PDV Templates and Metrics for Predicting Time Error Behavior

WSTS 2015, San Jose

Kishan Shenoi
CTO, Qulsar, Inc.
Email: kshenoi@qulsar.com

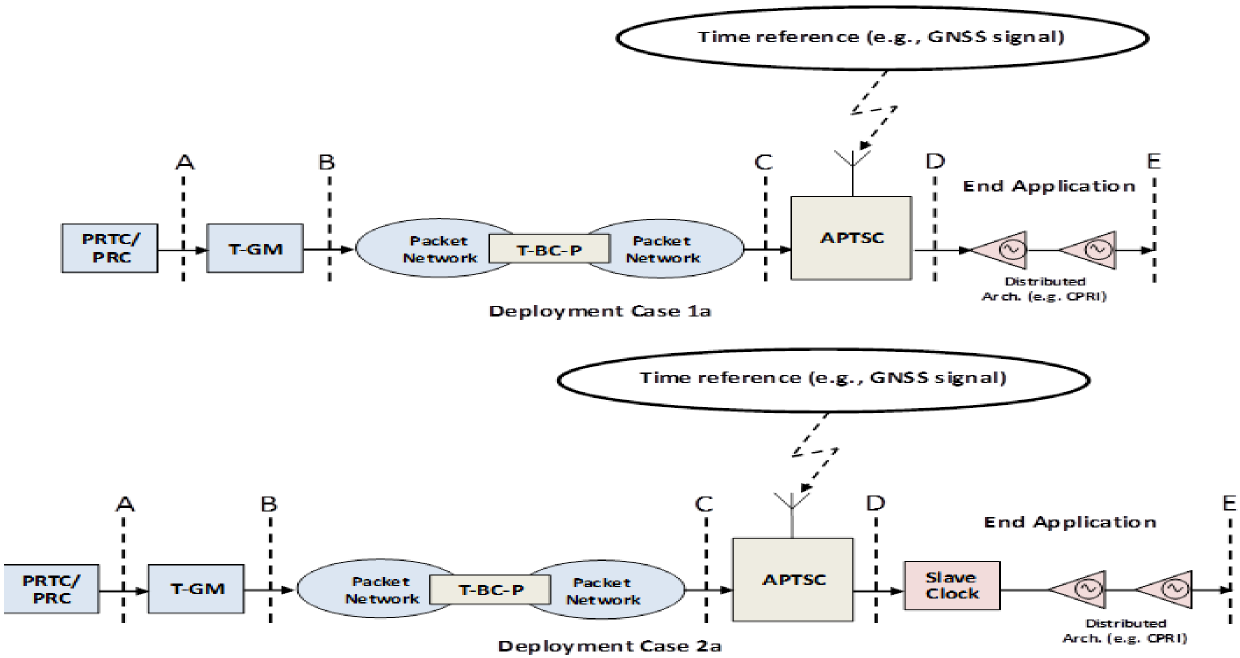
Presentation Outline

QULSAR™

- Motivation (APTSC)
- Generating PDV Templates for Testing Telecom Packet Clocks
- Time Error Estimation and Suitable Metrics
- Examples of Calculations
- Concluding Remarks
- (Back-up slides for information)

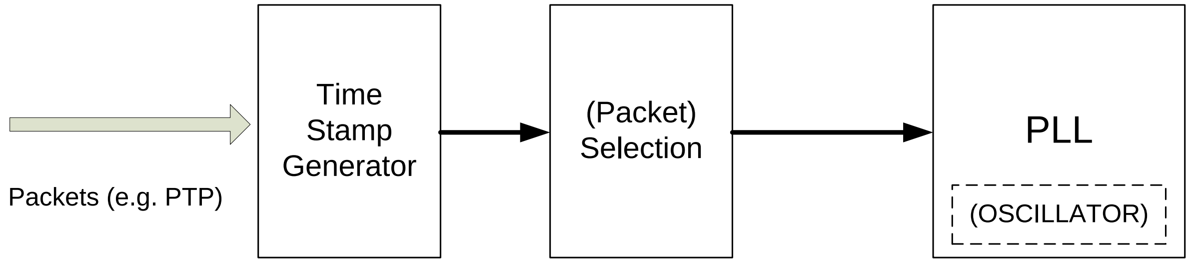
Conceptual View of Assisted Partial-Timing Support

(From ITU-T Contributions)



- Primary reference for APTSC <u>and</u> PRTC/T-GM is GNSS (e.g. GPS)
- The packet network between device and upstream master (GM or T-BC) may not be full on-path support (hence "partial-timing support")
- PTP provides time-holdover when GNSS becomes unavailable (hence "assisted")

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

Operational Principles

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)

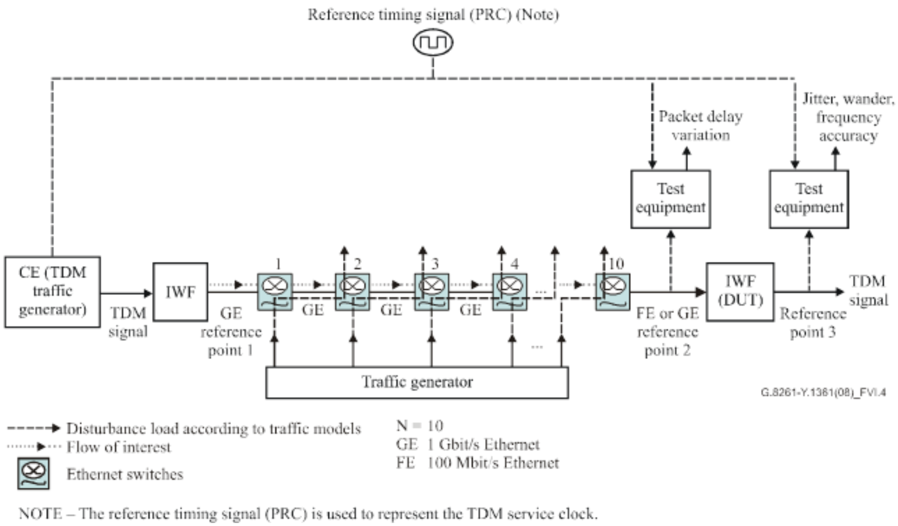
Secondary Reference : PTP

- 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

PDV Templates

- Motivation (APTSC)
- Generating PDV Templates for Testing Telecom Packet Clocks (Methodology)
  - Based on principles of G.8261 Appendix VI
    - Network size(s) 10 & 5 switches
    - Revised profile for interfering traffic
    - Short-term load variations based on Flicker (self-similar) behavior
  - Monte Carlo methods applied for generating delay (per-packet, per-switch)
  - General Assumptions:
    - Timing traffic assigned highest priority
    - Equipment assumed to be “telecom grade”

G.8261 Appendix VI



From G.8261:

- 10 switches
- Geared towards frequency
- Two models for interfering traffic

- G.8261 Appendix VI proposes network of 10 switches between Master and Slave; in wireless scenario fewer, viz. 5, may be more appropriate
- Test Cases 12, 13, 14 address load related packet delay variation; 15, 16, 17 address transient effects
  - TC-12 : constant (high) load (average)
  - TC-13 : Changing load (average) with load changing at different times in the two directions
  - TC-14 : Slowly changing load (average)
- Recent studies suggest using a slightly different model for interfering traffic

Simulation Methodology

QULSAR

- Monte Carlo simulation of delay introduced in each switch on a packet-by-packet basis
  - Load (fraction) ↔ probability of encountering head-of-line-blocking
  - Interfering traffic profile ↔ probability of interfering packet being “small” or “large”
  - Random number (between 0 and 1) determines fraction of interfering packet remaining (determines delay)
- Interfering traffic modelled as 30% “small” and 70% “large” (modified version of Traffic Model 2 of G.8261 with “medium” packets treated as “large”)
- Traffic load of X% modeled using a flicker pattern for short-term variation
  - change every ~100s with mean of X% and std. dev. 10%

Simulation Considerations

QULSAR

- Delay in interconnect not included
- Flat delay in switch not included
- Overload (load “greater than 100%”) not considered
- Two directions assumed to be independent of each other
- Packet rate: 32 packets/second

Mathematical Basis (APTSC)

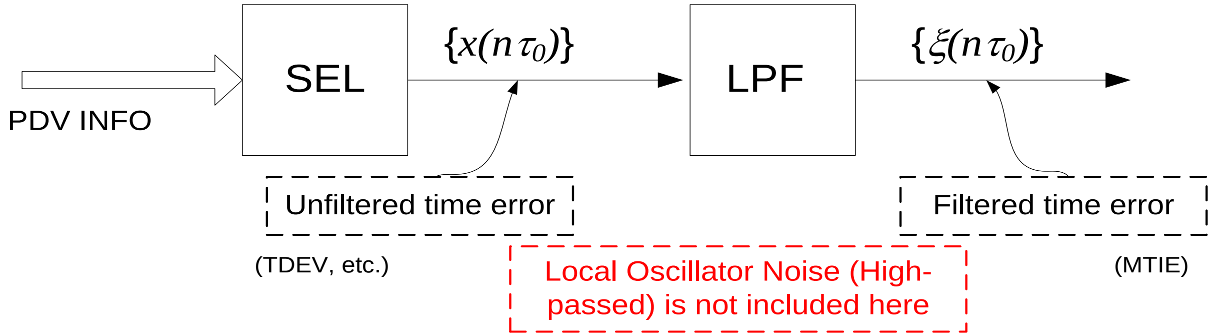
QULSAR

- Let $t = 0$ be the point that GNSS declared invalid. The time error of the "holdover clock" modeled as:

$$x(t) = x_0 + y_0 \cdot t + \underbrace{\int_0^t \gamma(\tau)d\tau + \varphi(t)}_{\text{Holdover error}}$$

  - x_0 is the initial error (GNSS error + transient effect) (reduces holdover budget)
  - y_0 is the initial frequency error (generally ≈ 0)
  - $\gamma(\ )$ is the frequency error due to temperature changes and aging
  - $\varphi(\ )$ represents the random noise component
  - Performance metrics computed on "holdover error" while GNSS valid to develop KPIs

PDV Analysis (Metrics) basis

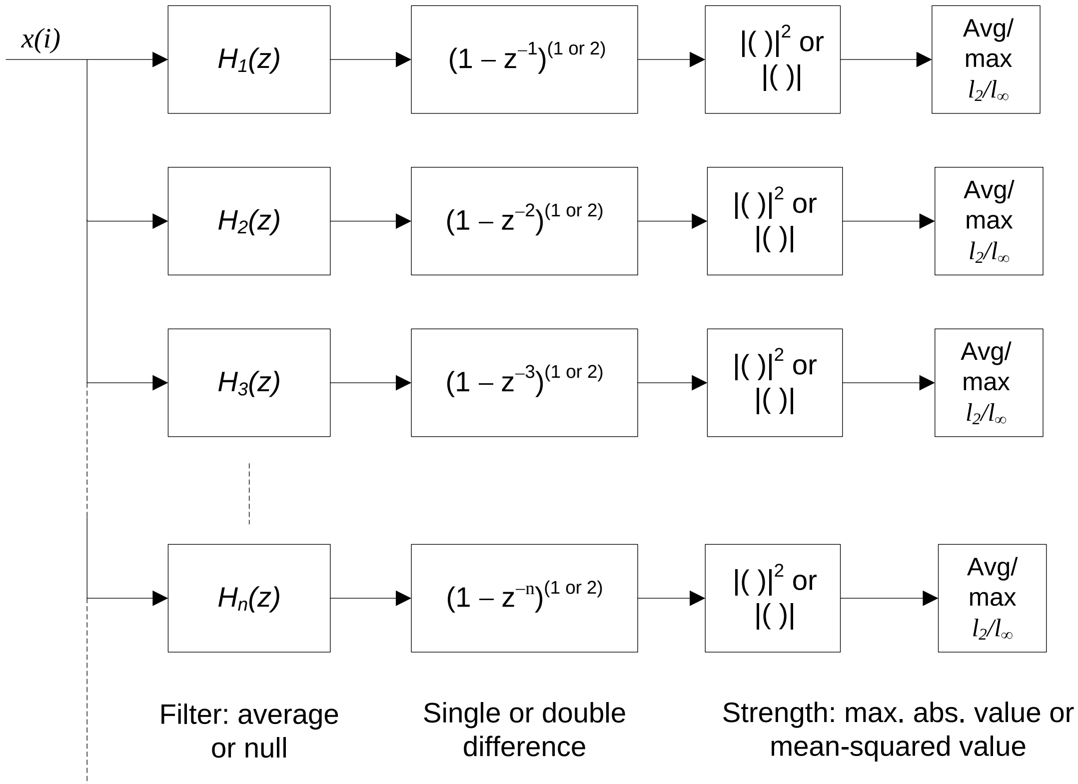


- PTP clock recovery could be based on one-way (F or R) or two-way
- The PTP "clock recovery" processing block includes non-linear operations such as packet selection
  - Metrics such as TDEV can be computed on post-selection data
- The PTP "clock recovery" processing block may include linear-time-invariant operations such as low-pass filtering
  - MTIE computed on post-filtered (synthetic low-pass filter) signal
- Impact of oscillator not considered here

Metrics - Computation

- Metrics are computed on time error sequence $\{x(k)\}$; implied sampling interval = τ_0
- Intent is to see how much dispersion could occur in an interval (*aka* observation interval) $\tau = n\tau_0$
- *First difference* : $\{x(k+n) - x(k)\}$ removes constant time error x_0
- Double difference : $\{x(k+2n) - 2x(k+n) + x(k)\}$ removes x_0 as well as frequency offset y_0
- Smoothing function (optional) : Average over *n* consecutive values
- Strength calculation: maximum-absolute value or mean-square value (variance) (square-root gives rms or standard deviation)

Metrics - Computation



$$H_n(z) = \frac{1}{n} \cdot \sum_{k=0}^{n-1} z^{-k}$$

(average over n consecutive values)

- MTIE calculation does not fit neatly into this model
- Boundary points need to be handled with care when data set is finite

