Symmetricom®

Leading the world in precise time solutions.

Measurements and Metrics for Frequency, Time, and Packet Signals

Lee Cosart

lcosart@symmetricom.com

WSTS 2013

Presentation Outline

- Introduction
  - TIE vs. PDV
  - Frequency vs. Time
  - Network vs. Equipment Measurements
  - Phase Detector and Packet Probe

- Metrics: Synchronization and Packet Analysis
  - TIE and PDV based metrics (G.810 and G.8260)
  - Packet selection processes and methods
  - Frequency transport PDV metrics
  - Time transport PDV metrics

- Measurement Case Studies
  - Networks
    - Time/frequency transport
  - Equipment
    - GM, BC, PRTC

- Conclusions

Frequency signal "TIE" vs. "PDV"

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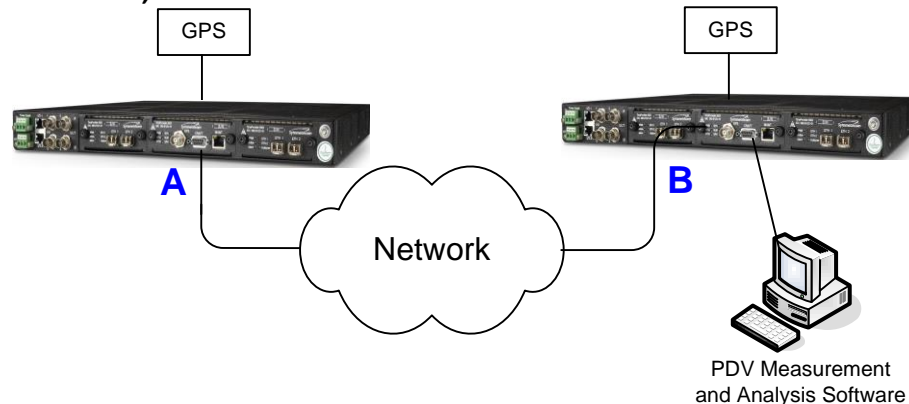 - Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed

0 µs   1.001 µs   1.997 µs   3.005 µs

Network — E1 — PRC

Probe

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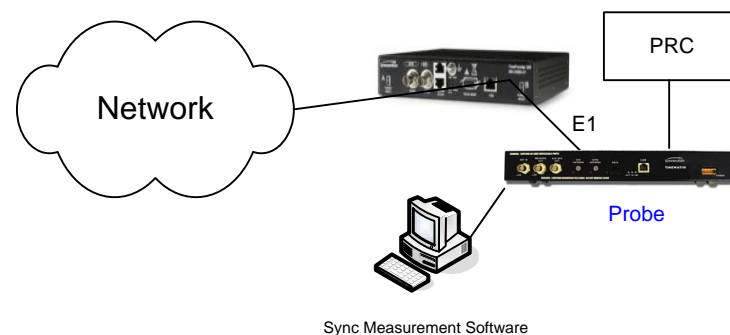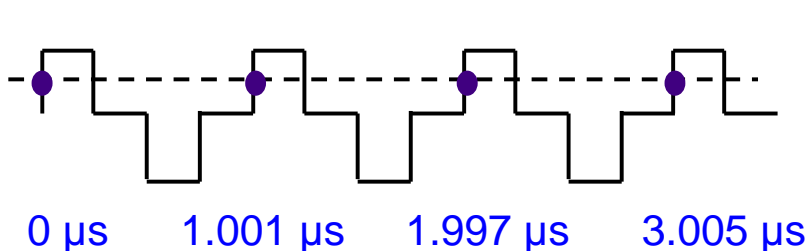
- **"PDV"** (Dual Point Measurement)
  - Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed
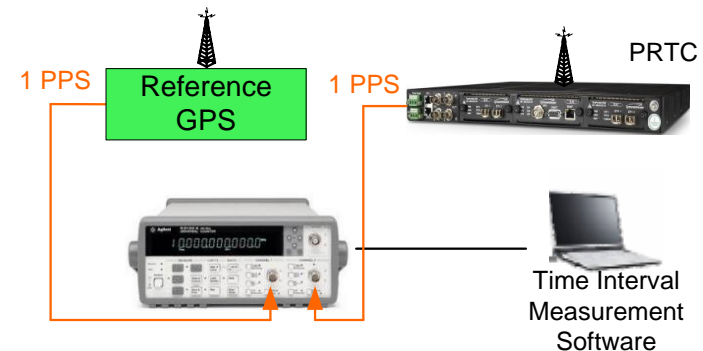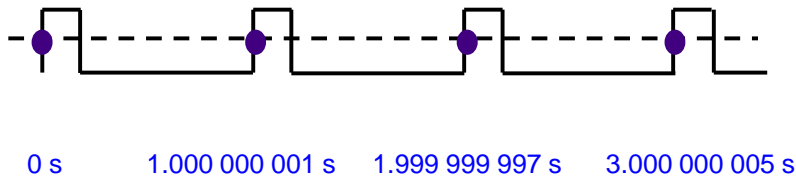
Timestamp A   Timestamp B

```
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
```


GPS   GPS

A   B

Network

PDV Measurement and Analysis Software

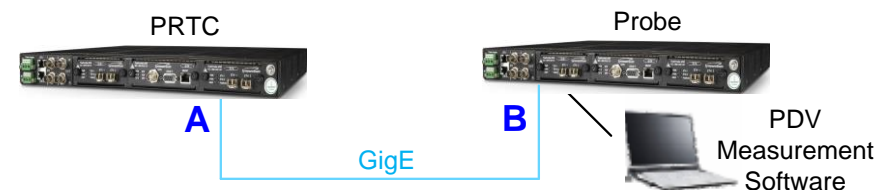# Time signal "Physical" vs. "Packet"

- **"1 PPS"** (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

0 s   1.000 000 001 s   1.999 999 997 s   3.000 000 005 s
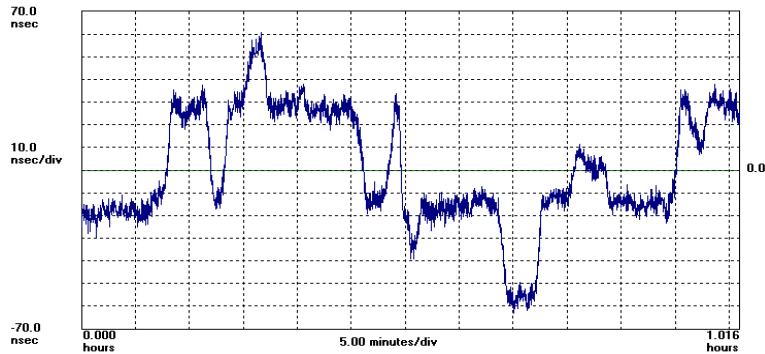
- **"Packet"** (Dual Point Measurement)
  - Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed

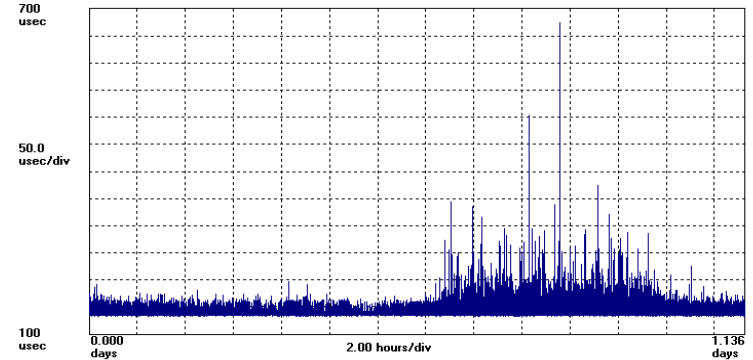| Timestamp A	Timestamp B
F 1286231440.883338640	1286231440.883338796
R 1286231441.506929352	1286231441.506929500
F 1286231441.883338640	1286231441.883338796
R 1286231442.506929352	1286231442.506929500
F 1286231442.883338640	1286231442.883338796
R 1286231443.506929352	1286231443.506929516

4

Network TIE

Network PDV

Equipment TIE

Equipment PDV

Packet Probe

Passive Probe vs. Active Probe

Passive Probe

(1) Hub or Ethernet Tap
(2) IEEE 1588 Slave
(3) Collection at Both Nodes
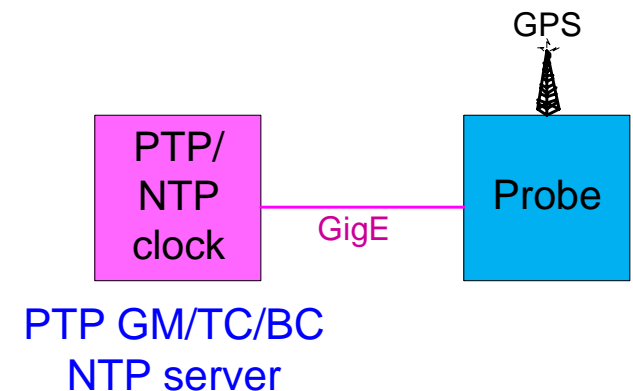
Passive probe sniffs packets: extra equipment required

Active Probe

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

Active probe generates protocol: self-contained

Network vs. Equipment PDV Measurement

GPS

Master /Server — GigE — Network — GigE — Probe   GPS

PTP/ NTP clock — GigE — Probe   GPS

PTP GM/TC/BC
NTP server
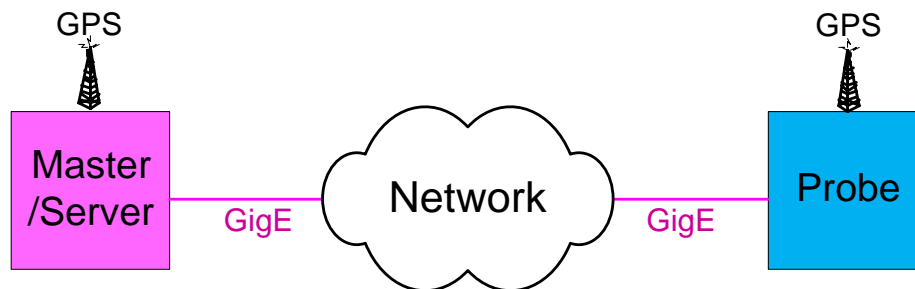
"TIE" Analysis vs. "PDV" Analysis

"TIE" Analysis (G.810)

- Phase (TIE)
- Frequency accuracy
- Dynamic frequency
- MTIE
- TDEV

"PDV" Analysis (G.8260)

- Phase (PDV)
- Histogram/PDF*,CDF**,statistics
- Dynamic statistics
- MATIE/MAFE
- TDEV/minTDEV/bandTDEV
- Two-way metrics: minTDISP etc.

