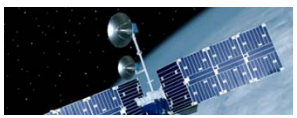

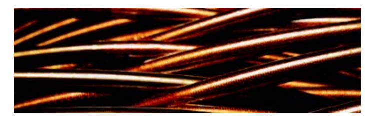

Synchronization Measurement and Analysis: TDM and Packet Networks

ITSF 2008

Lee Cosart

lcosart@symmetricom.com

Symmetricom®

Measurement & Analysis: Outline

Symmetricom

1. Introduction ←

2. TDM Measurement and Analysis

3. Packet Measurement and Analysis

Extra slides for reference:

Appendix 1: TDM Measurement Examples

Appendix 2: Packet Measurement Examples

TDM and Packet Measurements

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- Some kind of phase detector, phase measurement device, or timestamper is needed for both TDM and Packet timing measurements
  - TDM phase measurement: “TIE” (phase deviation)
  - Packet phase measurement: “PDV” (packet delay sequence)

“TIE” vs. “PDV”

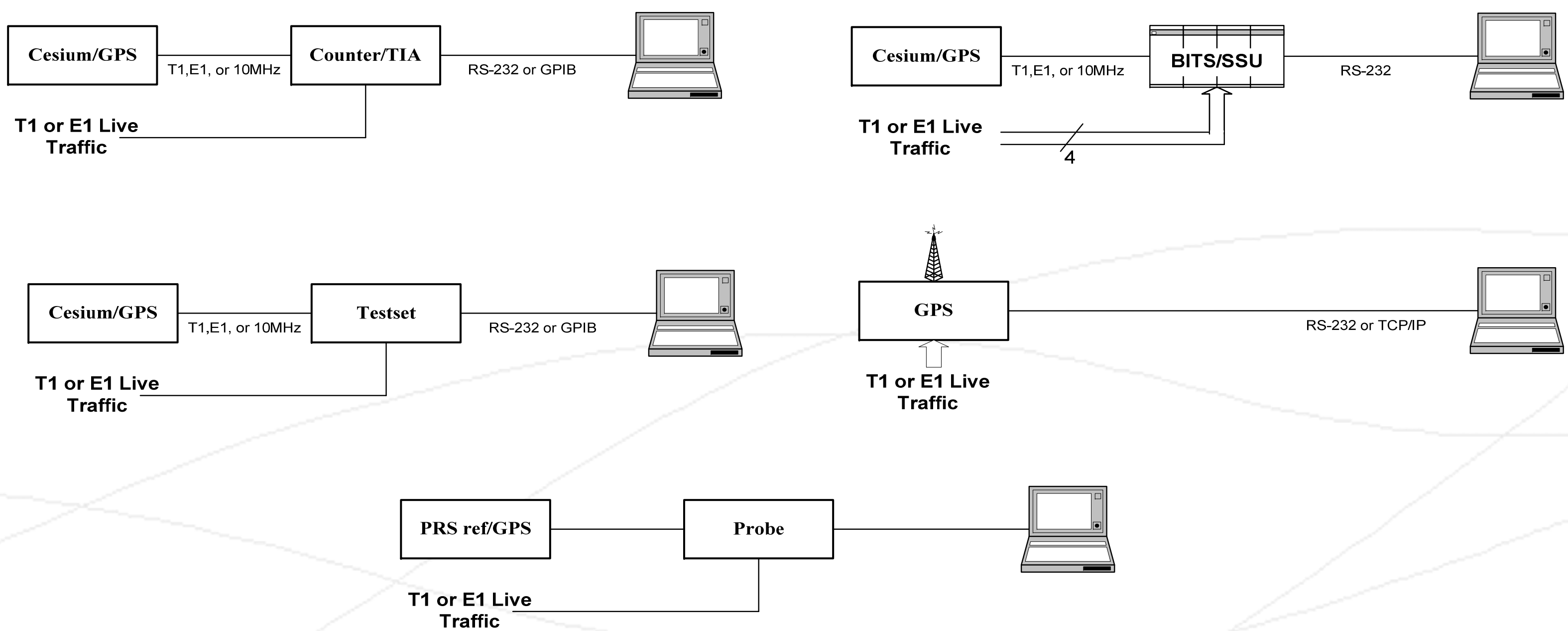
- “TIE” vs “PDV”
  - Traditional TDM synchronization measurements: signal edges are timestamped producing a sequence of samples
  - Packet timing measurements: packet departure/arrival times are sampled and packet delay sequences are formed

- 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 Measurement Example Configurations

Five Example Measurement Equipment Configurations

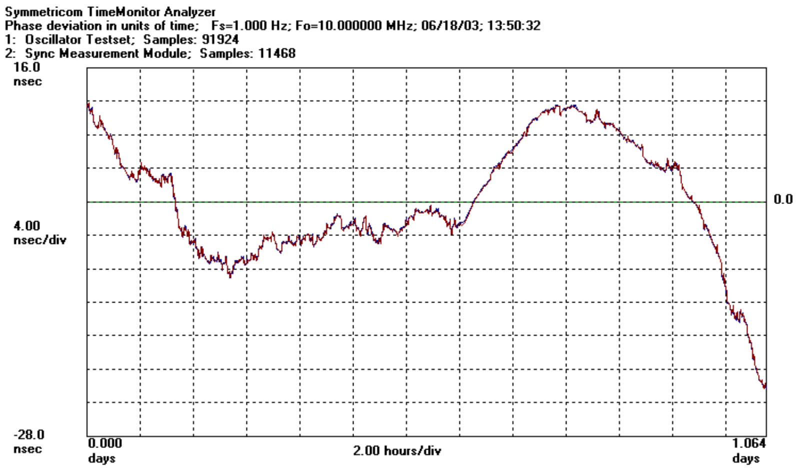


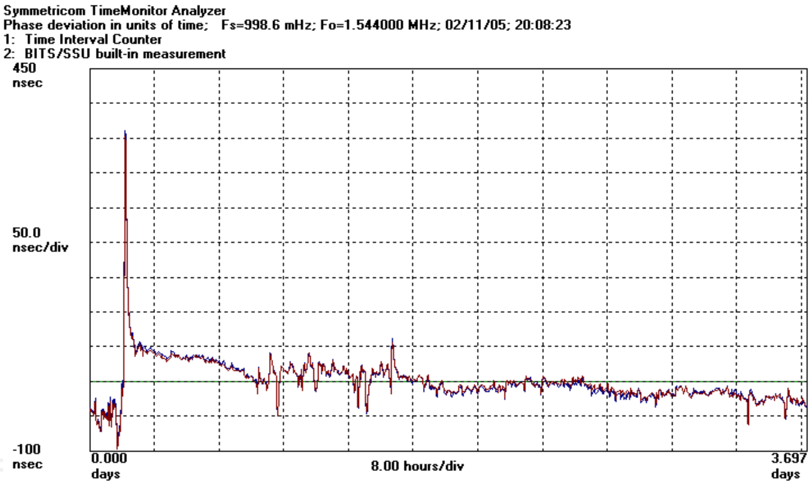
TIE Measurements: Equipment Comparisons

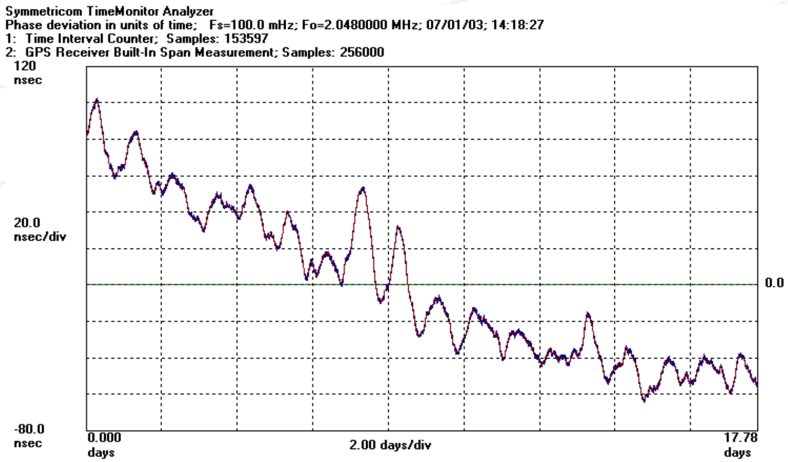
Symmetricom®

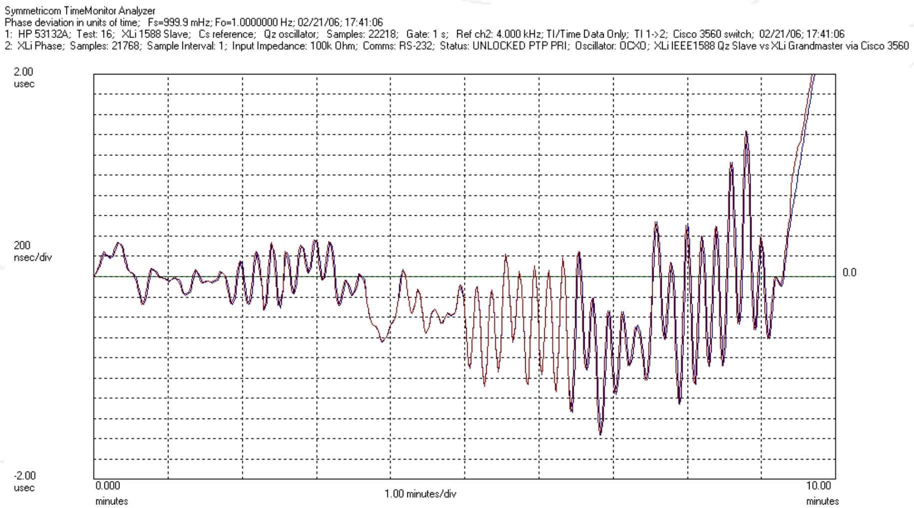
Phase measurements made simultaneously on two different kinds of equipment

Each plot has two traces





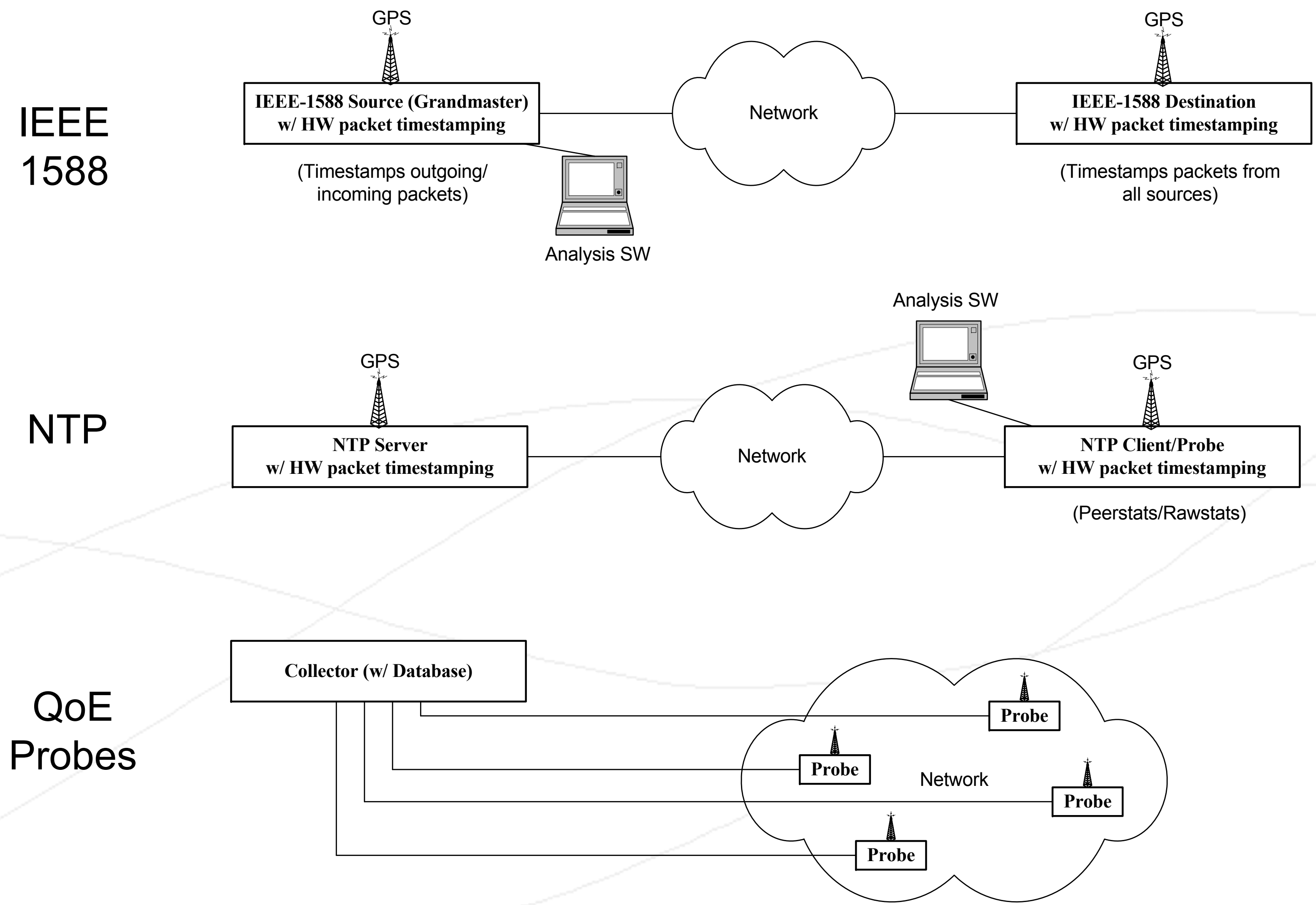




Packet Measurement Example Configurations

Example Measurement Equipment Configurations

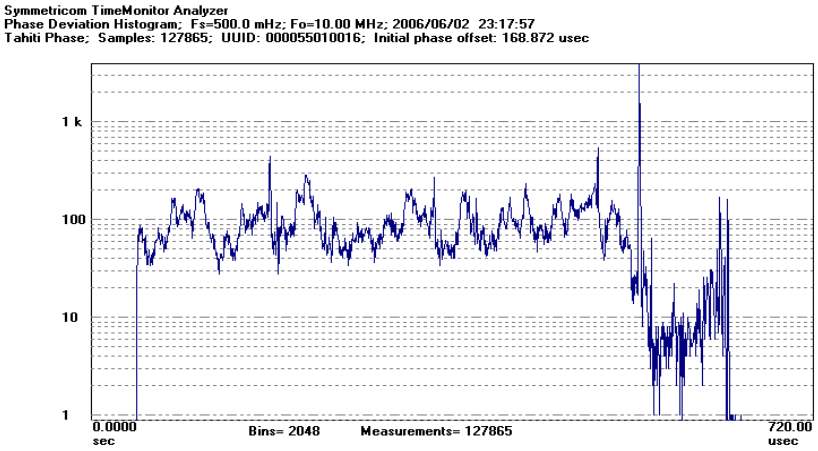
Need (1) PRC TOD reference (2) Precision Packet TimeStamping (3) Analysis SW

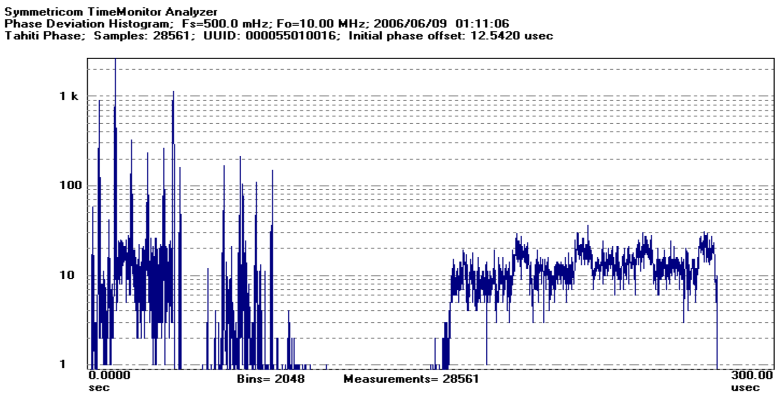


PDV Measurements: Equipment Comparisons

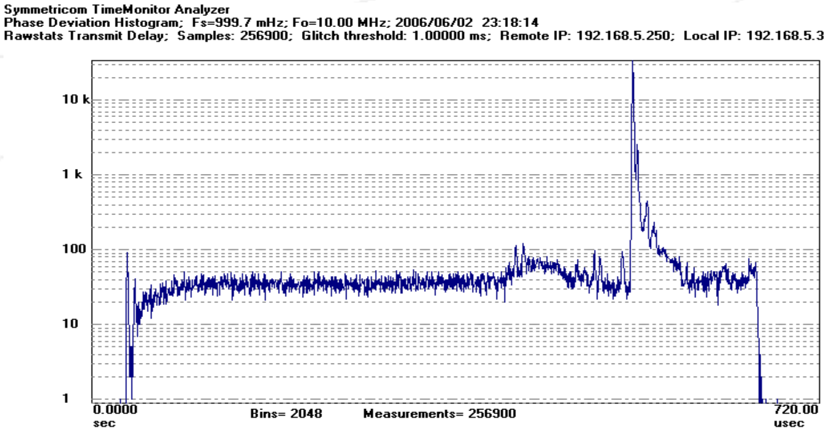
Symmetricom

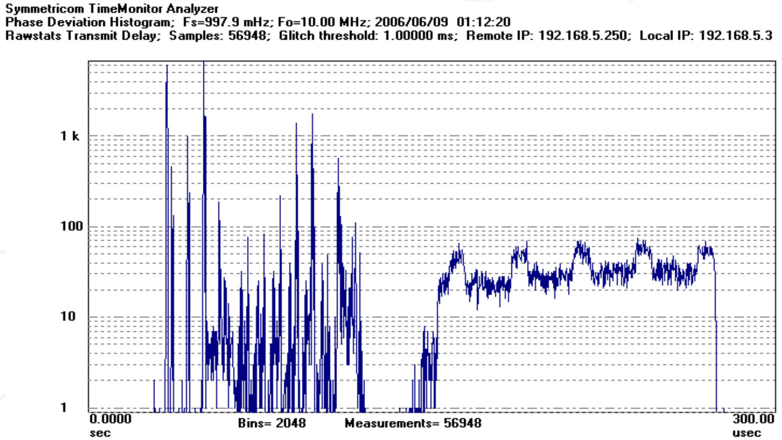
Packet measurements made simultaneously on two different kinds of equipment





IEEE 1588





NTP

“TIE” vs. “PDV”

Symmetricom

- “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

“PDV” Measurement Setup Options

- “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

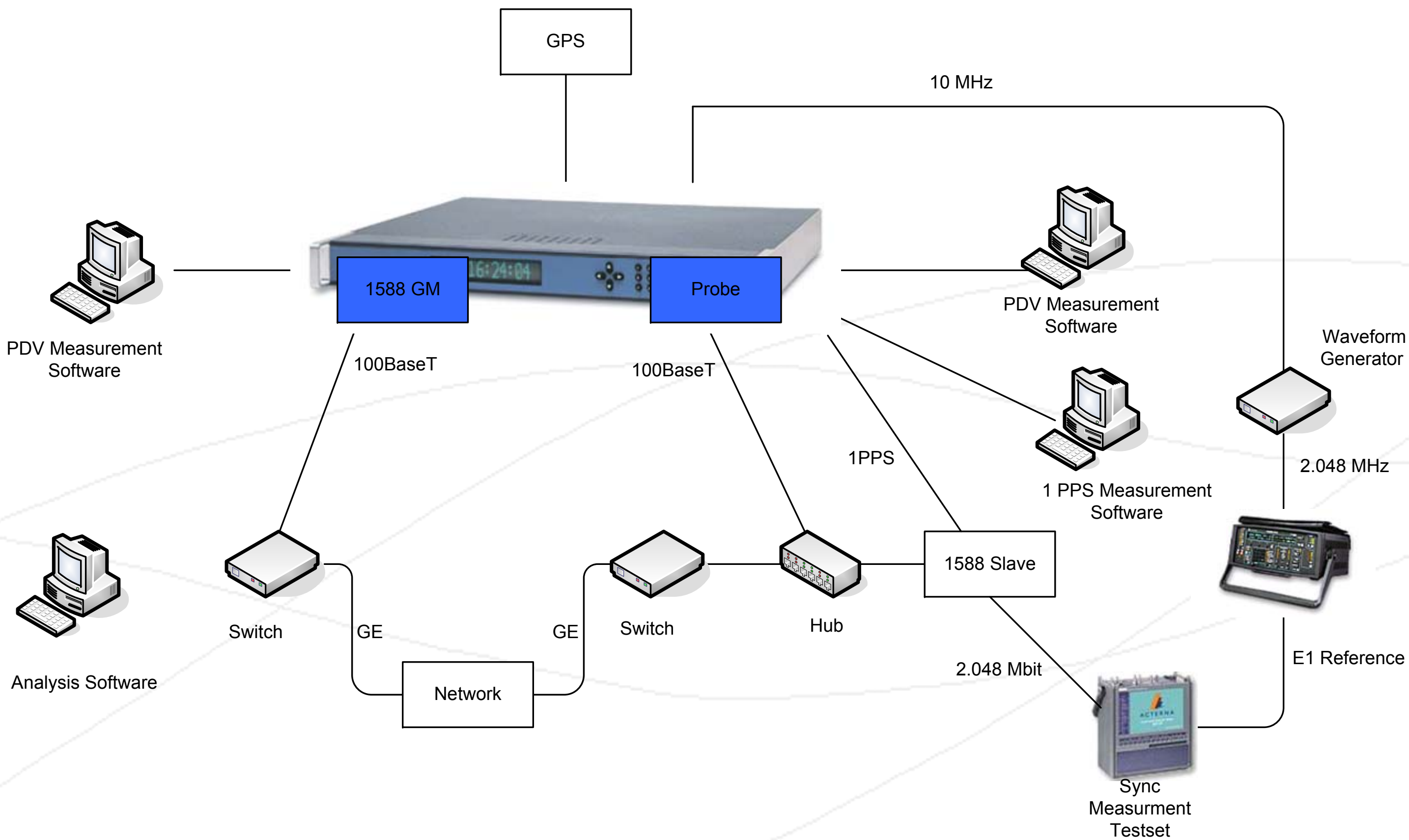
Symmetricom

- 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”

Symmetricom

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

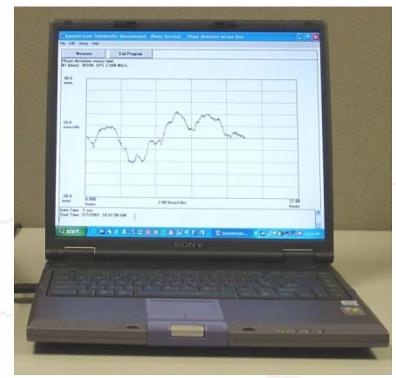


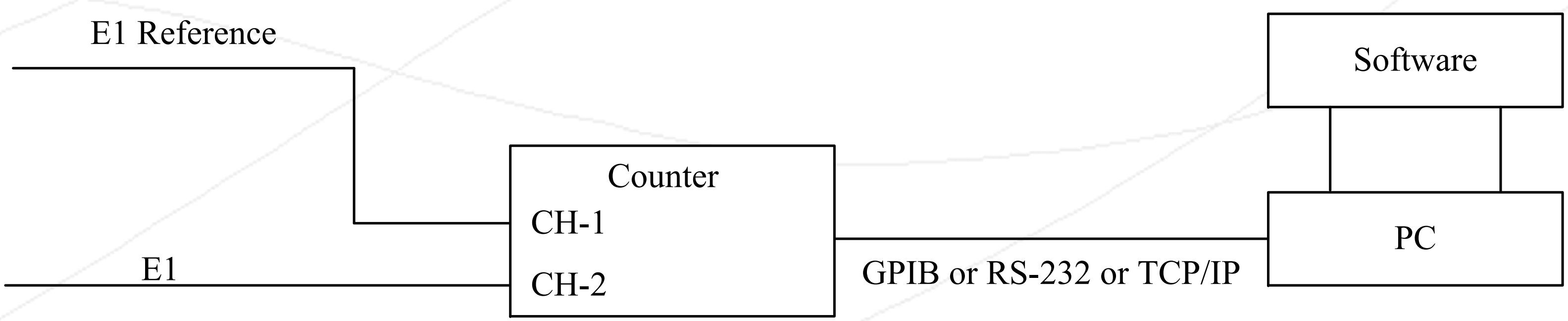
Measurement & Analysis: Outline

1. Introduction
2. TDM Measurement and Analysis
3. Packet Measurement and Analysis

Making TIE Measurements with a Counter

- Jitter & Wander Measurement Setup
  - Computer
  - Software
  - Off-the-shelf counter (or counters)





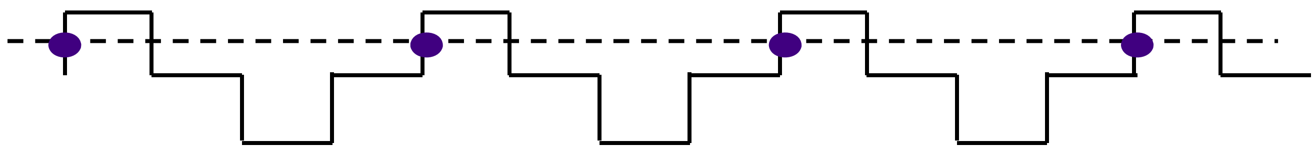
Measuring Phase with a Counter: TI 1 to 2 → Phase

- Using a reference signal at the same frequency (or sub-multiple) of the signal of interest, a counter can be used to measure phase (TIE) directly.
- Software can take care of data clock recovery (no data clock recovery hardware required), phase rollover, and any other processing required to convert the counter measurements to phase.
- Thus an inexpensive counter can be used to measure phase on signals such as traffic bearing E1s directly.
- Any signal rate
  - T1/DS1 (1.544 M)
  - E1 (2.048 M)
  - DS2 (6.312 M)
  - DS3 (44.76 M)
  - 64 kbit
  - 1 PPS
  - 10 MHz
  - STS-1/OC-1 electrical (51.84 M)
  - 140 Mb/s Tributary (139.264 M)
  - STS-3/STM-1/OC-3 electrical(155.52 M)

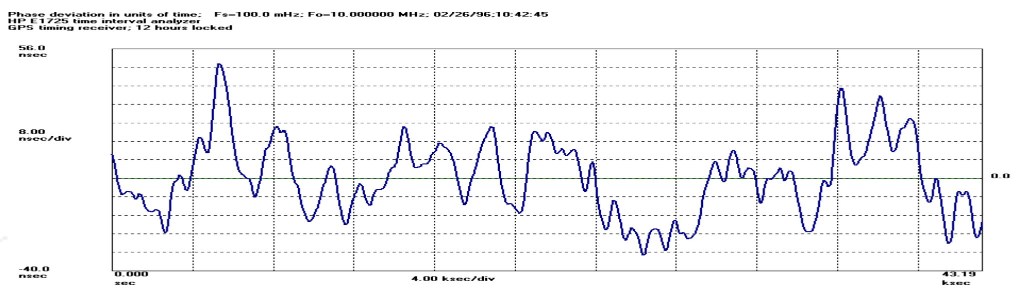
Synchronization Measurements w/ Phase Digitizing: 3 step process

Symmetricom

1. Timestamps

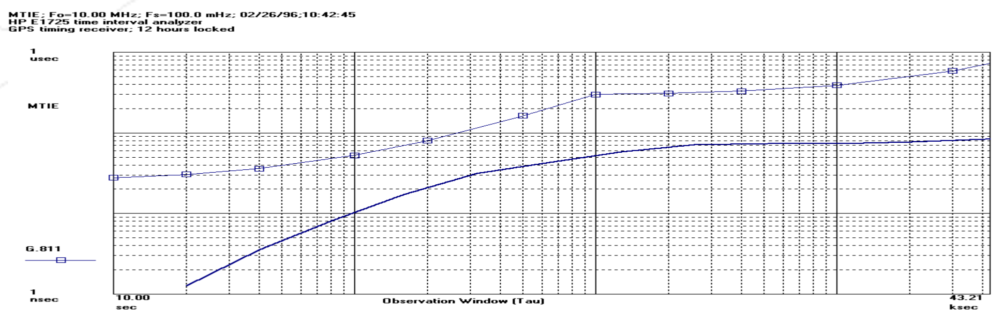


2. Phase



Phase Deviation or TIE

3. Analysis

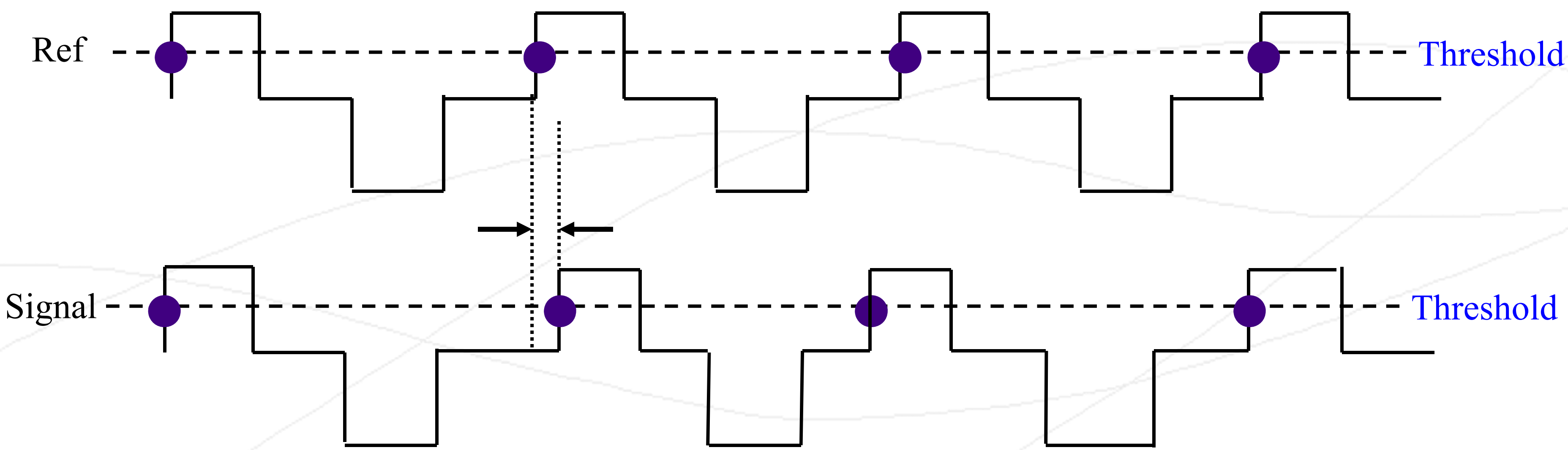


MTIE, TDEV, Allan Variance, Frequency, PPSD, etc.

Phase Digitizing using a Reference Signal at the Same Frequency

Symmetricom

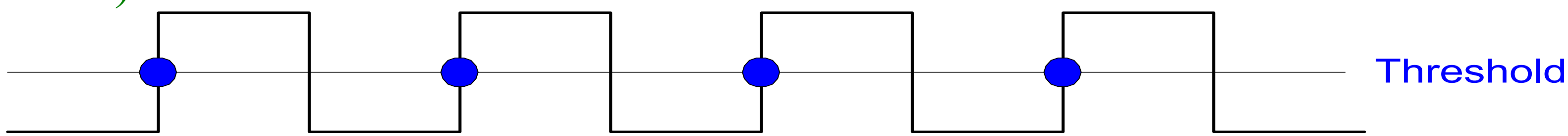
A time interval counter is used to time threshold crossings of a signal very precisely. This process is unaffected by amplitude modulation.



Timestamps: 1 MHz signal

Symmetricom

Perfect mathematical reference (constant carrier)	0 µs	1 µs	2 µs	3 µs



Real signal measurement	0 µs	1.001 µs	1.997 µs	3.005 µs
φdev (time)/TIE	0 nsec	- 1 nsec	+ 3 nsec	- 5 nsec
φdev (degrees)	0°	- 0.36°	+ 1.08°	- 1.8°
φdev (UI)	0 UI	- 0.001 UI	+ 0.003 UI	- 0.005 UI

Phase Modulation Signal Model

Symmetricom

$$v(t) = a(t) \cdot \sin(\phi(t))$$

$$\phi(t) = \omega_o \cdot t + \theta(t)$$

$$\phi(t_i) = \omega_o \cdot t_i + \theta(t_i) = n_i \cdot 2\pi$$

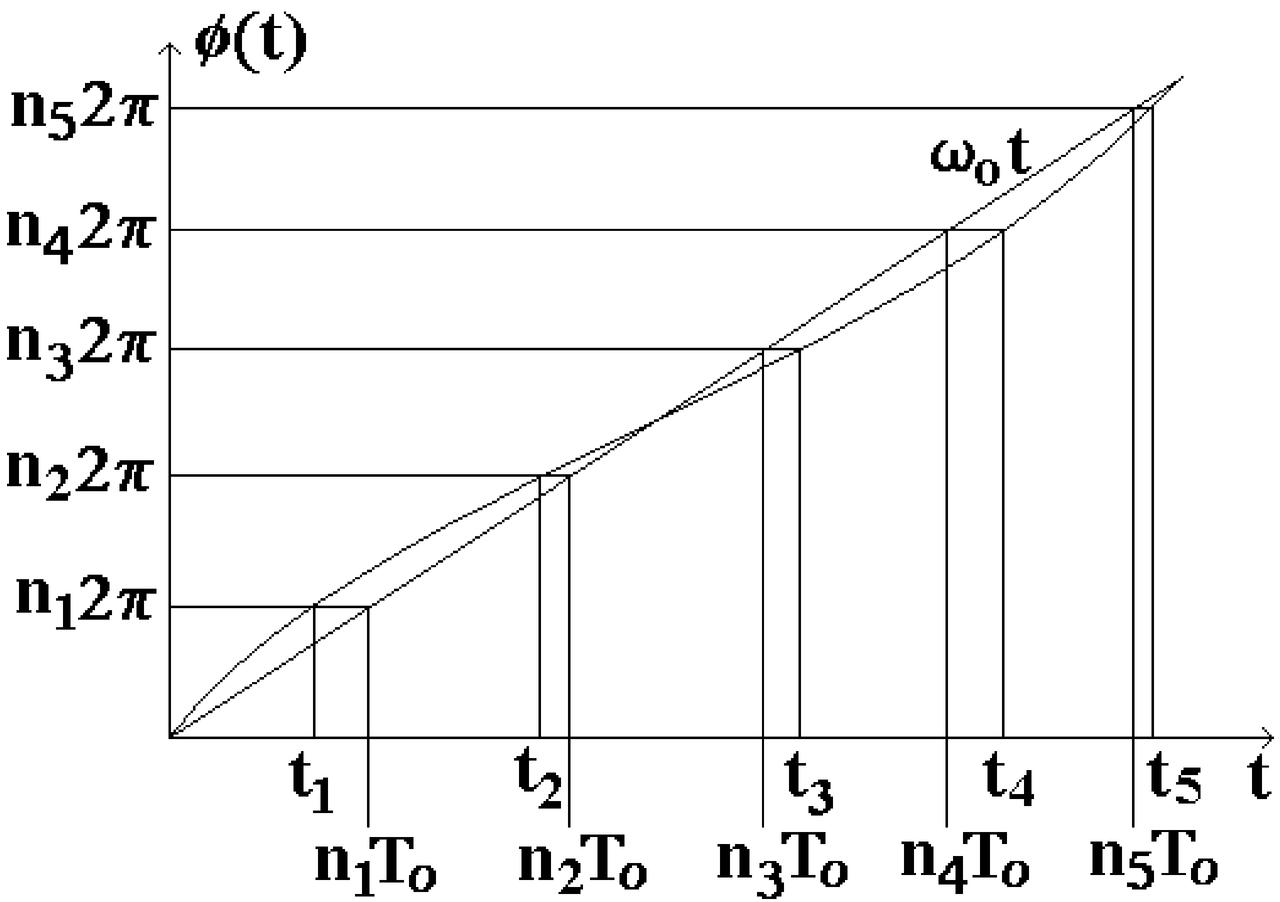
Phase deviation or TIE

$$\theta(t_i) = n_i \cdot 2\pi - \omega_o \cdot t_i = \omega_o \cdot (n_i \cdot T_o - t_i)$$

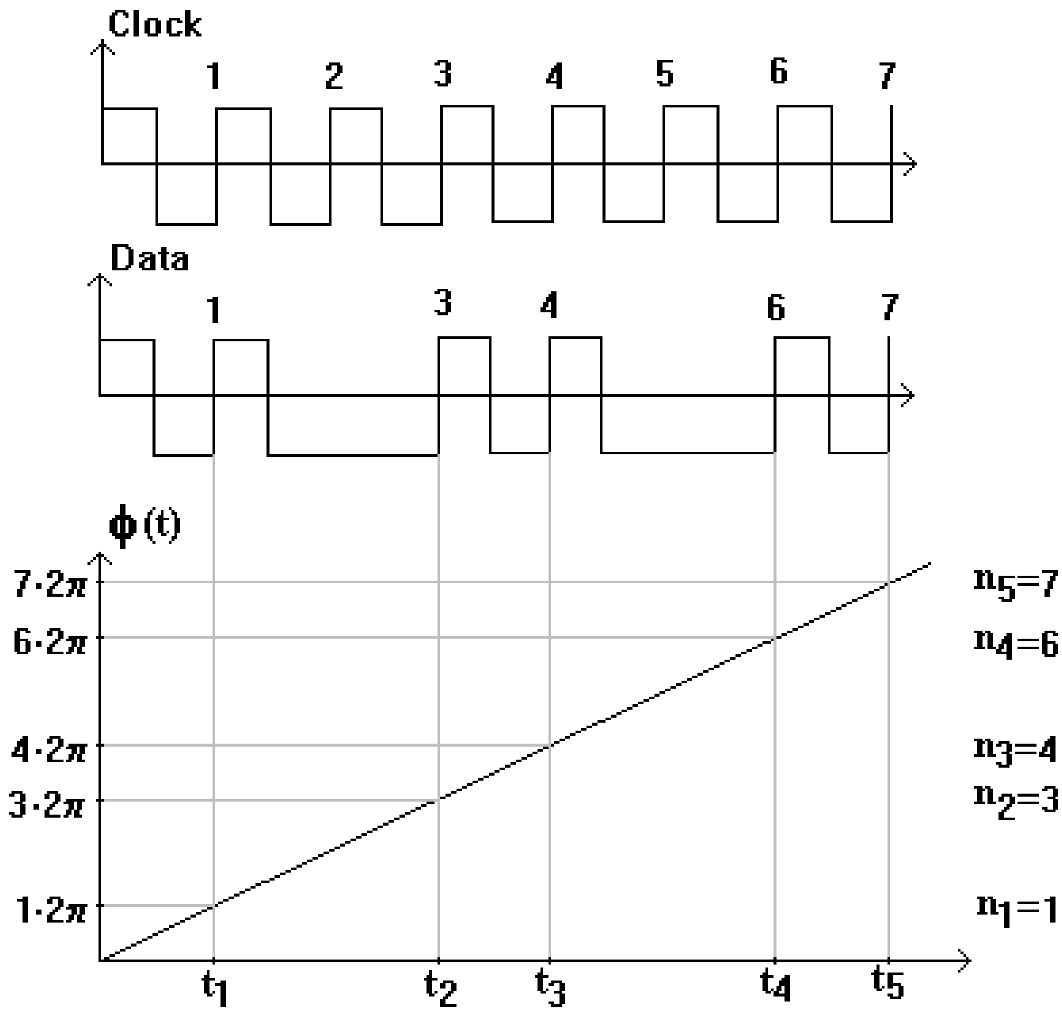
Reference frequency

Phase vs. Time

Phase deviation (TIE) is the difference between these two curves



Data Signal Phase vs. Time



Interpretation of Measurement Results

Symmetricom

- For 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 ATIS/ANSI, Telcordia/Bellcore, ETSI, & ITU-T requirements

The Importance of Phase (TIE)

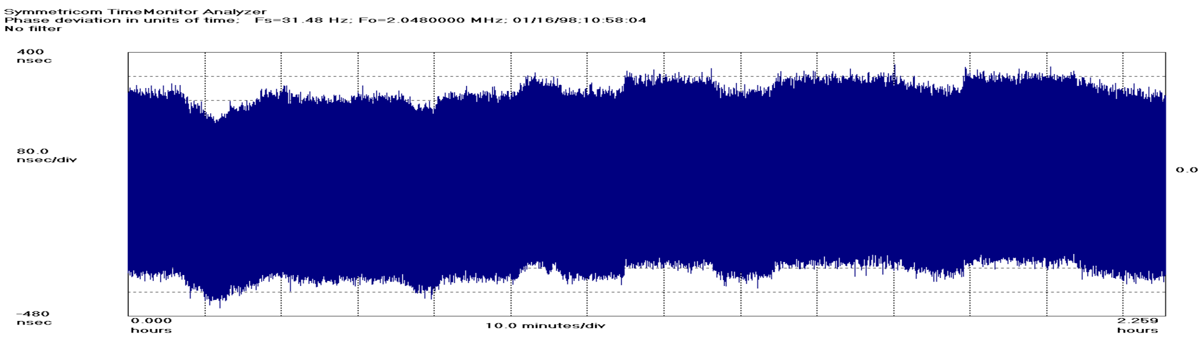
Symmetricom

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?

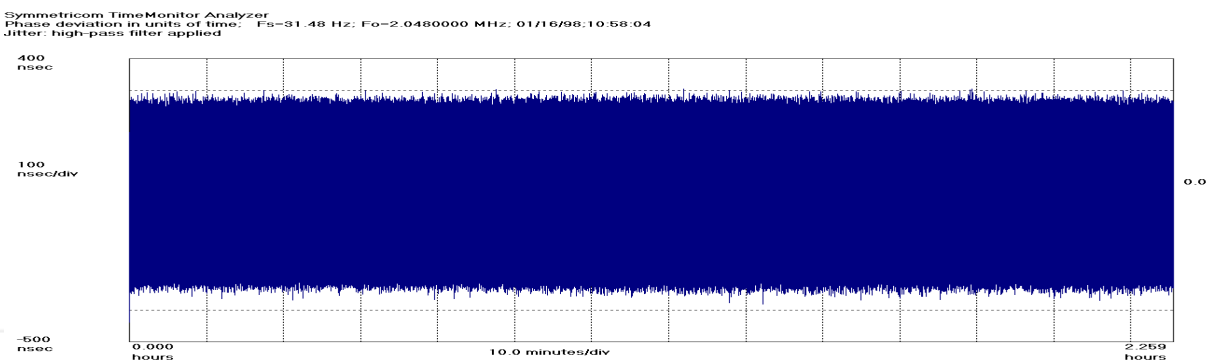
- Typical reports: 80% - 90% of the plots are phase plots

Analysis from Phase: Jitter & Wander

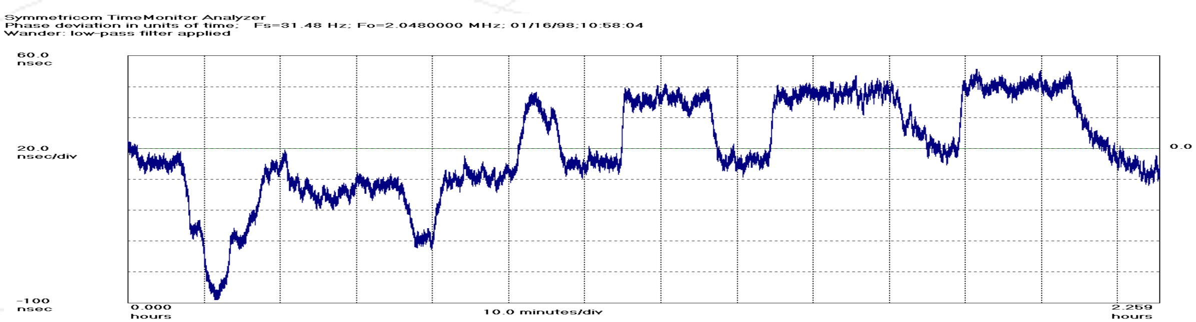
Symmetricom



Signal (no filter)



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



Wander (high-pass filter)

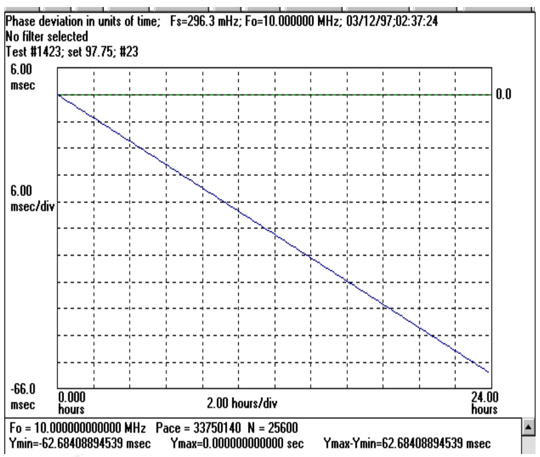
Analysis from Phase: Frequency

Symmetricom

- Recall the relationship between frequency and phase:

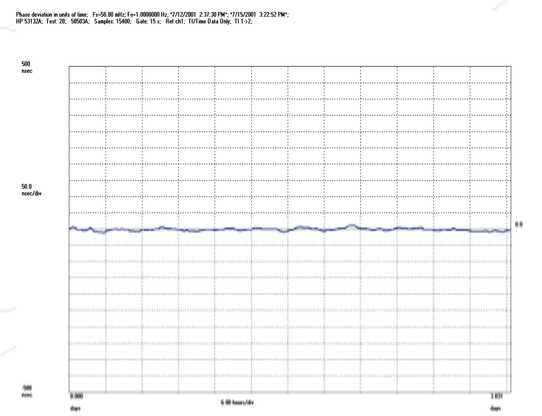
$$\omega = \frac{d\phi}{dt}$$

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



Frequency offset present

No offset: ideal phase plot (flat)

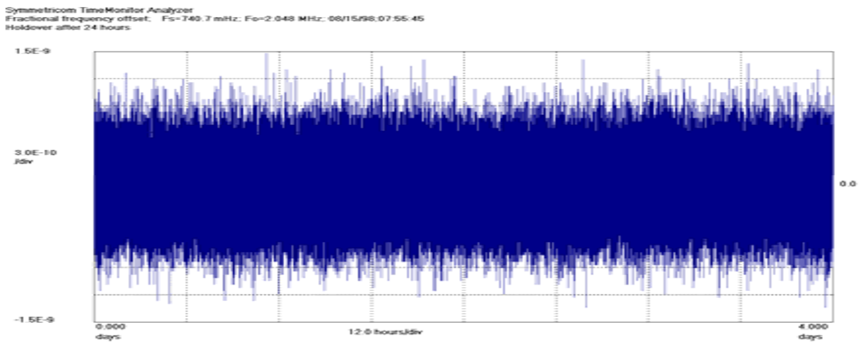


Measurement Analysis: Frequency

- Dynamic frequency: FDEV/FFOFF
  - Instantaneous frequency plotted over time
  - Fractional frequency offset is a normalized version of frequency deviation
  - Limited resolution as measurement interval decreases
- Frequency accuracy
  - Derived from longer term measurement
  - Phase slope calculation (least-square-fit)
  - Example: PRS 1 part in 10^{11} requirement
- To sum up: a tradeoff exists between precision of frequency result and pinpointing when it occurred

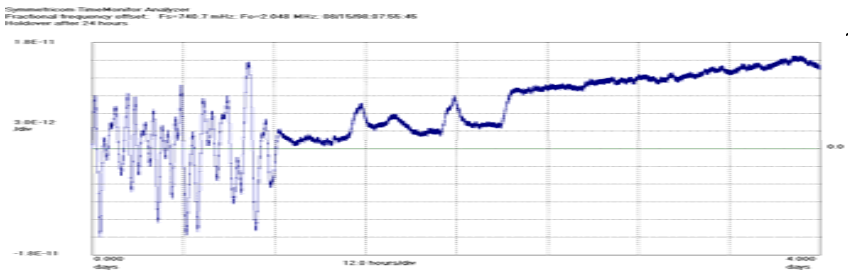
Approaches to Frequency Calculation

Symmetricom



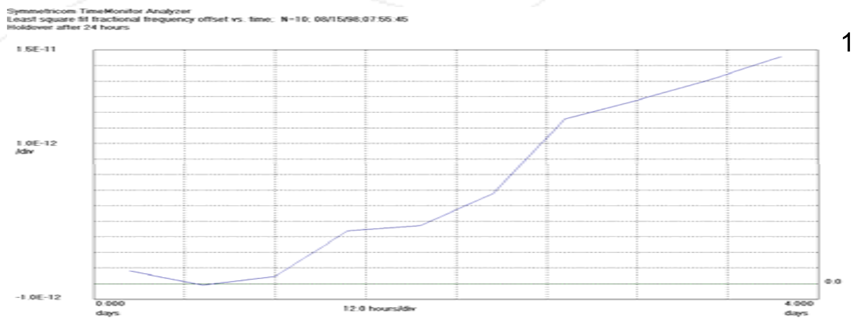
1.5 E-9

Point-by-point



1.8 E-11

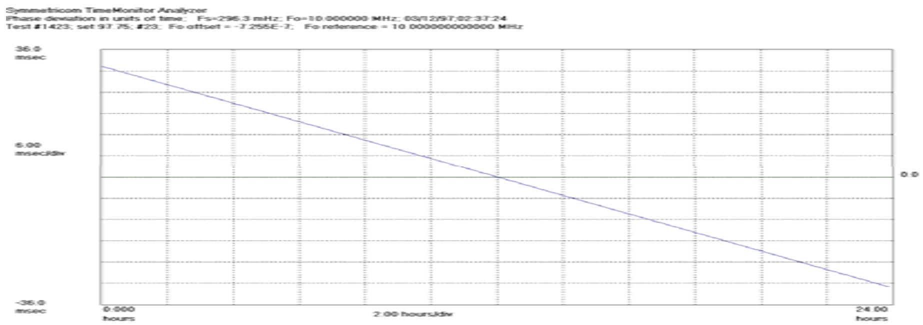
Point-by-point w/ low-pass filter



1.5 E-11

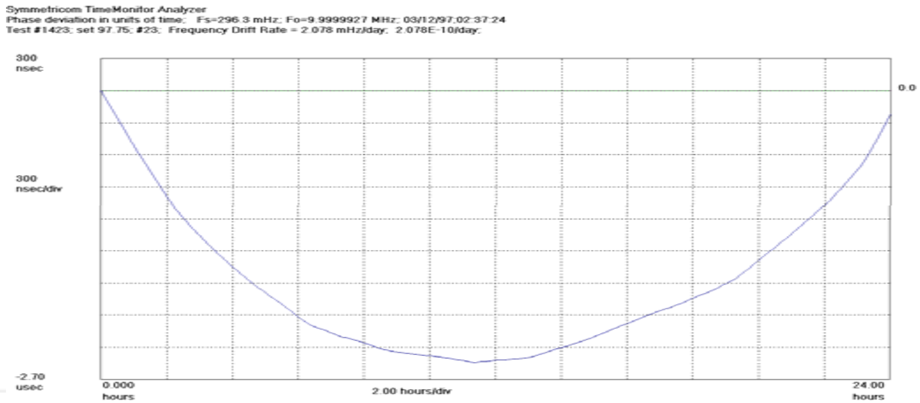
Segmented LSF

Frequency Offset and Drift



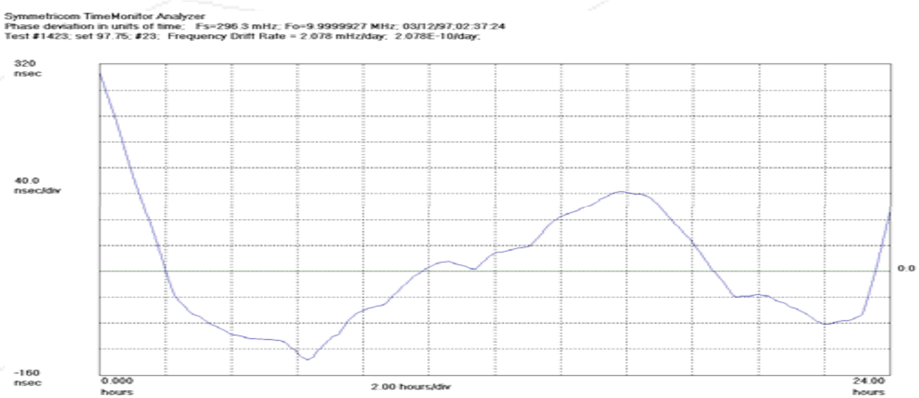
70 ms p-p

Original oscillator phase measurement (0.7ppm frequency offset)