Important Metrics

QULSAR

Metric	Strength calc.	Filter	Difference level	Comments
MATIE (MAFE)	maximum	averaging	First difference	Identifies frequency offset
TIE_{rms}	(root) mean-square	none	First difference	Power of time error
TEDEV (TEVAR)	(root) mean-square	averaging	First difference	Power of time error
TDEV (TVAR)	(root) mean-square	averaging	Second difference	Power of time error
ADEV (AVAR)	(root) mean-square	none	Second difference	Power of time error (indirect)
MDEV (MVAR)	(root) mean-square	averaging	Second difference	Power of time error (indirect)

optimum prediction of time dispersion is proportional to τ·ADEV (proportional to TDEV):

$$\Delta t(\tau) = constant \cdot \tau \cdot \sigma_y(\tau)$$

Estimating Time Dispersion

QULSAR

Optimum Prediction is Based on Noise Types

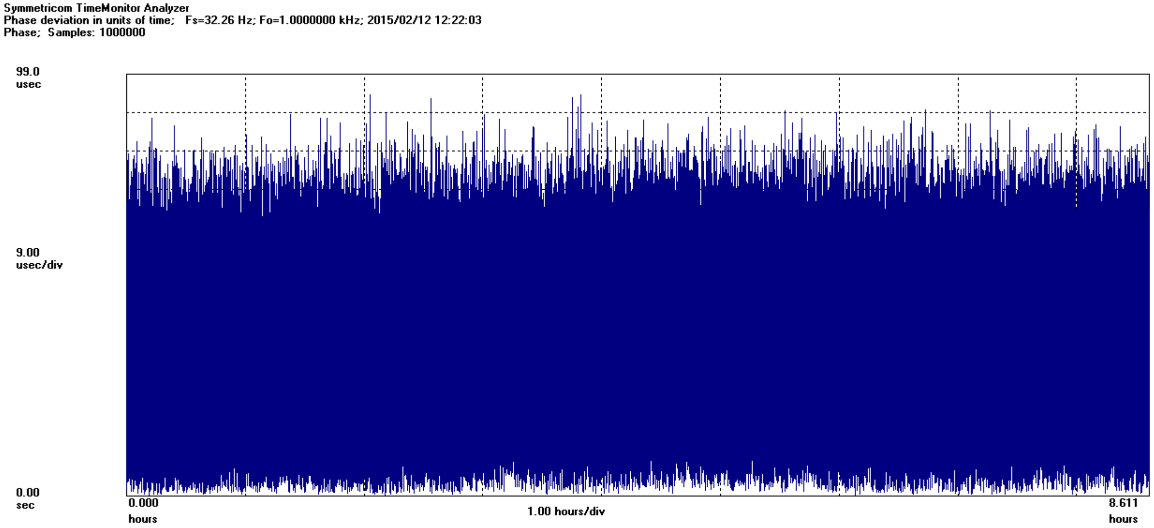
α	Typical Noise Types Name	Optimum Prediction $x(\tau_p)$ rms[a]	Time Error: Asymptotic Form
2	white-noise PM	$\tau_p \cdot \sigma_y(\tau_p)/\sqrt{3}$	constant
1	flicker-noise PM	$\sim \tau_p \cdot \sigma_y(\tau_p)\sqrt{\ln \tau_p / 2 \ln \tau_0}$	$\sqrt{\ln \tau_p}$
0	white-noise FM	$\tau_p \cdot \sigma_y(\tau_p)$	$\tau_p^{1/2}$
−1	flicker-noise FM	$\tau_p \cdot \sigma_y(\tau_p)/\sqrt{\ln 2}$	τ_p
−2	random-walk FM	$\tau_p \cdot \sigma_y(\tau_p)$	$\tau_p^{3/2}$

[a] τ_p is the prediction interval.