▶ The importance of raw TIE/PDV:
- Basis for frequency/statistical/MTIE/TDEV analysis
- Timeline (degraded performance during times of high traffic?)
- Measurement verification (jumps? offsets?)

* *PDF = probability density function*

** *CDF = cumulative distribution function*

Stability Metrics

- Traditional Clock Metrics
  - ADEV, TDEV, MTIE
  - Traditionally applied to oscillators, synchronization interfaces
  - Also applied to lab packet equipment measurements

  GM, BC

- Frequency Transport Packet Metrics
  - minTDEV, MAFE, MATIE
  - Applied to one-way packet delay data
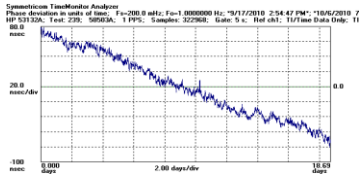 - FPP/FPR/FPC (floor packet percentage/rate/count)

  Packet Networks

- Time Transport Packet Metrics
  - minOffset, minTDISP
  - Applied to two-way packet delay data
  - Assesses link asymmetry

Analysis from Phase: Frequency

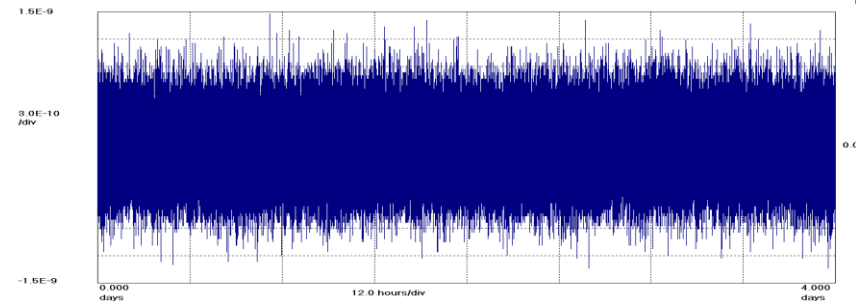$\longrightarrow$ $-8.97 \cdot 10^{-14}$

Frequency Accuracy

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

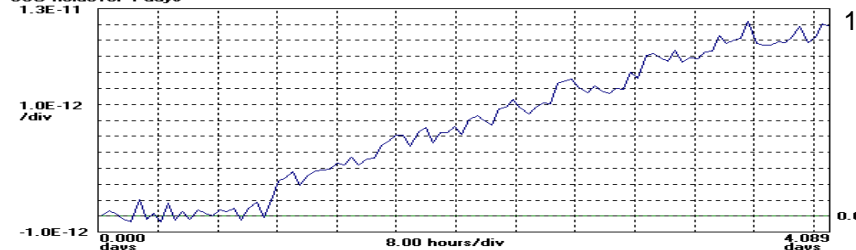slope/linear: frequency offset
curvature/quadratic: frequency drift

1.5 E-9

Point-by-point

1.2 E-11

Segmented LSF
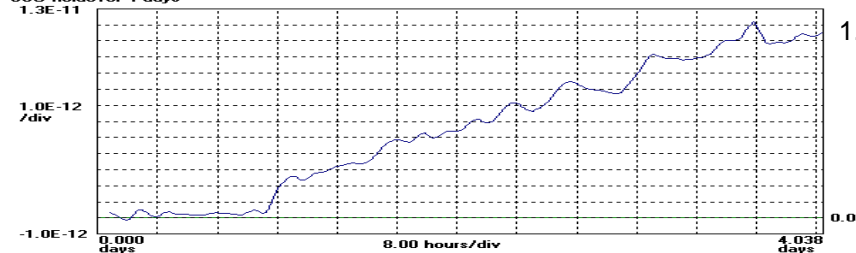
1.2 E-11

Sliding Window Averaging

9

Analysis from Phase: MTIE/TDEV

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

MTIE is a peak detector
MTIE detects frequency offset
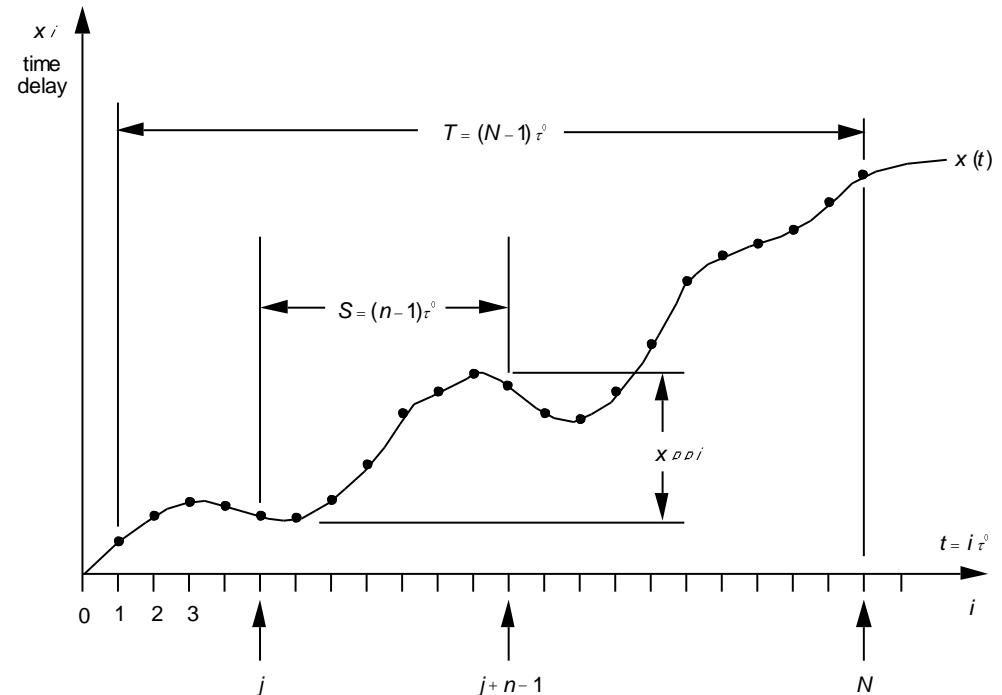
$$\sigma_x(\tau) = TDEV(\tau) = \sqrt{\frac{1}{6}\left\langle \left[\frac{1}{n}\sum_{i=1}^{n} x_{i+2n} - 2\frac{1}{n}\sum_{i=1}^{n} x_{i+n} + \frac{1}{n}\sum_{i=1}^{n} x_i \right]^2 \right\rangle}$$

TDEV is a highly averaged "rms" type of calculation
TDEV shows white, flicker, random walk noise processes
TDEV does not show frequency offset

MTIE and TDEV analysis allows comparison to ATIS, Telcordia, ETSI, & ITU-T requirements

Stability metrics for PDV

- Packet Selection Processes

  1) *Pre-processed:* packet selection step prior to calculation

     - Example: *TDEV*(*PDVmin*) where *PDVmin* is a new sequence based on minimum searches on the original PDV sequence

  2) *Integrated:* packet selection integrated into calculation

     - Example: *minTDEV*(*PDV*)

- Packet Selection Methods

  - Minimum: $x_{\min}(i) = \min\lfloor x_j \rfloor for (i <= j <= i+n-1)$
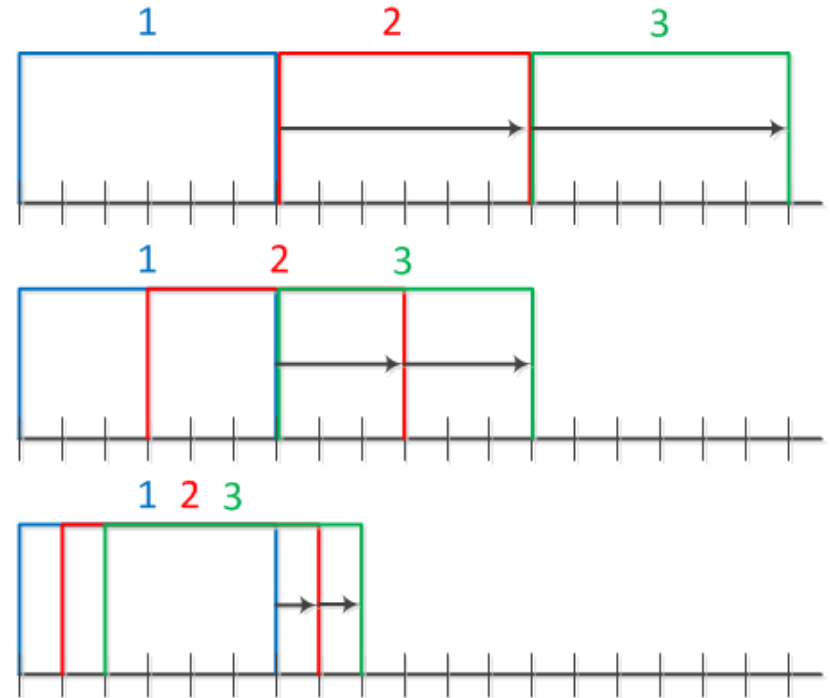
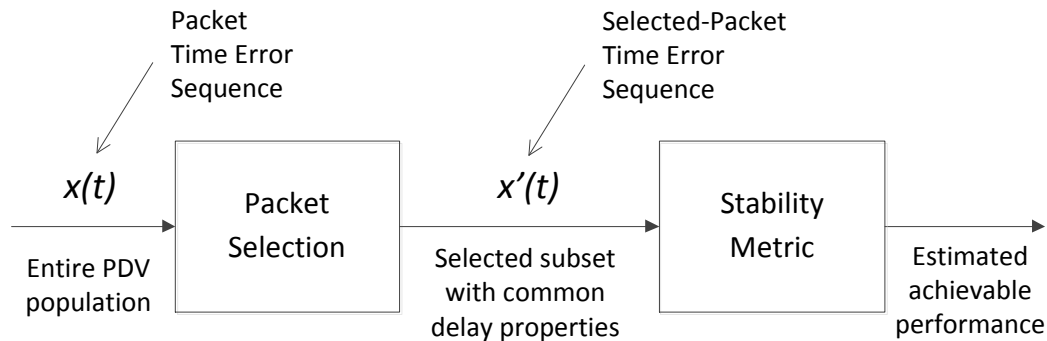 - Percentile: $x'_{pct\_mean}(i) = \frac{1}{m} \sum_{j=0}^{b} x'_{j+i}$