2.5 μs p-p

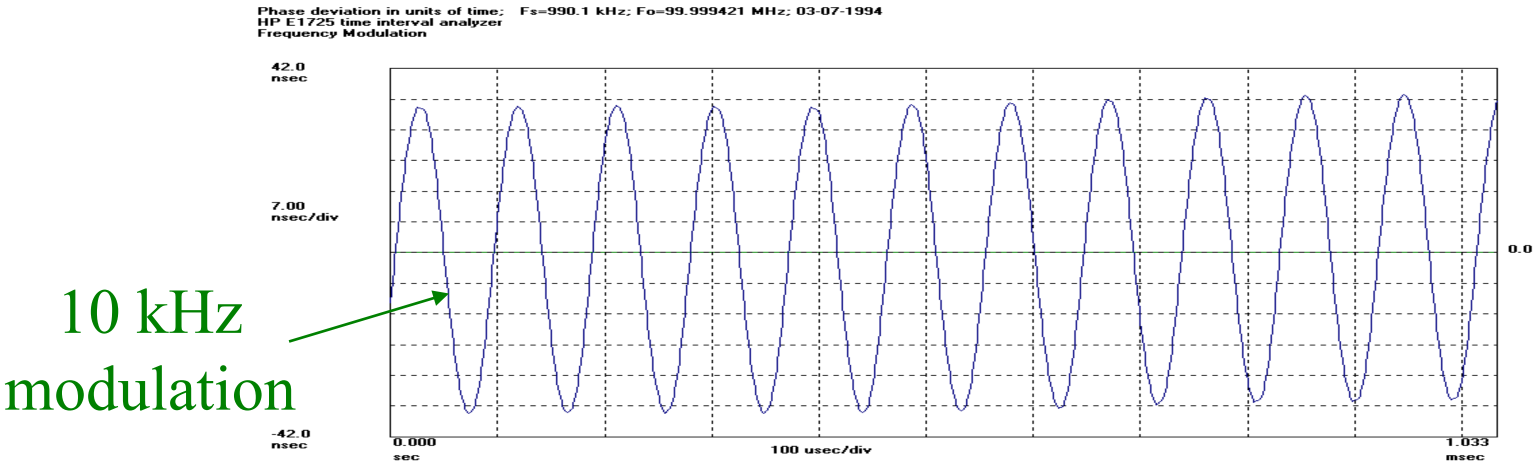
Frequency offset removed (quadratic shape shows linear frequency drift of 0.2 ppb/day)

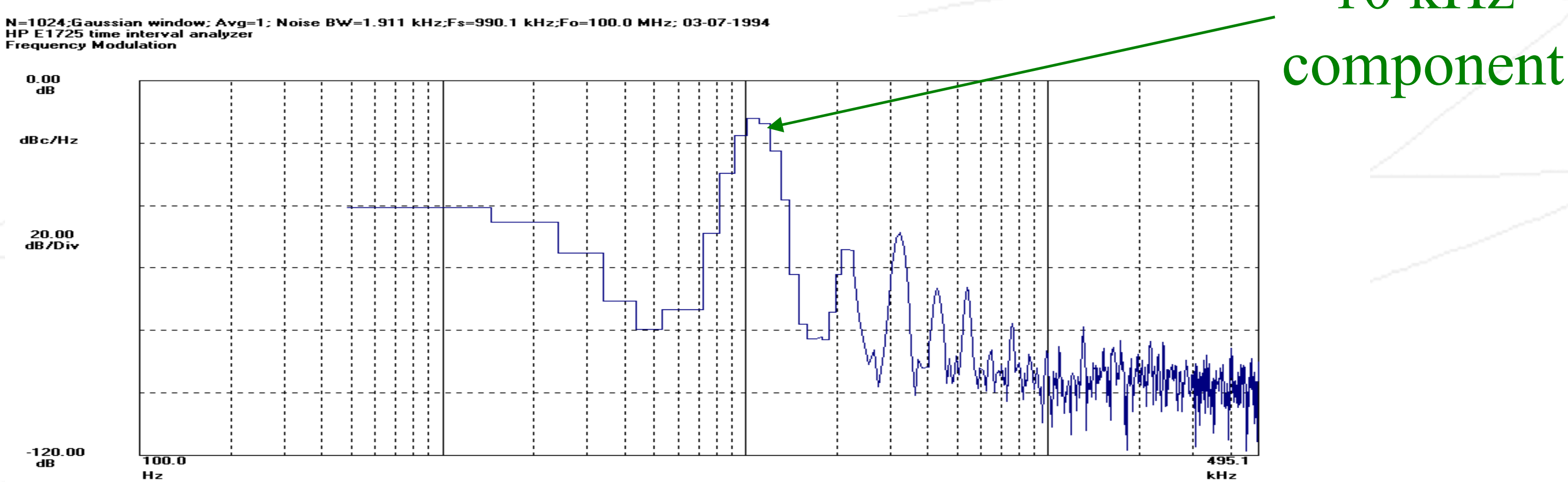


500 ns p-p

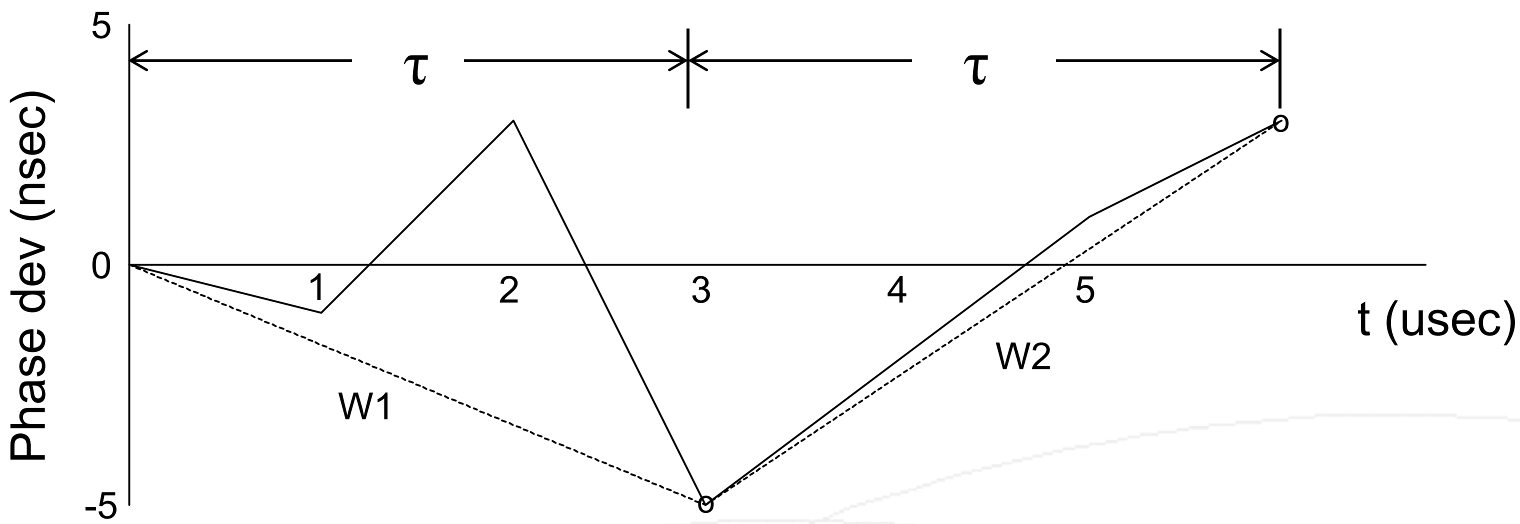
Frequency drift removed (shows residual phase movement)

Analysis from Phase:
Phase Power Spectral Density





Analysis from Phase: Allan Variance

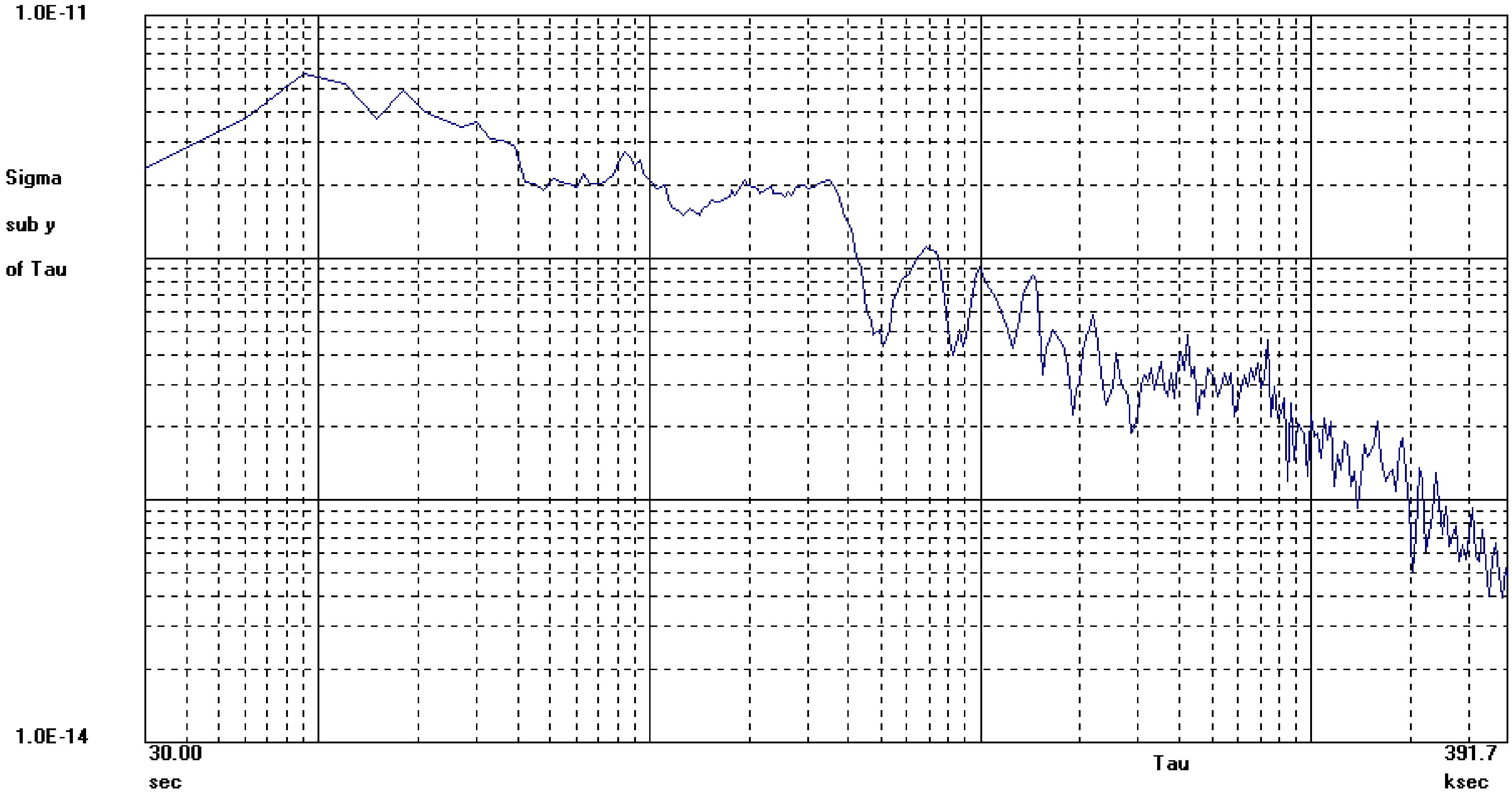


Allan Variance is a measurement of frequency stability used for characterizing oscillators.

Difference in slope = ΔW = $W2 - W1$ => AVAR = $\frac{1}{2}\langle(\Delta W_{\tau})\rangle^2$

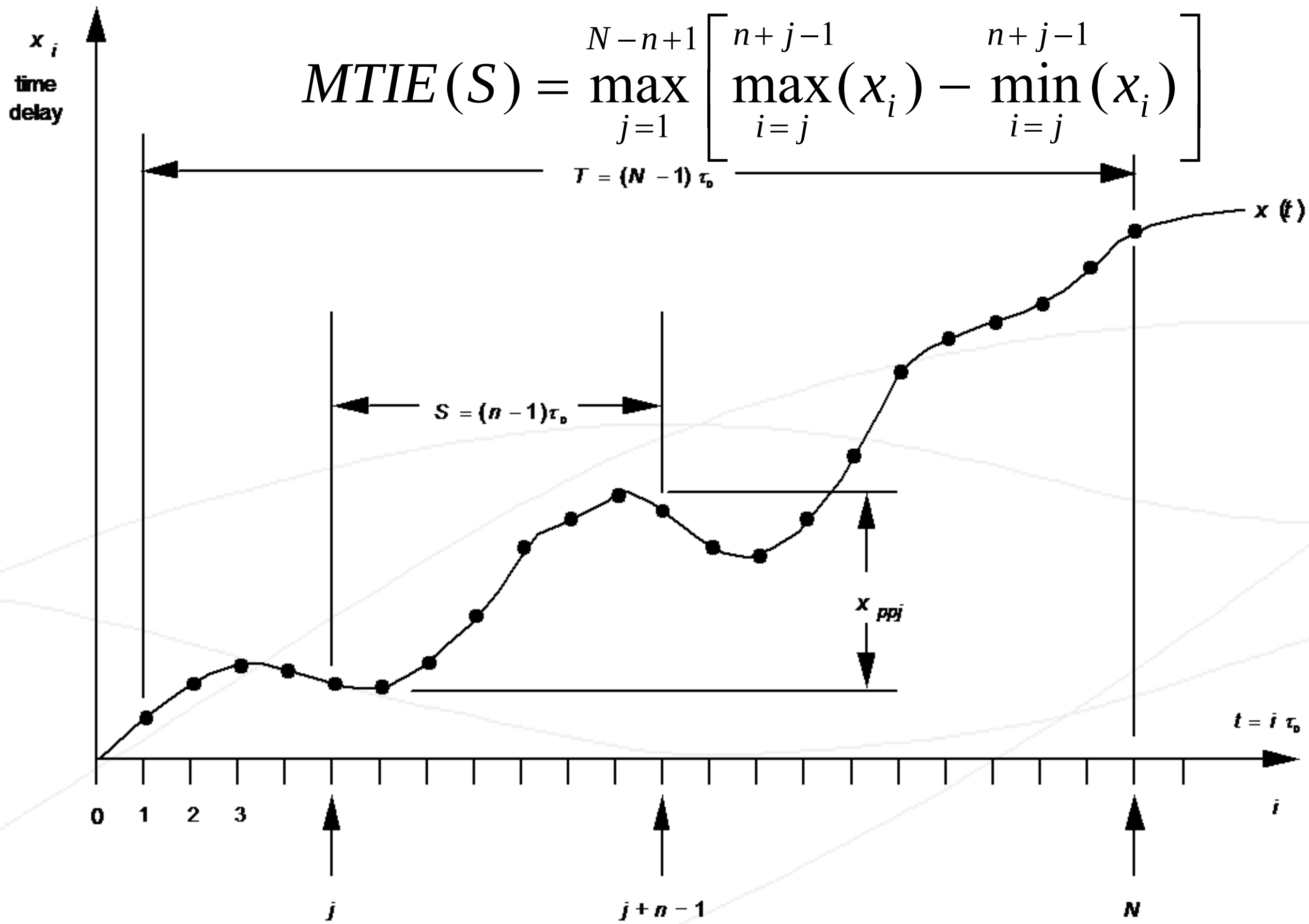
Analysis from Phase: Allan Variance (AVAR)

Root Allan variance; No. Avg=5; Fo=10.00 MHz; Fs=33.33 mHz; *6/19/2000 11:09:59 AM*; *8/3/2000 7:07:14 PM*;
HP 53132A; Test: 28; HP 58503A; 1 PPS; Samples: 130535; Gate: 30 s; Glitch: 100.0 nsec; Ref ch1; TI/Time Data Only; TI 1->2;



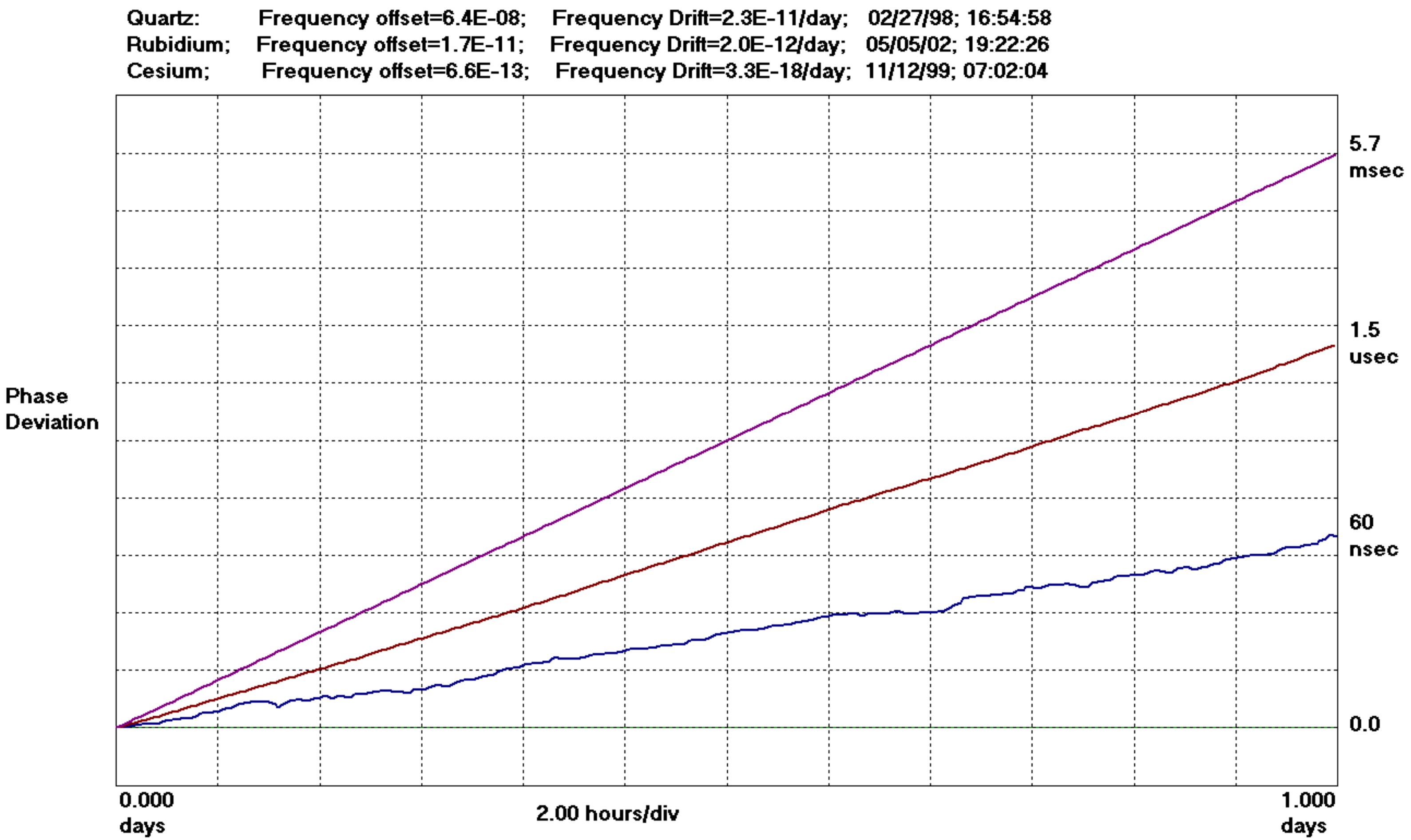
Analysis from Phase: MTIE

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



Frequency Accuracy and Stability

Quartz, Rubidium, and Cesium



Synchronization Measurements

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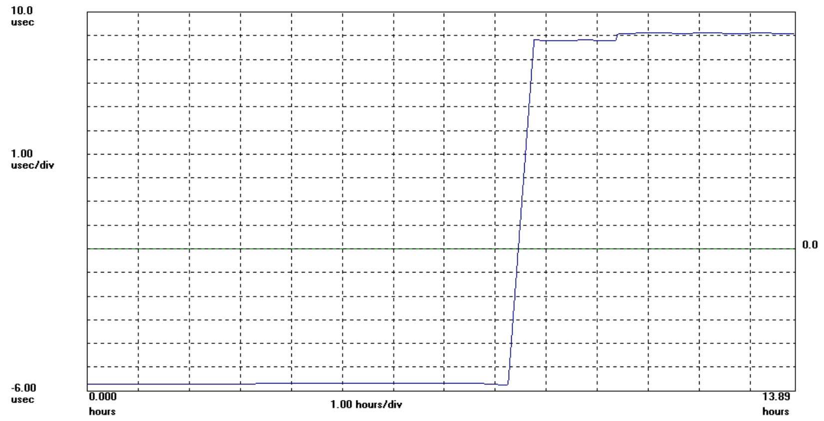
- Both MTIE and TDEV are measures of wander over ranges of values from very short-term wander to long-term wander
- MTIE is a peak detector: shows largest phase swings for various observation time windows
- TDEV is a highly averaged, “rms” type of calculation showing values over a range of integration times

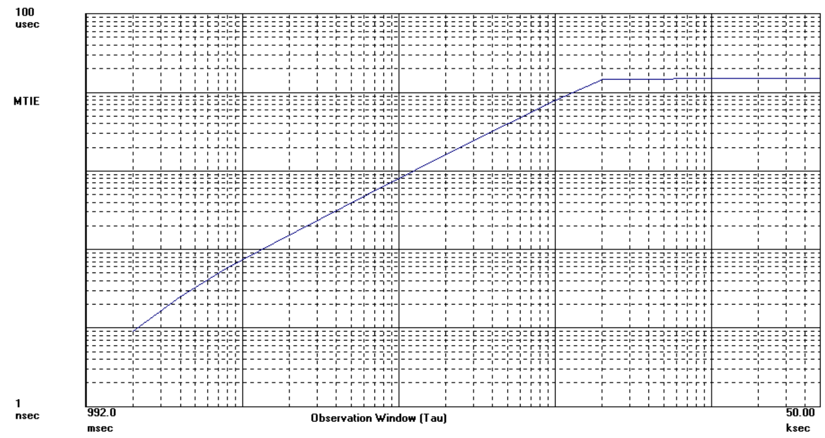
MTIE: shows a step in phase

Phase



Phase steps upwards 15 μsec about 8 hours into the measurement

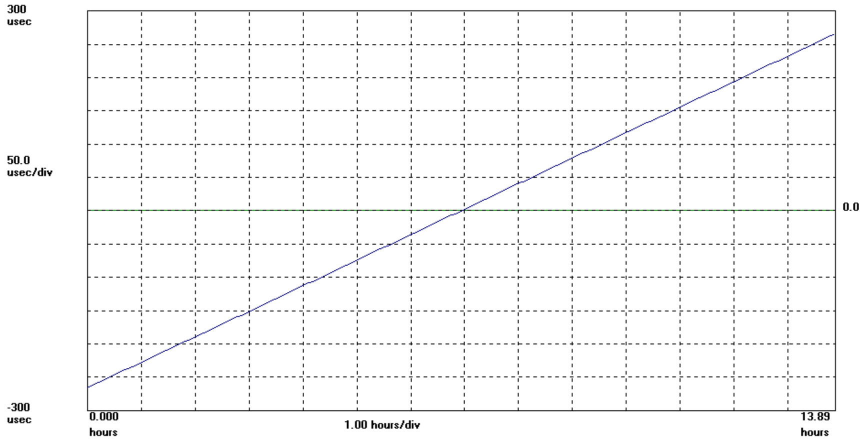
MTIE



MTIE flattens after a certain tau value (moving from left to right)

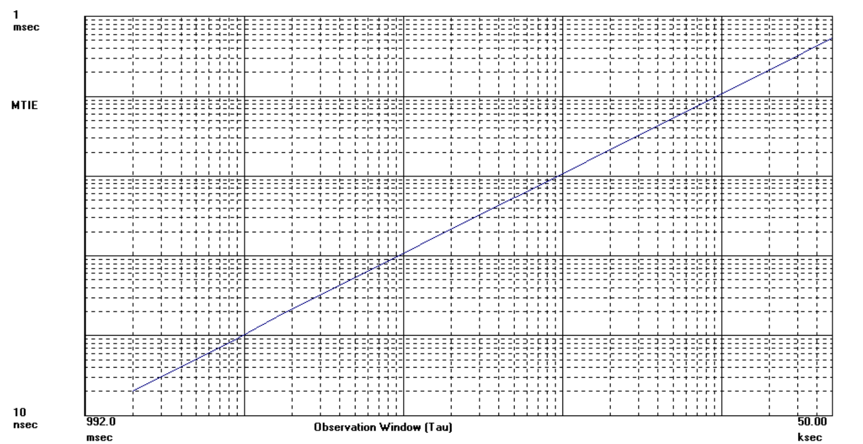
MTIE: shows a frequency offset

Phase



A frequency offset is seen as a constant slope in phase

MTIE



MTIE constantly increases with increasing observation time

TDEV: shows a phase modulation consistent throughout measurement

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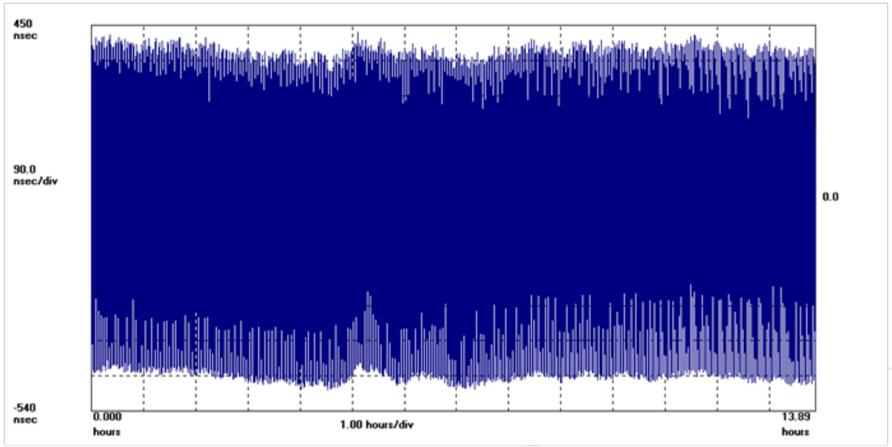
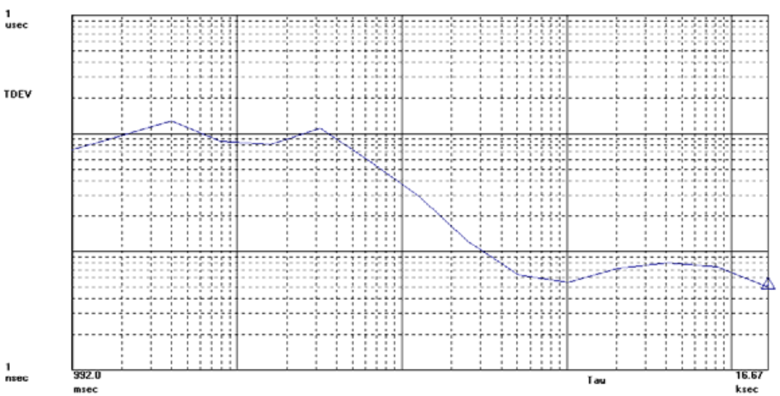
Phase



Phase shows large swings in the short term but is flat in the long term

TDEV

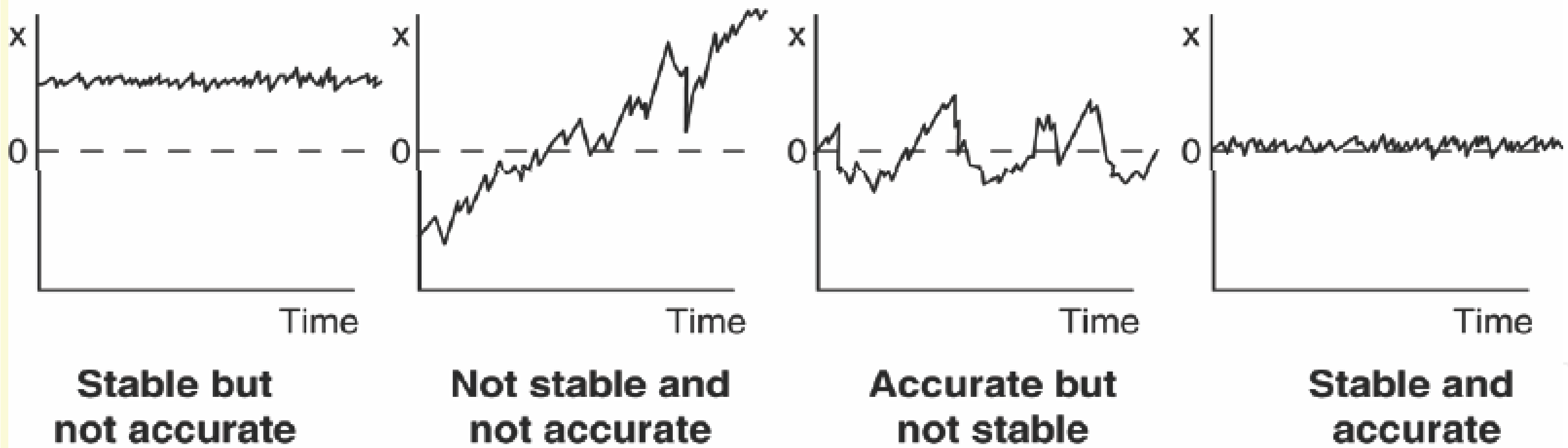


TDEV is elevated for shorter term wander (left) but relatively reduced for longer term (right)

Stability and Accuracy

Symmetricom

Fractional Frequency Offset vs. Time



Adapted from Tutorial on Quartz Crystal Resonators and Oscillators by John R. Vig

The Allan Variance family of analysis metrics is concerned with the characterization of stability

Diagram from "Time Domain Representation of Oscillator Performance", Marc A. Weiss, Ph.D. NIST

Systematics and Stochastics

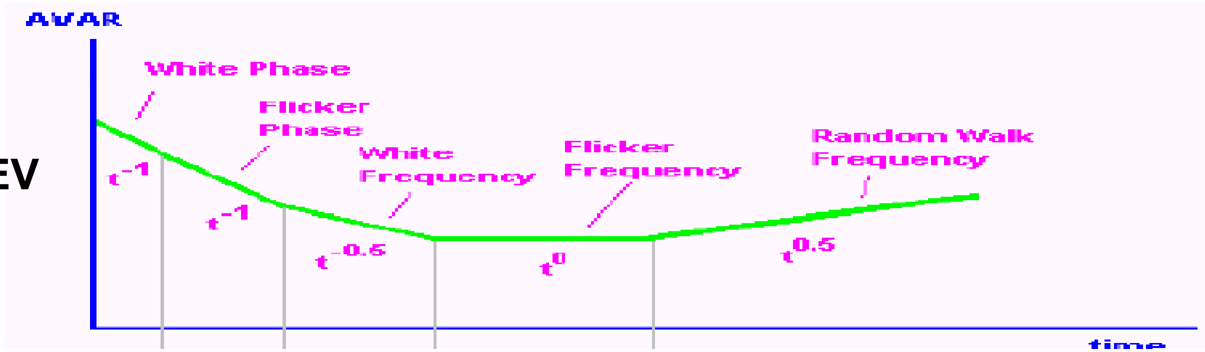
Symmetricom

- Systematics
  - Frequency offset
  - Frequency drift
  - Environmentals (temperature, humidity, pressure, etc.)

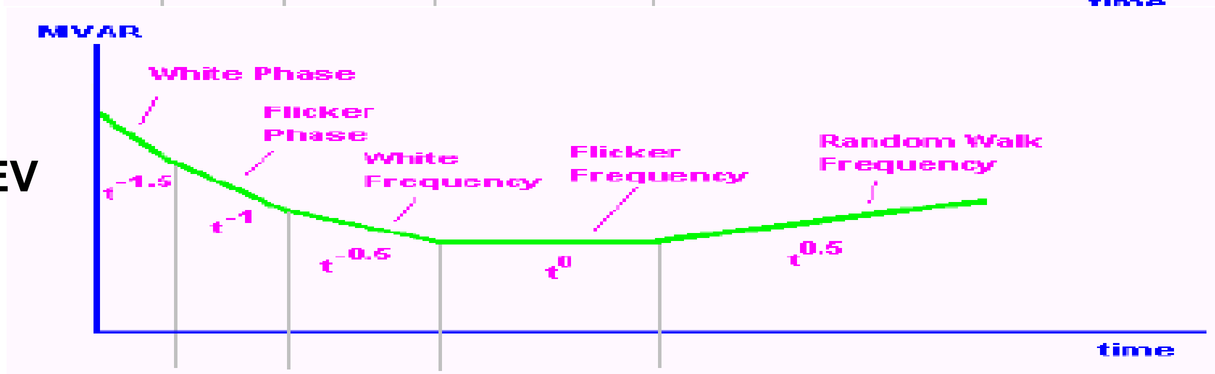
- When systematics are removed, what remains is noise (stochastic processes). Five major noise types:
  - WPM (white phase modulation)
  - FPM (flicker phase modulation)
  - RWPM = WFM (random walk PM = white FM)
  - FFM (flicker frequency modulation)
  - RWFM (random walk frequency modulation)

ADEV to MDEV to TDEV

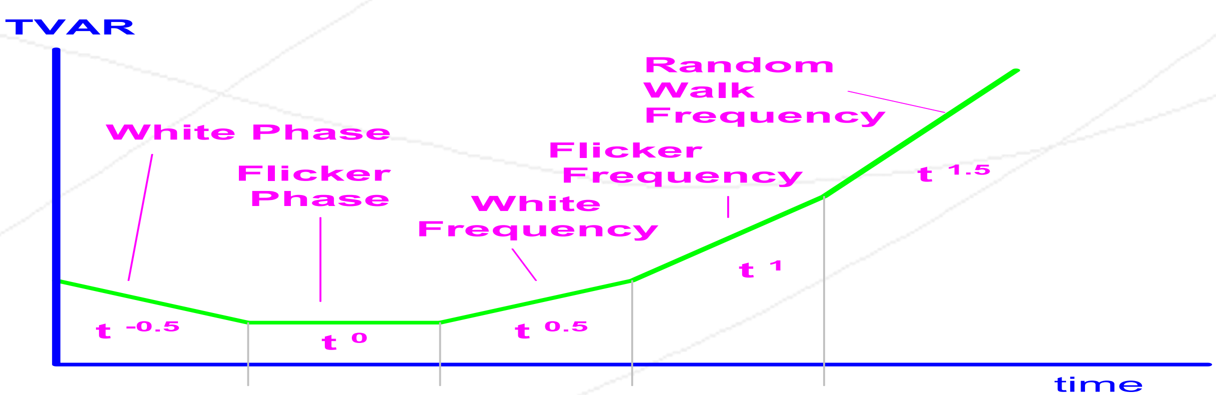
ADEV



MDEV



TDEV



Measurement & Analysis: Outline

Symmetricom

1. Introduction

2. TDM Measurement and Analysis

3. Packet Measurement and Analysis

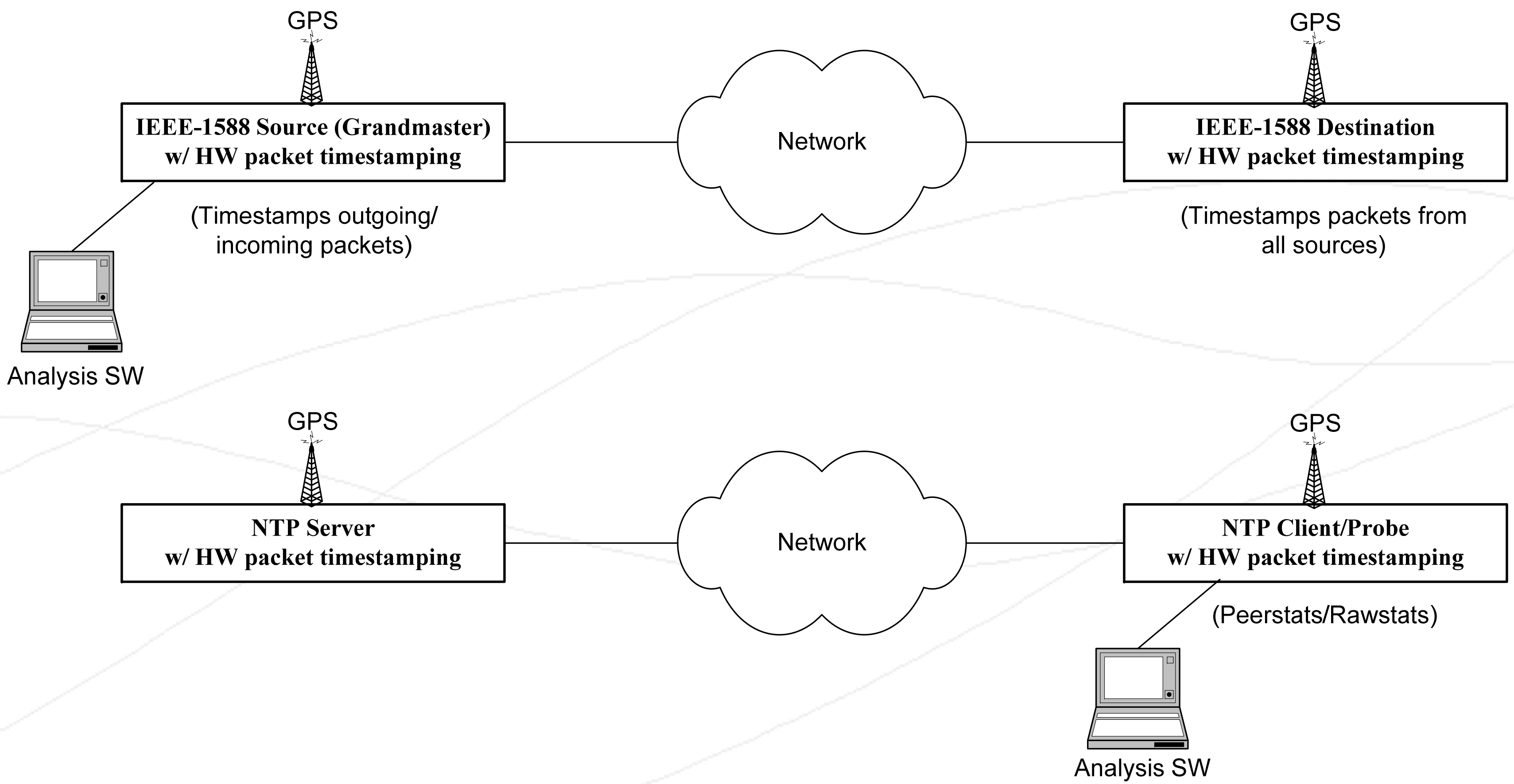
Packet Network Measurement Setup

- Measurement equipment with precision IEEE-1588 or NTP hardware time-stamping
- GPS time-of-day reference in each unit
  - Required for sub-microsecond end-to-end analysis
  - Log-files of the time-stamp data is post-processed
- Network configurations
  - Basic: crossover cable, hub, switch
  - Baseline: switch, router, multi-hop with no traffic
  - Traffic: load based upon G.8261 “data” profile
  - Production Network with Live Traffic
  - Company LAN and Public Internet

Packet Measurement Example Configurations

Example Measurement Equipment Configurations

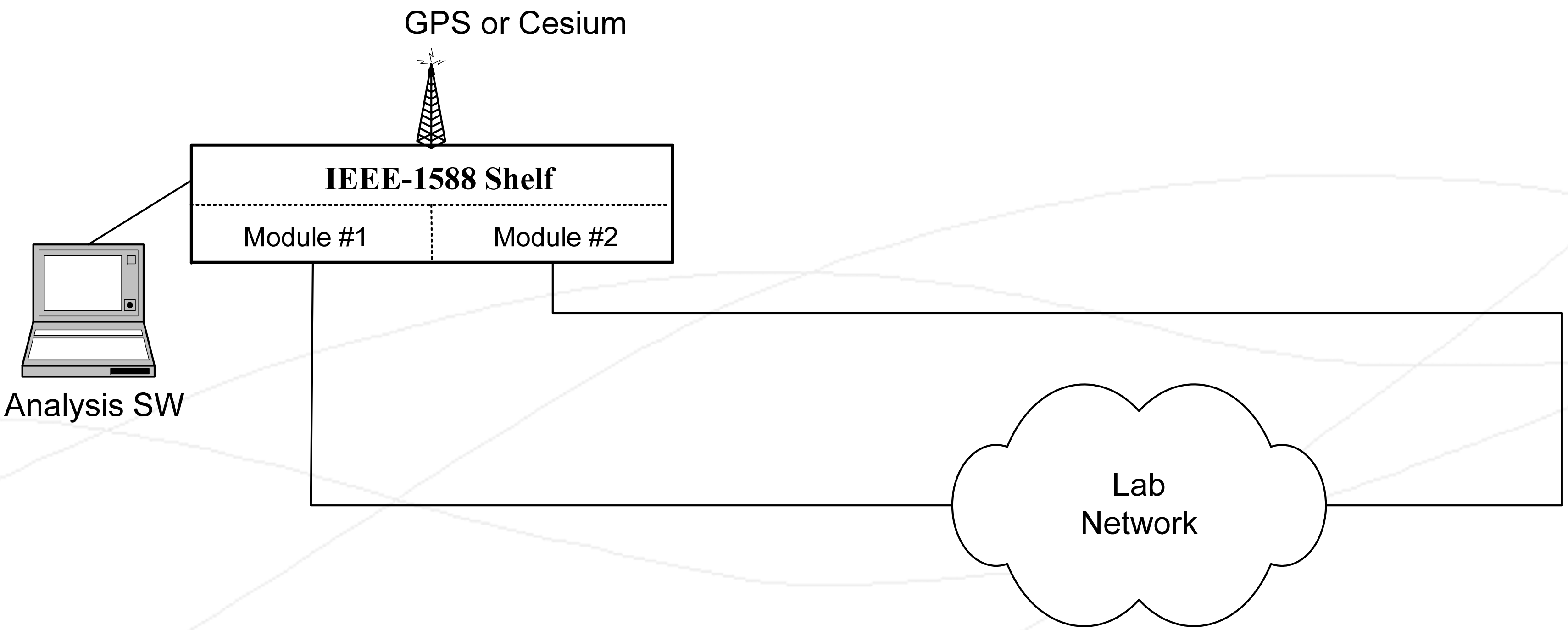
- Need (1) PRC TOD reference (2) Precision Packet TimeStamping (3) Analysis SW
- Probes may be "active" (require master/probe) or "passive" (require master/slave/probe)
- Passive probes also require Ethernet taps or hubs to "see" packets



Packet Measurement Example Configurations

Symmetricom

Alternate Measurement Equipment Configuration for Lab



PTP PDV Files

Source File:

SEQ: 01195 UUID: 00A069012FB9 UTC: DATE 2006:124:01:48:56 NSEC 0650092776
SEQ: 23238 UUID: 000055010016 UTC: DATE 2006:124:01:48:56 NSEC 0772791251
SEQ: 23906 UUID: 000055010017 UTC: DATE 2006:124:01:48:56 NSEC 0942353061
SEQ: 23239 UUID: 000055010016 UTC: DATE 2006:124:01:48:57 NSEC 0742766301
SEQ: 23907 UUID: 000055010017 UTC: DATE 2006:124:01:48:58 NSEC 0122405371
SEQ: 01196 UUID: 00A069012FB9 UTC: DATE 2006:124:01:48:58 NSEC 0649898076
SEQ: 23908 UUID: 000055010017 UTC: DATE 2006:124:01:48:59 NSEC 0512342921
SEQ: 23240 UUID: 000055010016 UTC: DATE 2006:124:01:49:00 NSEC 0372820611
SEQ: 01197 UUID: 00A069012FB9 UTC: DATE 2006:124:01:49:00 NSEC 0649723496

Destination File:

SEQ: 01195 UUID: 00A069012FB9 UTC: DATE 2006:124:01:48:56 NSEC 0650356493
SEQ: 23238 UUID: 000055010016 UTC: DATE 2006:124:01:48:56 NSEC 0772511963
SEQ: 23906 UUID: 000055010017 UTC: DATE 2006:124:01:48:56 NSEC 0942073173
SEQ: 23239 UUID: 000055010016 UTC: DATE 2006:124:01:48:57 NSEC 0742522643
SEQ: 23907 UUID: 000055010017 UTC: DATE 2006:124:01:48:58 NSEC 0122085883
SEQ: 01196 UUID: 00A069012FB9 UTC: DATE 2006:124:01:48:58 NSEC 0650169943
SEQ: 23908 UUID: 000055010017 UTC: DATE 2006:124:01:48:59 NSEC 0512088553
SEQ: 23240 UUID: 000055010016 UTC: DATE 2006:124:01:49:00 NSEC 0372557873
SEQ: 01197 UUID: 00A069012FB9 UTC: DATE 2006:124:01:49:00 NSEC 0649977513
SEQ: 23909 UUID: 000055010017 UTC: DATE 2006:124:01:49:01 NSEC 0712120953

NTP Rawstats File

```
53670 65597.542   69.25.96.14   192.168.5.26 3339425597.531763871 3339425597.538087700 3339425597.538856700 3339425597.541986235
53670 65598.621   69.25.96.14   192.168.5.26 3339425598.531791267 3339425598.534250000 3339425598.618500000 3339425598.620880216
53670 65599.535 192.168.5.198 192.168.5.26 3339425599.531832760 3339425598.532465024 3339425598.533733347 3339425599.534835067
53670 65599.542   69.25.96.14   192.168.5.26 3339425599.531982140 3339425599.538061600 3339425599.538876600 3339425599.541980469
53670 65600.535 192.168.5.130 192.168.5.26 3339425600.531867351 3339425599.532509826 3339425599.533609608 3339425600.534661374
53670 65600.621   69.25.96.11   192.168.5.26 3339425600.532010593 3339425600.534500000 3339425600.618500000 3339425600.620820180
53670 65601.535 192.168.5.169 192.168.5.26 3339425601.531921841 3339425600.532630898 3339425600.533767482 3339425601.534763148
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53670 65601.538   69.25.96.14   192.168.5.26 3339425601.532133066 3339425601.534439900 3339425601.535208200 3339425601.538359975
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53670 65602.621   69.25.96.11   192.168.5.26 3339425602.532087416 3339425602.534750000 3339425602.618500000 3339425602.620799283
53670 65603.535 192.168.5.169 192.168.5.26 3339425603.532041932 3339425602.532687434 3339425602.533824018 3339425603.534817907
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53670 65605.535 192.168.5.169 192.168.5.26 3339425605.532243575 3339425604.532901844 3339425604.534038427 3339425605.535154785
53670 65605.536 192.168.5.198 192.168.5.26 3339425605.532383388 3339425604.532955713 3339425604.534222968 3339425605.535882222
53670 65605.539   69.25.96.14   192.168.5.26 3339425605.532451524 3339425605.534802900 3339425605.535569800 3339425605.538810443
53670 65606.535 192.168.5.130 192.168.5.26 3339425606.532160571 3339425605.532799972 3339425605.533900287 3339425606.534984607
53670 65606.641   69.25.96.11   192.168.5.26 3339425606.532307531 3339425606.540500000 3339425606.638500000 3339425606.640780864
```
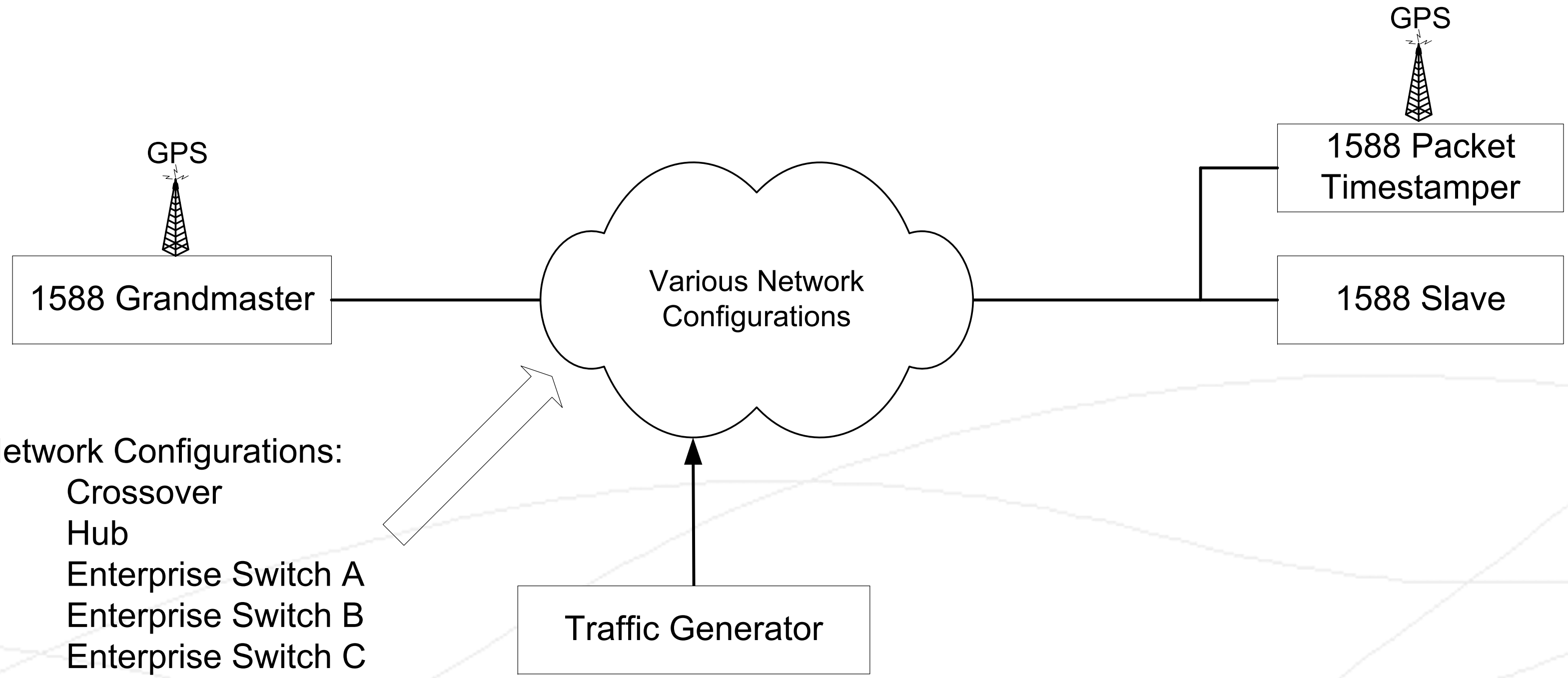

