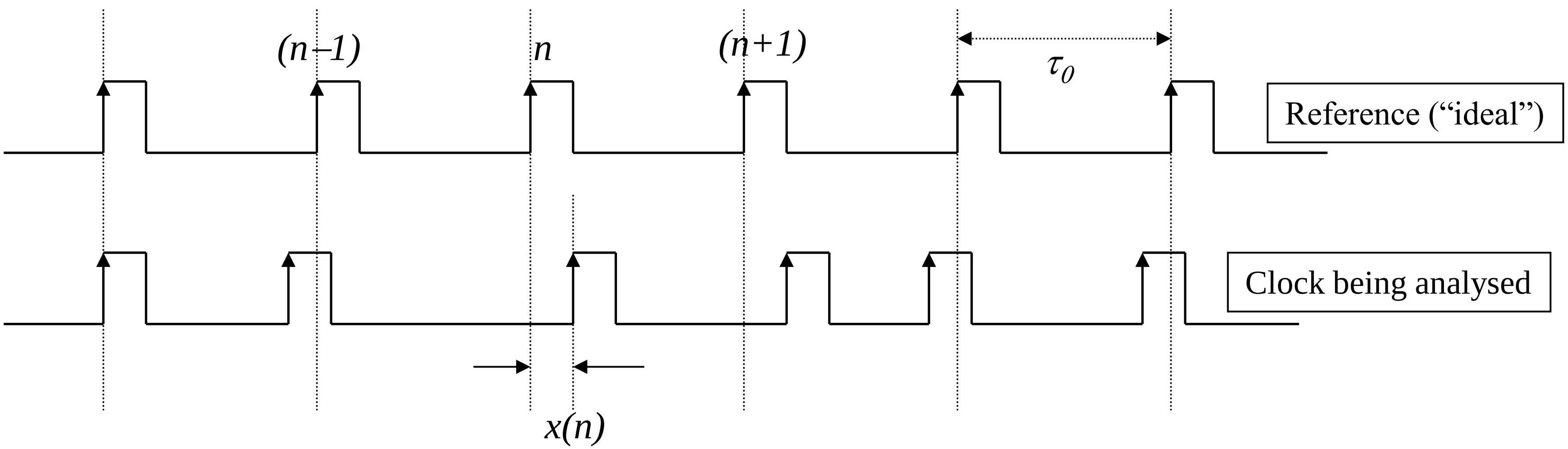
- TDEV Then…computed on time error measurements
  - Origins of ADEV, MDEV, and TDEV
  - Why is TDEV so useful?
- TDEV Now…computed on packet-based time error sequences
  - Packet-based formulations for time error
  - Examples of Calculations
- Concluding Remarks

Time Error



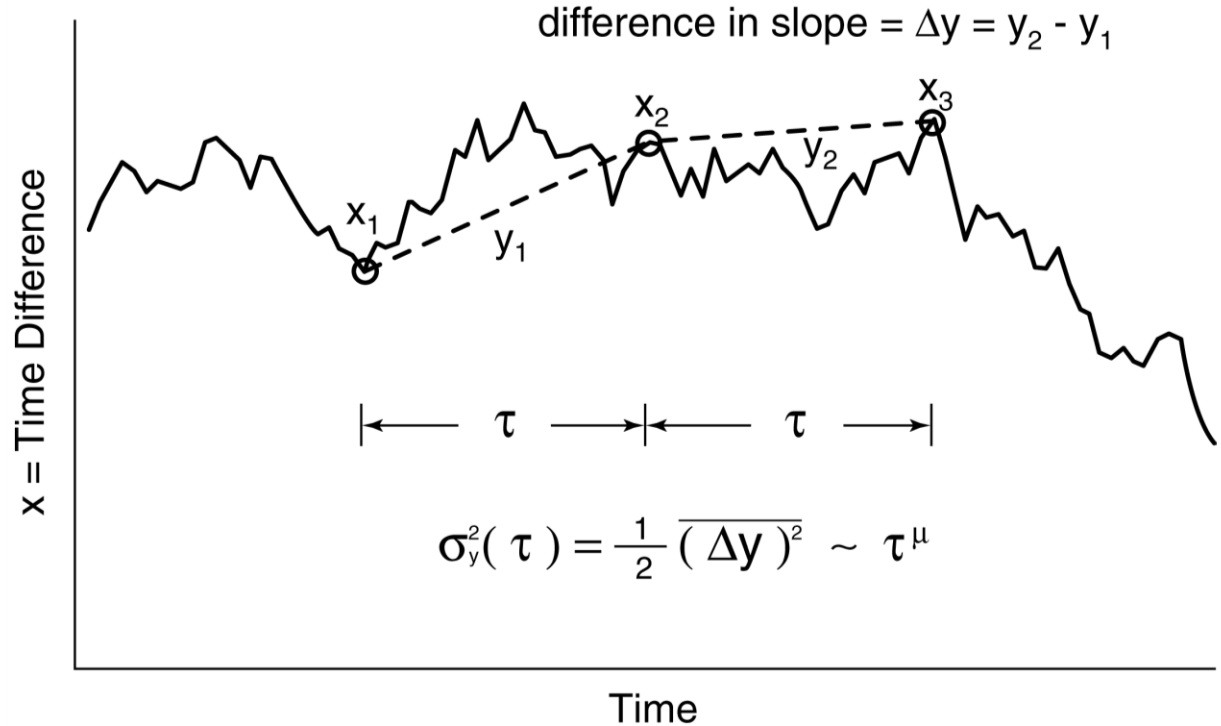
Generic Clock Waveform:

- Periodic
- Defined "event" (rising edge)



- Time error *x(n)* = time difference between the *n*th event of the clock under test with respect to the reference clock

