Bringing Expertise Into Focus

Time and Frequency Measurements in Synchronization and Packet Networks

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Your Network. Optimized.

Presentation Outline

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- Introduction
  - Synchronization “TIE” vs. packet “PDV” measurements
  - Measurement equipment overview
- Synchronization Measurements
  - Measuring TIE
  - Analysis from TIE
- Packet Metrics
  - Packet delay distribution
  - Tracked packet delay statistics
  - Frequency transport metrics
  - Time transport metrics
- Case Studies
  - Asymmetry in microwave, SHDSL, wireless backhaul
  - Metro Ethernet network
  - National Ethernet network

"TIE" vs. "PDV"

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- "TIE" vs "PDV"
  - Traditional TDM synchronization measurements: signal edges are timestamped producing a sequence of samples
  - Packet timing measurements: packet departure/arrival times are sampled and packet delay sequences are formed
  - Both require (1) PRC/GPS; (2) Precision HW timestamping; (3) PC + SW

- Phase measurements (TIE) can be made using:
  - Frequency/time interval counters
  - Time interval analyzers
  - Dedicated test-sets
  - BITS/SSU clocks with built-in measurement capability
  - GPS receivers with built-in measurement capability

- Packet phase measurements (PDV) can be made using:
  - IEEE 1588 grandmaster/probes
  - NTP servers/probes
  - Specialized network probes

"TIE" vs. "PDV"

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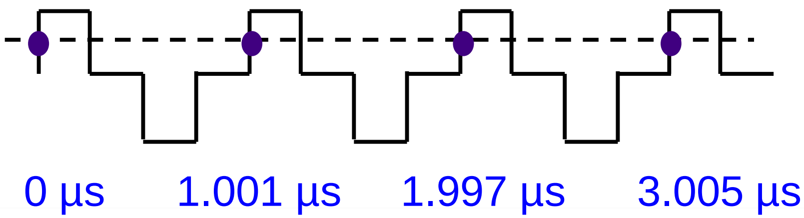
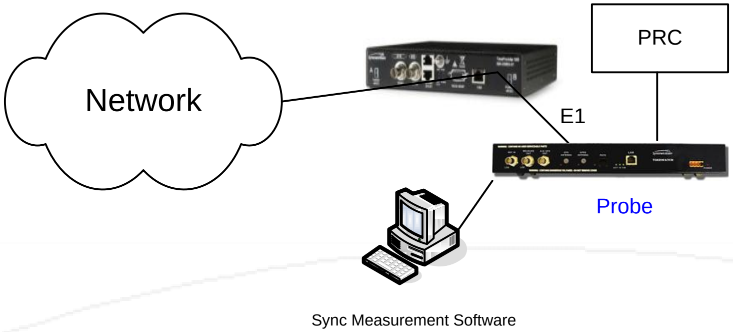
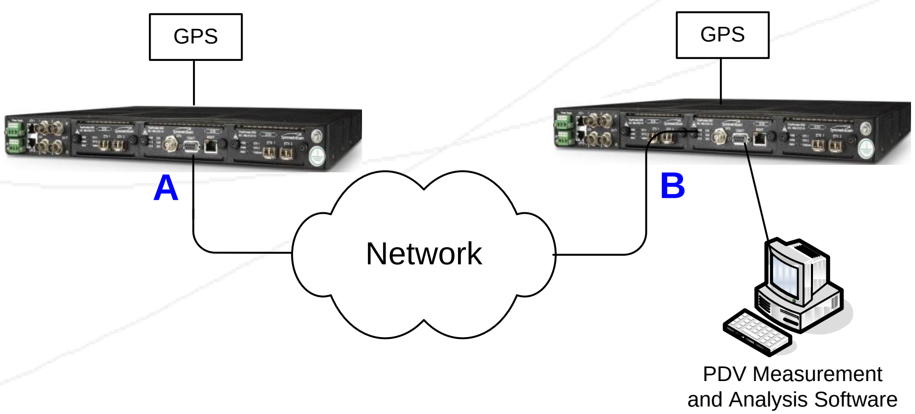
- "TIE" (Single Point Measurement)
  - Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed





- "PDV" (Dual Point Measurement)
  - Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed

	Timestamp A	Timestamp B
F	1233166476.991204496	1233166476.991389744
R	1233166476.980521740	1233166476.980352932
F	1233166477.006829496	1233166477.007014512
R	1233166476.996147084	1233166476.995977932
F	1233166477.022454496	1233166477.022639568
R	1233166477.011771820	1233166477.011602932



“PDV” Measurement Setup Options

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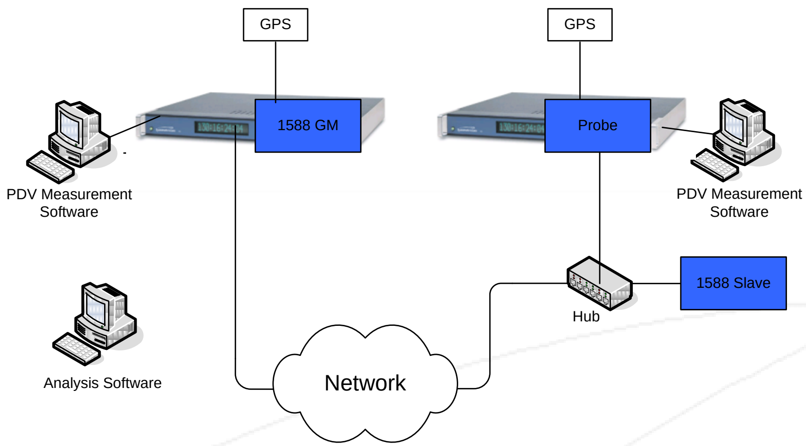
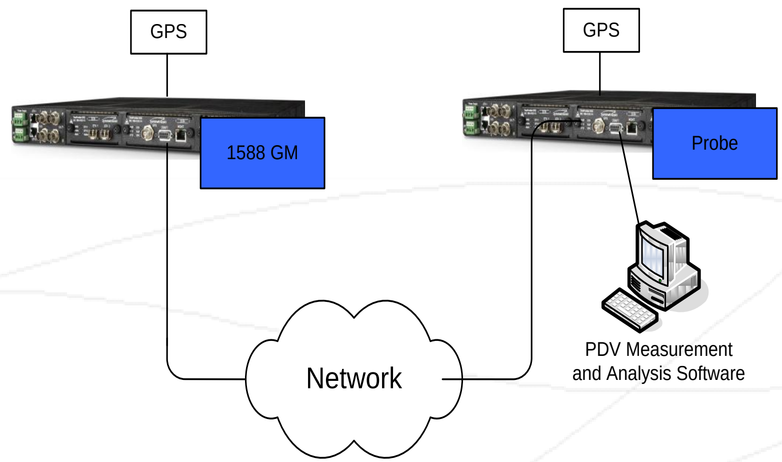
Passive Probe

(1) Hub or Ethernet Tap
(2) IEEE 1588 Slave
(3) Collection at Both Nodes



Active Probe

(1) No Hub or Ethernet Tap Needed
(2) No IEEE 1588 Slave Needed
(3) Collection at Probe Node Only



- “PDV”
  - Ideal setup - two packet timestampers with GPS reference so absolute latency can be measured as well as PDV over small to large areas
  - Alternative setup (lab) – frequency (or GPS) locked single shelf with two packet timestampers
  - Alternative setup (field) – frequency locked packet timestampers – PDV but not latency can be measured

“TIE” in a Packet World

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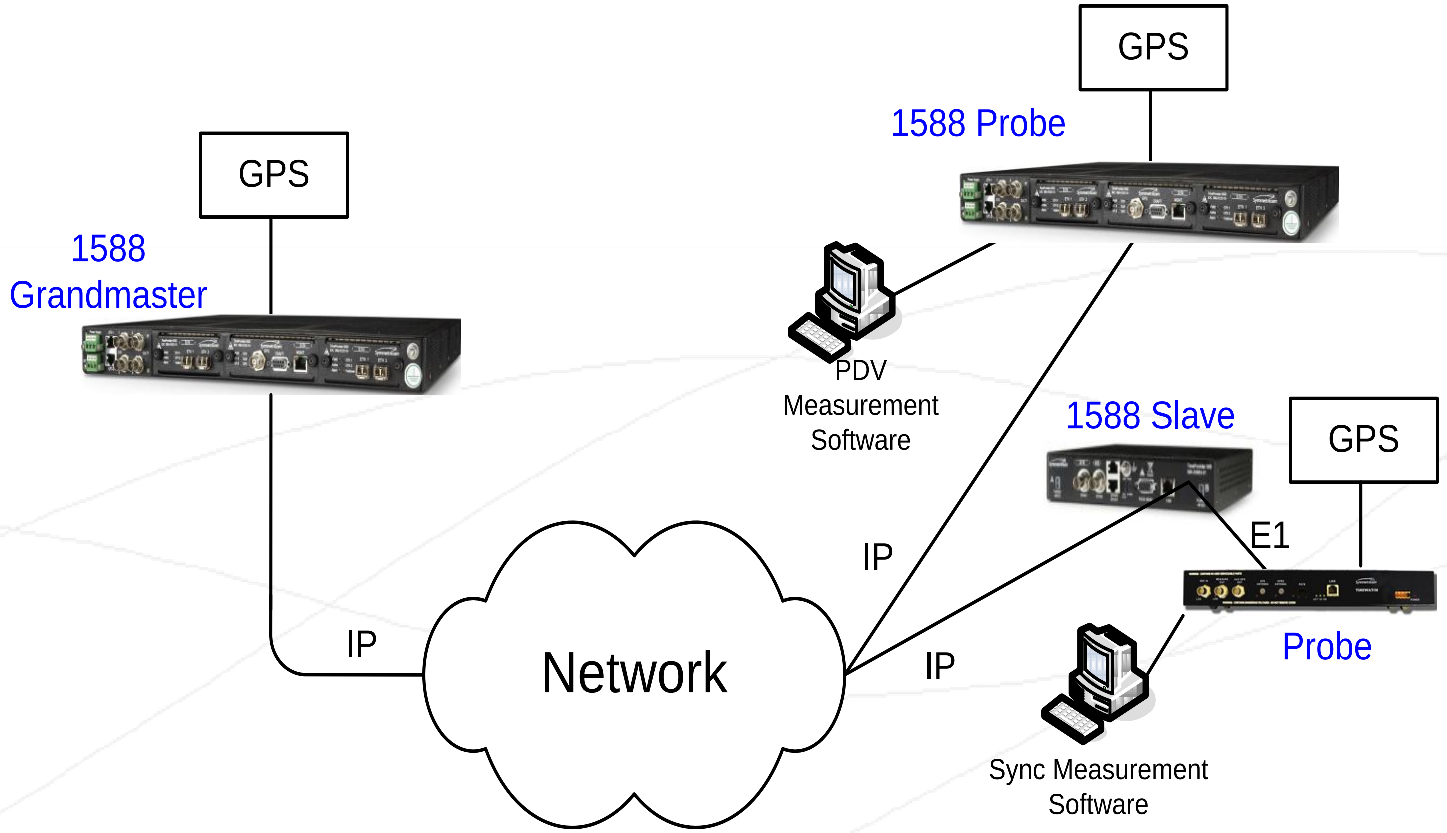
- Are “TIE” Measurements still important?   Yes!
  - Needed for the characterization of packet servo slaves such as IEEE 1588 slave devices
  - There are still oscillators and synchronization interfaces to characterize
  - “TIE” measurement/analysis background important to the understanding of “PDV” measurement/analysis
  - Many of the tools can be applied to either “TIE” or “PDV” data such as TDEV or spectral analysis
  - But there are new tools and new approaches to be applied to “PDV” with some of the traditional “TIE” tools less effective for “PDV” analysis

“TIE” and “PDV”

In most packet network measurement setups, both “TIE” and “PDV” are measured at the same time