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

Taken from earlier presentations by Dr. Marc Weiss

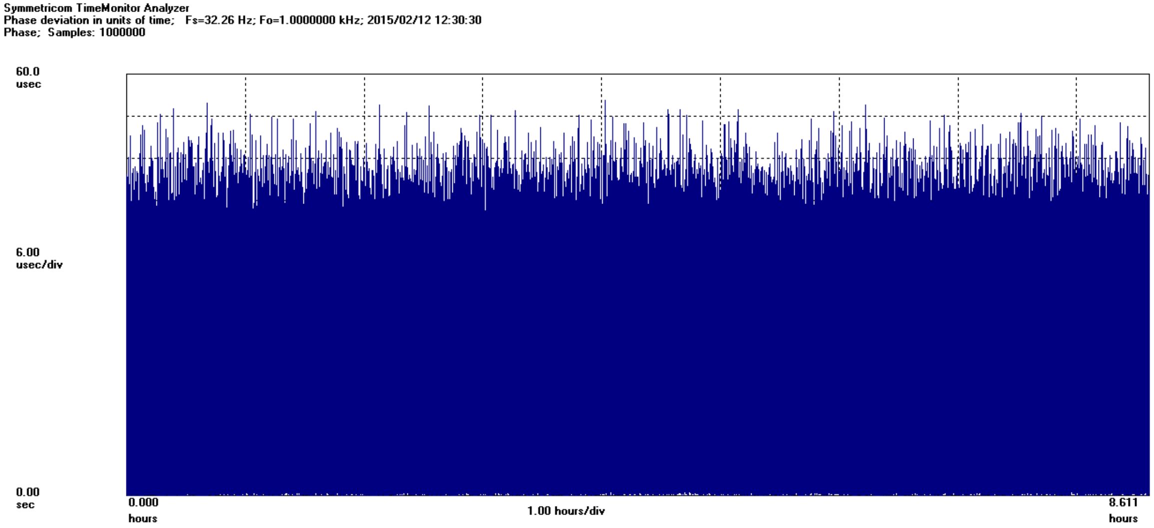
PDV : TC-12 Forward Direction



Transit Time Variation

10-switch case

Average Load: 80%



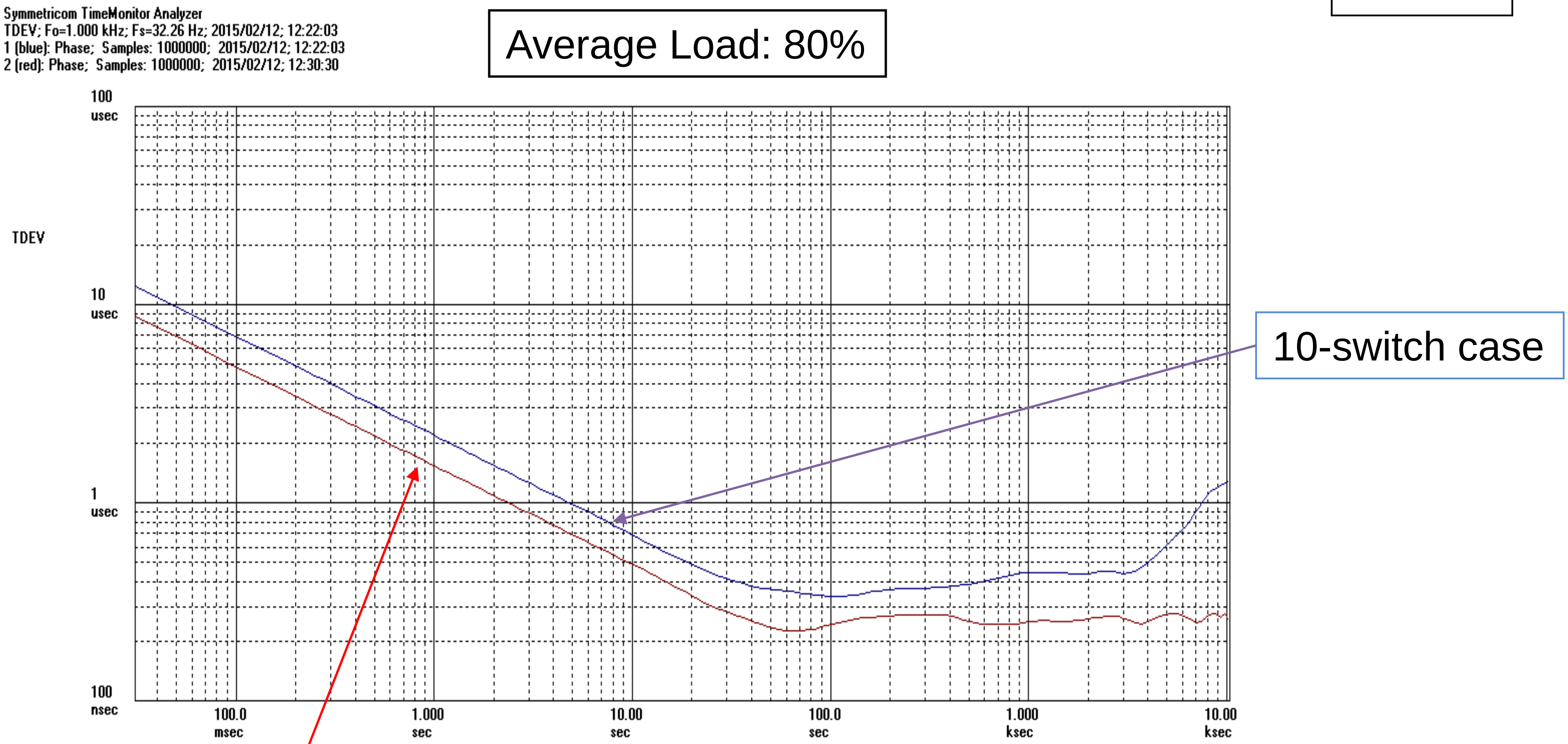
5-switch case

PDV : TC-12 Forward Direction

QULSAR

TDEV

Average Load: 80%

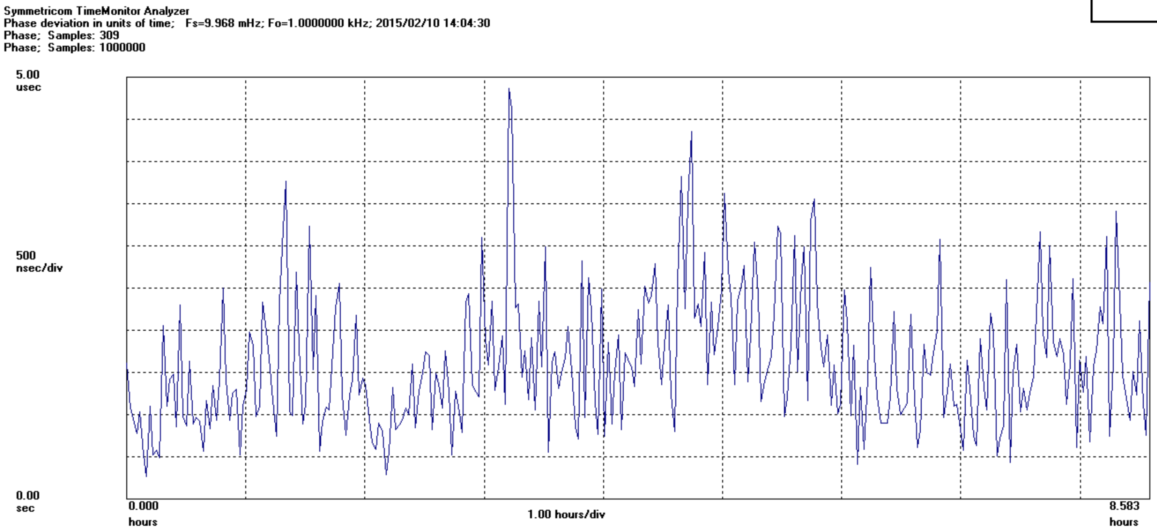


TDEV calculation not very reliable

PDV : TC-12 Forward Direction

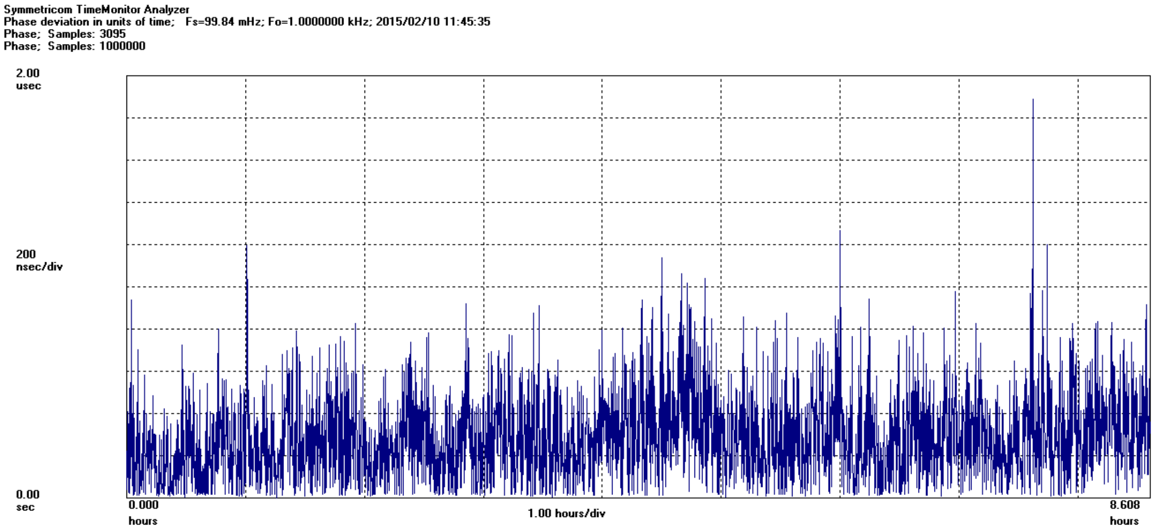
QULSAR

Transit Time Variation
Packet selection: minimum



10-switch case
Window: 100s

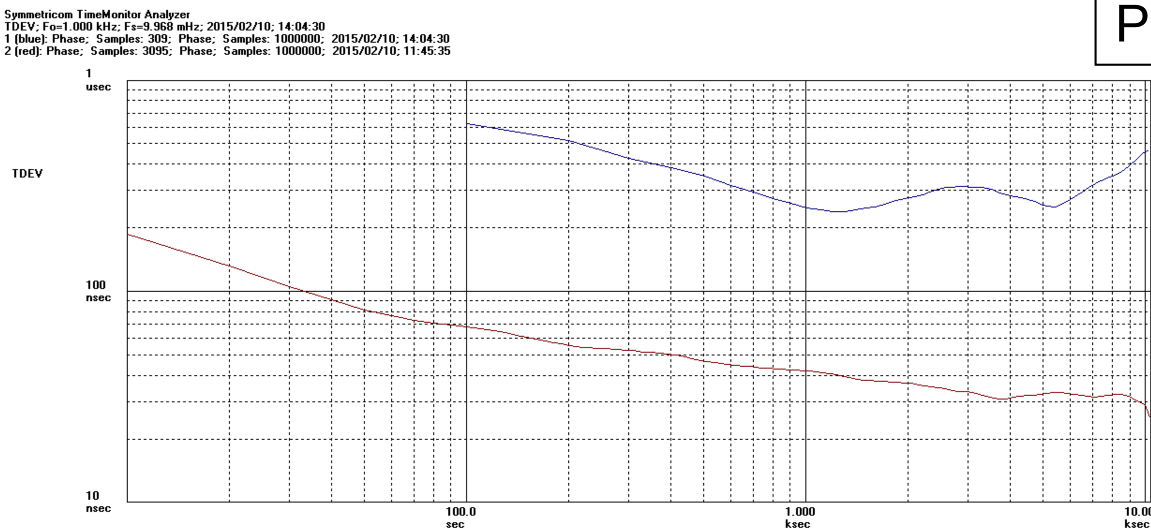
Average Load: 80%



5-switch case
Window: 10s

PDV : TC-12 Forward Direction

Transit Time Variation
Packet selection: minimum

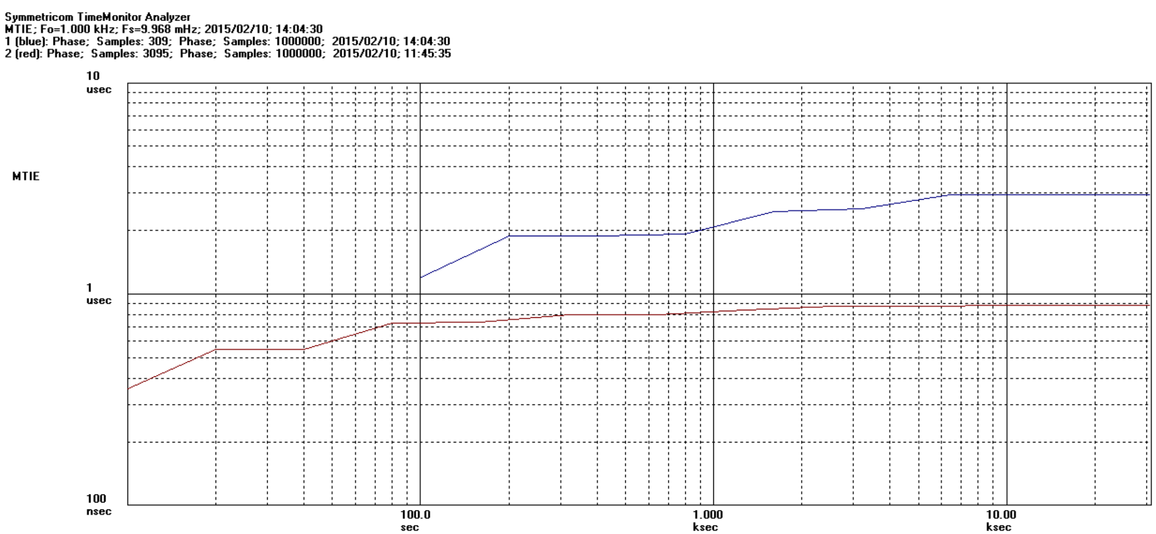


TDEV

10-switch case
Window: 100s

5-switch case
Window: 10s

Average Load: 80%



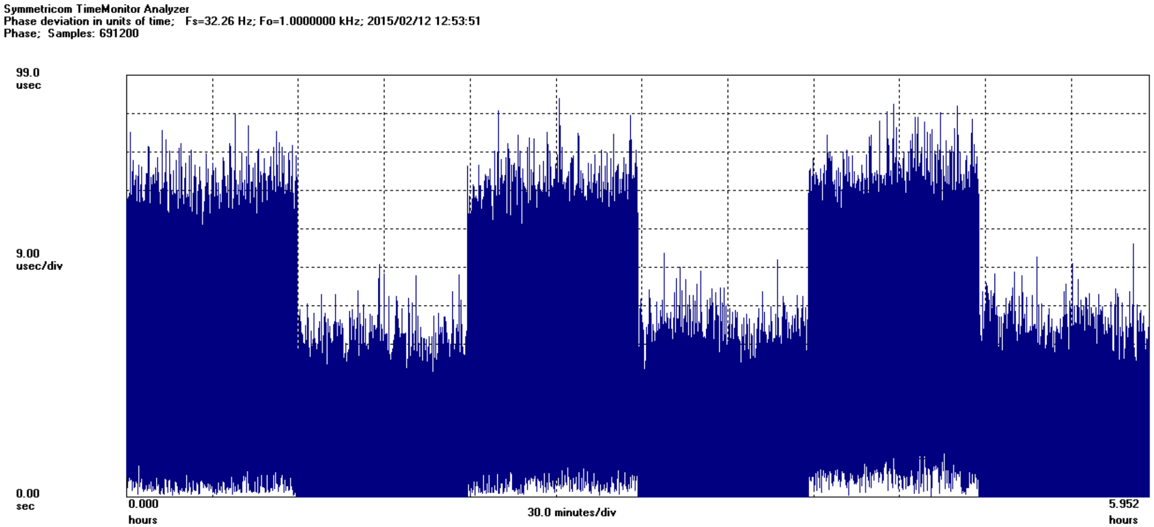
MTIE

10-switch case
Window: 100s
Filter: 1mHz

5-switch case
Window: 10s
Filter: 10mHz

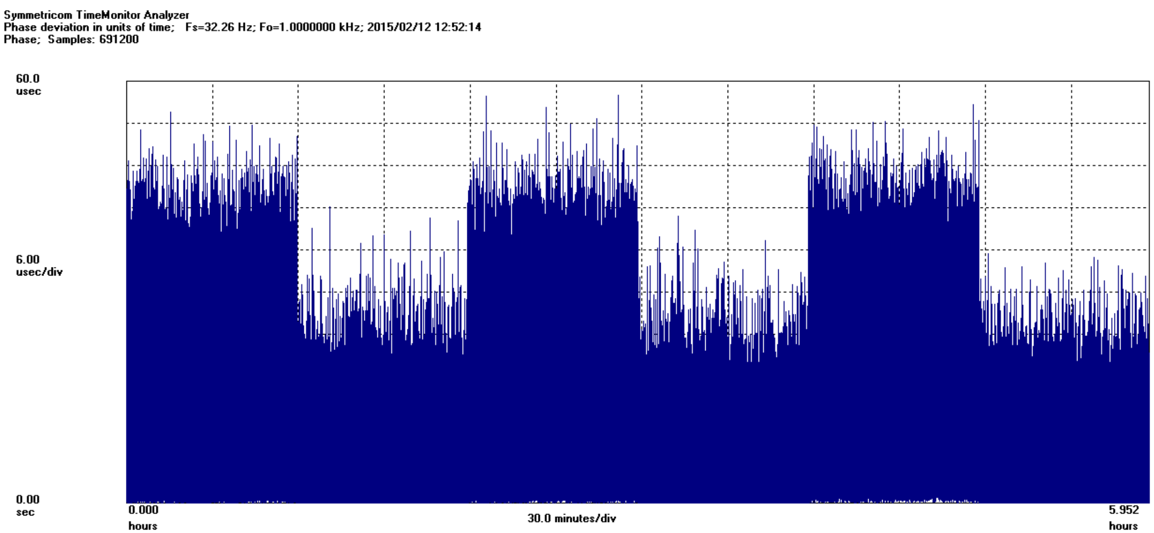
PDV : TC-13 Forward Direction

Transit Time Variation



10-switch case

Average Load: 80% and 20%