Allan Variance Concept



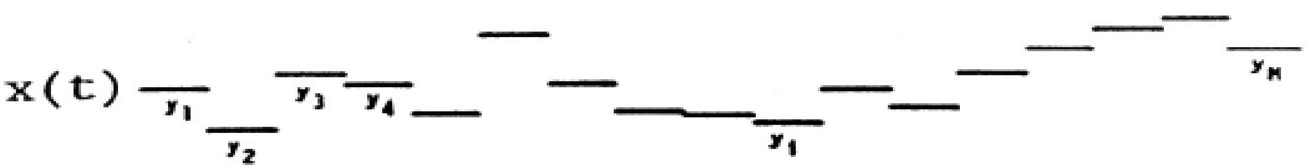
Stability : Measure of how “constant” is the slope

Allan vs. Classical Deviation

GIVEN THE TIME RESIDUALS FROM A PRECISSION CLOCK OR OSCILLATOR.

$\rightarrow\!| \ \tau \ |\!\leftarrow$

$$y_i = \frac{x_{i+1} - x_i}{\tau}$$



$$\sigma_{STD\ DEV\ y}(\tau) = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}(y_i - \bar{y})^2}$$

DOES NOT CONVERGE AS M INCREASES

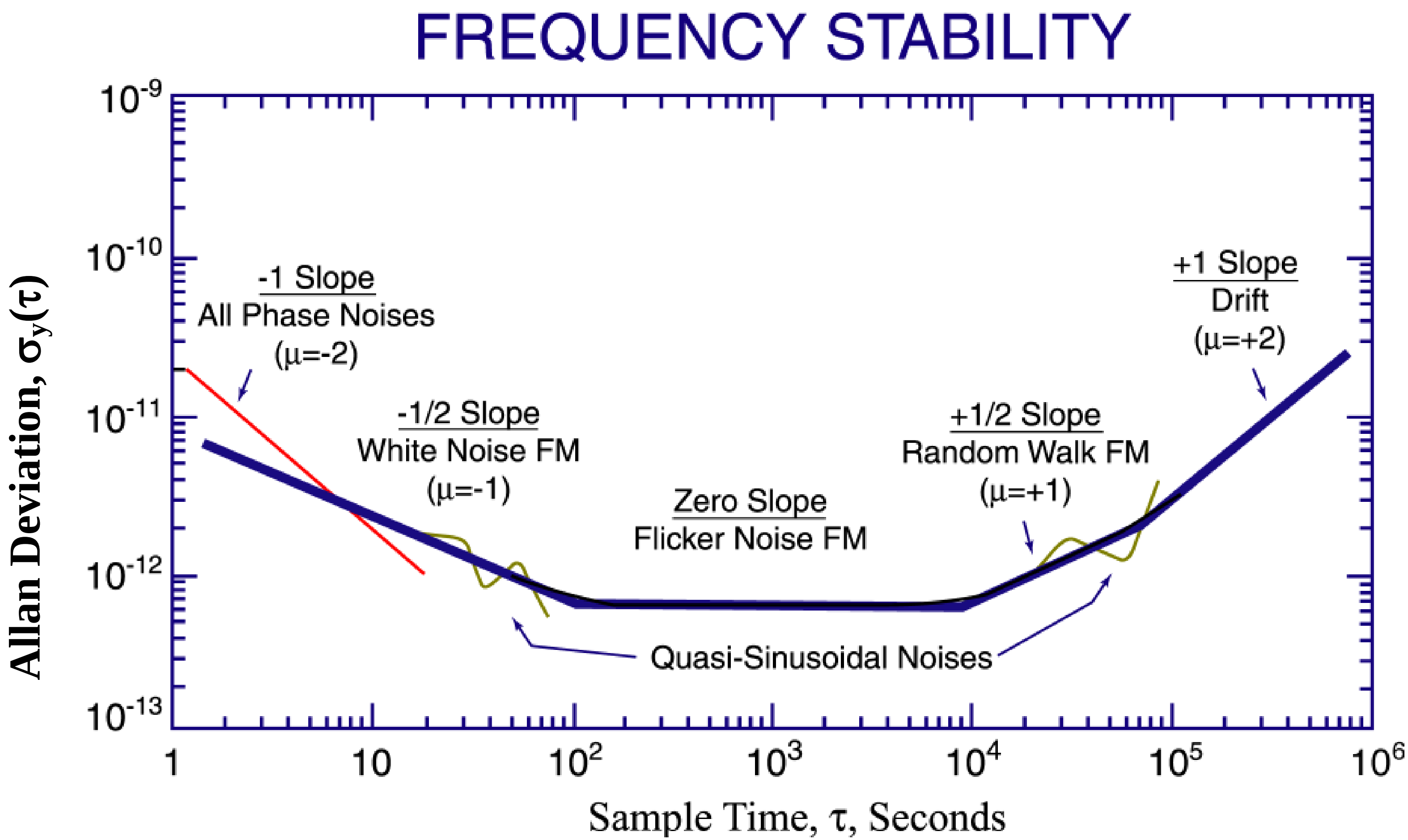
$$\sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)}\sum_{i=1}^{M-1}(y_{i+1} - y_i)^2}$$

DOES CONVERGE AS M INCREASES

There are many types of "Random"