  - Band: $x'_{band\_mean}(i) = \frac{1}{m} \sum_{j=a}^{b} x'_{j+i}$

  - Cluster: $x(n\tau_0) = \dfrac{\sum_{i=0}^{(K-1)} w((nK+i)\tau_P) \cdot \phi(n,i)}{\sum_{i=0}^{(K-1)} \phi(n,i)}$ $\phi(n,i) = \begin{cases} 1 & for \quad |w(nK+i) - \alpha(n)| < \delta \\ 0 & otherwise \end{cases}$
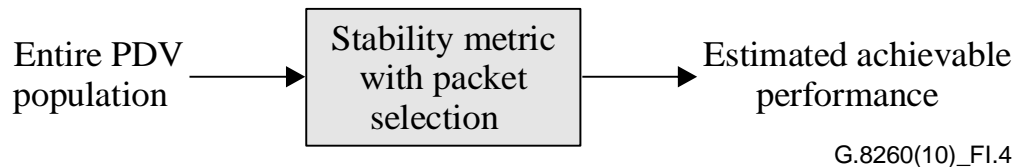
Packet Selection Windows

- Windows

  - **_Non-overlapping windows_** (next window starts at prior window stop)

  - **_Skip-overlapping windows_** (windows overlap but starting points skip over N samples)

  - **_Overlapping windows_** (windows slide sample by sample)

- Packet Selection Approaches (e.g. selecting fastest packets)

  - Select X% fastest packets (e.g. 2%)

  - Select N fastest packets (e.g. 10 fastest packets in a window)

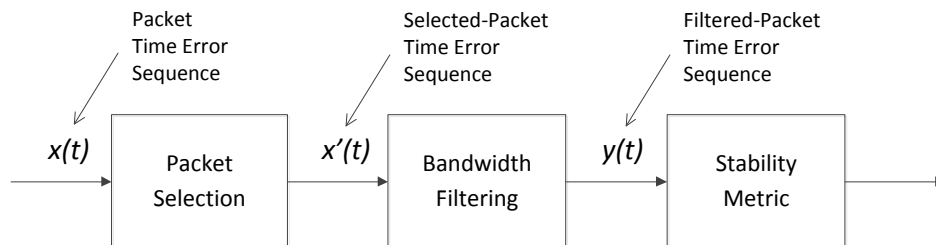 - Select all packets faster than Y (e.g. all packets faster than 150µs)

G.8260 Appendix I Metrics

Packet Time Error Sequence

Selected-Packet Time Error Sequence

$x(t)$

Entire PDV population

Packet Selection

$x'(t)$

Selected subset with common delay properties

Stability Metric

Estimated achievable performance

Figure I.3 – Pre-processed packet selection

Entire PDV population

Stability metric with packet selection

Estimated achievable performance

G.8260(10)_FI.4

Figure I.4 – Integrated packet selection

Packet Time Error Sequence

Selected-Packet Time Error Sequence

Filtered-Packet Time Error Sequence

$x(t)$

Packet Selection

$x'(t)$

Bandwidth Filtering

$y(t)$

Stability Metric

Metrics including pre-filtering

FPC, FPR, FPP: Floor Packet Count/Rate/Percentage

PDV metrics studying minimum floor delay packet population

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

Reverse

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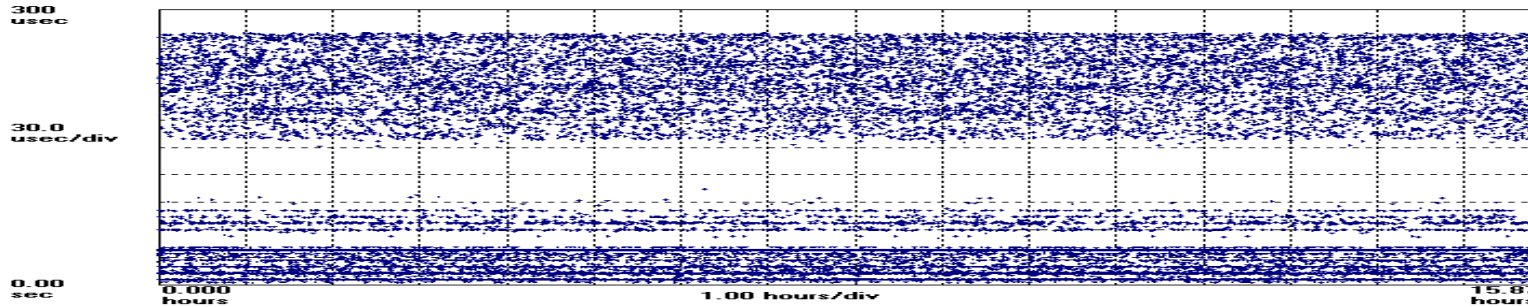0.0312,   2.273E-3
0.0467,   2.258E-3
0.0623,   2.322E-3

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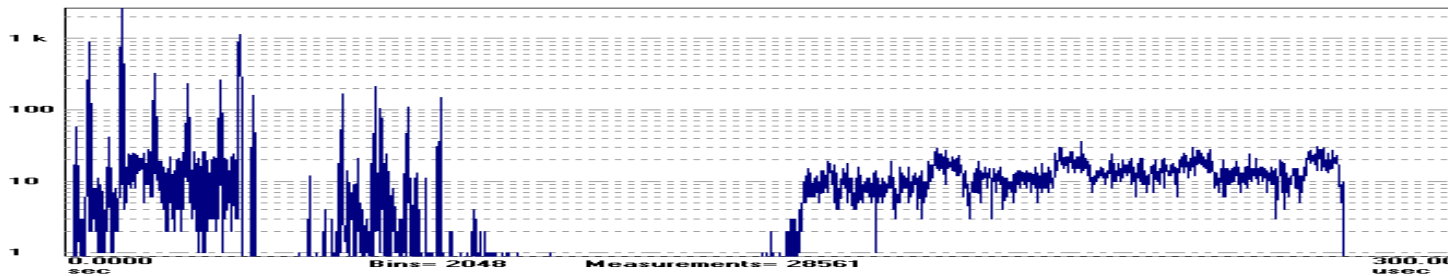0.0311,   2.826E-3
0.0467,   2.968E-3
0.0624,   3.065E-3

Packet Delay Distribution

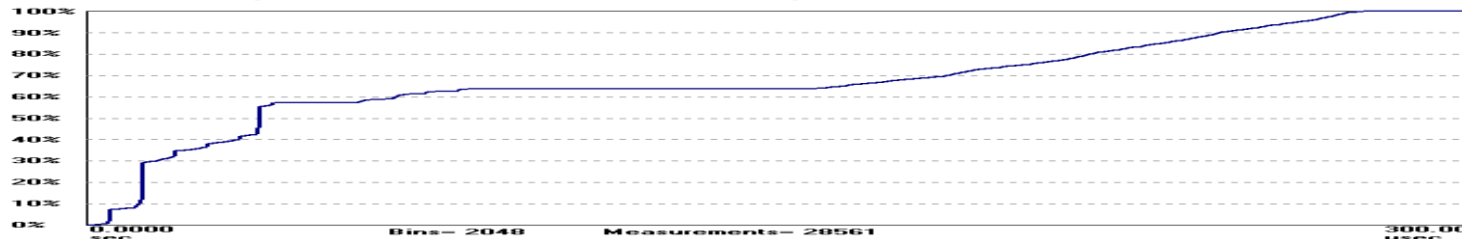Packet Delay Sequence

PDF

Statistics

Minimum: 1.904297 usec   Mean: 96.71927 usec
Maximum: 275.2441 usec   Standard Deviation: 97.34 usec
Peak to Peak: 273.3 usec   Population: 28561   Percentage: 100.%

CDF

50pct: 37.65 us; 90pct: 245.5 us; 95pct: 261.9 us; 99pct: 272.3 us; 99.9pct: 274.5 us