Lab Network Configurations

Example Lab Network Configurations



Network Configurations:

- Crossover
- Hub
- Enterprise Switch A
- Enterprise Switch B
- Enterprise Switch C
- Enterprise Switch D
- Multilayer Switch E
- Wirespeed router M
- Router X
- Router Y
- Multi-Hop: SwA/RtX/SwB
- Multi-Hop: SwA/RtM/SwB
- Multi-Hop: SwA/RtX/RtX/SwB
- Multi-Hop: SwA/RtX/RtY/SwB

Interpretation of Measurement Results (“TIE”)

- 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
  - TDEV/minTDEV/bandTDEV

Derived from PDV phase

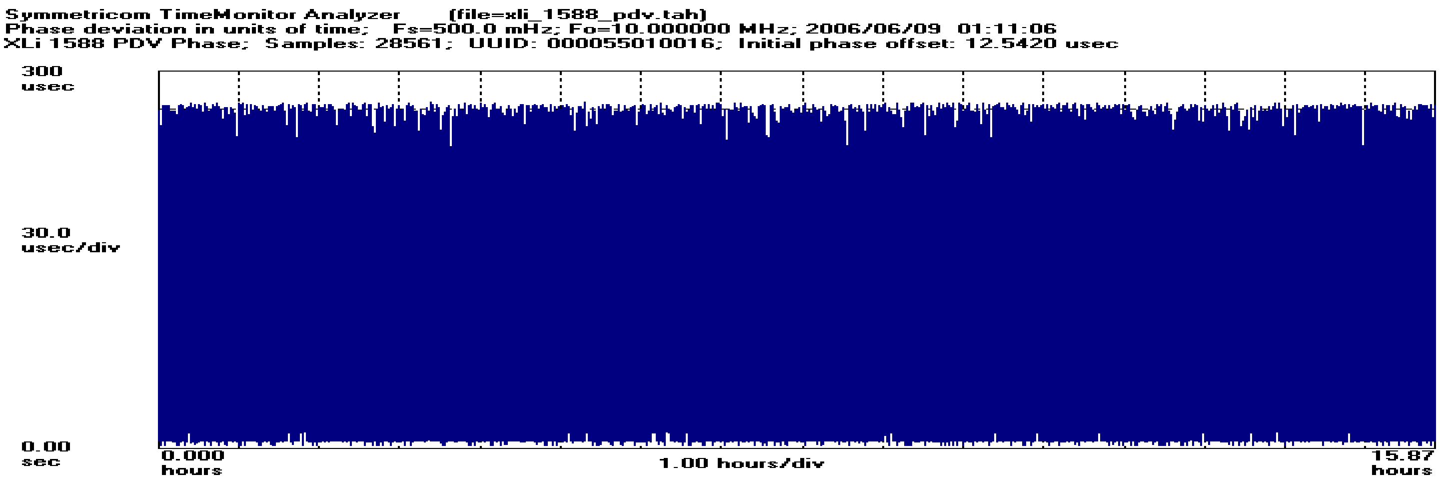
- minTDEV is under study at the ITU-T Q13/SG15 and has references in the latest G.8261 draft

* PDF = probability density function

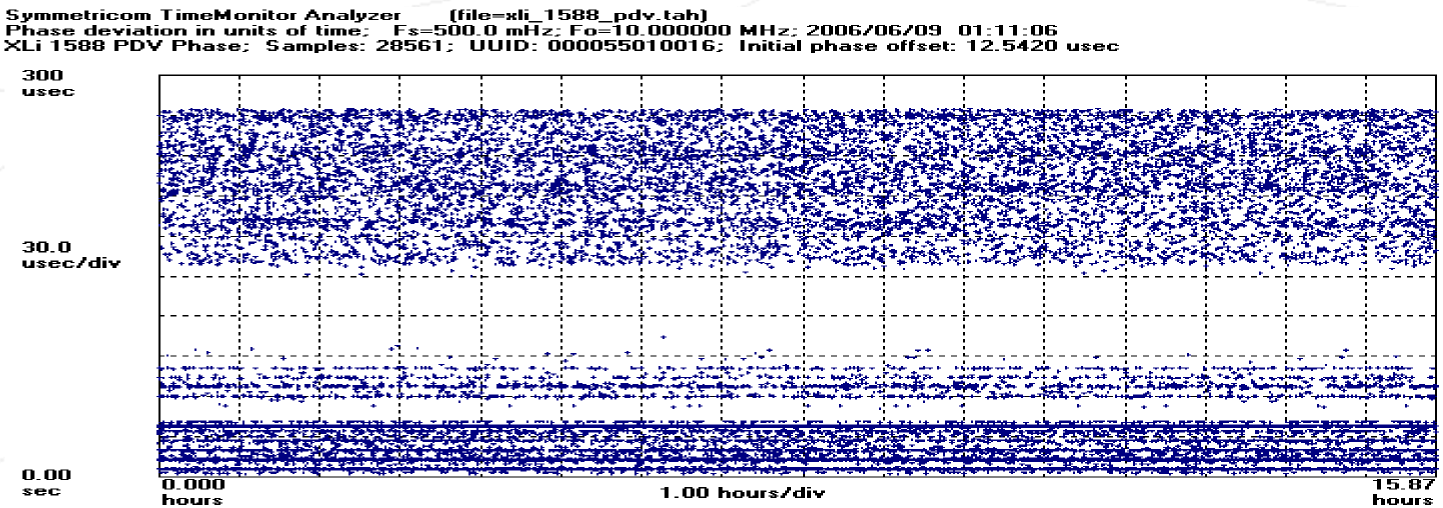
Viewing Phase (Packet Delay Sequence)

Symmetricom

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



Measurement points connected

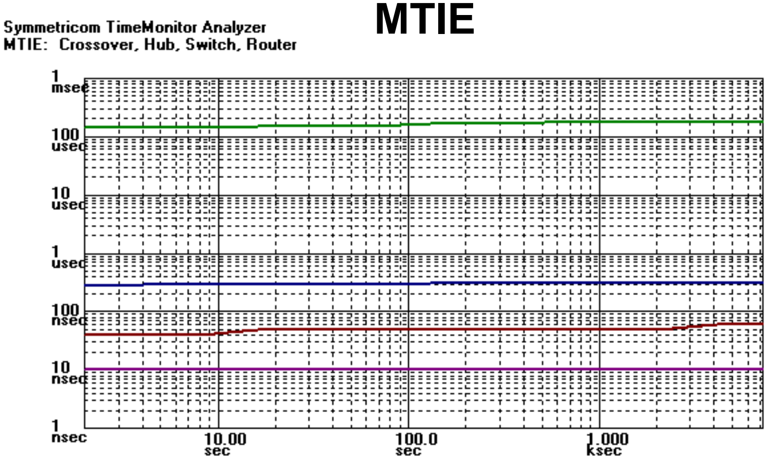


Measurement points as discrete dots

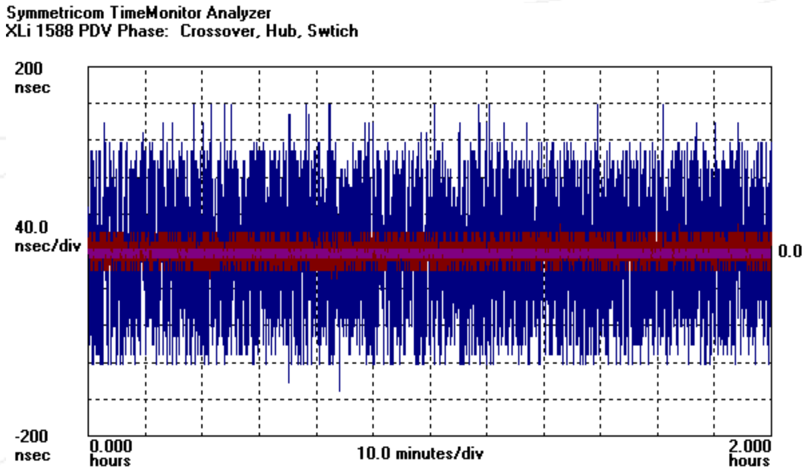
Performance Metrics

- Phase (Packet Delay vs. Time)
  - Basis for all calculations
- MTIE (Maximum Time Interval Error)
  - Typically one dimensional for packet delay data
- TDEV (Time Deviation)
  - Useful indicator of network traffic load

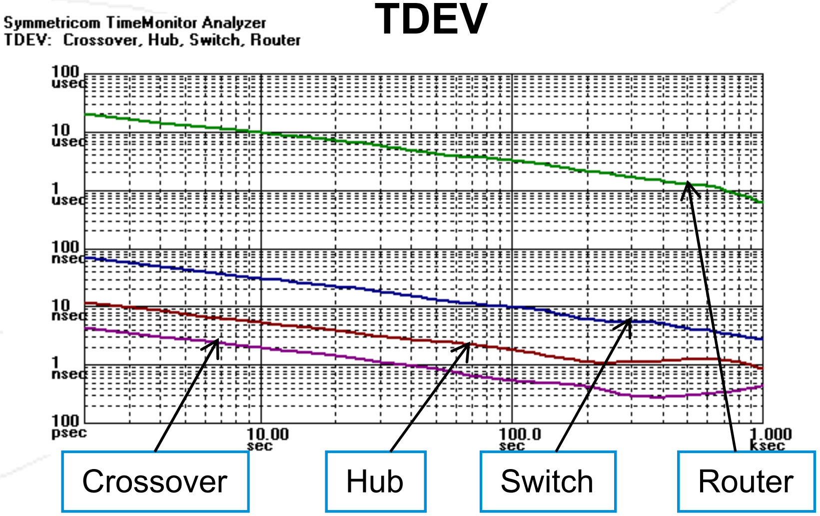
MTIE



Phase



TDEV



Performance Metrics

- Standard Deviation (PDV)
- Mean (Latency)
- Maximum Peak Deviation (PDV)

Statistics

Crossover cable:
Mean: 287.2818 nsec
Peak to Peak: 10.01 nsec
Standard Deviation: 4.450 nsec

Switch no traffic:
Mean: 16.75112 µsec
Peak to Peak: 310.0 nsec
Standard Deviation: 70.10 nsec

Hub:
Mean: 659.7955 nsec
Peak to Peak: 60.01 nsec
Standard Deviation: 12.13 nsec

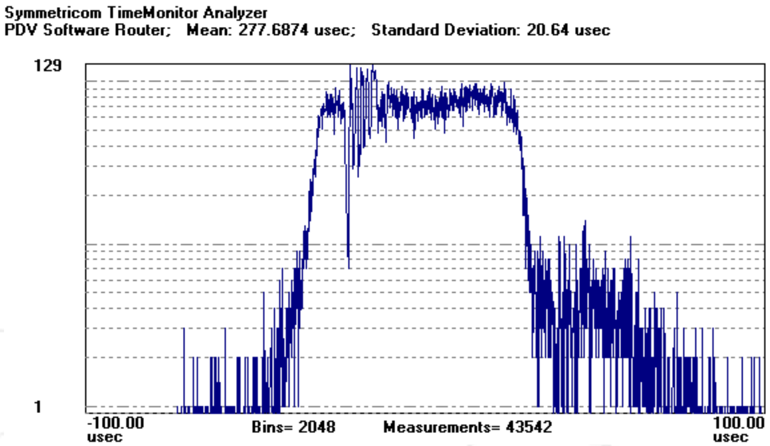
10% BW Utilization:
Mean: 17.93500 µsec
Peak to Peak: 121.4 µsec
Standard Deviation: 11.53 µsec

Switch:
Mean: 16.75112 µsec
Peak to Peak: 310.0 nsec
Standard Deviation: 70.10 nsec

25% BW Utilization:
Mean: 19.62525 µsec
Peak to Peak: 122.6 µsec
Standard Deviation: 17.61 µsec

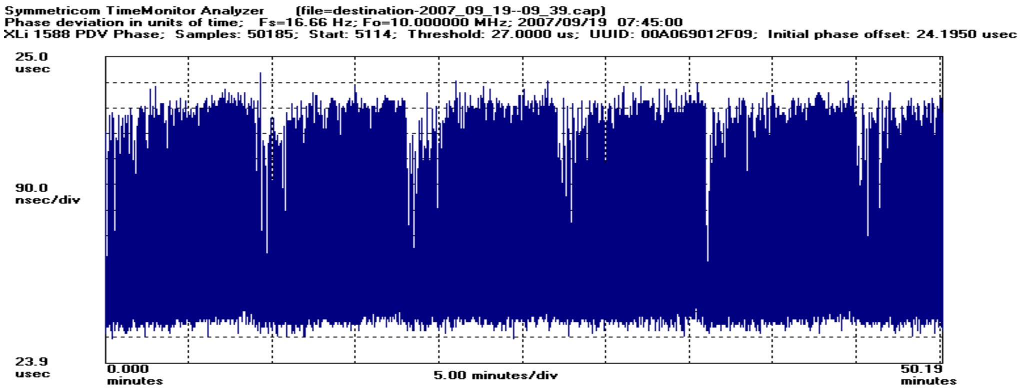
Router:
Mean: 277.6874 µsec
Peak to Peak: 212.5 µsec
Standard Deviation: 20.64 µsec

50% BW Utilization:
Mean: 47.99551 µsec
Peak to Peak: 122.8 µsec
Standard Deviation: 50.90 µsec

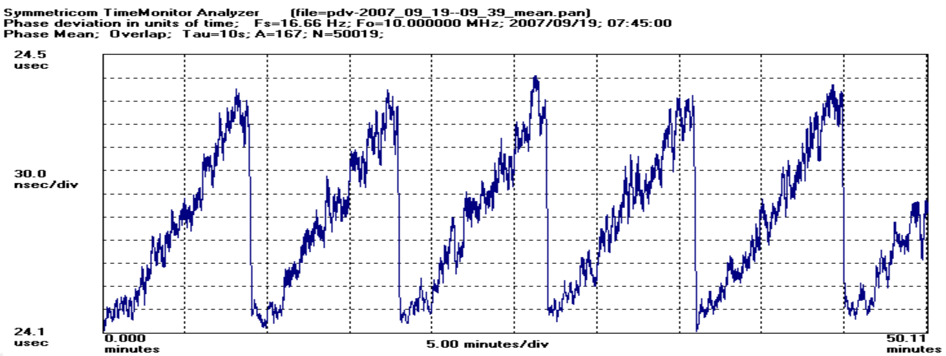


Raw PDV vs. Running Statistics

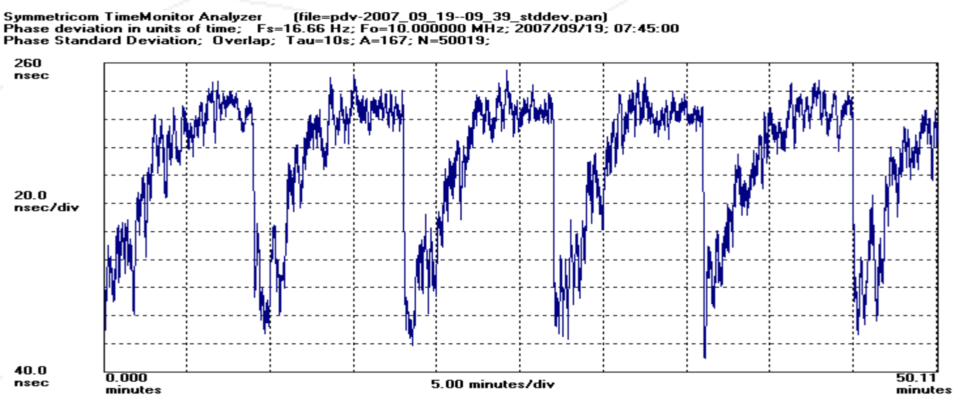
Symmetricom



Raw packet delay appears relatively static over time



Mean vs. time shows cyclical ramping more clearly

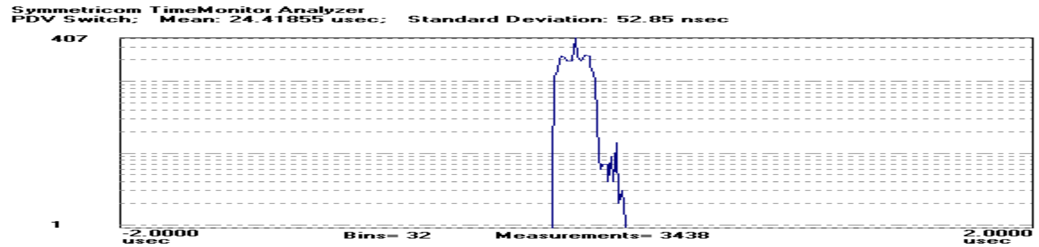


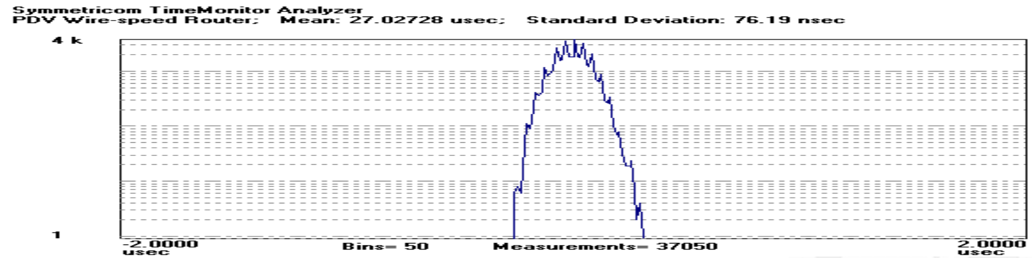
Standard deviation vs. time shows a quick ramp up to a flat peak

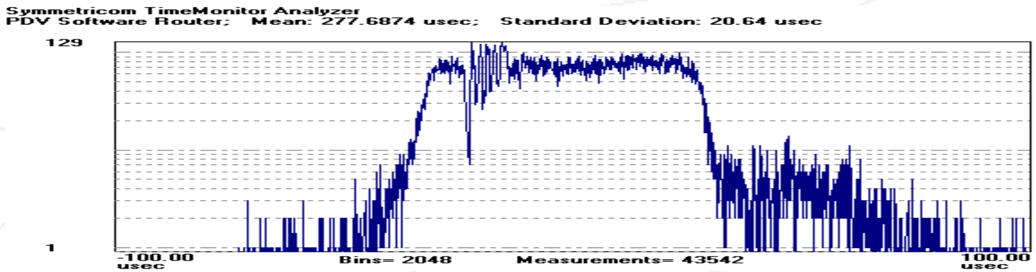
Not All Devices are *Equal*

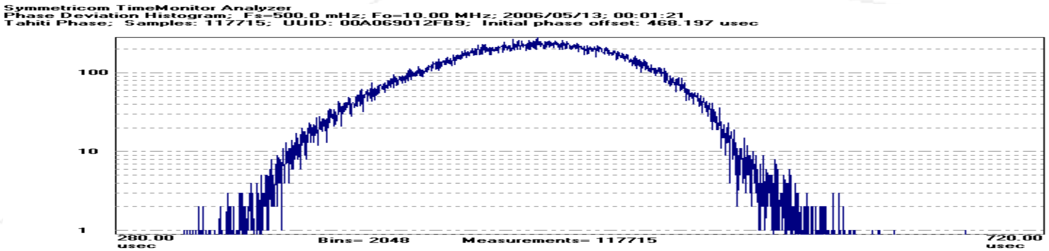
Symmetricom

Switch vs. Multilayer switch vs. Router vs. Two Routers









Statistics

Switch:
Mean: 24.41855 μsec
Peak to Peak: 334.8 nsec
Standard Deviation: 52.85 nsec

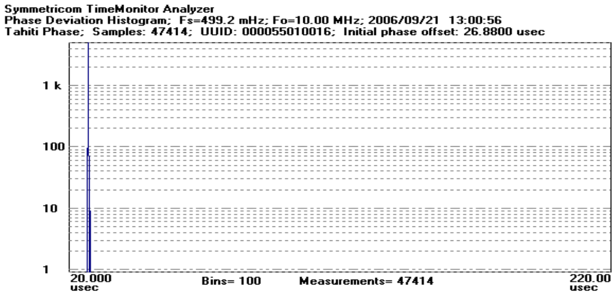
Multilayer Switch:
Mean: 27.02728 μsec
Peak to Peak: 576.0 nsec
Standard Deviation: 76.19 nsec

Router:
Mean: 277.6874 μsec
Peak to Peak: 212.5 μsec
Standard Deviation: 20.64 μsec

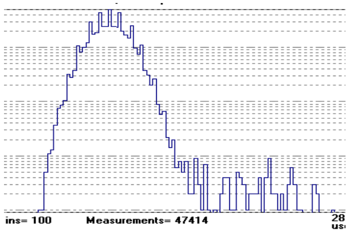
Two Routers:
Mean: 477.6874 µsec
Peak to Peak 369.7 µsec
Standard Deviation: 43.18 msec

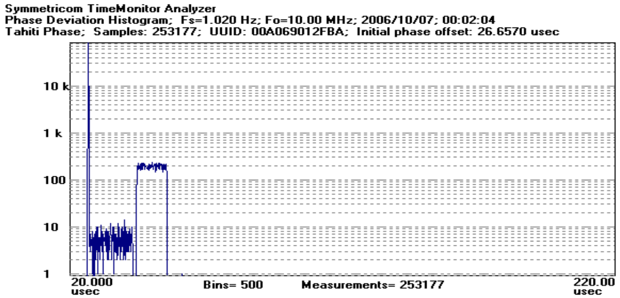
Multilayer Switch with Traffic

Symmetricom

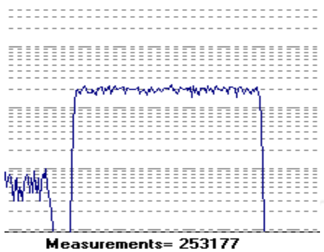


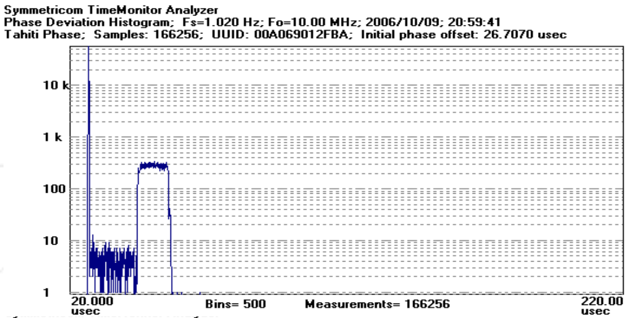
5%



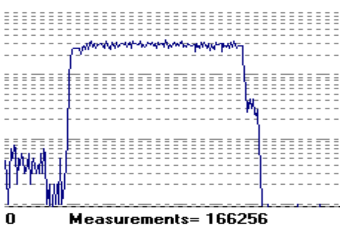


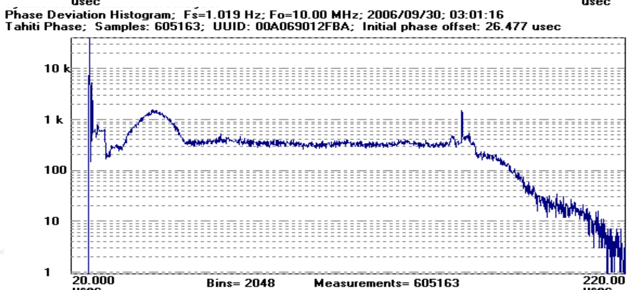
10%





20%





50%

Zooms

No traffic:
Mean: 26.9586 µsec
Peak to Peak: 620.4 nsec
Standard Deviation: 73.20 nsec

5% BW Utilization:
Mean: 26.9462 µsec
Peak to Peak: 1.209 µsec
Standard Deviation: 79.12 nsec

10% BW Utilization:
Mean: 28.9450 µsec
Peak to Peak: 34.77 µsec
Standard Deviation: 7.008 µsec

20% BW Utilization:
Mean: 31.2810 µsec
Peak to Peak: 40.41 µsec
Standard Deviation: 9.426 µsec

30% BW Utilization:
Mean: 33.6201 µsec
Peak to Peak: 41.70 µsec
Standard Deviation: 10.88 µsec

50% BW Utilization (2 Traffic Sources):
Mean: 80.8216 µsec
Peak to Peak: 206.6 µsec
Standard Deviation: 47.06 µsec

Multilayer Switch with Traffic

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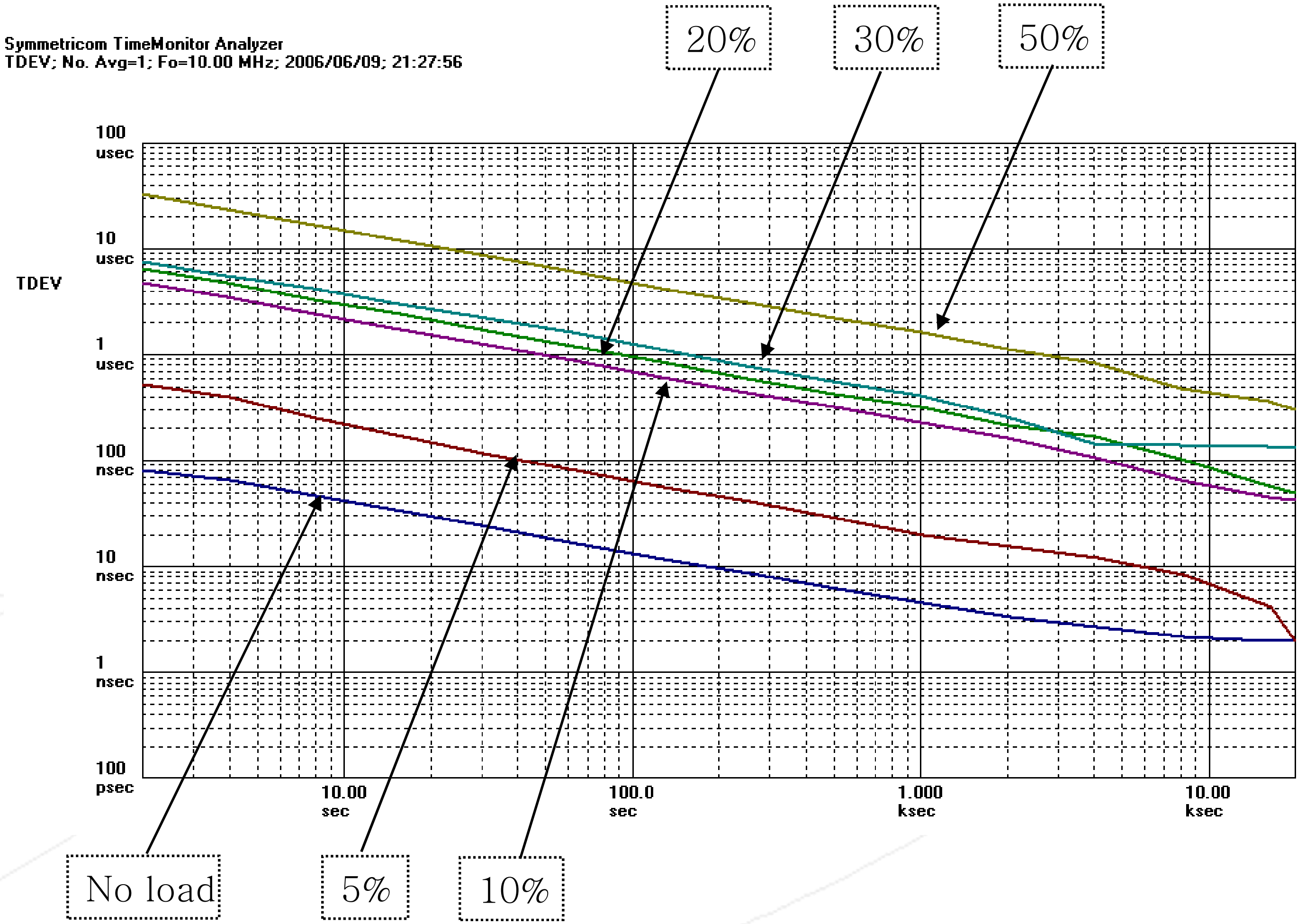
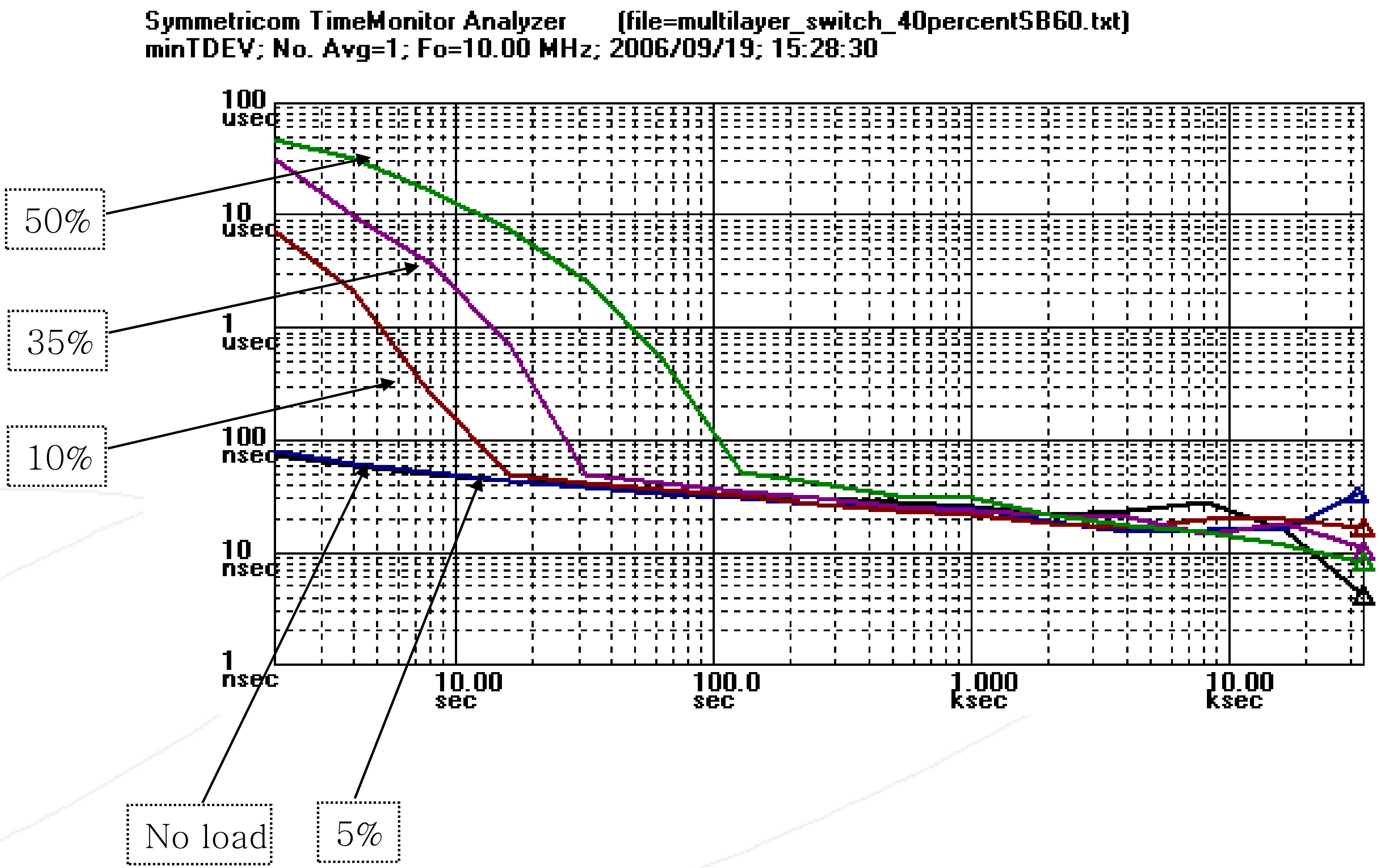


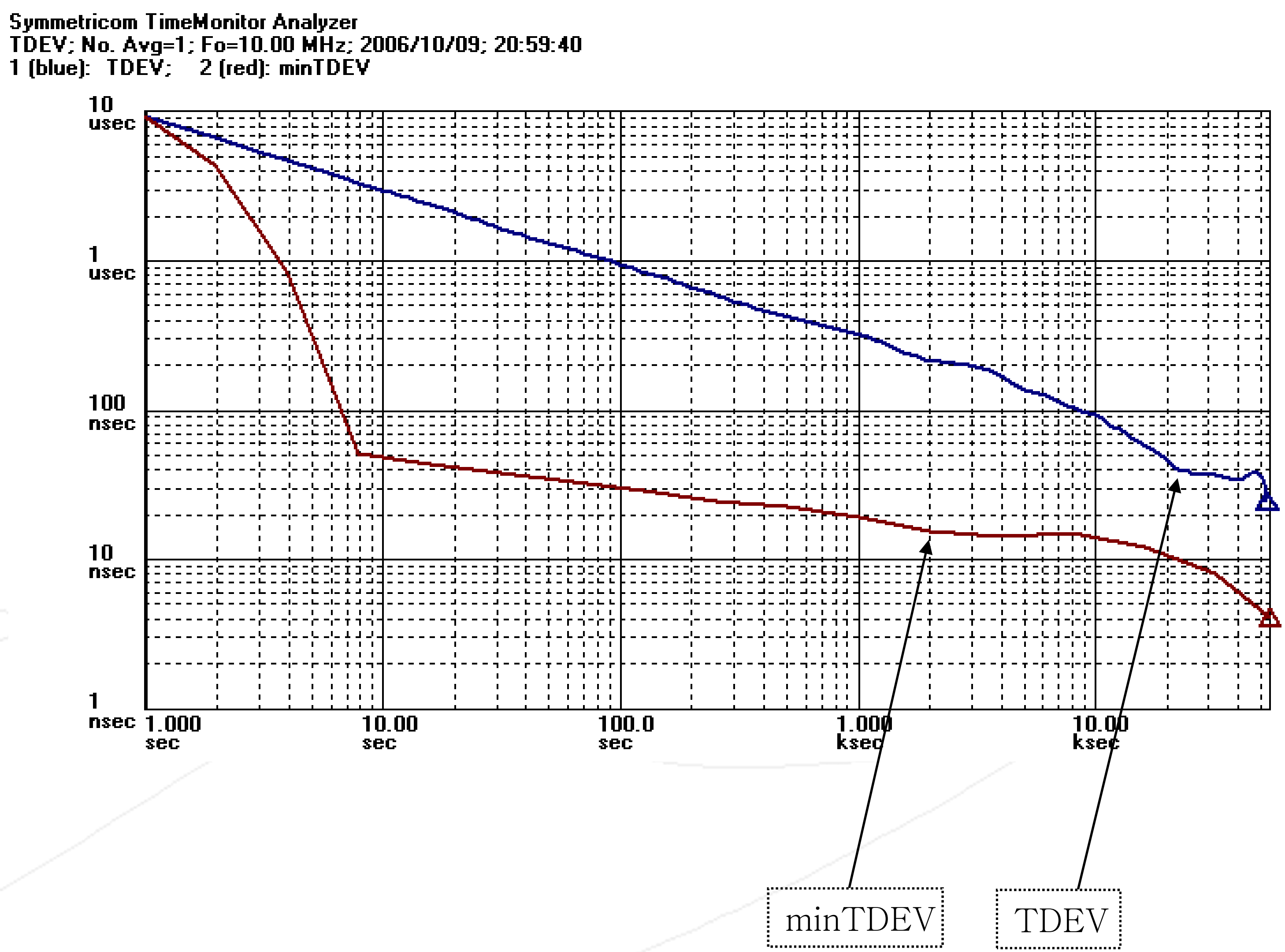
TDEV

TDEV with Selection Algorithm: minTDEV

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



Definition of bandTDEV

Symmetricom®

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

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

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

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

Example bandTDEV Calculation

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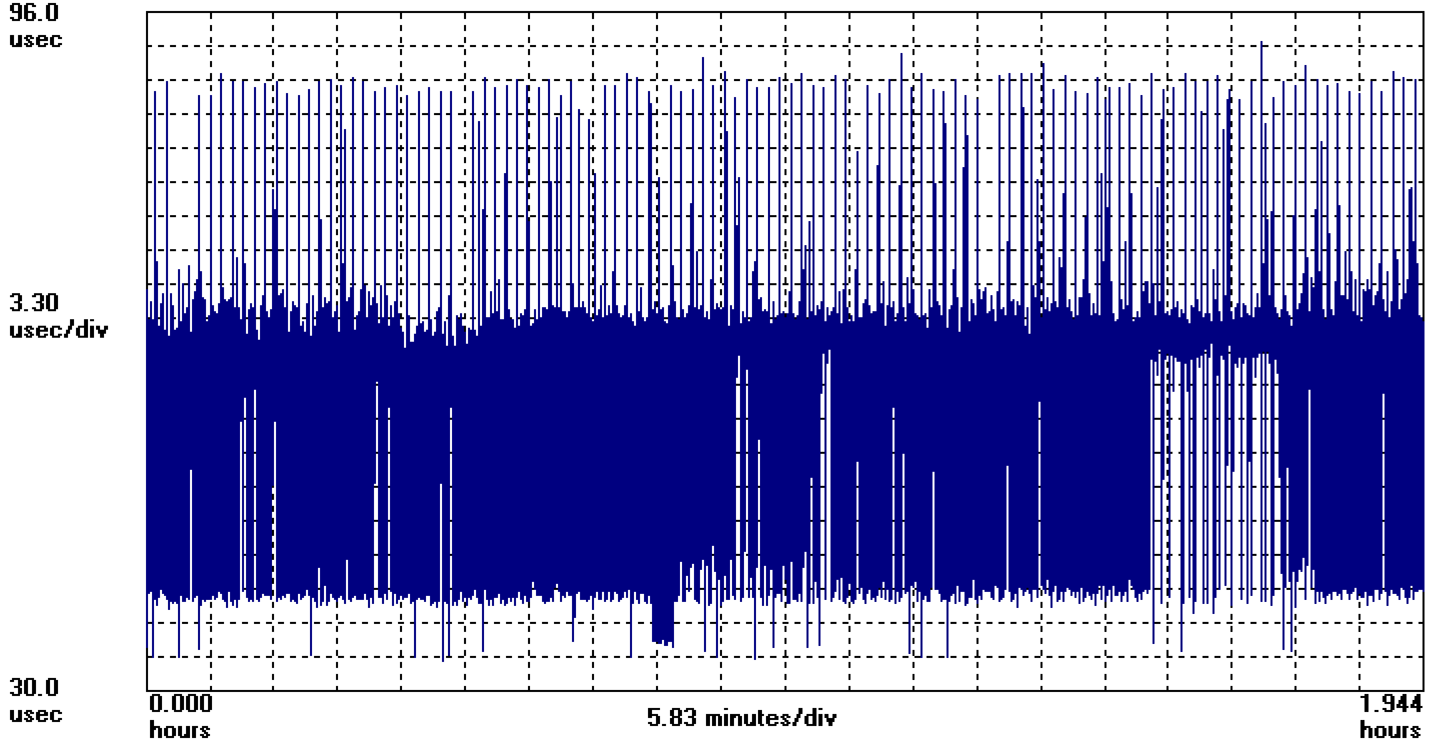
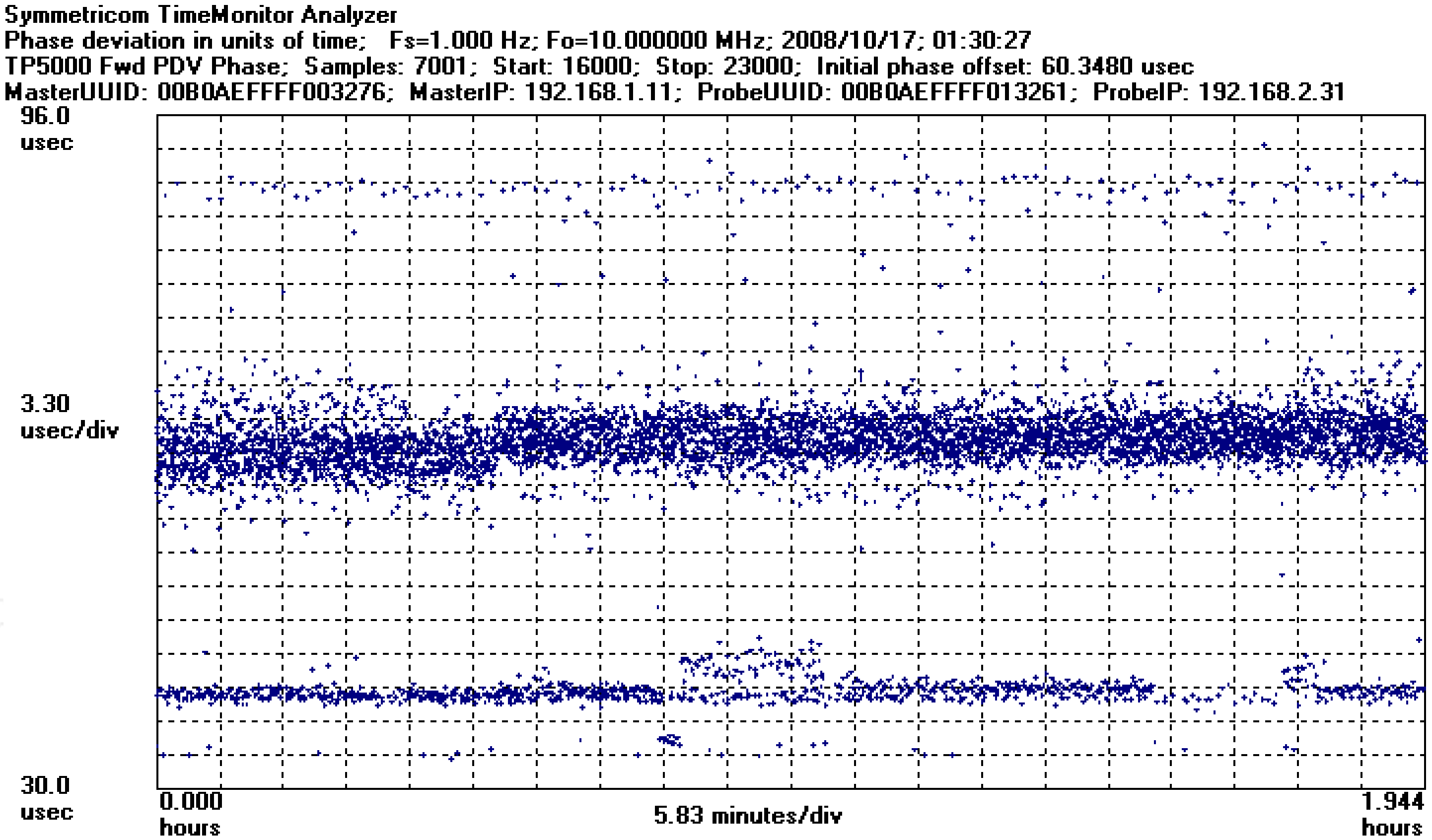
Phase (Packet Delay Sequence)

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=1.000 Hz; Fo=10.000000 MHz; 2008/10/17; 01:30:27
TP5000 Fwd PDV Phase; Samples: 7001; Start: 16000; Stop: 23000; Initial phase offset: 60.3480 usec
MasterUUID: 00B0AEFFFF003276; MasterIP: 192.168.1.11; ProbeUUID: 00B0AEFFFF013261; ProbeIP: 192.168.2.31



Example bandTDEV Calculation

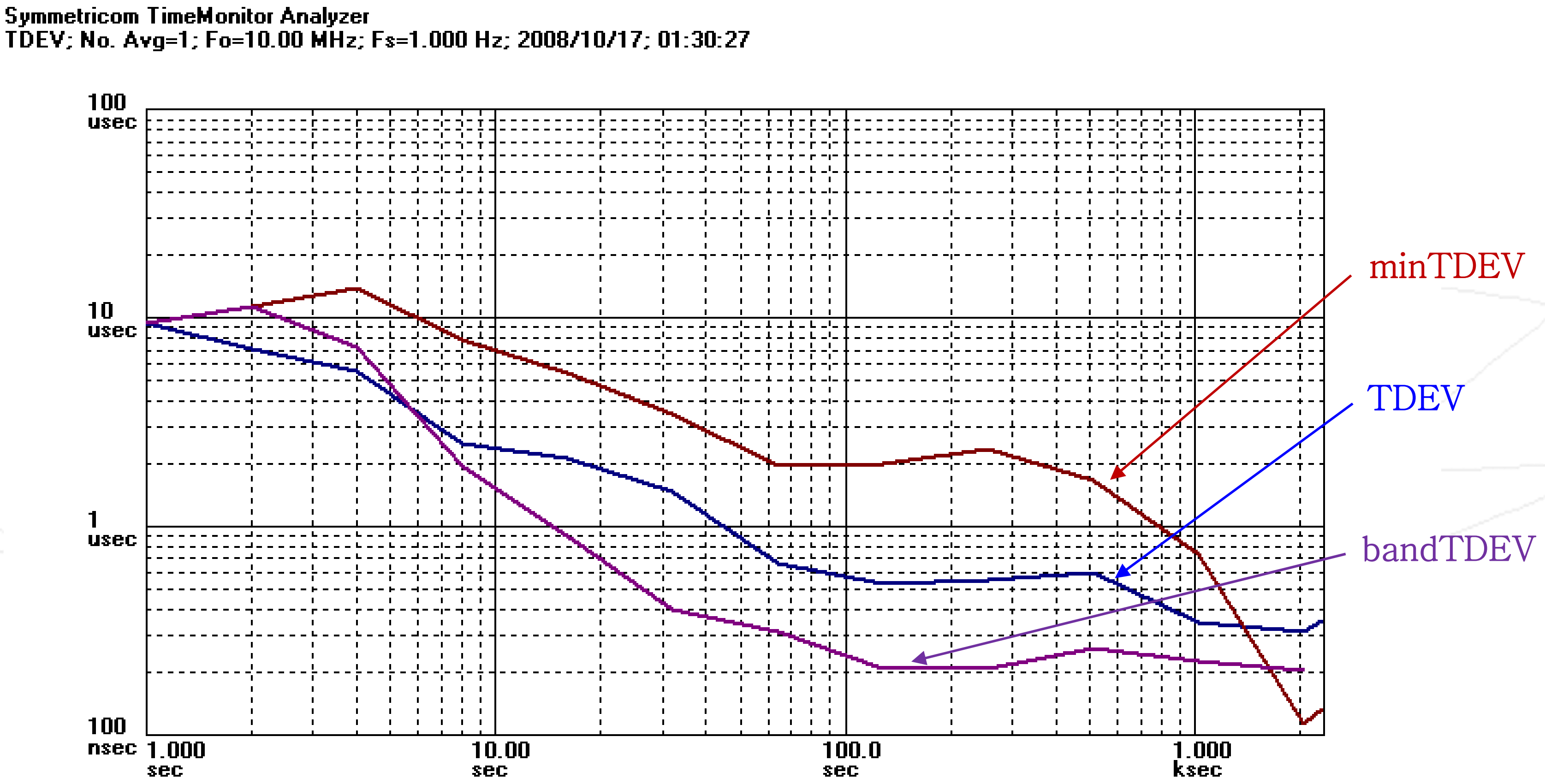
Phase Scatter Plot (Packet Delay Sequence)



Example bandTDEV Calculation

Symmetricom

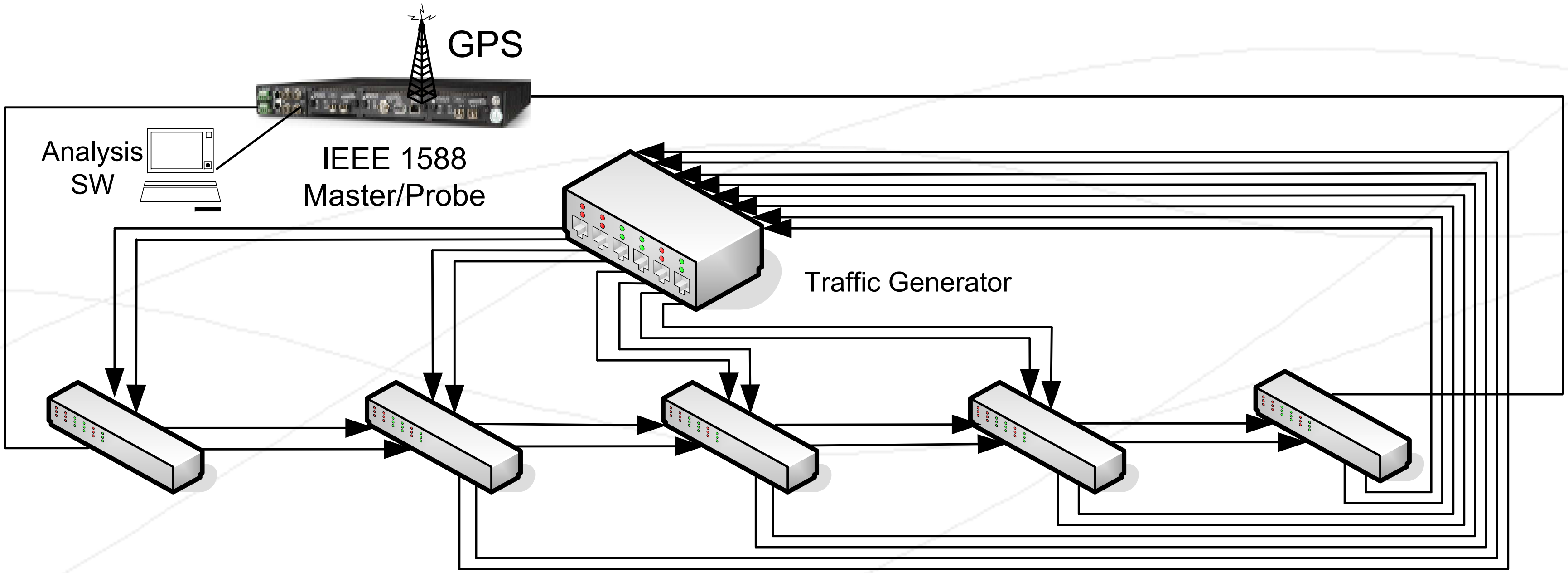
TDEV
minTDEV
bandTDEV (0.4 to 0.6)



Effects of Different Approaches to Traffic Generation on PDV

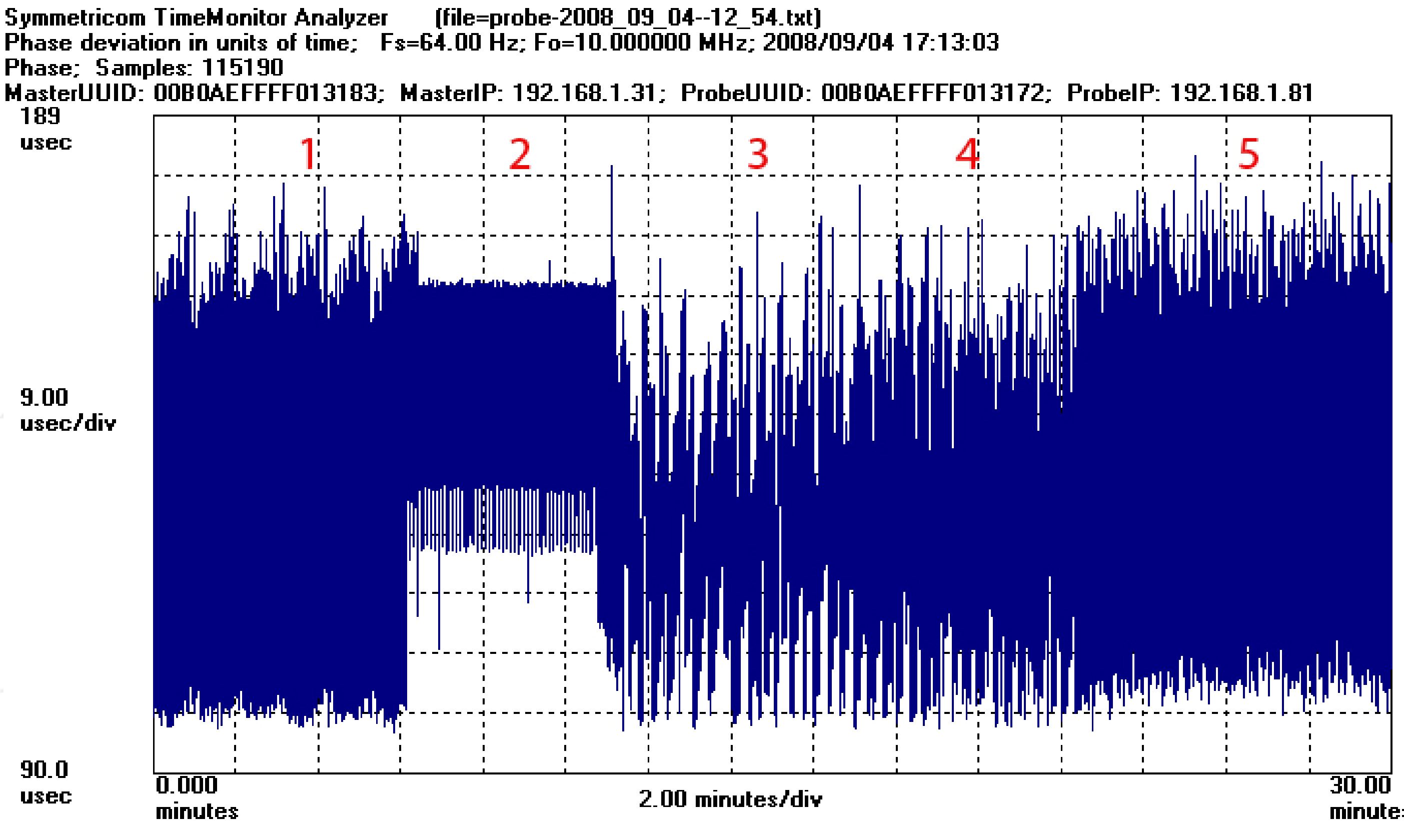
Many aspects of traffic generation, from the choice of equipment to the way the equipment is configured, can have a great impact on packet delay variation and by extension on the performance of devices timing from the packet flows, such as IEEE 1588 slaves.