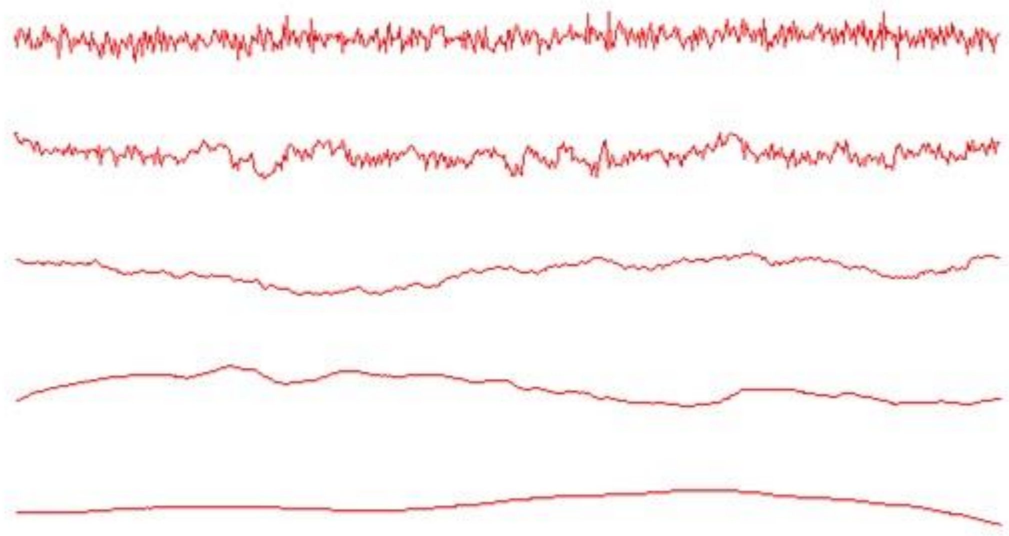
The Standard Deviation may not mean anything.