Tracked Packet Delay Statistics

Symmetricom TimeMonitor Analyzer   [file=destination-2007_09_19--09_39.cap]
Phase deviation in units of time; Fs=16.66 Hz; Fo=10.000000 MHz; 2007/09/19 07:45:00
XLi 1588 PDV Phase; Samples: 50185; Start: 5114; Threshold: 27.0000 us; UUID: 00A069012F09; Initial phase offset: 24.1950 usec
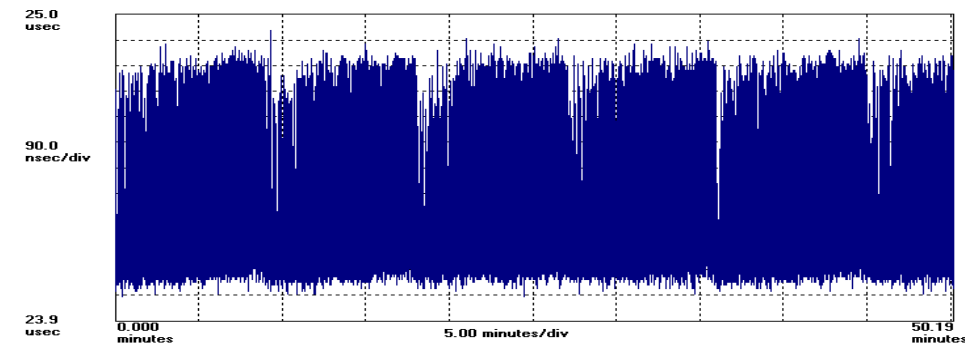
Raw packet delay appears relatively static over time

Symmetricom TimeMonitor Analyzer   [file=pdv-2007_09_19--09_39_mean.pan]
Phase deviation in units of time; Fs=16.66 Hz; Fo=10.000000 MHz; 2007/09/19; 07:45:00
Phase Mean; Overlap; Tau=10s; A=167; N=50019;
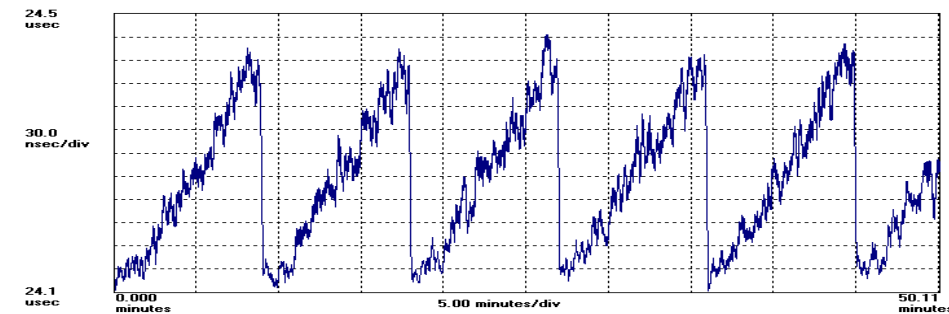
Mean vs. time shows cyclical ramping more clearly

Symmetricom TimeMonitor Analyzer   [file=pdv-2007_09_19--09_39_stddev.pan]
Phase deviation in units of time; Fs=16.66 Hz; Fo=10.000000 MHz; 2007/09/19; 07:45:00
Phase Standard Deviation; Overlap; Tau=10s; A=167; N=50019;
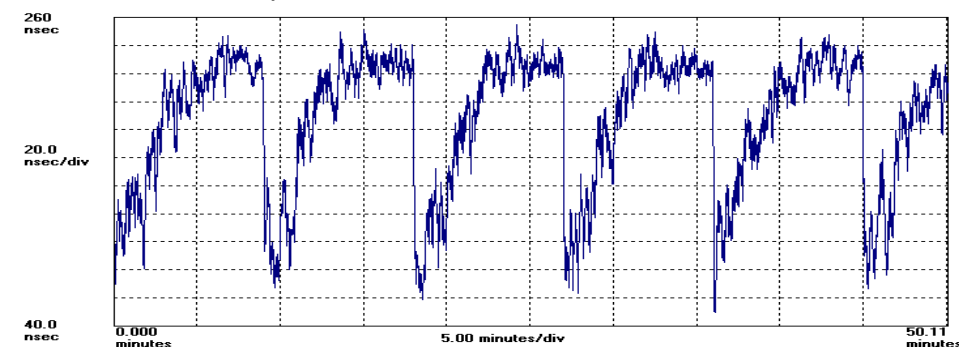
Standard deviation vs. time shows a quick ramp up to a flat peak

16

minTDEV, bandTDEV, MATIE, MAFE

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

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

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

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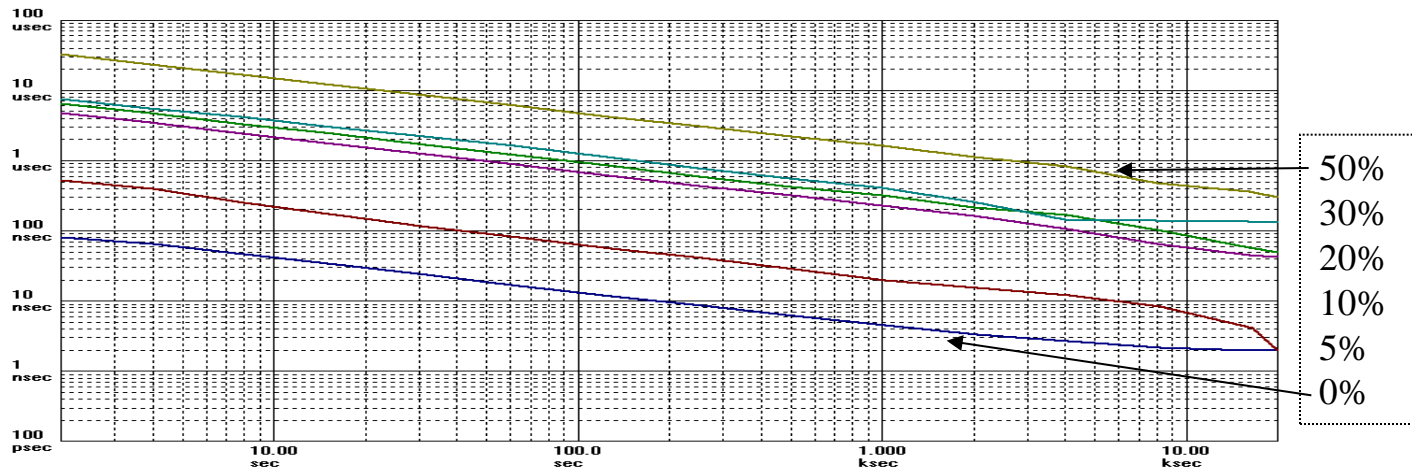
MAFE
$$MAFE(n\tau_0) = \frac{MATIE(n\tau_0)}{n\tau_0}$$

minMAFE
$$\min MAFE(n\tau_0) \cong \frac{\max_{1 \le k \le N-2n+1}\left|\sum_{i=k}^{n+k-1}(x_{\min}(i+n) - x_{\min}(i))\right|}{n\tau_0}$$

where n = 1, 2, ..., integer part (N/2) and where
$$x_{\min}(i) = \min\lfloor x_j \rfloor for(i <= j <= i+n-1)$$

References: (1) ITU-T G.8260 *Definitions and terminology for synchronization in packet networks*, Appendix I, Feb. 2012
(2) ATIS-0900003.2010 Technical Report: *Metrics Characterizing Packet-Based Network Synchronization*, Oct. 2010.

TDEV & minTDEV with Traffic

TDEV

50%
30%
20%
10%
5%
0%

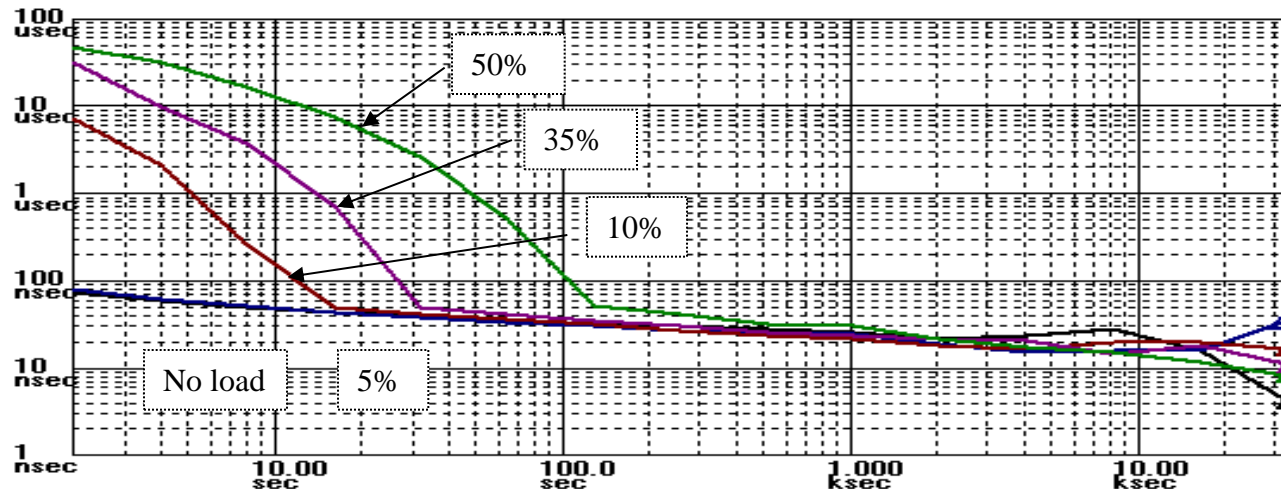**Lower levels of noise with the application of a MINIMUM selection algorithm minTDEV at various traffic levels on a switch (0% to 50%) converge**