PDV Measurement Equipment Complement: Network Emulator

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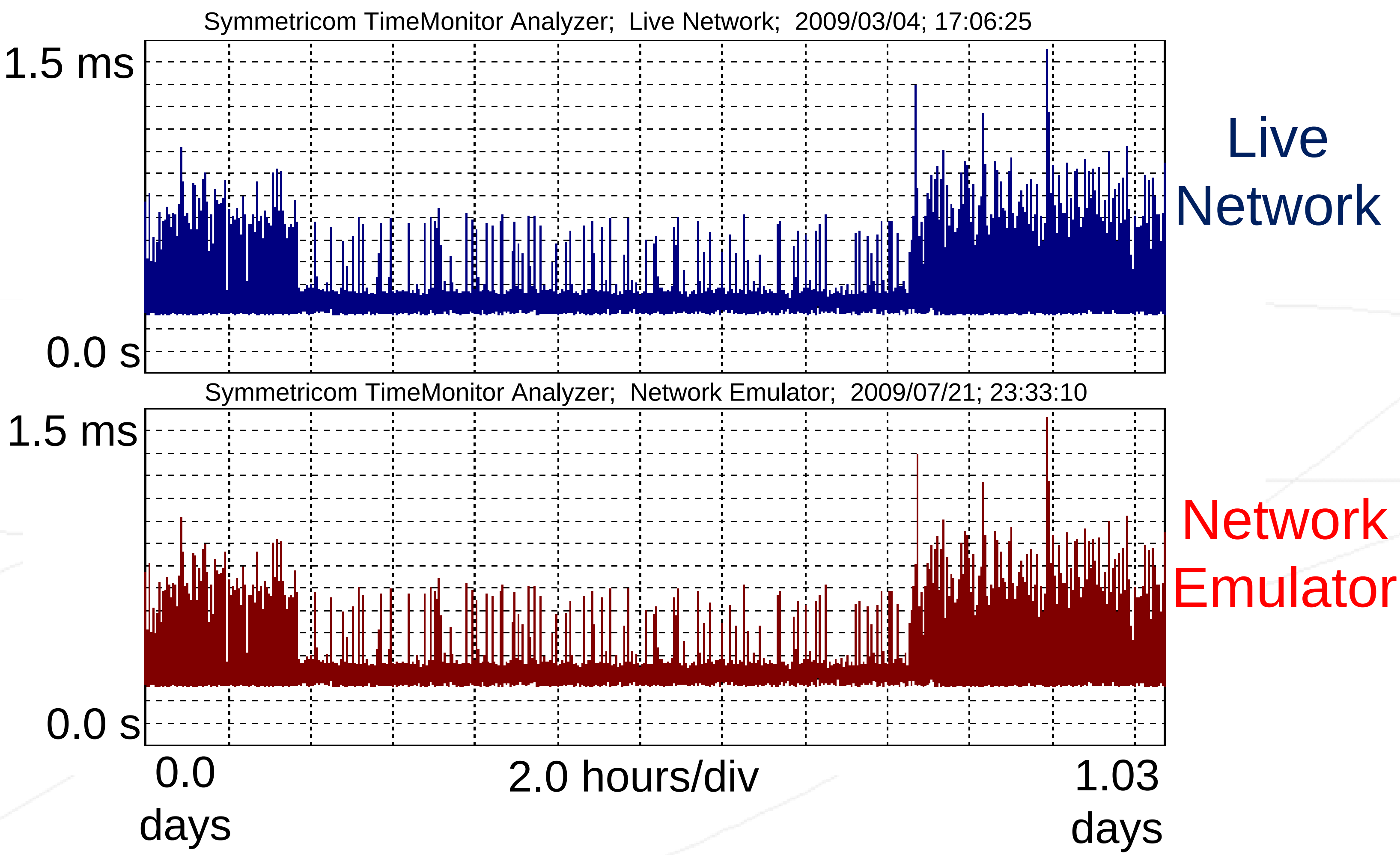
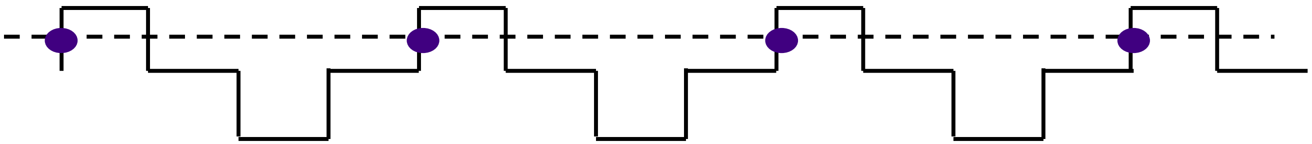
Network Emulator

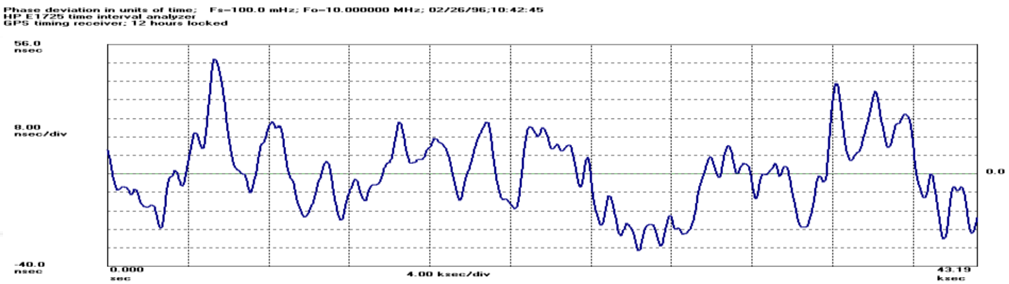


TIE Measurement and Analysis: 3 step process

1. Timestamps

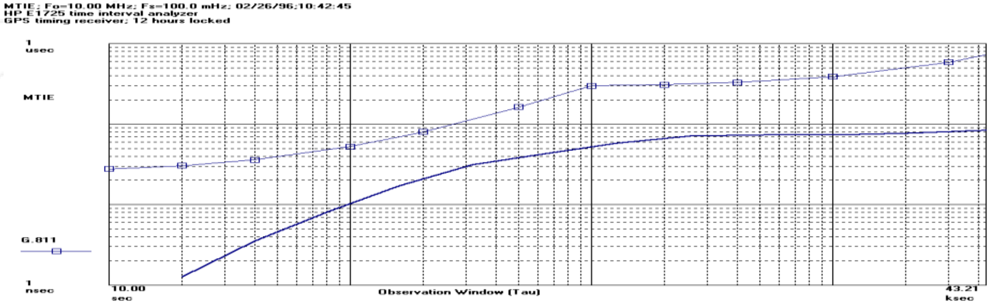


2. Phase



Phase Deviation or TIE

3. Analysis



MTIE, TDEV, Allan Variance, Frequency, PPSD, etc.

The Importance of Phase (TIE)

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1. ***Analysis***: Frequency/MTIE/TDEV etc. derived from phase
2. ***Check:*** Verify measurement is properly made
   - Sudden (point-to-point) large movements of phase are suspect. For example, if MTIE fails the mask, it could be a measurement problem. Phase will help to investigate this.
   - Large frequency offset is easily seen: Is the reference OK? Is the equipment set to use the external reference?
3. ***Timeline:*** The processed measurements don't show what happened over time. Is the measurement worse during peak traffic times? Is the measurement worse in the middle of the night during maintenance activities?

Analysis from Phase: Jitter & Wander

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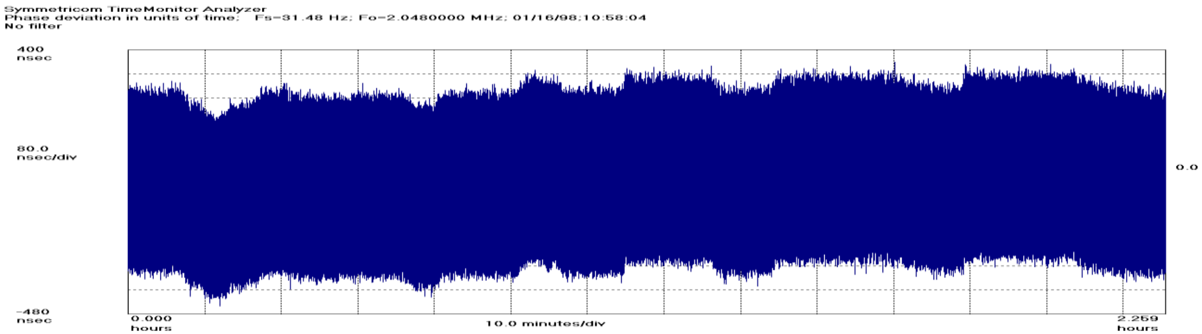
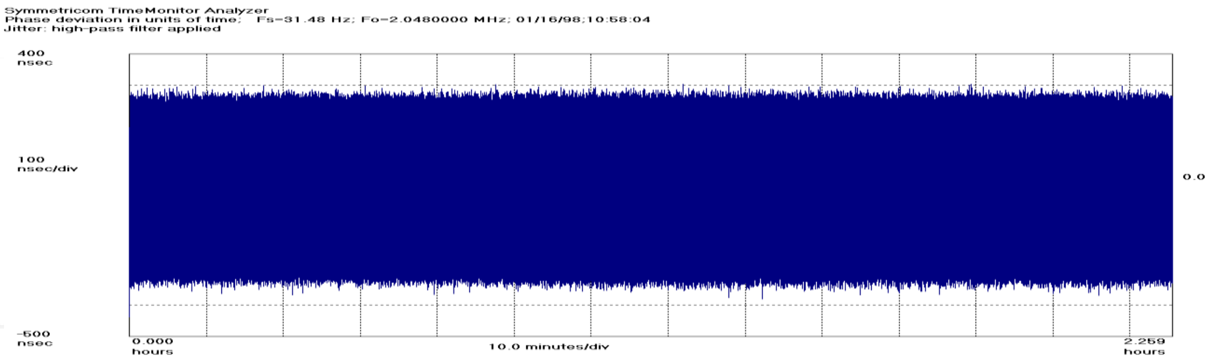
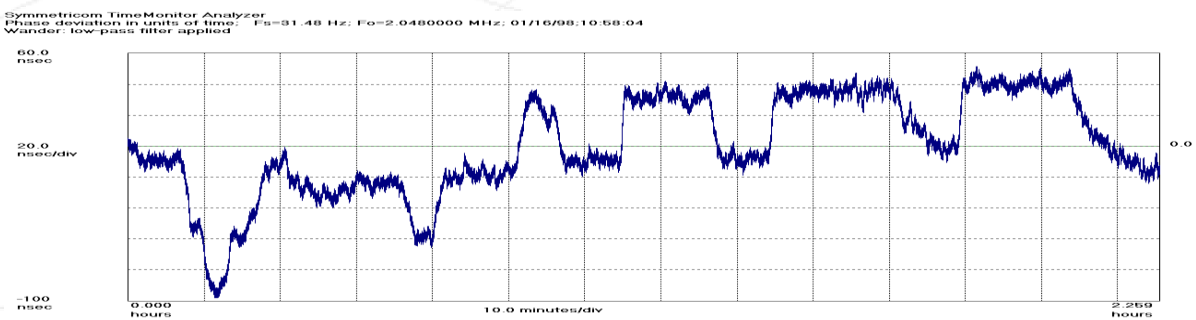


Signal (no filter)



Jitter (high-pass filter)
1.52 UI peak-to-peak (E1)



Wander (low-pass filter)

Analysis from Phase: Frequency

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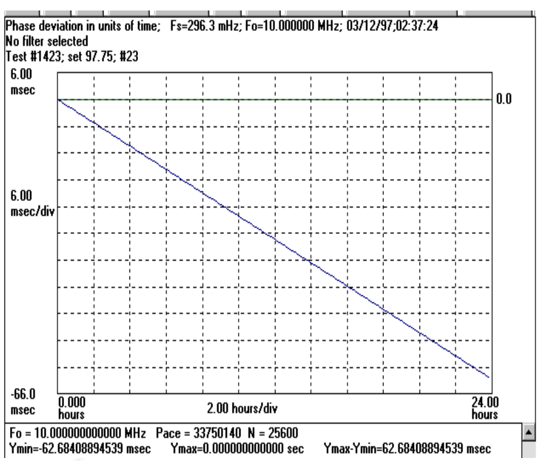
- Recall the relationship between frequency and phase:

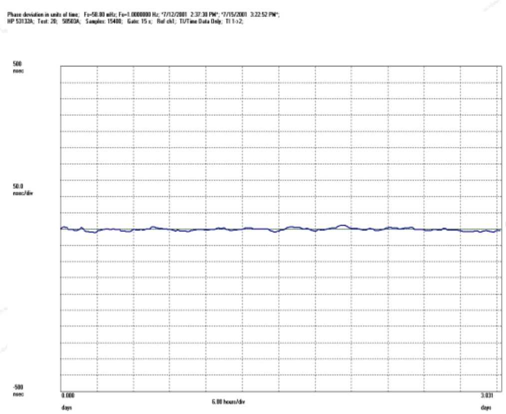
$$\omega = \frac{d\phi}{dt}$$

- Important point: Frequency is the slope in the phase plot



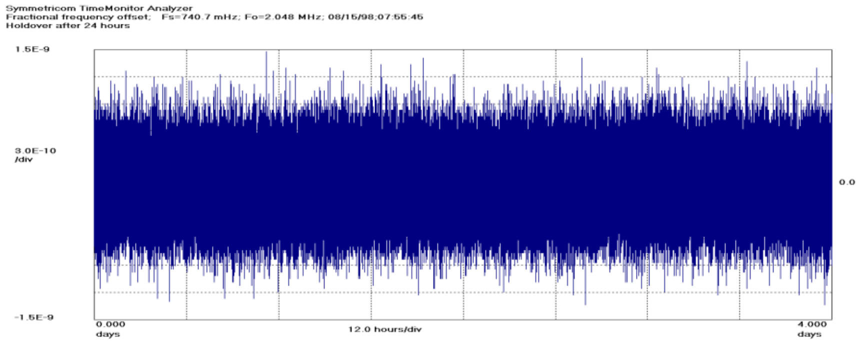
← Frequency offset present

No offset: ideal phase plot (flat) →



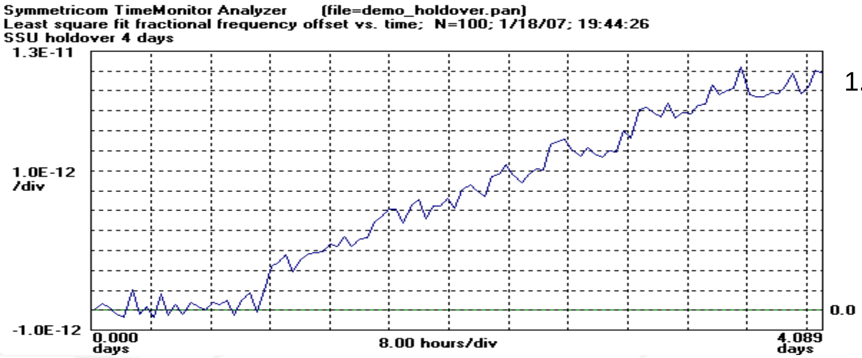
We can reduce a phase ramp to a single frequency value

Approaches to Frequency Calculation



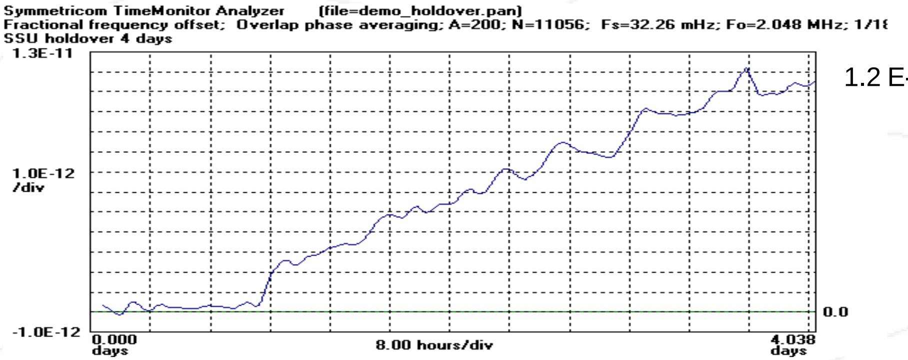
1.5 E-9

Point-by-point



1.2 E-11

Segmented LSF



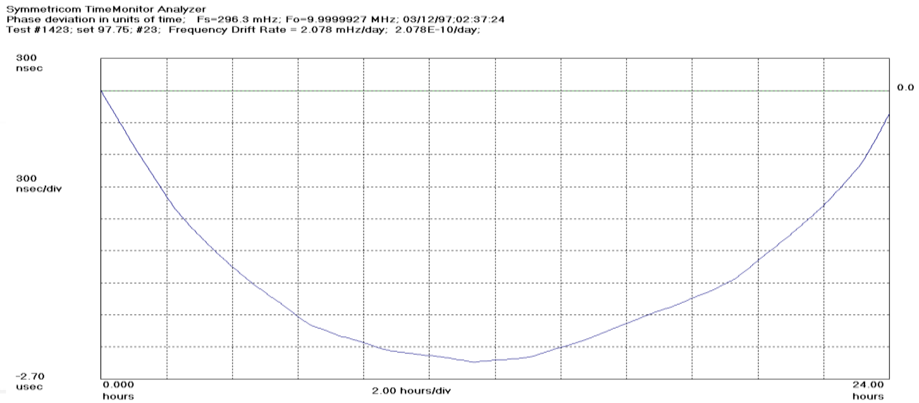
1.2 E-11

Sliding Window Averaging

Frequency Offset and Drift

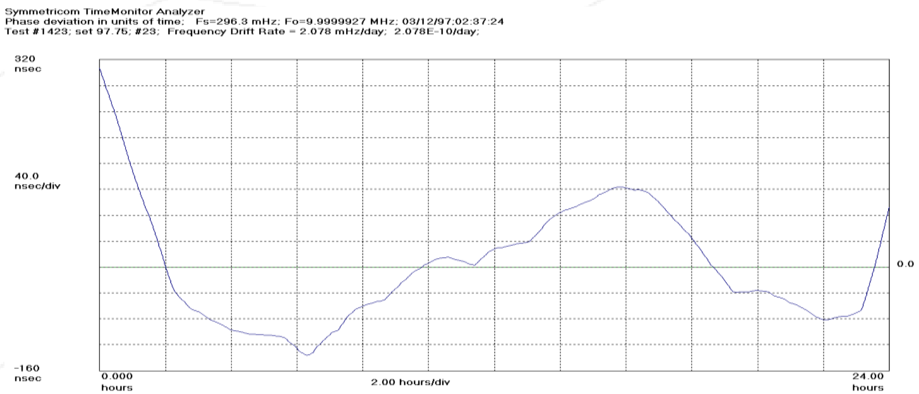
70 ms p-p

Original oscillator phase measurement (0.7ppm frequency offset)



2.5 µs p-p

Frequency offset removed (quadratic shape shows linear frequency drift of 0.2 ppb/day)



500 ns p-p

Frequency drift removed (shows residual phase movement)

Analysis from Phase: MTIE/TDEV

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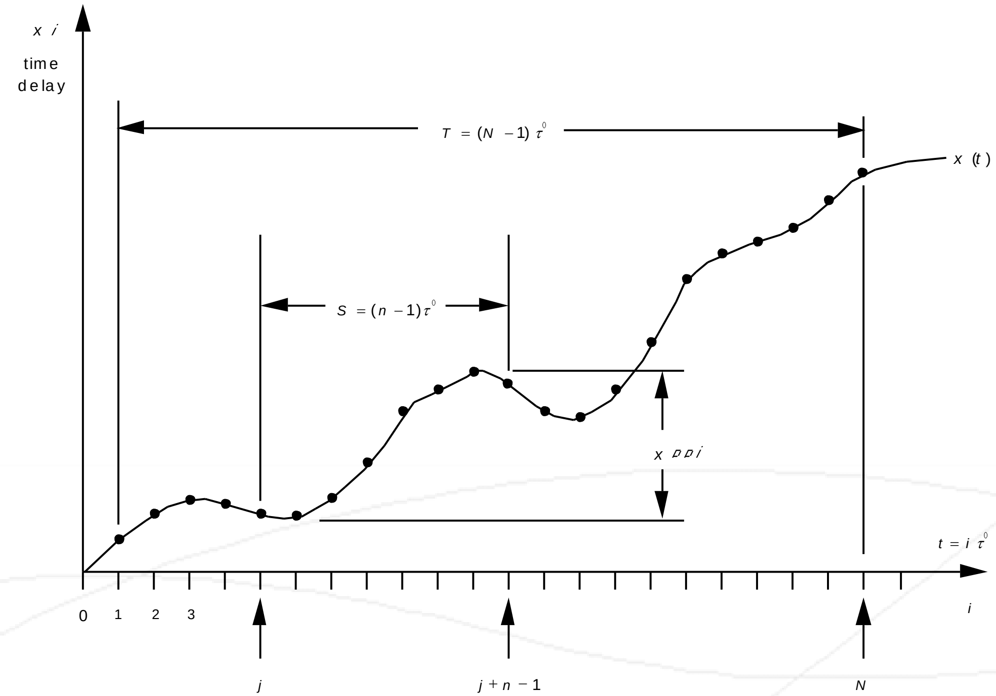
$$MTIE(S) = \max_{j=1}^{N-n+1}\left[\max_{i=j}^{n+j-1}(x_i) - \min_{i=j}^{n+j-1}(x_i)\right]$$



MTIE is a peak detector

MTIE detects frequency offset

$$\sigma_x(\tau) = TDEV(\tau) = \sqrt{\tfrac{1}{6}\left\langle\left[\tfrac{1}{n}\sum_{i=1}^{n} x_{i+2n} - 2\tfrac{1}{n}\sum_{i=1}^{n} x_{i+n} + \tfrac{1}{n}\sum_{i=1}^{n} x_i\right]^2\right\rangle}$$

TDEV is a highly averaged “rms” type of calculation

TDEV shows white, flicker, random walk noise processes

TDEV does not show frequency offset

Interpretation of Measurement Results ("TIE")

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- For traditional synchronization measurements, the measurement analysis used primarily is:
  - Phase (TIE)
  - Frequency (fractional frequency offset)
  - Frequency accuracy
  - MTIE
  - TDEV

  } All are derived from phase

- MTIE and TDEV analysis shows comparison to ANSI, Telcordia/Bellcore, ETSI, & ITU-T requirements

Interpretation of Measurement Results (“PDV”)

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- For packet synchronization measurements, some of the measurement analysis used is:
  - Phase (PDV)
  - Histogram/PDF* & Statistics
  - Running Statistics
  - MATIE/MAFE
  - TDEV/minTDEV/bandTDEV
  - Two-way metrics such as minTDISP

} Derived from PDV phase

- minTDEV is under study at the ITU-T Q13/SG15 and has references in the latest G.8261 draft

* PDF = probability density function

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Packet Delay Sequence

```
R,00162; 1223305830.478035356; 1223305830.474701511
F,00167; 1223305830.488078908; 1223305830.490552012
R,00163; 1223305830.492882604; 1223305830.489969511
F,00168; 1223305830.503473436; 1223305830.505803244
R,00164; 1223305830.508647148; 1223305830.505821031
F,00169; 1223305830.519029300; 1223305830.521302172
R,00165; 1223305830.524413852; 1223305830.521446071
F,00170; 1223305830.534542972; 1223305830.536801164
R,00166; 1223305830.540181132; 1223305830.537115991
F,00171; 1223305830.550229692; 1223305830.552551628
```

Packet Timestamps

Forward

#Start: 2009/10/06 15:10:30
0.0000, 2.473E-3
0.0155, 2.330E-3
0.0312, 2.273E-3
0.0467, 2.258E-3
0.0623, 2.322E-3