ADEV Maps the Spectrum for Power-Law FM Noise

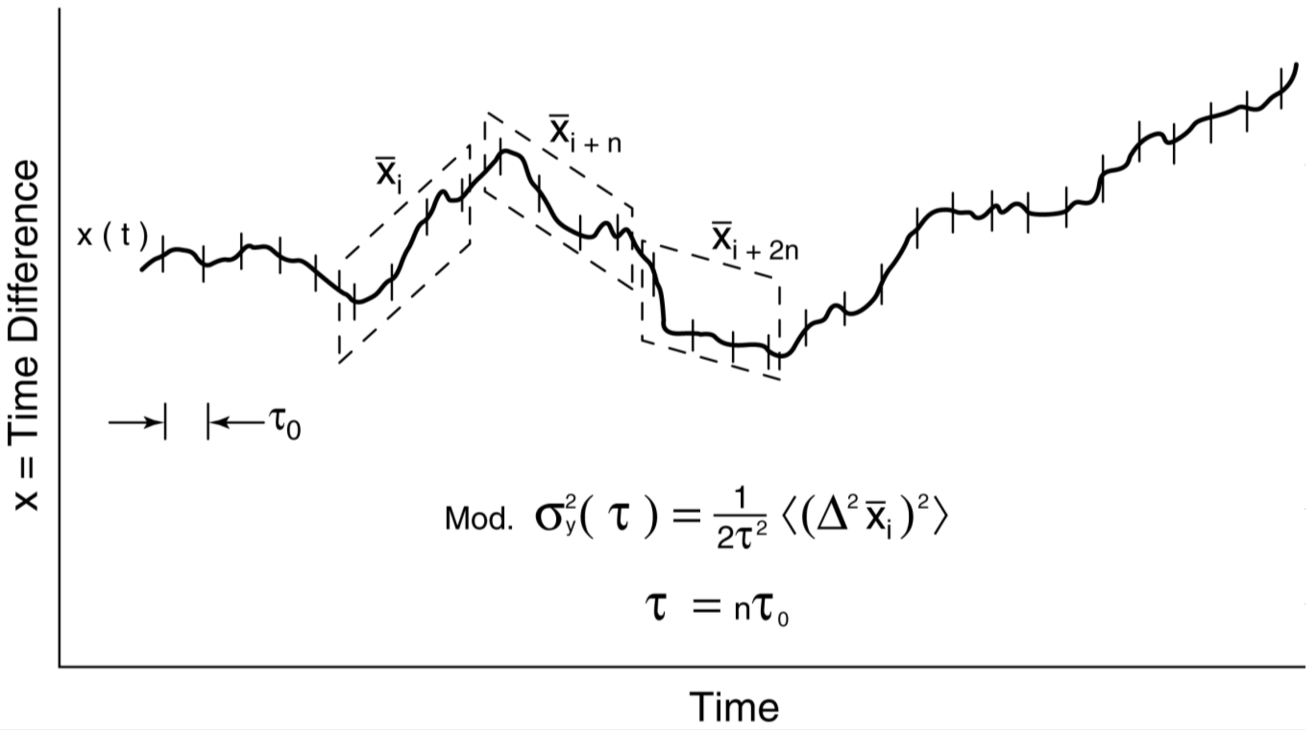


The 5 Noise Types

α	β	type
+2	0	WhPM
+1	-1	FlPM
	-2	RWPM=
0		WhFM
-1	-3	FlFM
-2	-4	RWFM

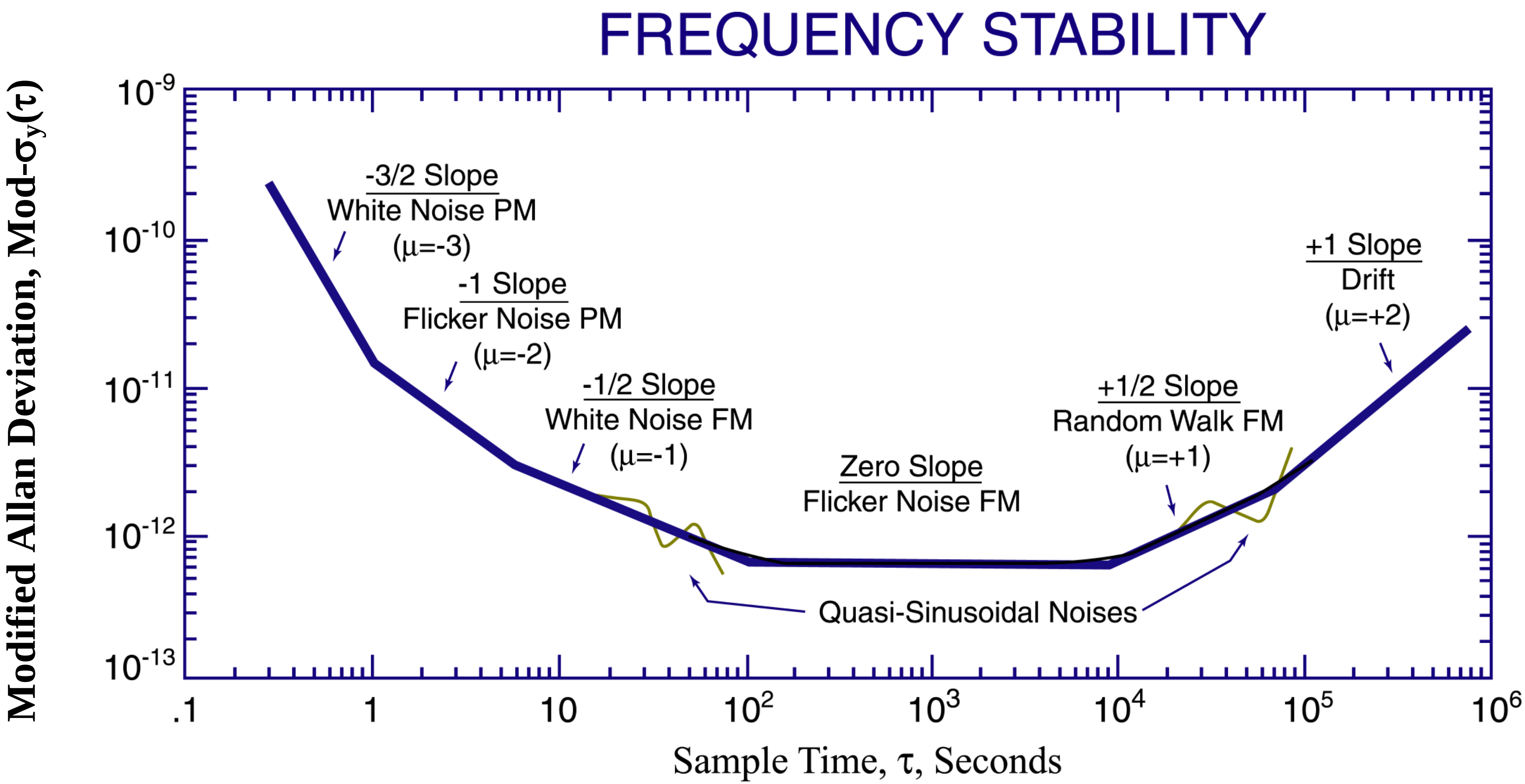


Modified Allan Variance Concept

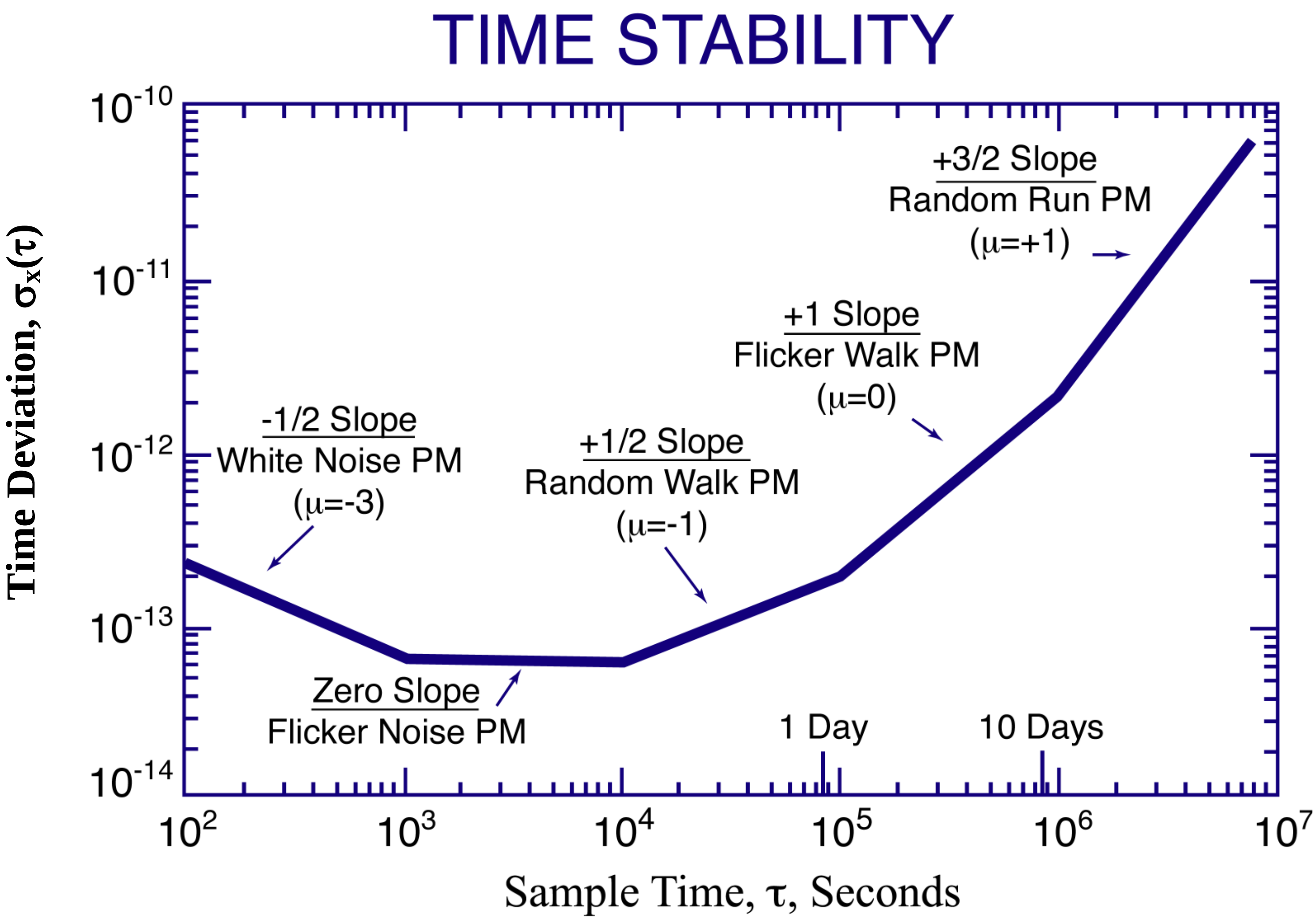


MVAR versus AVAR : Averaging (smoothing) over the observation interval differentiates White Phase Noise from Flicker

MDEV: Now one can see White PM



TDEV makes the focus on PM instead of FM



Taken from earlier presentations by Dr. Marc Weiss

Properties: Noise Types

Relations among Power-Law Spectra and Variances

	$S_x(f) \propto f^{\beta}$	$S_y(f) \propto f^{\alpha}$	$\sigma_x^2(\tau) \propto \tau^{\upsilon}$	$mod.\sigma_y^2(\tau) \propto \tau^{\mu}$
Noise Type	β	α	υ	μ