Symmetricom TimeMonitor Analyzer   (file=multilayer_switch_40percentSB60.txt)
minTDEV; No. Avg=1; Fo=10.00 MHz; 2006/09/19; 15:28:30

minTDEV

50%

35%

10%

No load   5%

18

Packet Time Transport

"PDV" measurement setup for time transport

✔ – 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

Metrics: Time Transport

Symmetricom
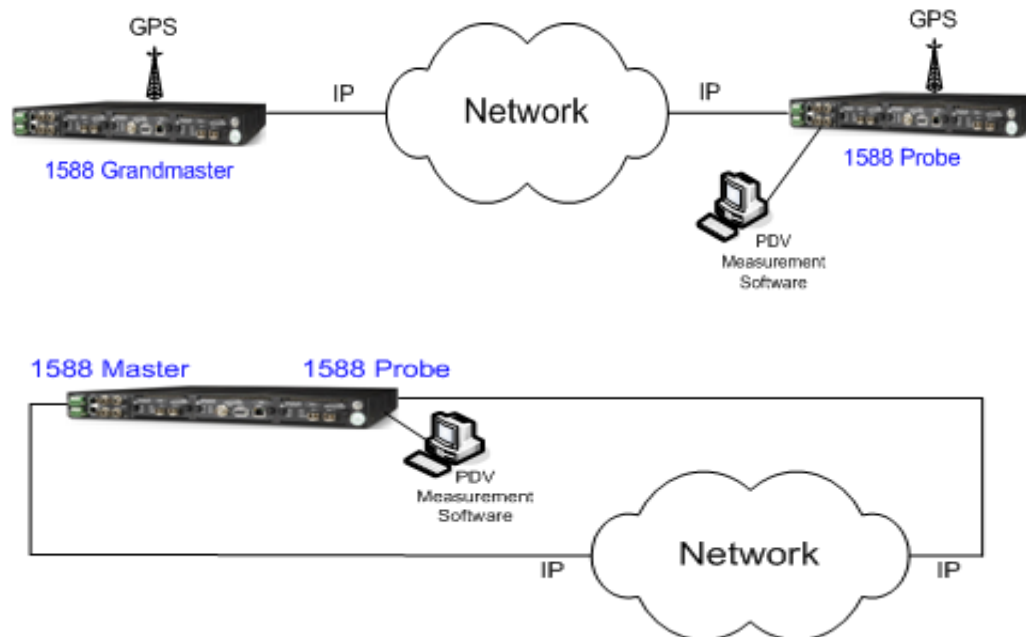
Forward Packet Delay Sequence

#Start: 2010/03/06 17:15:30
0.0000,   1.47E-6
0.1000,   1.54E-6
0.2000,   1.23E-6
0.3000,   1.40E-6
0.4000,   1.47E-6
0.5000,   1.51E-6

Reverse Packet Delay Sequence

#Start: 2010/03/06 17:15:30
0.0000,   1.11E-6
0.1000,   1.09E-6
0.2000,   1.12E-6
0.3000,   1.13E-6
0.4000,   1.22E-6
0.5000,   1.05E-6

#Start: 2010/03/06 17:15:30
0.0000,   1.47E-6,   1.11E-6
0.1000,   1.54E-6,   1.09E-6
0.2000,   1.23E-6,   1.12E-6
0.3000,   1.40E-6,   1.13E-6
0.4000,   1.47E-6,   1.22E-6
0.5000,   1.51E-6,   1.05E-6

Two-way
Data Set

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		

Minimum Search
Sequence

Packet Time Transport Metrics

Normalized roundtrip:

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

Normalized offset:

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

minRoundtrip:

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

minOffset:

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

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

Symmetricom

minOffset Statistics
(Two-way minimum offset statistics vs. tau)

Symmetricom TimeMonitor Analyzer
Time stats plot in units of time; 2008/09/04; 16:55:05
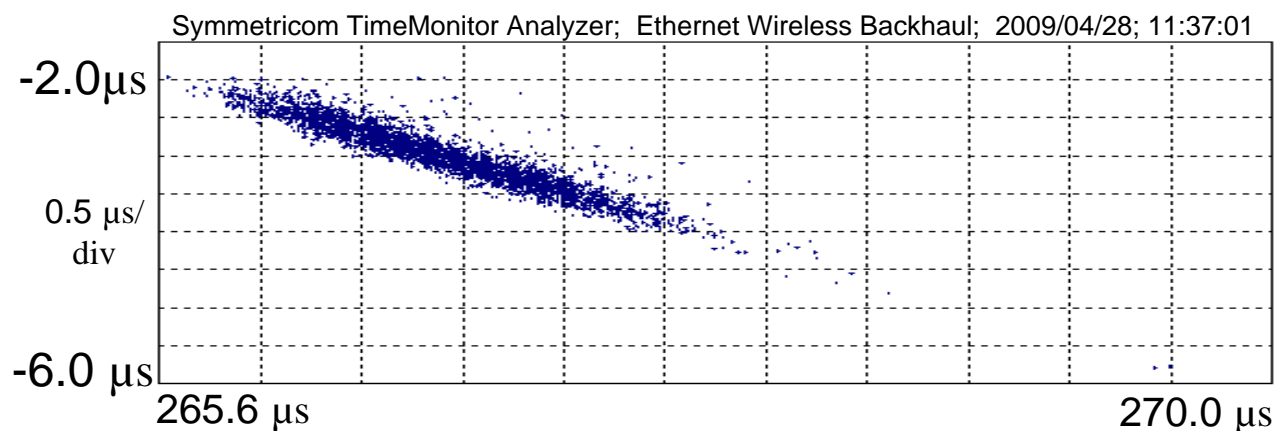minOffset mean (blue); minOffset stddev (red); minOffset 95% (magenta)
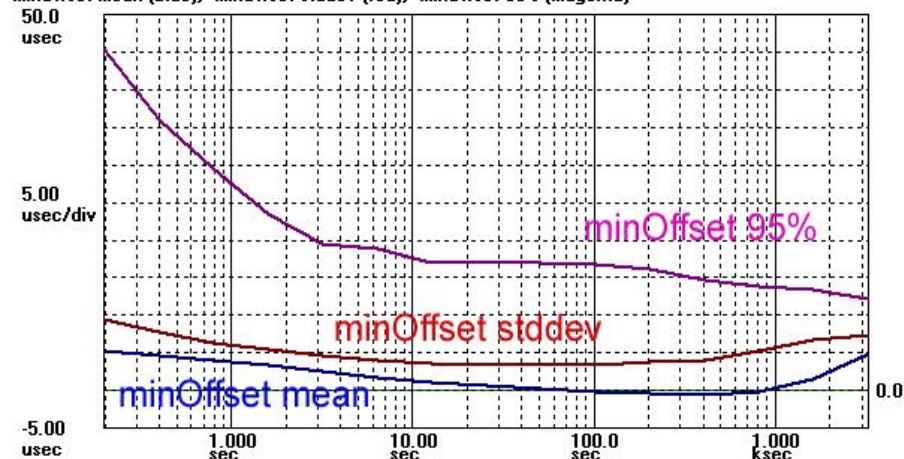
Two-way MAFE
(MAFE of minOffset)

Symmetricom TimeMonitor Analyzer   (file=probe-2008_09_04--12_54d.tpk)
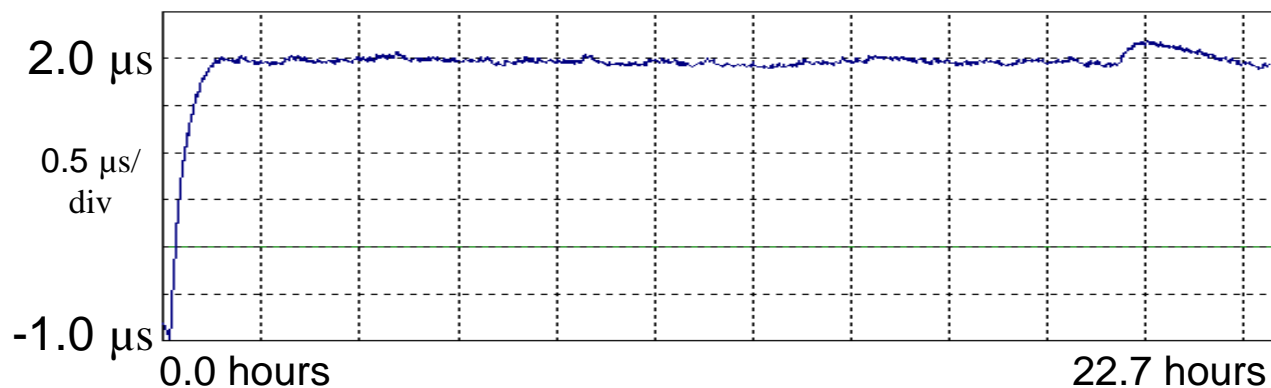MAFE; Fo=10.00 MHz; Fs=100.6 mHz; 2008/09/04; 16:55:05
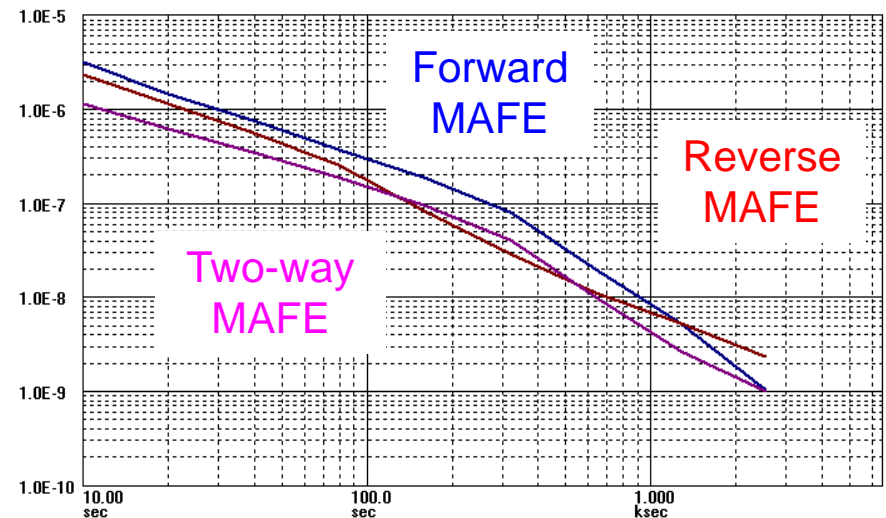
Asymmetry in Wireless Backhaul
(Ethernet wireless backhaul asymmetry and IEEE 1588 slave 1PPS under these asymmetrical network conditions)