Network Setup



Effects of Different Approaches to Traffic Generation on PDV

	Total BW	BW Port 1/2	Frame Size	Burst Length	Interburst Gap
1	40%	20% / 20%	Different	200000	Same
2	40%	20% / 20%	Same	200000	Same
3	40%	20% / 20%	Same	50000	Same
4	40%	20% / 20%	Same	50000	Different
5	40%	21% / 19%	Same	50000	Different

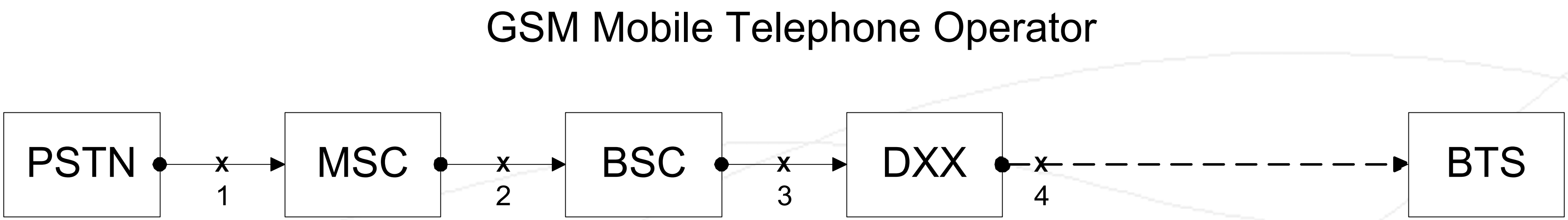


Symmetricom

TDM Network Measurement Examples

Sync Measurement #1: Network Element Cascading

Sync degradation with cascading: PSTN-MSC-BSC-DXX

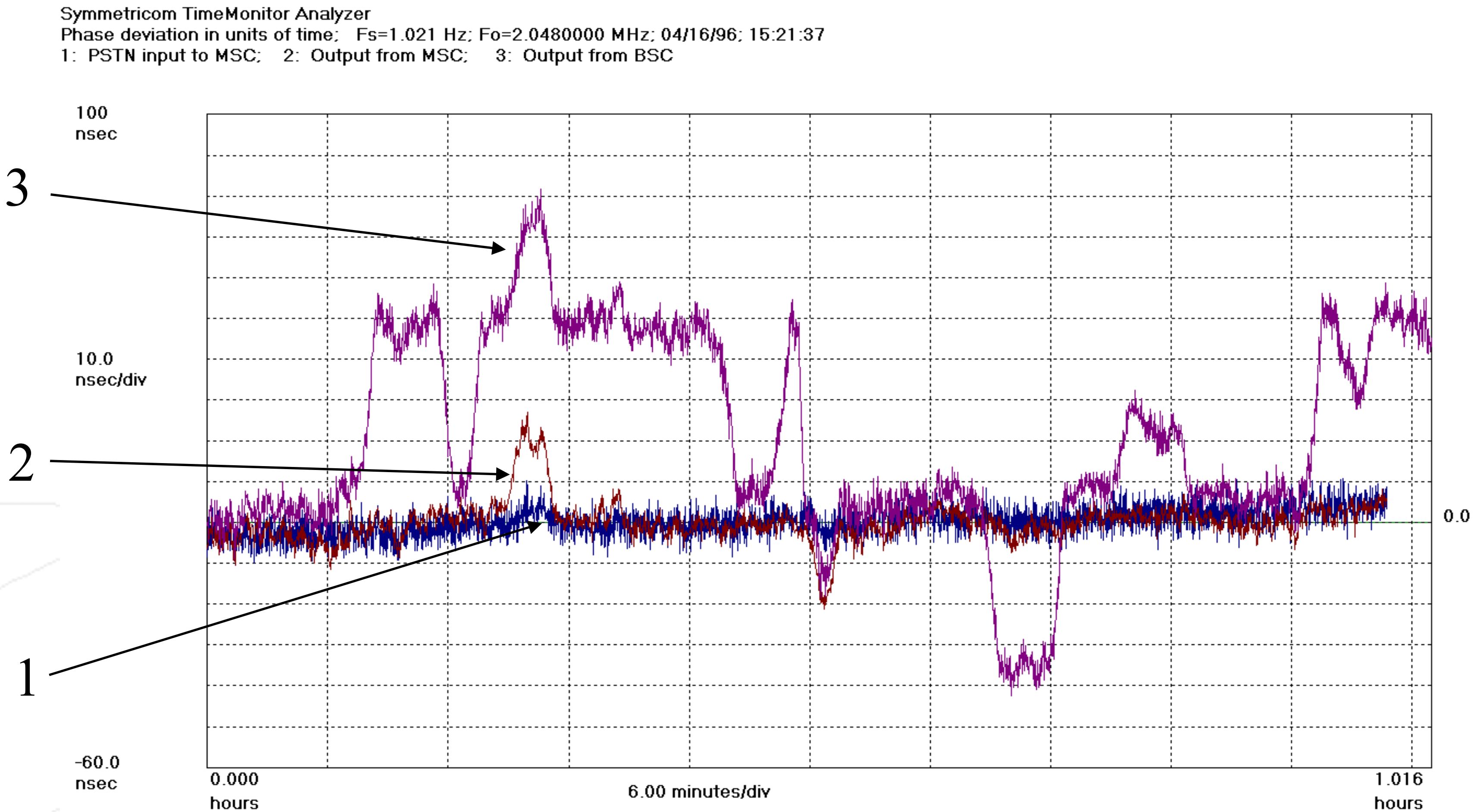


x: measurement points

Sync Measurement #1: Network Element Cascading

Symmetricom

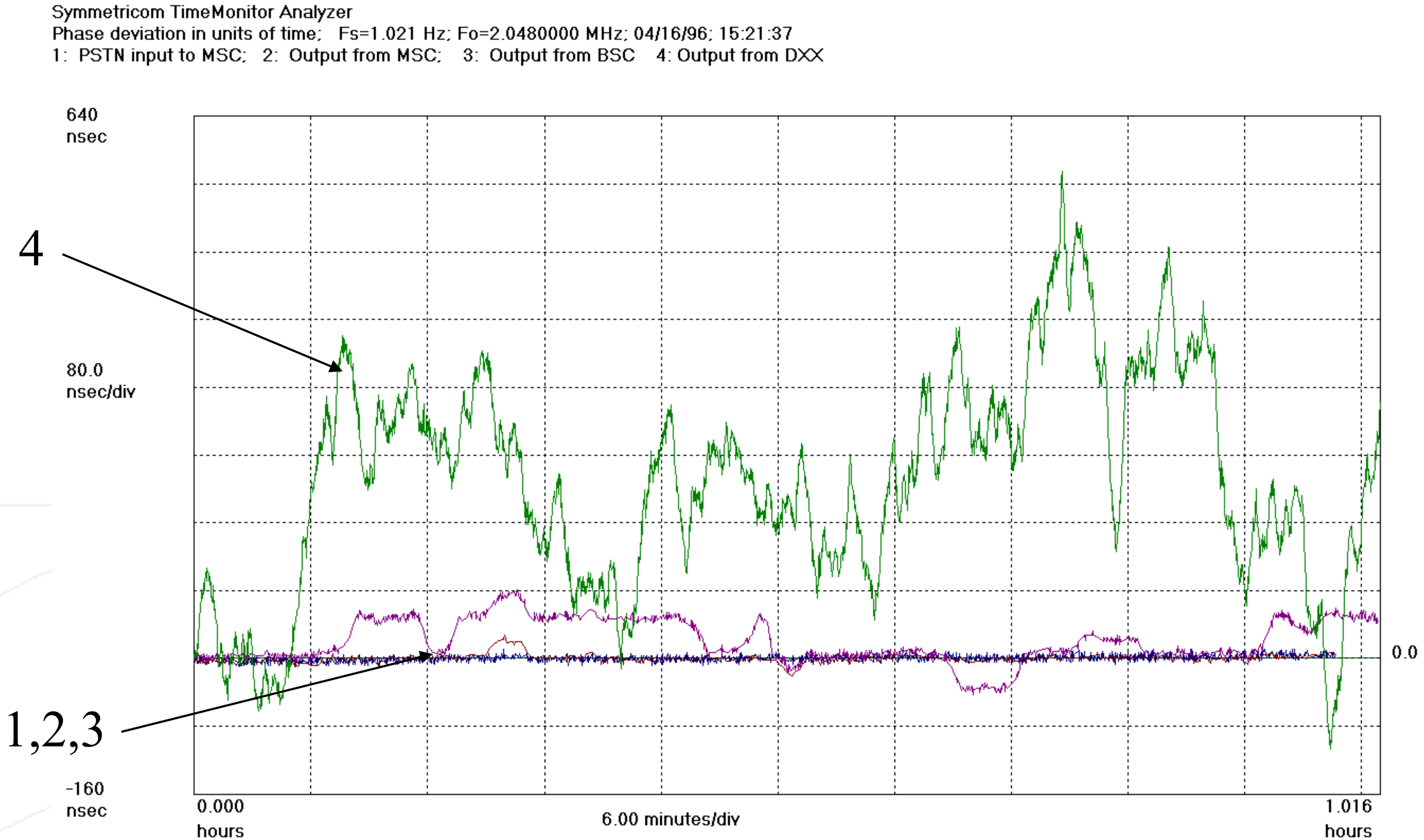
Sync degradation with cascading: PSTN-MSC-BSC-DXX
21 nsec to 48 nsec to 124 nsec to 682 nsec peak-to-peak TIE



Sync Measurement #1: Network Element Cascading

Symmetricom

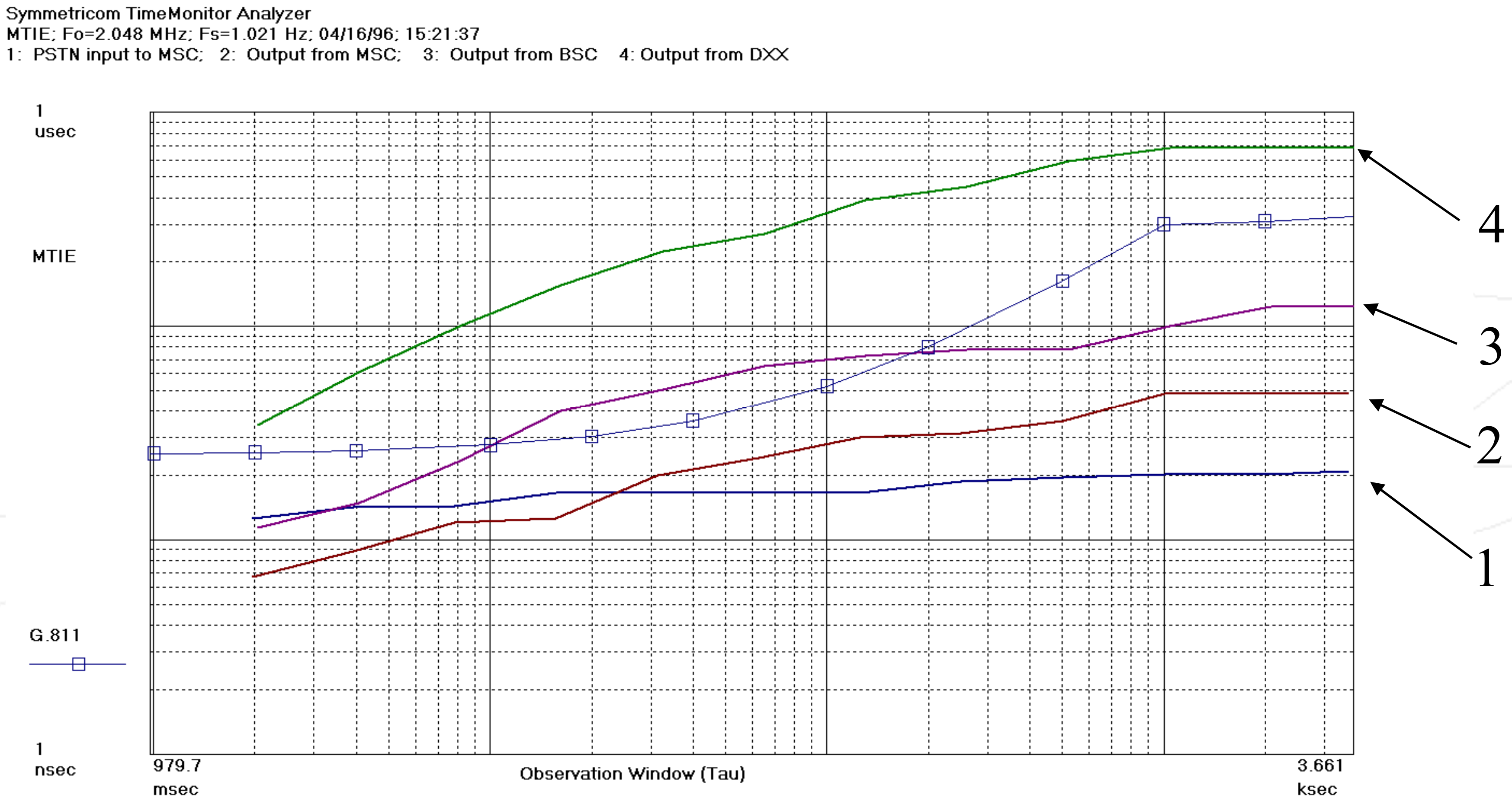
Sync degradation with cascading: PSTN-MSC-BSC-DXX
21 nsec to 48 nsec to 124 nsec to 682 nsec peak-to-peak TIE



Sync Measurement #1: Network Element Cascading

Symmetricom

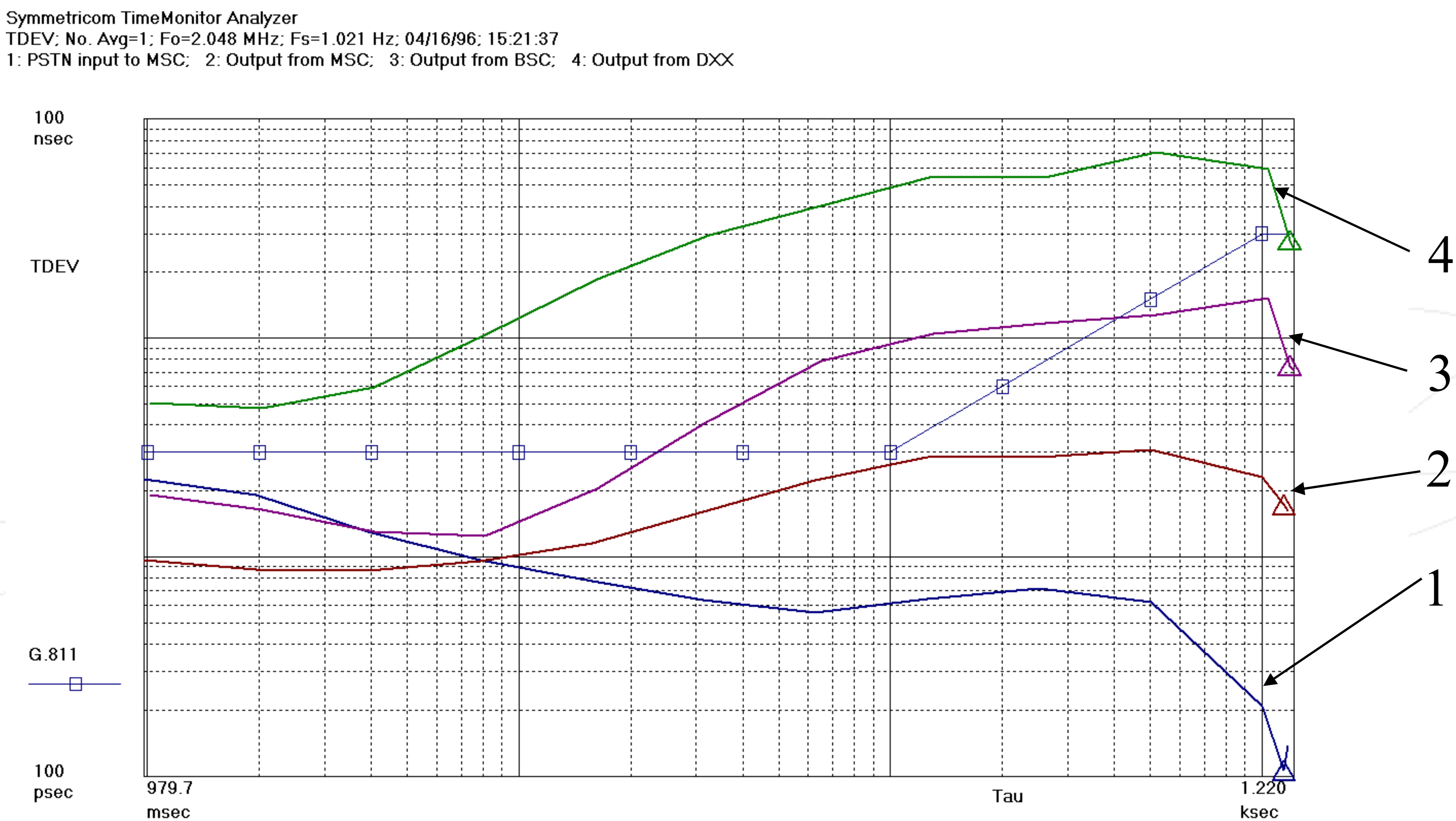
Sync degradation with cascading: PSTN-MSC-BSC-DXX MTIE



Sync Measurement #1: Network Element Cascading

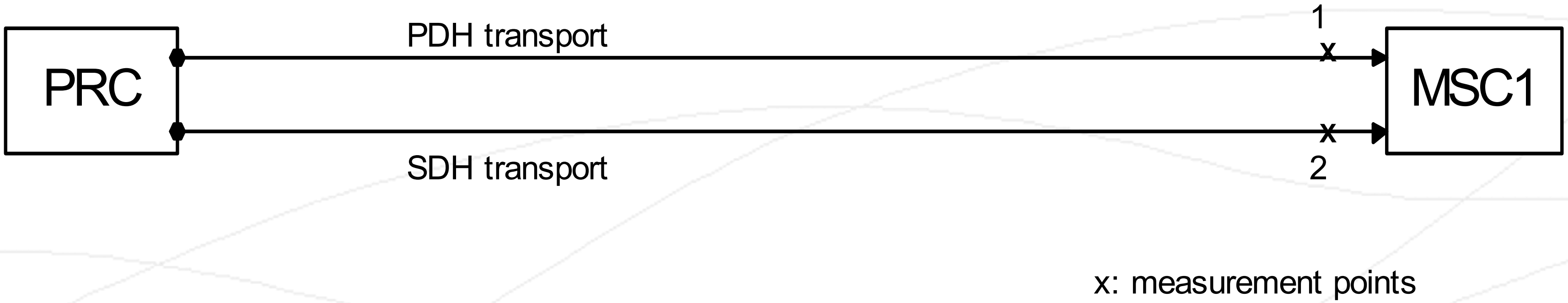
Symmetricom

Sync degradation with cascading: PSTN-MSC-BSC-DXX TDEV



Sync Measurement #2: SDH/SONET vs. PDH Transport

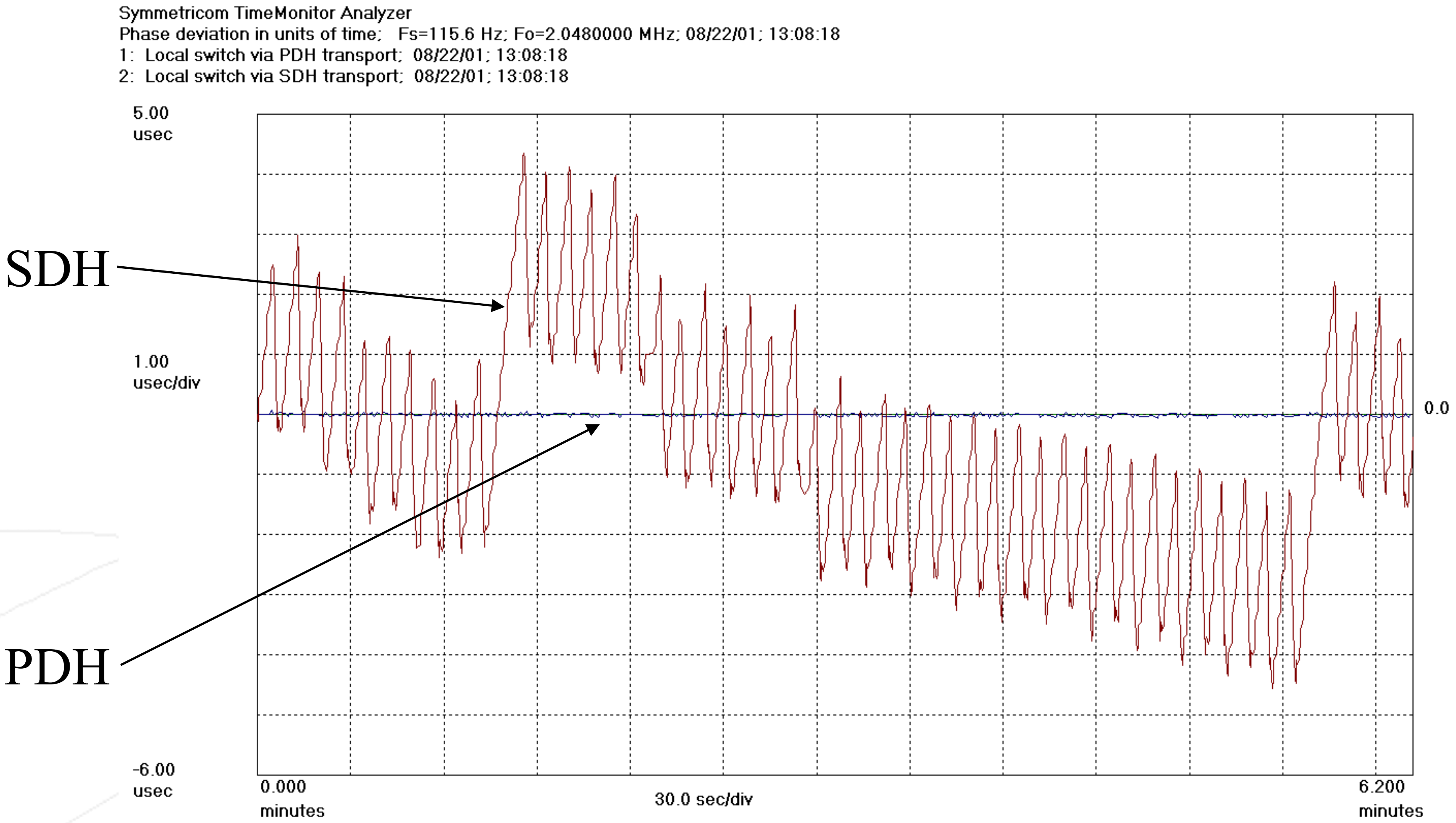
MSC PSTN timing: PDH vs. SDH transport



Sync Measurement #2: SDH/SONET vs. PDH Transport

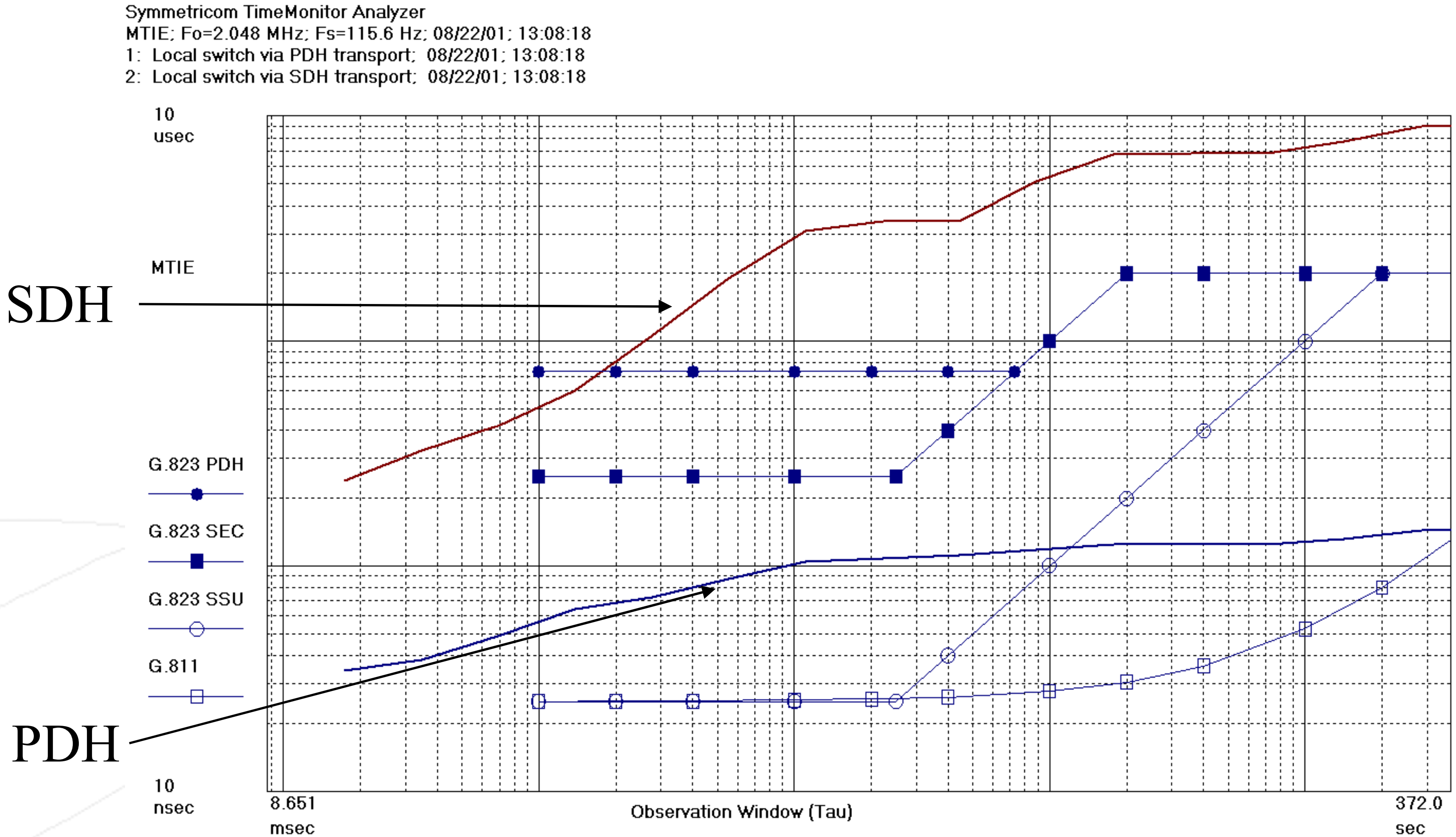
Symmetricom

PDH vs. SDH transport



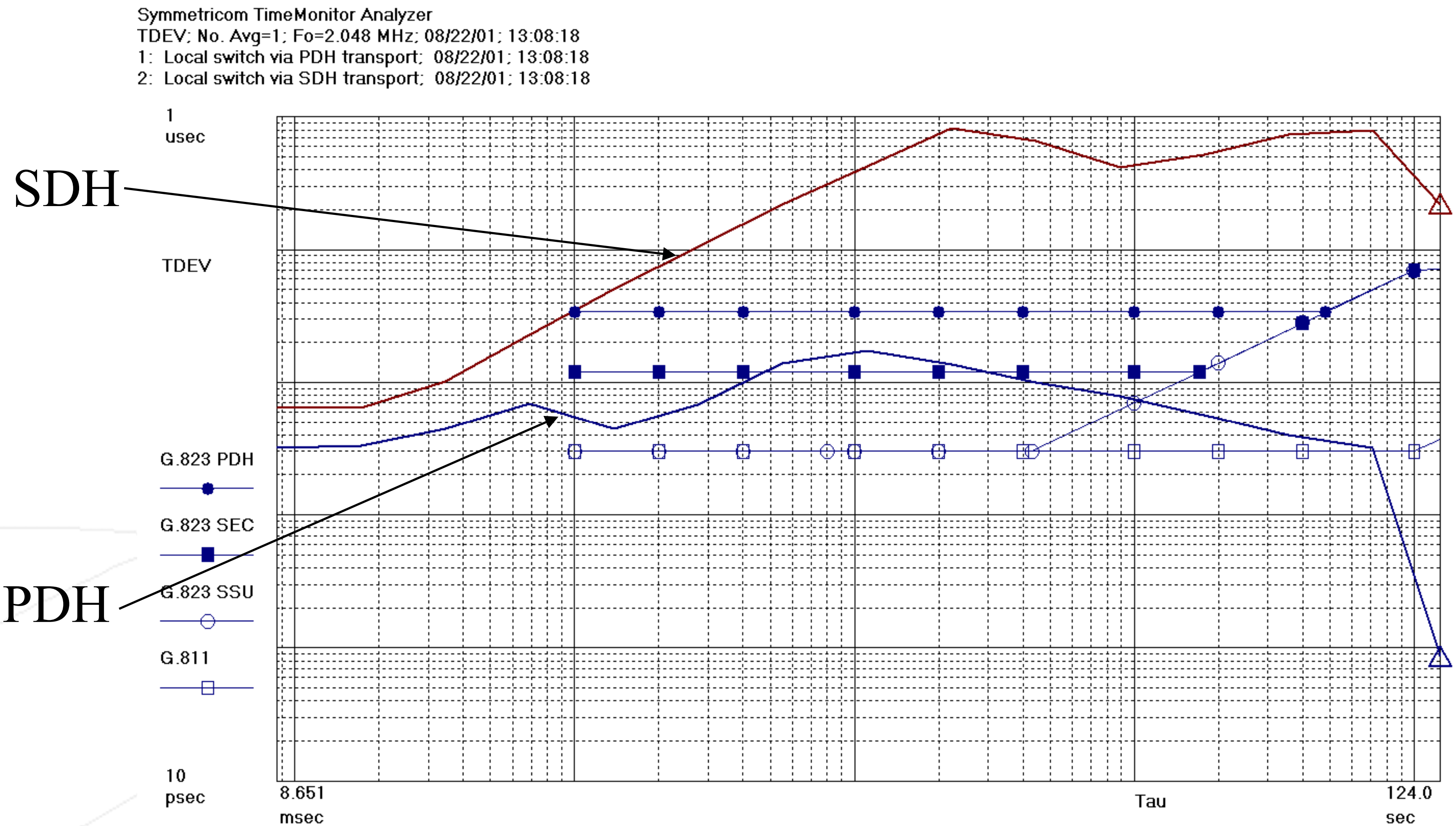
Sync Measurement #2: SDH/SONET vs. PDH Transport

PDH vs. SDH transport



Sync Measurement #2: SDH/SONET vs. PDH Transport

PDH vs. SDH transport

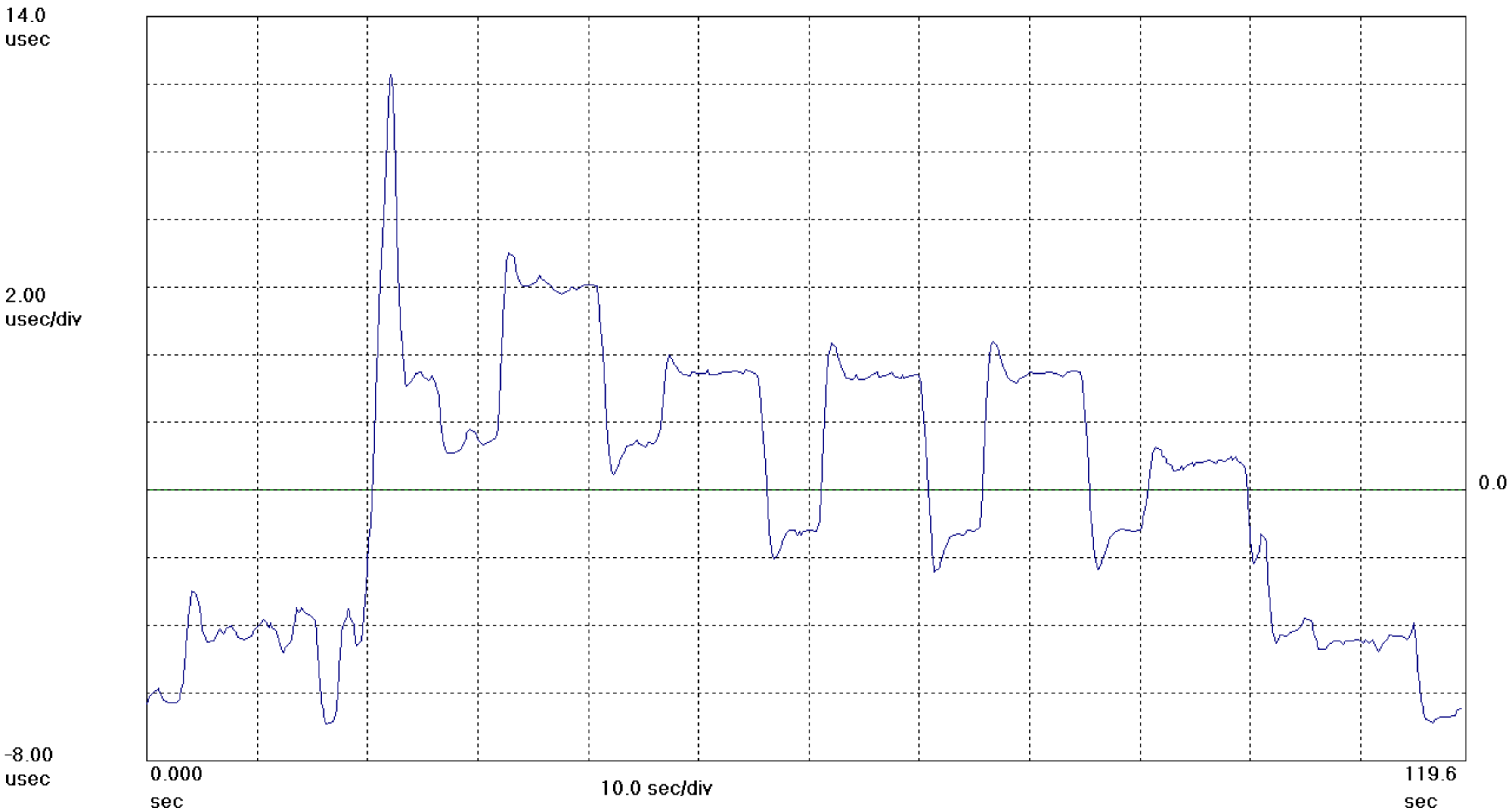


Sync Measurement #2: SDH/SONET vs. PDH Transport

Symmetricom

SONET pointer justifications on DS1

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=167.3 Hz; Fo=1.5440000 MHz; 02/19/98;20:57:50
DS1 transported in SONET VT payload with pointer justifications; Ymax-Ymin=2.542628863011 usec

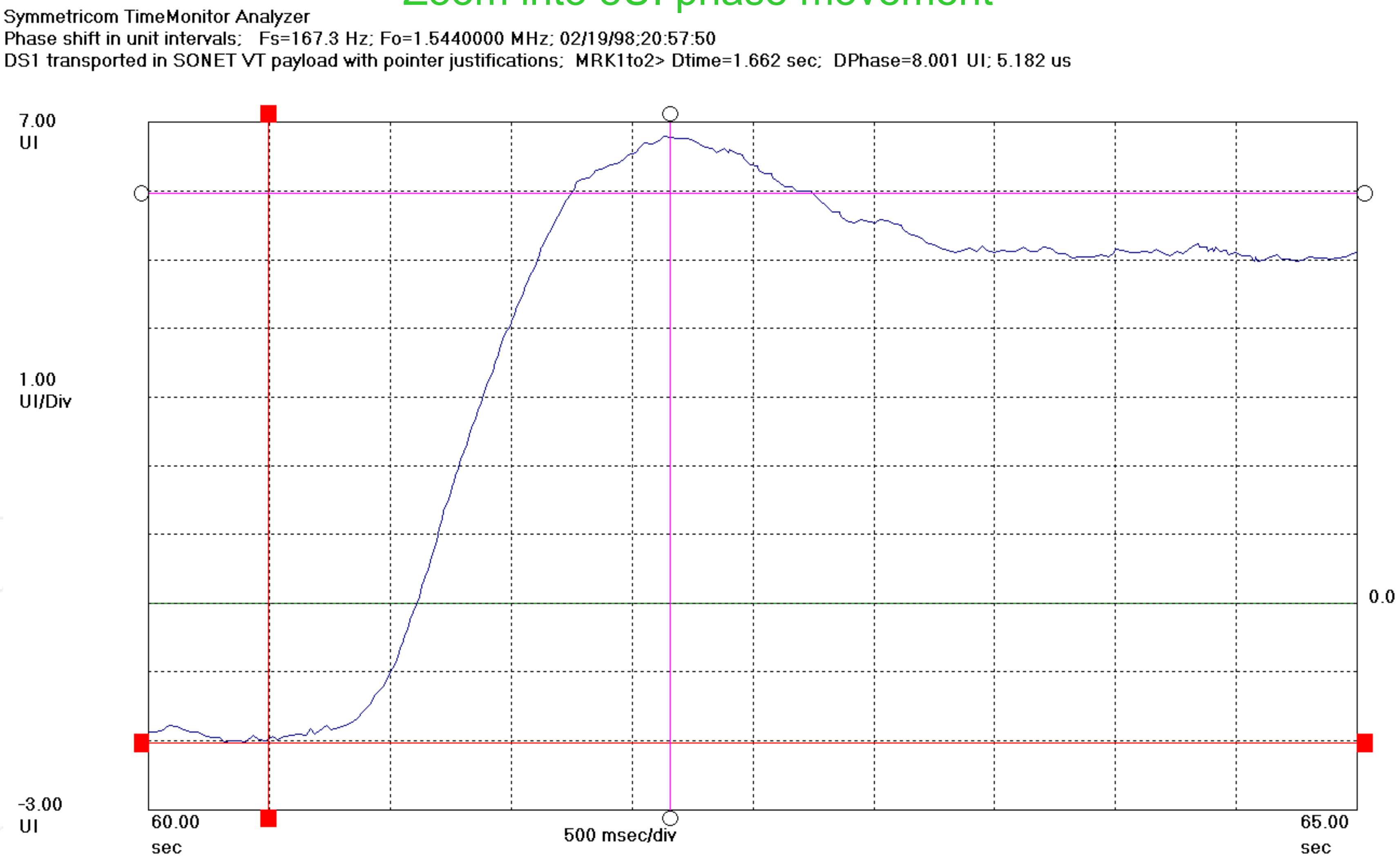


Sync Measurement #2: SDH/SONET vs. PDH Transport

Symmetricom

SONET pointer justifications on DS1

Zoom into 8UI phase movement

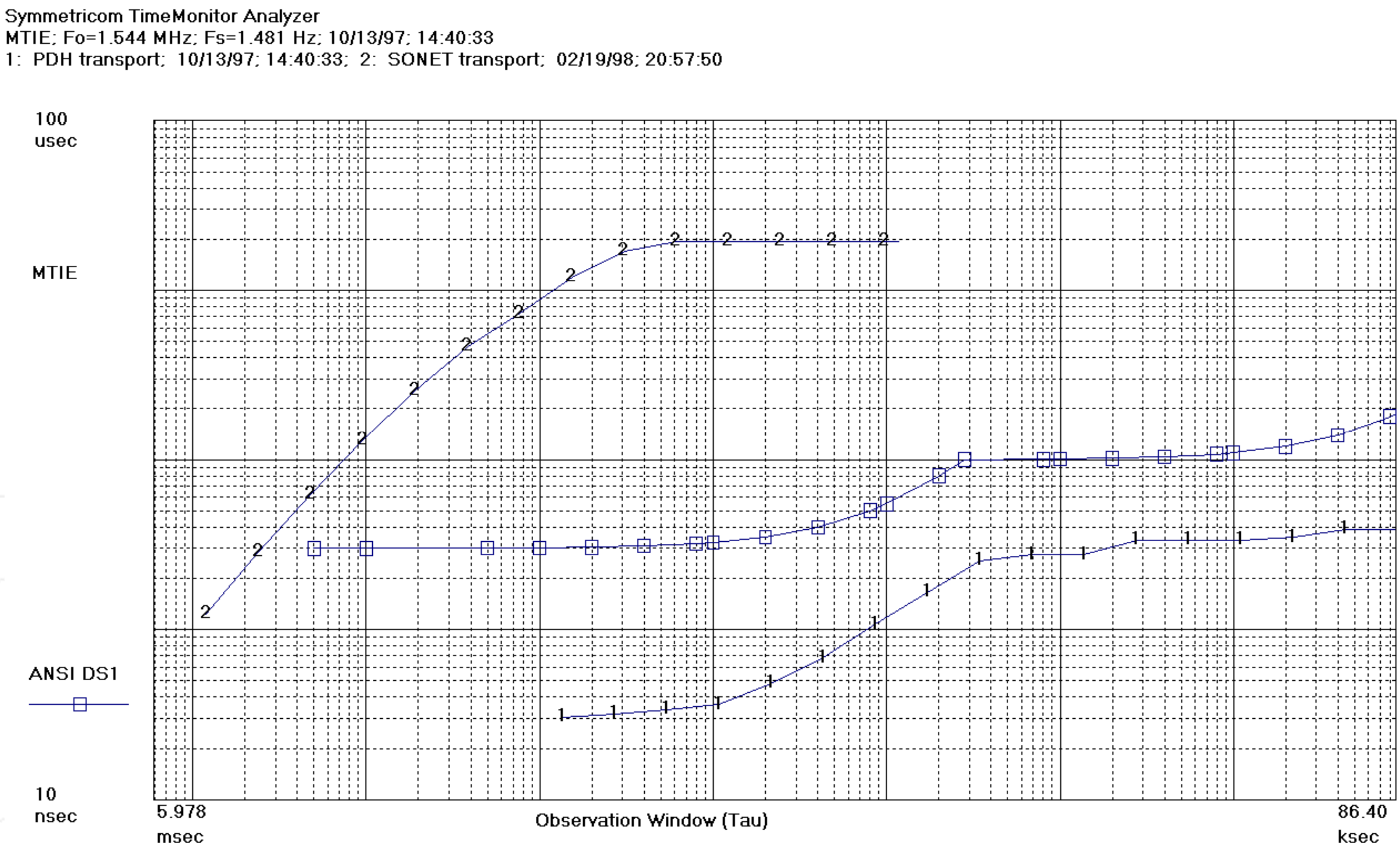


Sync Measurement #2: SDH/SONET vs. PDH Transport

Symmetricom

SONET pointer justifications on DS1

SONET vs. PDH transport MTIE comparison



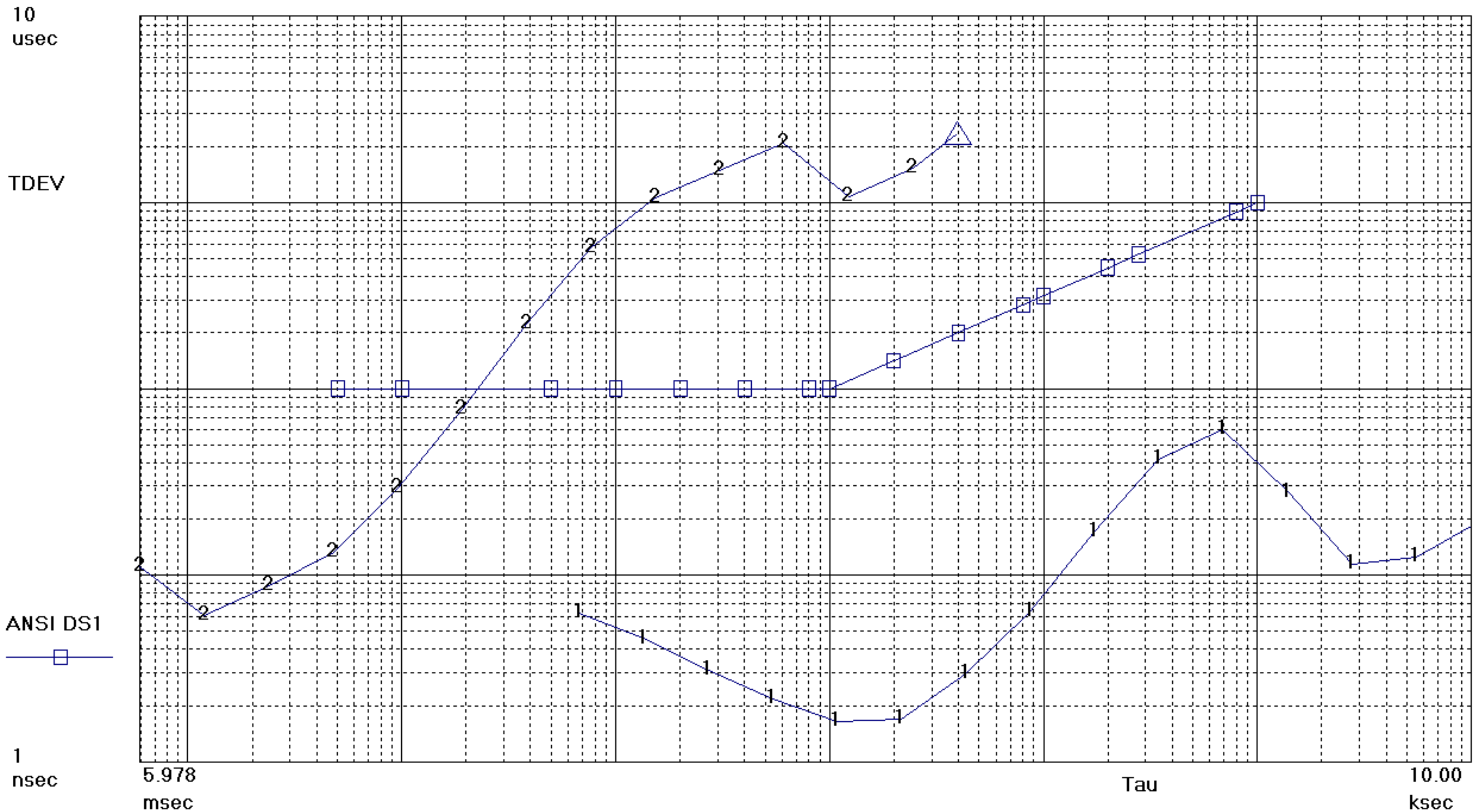
Sync Measurement #2: SDH/SONET vs. PDH Transport