White PM (WhPM)	0	+2	–1	-3
Flicker PM (FlPM)	-1	+1	0	-2
White FM (WhFM)	-2	0	+1	–1
Flicker FM (FhFM)	–3	–1	+2	0
Random Walk FM (RWFM)	–4	–2	+3	+1
Flicker Walk FM (FWFM)	–5	–3	+4	+2
Random Run FM (RRFM)	–6	–4	+5	+3

TVAR MVAR

Why TDEV is So Useful for Telecom

- TDEV, like all of the Allan Variance family, maps directly to power-law spectra
- TDEV focuses on Phase Modulation noise, which dominates telecom
- TDEV, especially with packet selection, matches the way systems respond
  - A PLL will have an averaging time like the reciprocal of the bandwidth
  - The lock time of the PLL will give deviation of the TDEV value

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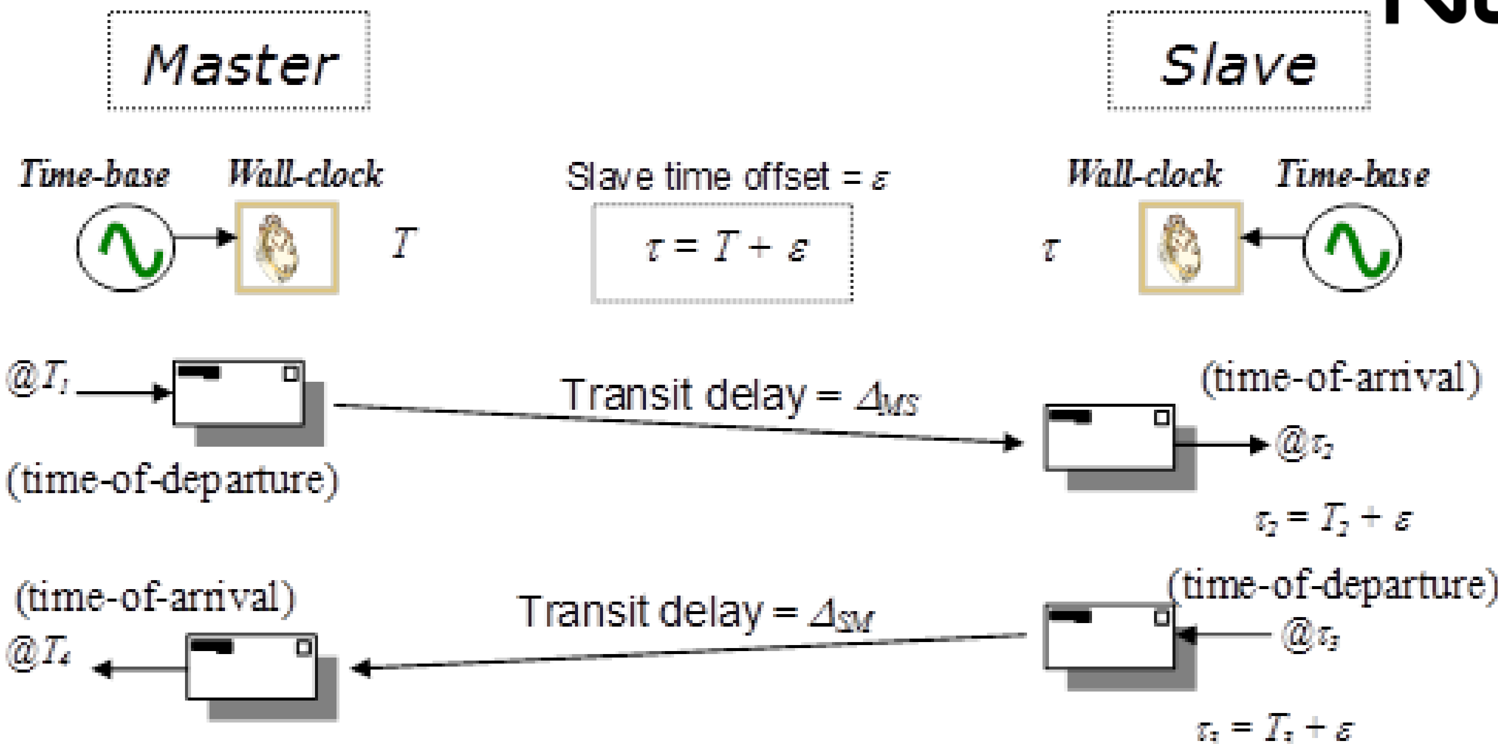
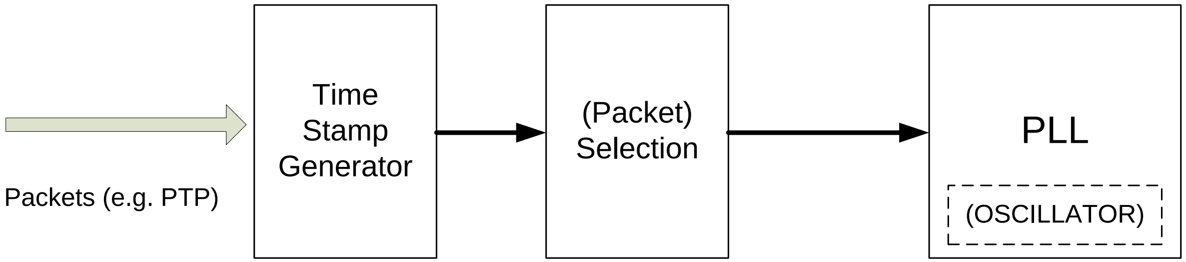
Packet Timing Signal