Reverse

#Start: 2009/10/06 15:10:30
0.0000, 3.334E-3
0.0153, 2.913E-3
0.0311, 2.826E-3
0.0467, 2.968E-3
0.0624, 3.065E-3

Packet Delay Sequence

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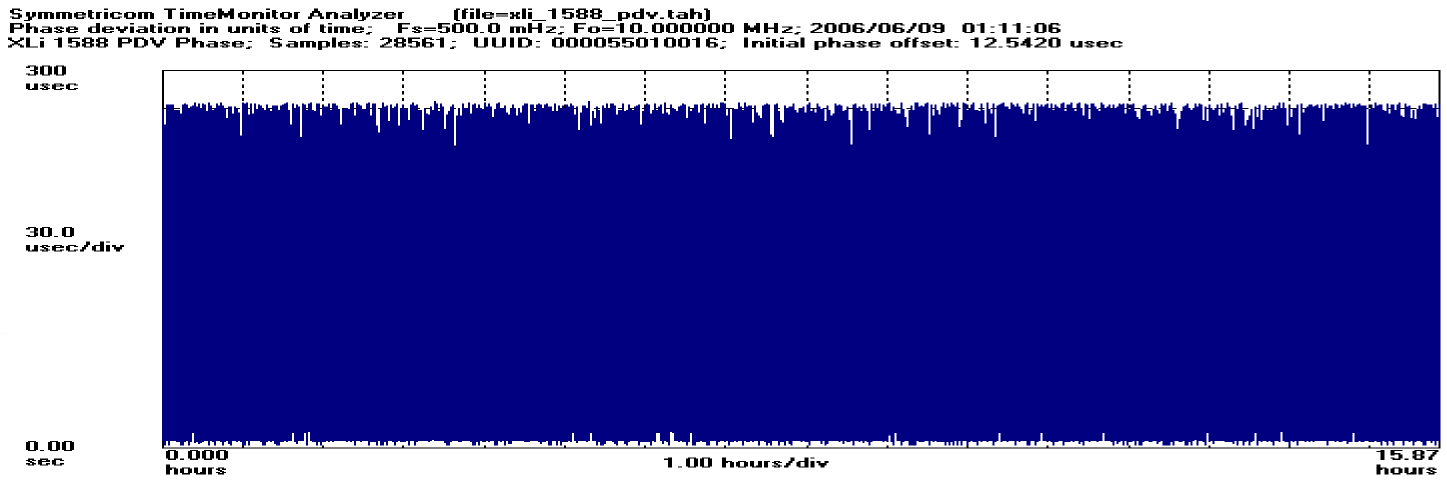
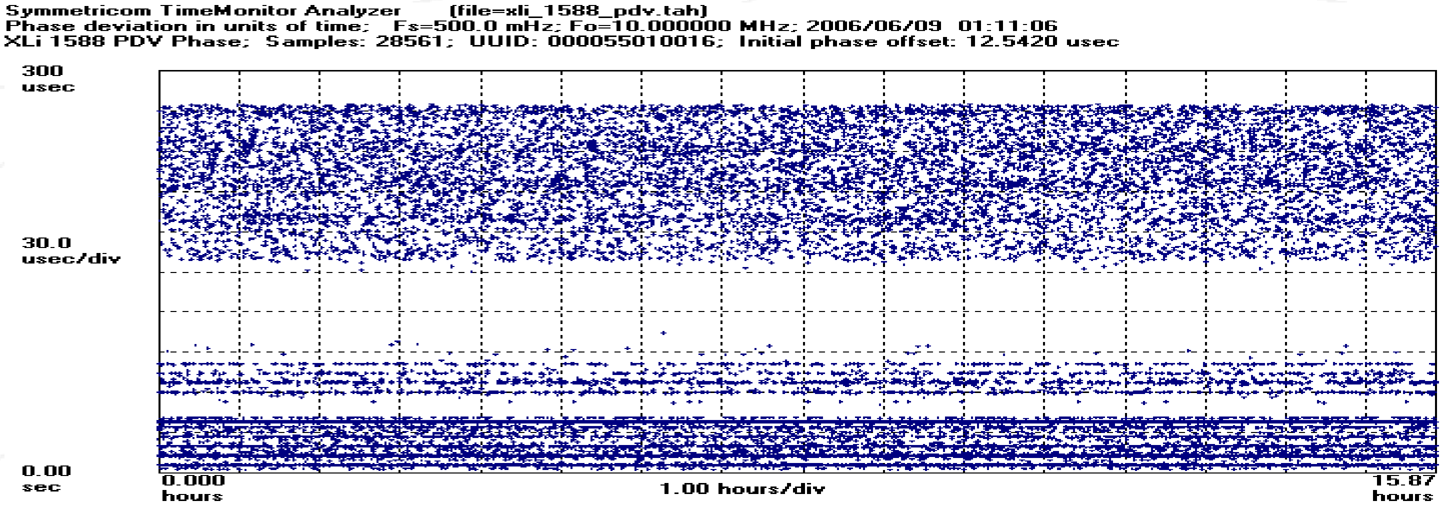
When graphing packet delay phase it is often best not to connect the dots



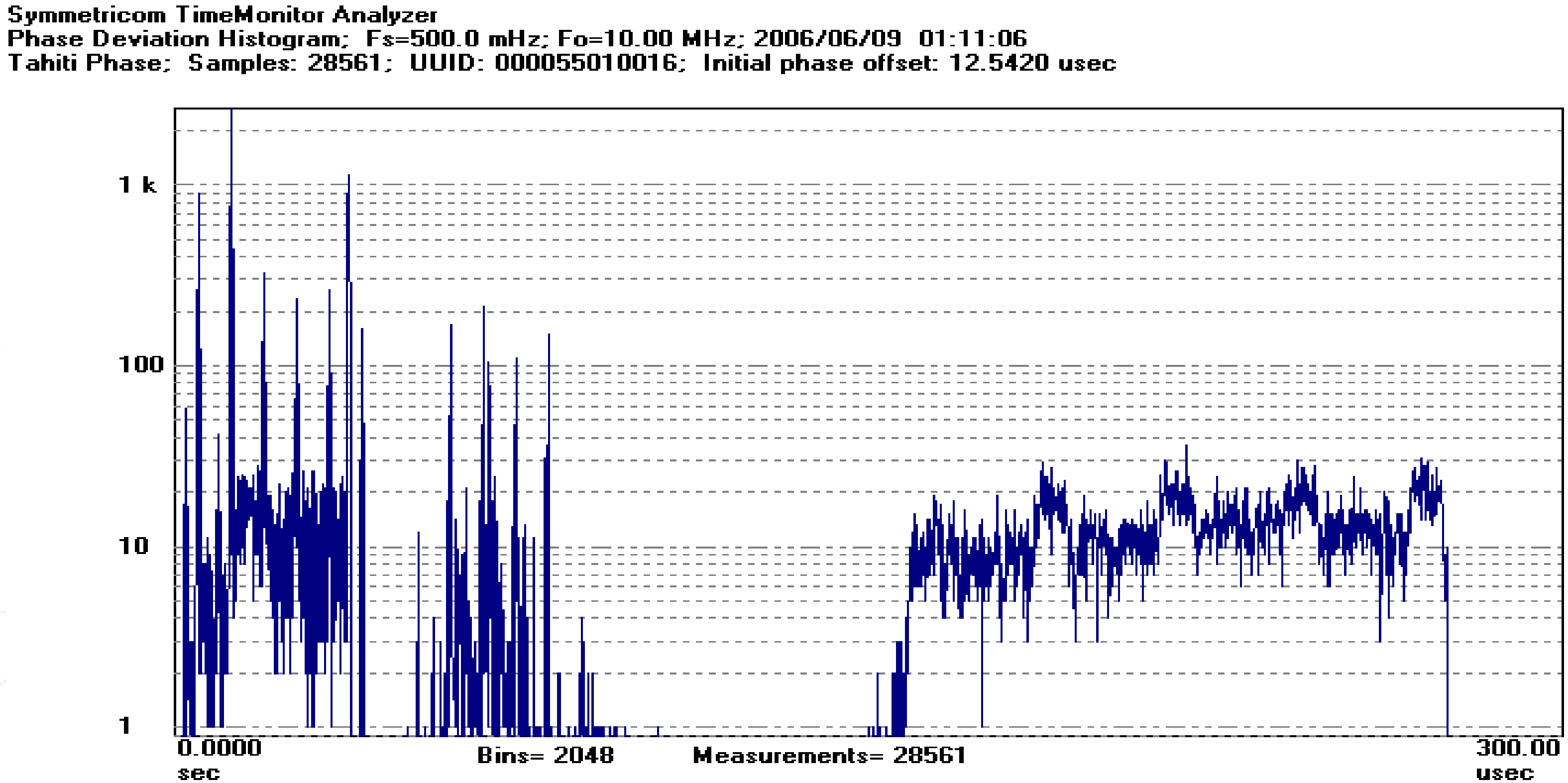
Measurement points connected



Measurement points as discrete dots

Packet Delay Distribution

Packet Delay Distribution



Minimum: 1.904297 usec
Maximum: 275.2441 usec
Peak to Peak: 273.3 usec

Mean: 96.71927 usec
Standard Deviation: 97.34 usec
Population: 28561
Percentage: 100.%

Tracked Packet Delay Statistics

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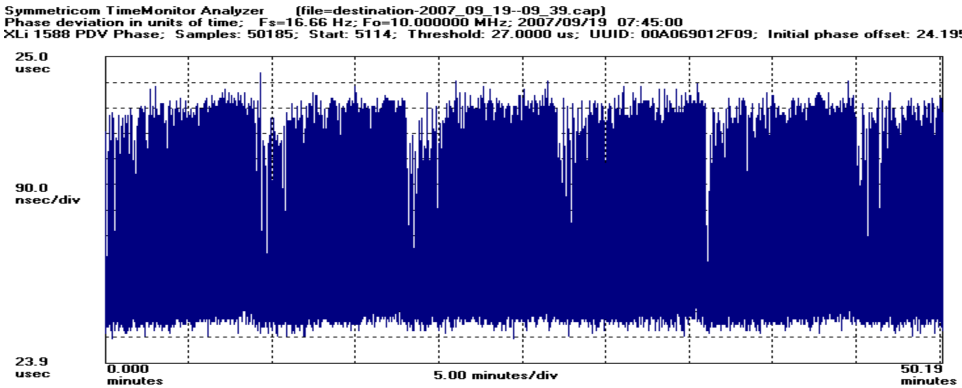
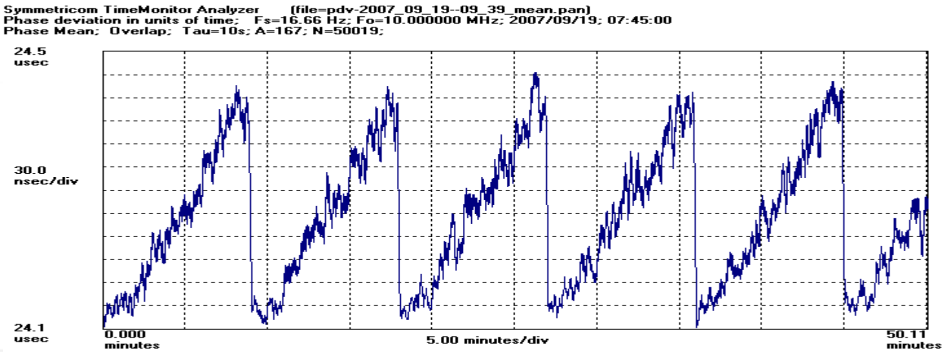
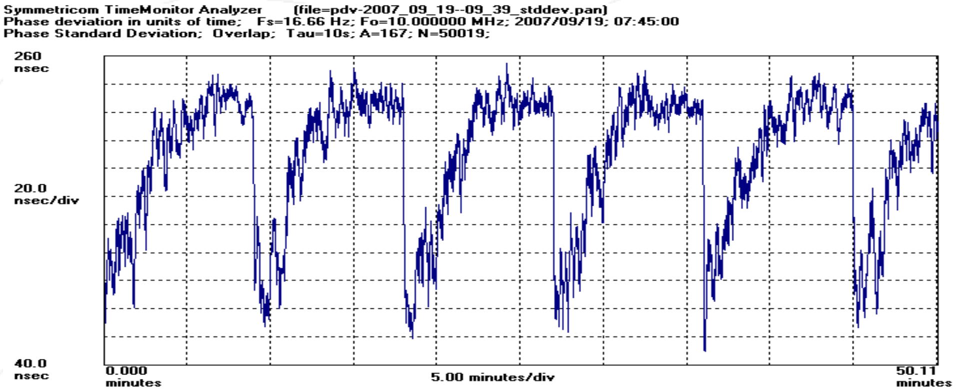