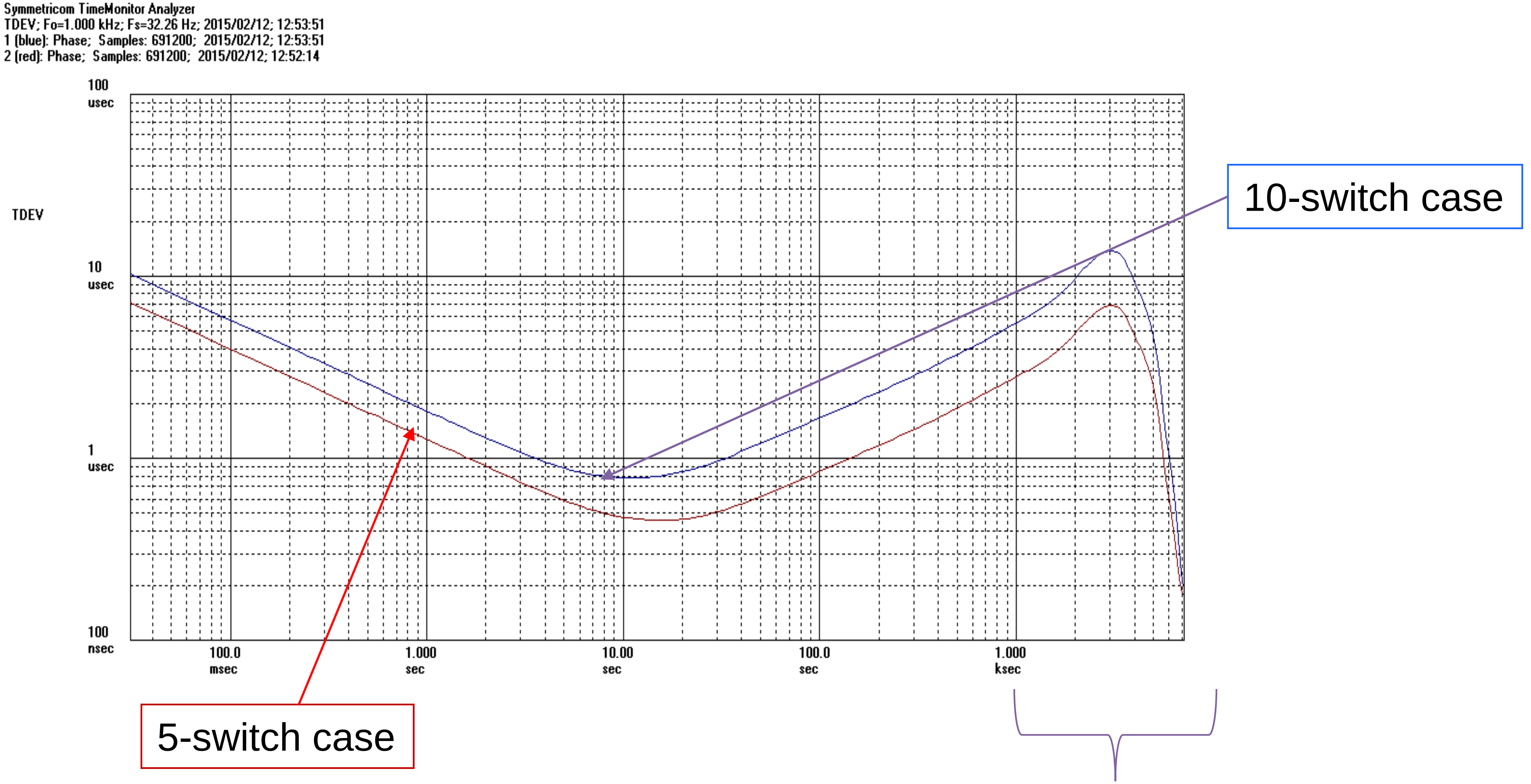
5-switch case

PDV : TC-13 Forward Direction

QULSAR

Average Load(s): 80% and 20%

TDEV

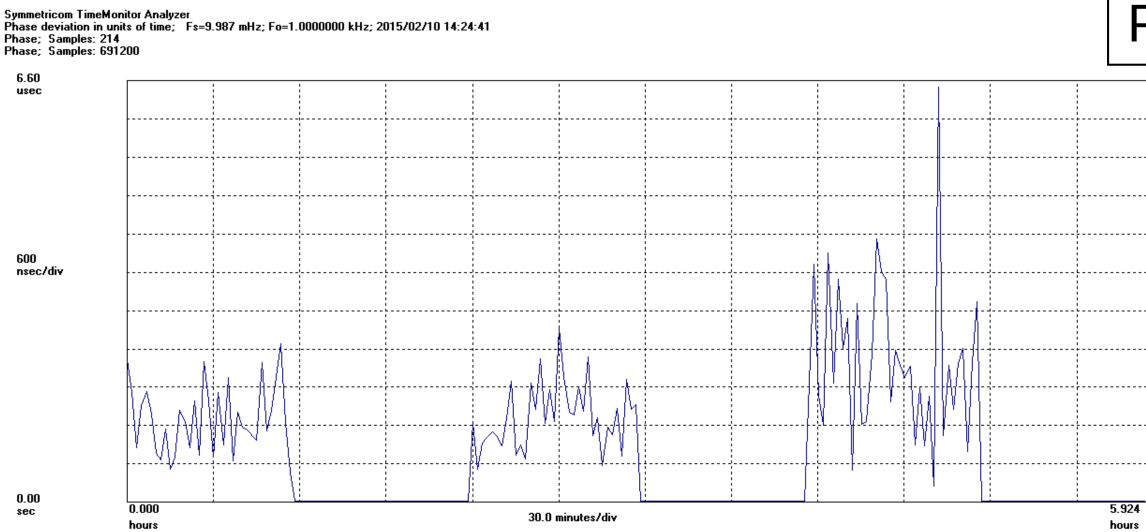


TDEV calculation not very reliable

PDV : TC-13 Forward Direction

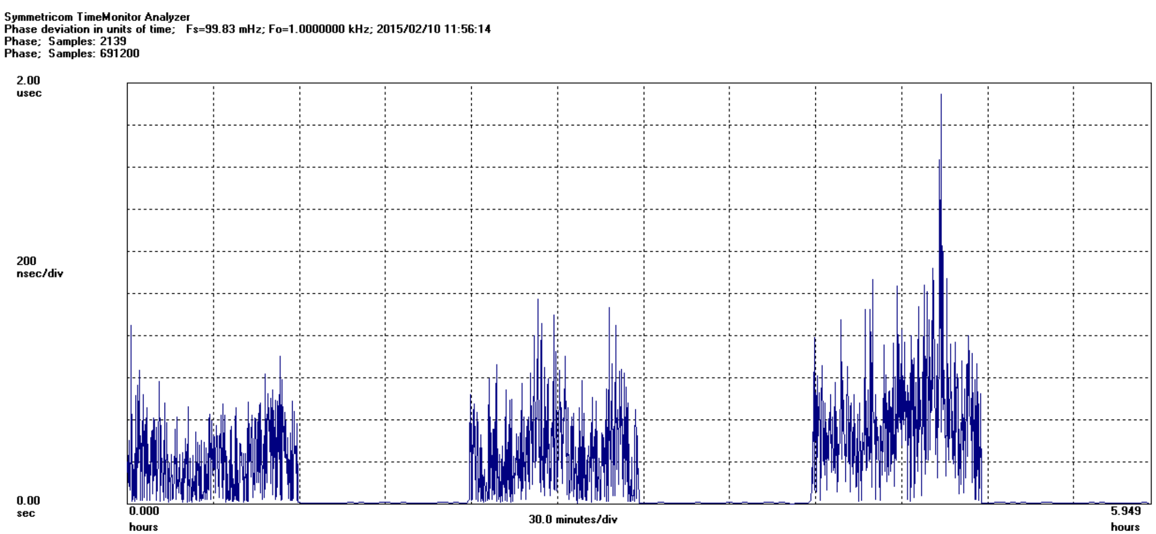
QULSAR

Transit Time Variation
Packet selection: minimum



10-switch case
Window: 100s

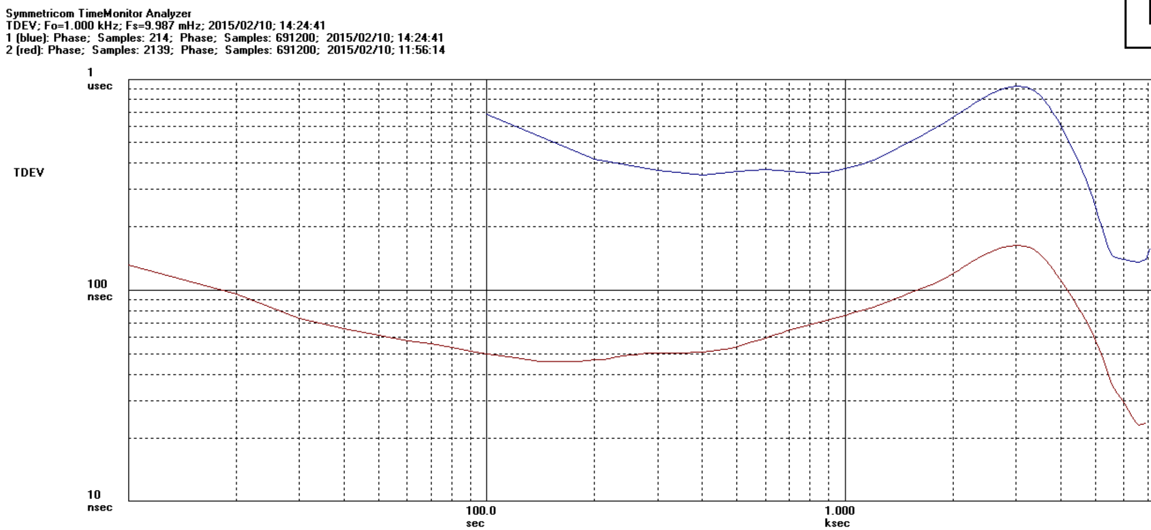
Average Load(s):
80% and 20%



5-switch case
Window: 10s

PDV : TC-13 Forward Direction

Transit Time Variation
Packet selection: minimum

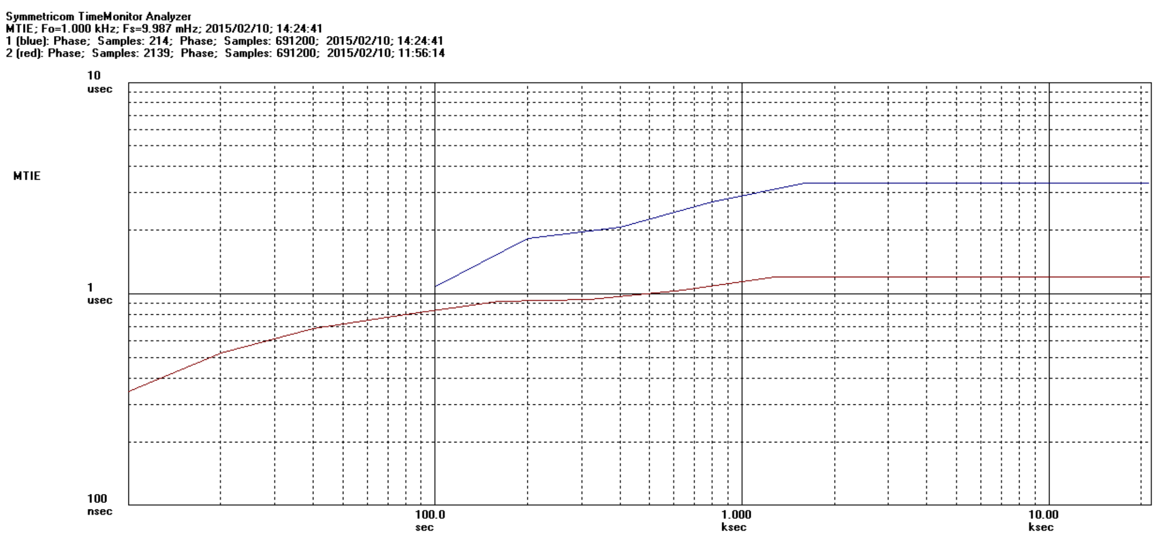


TDEV

10-switch case
Window: 100s

5-switch case
Window: 10s

Average Load(s):
80% and 20%



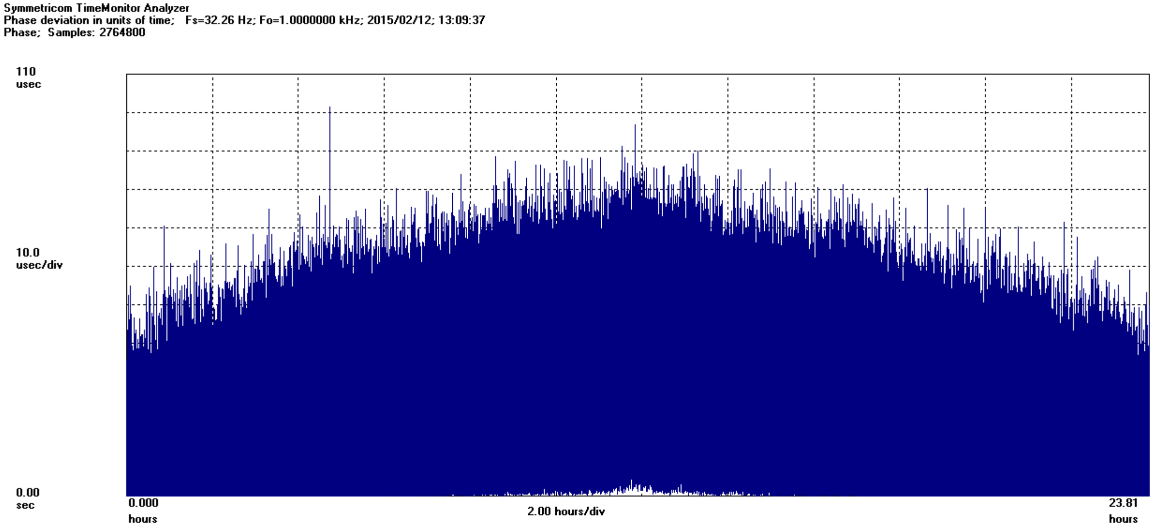
MTIE

10-switch case
Window: 100s
Filter: 1mHz

5-switch case
Window: 10s
Filter: 10mHz

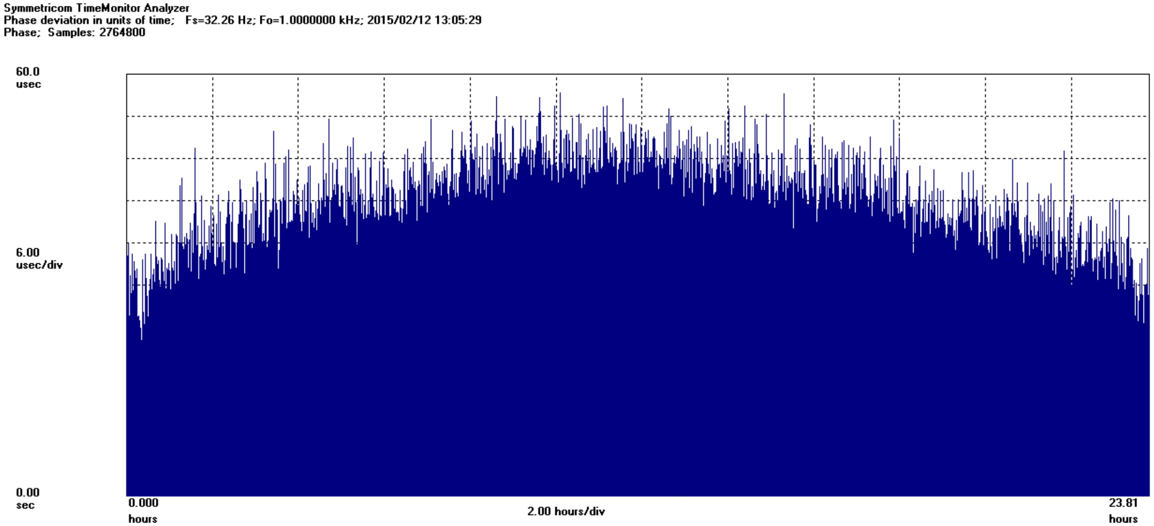
PDV : TC-14 Forward Direction

Transit Time Variation



10-switch case

Average Load:
Max:80%
Min: 20%



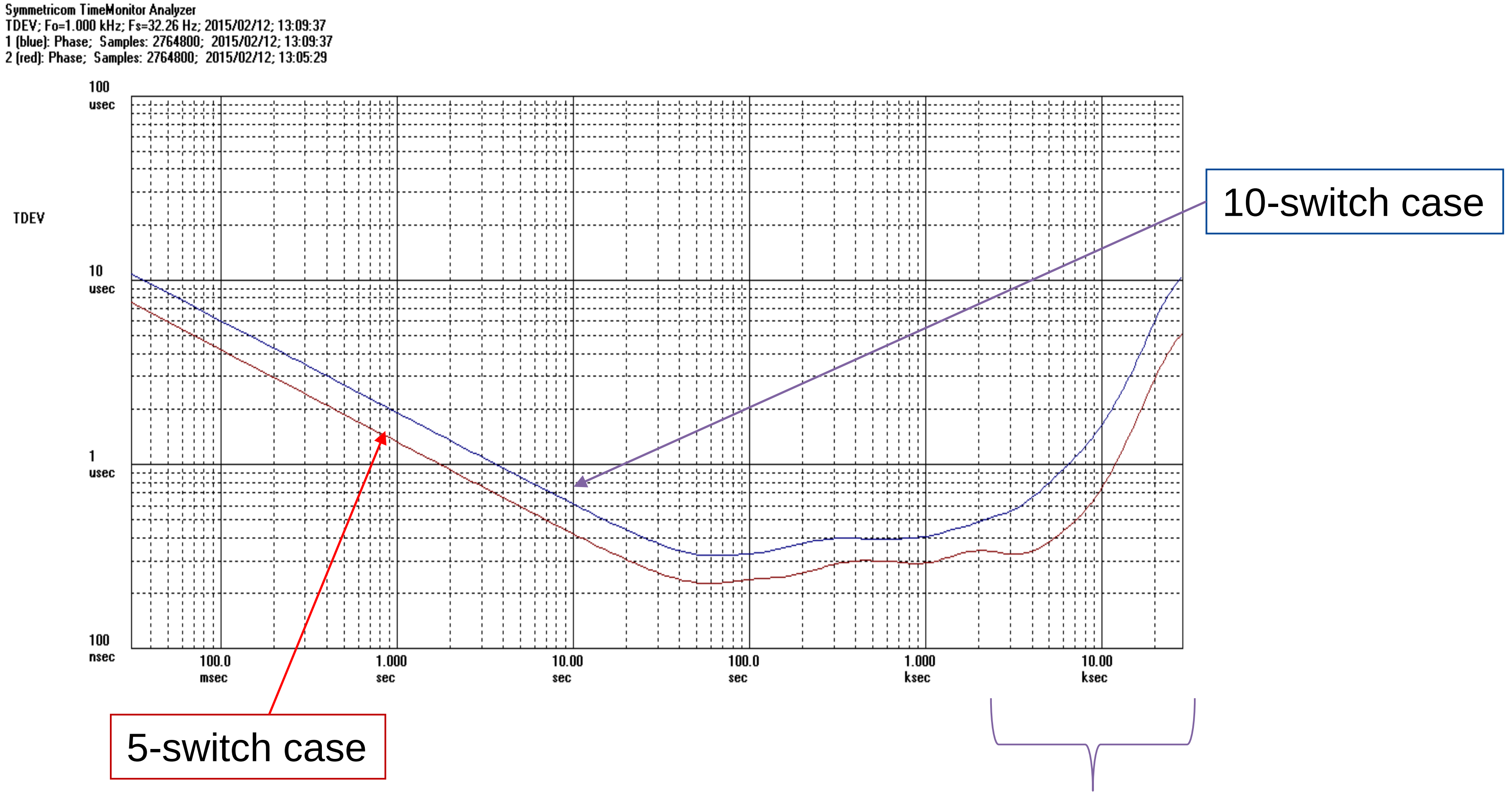
5-switch case

PDV : TC-14 Forward Direction

QULSAR

Average Load(s) : ramp between 20% and 80%

TDEV

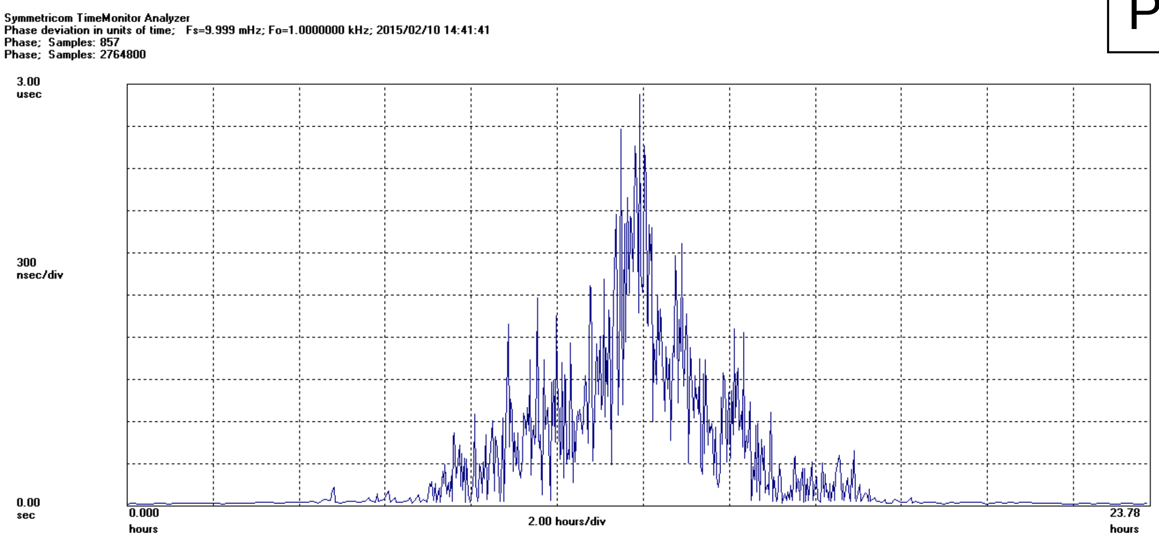