$$\varepsilon \cong \frac{(\tau_2 - T_1) - (T_4 - \tau_3)}{2} \quad ; \quad \varepsilon_{err} = \frac{\Delta_{MS} - \Delta_{SM}}{2}$$

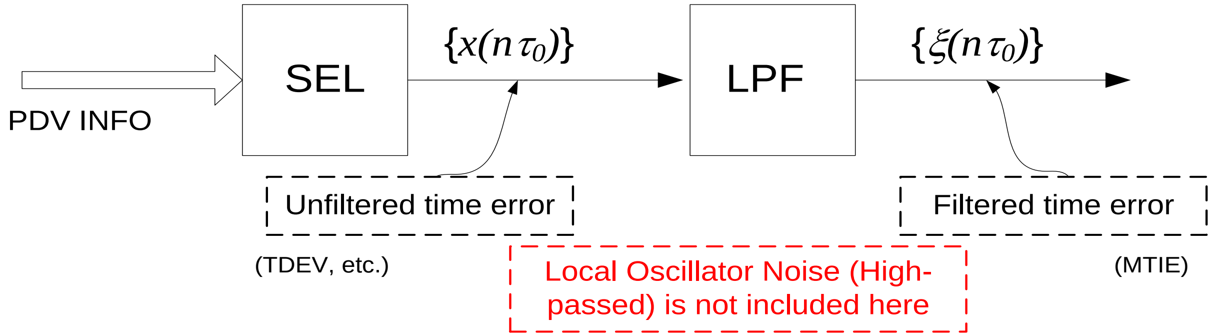
Packet Timing Signal consists of the exchange of time-stamped packets

Conceptual View of Packet Clock



- The packet timing signal is composed of event messages (packet)
- Time Stamp Generator determines the time-of-departure and time-of-arrival of event messages for computing transit delay of packets
- Packet selection involves retaining a representative transit delay for each “window”. Selection methods include:
  - Minimum value of transit delay over window
  - Average of the least 1% of the packet transit delays in the window
- A Phase Locked Loop (PLL) arrangement is used to discipline the local oscillator and/or local time-clock based on the representative transit delay
- Proprietary algorithms can be used for improved performance

PDV Analysis (Metrics) basis



- The PTP "clock recovery" processing block includes non-linear operations such as packet selection
  - TDEV can be computed on post-selection data
- The PTP "clock recovery" processing block may include linear-time-invariant operations such as low-pass filtering
  - MTIE computed on post-filtered (synthetic low-pass filter) signal
  - Post-filtered TDEV can be derived from TDEV computed on post-selection data
- Impact of oscillator not considered here

Estimating Time Dispersion

Optimal prediction of time dispersion for five different noise types

α	Noise Type	Optimum Prediction of Dispersion, rms, at prediction interval τ_p	Asymptotic Time Error
2	White PM	$\tau_p \bullet \sigma_y(\tau_p) / \sqrt{3}$	constant
1	Flicker PM	$\sim\tau_p \bullet \sigma_y(\tau_p) \bullet \sqrt{(\ln \tau_p / 2 \ln \tau_0)}$	$\sqrt{(\ln \tau_p)}$
0	Random-Walk PM or White FM	$\tau_p \bullet \sigma_y(\tau_p)$	$\tau_p^{1/2}$
-1	Flicker FM	$\tau_p \bullet \sigma_y(\tau_p) / \sqrt{(\ln 2)}$	τ_p
-2	Random-Walk FM	$\tau_p \bullet \sigma_y(\tau_p)$	$\tau_p^{3/2}$

These expressions are in terms of the Allan Deviation : $\sigma_y(\tau)$

Example : APTSC

Primary Reference : GNSS

- While GNSS is active ("valid"):
  - Generate output clock (time/frequency) – time error < 100ns
  - Measure packet-delay variation (PDV) for PTP packets and compute metrics that enable prediction of time-holdover when PTP used to generate output
    - Monitor performance of local oscillator and other references (if available)