Raw packet delay appears relatively static over time



Mean vs. time shows cyclical ramping more clearly



Standard deviation vs. time shows a quick ramp up to a flat peak

MATIE/MAFE Packet Metrics

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MATIE $$MATIE(n\tau_0) \cong \max_{1 \le k \le N-2n+1} \frac{1}{n} \left| \sum_{i=k}^{n+k-1} (x_{i+n} - x_i) \right|$$, n = 1, 2, ..., integer part (N/2)

MAFE $$MAFE(n\tau_0) = \frac{MATIE(n\tau_0)}{n\tau_0}$$

Reference: *Maximum Average Time Interval Error*, WD 60, Nokia-Siemens Networks, ITU-T Q13/15, Rome, Sep. 2008.

minTDEV & bandTDEV

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TDEV $$\sigma_x(\tau) = TDEV(\tau) = \sqrt{\tfrac{1}{6}\left\langle \left[\tfrac{1}{n}\sum_{i=1}^{n} x_{i+2n} - 2\tfrac{1}{n}\sum_{i=1}^{n} x_{i+n} + \tfrac{1}{n}\sum_{i=1}^{n} x_i \right]^2 \right\rangle}$$

minTDEV $$\sigma_{x\_\min}(\tau) = \min TDEV(\tau) = \sqrt{\tfrac{1}{6}\left\langle \left[x_{\min}(i+2n) - 2x_{\min}(i+n) + x_{\min}(i) \right]^2 \right\rangle} \qquad x_{\min}(i) = \min\left[x_j\right] for (i <= j <= i+n-1)$$

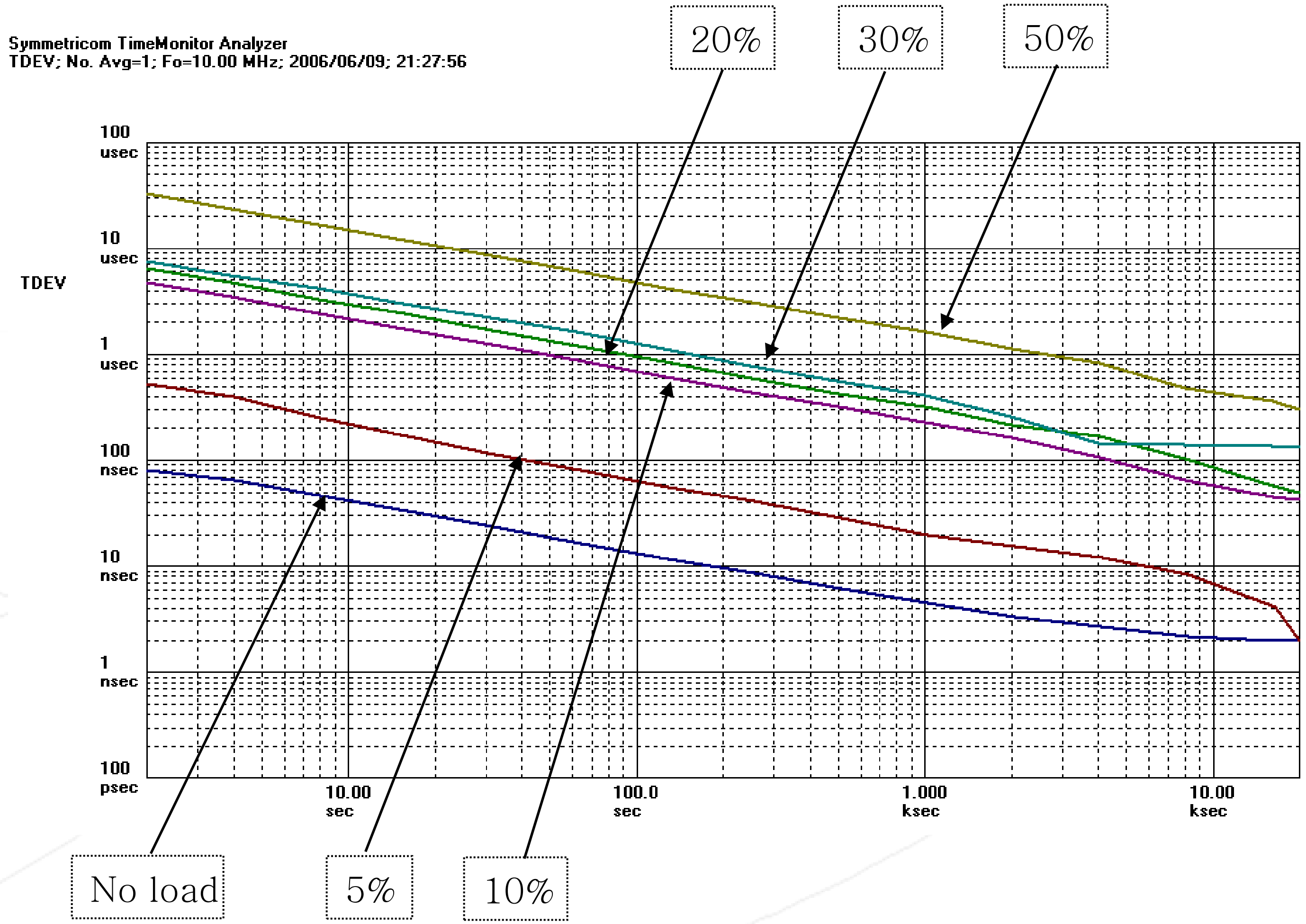
bandTDEV $$\sigma_{x\_band}(\tau) = bandTDEV(\tau) = \sqrt{\tfrac{1}{6}\left\langle \left[x'_{band\_mean}(i+2n) - 2x'_{band\_mean}(i+n) + x'_{band\_mean}(i) \right]^2 \right\rangle} \qquad x'_{band\_mean}(i) = \tfrac{1}{m}\sum_{j=a}^{b} x'_{j+i}$$

To define bandTDEV, it is first necessary to represent the sorted phase data. Let “x´” represent this sorted phase sequence from minimum to maximum over the range i ≤ j ≤ i+n-1. Next it is necessary to represent the indices which are themselves set based on the selection of two percentile levels. Let “a” and “b” represent indices for the two selected percentile levels. The averaging is then applied to the “x´” variable indexed by “a” and “b”. The number of averaged points “m” is related to “a” and “b”: m=b-a+1.

1. TDEV is bandTDEV(0.0 to 1.0)
2. minTDEV is bandTDEV(0.0 to 0.0)
3. percentileTDEV is bandTDEV(0.0 to B) with B between 0.0 and 1.0

References: *Definition of Minimum TDEV (minTDEV),* WD 27, ITU-T Q13/15, Geneva, June 2007
Definition of BandTDEV, Symmetricom, WD 68, ITU-T Q13/15, Rome, Sep. 2008.

TDEV with Traffic



TDEV

minTDEV with Traffic

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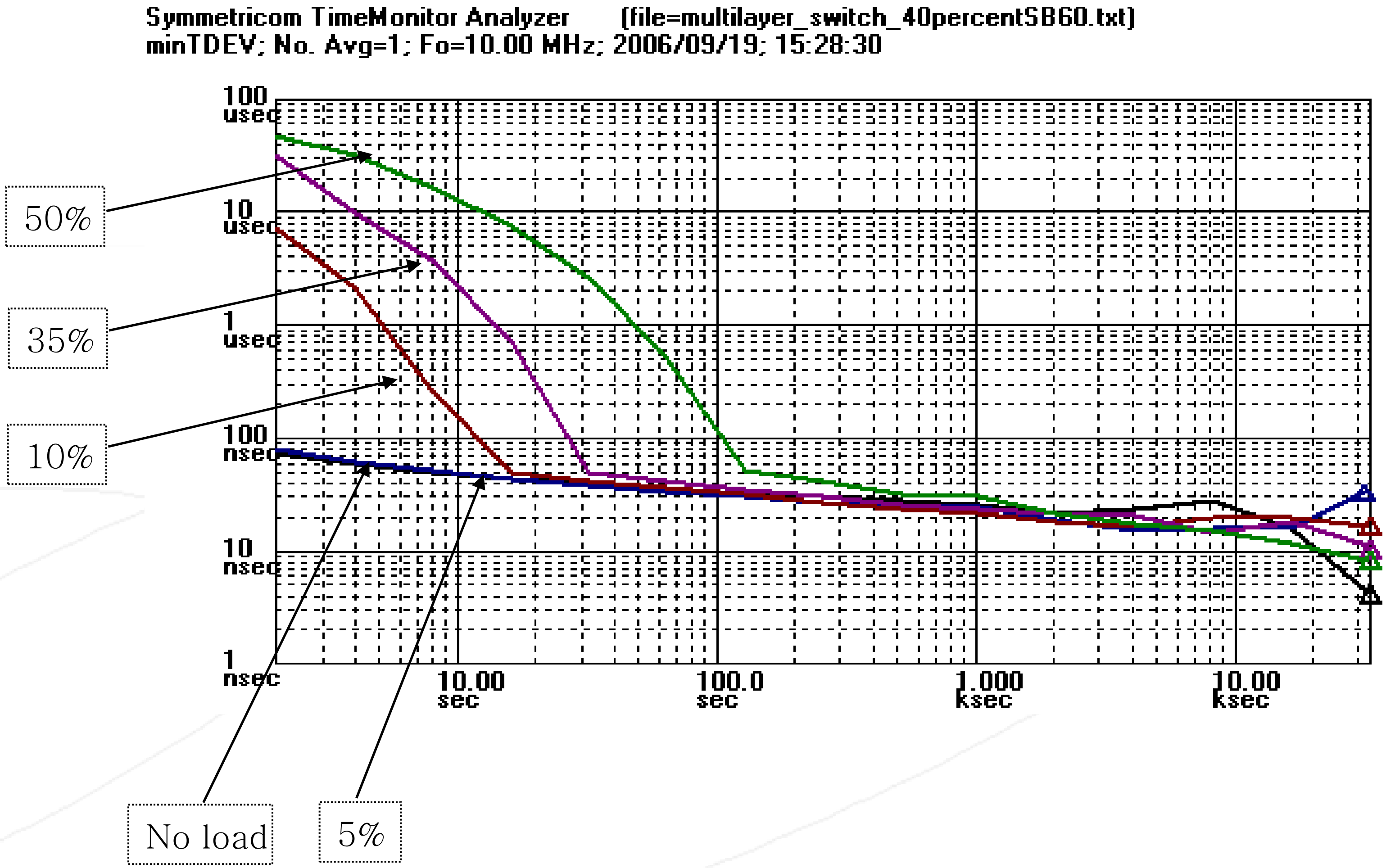
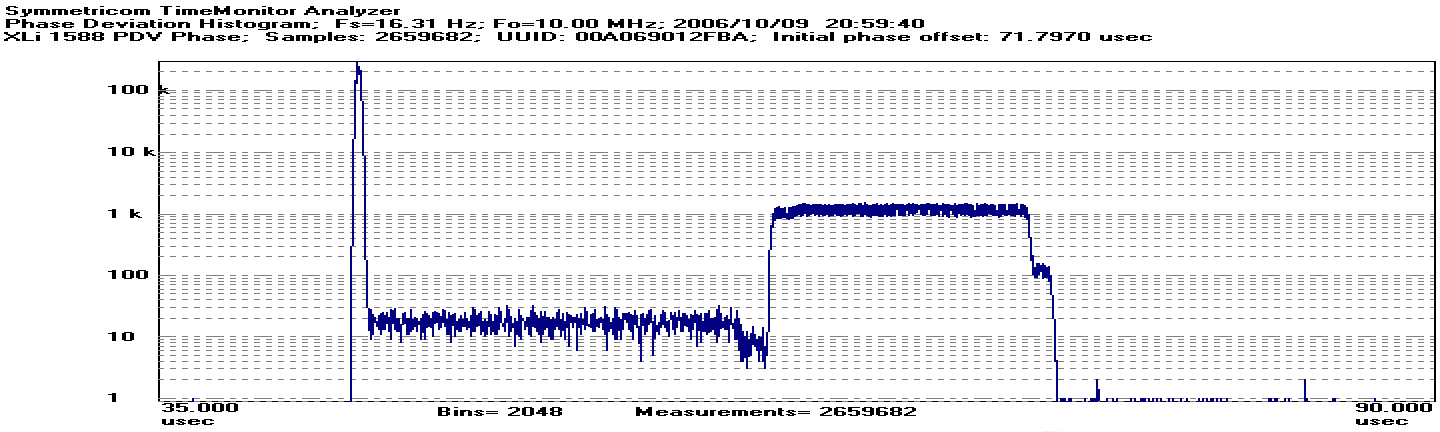
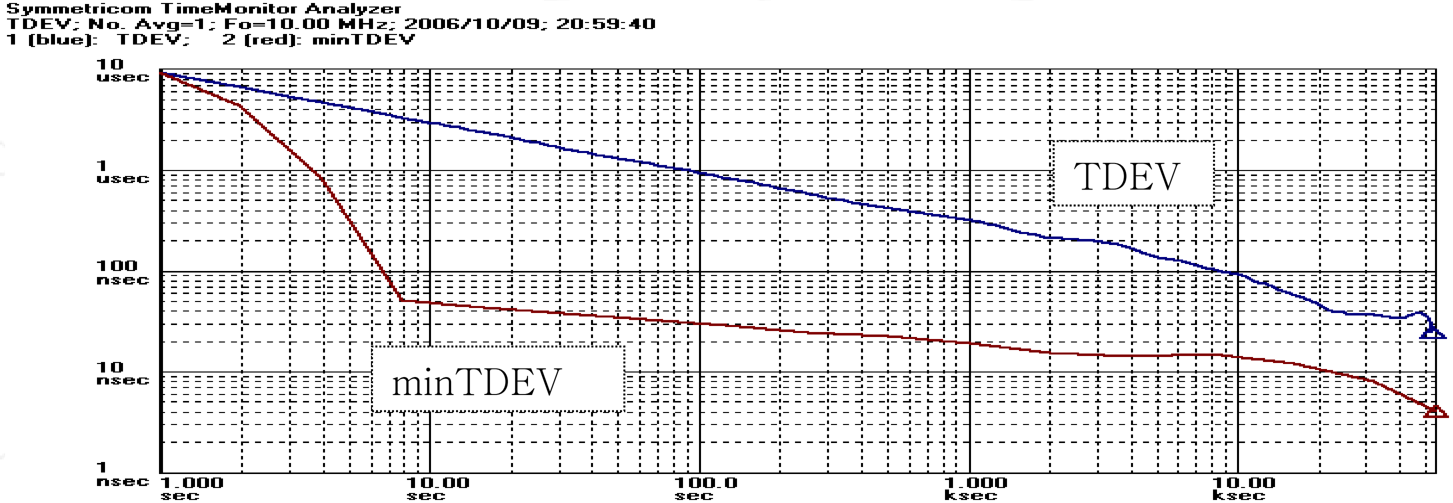
Lower levels of noise with the application of a MINIMUM selection algorithm
TDEV at various traffic levels on a switch (0% to 50%) converge