TDEV calculation not very reliable

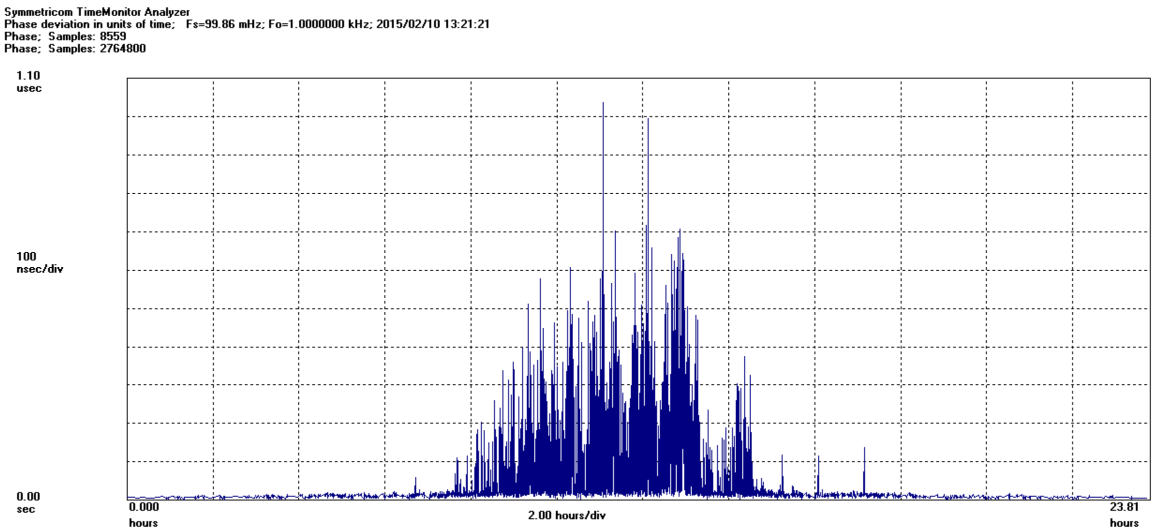
PDV : TC-14 Forward Direction

QULSAR

Transit Time Variation
Packet selection: minimum



10-switch case
Window: 100s

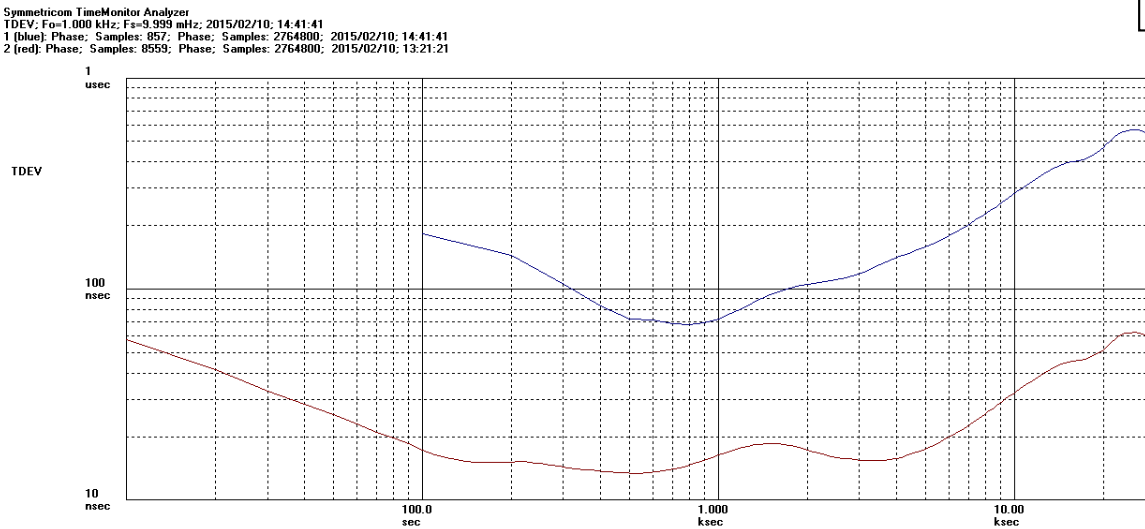


5-switch case
Window: 10s

PDV : TC-14 Forward Direction

QULSAR

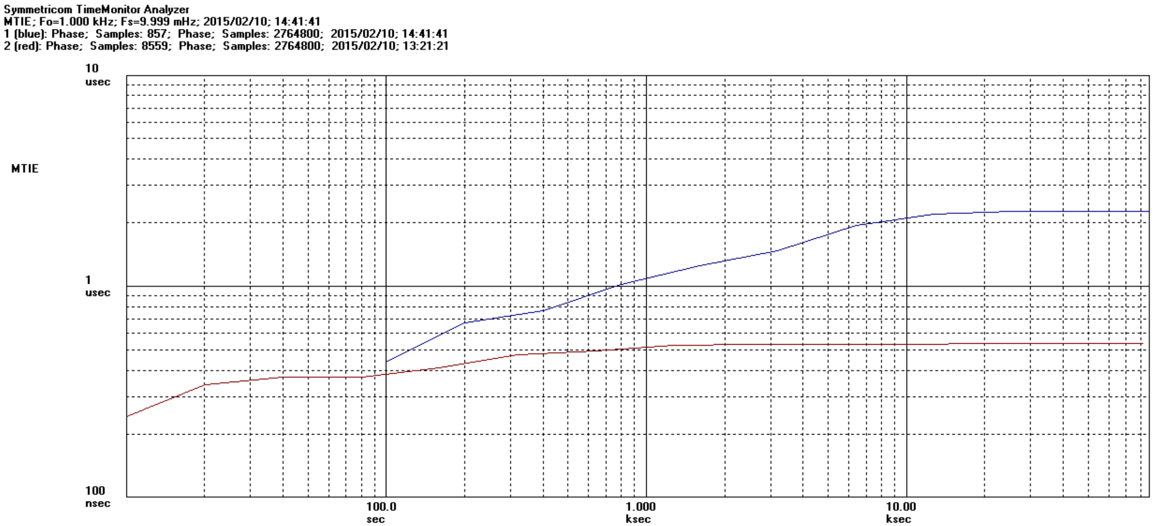
Transit Time Variation
Packet selection: minimum



TDEV

10-switch case
Window: 100s

5-switch case
Window: 10s



MTIE

10-switch case
Window: 100s
Filter: 1mHz

5-switch case
Window: 10s
Filter: 10mHz

Concluding Remarks

QULSAR

- Time holdover using PTP can be predicted
- When GNSS is active the network PDV can be measured and quantified
  - Metrics are computed on measured PDV and not necessarily related to network configuration (such as number of switches)
- Metrics (e.g. MTIE, TDEV, etc.) quantify strength of noise process and estimates of (future) time dispersion if in holdover
- Sample PDV cases for G.8261-style testing can be developed using simulation methods

Thank you …

Questions?

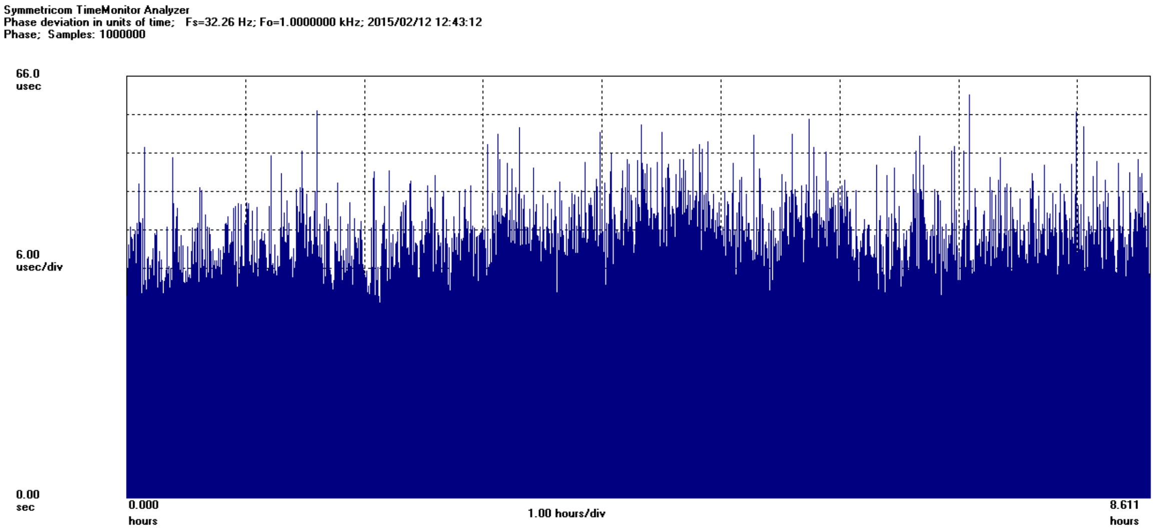
Kishan Shenoi
CTO, Qulsar, Inc.
Email: kshenoi@qulsar.com
www.qulsar.com
@qulsar