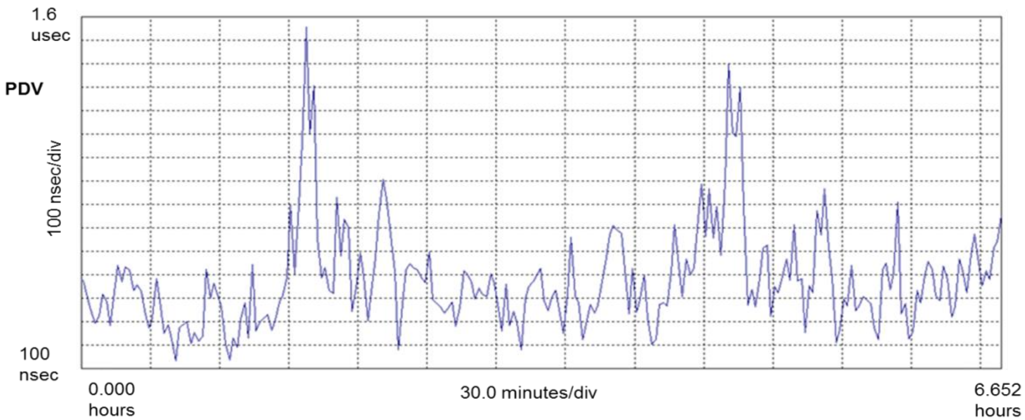
Secondary Reference : PTP

- When GNSS is lost ("invalid"):
  - Use PTP timing to control progression of time-clock
    - Alternative: use PTP time-clock (assuming asymmetry calibration)
- Tertiary Reference : LO / other Reference

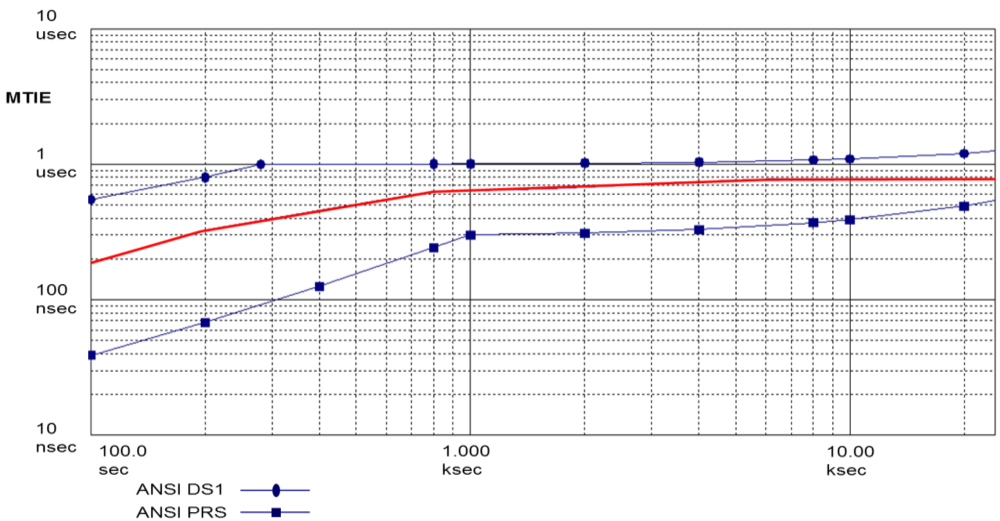
Simulated Example of Performance Estimation

- Assume:
  - Overall time-holdover requirement: 1.5μs
  - Budget for GNSS error and switching transient: 500ns
  - Holdover using PTP frequency recovery using master-slave direction (*sync_messages*)
    - Packet rate: 32 pps
    - Selection mechanism: 1% over 100s windows
    - Filtering bandwidth: 1mHz
- One possible metric: MTIE
  - Requirement: MTIE(τ) < 1000ns
- Simulation:
  - 5 GigE switches
  - Load : mean load = 60% ; standard deviation = 20%

Simulation Example



Packet-delay-variation (PDV) based on:
– 1-percentile
– 100s window
– representative transit delay equal 1-percentile average