Symmetricom

SONET pointer justifications on DS1

SONET vs. PDH transport TDEV comparison

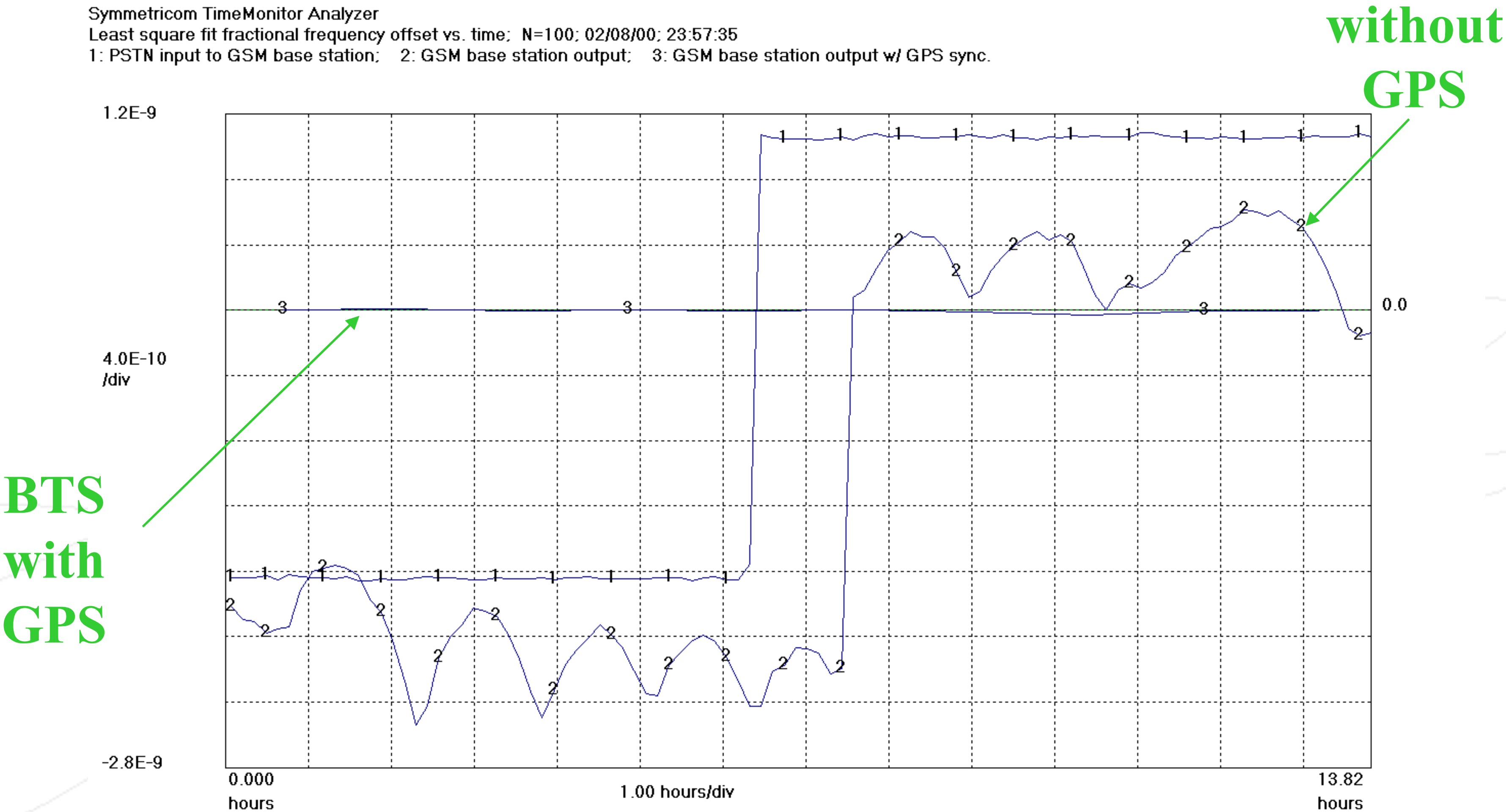
Symmetricom TimeMonitor Analyzer
TDEV; No. Avg=1; Fo=1.544 MHz; 10/13/97; 14:40:33
1: PDH transport; 2: SONET transport



Sync Measurement #3: GSM BTS: GPS vs. PSTN timing

Symmetricom

Frequency jump from PSTN at GSM base station

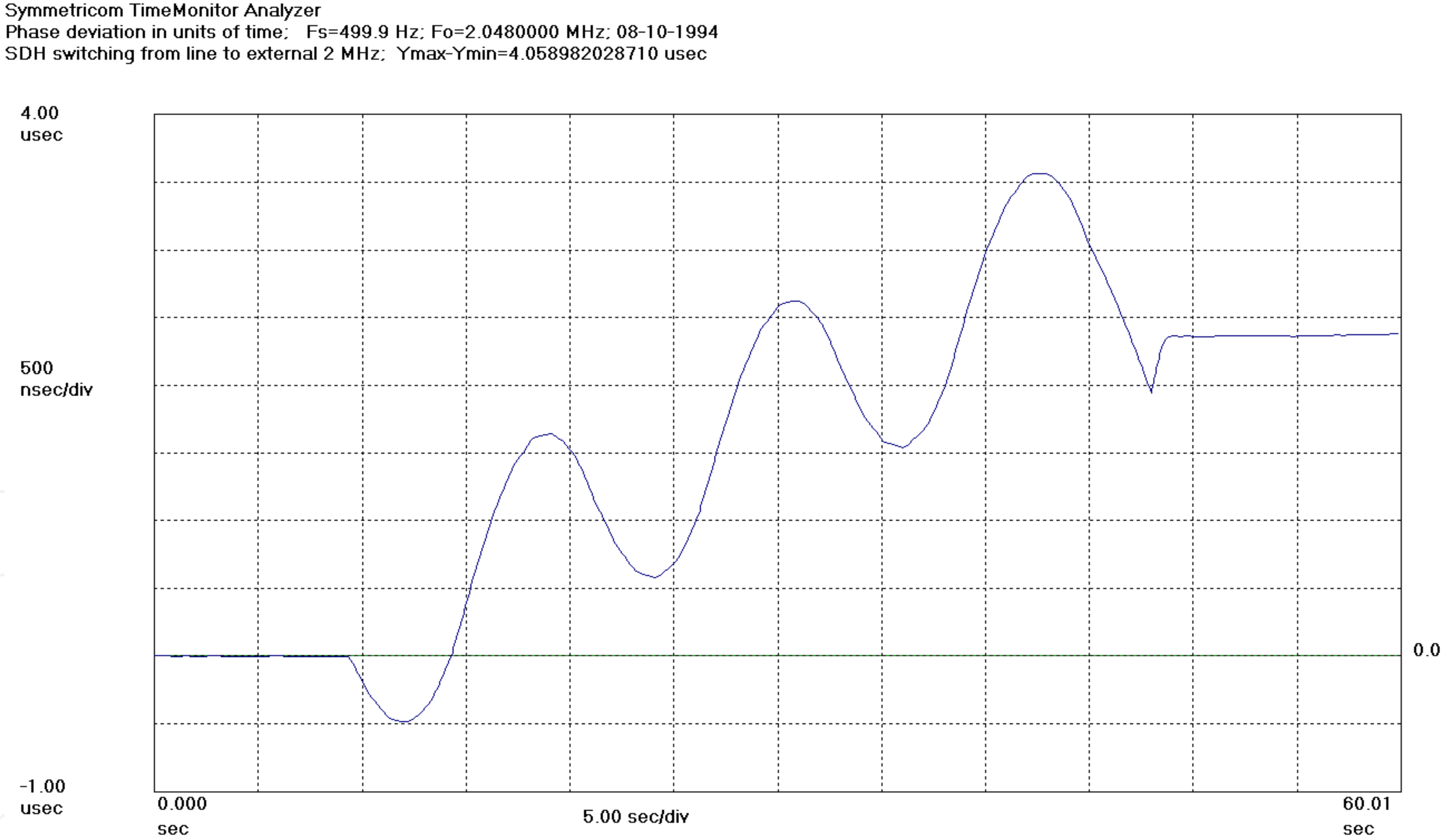


Sync Measurement #4: NE Reference Switching

Symmetricom

Reference switching

Phase deviation ringing and overall phase shift of 2.4 μsec

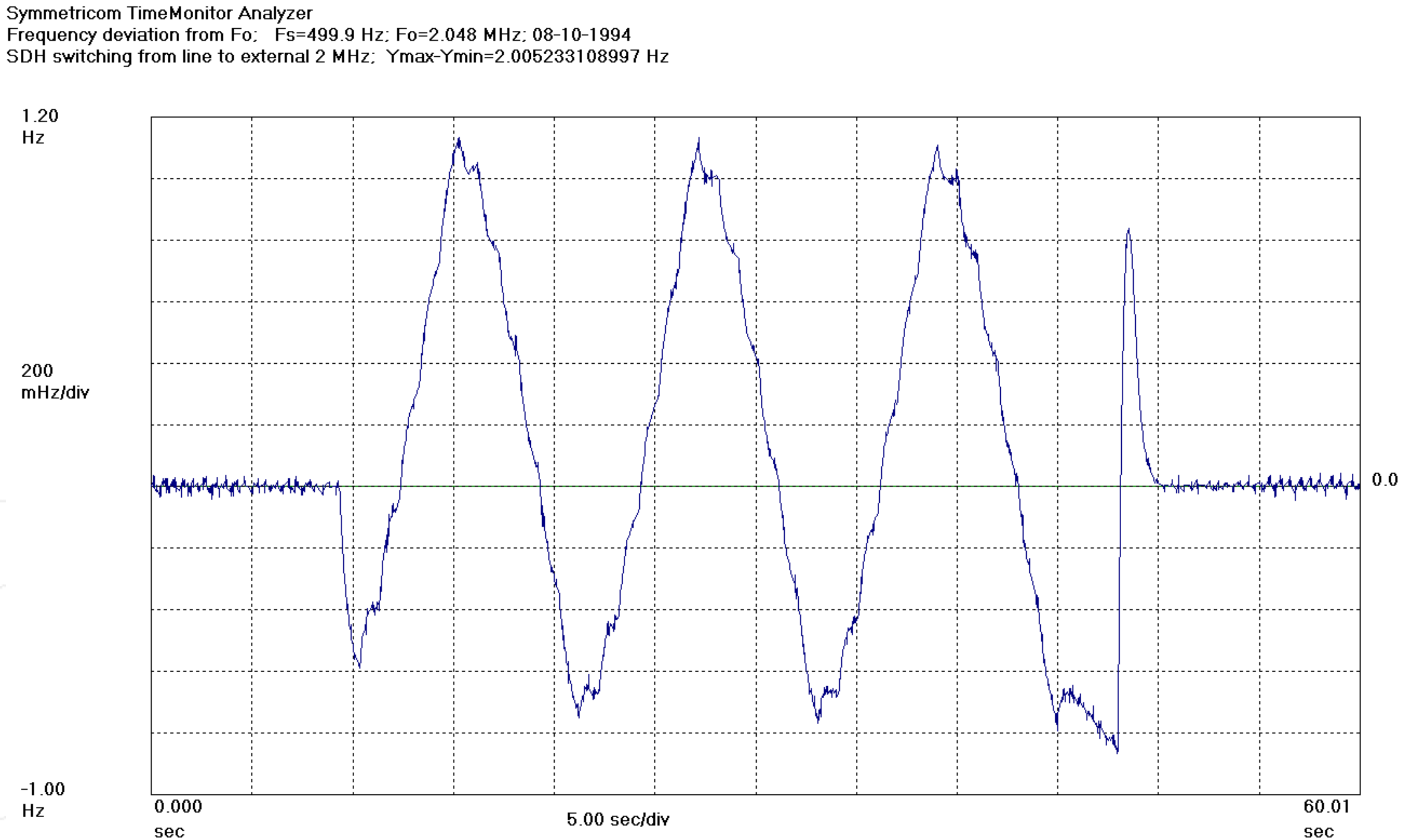


Sync Measurement #4: NE Reference Switching

Symmetricom

Reference switching

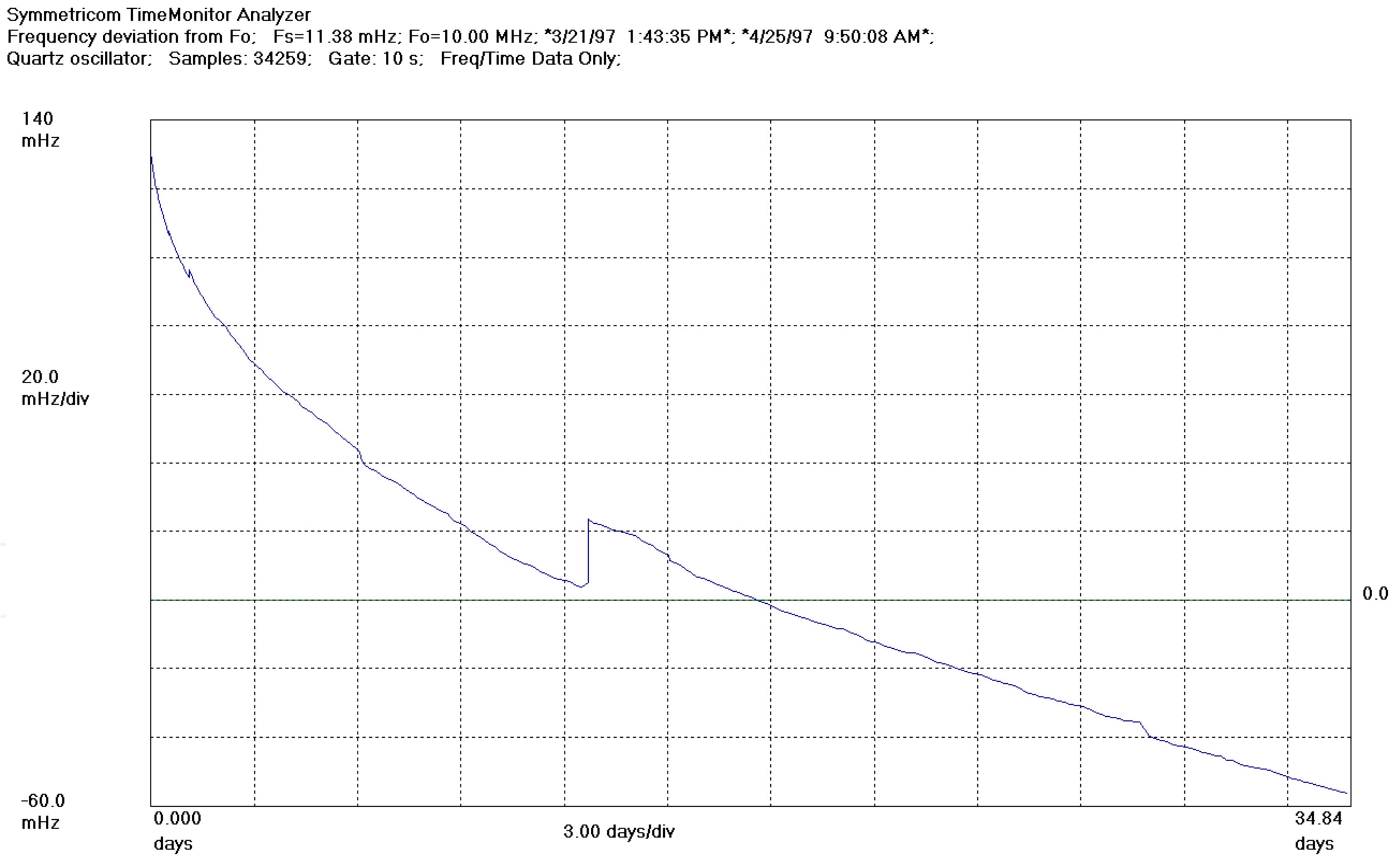
Frequency movement +/- 1 Hz



Sync Measurement #5: Oscillator Frequency Jump

Symmetricom

Oscillator frequency jump: effect on holdover

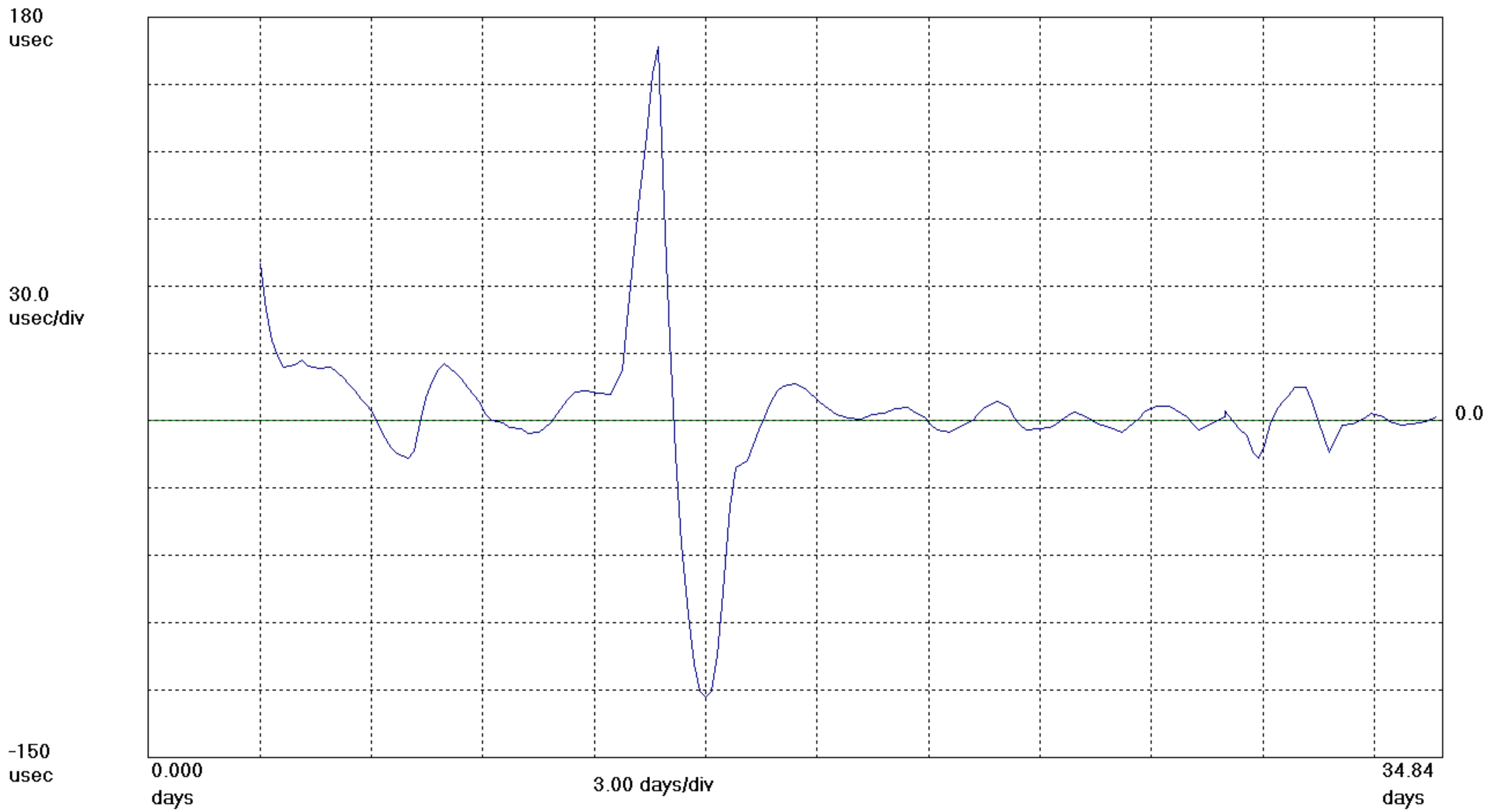


Sync Measurement #5: Oscillator Frequency Jump

Symmetricom

Oscillator frequency jump: effect on holdover
> 150 µsec rather than 1 to 10 µsec

Symmetricom TimeMonitor Analyzer
Holdover vs. time; N=200; Start/Learn/Holdover(h): 0.000,48.00,24.00; *3/21/97 1:43:35 PM*; *4/25/97 9:50:08 AM*;
Quartz oscillator; Samples: 34259; Gate: 10 s; Freq/Time Data Only;

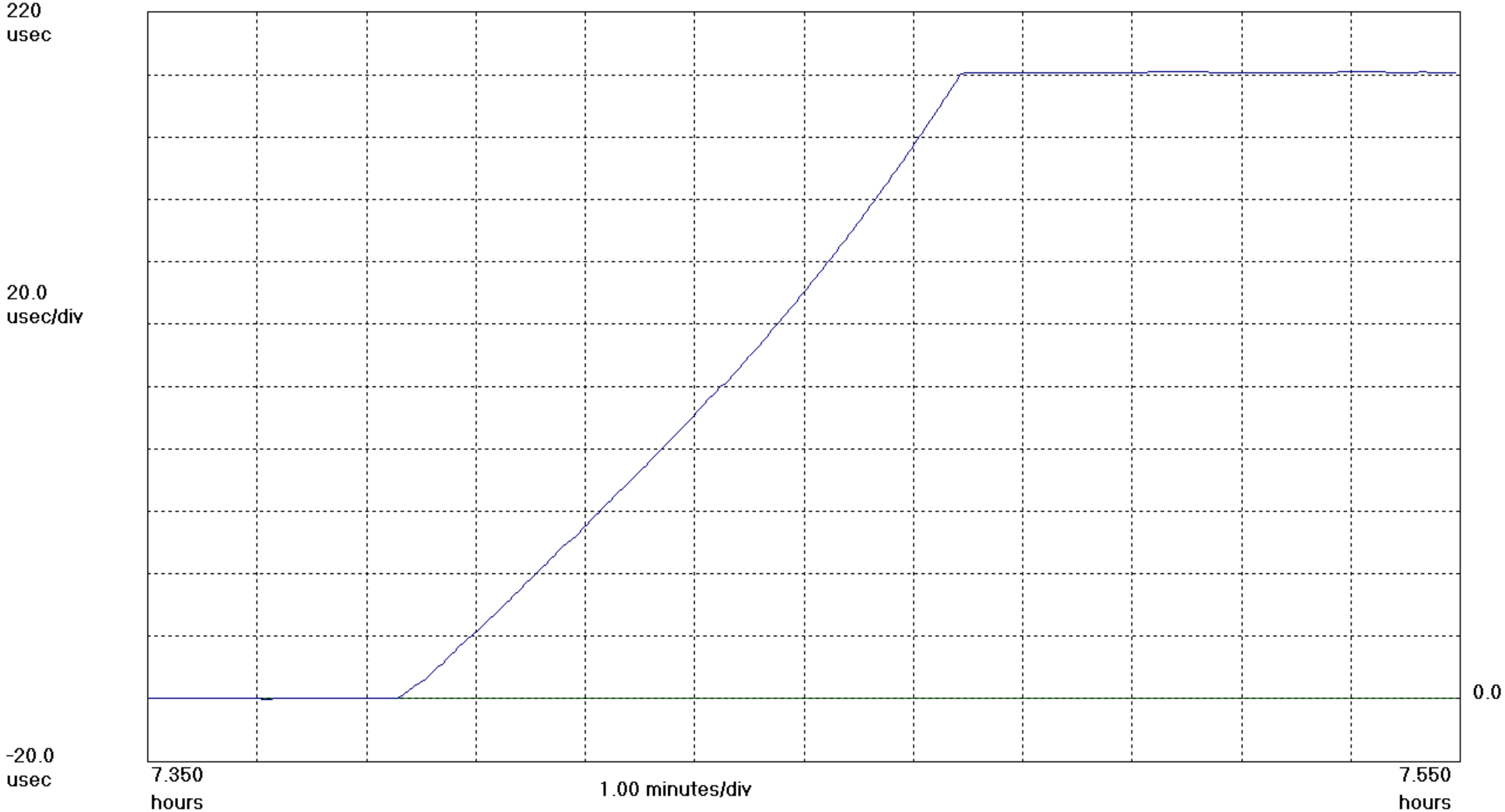


Sync Measurement #6: Microwave Link Down

Symmetricom

Microwave link down: 200 μsec over 5 minutes

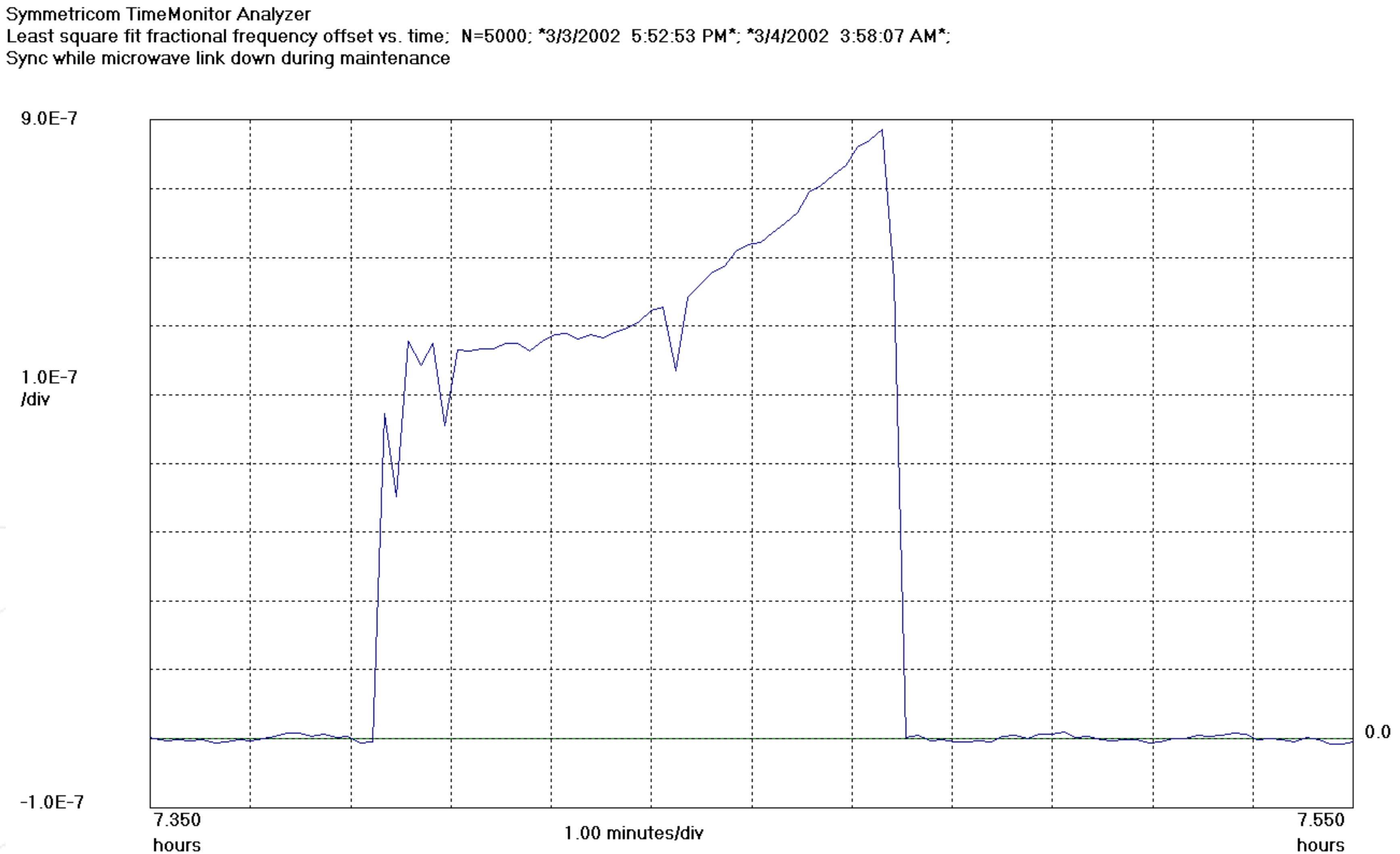
Symmetricom TimeMonitor Analyzer
Phase deviation in units of time;   Fs=5.457 Hz; Fo=2.0480000 MHz; *3/3/2002 5:52:53 PM*; *3/4/2002 3:58:07 AM*;
Sync while microwave link down during maintenance



Sync Measurement #6: Microwave Link Down

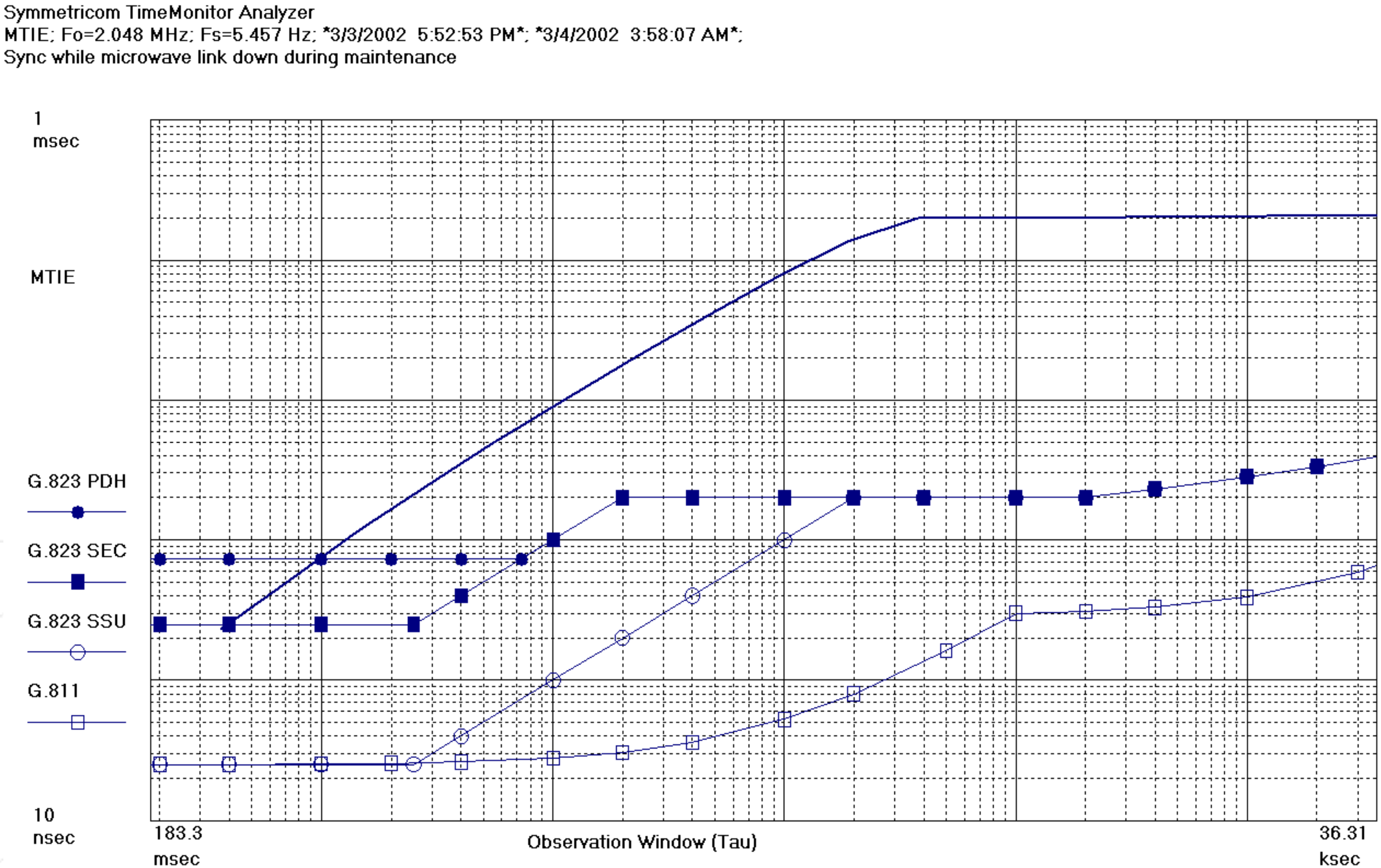
Symmetricom

Microwave link down: Frequency offset reaches 1 ppm



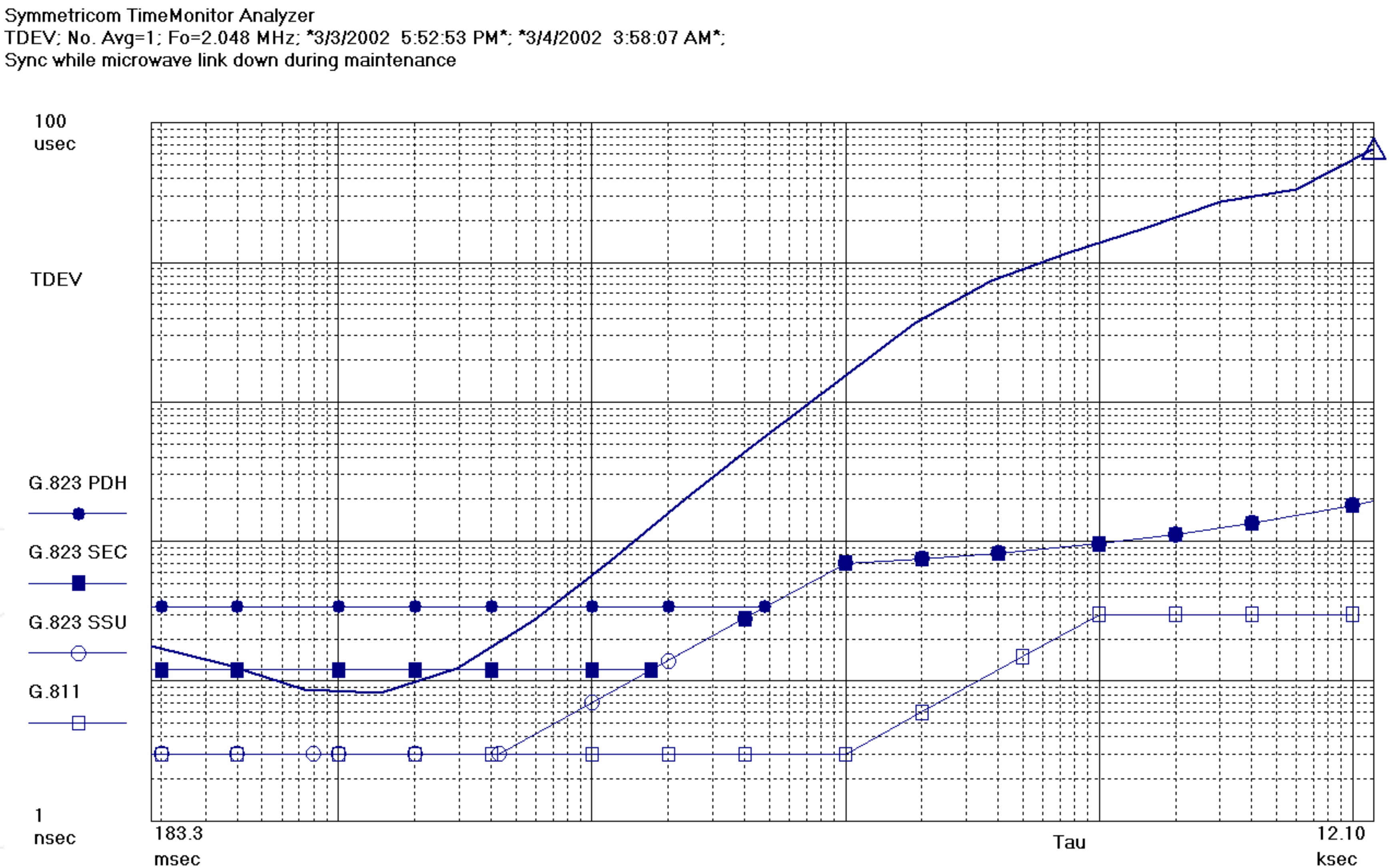
Sync Measurement #6: Microwave Link Down

Microwave link down: MTIE network limits exceeded by a large margin

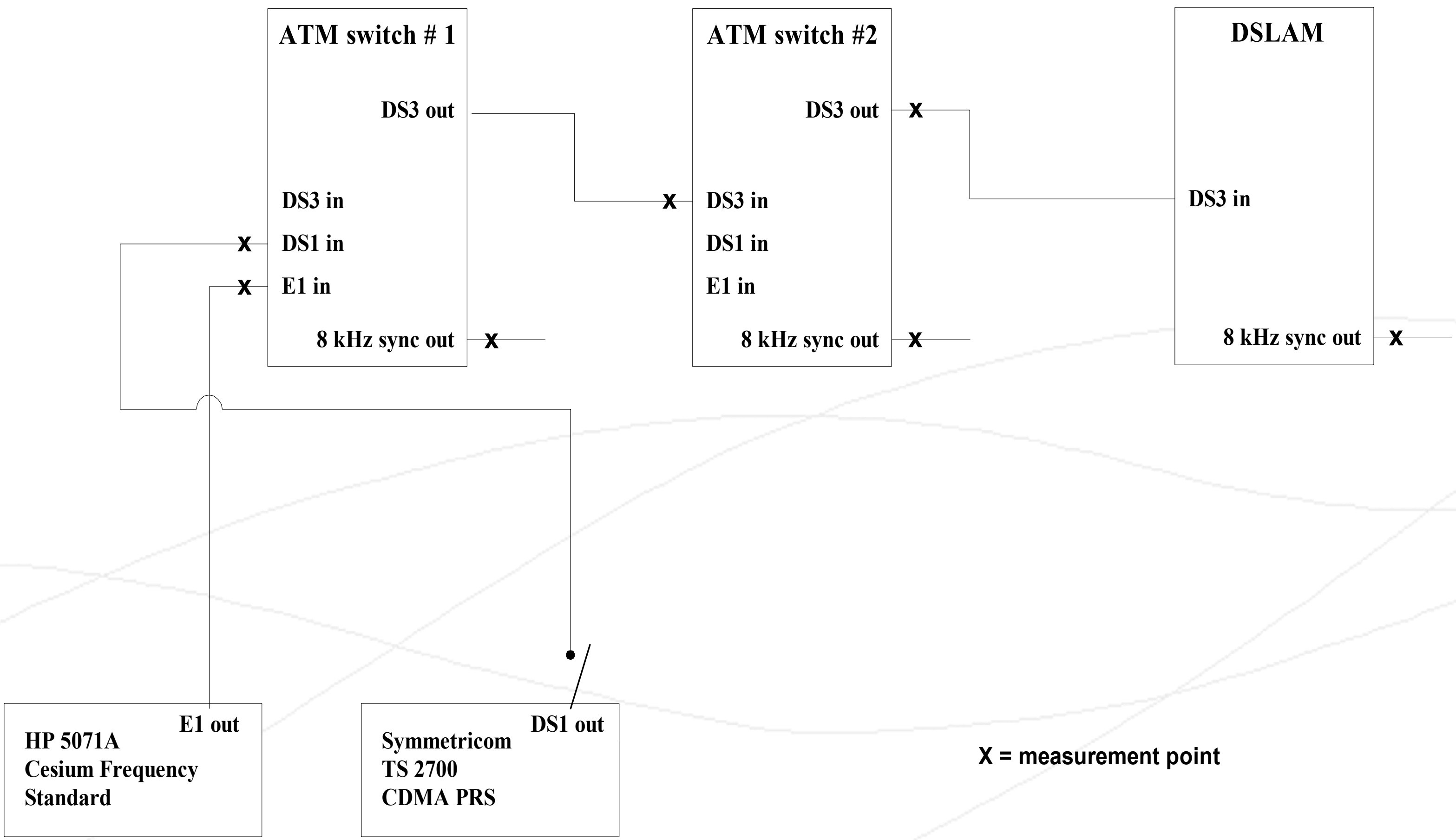


Sync Measurement #6: Microwave Link Down

Microwave link down: TDEV network limits exceeded by a large margin



Sync Measurement #7: DSL Synchronization

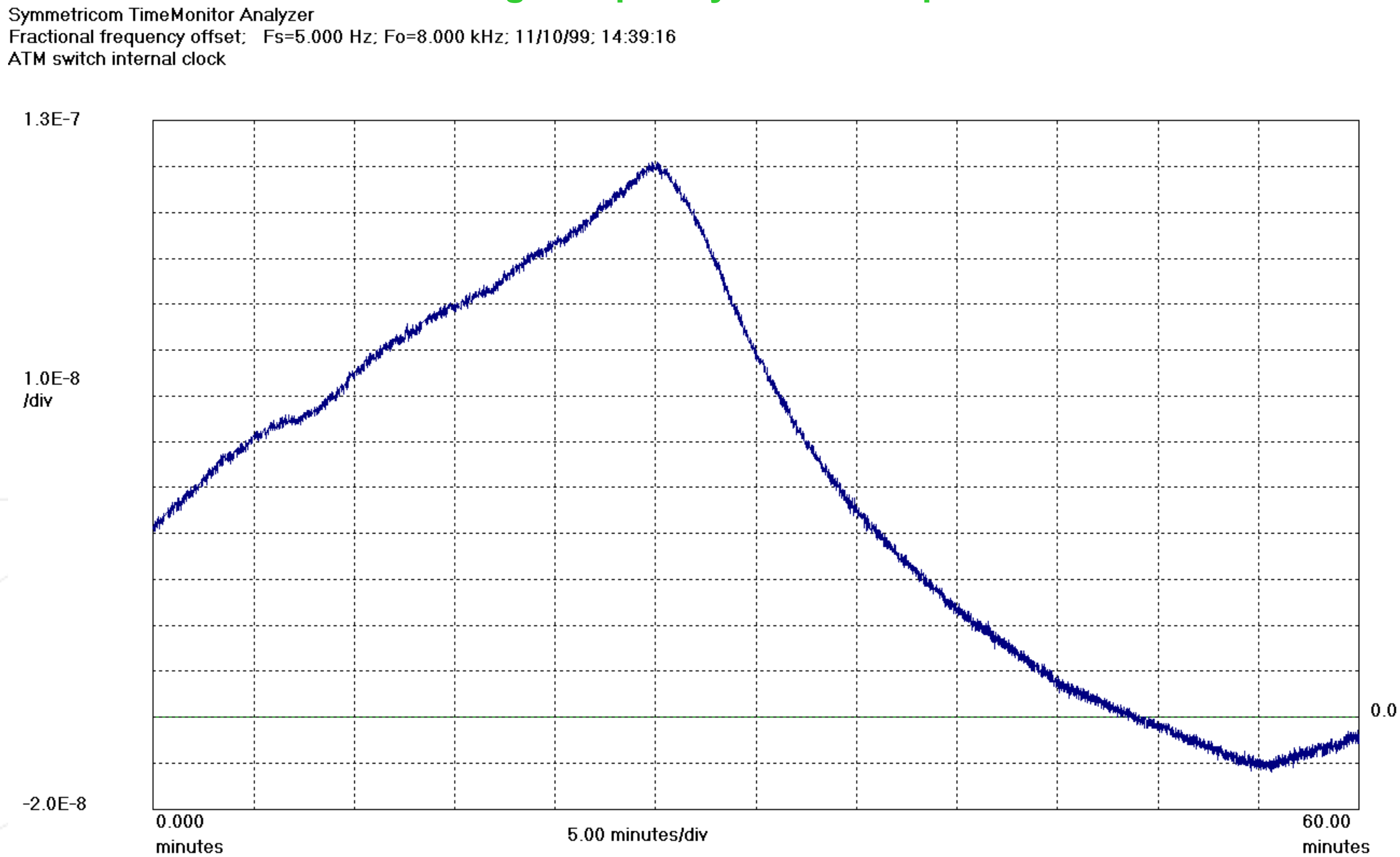


Sync Measurement #7: DSL Synchronization

ATM switch internal oscillator

Frequency drifting between –1.2 and 12 parts in 10^8 over one hour

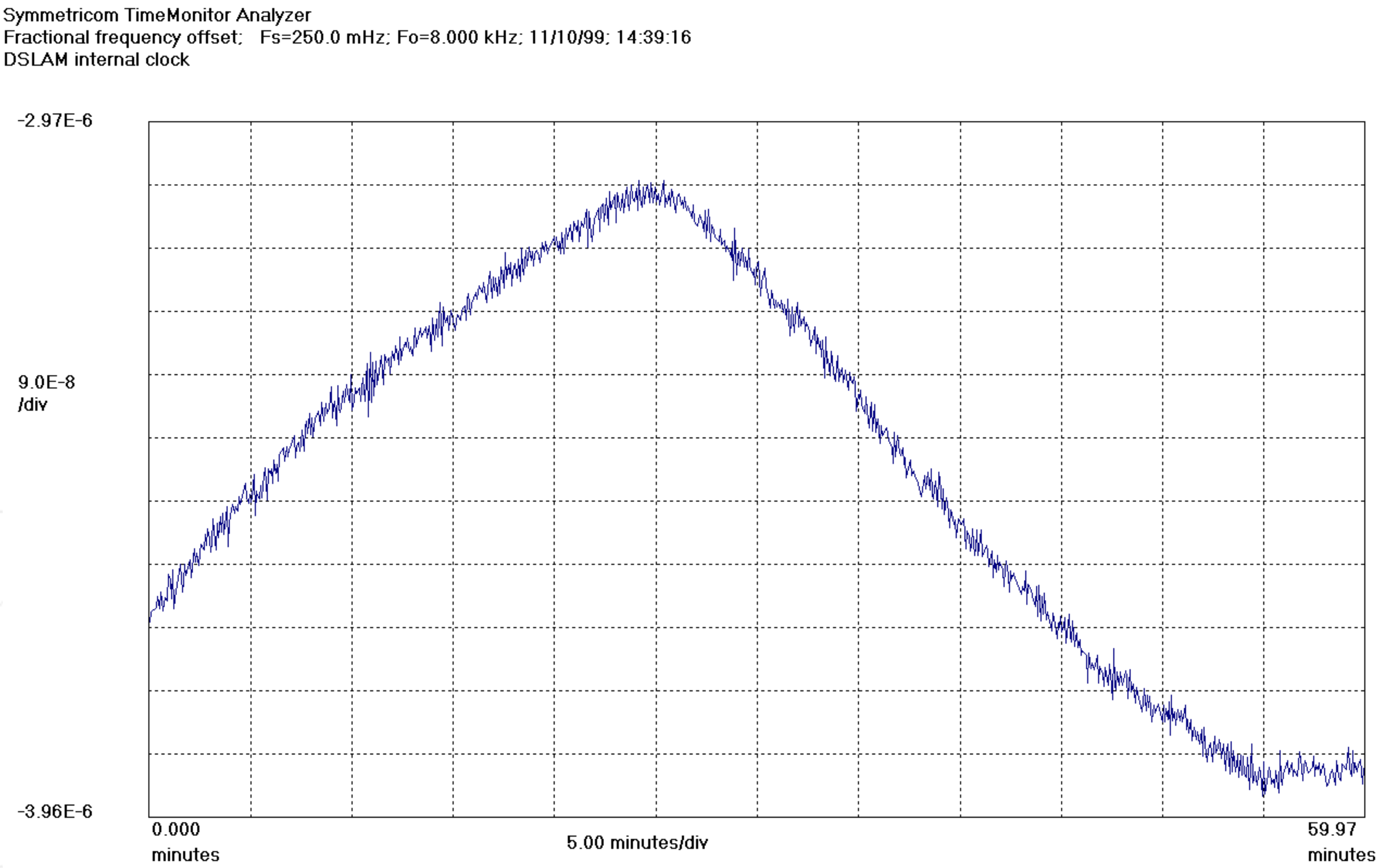
Average frequency offset: 6.0 parts in 10^8



Sync Measurement #7: DSL Synchronization

DSLAM internal oscillator

Frequency drifting between –3 and –4 parts in 10^6 over 1 hour
Average frequency offset: -3.4 parts in 10^6

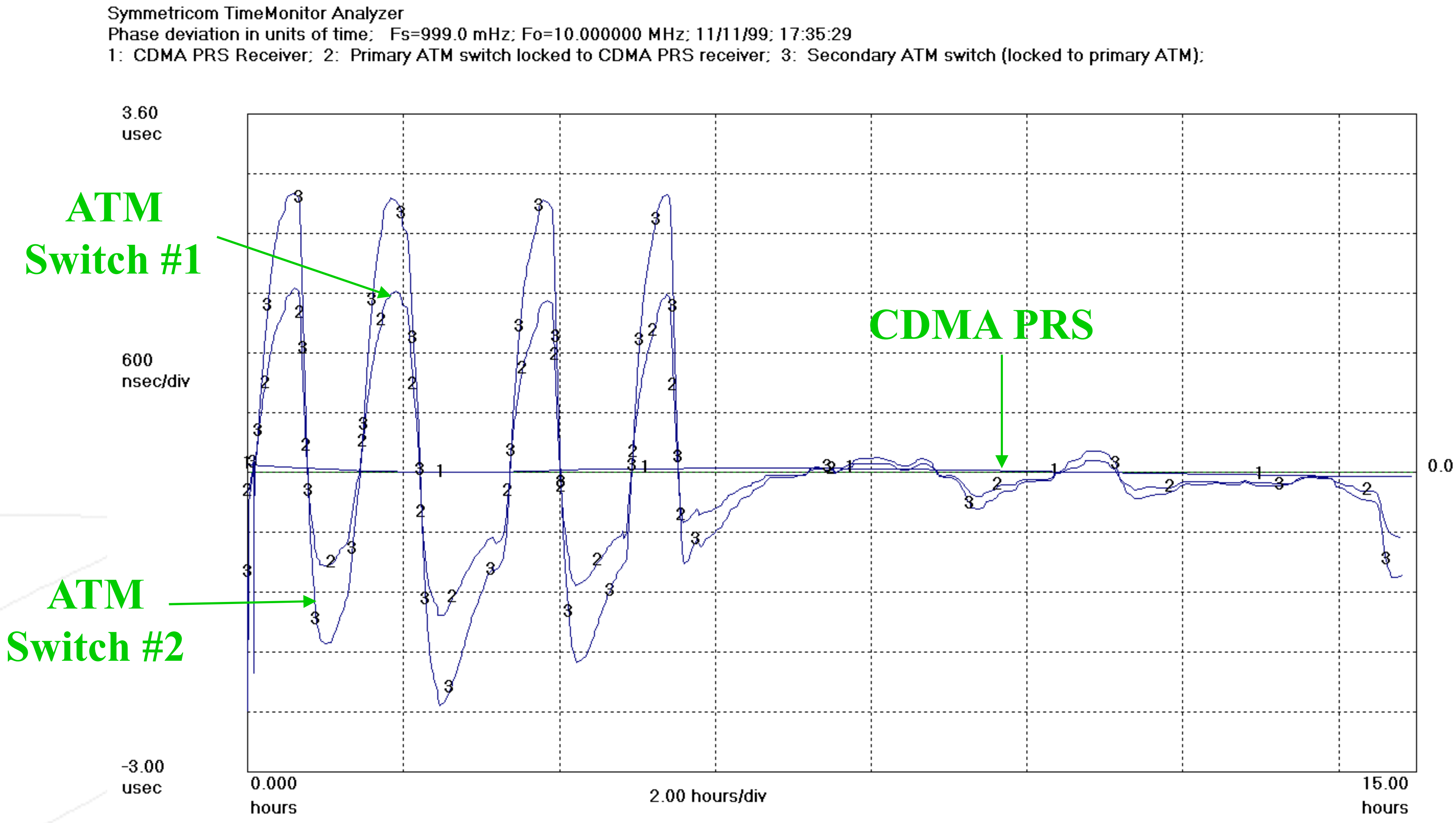


Frequency offset is 2 orders of magnitude worse than the ATM switch internal oscillator

Sync Measurement #7: DSL Synchronization

Symmetricom

ATM switch phase-locked loop affected by daytime temperature swings from air conditioning system (□T = 20 degrees F)

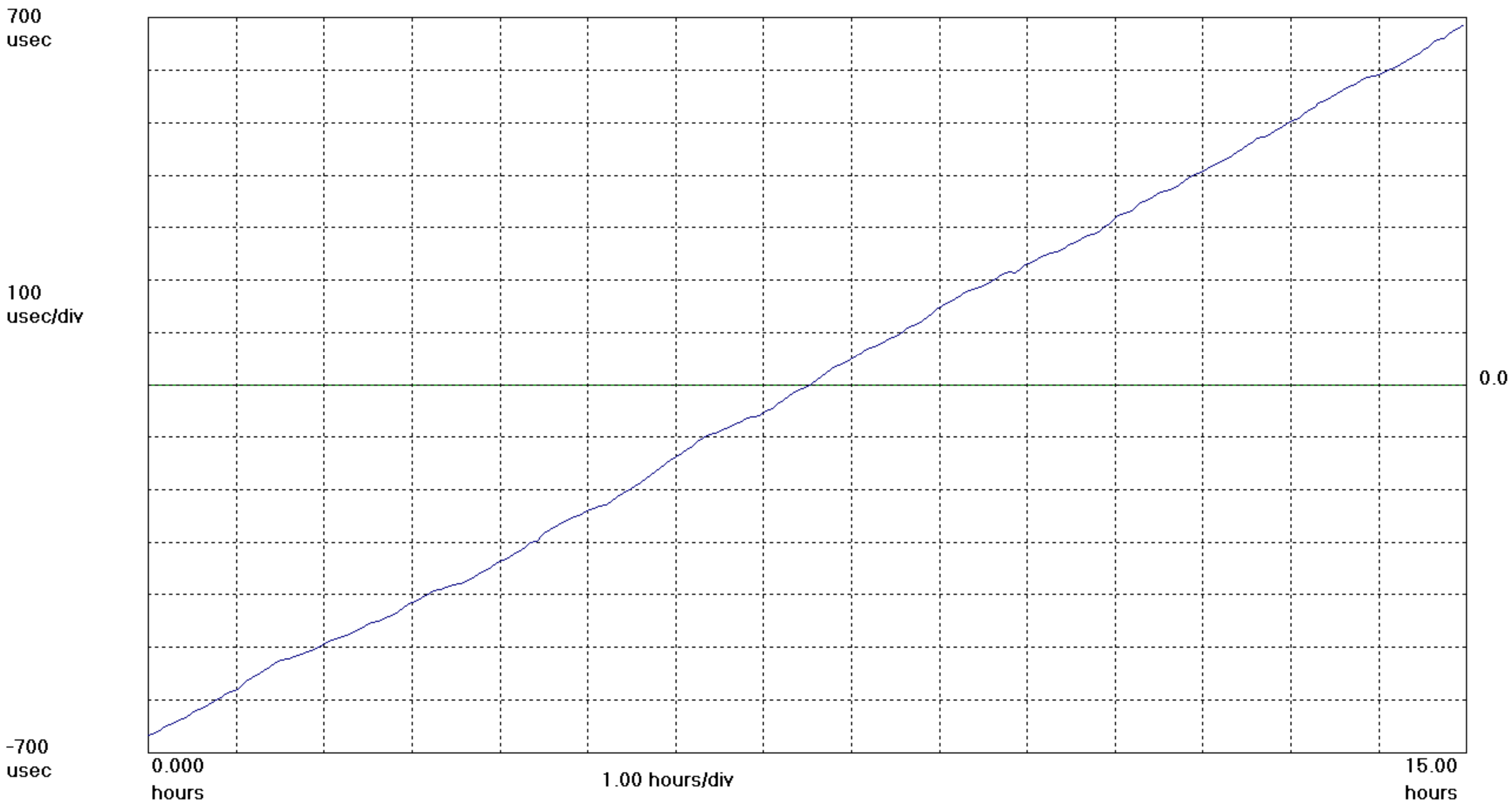


Sync Measurement #7: DSL Synchronization

DSLAM w/ External Sync

Does not really synchronize to external signal: 2.5 parts in 10^8 frequency offset!!