Back-up Slides

Includes Additional PDV Slides

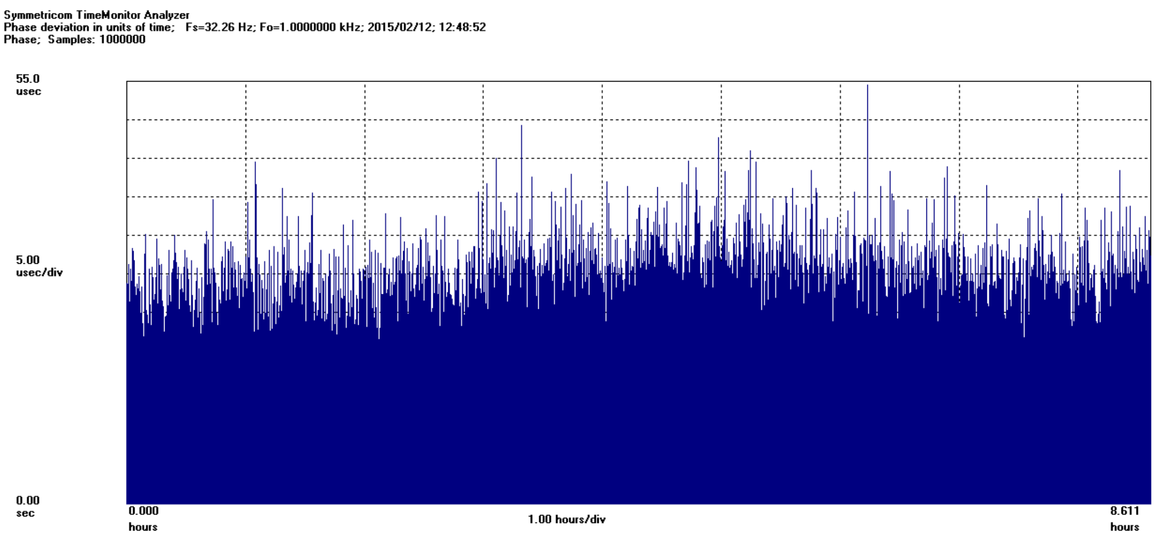
PDV : TC-12 Reverse Direction

Transit Time Variation



10-switch case

Average Load: 20%



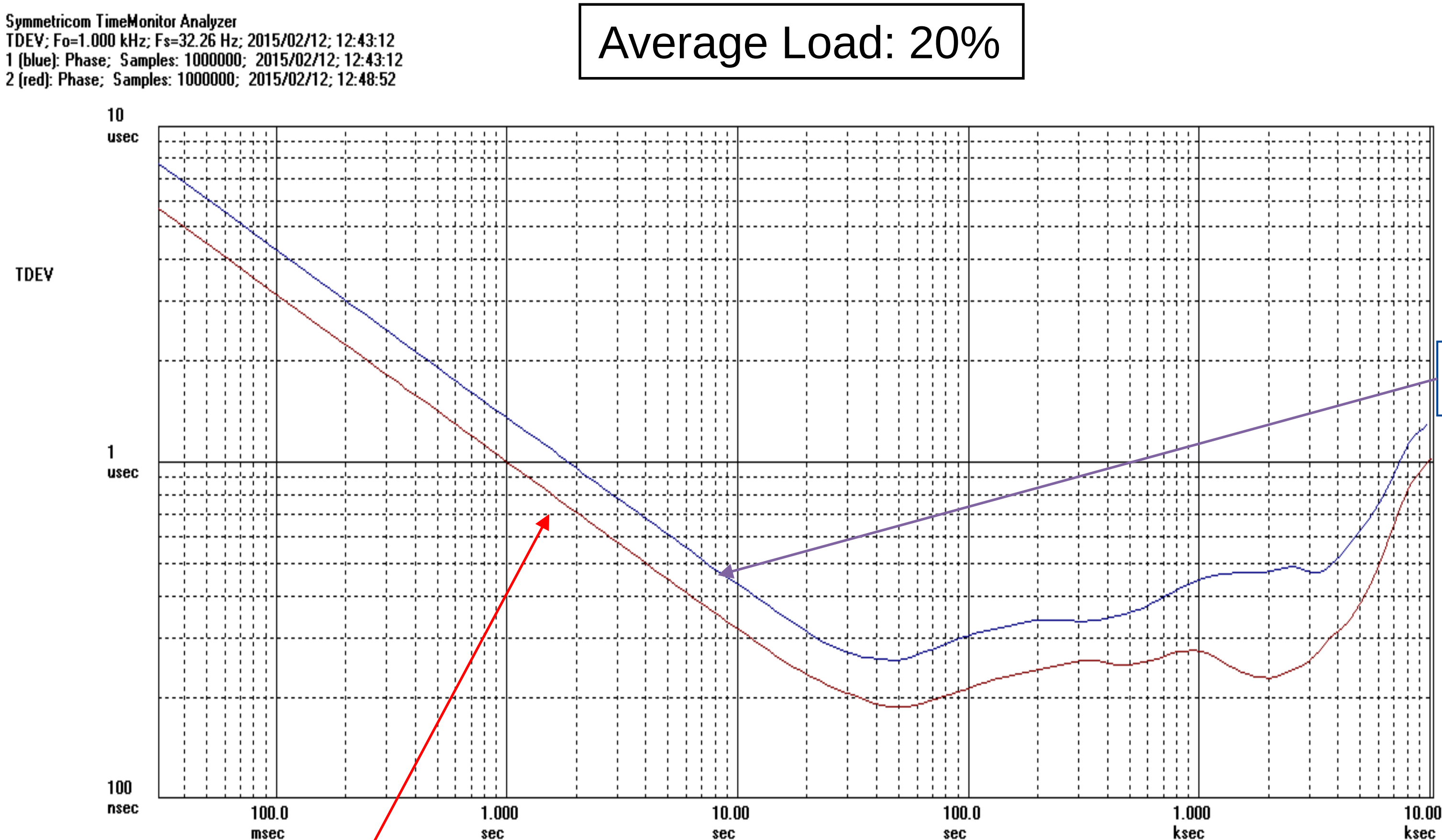
5-switch case

PDV : TC-12 Reverse Direction

QULSAR

TDEV

Average Load: 20%



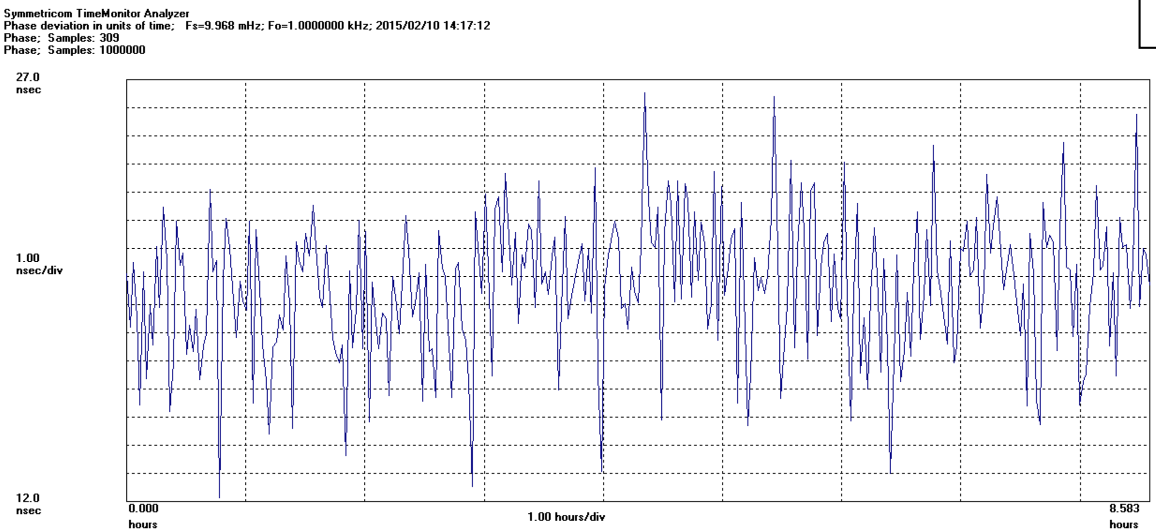
10-switch case

5-switch case

TDEV calculation not very reliable

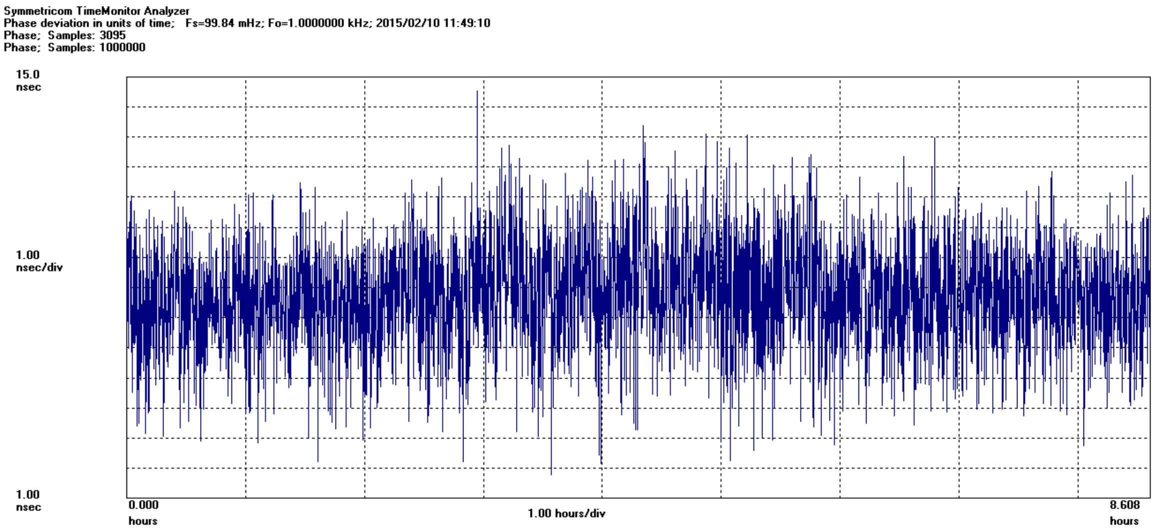
PDV : TC-12 Reverse Direction

Transit Time Variation
Packet selection: minimum



10-switch case
Window: 100s

Average Load: 20%

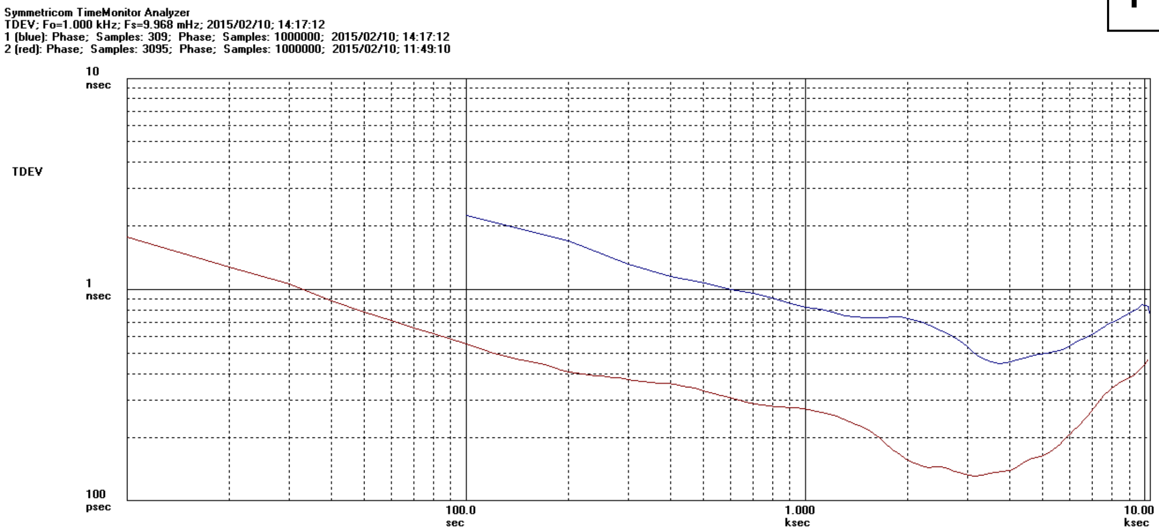


5-switch case
Window: 10s

PDV : TC-12 Reverse Direction

QULSAR

Transit Time Variation
Packet selection: minimum

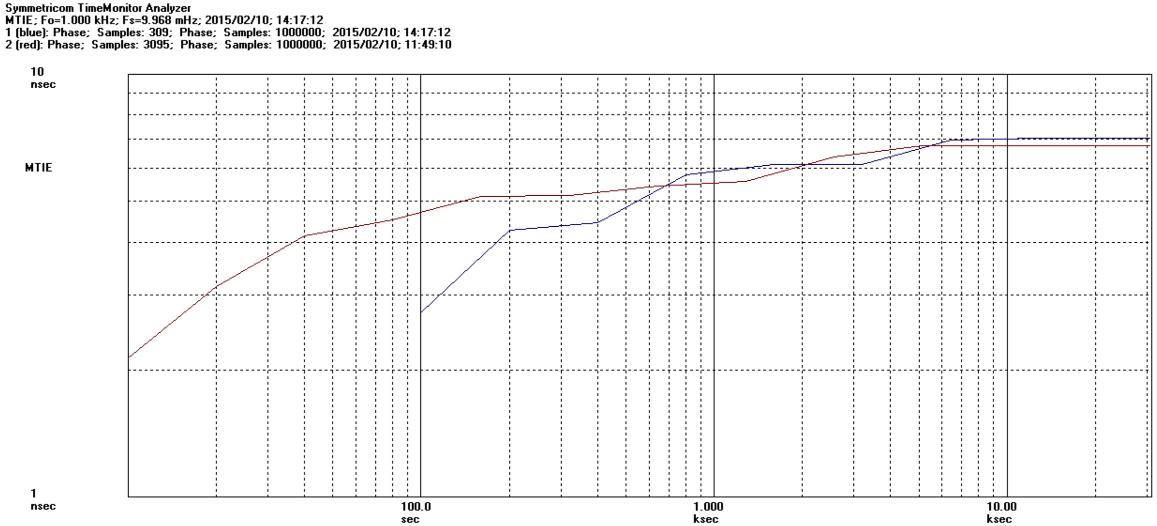


TDEV

10-switch case
Window: 100s

5-switch case
Window: 10s

Average Load: 20%



MTIE

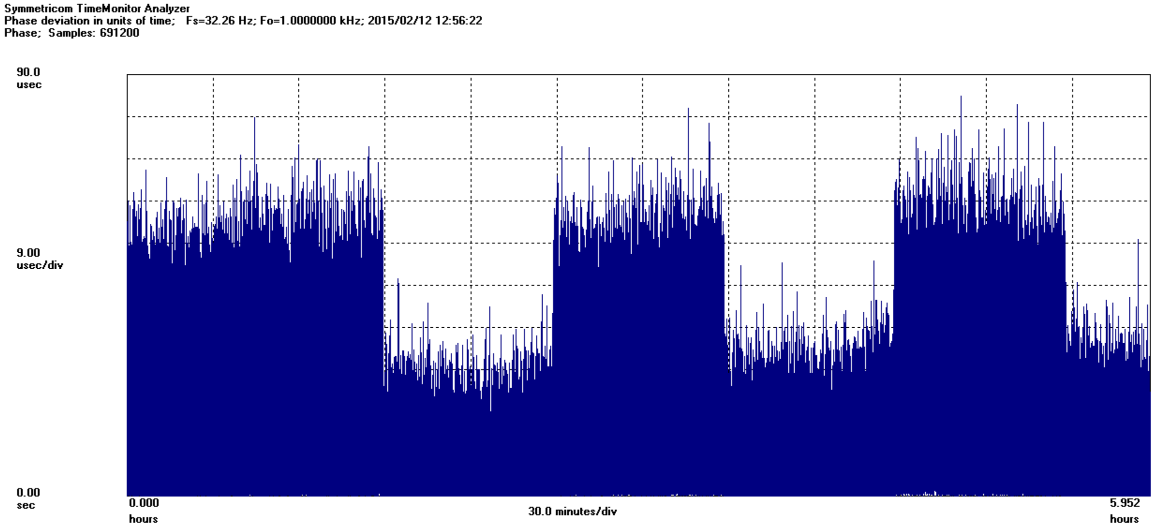
10-switch case
Window: 100s
Filter: 1mHz