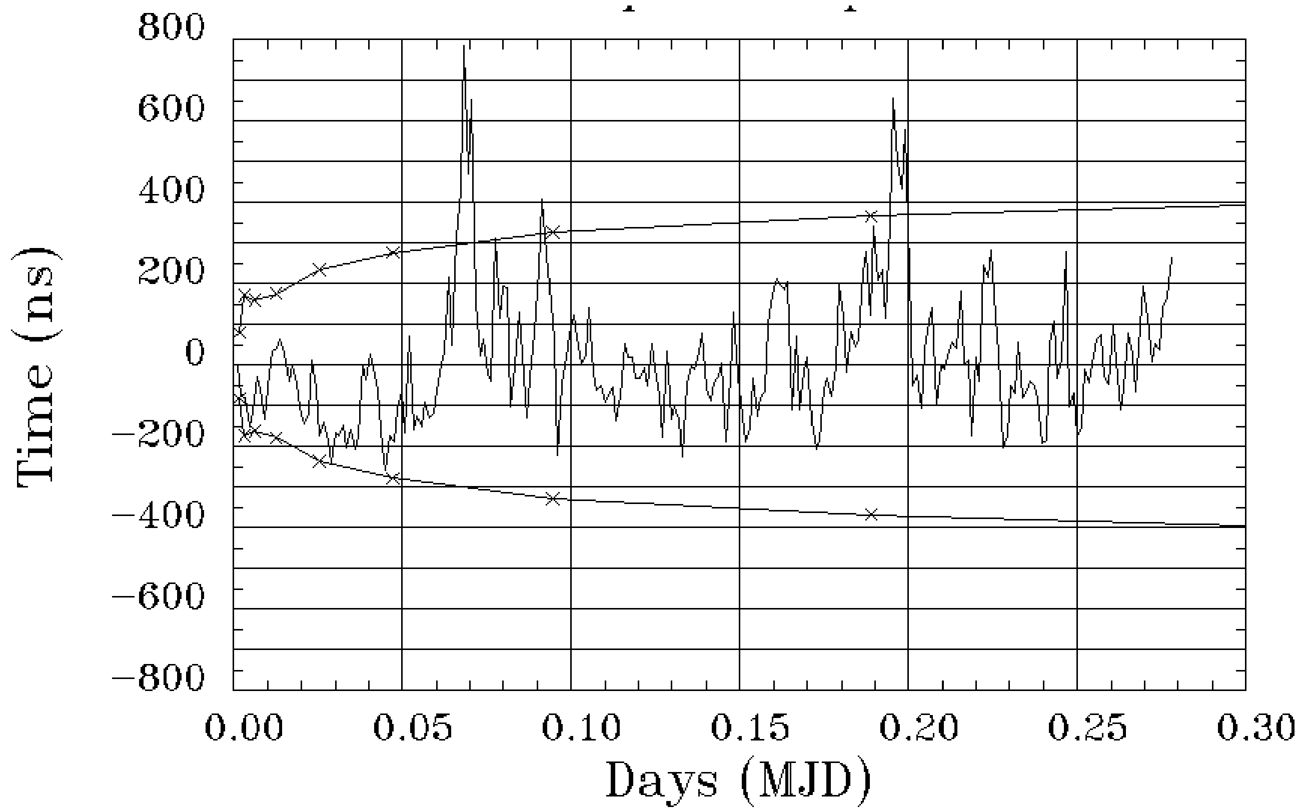


MTIE :
– 1mHz filter
– $<1\mu s$

Conclusion:
– With this network PDV, PTP (one-way-frequency) can support time-holdover indefinitely
– “Alarm” condition: GREEN

Simulation Example

Expected Dispersion based on simulated PDV



Concluding Remarks

- ADEV, MDEV, TDEV are useful tools for analyzing and predicting the performance of timing solutions
- TDEV (ADEV, MDEV) provide valuable insight into underlying noise processes, critical for predicting performance
- TDEV can be computed on packet-based timing signals
  - Generally includes some packet-selection mechanism
- Packet-based timing signals can be analyzed using TDEV both before and after non-linear processing (packet selection)
- Application in APTSC:
  - When GNSS is active the network PDV can be measured and quantified
  - Metrics (TDEV) quantify strength of noise process and estimates of (future) time dispersion if in holdover

Thank you …

Questions?

Extra Slides for reference

Computing the Allan Variance

$$\sigma_y^2(\tau) = \frac{1}{2\tau^2(N-2n)} \sum_{i=1}^{N-2n} \left(x_{i+2n} - 2x_{i+n} + x_i \right)^2$$

where:

x_i are the data separated by a time interval τ_0,

$\tau = n \cdot \tau_0$

N is the total number of data points.

Modified Allan Variance for Equally Spaced Time Series:

$$\text{mod.}\sigma^2_y(\tau) = \frac{1}{2\tau^2 n^2 (N-3n+1)} \cdot \sum_{j=1}^{N-3n+1} \left(\sum_{i=j}^{n+j-1} (x_{i+2n} - 2x_{i+n} + x_i) \right)^2$$

Smoothing over n terms

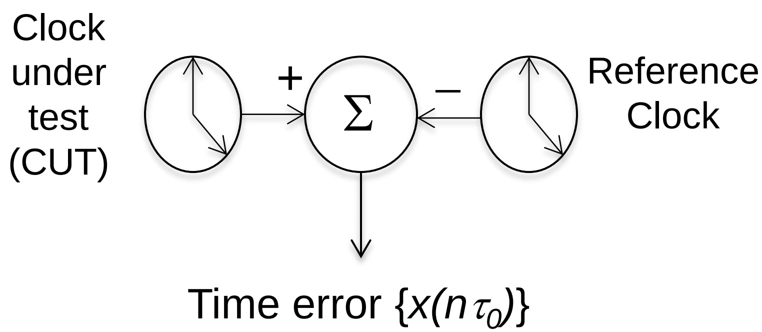
where:

x_i are the data separated by a time interval, τ_0,

$\tau = n \cdot \tau_0$, and

N is the total number of data points.

Metrics Mathematics



Clock Error model

$$x(n\tau_0) = a_0 + \eta \cdot (n \cdot \tau_0) + \varphi(n \cdot \tau_0)$$

a_0 : constant time error
η : frequency offset
φ : Noise terms ("random")
Frequency drift: lumped into φ

- Metrics establish "strength" of time error. Different metrics focus on different aspects of this "strength".
- Maximum absolute time error : $|x(n\tau_0)|_{max}$ is the overarching time error metric (maximum over all time)
- First difference eliminates a_0 : strength of $\{x(n+k) - x(n)\}$ quantifies stability of the time error
  - Variations include MTIE, MATIE, TEDEV
- Second difference eliminates η and a_0 : strength of $\{x(n+2k)-2x(n+k)+x(n)\}$ quantifies stability of the frequency (e.g. TDEV, ADEV, MDEV)

Computing Metrics on time error

- For a measured time error sequence $\{x(n)\}$ or filtered time error sequence $\{\xi(n)\}$ (commonly proposed b/w: 10 mHz):
  - Max (absolute) time error : $|x(n)|_{max}$
  - cTE… estimate of constant time error: average of N samples
  - Max (absolute) filtered time error : $|\xi(n)|_{max}$
  - MTIE… maximum (absolute) time interval error (stability metric)
  - TDEV… stability metric that describes power (and type) of noise
  - MATIE… maximum (absolute) averaged time interval error
    - MAFE… related to MATIE
  - TEDEV… standard deviation of averaged time interval error
  - Other [e.g. percentile values for maximum and minimum (floor)]