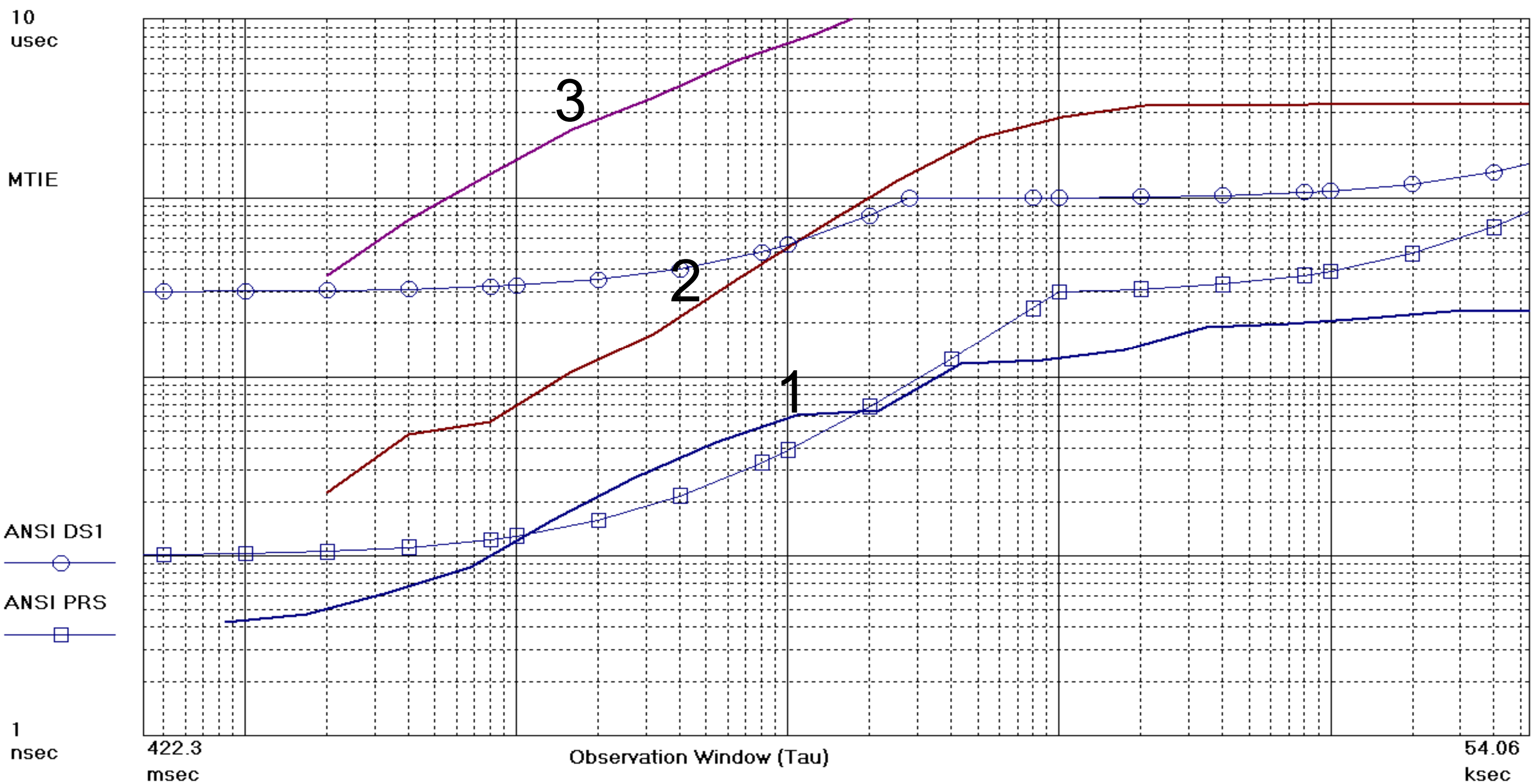
Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=1.000 Hz; Fo=8.0000000 kHz; 11/10/99; 17:44:52
DSLAM switch locked to ATM switch (with ATM switch locked to cesium clock); Fo offset = 2.529E-8



Sync Measurement #7: DSL Synchronization

ATM vs. ATM Δ T vs. DSLAM

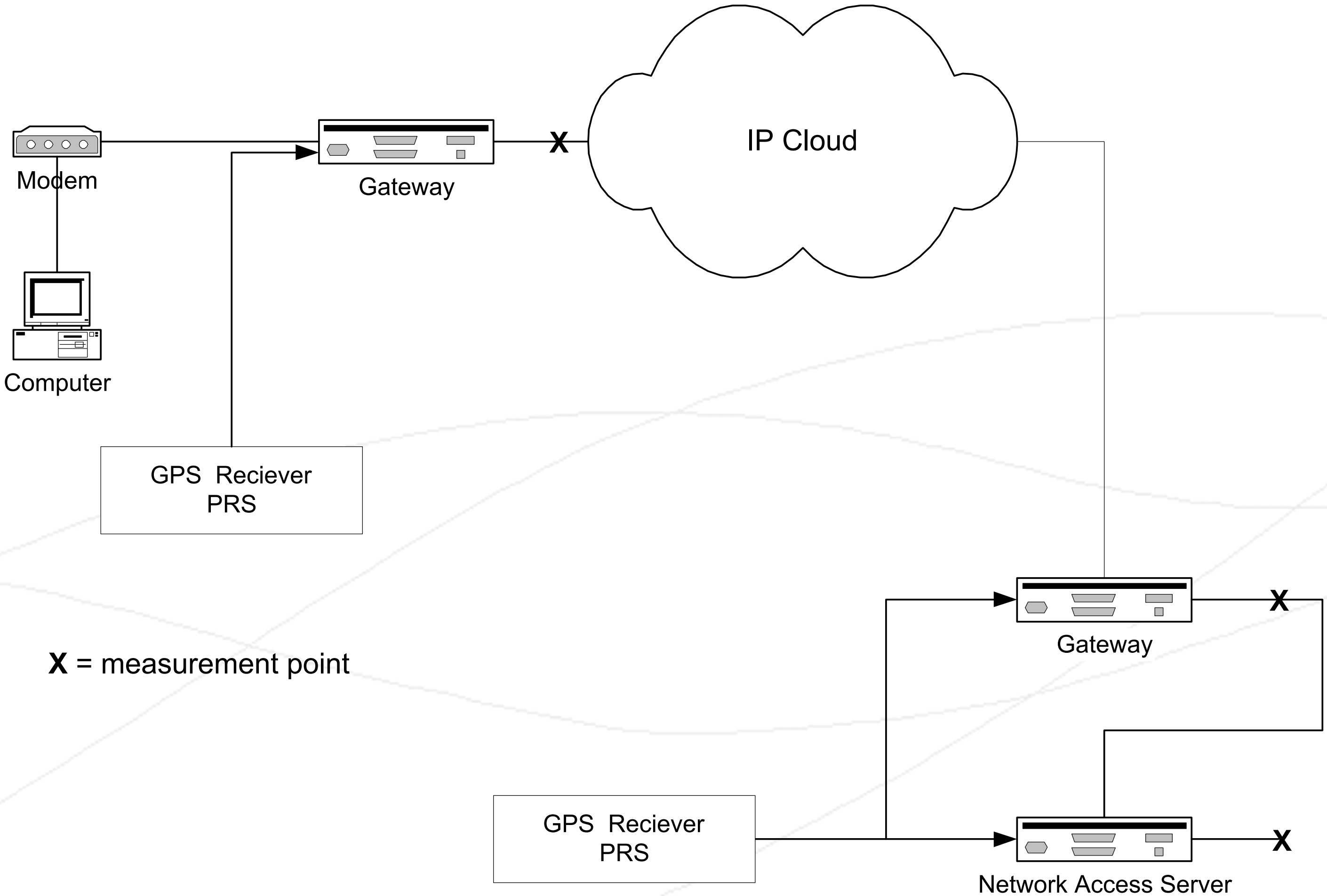
Symmetricom TimeMonitor Analyzer
MTIE; 1: ATM switch locked to PRS with constant temperature
2: ATM switch locked to PRS with temperature fluctuations due to improperly functioning air conditioning system
3: DSLAM switch locked to ATM switch (with ATM switch locked to PRS)



Sync Measurement #8: IP Synchronization

Symmetricom

Modem over IP fails without synchronization



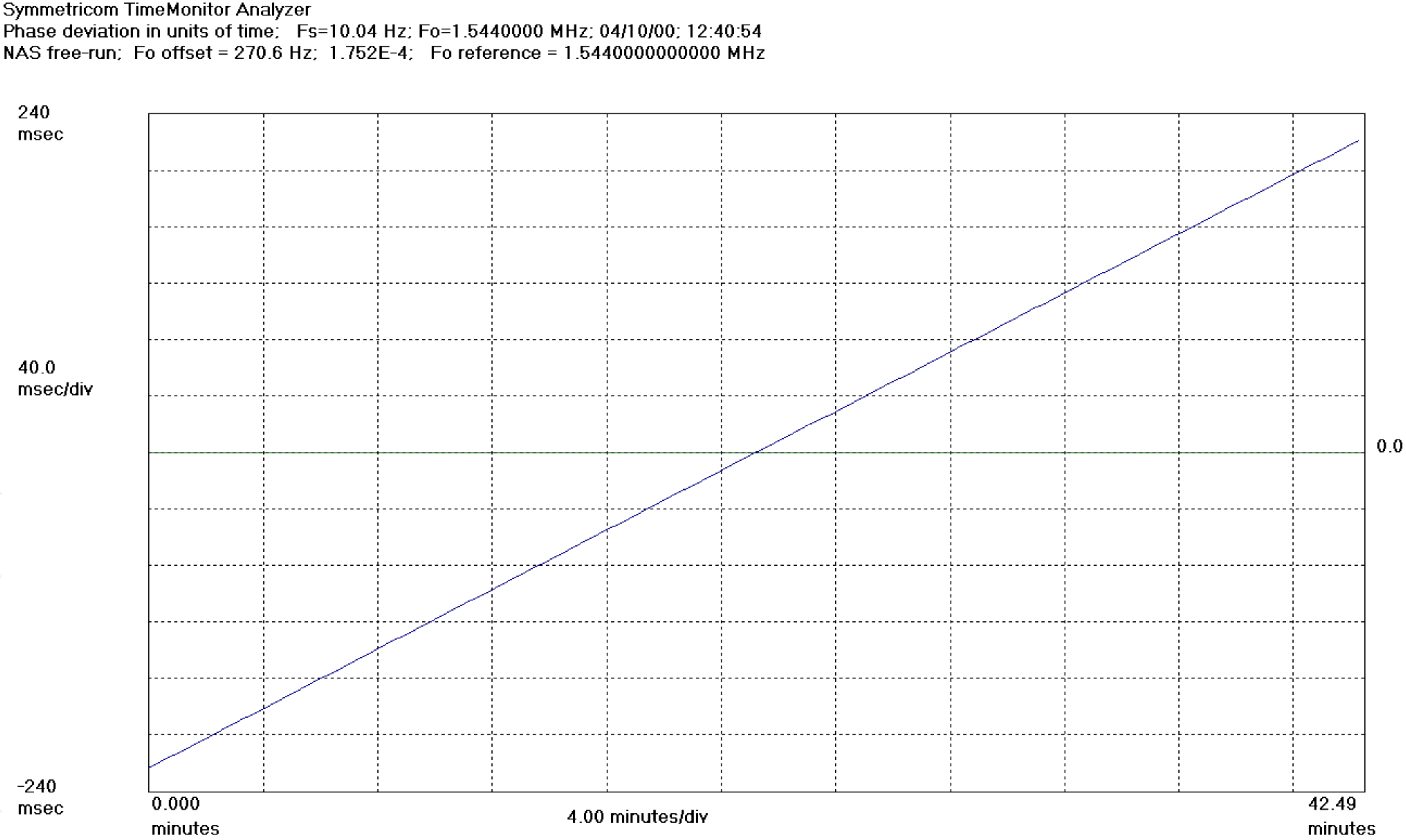
X = measurement point

Sync Measurement #8: IP Synchronization

Symmetricom

IP network access server internal oscillator

175 ppm: much worse than stratum 4 requirement of 32 ppm

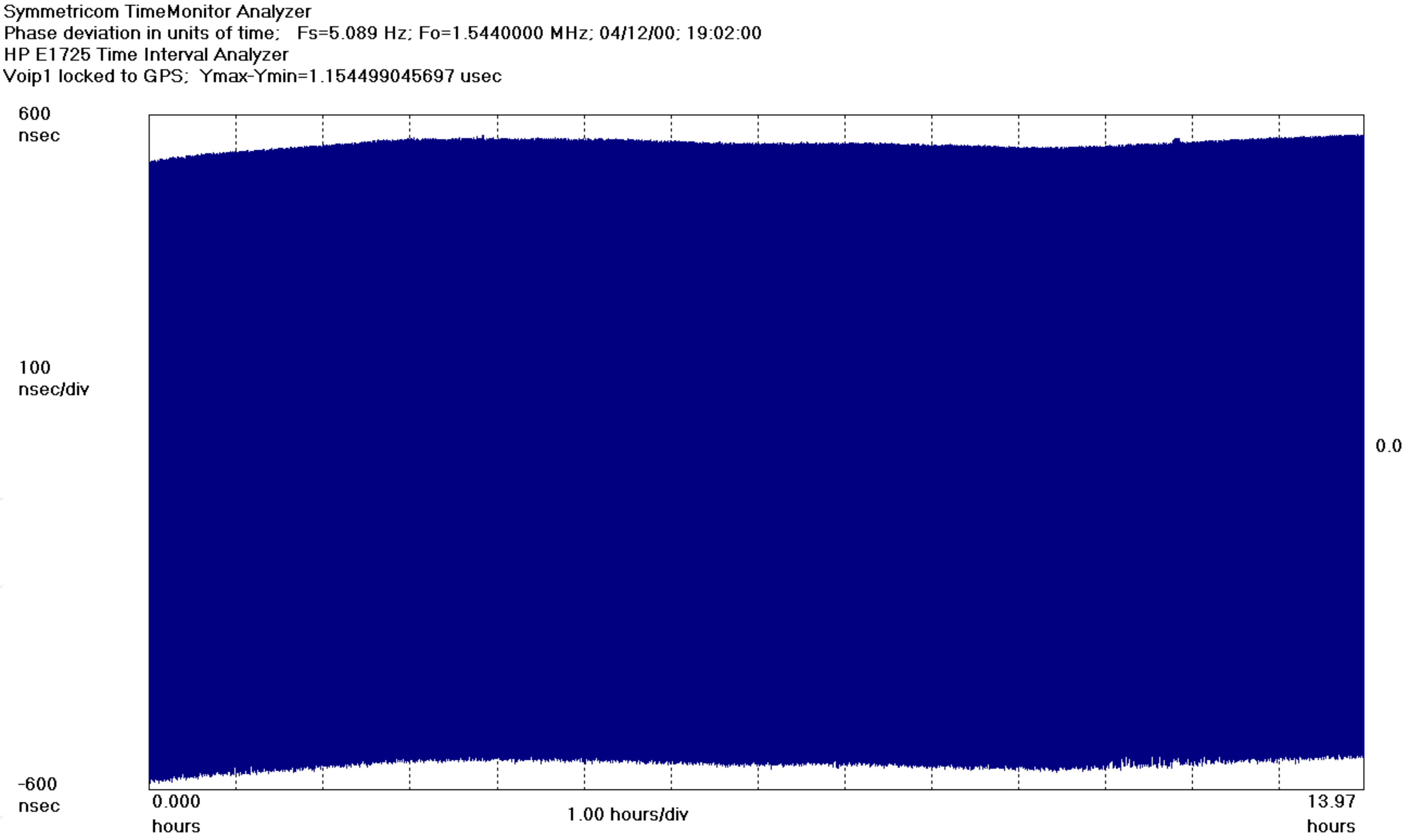


Sync Measurement #8:
IP Synchronization

Symmetricom

IP network access server locked to external PRS reference

Short-term wander at 1.15 μsec peak-to-peak

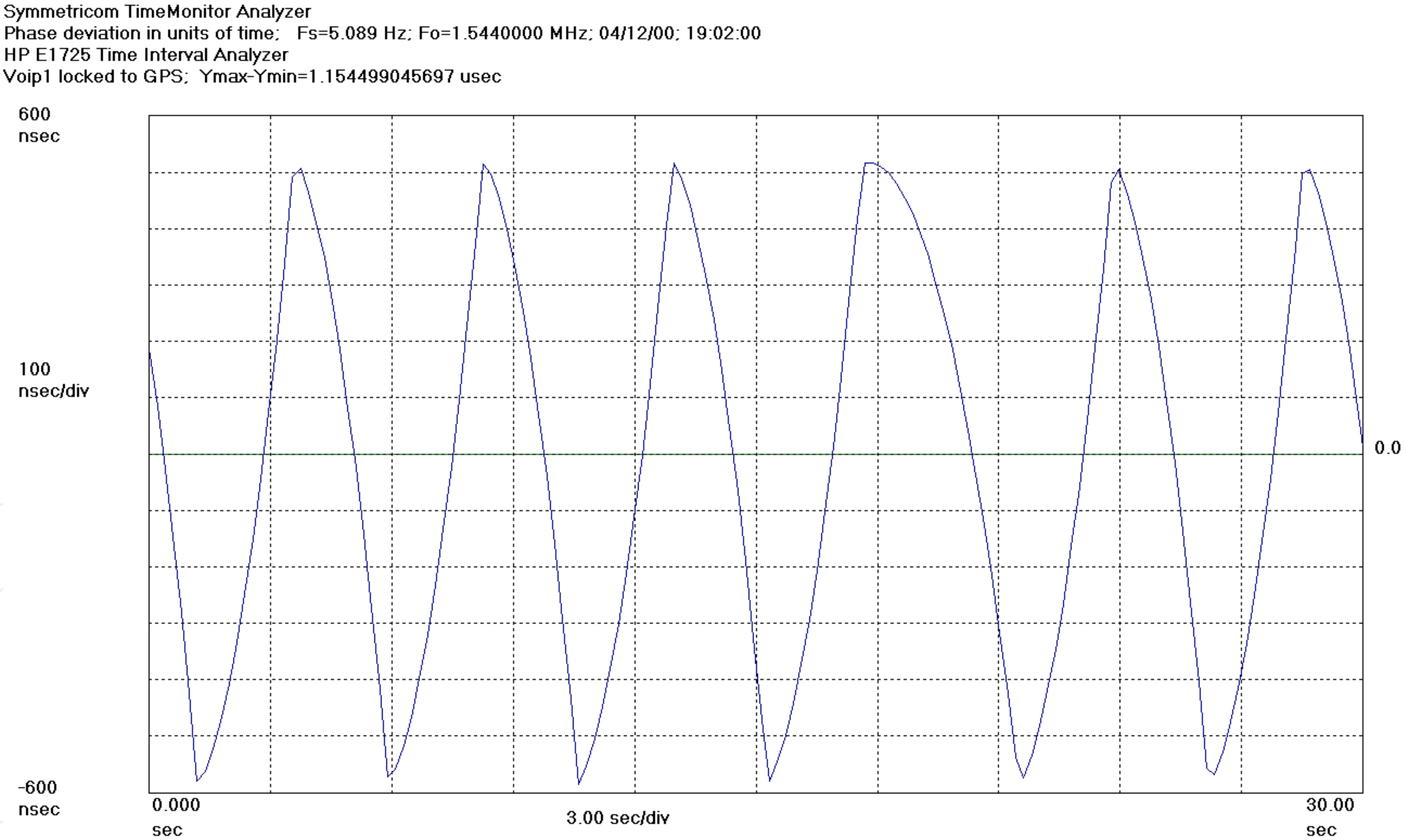


Sync Measurement #8: IP Synchronization

Symmetricom

IP network access server locked to external PRS reference

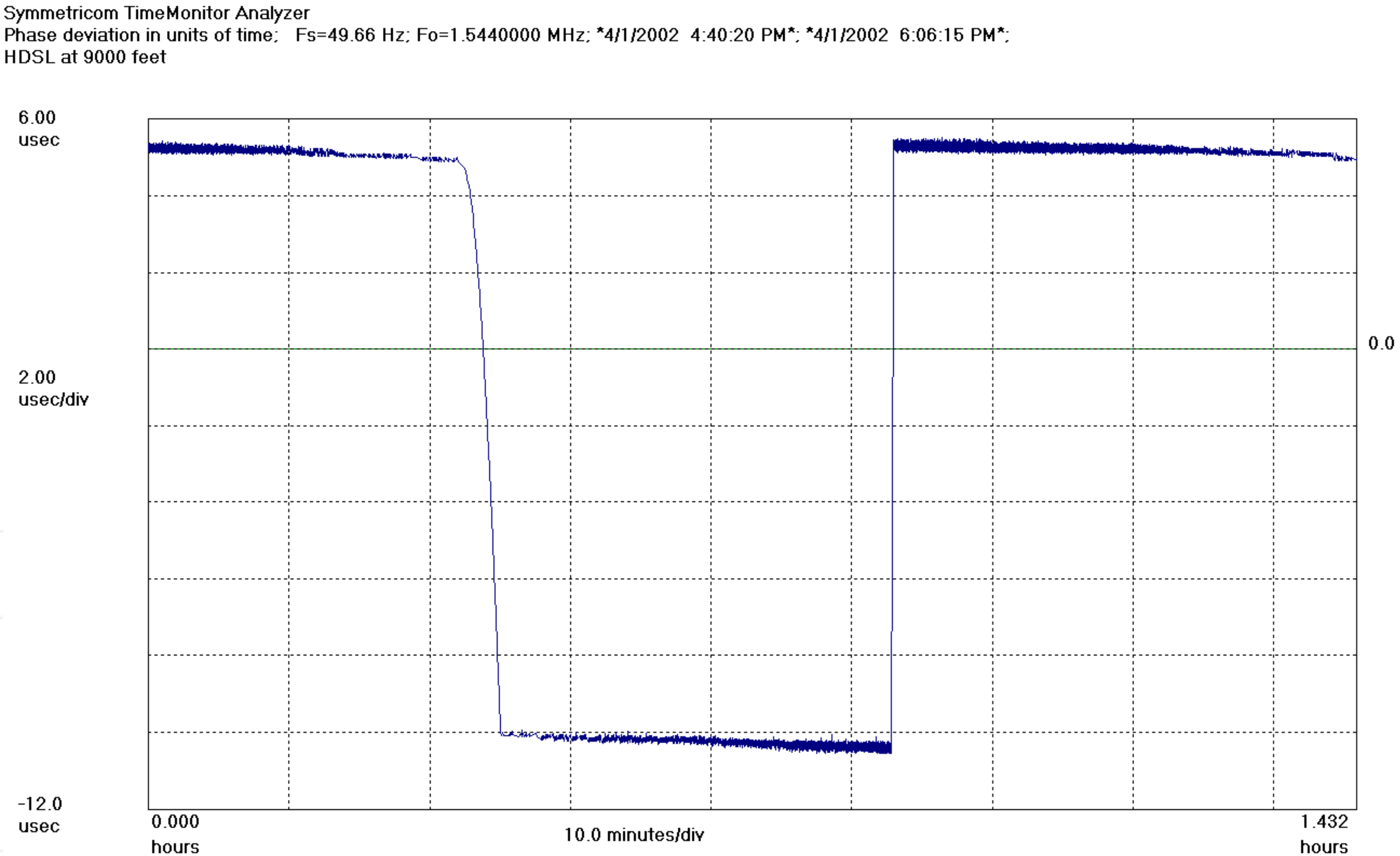
Zoom into first 30 seconds: wander pattern observed



Sync Measurement #9:
HDSL: Unsuitable for Sync Transport

Symmetricom

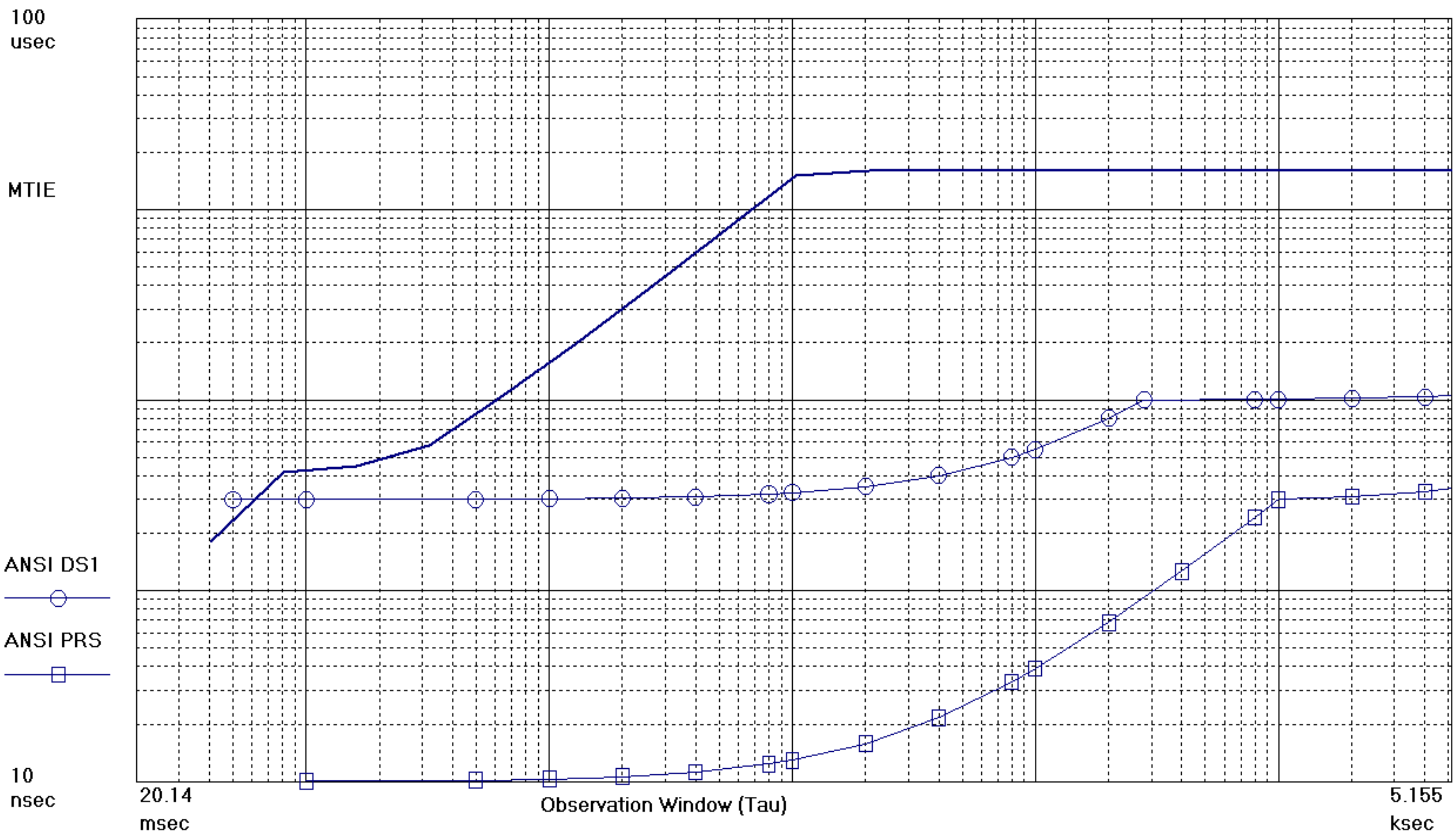
HDSL DS1: 15 µsec phase steps every 30 minutes



Sync Measurement #9: HDSL: Unsuitable for Sync Transport

HDSL DS1: ANSI T1.101 DS1 MTIE requirement exceeded by a large margin

Symmetricom TimeMonitor Analyzer
MTIE; Fo=1.544 MHz; Fs=49.66 Hz; *4/1/2002 4:40:20 PM*; *4/1/2002 6:06:15 PM*;
HDSL at 9000 feet



Sync Measurement #9:
HDSL: Unsuitable for Sync Transport

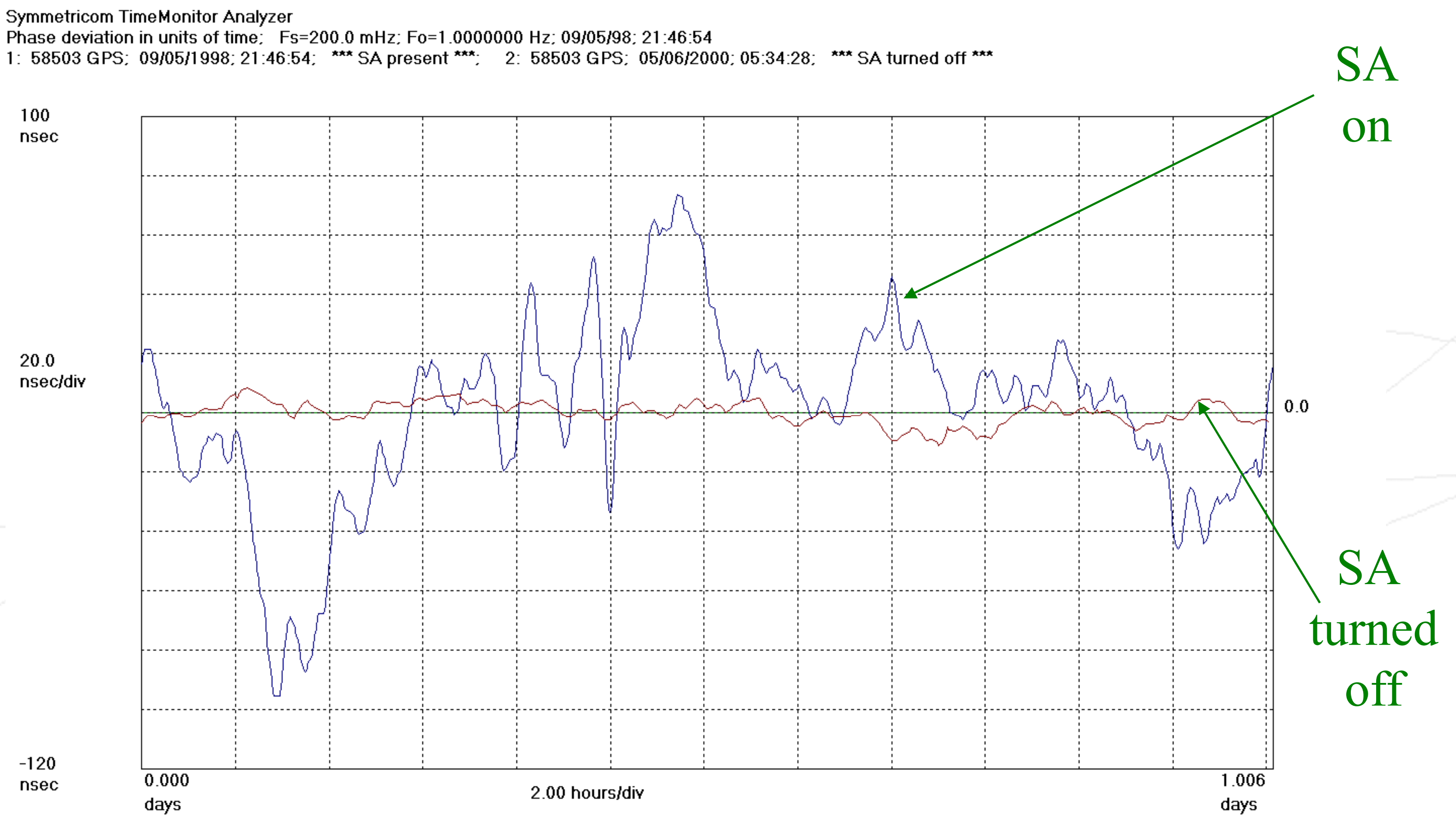
Symmetricom

HDSL DS1: ANSI T1.101 DS1 TDEV requirement exceeded by a large margin

Sync Measurement #10:
GPS: Effect of SA Being Turned Off

Symmetricom

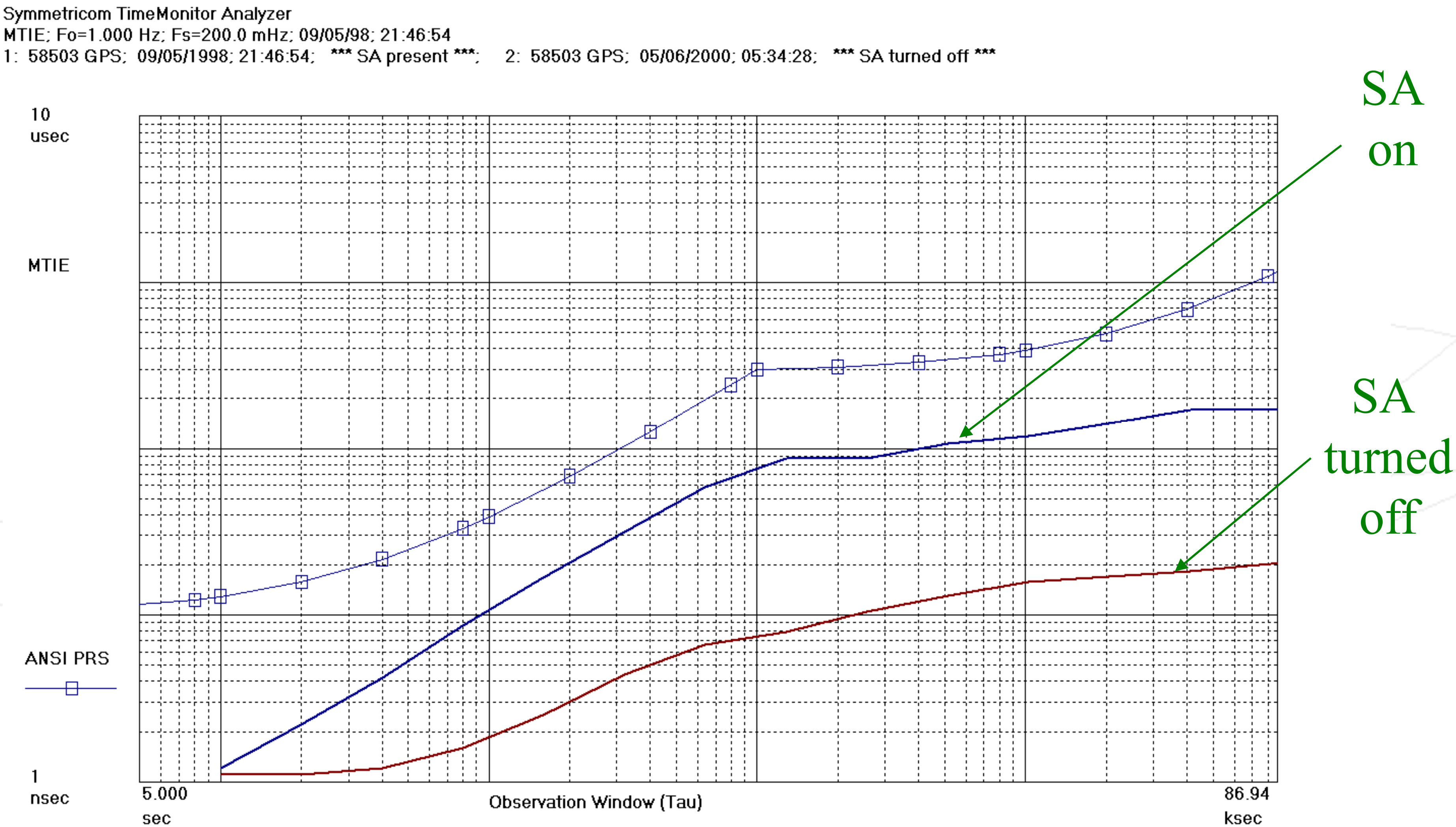
Effect of turning off SA on GPS receivers



Sync Measurement #10: GPS: Effect of SA Being Turned Off

Symmetricom

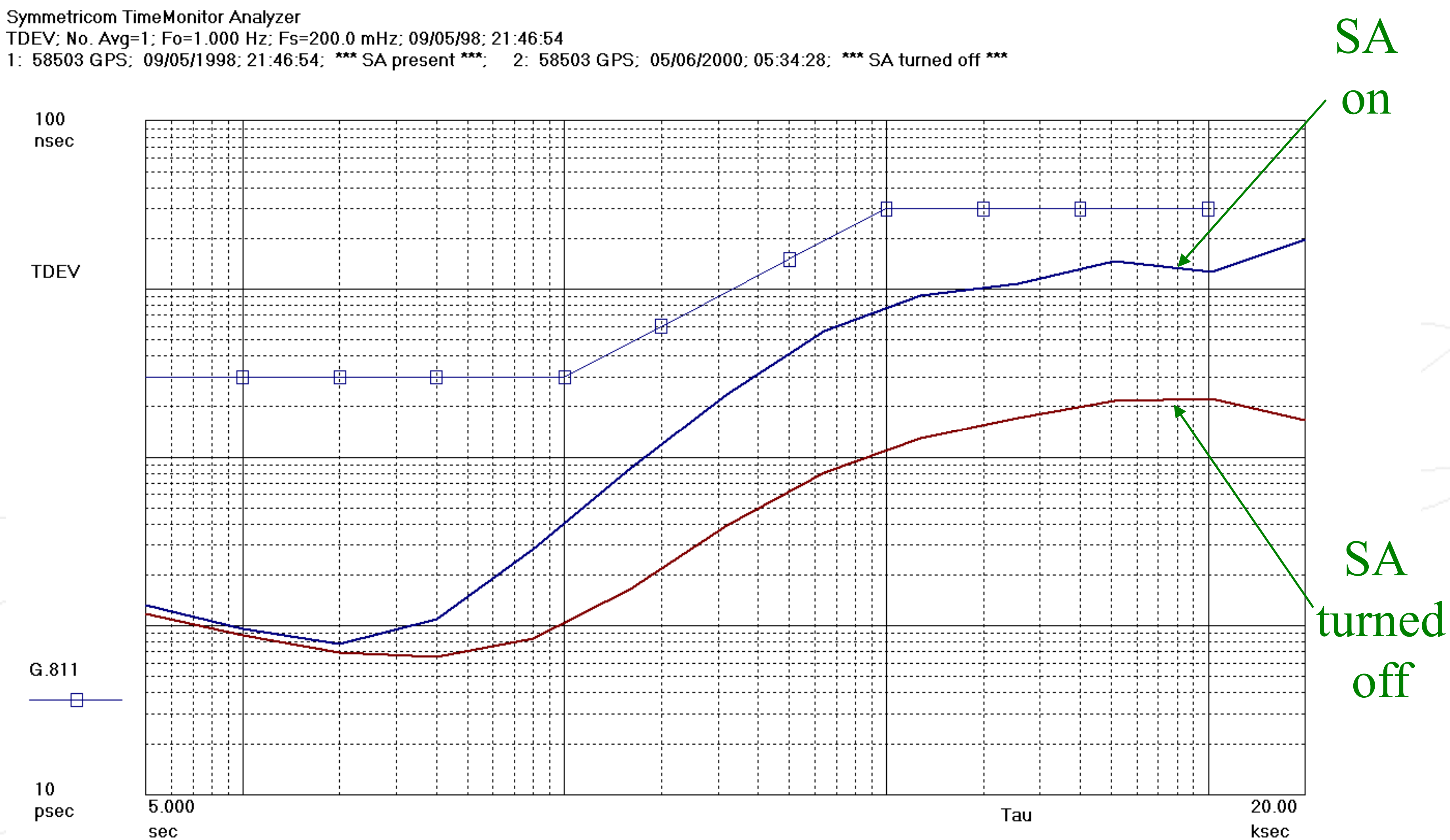
Effect of turning off SA on GPS receivers: MTIE



Sync Measurement #10:
GPS: Effect of SA Being Turned Off

Symmetricom

Effect of turning off SA on GPS receivers: TDEV

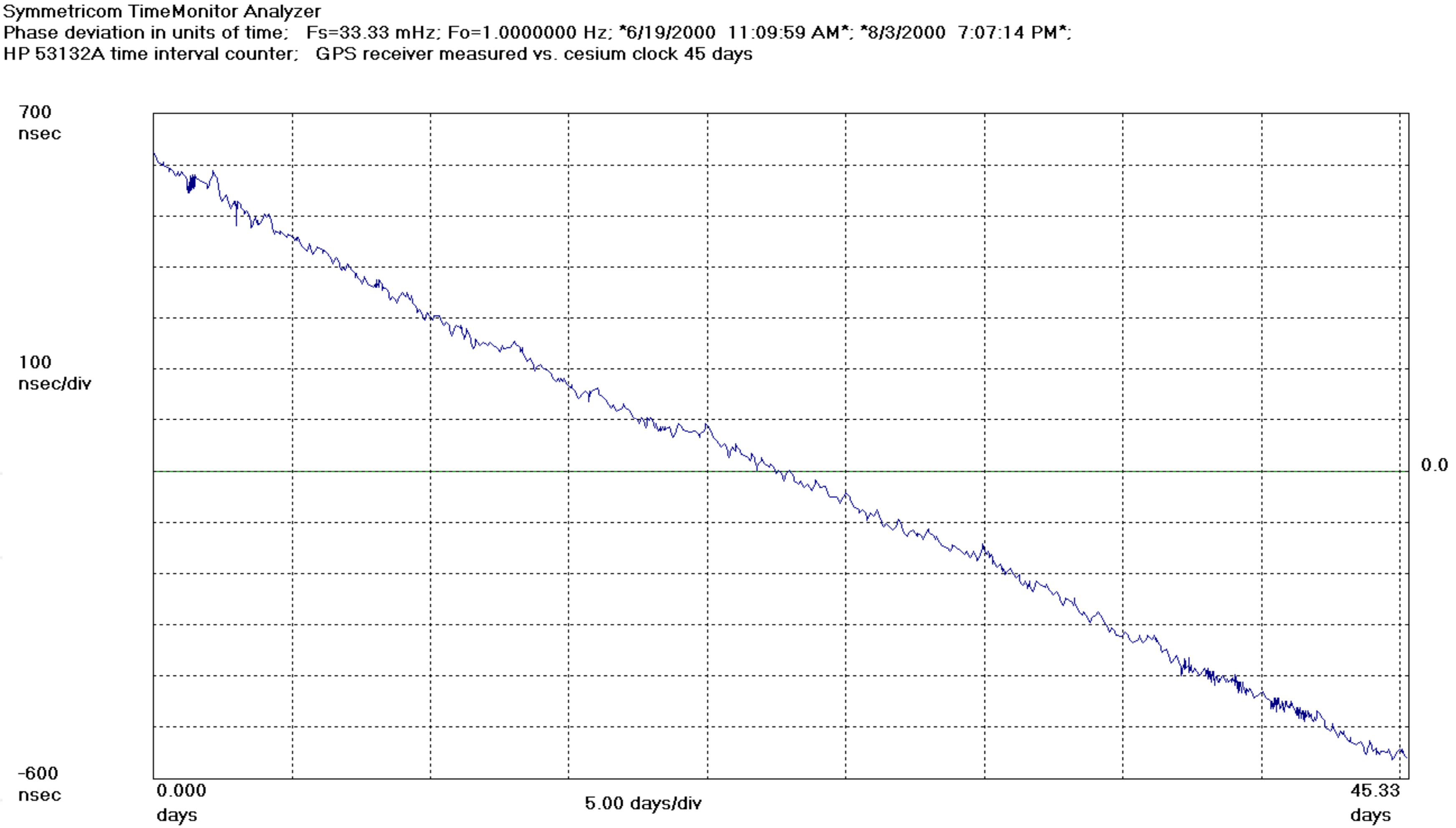


Sync Measurement #11:
GPS vs. Cesium: Measuring Cesium Offset

Measuring cesium clock offset with GPS: -2.7 parts in 10^{13}

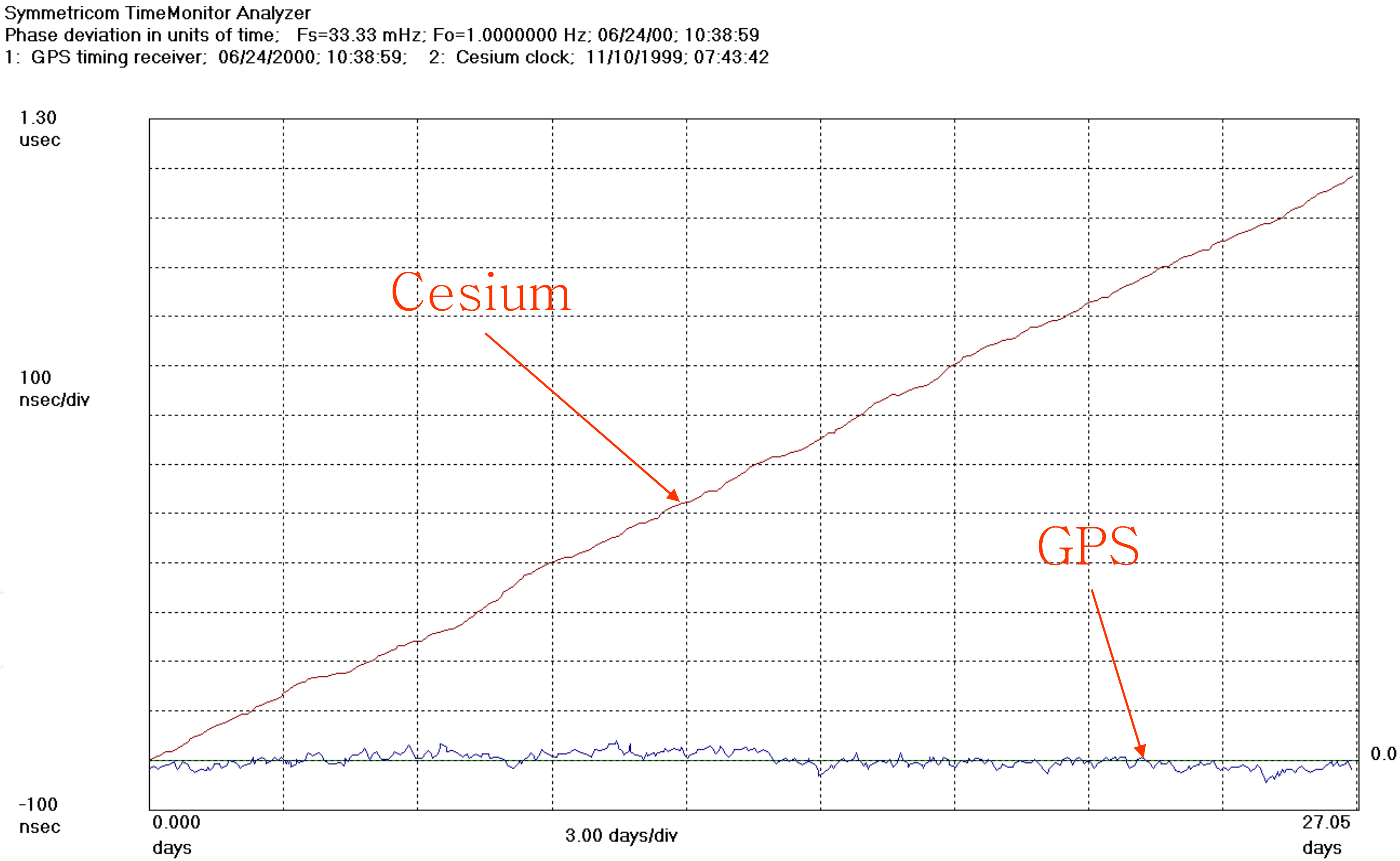
24 hour measurement: cesium can be used to measure GPS