5-switch case
Window: 10s
Filter: 10mHz

PDV : TC-13 Reverse Direction

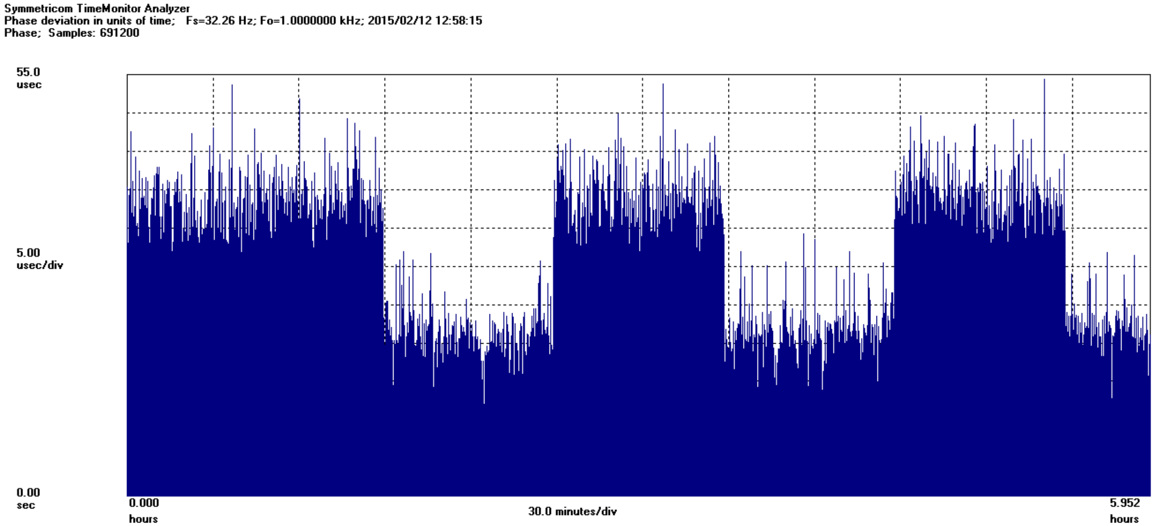
QULSAR

Transit Time Variation



10-switch case

Average Load: 50% and 10%



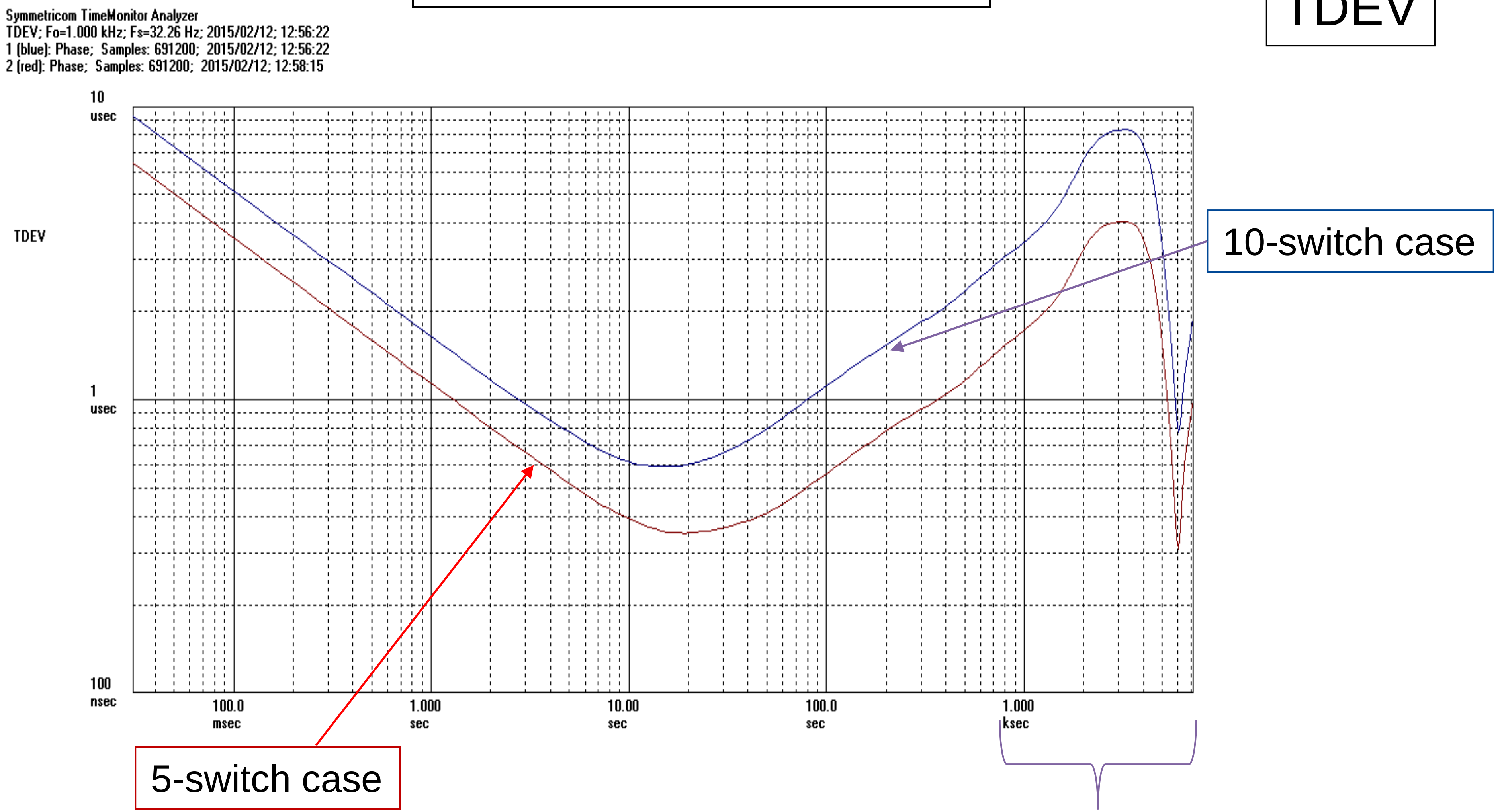
5-switch case

PDV : TC-13 Reverse Direction

QULSAR

Average Load(s): 50% and 10%

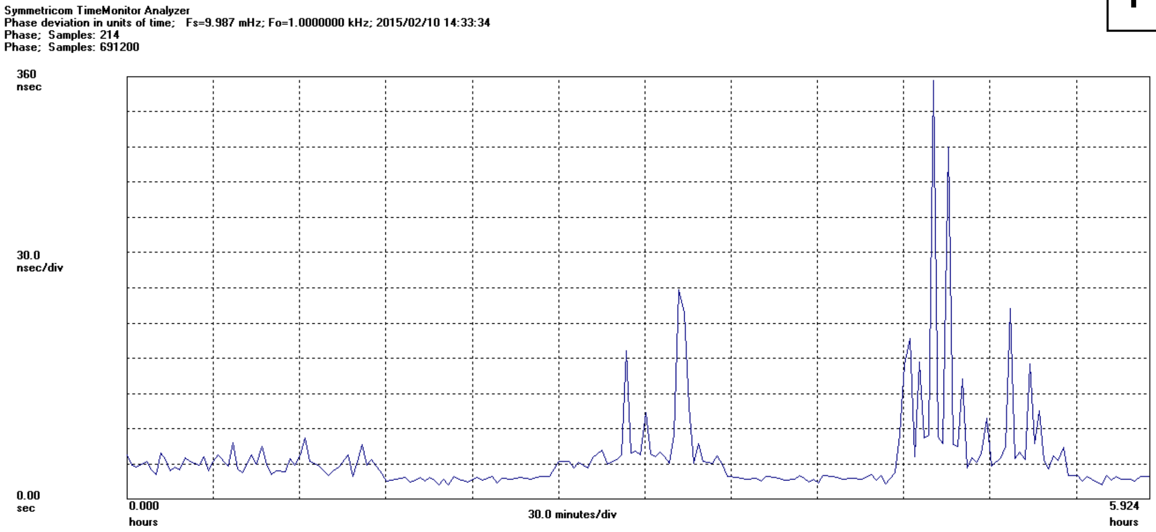
TDEV



TDEV calculation not very reliable

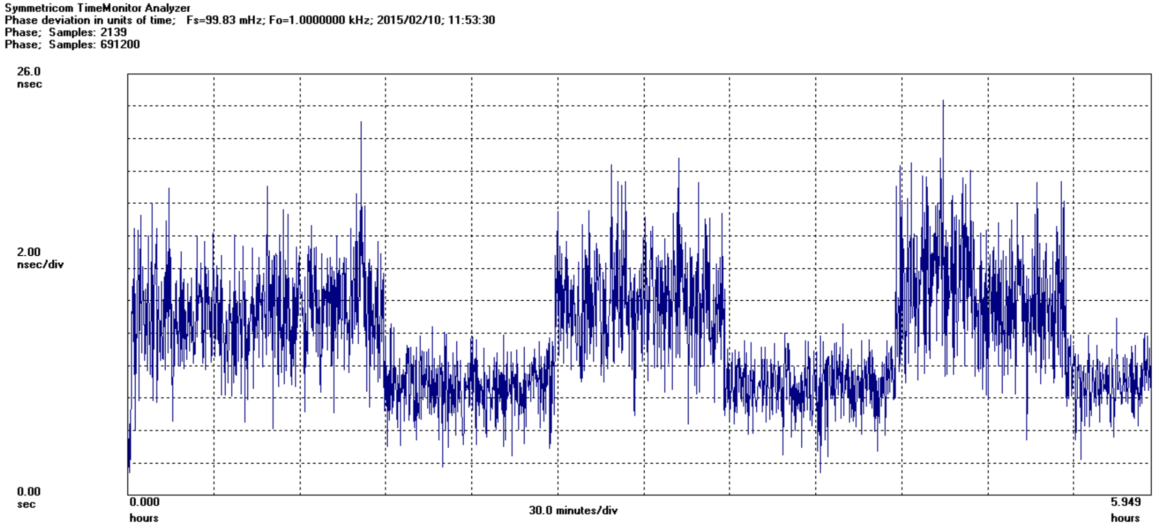
PDV : TC-13 Reverse Direction

Transit Time Variation
Packet selection: minimum



10-switch case
Window: 100s

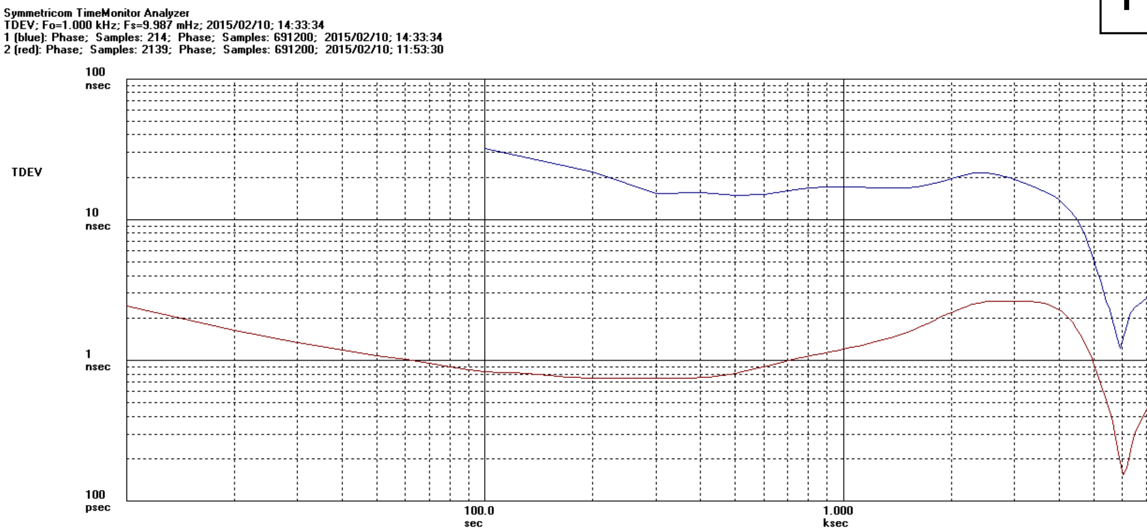
Average Load(s):
50% and 10%



5-switch case
Window: 10s

PDV : TC-13 Reverse Direction

Transit Time Variation
Packet selection: minimum

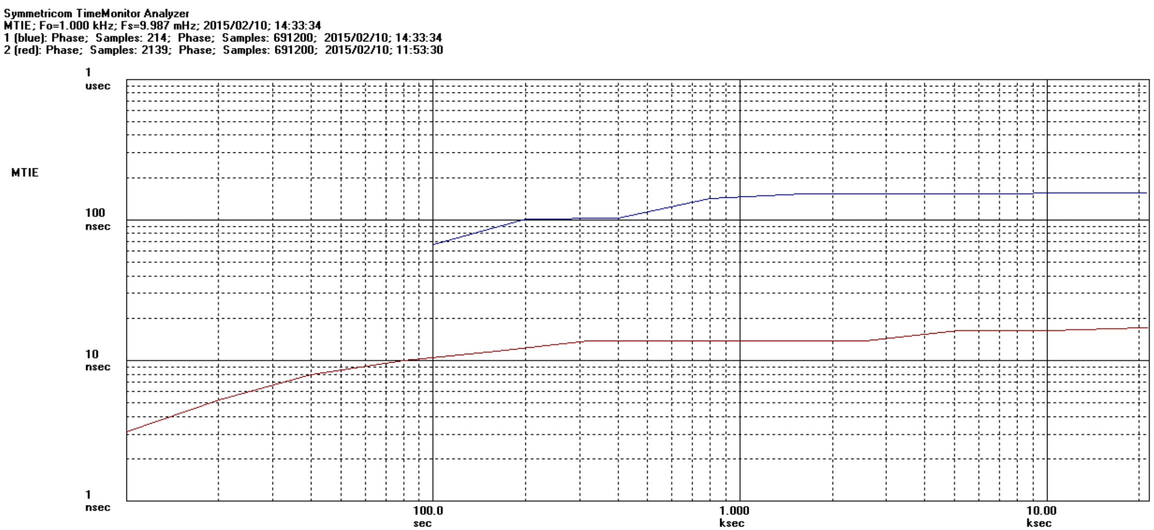


TDEV

10-switch case
Window: 100s

5-switch case
Window: 10s

Average Load(s):
50% and 10%



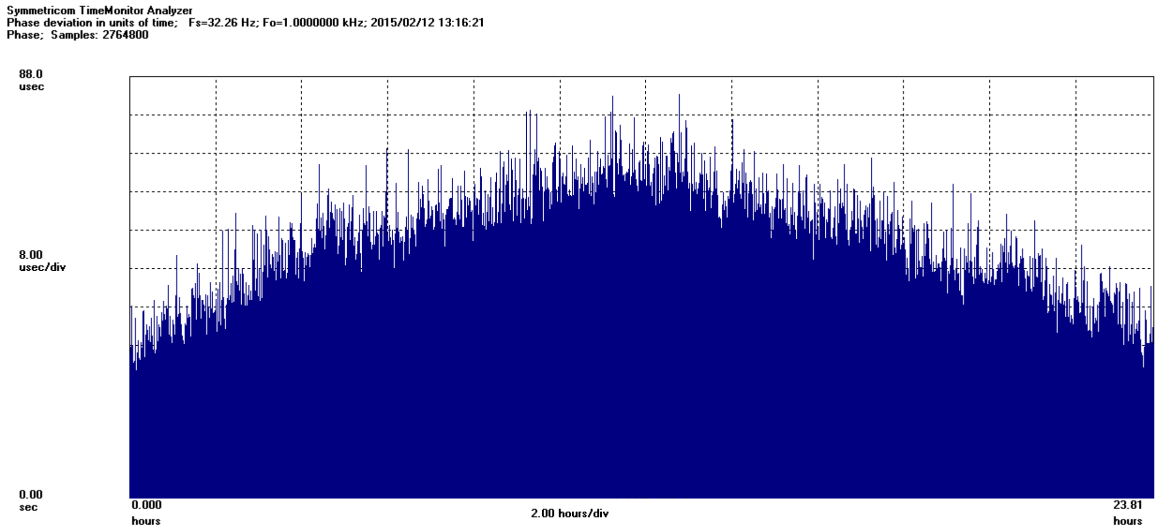
MTIE

10-switch case
Window: 100s
Filter: 1mHz

5-switch case
Window: 10s
Filter: 10mHz

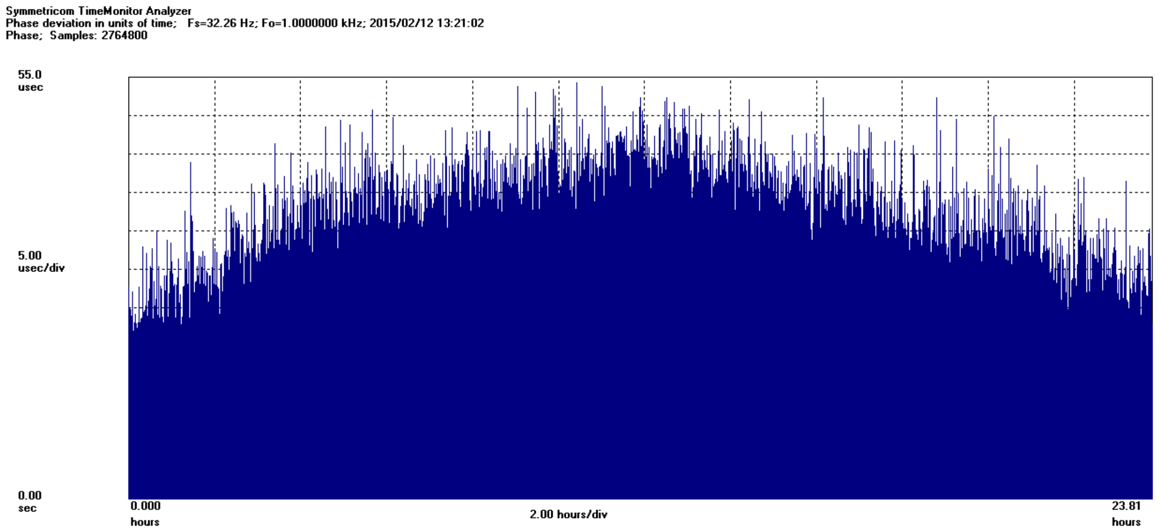
PDV : TC-14 Reverse Direction

Transit Time Variation



10-switch case

Average Load:
Max:55%
Min: 10%



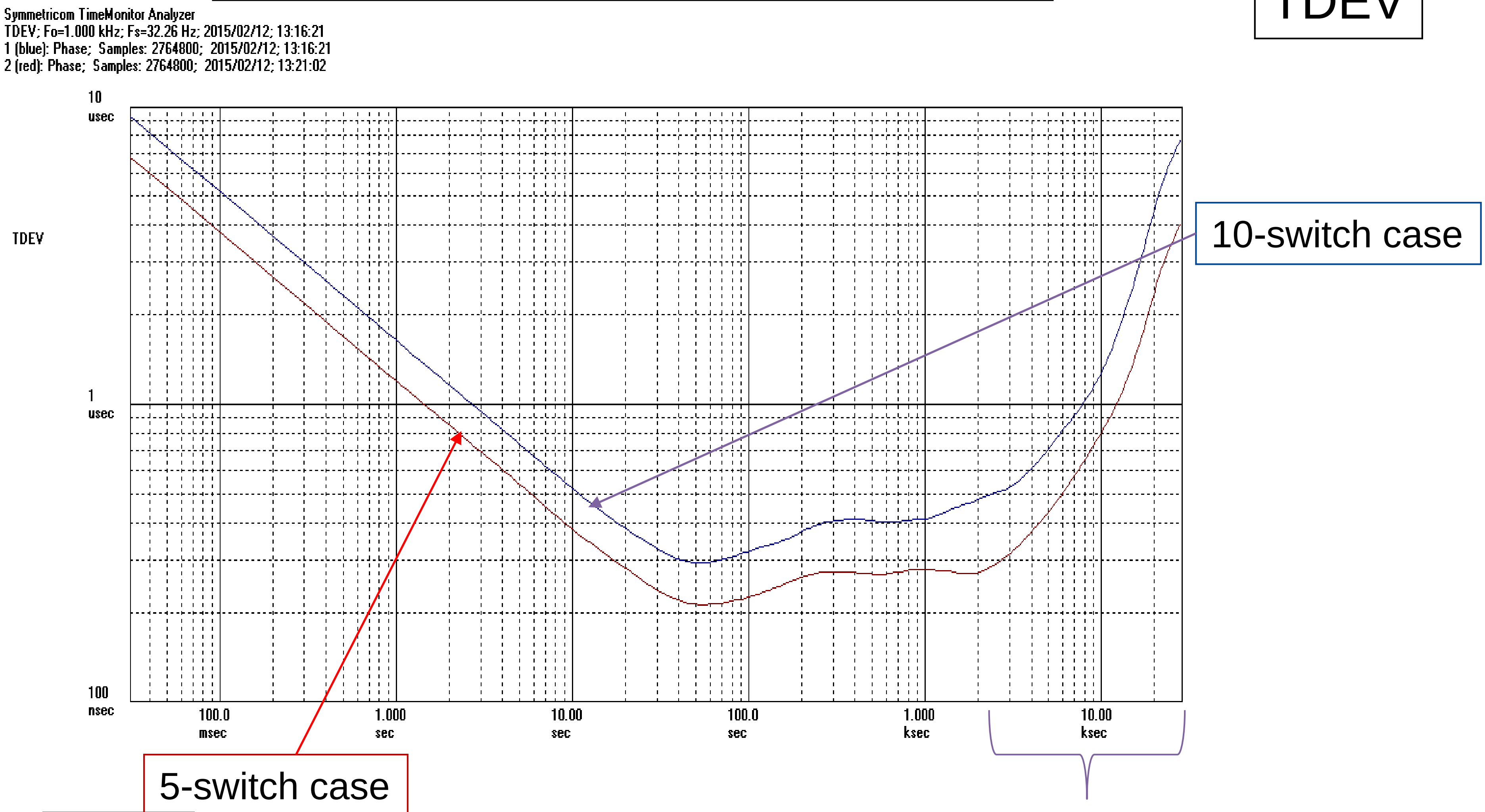
5-switch case

PDV : TC-14 Reverse Direction

QULSAR

Average Load(s) : ramp between 10% and 55%

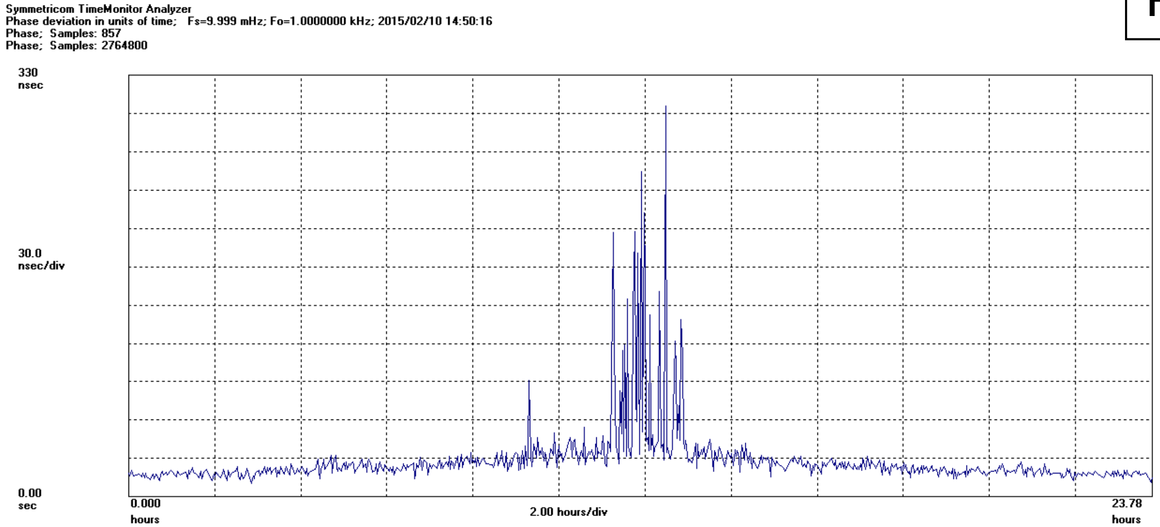
TDEV



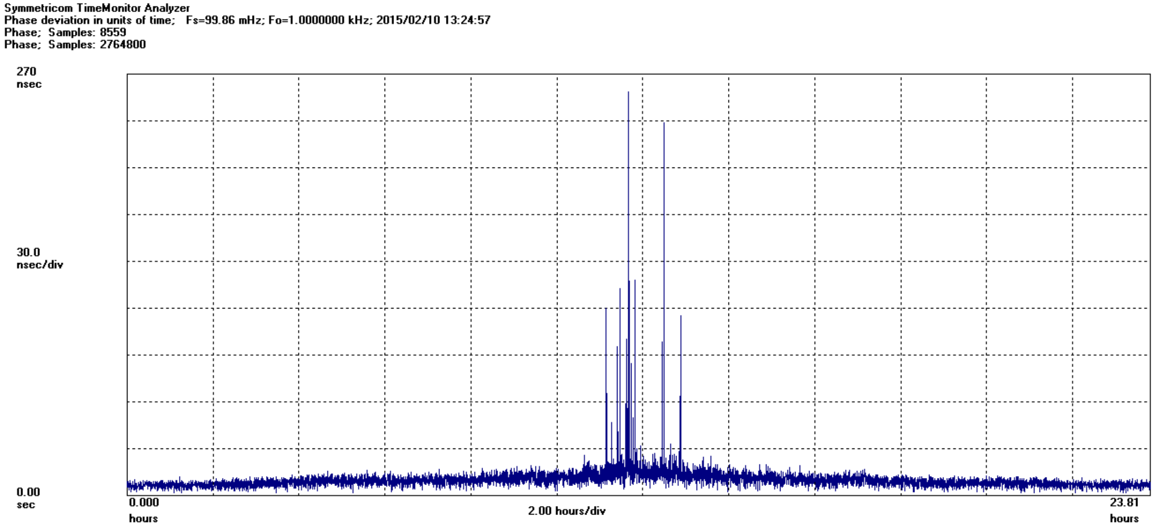