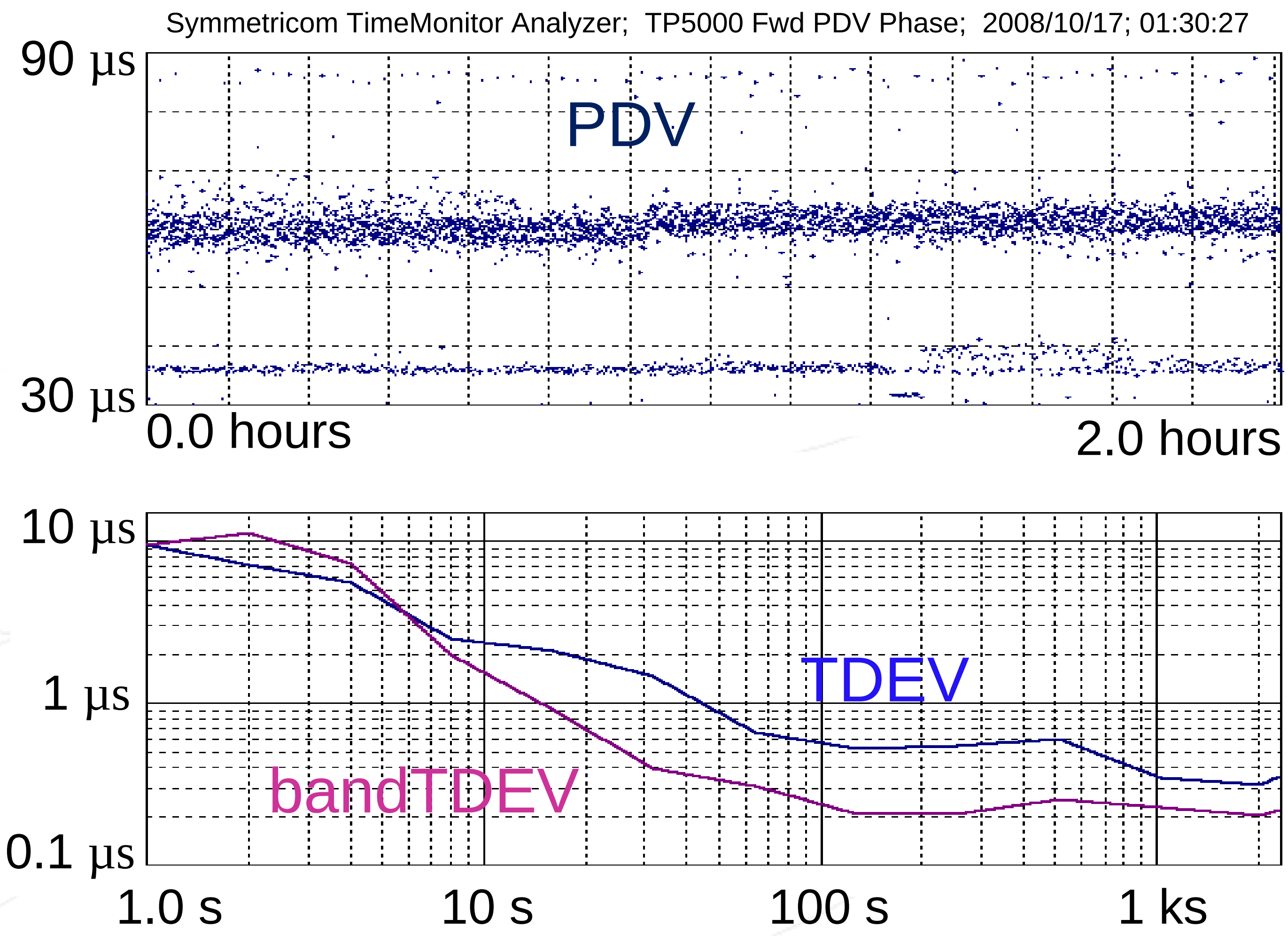
Loaded Multilayer Switch: TDEV and minTDEV

Mean: 48.3 µsec / Peak to Peak: 50.9 µsec / Standard Deviation: 9.43 µsec





bandTDEV Calculation



Metrics: Time Transport

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Two-way Data Set

Forward Packet Delay Sequence

```
#Start: 2009/10/06 15:10:30
0.0000,    2.473E-3
0.0155,    2.330E-3
0.0312,    2.273E-3
0.0467,    2.258E-3
0.0623,    2.322E-3
```

Reverse Packet Delay Sequence

```
#Start: 2009/10/06 15:10:30
0.0000,    3.334E-3
0.0153,    2.913E-3
0.0311,    2.826E-3
0.0467,    2.968E-3
0.0624,    3.065E-3
```

Two-way Data Set

```
#Start: 2009/10/06 15:10:30
0.0000,    2.473E-3,    3.334E-3
0.0155,    2.330E-3,    2.913E-3
0.0312,    2.273E-3,    2.826E-3
0.0467,    2.258E-3,    2.968E-3
0.0623,    2.322E-3,    3.065E-3
```

Metrics: Time Transport

Minimum Search Sequences

Constructing *f ´* and *r ´* from *f* and *r* with a 3-sample time window

Time(s)	f(μs)	r(μs)	f'(μs)	r'(μs)
0.0	1.47	1.11		
0.1	1.54	1.09	1.23	1.09
0.2	1.23	1.12		
0.3	1.40	1.13		
0.4	1.47	1.22	1.40	1.05
0.5	1.51	1.05		

Metrics: Time Transport

Packet Time Transport Metrics

Normalized roundtrip: $$r(n) = \left(\frac{1}{2}\right) \cdot [F(n) + R(n)]$$

Normalized offset: $$\eta_2(n) = \left(\frac{1}{2}\right) \cdot [F(n) - R(n)]$$

minRoundtrip: $$r'(n) = \left(\frac{1}{2}\right) \cdot [F'(n) + R'(n)]$$

minOffset: $$\eta_2{}'(n) = \left(\frac{1}{2}\right) \cdot [F'(n) - R'(n)]$$

minTDISP (minimum time dispersion): minOffset {y} plotted against minRoundtrip {x} as a scatter plot

minOffset statistics: minOffset statistic such as mean, standard deviation, or 95 percentile plotted as a function of time window tau

Metrics: Time Transport

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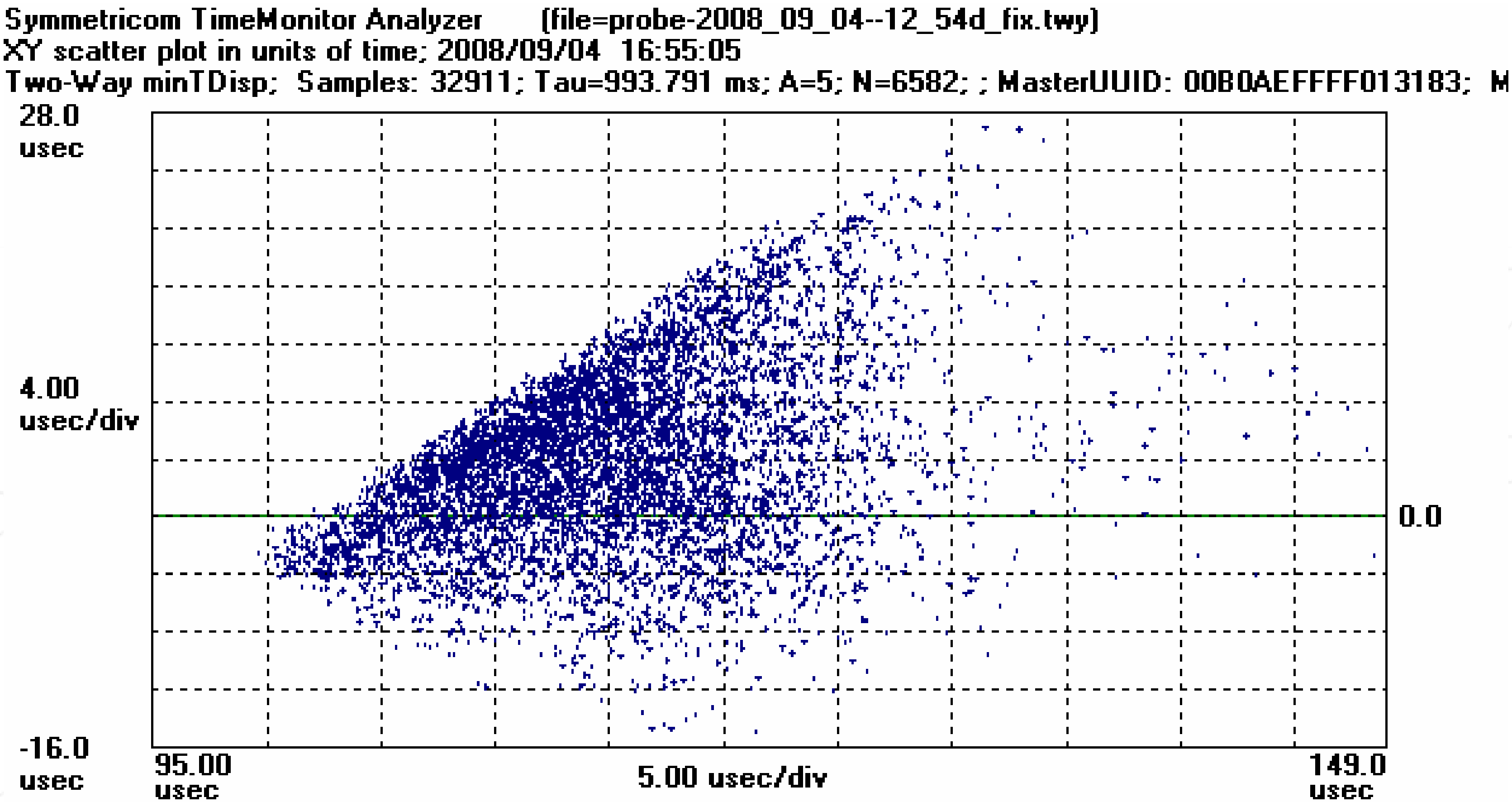
minTDISP