45 day measurement: GPS can be used to measure cesium



Sync Measurement #11: GPS vs. Cesium

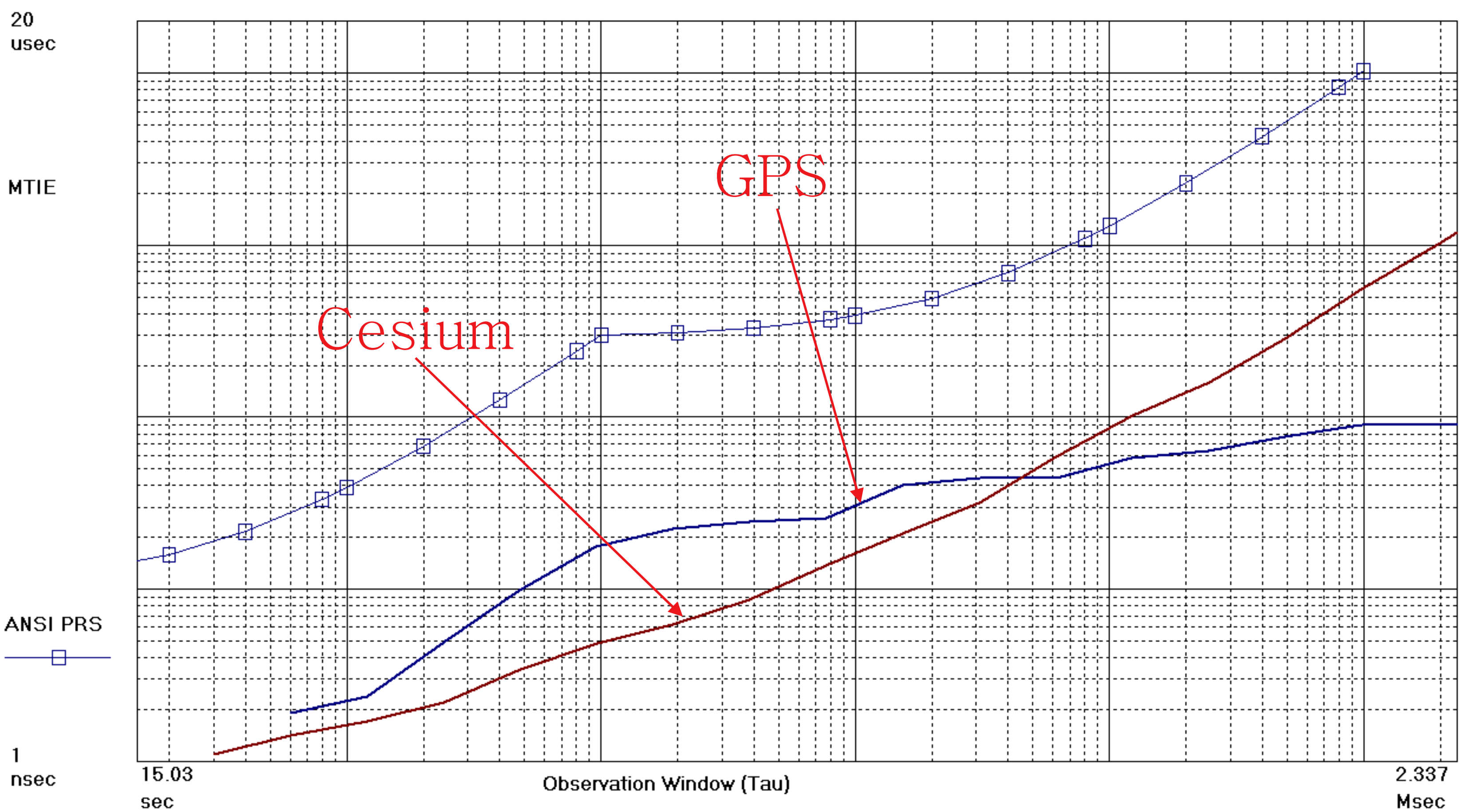
Symmetricom



Sync Measurement #11: GPS vs. Cesium

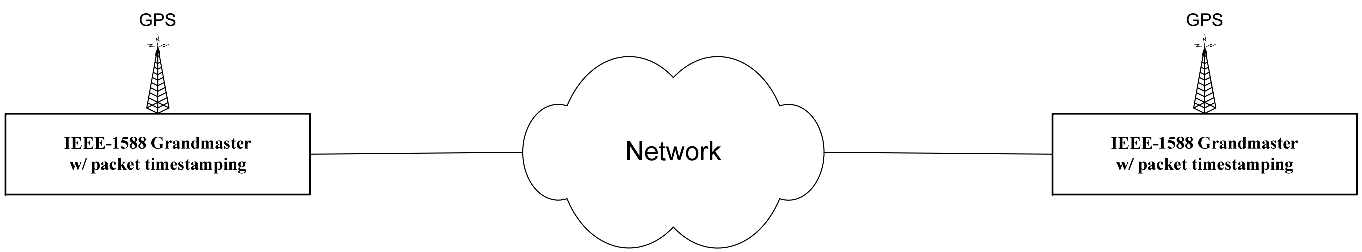
Intersect point at 12.7 hours
Both meet PRS requirements by a large margin

Symmetricom TimeMonitor Analyzer
MTIE; Fo=1.000 Hz; Fs=33.33 mHz; 06/24/00; 10:38:59
1: GPS timing receiver; 06/24/2000; 10:38:59; 2: Cesium clock; 11/10/1999; 07:43:42

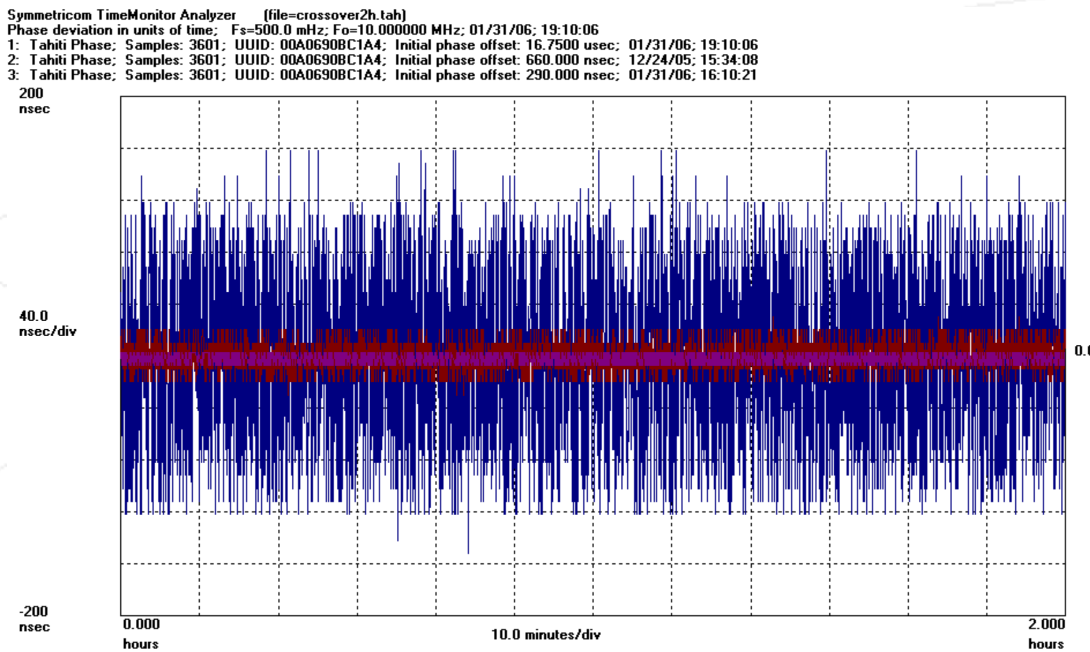


Sync Measurement #12: Packet Delay Variation Measurements

PDV from timestamping at both ends of a network



Crossover cable vs. hub vs. switch



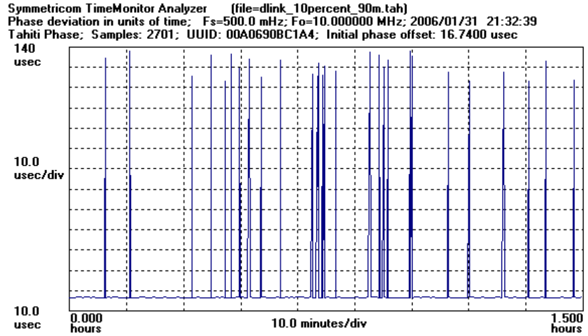
Sync Measurement #12: Packet Delay Variation Measurements

Symmetricom

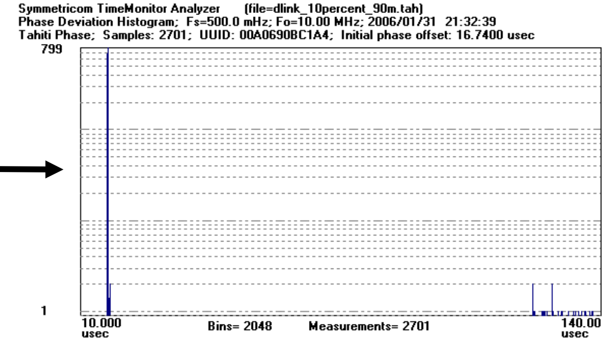
With traffic

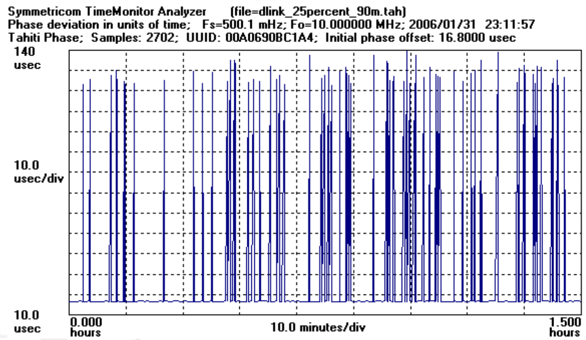
Phase

Stats

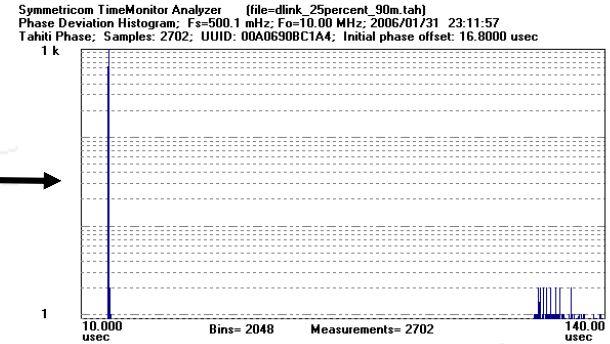


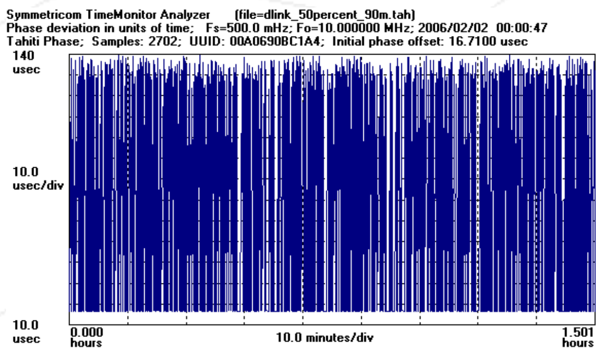
← 10% load →



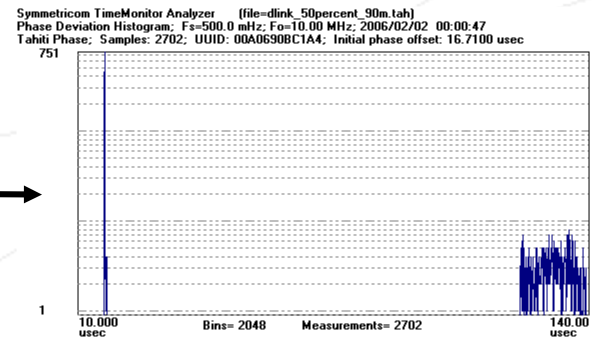


← 25% load →





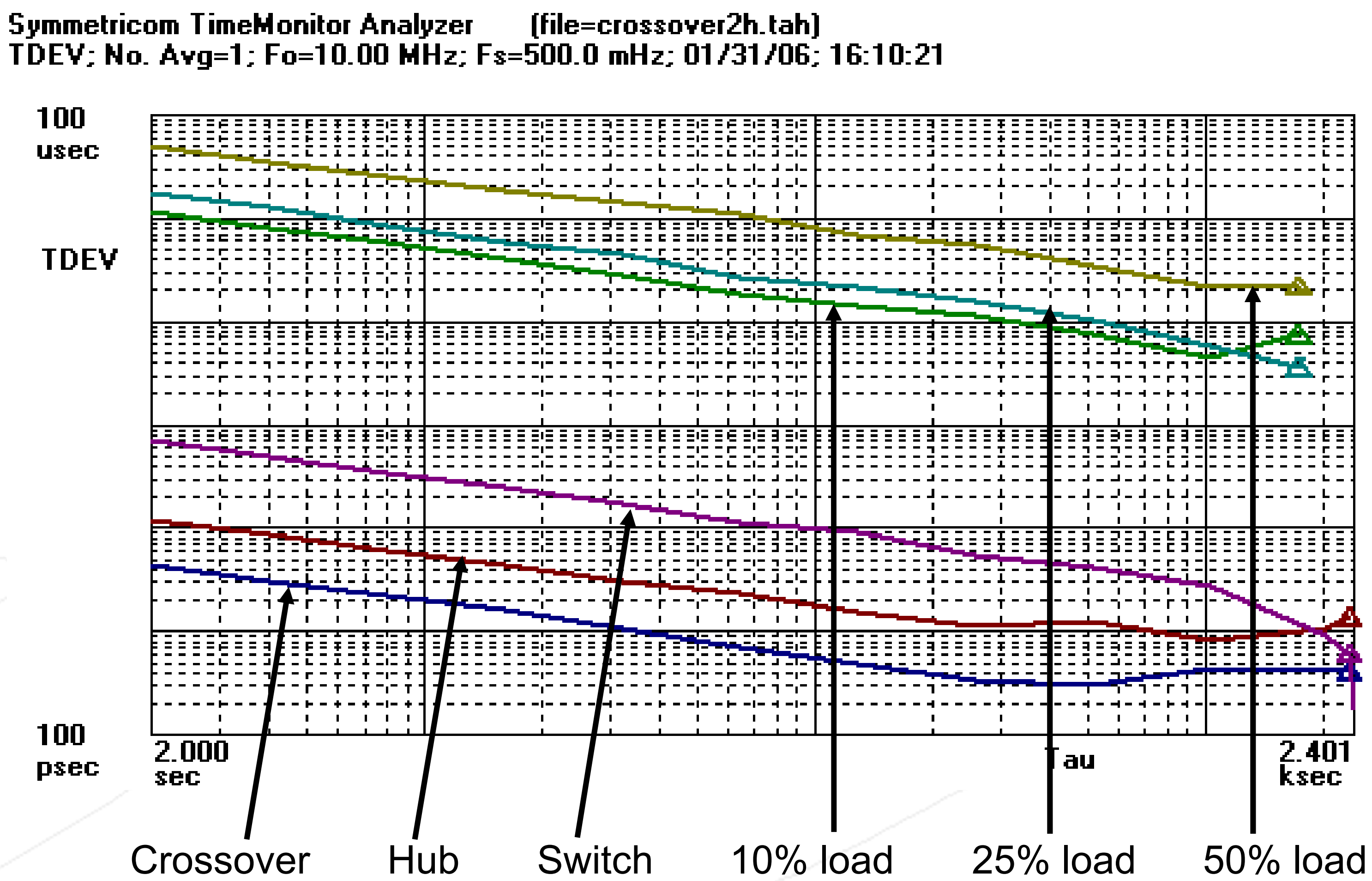
← 50% load →



Sync Measurement #12:
Packet Delay Variation Measurements

Symmetricom

TDEV comparison

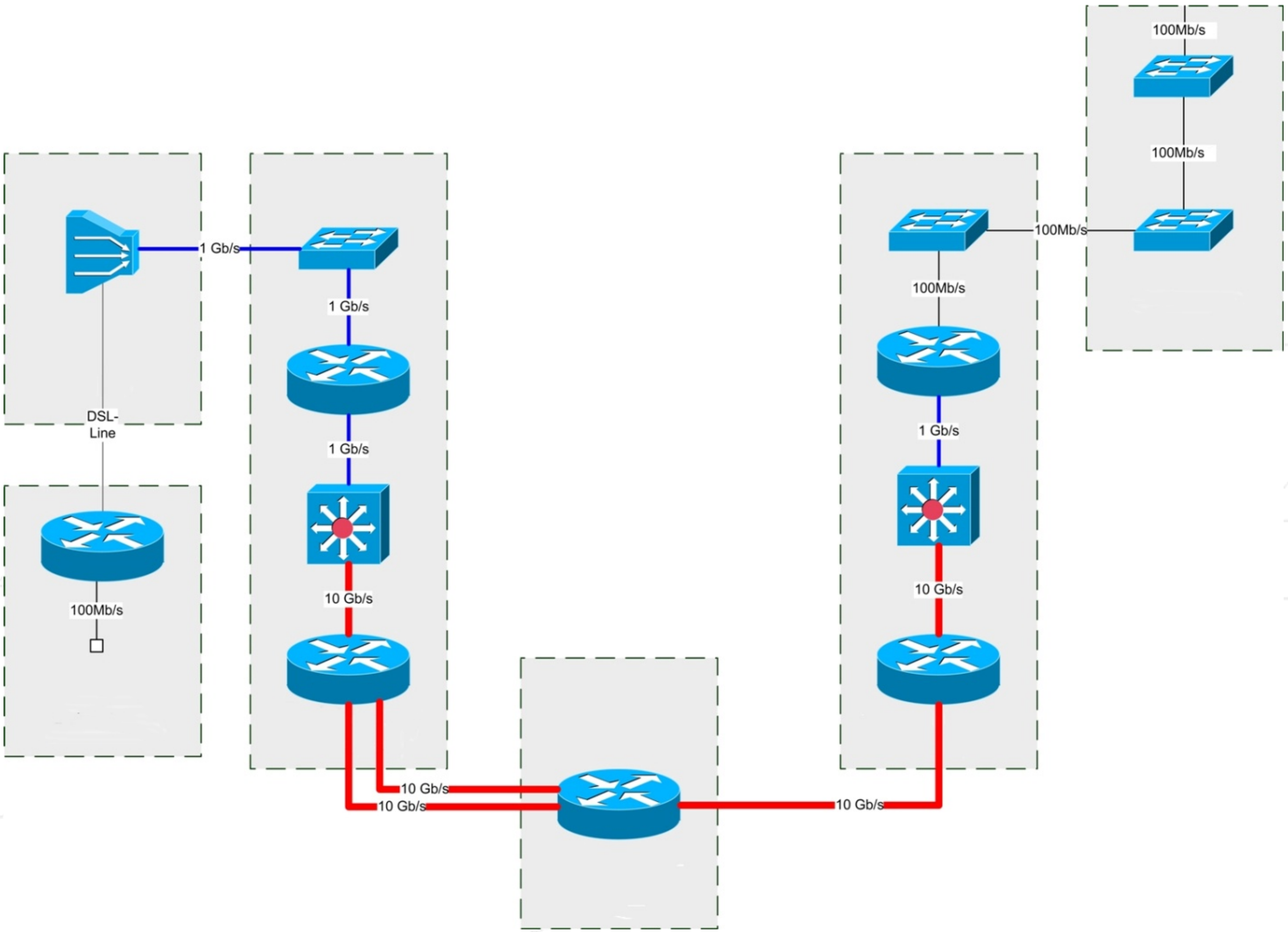


Appendix 2

Packet Network Measurement Examples

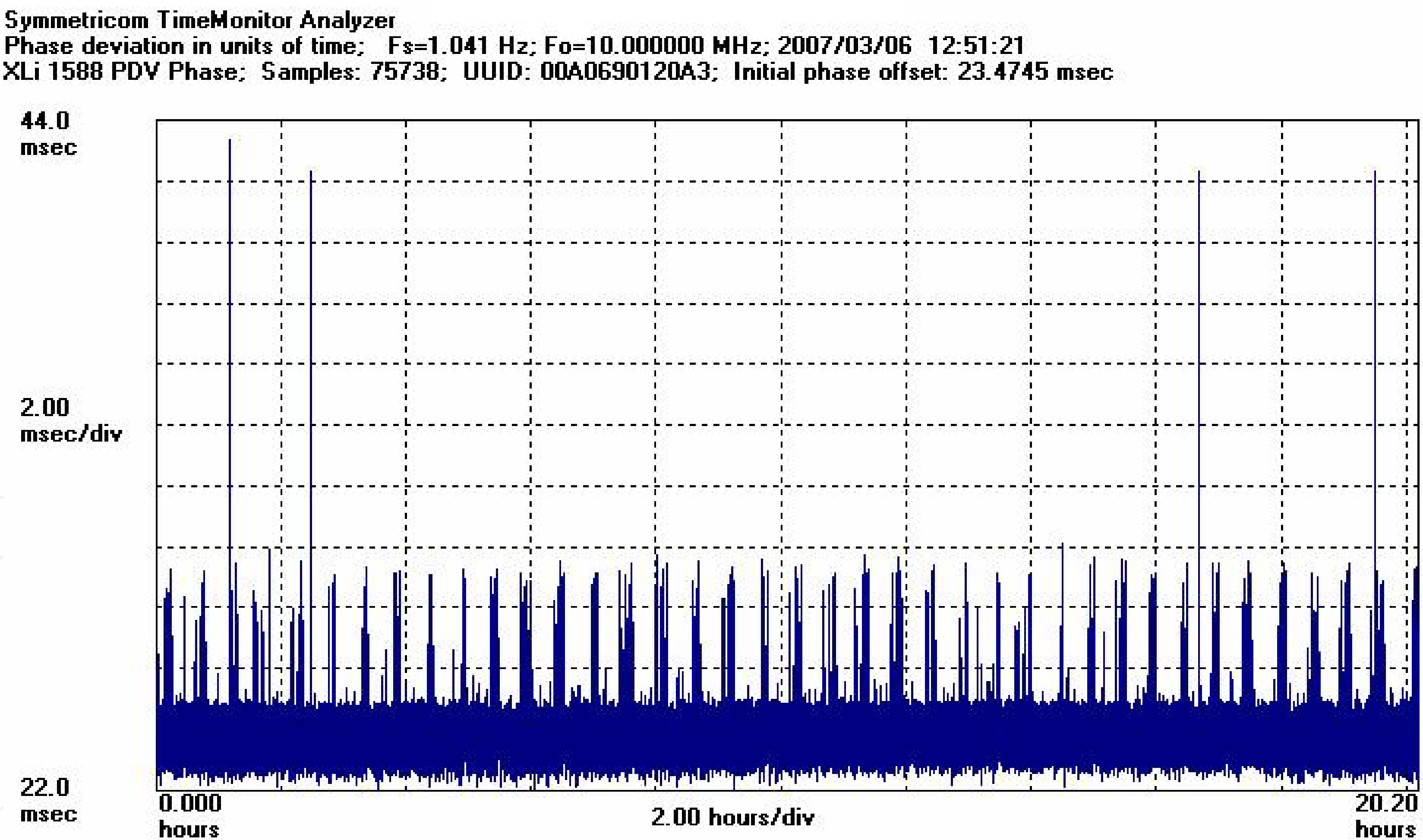
Production Network with DSL Access

Network spanning 500 km between two European cities



Production Network with DSL Access

Packet delay changes over time periodically due to periodic change in network loading (30 minute cycles)

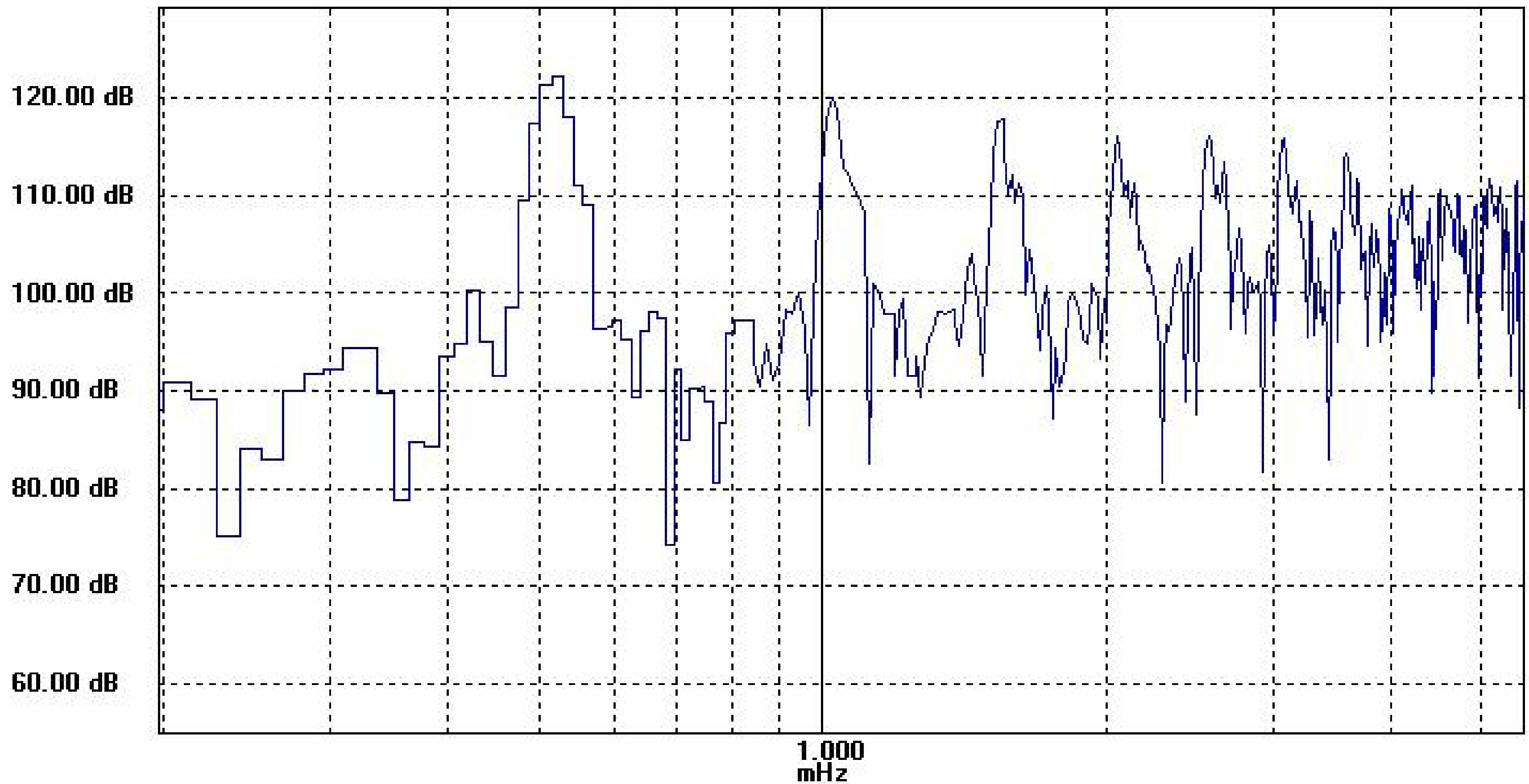


Production Network with DSL Access

Symmetricom

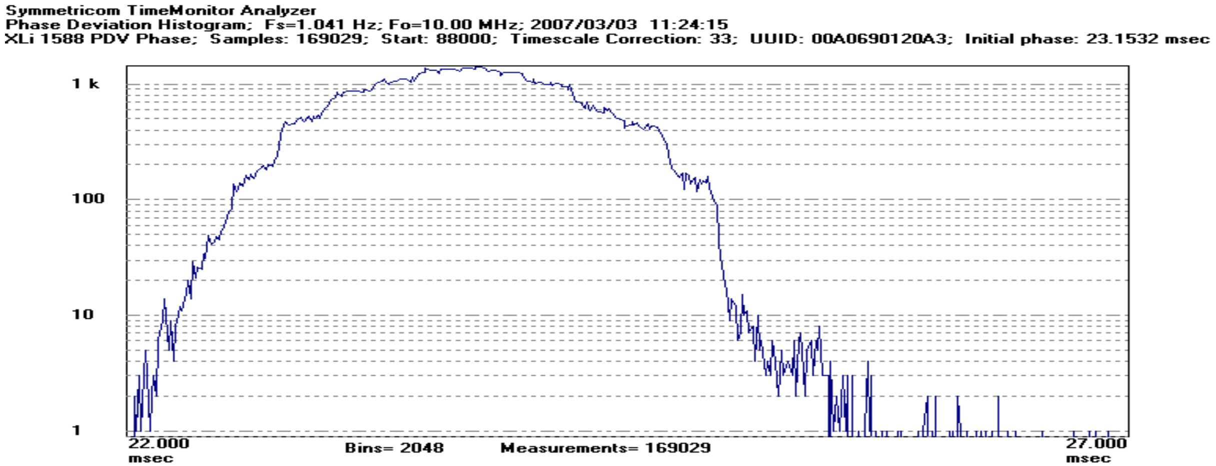
Phase power spectral density (PPSD) analysis clearly shows periodicity

Symmetricom TimeMonitor Analyzer
N=131072;Gaussian window; Avg=1; Noise BW=27.17 uHz;Fs=1.802 Hz;Fo=10.00 MHz; 2007/03/06 12:51:21
XLi 1588 PDV Phase; Samples: 75738; UUID: 00A0690120A3; Initial phase offset: 23.4745 msec

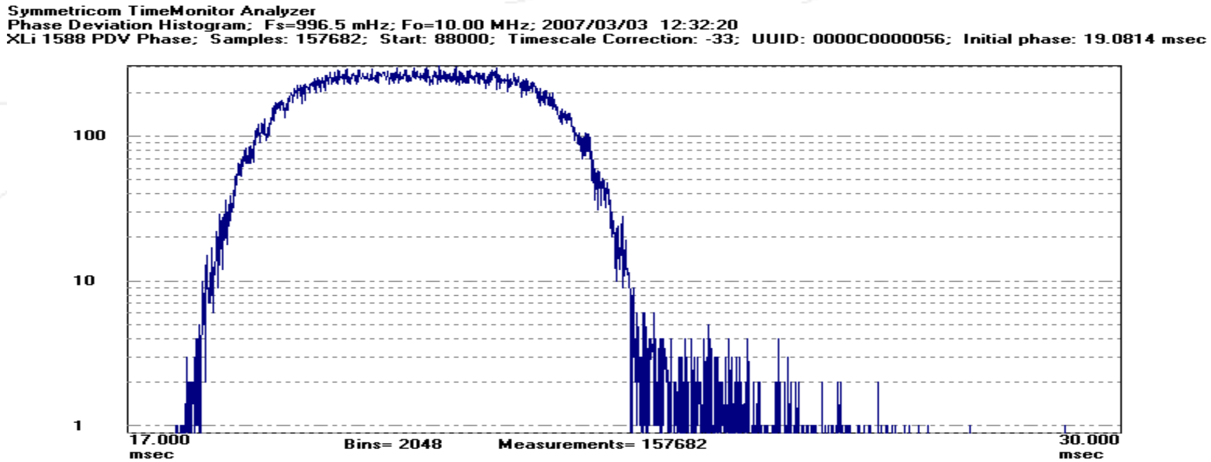


Production Network with DSL Access

Asymmetrical packet delay with DSL



Upstream Packet Delay
Minimum: 22.04297 msec
Peak to Peak: 4.866 msec

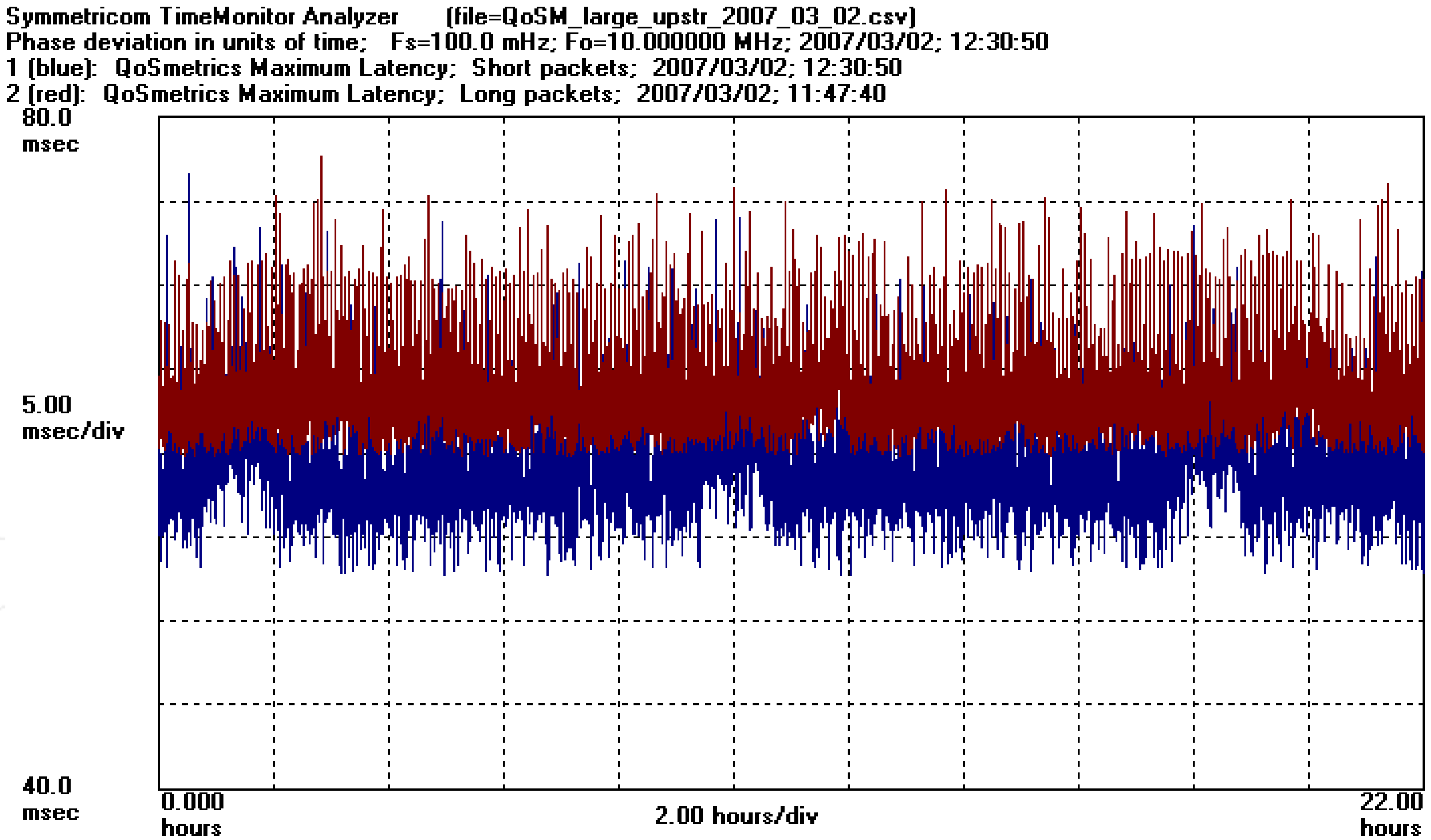


Downstream Packet Delay
Minimum: 17.64111 msec
Peak to Peak: 11.64 msec

Production Network with DSL Access

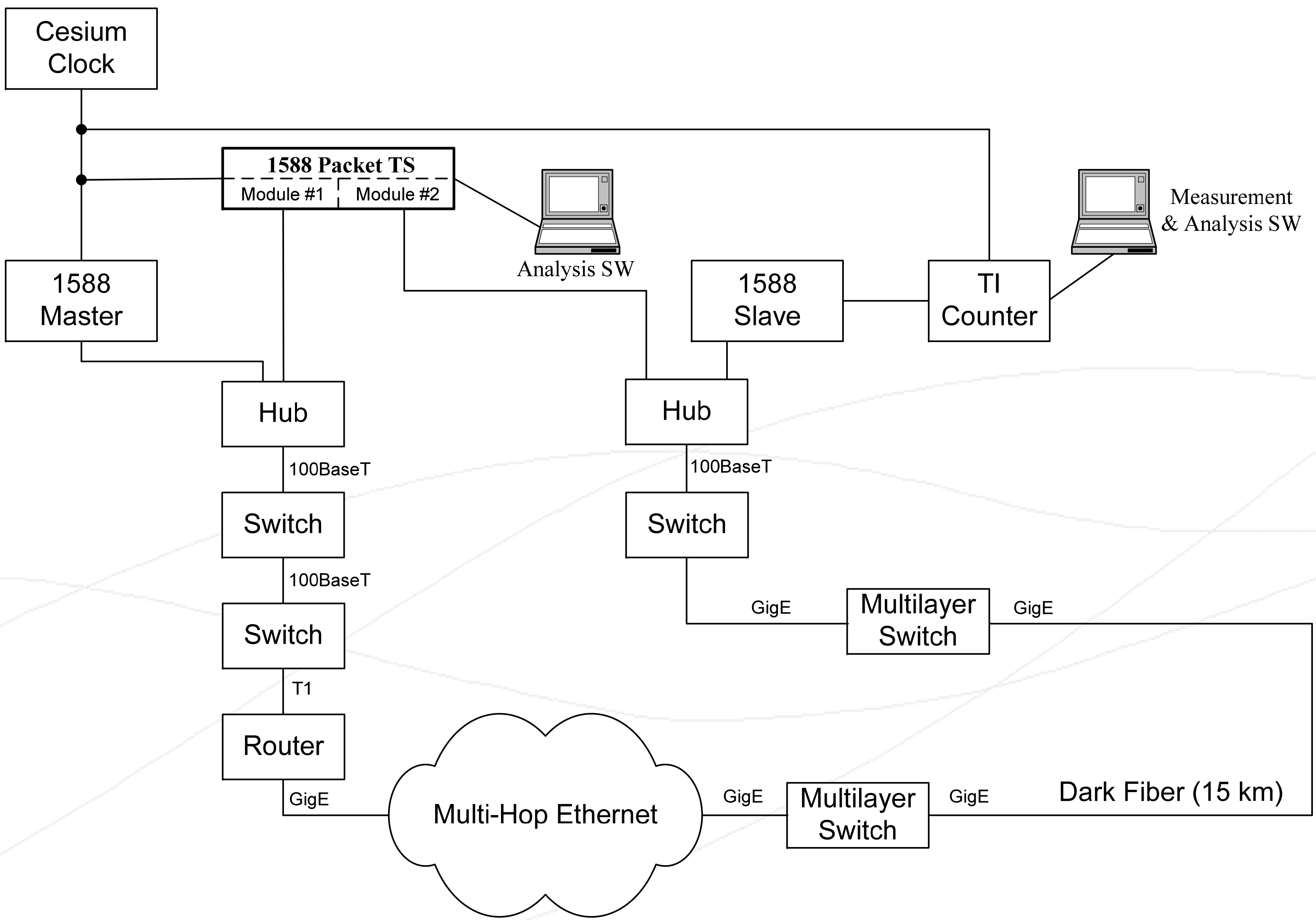
Symmetricom

Short packets vs. long packets



Production Network with Live Traffic

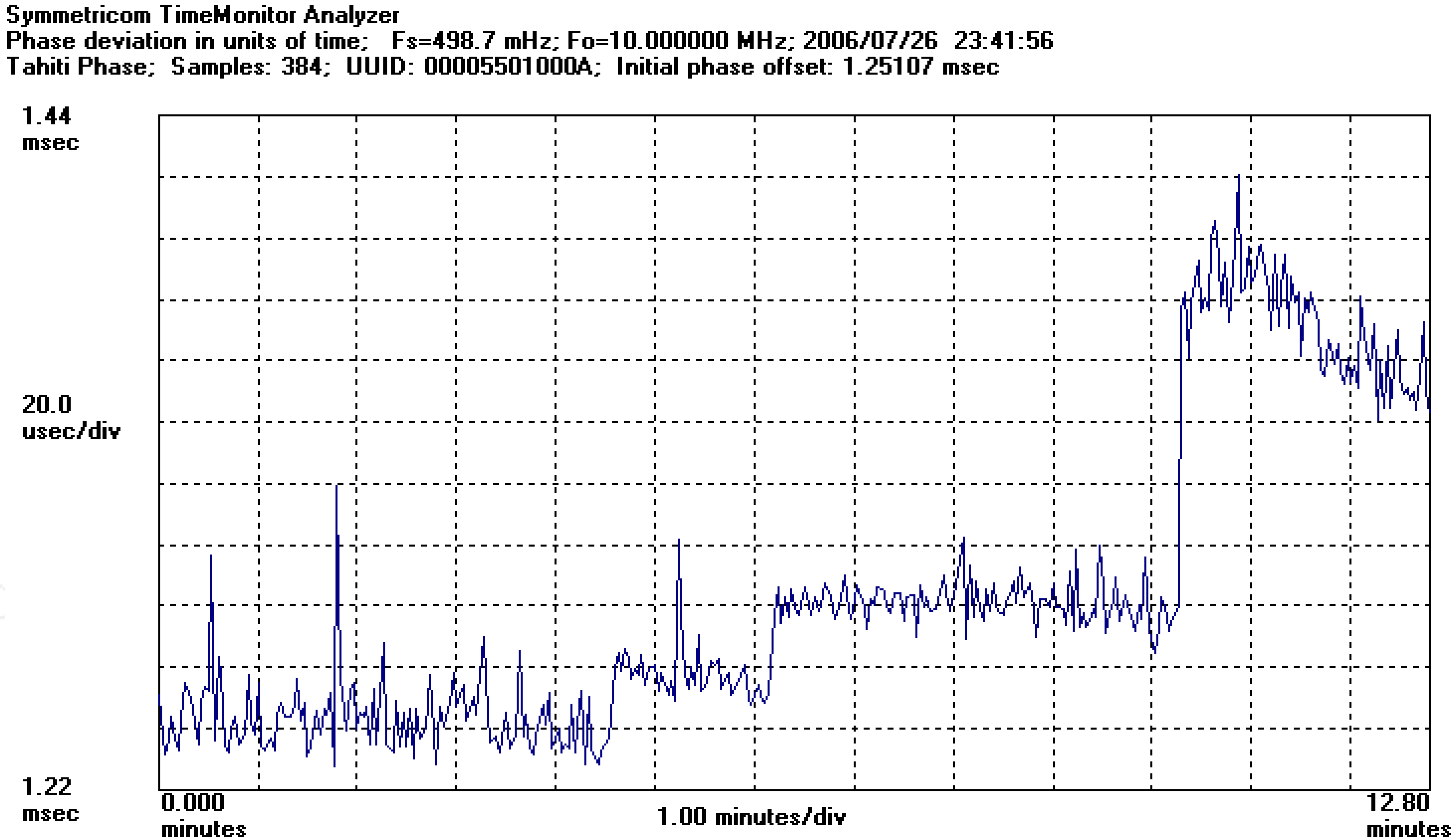
Symmetricom



Production Network with Live Traffic

Symmetricom

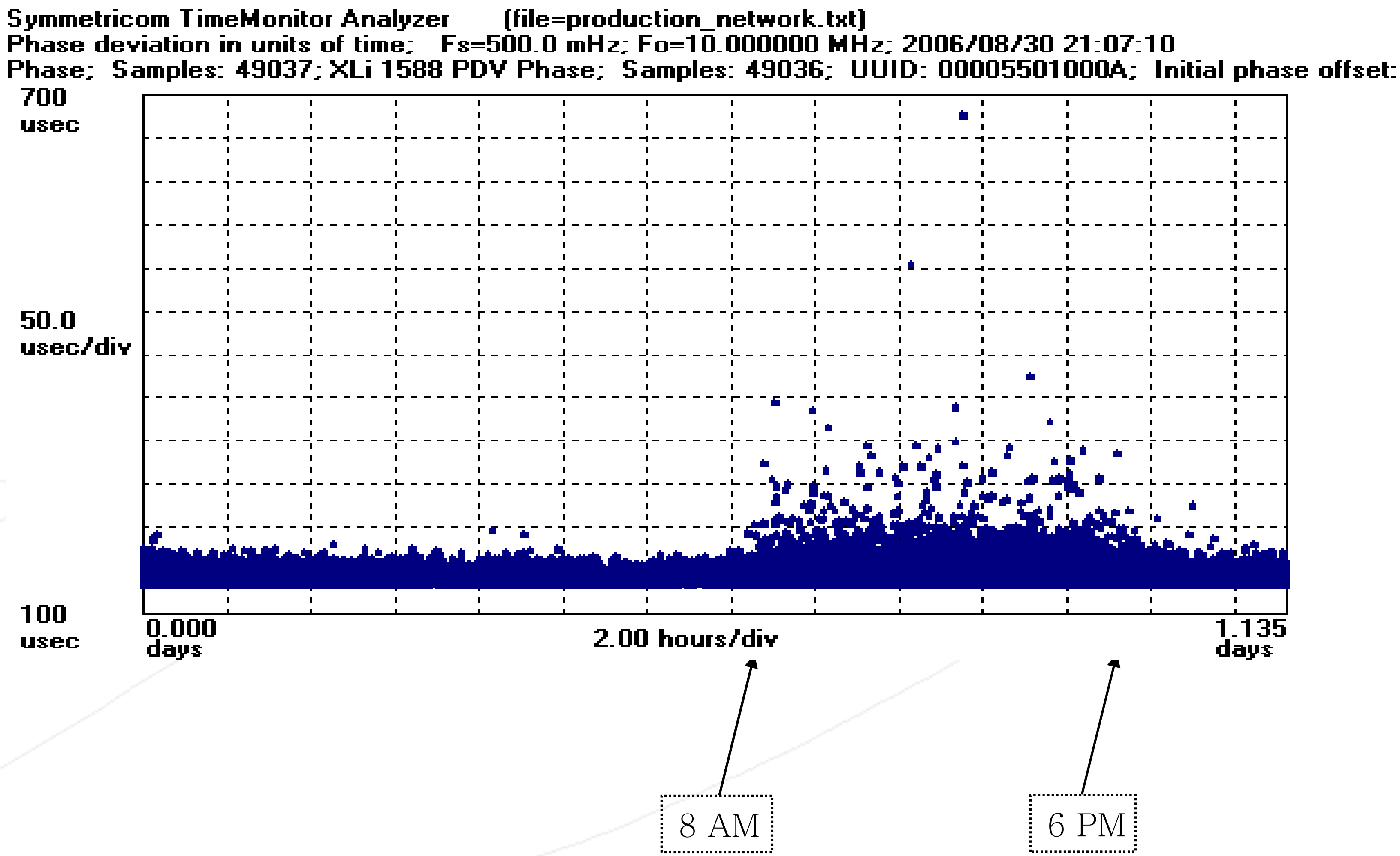
Packet delay changes over time with live traffic in a production network



Production Network with Live Traffic

Symmetricom

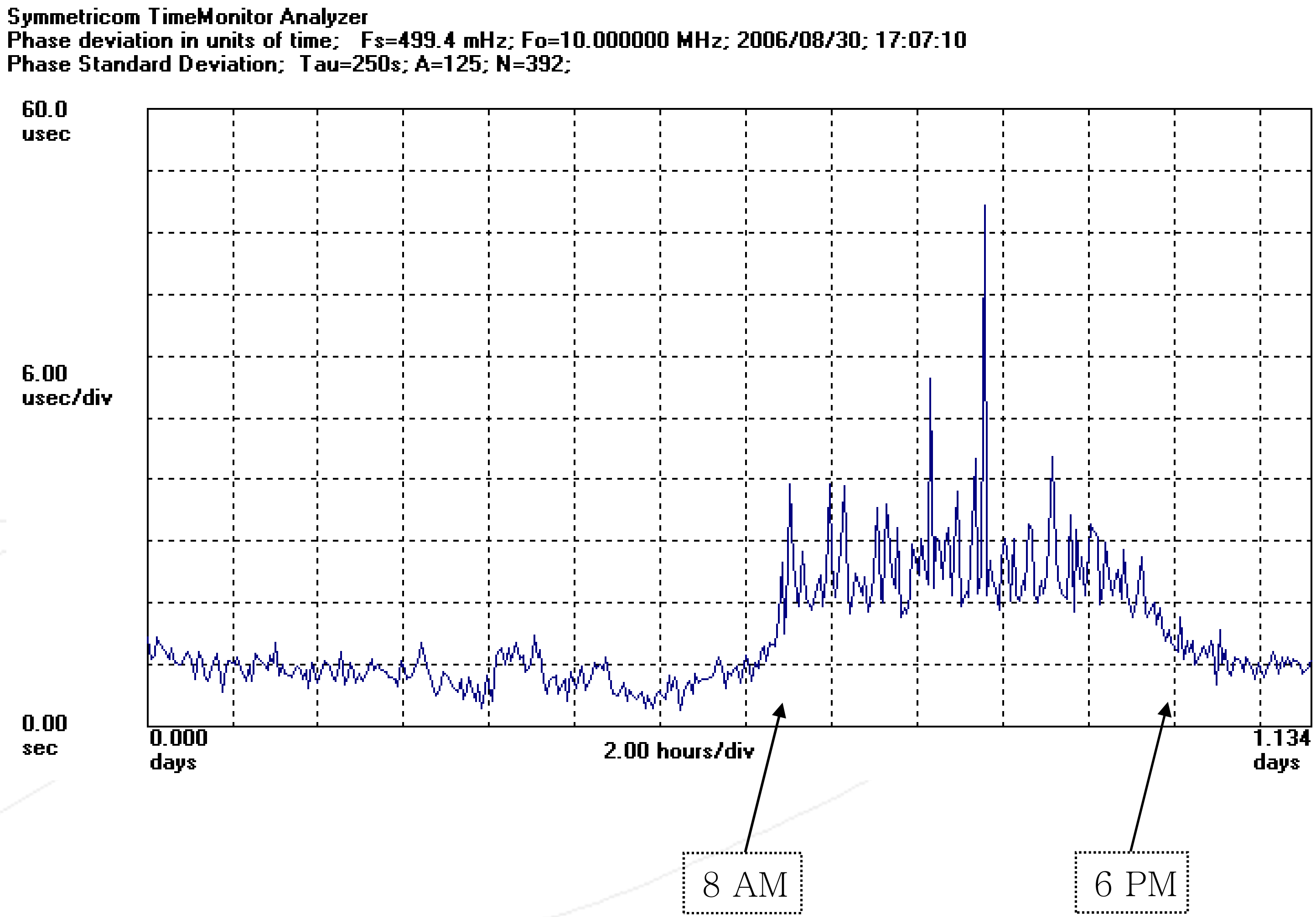
In another measurement, minimum packet delay remains constant but packet delay variation (PDV) changes over time (diurnal)