Symmetricom TimeMonitor Analyzer; Ethernet Wireless Backhaul; 2009/04/28; 11:37:01

-2.0µs

0.5 µs/ div

-6.0 µs

265.6 µs   270.0 µs

Min TDISP

2.0 µs

0.5 µs/ div

-1.0 µs

0.0 hours   22.7 hours

1588 Slave 1 PPS vs.GPS
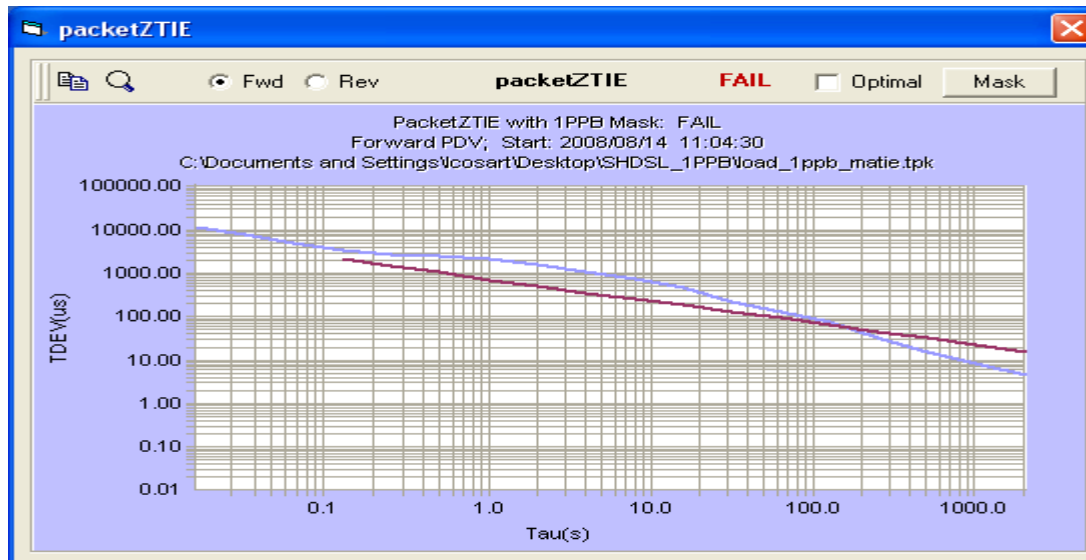
Packet measurement

**Packet data analysis:
1PPB offset predicted**
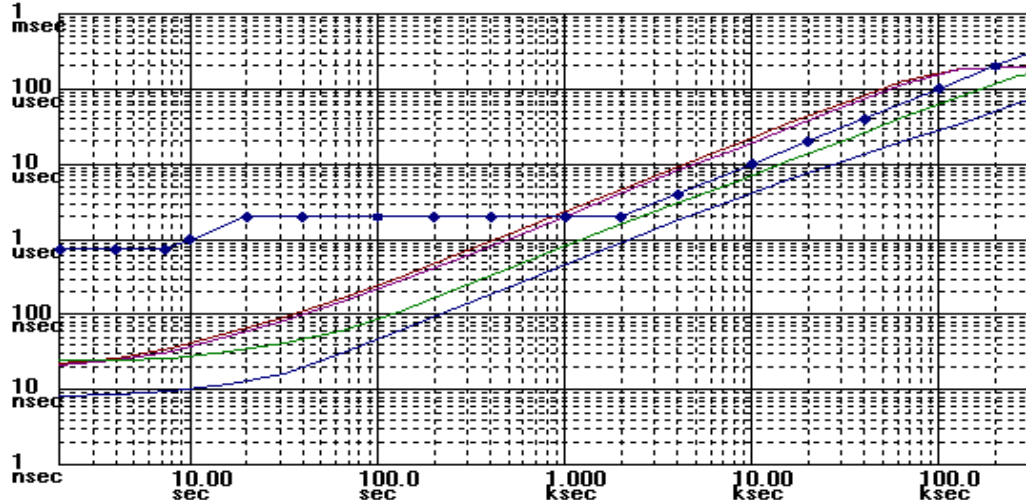
Sync measurement

**1588 slave performance:
1 PPB offset measured**

Case Studies: Networks

Symmetricom®
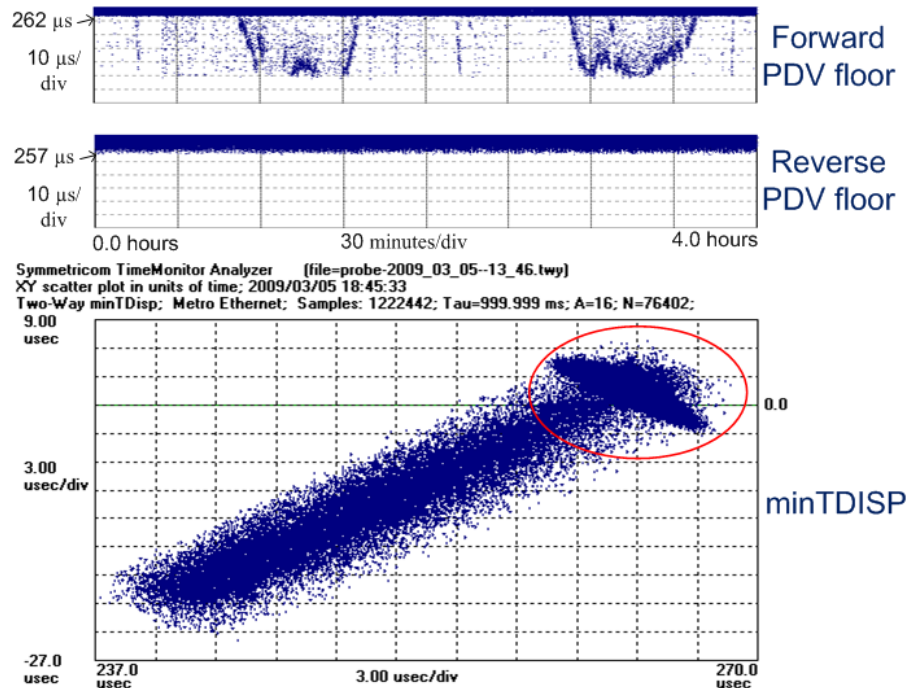
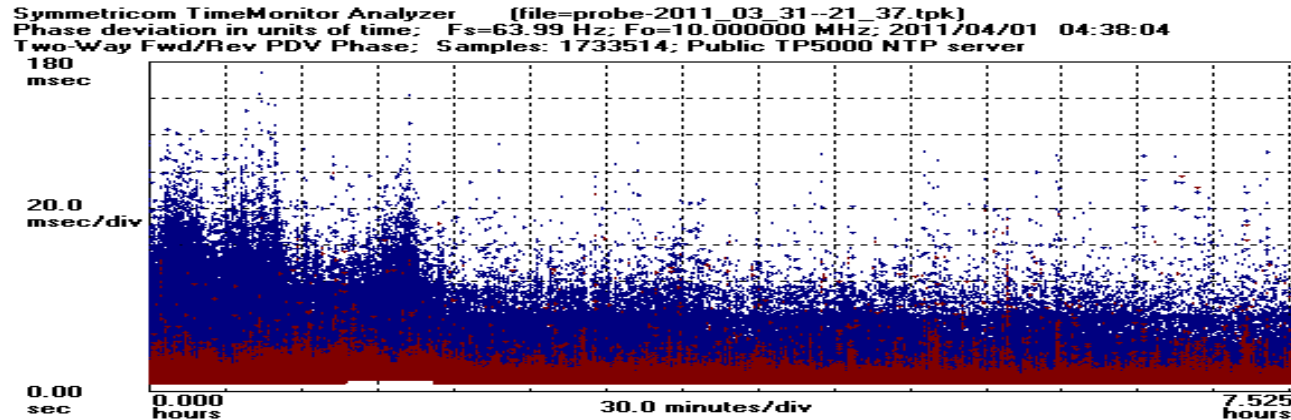Metro Ethernet Network   National Ethernet Network
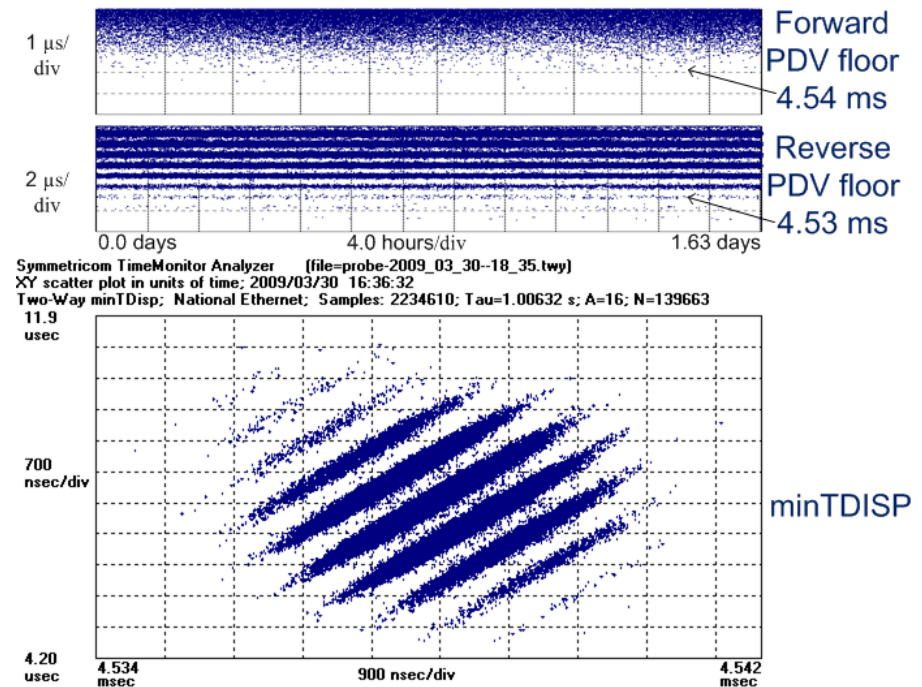
Forward and reverse packet delay sequences with
zooms into the respective floors and minTDISP
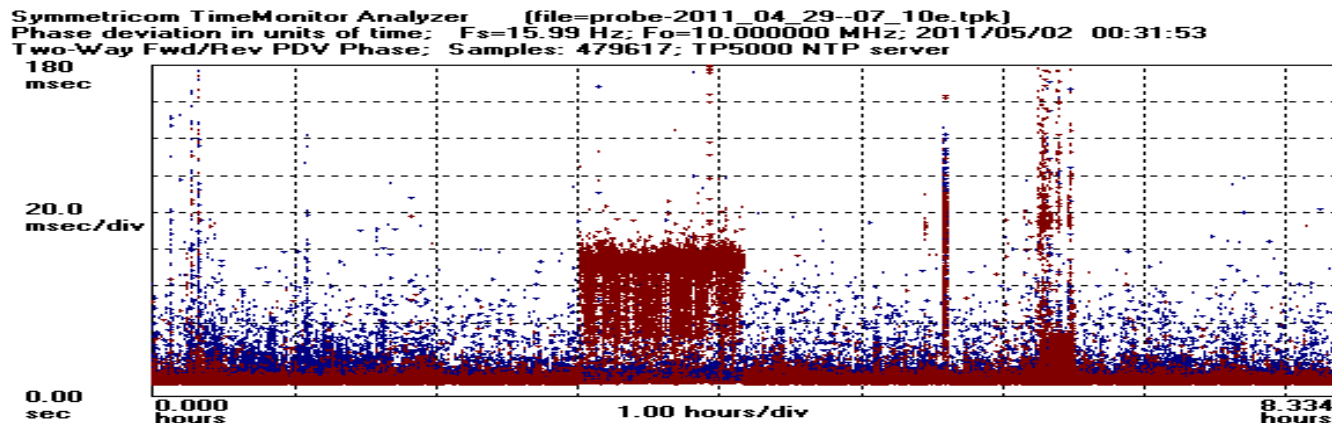
Case Studies: Networks