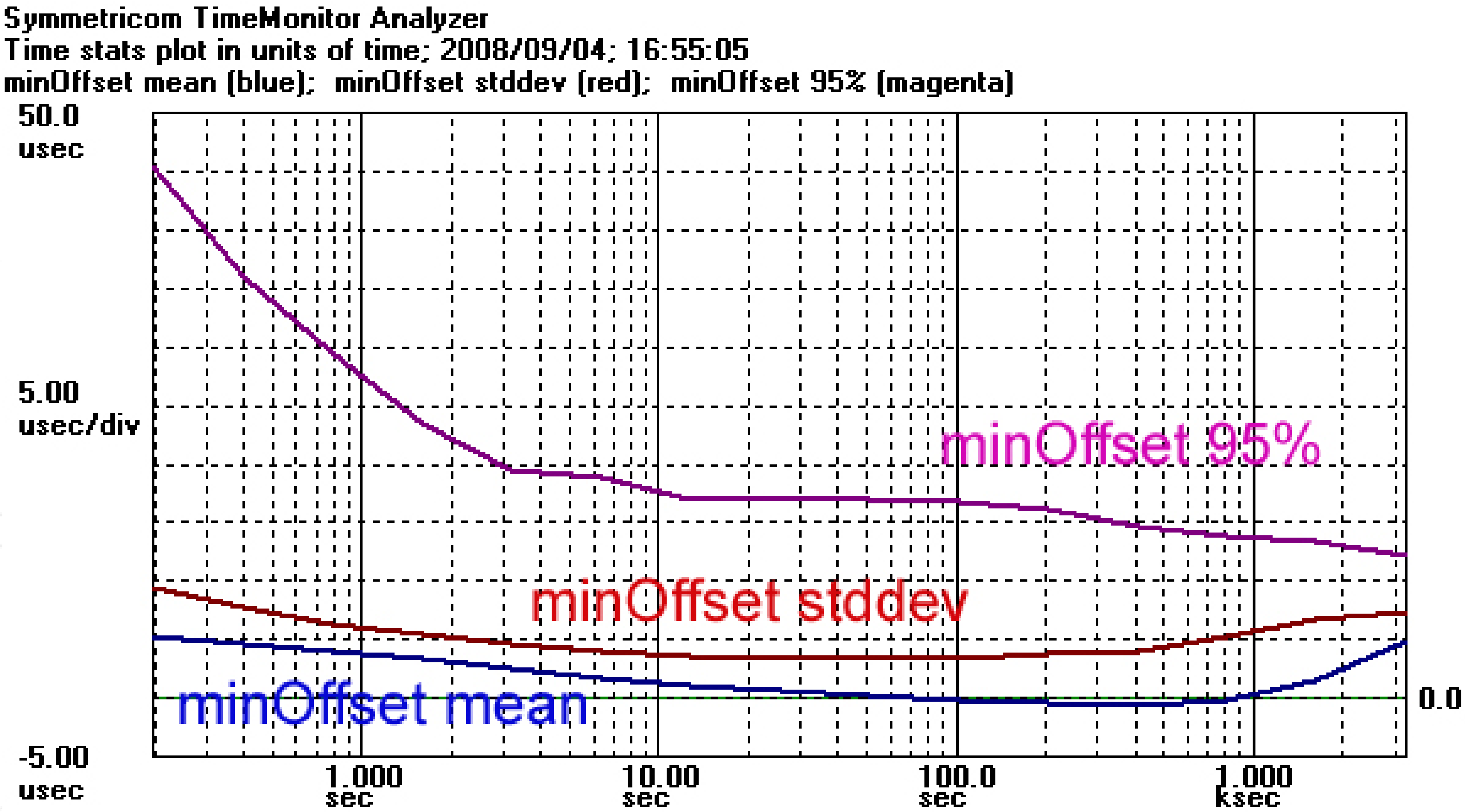
(minOffset vs. minRoundtrip)



Metrics: Time Transport

minOffset Statistics

(Two-way minimum offset statistics vs. τ)



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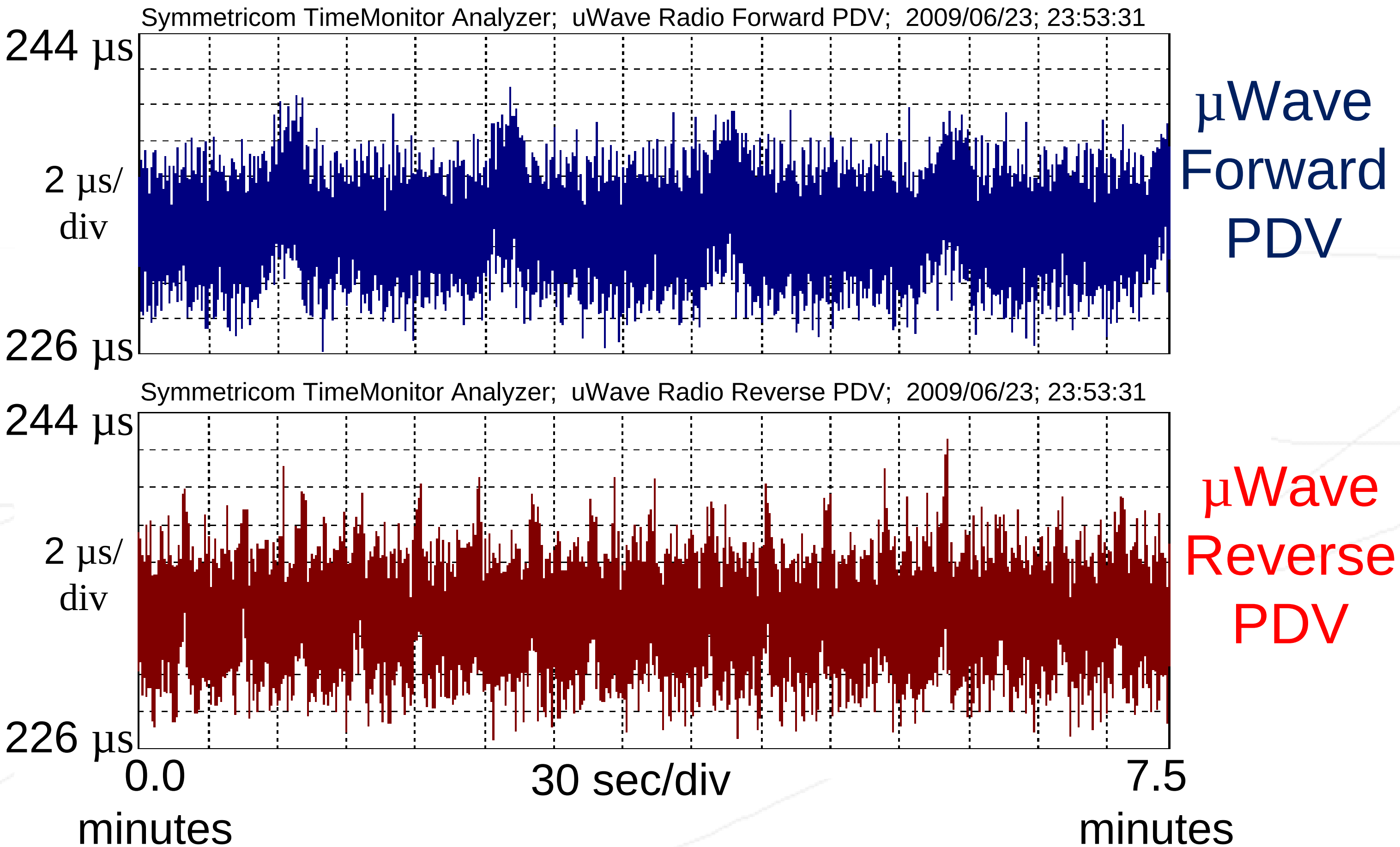
Asymmetry in Microwave Transport

(Ethernet microwave radio packet delay pattern asymmetry)



Case Studies

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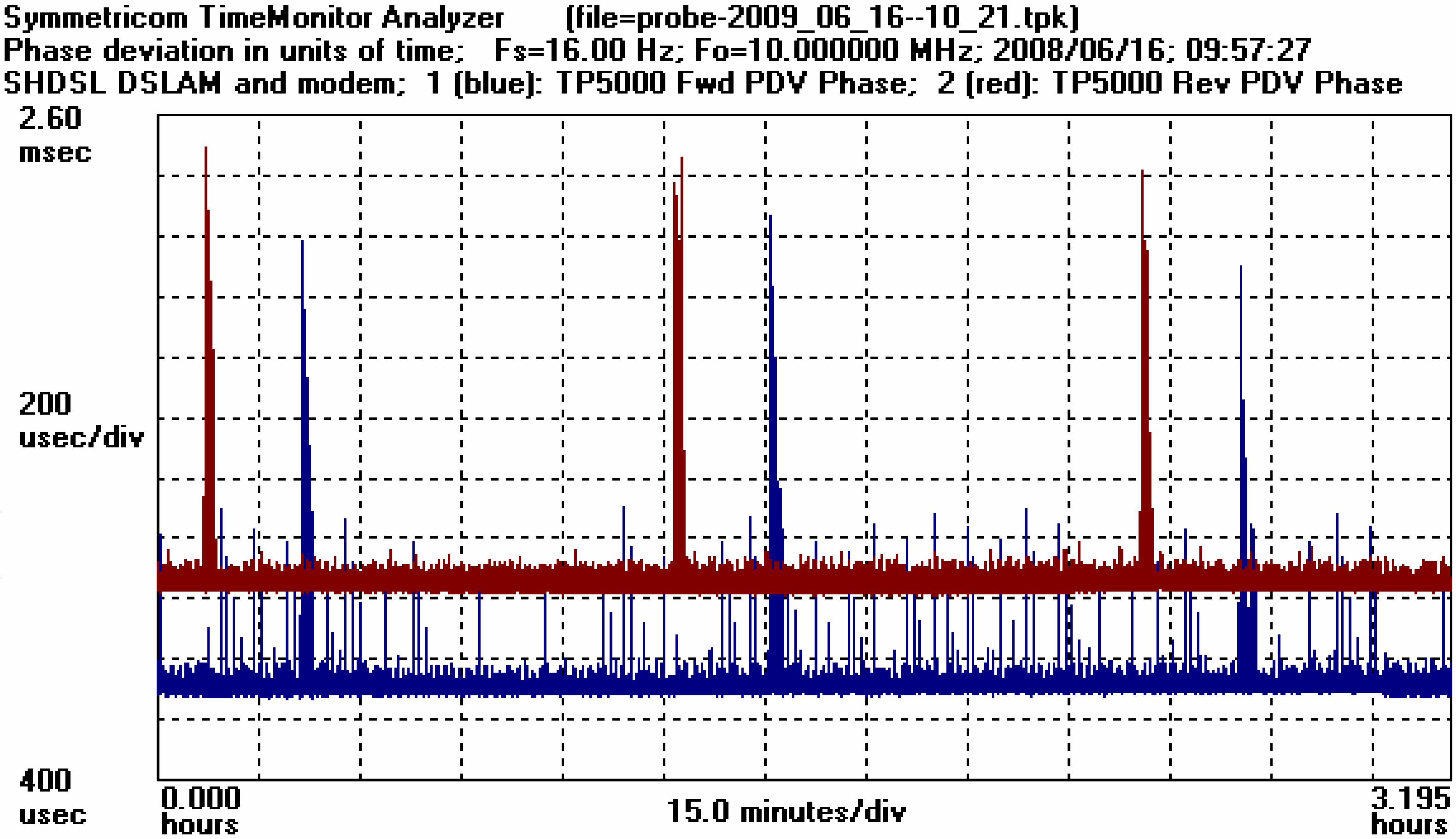
Asymmetry in SHDSL