Production Network with Live Traffic

Symmetricom

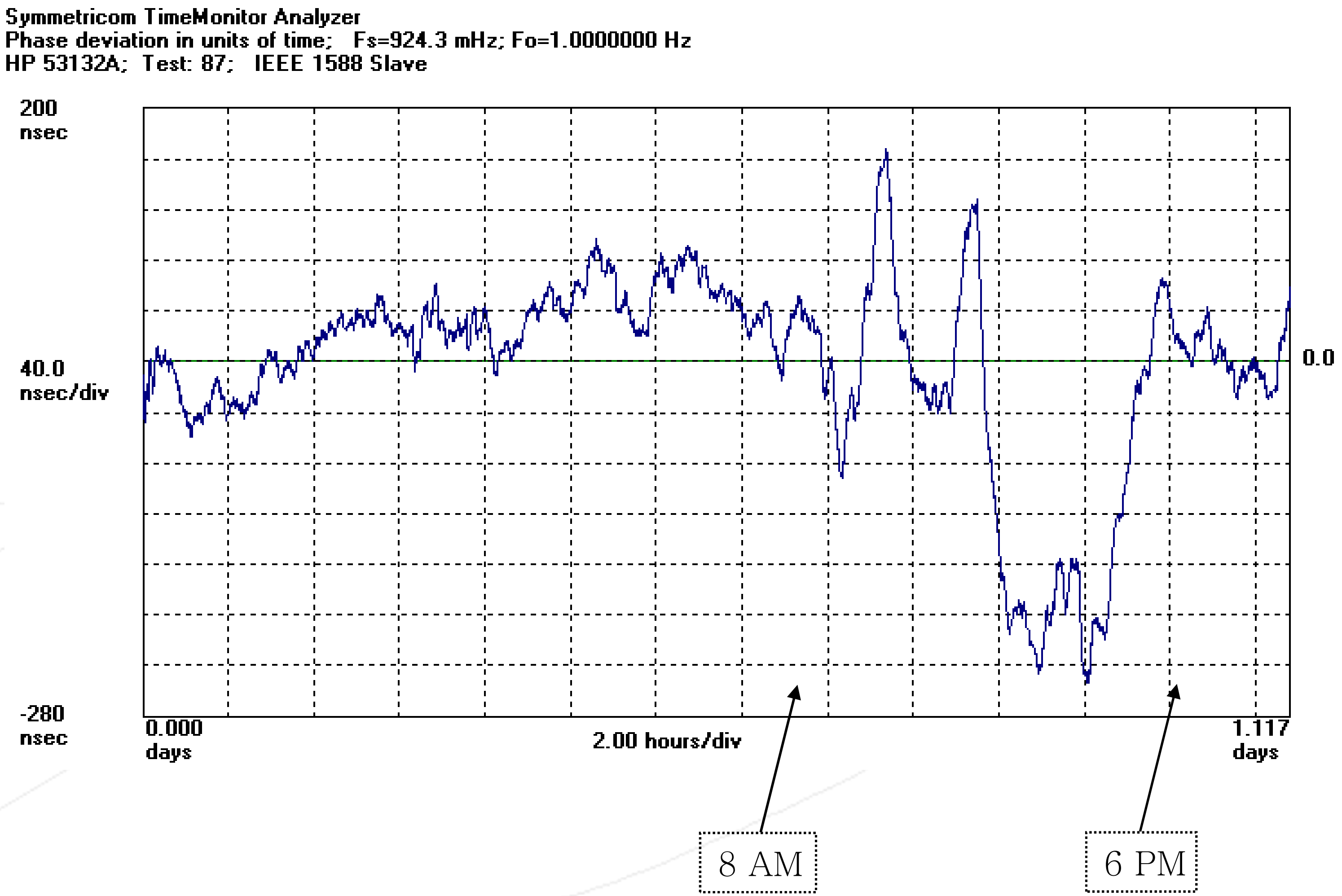
Tracking packet standard deviation over time shows gradual decrease through the night and then large increase during business hours



Production Network with Live Traffic

Symmetricom

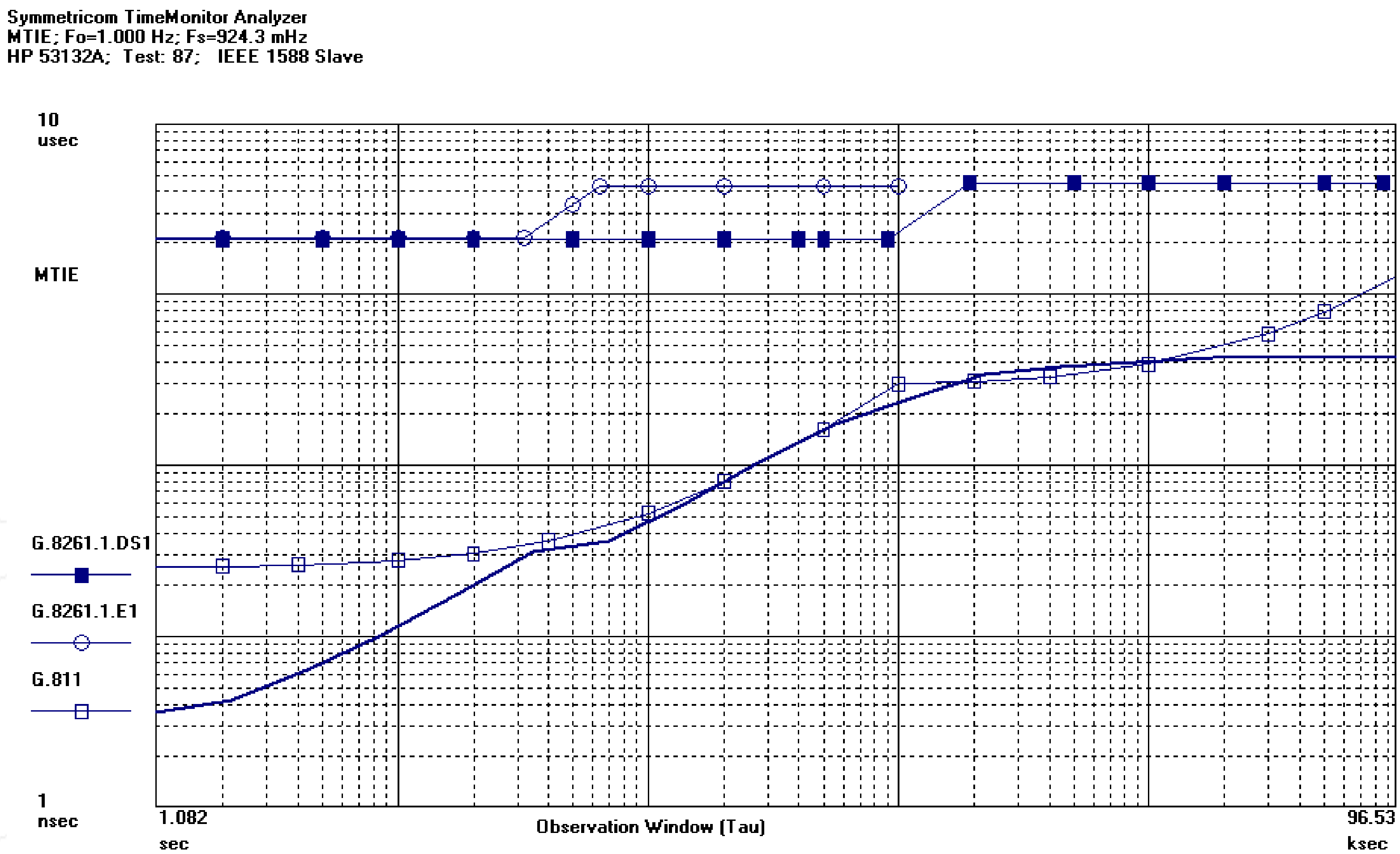
IEEE 1588 slave performance can be correlated with PDV variations



Production Network with Live Traffic

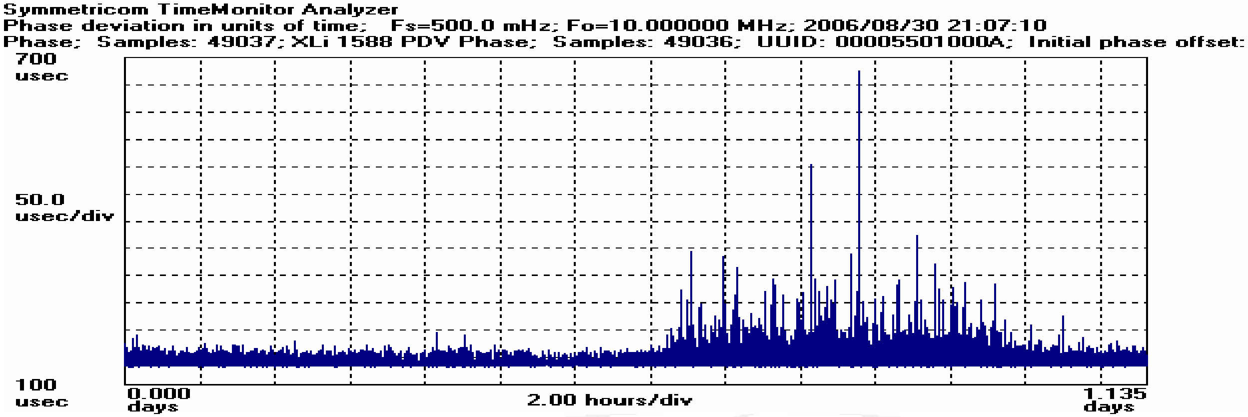
Symmetricom

For the entire 24 hour period the IEEE 1588 slave meets G.8261 requirements and nearly meets G.811 requirements

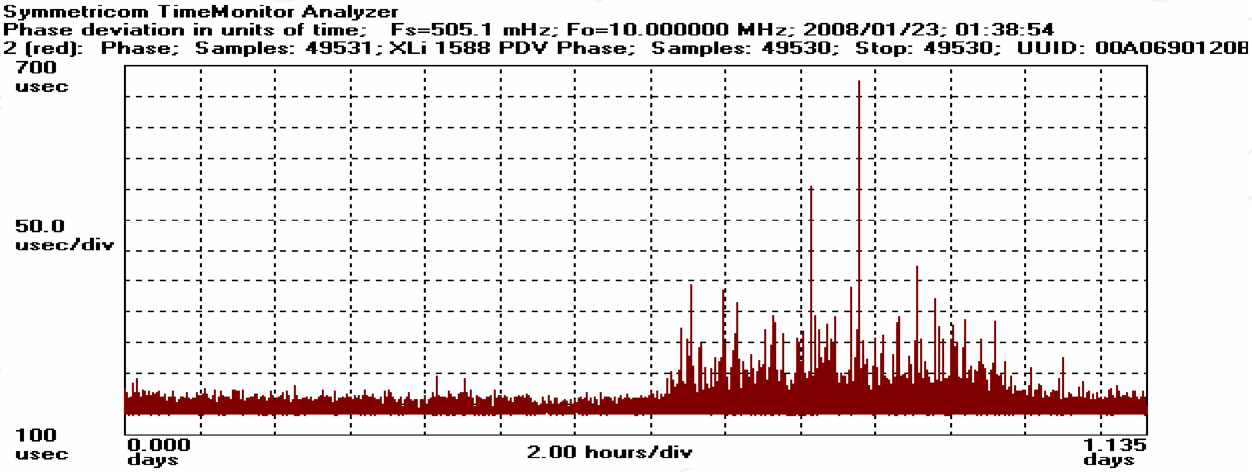


Production Network with Live Traffic: Playback vs. Live

A powerful combination: network PDV capture measurement with network emulator playback



Measurement of live network

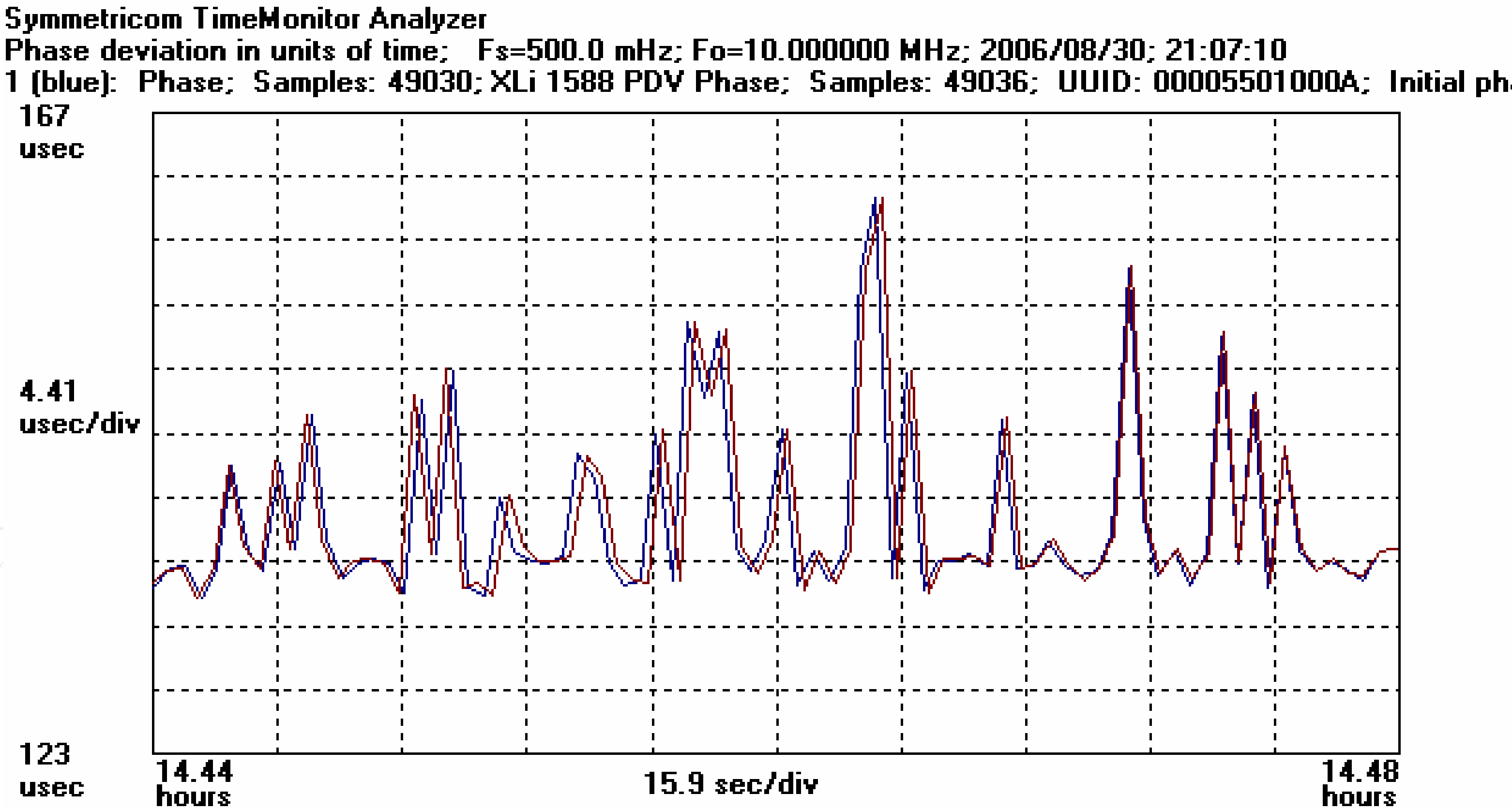


Measurement of emulator playback

Production Network with Live Traffic: Playback vs. Live

Symmetricom

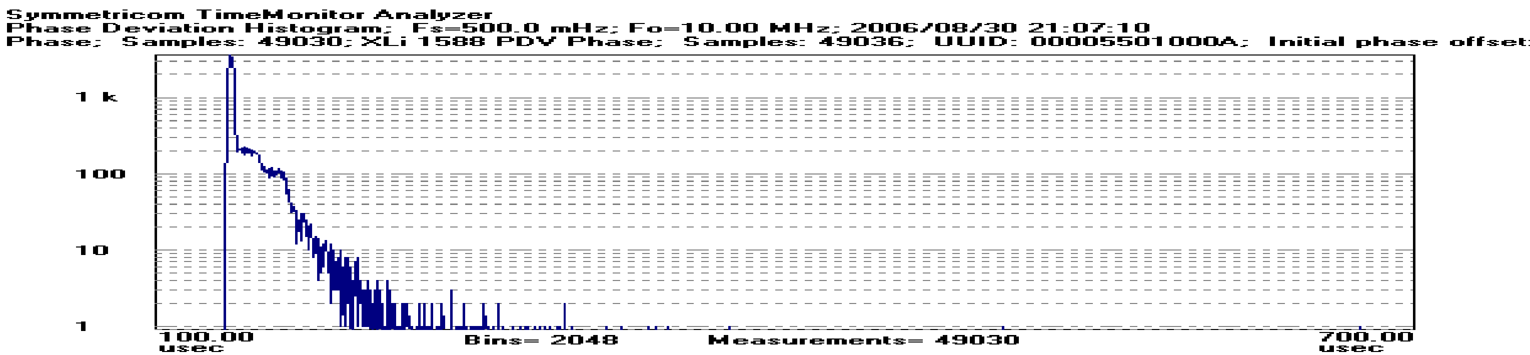
Live vs. emulator (overlay zoom)



Production Network with Live Traffic: Playback vs. Live

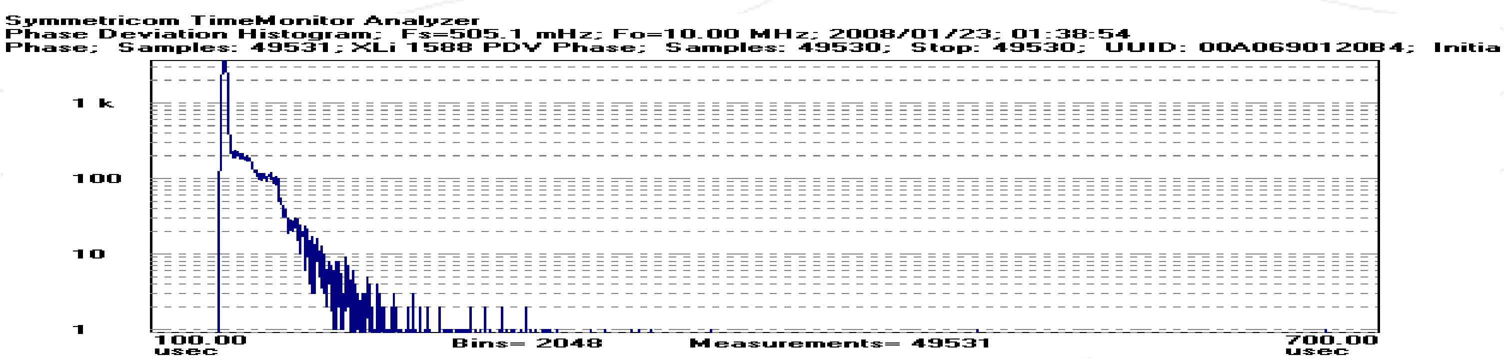
Symmetricom

Live vs. emulator: distribution



Measurement of live network

Minimum: 132.8125 usec Mean: 140.4341 usec
Maximum: 675.0976 usec Standard Deviation: 11.00 usec
Peak to Peak: 542.3 usec Population: 49030 Percentage: 100.%

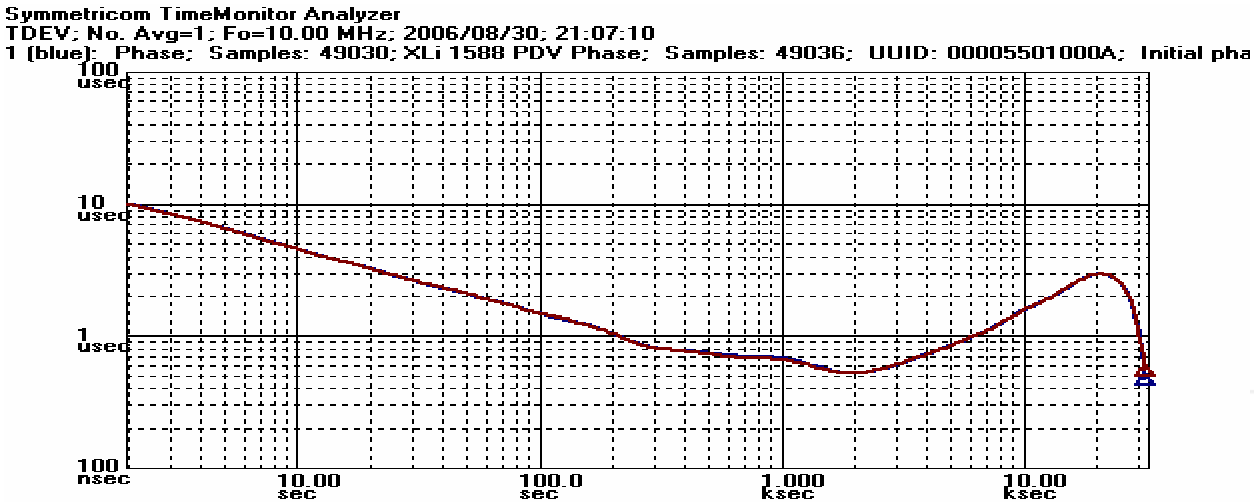


Measurement of emulator playback

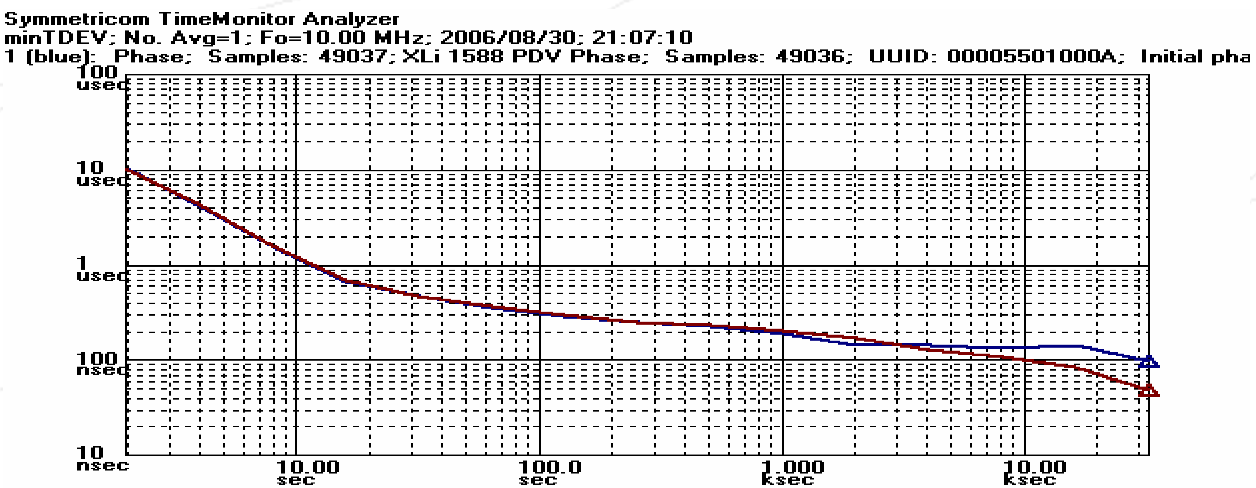
Minimum: 132.8125 usec Mean: 140.4764 usec
Maximum: 675.0976 usec Standard Deviation: 10.99 usec
Peak to Peak: 542.3 usec Population: 49532 Percentage: 100.%

Production Network with Live Traffic: Playback vs. Live

Live vs. emulator: TDEV and minTDEV



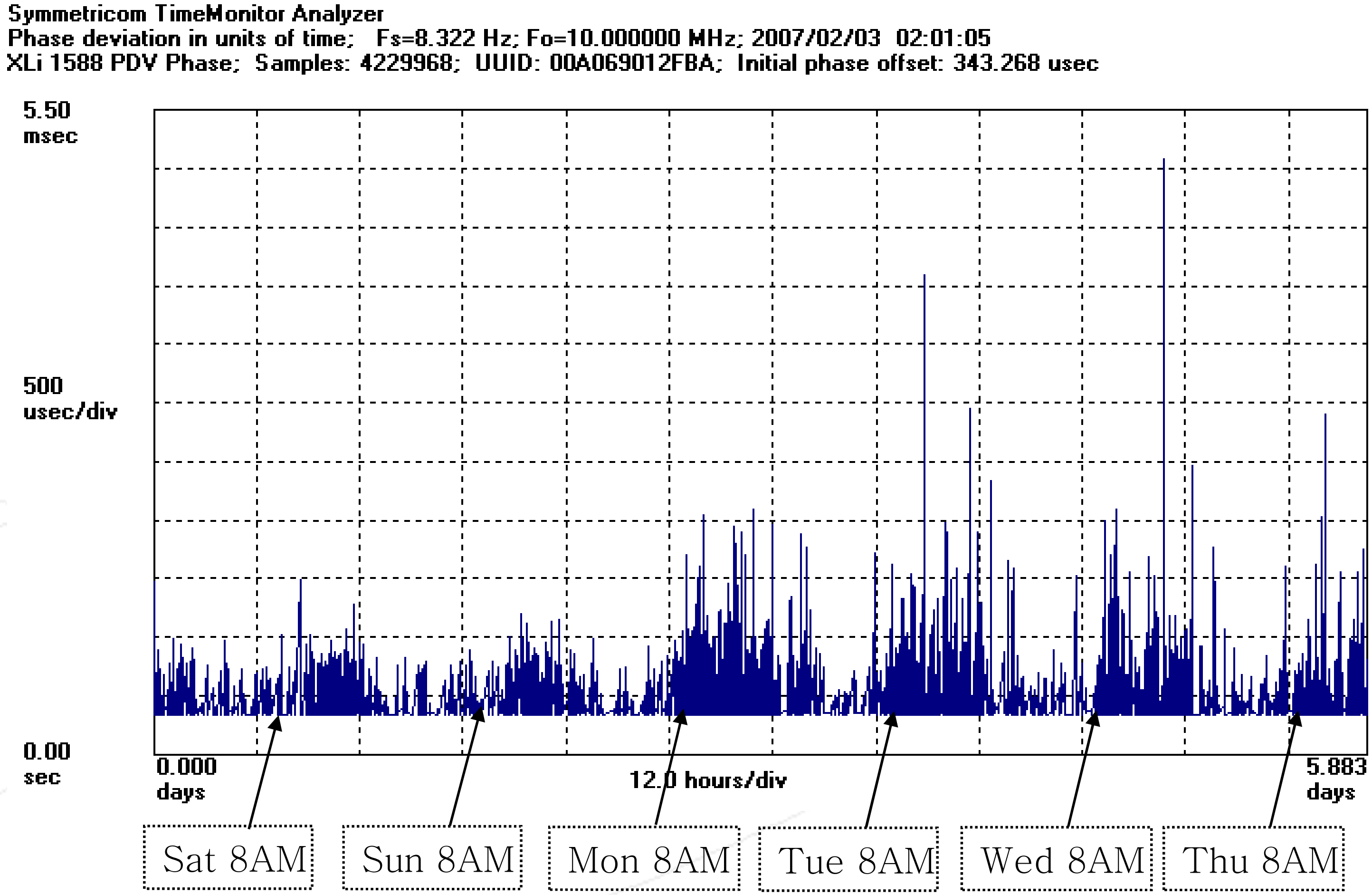
TDEV



minTDEV

Company LAN San Jose

Packet delay: 335 usec to 5.08 msec



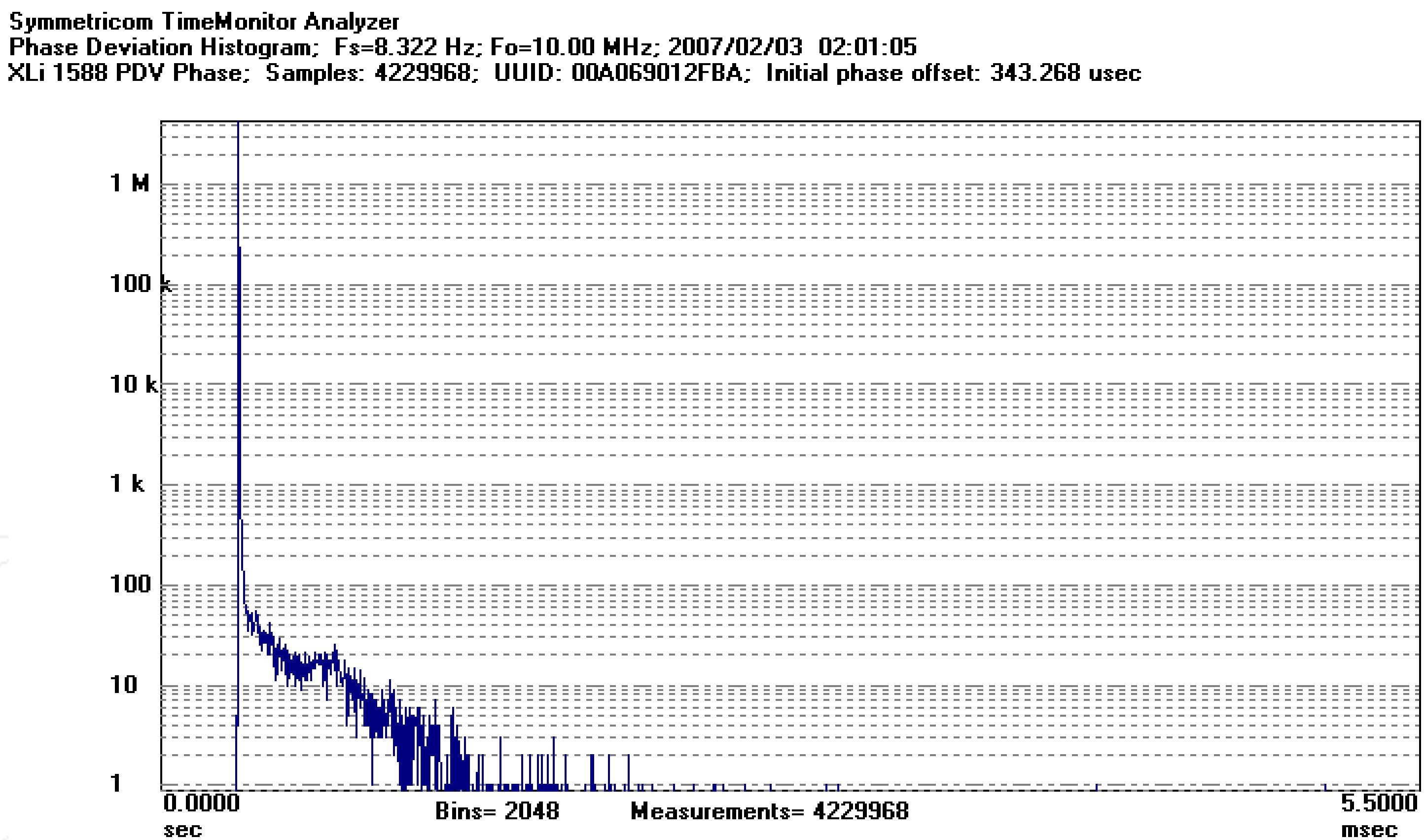
Company LAN San Jose

Symmetricom

Mean: 342.8 µsec

Peak to Peak: 4.75 msec

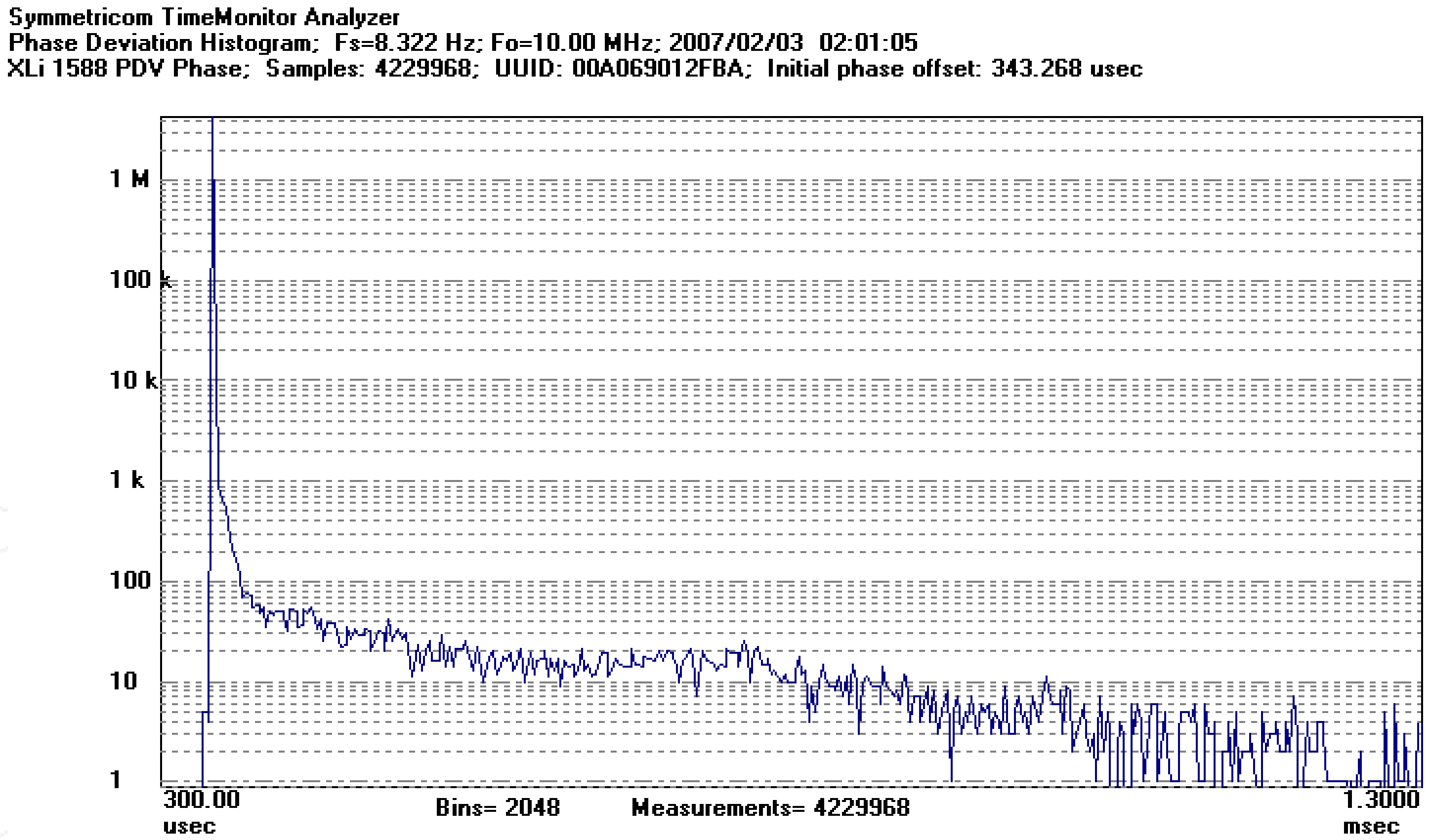
Standard Deviation: 14.03 µsec



Company LAN San Jose

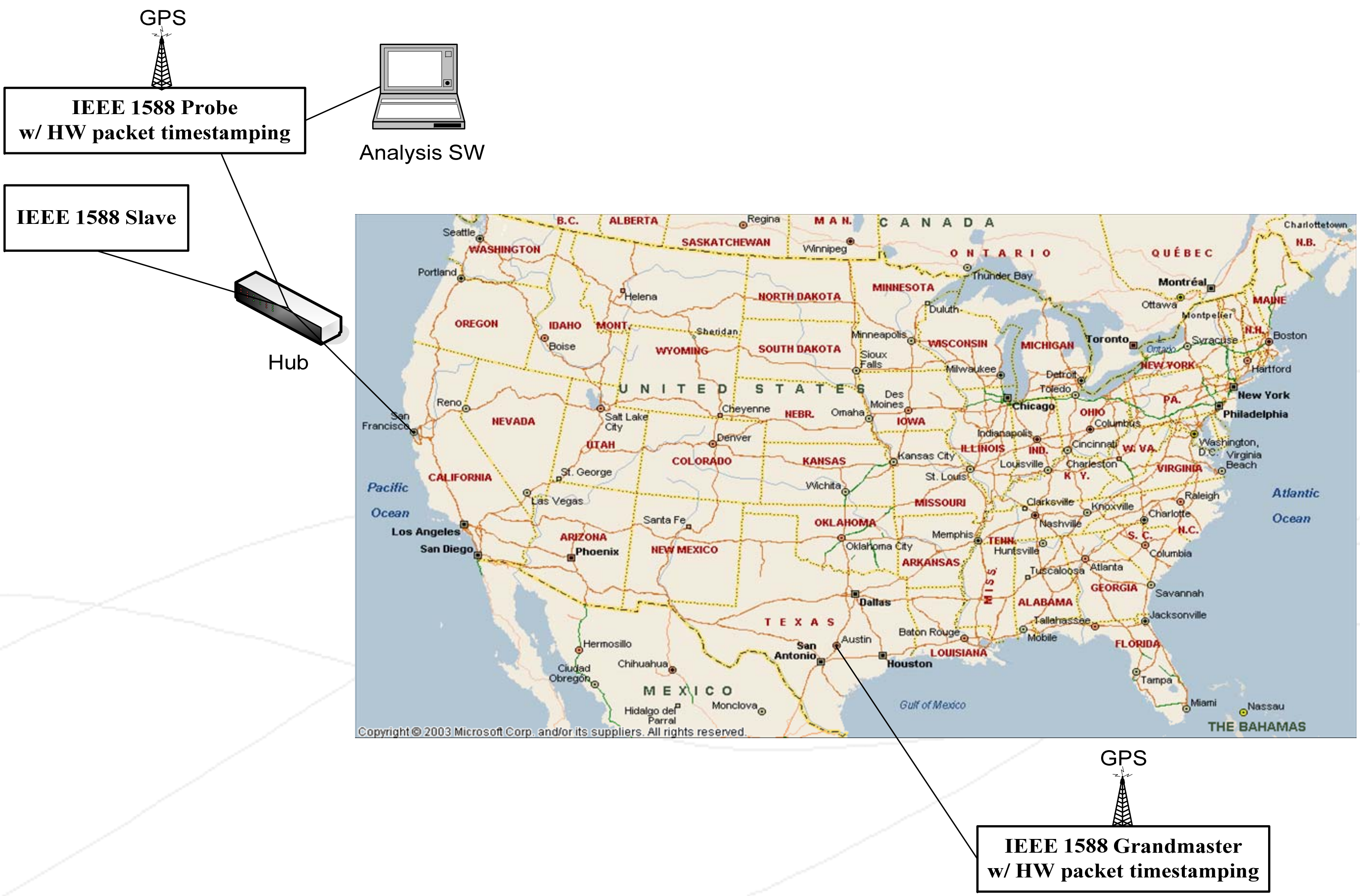
Zoom into 300-1300 μsec

Mean: 342.8 μsec
Peak to Peak: 4.75 msec
Standard Deviation: 14.03 μsec



Public Internet San Jose-Austin

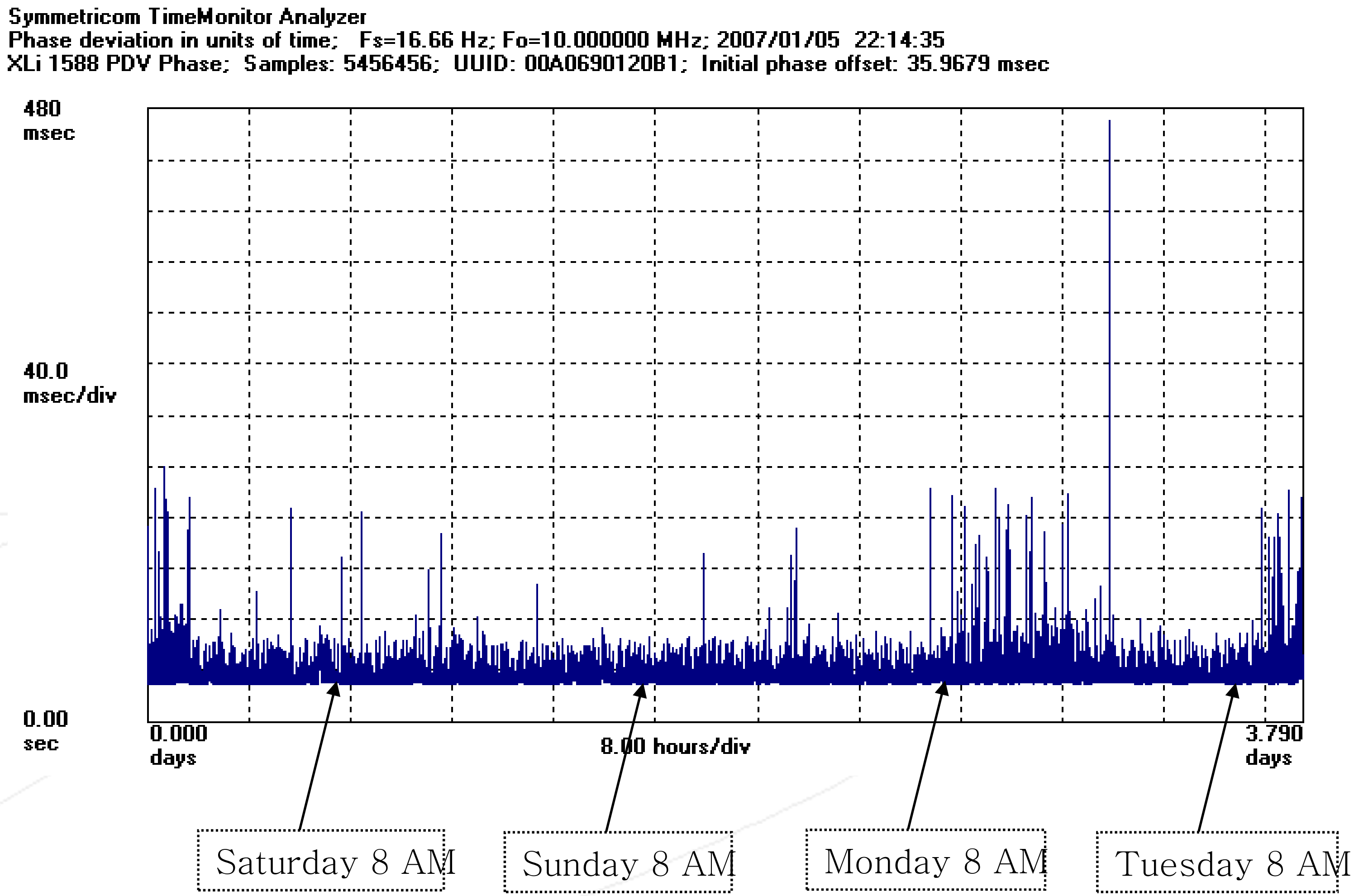
Symmetricom



Public Internet San Jose-Austin

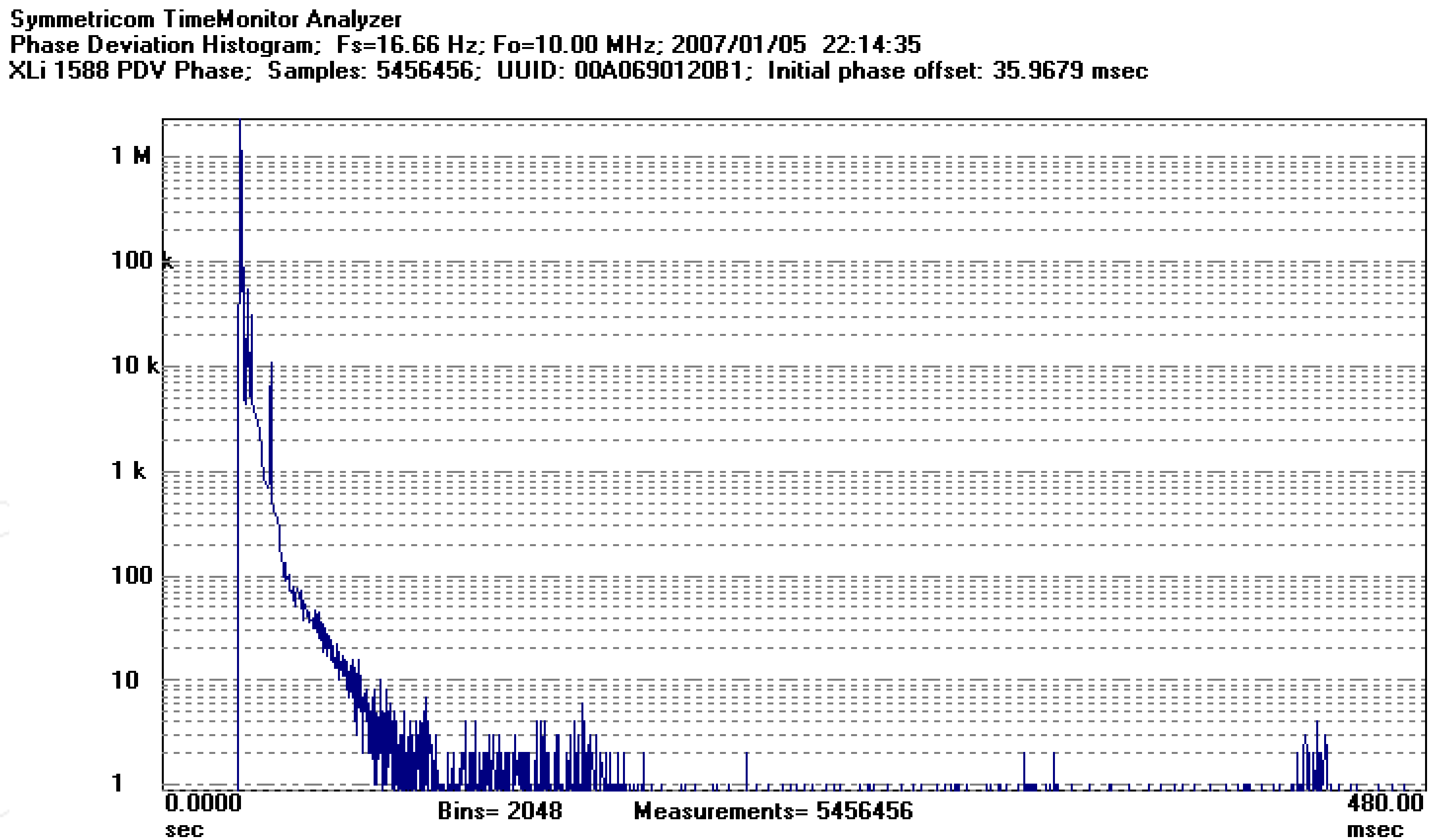
Symmetricom

Packet delay: 29 to 471 msec



Public Internet San Jose-Austin

Mean: 30.28 msec
Peak to Peak: 442.7 msec
Standard Deviation: 2.54 msec

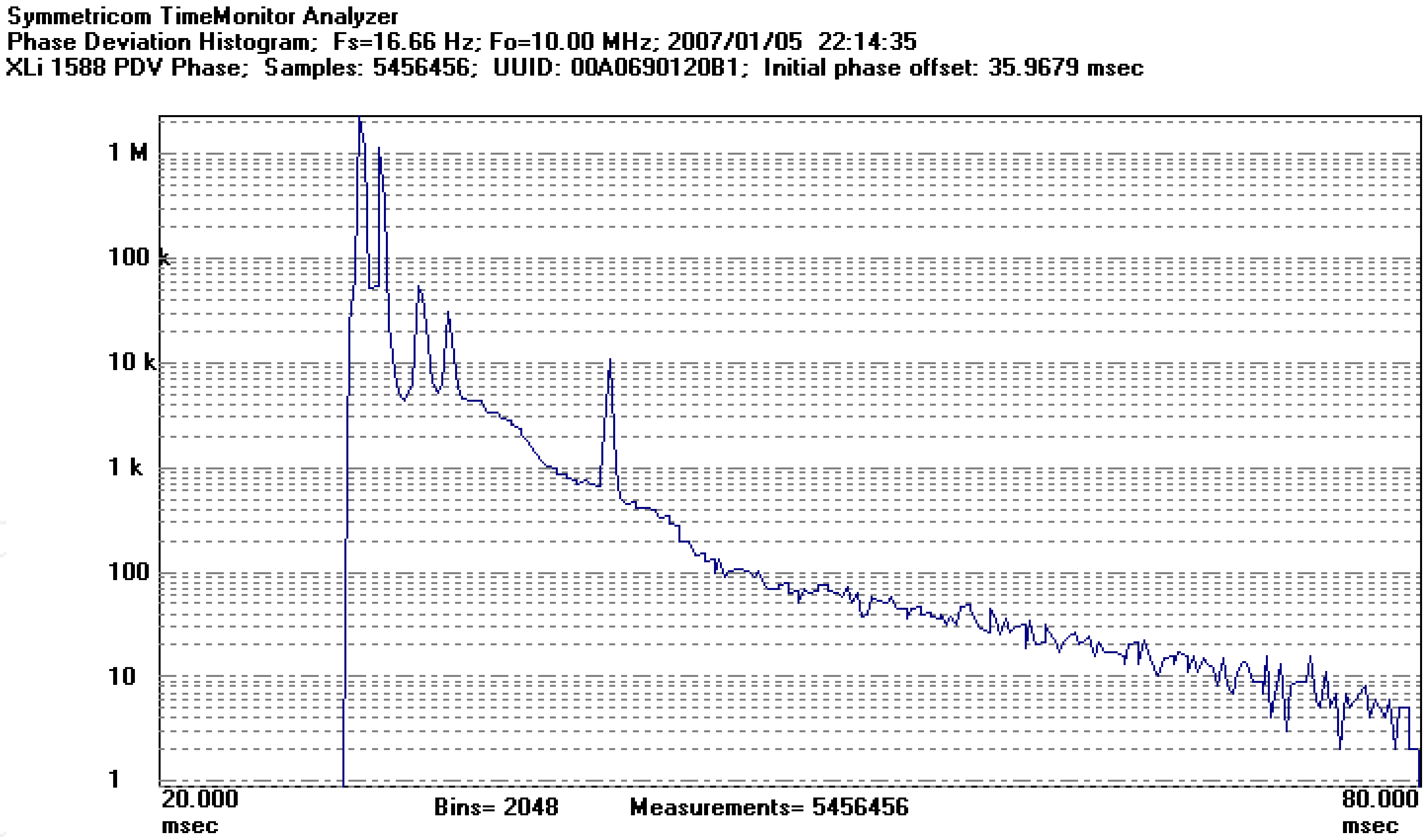


Public Internet San Jose-Austin

Symmetricom

Zoom into 20-80 msec

Mean: 30.28 msec
Peak to Peak: 442.7 msec
Standard Deviation: 2.54 msec



Packet Network Measurements

Symmetricom®

- Timing measurements in packet networks
  - Precision hardware timestamping together with UTC traceable TOD provides a precision tool for studying even the fastest networks and network equipment
  - Unicast capability is critical for the study of production networks and certain network devices such as DSLAM's (upstream multicast messages not provisionable for security reasons - depends on vendor)
  - Use of fast sync rates provides a means of characterizing rapid temporal packet network and device behavior (transients and systematics), facilitates selection algorithms both for analysis and servo design, and allows for quick collection of statistics