TDEV calculation not very reliable

PDV : TC-14 Reverse Direction

Transit Time Variation
Packet selection: minimum



10-switch case
Window: 100s

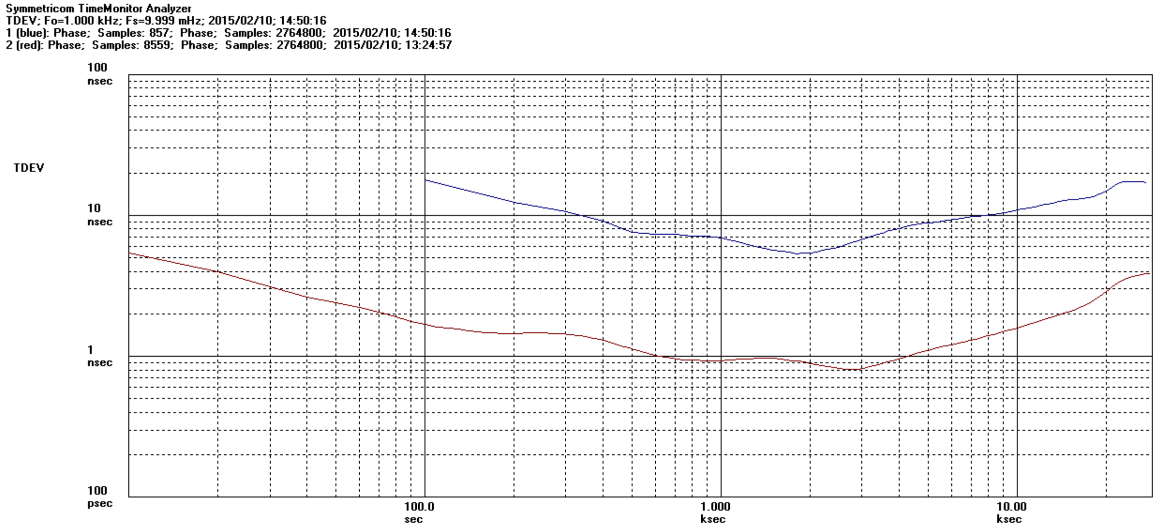


5-switch case
Window: 10s

PDV : TC-14 Reverse Direction

QULSAR

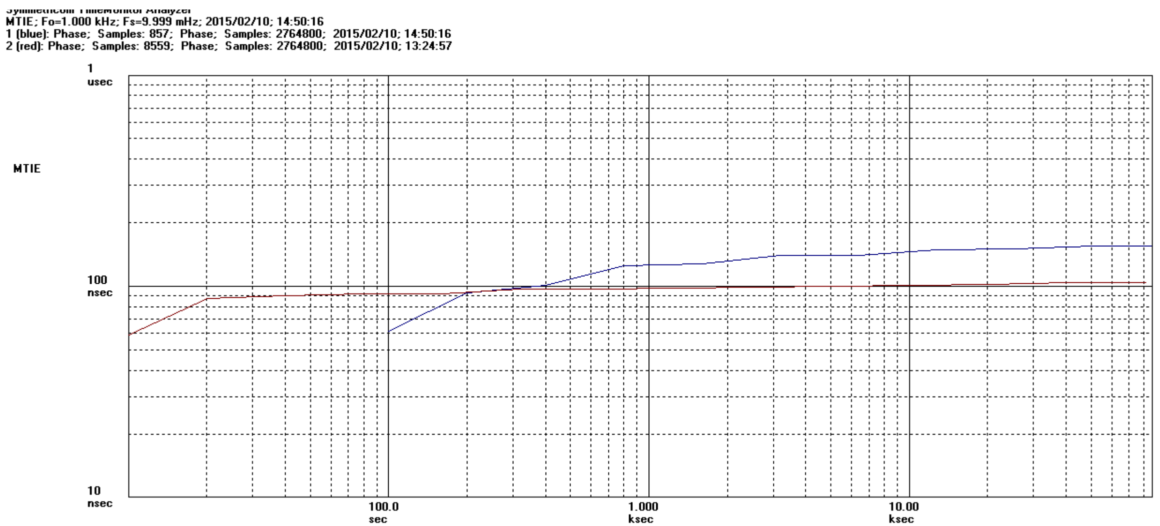
Transit Time Variation
Packet selection: minimum



TDEV

10-switch case
Window: 100s

5-switch case
Window: 10s



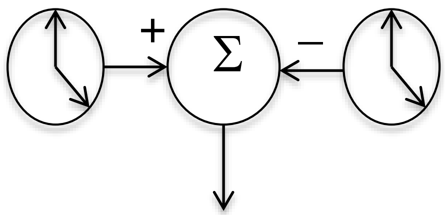
MTIE

10-switch case
Window: 100s
Filter: 1mHz

5-switch case
Window: 10s
Filter: 10mHz

Metrics Mathematics

QULSAR



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)

Metrics Mathematics

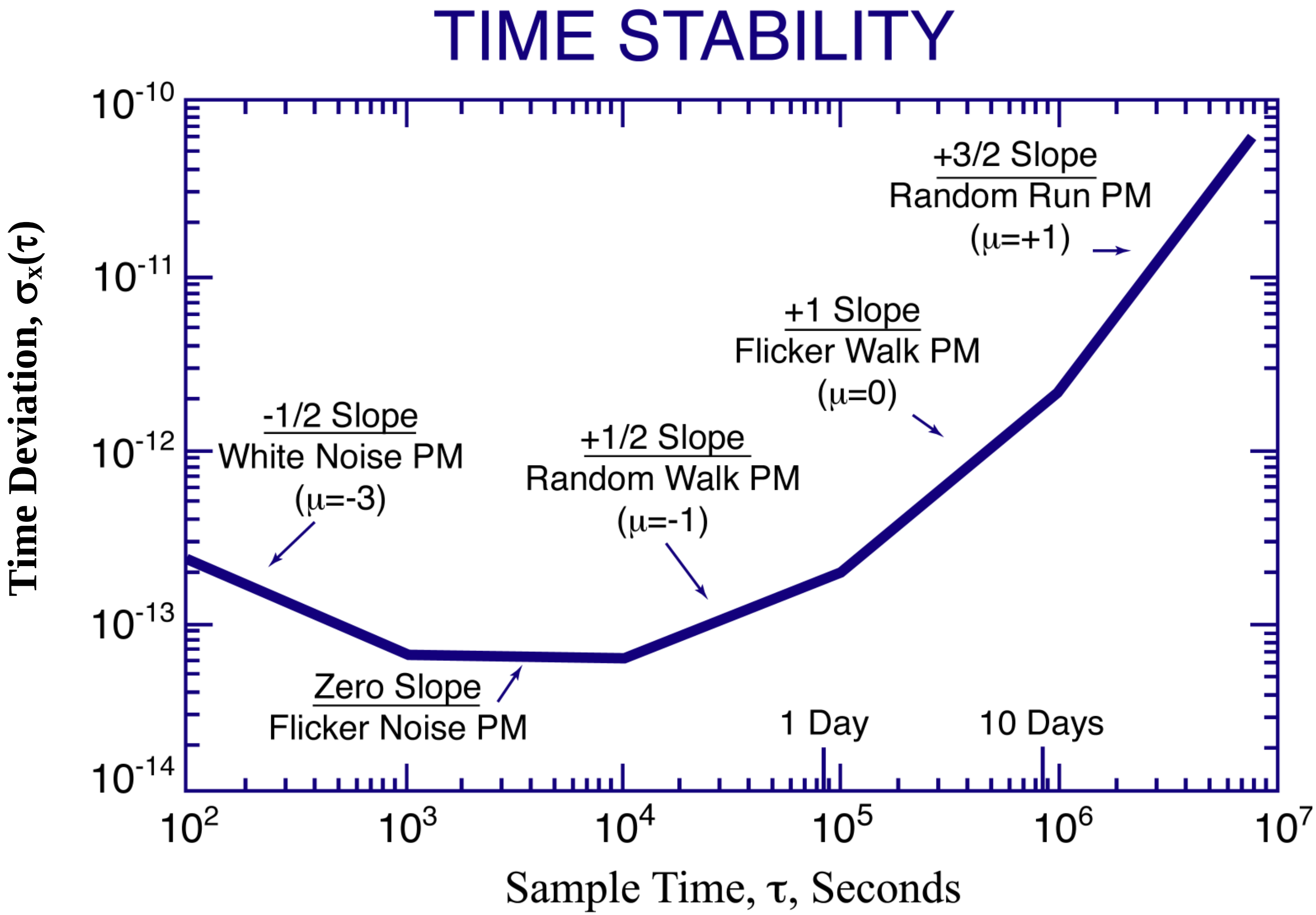
- Possible to separate "high-band" and "low-band" time error by filtering $\{x(n)\}$ to get $\{\xi(n)\}$
  - Identifies the component that could be in the pass-band of the down-stream clock
  - Reasonable choice of cut-off frequency = 0.1Hz
- Some metrics include an average over one observation interval (k samples) that is incorporated into the formula
  - MATIE, TEDEV, TDEV, 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 [TBD; e.g. percentile values for maximum and minimum (floor)]

TDEV Reveals the Noise Type



Taken from earlier presentations by Dr. Marc Weiss

Thank you …

Further Questions?

Kishan Shenoi
CTO, Qulsar, Inc.
Email: kshenoi@qulsar.com
www.qulsar.com
@qulsar