Public Internet w/ Cable Modem Access (NTP probe)

Symmetricom TimeMonitor Analyzer   (file=probe-2011_03_31--21_37.tpk)
Phase deviation in units of time;   Fs=63.99 Hz; Fo=10.000000 MHz; 2011/04/01 04:38:04
Two-Way Fwd/Rev PDV Phase; Samples: 1733514; Public TP5000 NTP server

Downstream maintains 8.7 msec minimum
Upstream minimum steps from 4.9 msec to 6.4 msec for 35 minutes
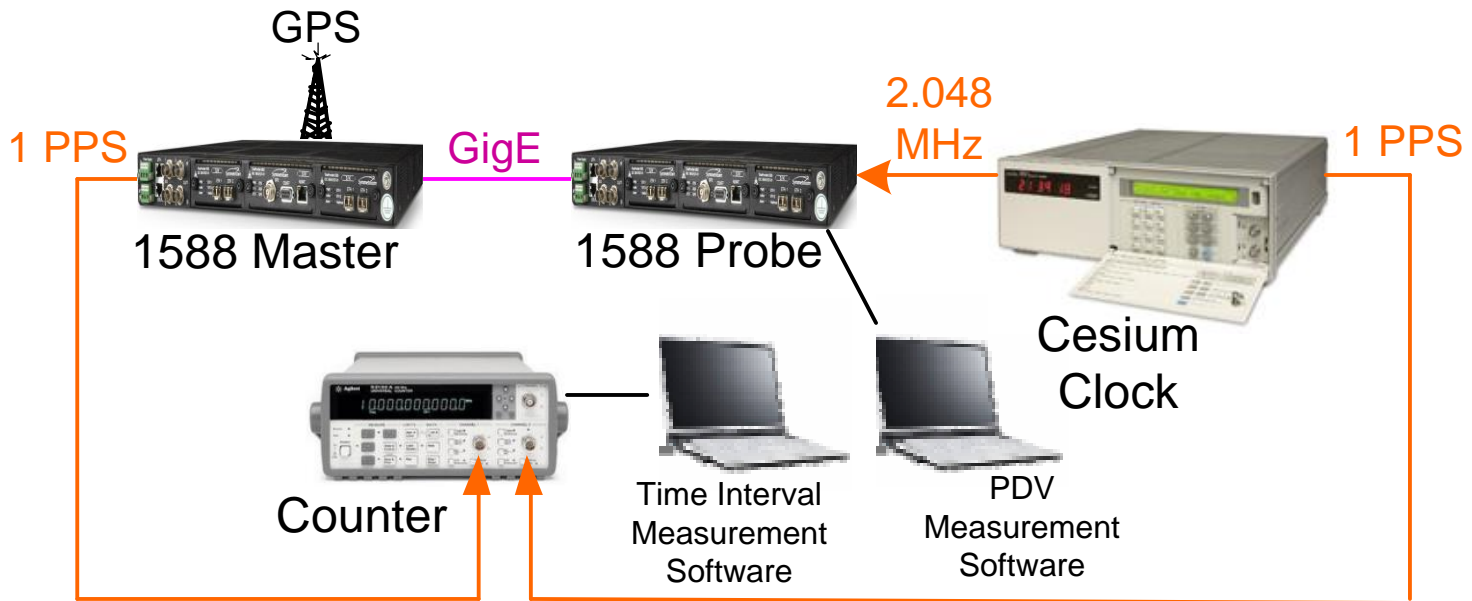
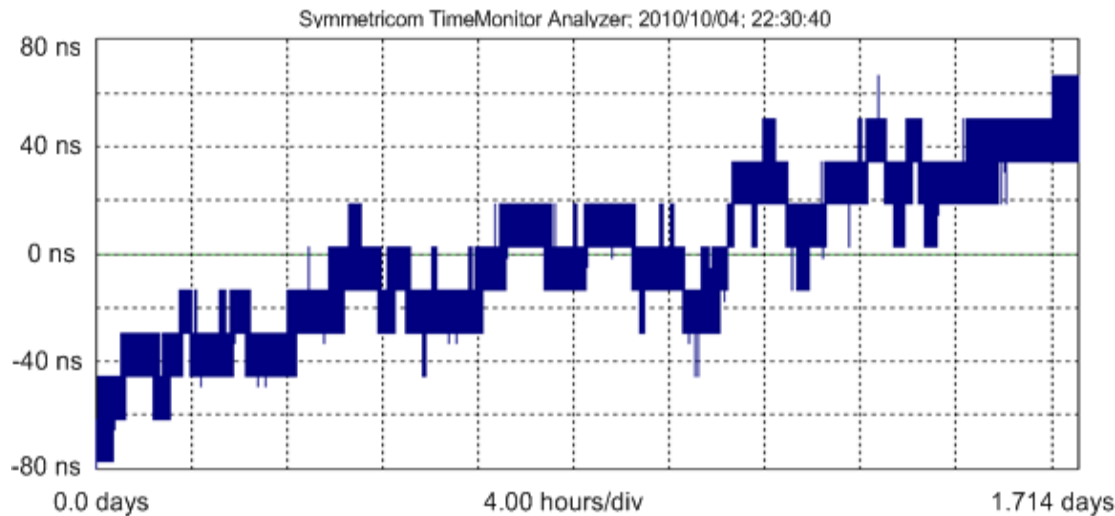## Public Internet w/ ADSL Modem Access (NTP probe)

Symmetricom TimeMonitor Analyzer   (file=probe-2011_04_29--07_10e.tpk)
Phase deviation in units of time;   Fs=15.99 Hz; Fo=10.000000 MHz; 2011/05/02 00:31:53
Two-Way Fwd/Rev PDV Phase; Samples: 479617; TP5000 NTP server

Downstream typically 9.0 msec minimum
Upstream typically 6.7 msec minimum, steps to 70 msec for 1 hour
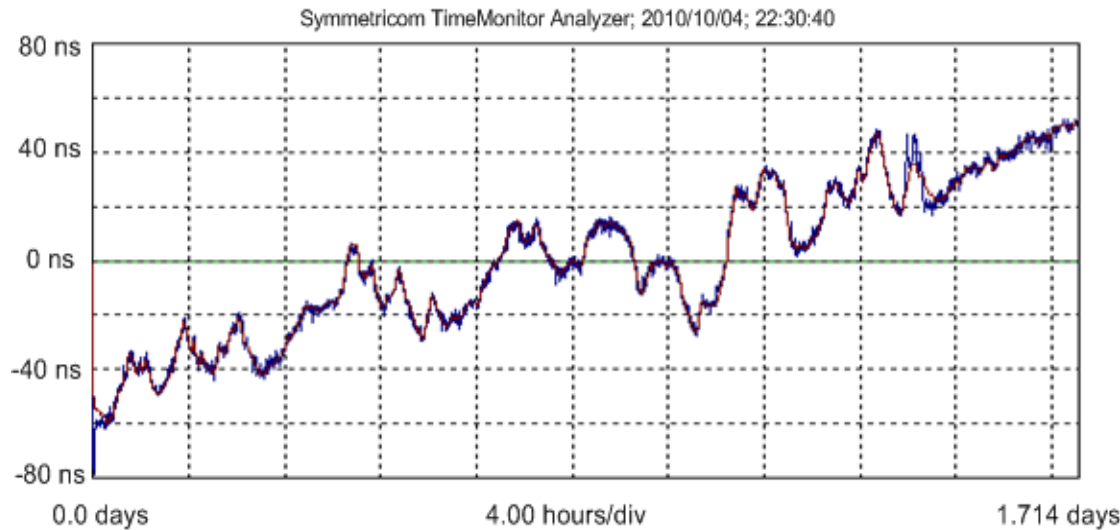Not shown: delays as much as several seconds