(SHDSL forward/reverse packet delay asymmetry)



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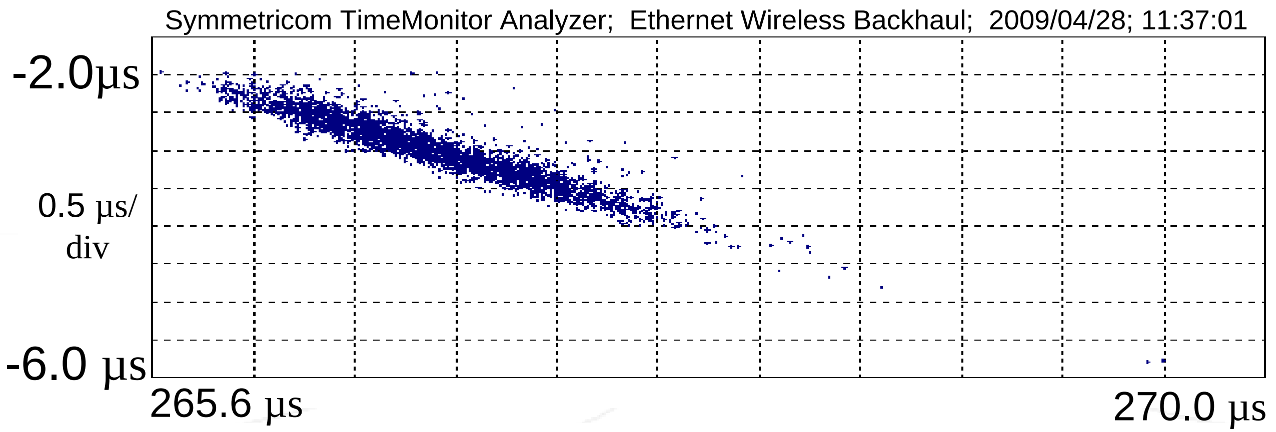
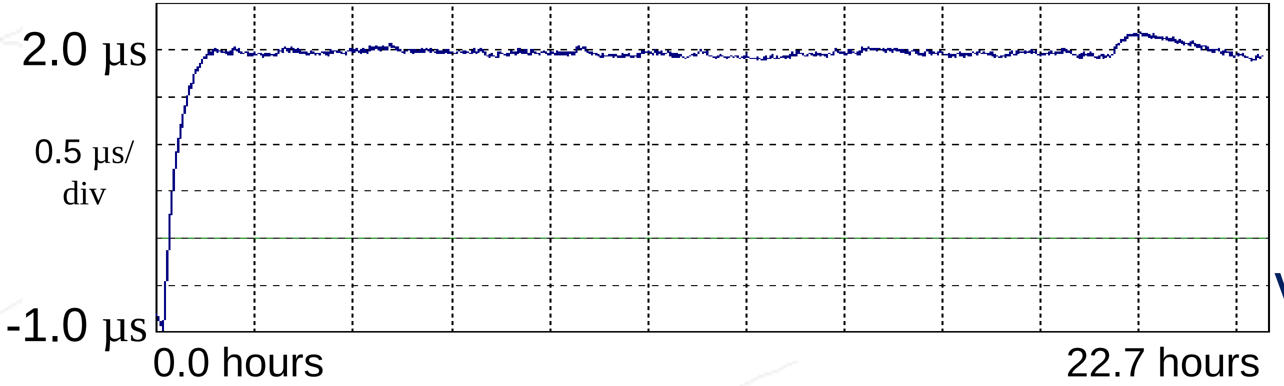
Asymmetry in Wireless Backhaul

(Ethernet wireless backhaul asymmetry and IEEE 1588 slave 1PPS under these asymmetrical network conditions)



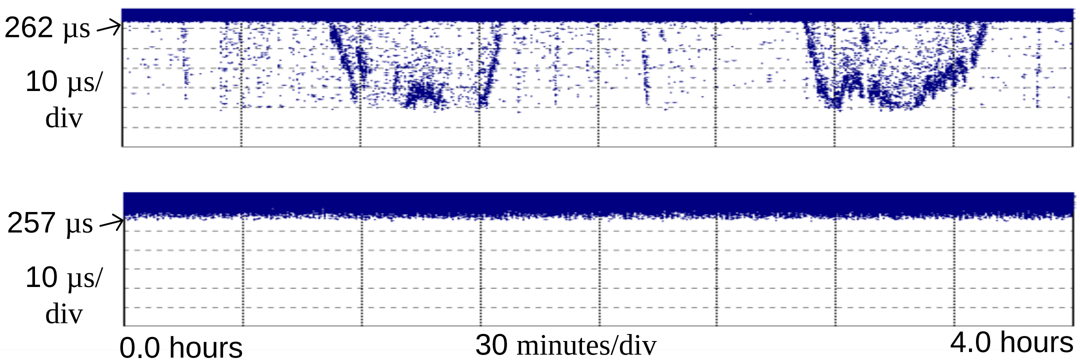
Min TDISP



1588 Slave 1 PPS vs.GPS

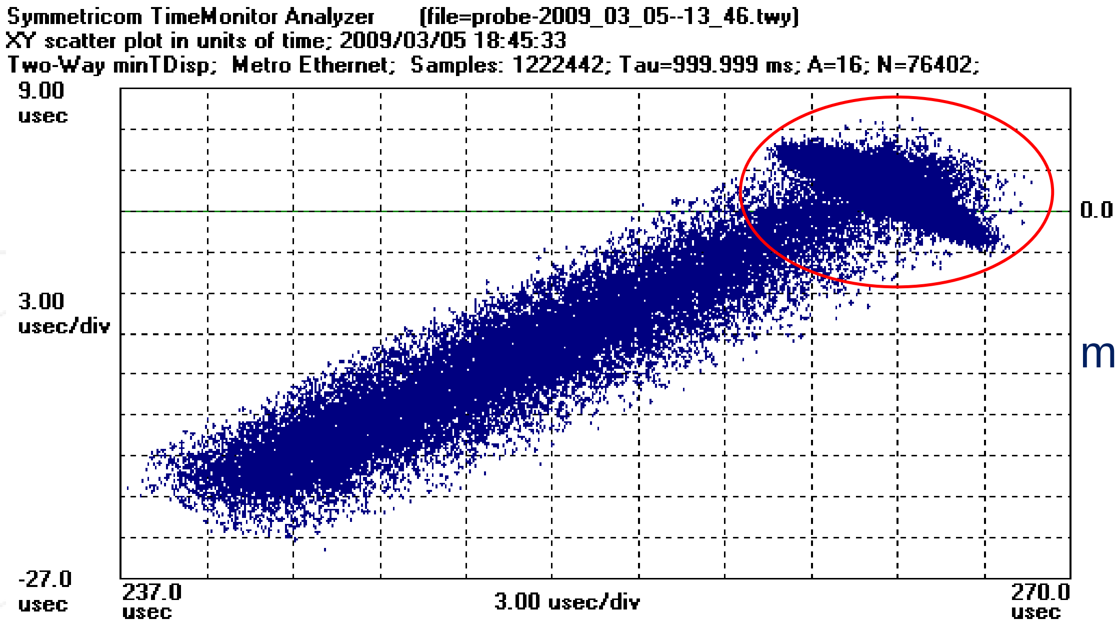
Case Studies

Metro Ethernet Network



Forward PDV floor

Reverse PDV floor



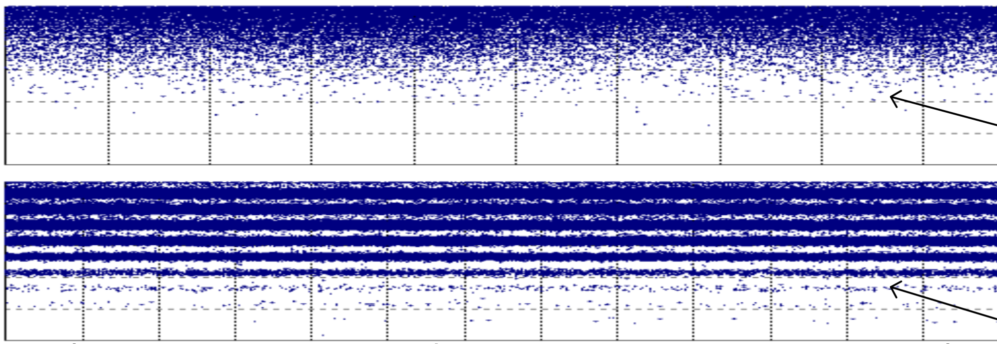
minTDISP

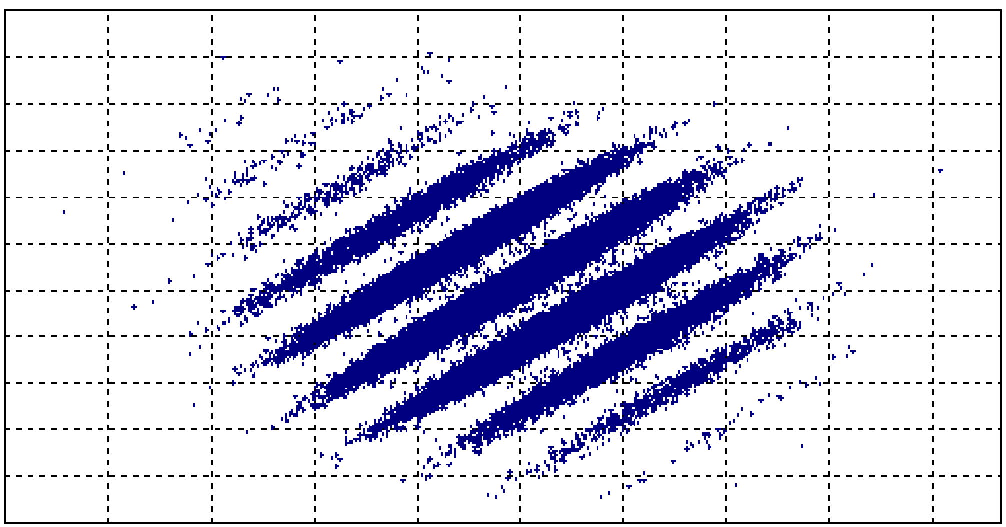
Metro Ethernet forward and reverse packet delay sequences with zooms into the respective floors and minTDISP

Case Studies

Symmetricom

National Ethernet Network





National Ethernet forward and reverse packet delay sequences with zooms into the respective floors and minTDISP

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