## Grandmaster Measurement Setup

GPS

1 PPS

1588 Master

GigE

1588 Probe

2.048 MHz

1 PPS

Cesium Clock

Counter

Time Interval Measurement Software

PDV Measurement Software

Case Studies: Grandmaster Clock

Symmetricom TimeMonitor Analyzer; 2010/10/04; 22:30:40

Raw unfiltered probe measurement

Symmetricom TimeMonitor Analyzer; 2010/10/04; 22:30:40

Overlay of filtered probe and 1PPS measurement

Symmetricom®

Traditional Metrics Applied to Filtered Probe Measurement

Symmetricom TimeMonitor Analyzer; 2010/10/04; 22:30:40
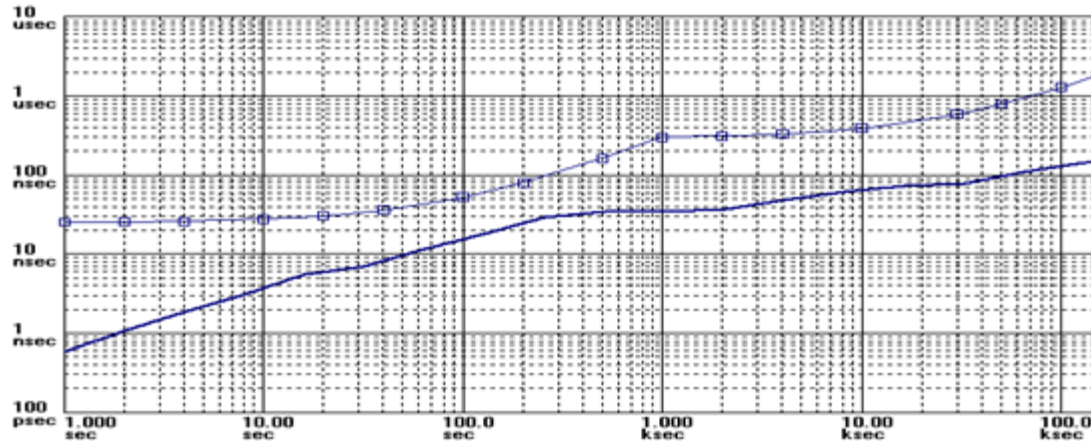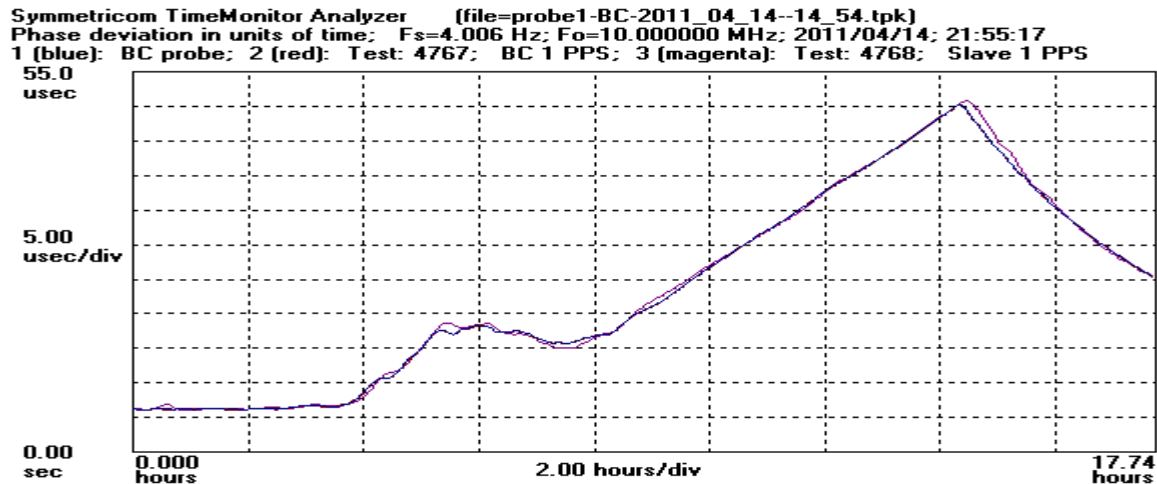
MTIE below G.811 PRC mask
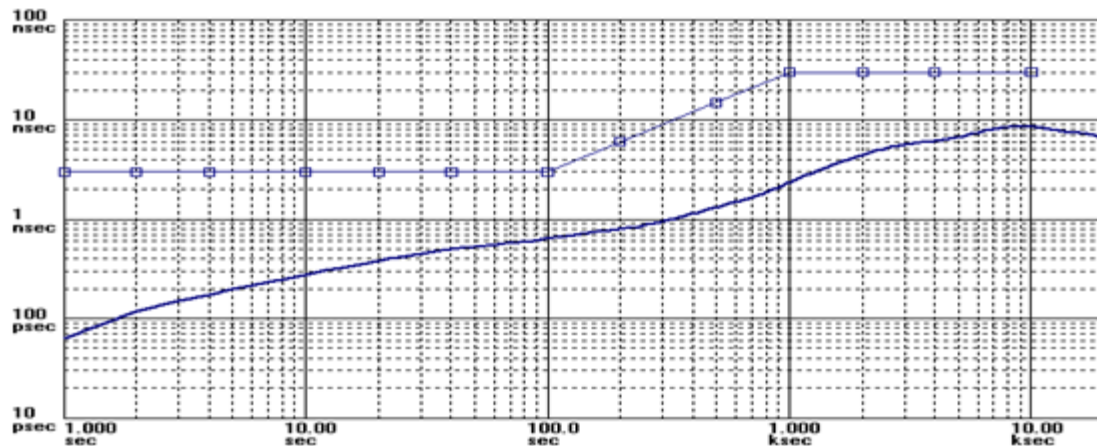
TDEV below G.811 PRC mask

Case Studies: Boundary Clocks

Boundary Clock Measurement Setup

Case Studies: Boundary Clocks
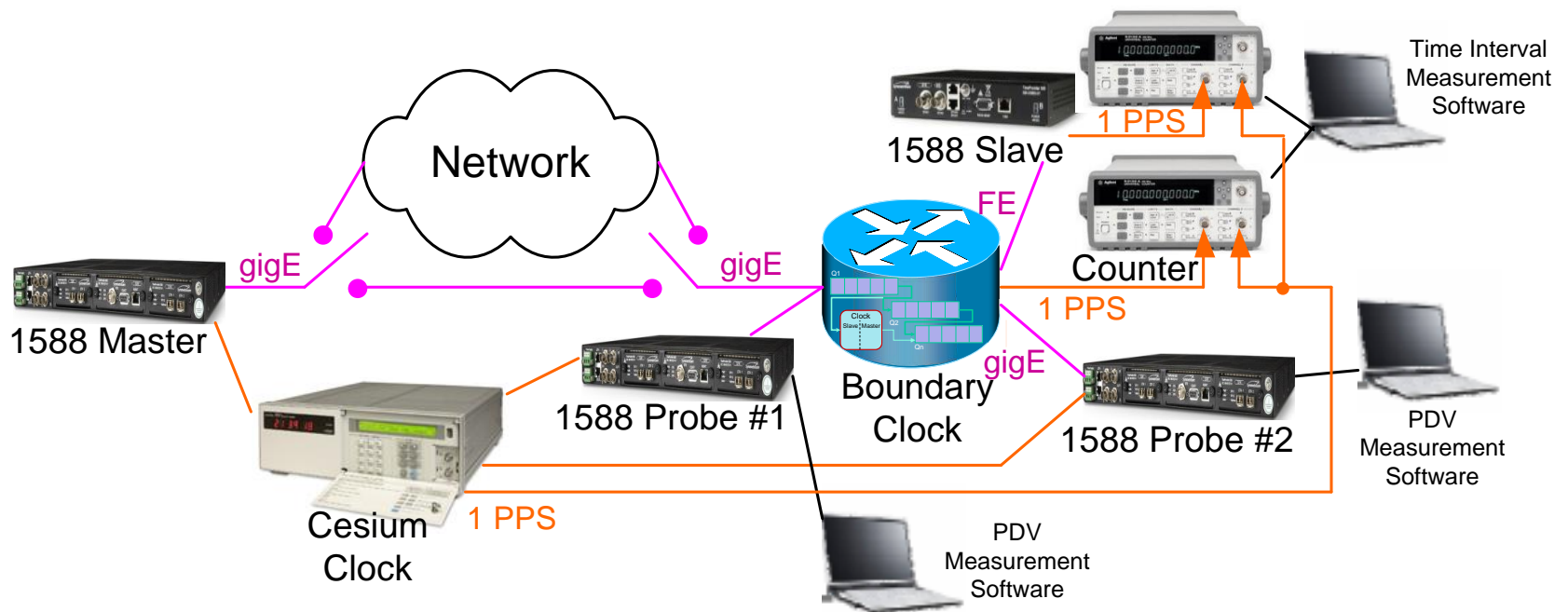
Symmetricom

Boundary Clock Measurement: 3 Approaches
(1) Packet probe; (2) BC 1PPS; (3) Connected slave 1PPS

Symmetricom TimeMonitor Analyzer   (file=probe1-BC-2011_04_14--14_54.tpk)
Phase deviation in units of time; Fs=4.006 Hz; Fo=10.000000 MHz; 2011/04/14; 21:55:17
1 (blue): BC probe; 2 (red): Test: 4767; BC 1 PPS; 3 (magenta): Test: 4768; Slave 1 PPS

Symmetricom TimeMonitor Analyzer   (file=phase3.pnm)
Phase deviation in units of time; Fs=4.006 Hz; Fo=10.000000 MHz; 2011/04/14; 21:55:17
1 (blue): BC probe; 2 (red): Test: 4767; BC 1 PPS; 3 (magenta): Test: 4768; Slave 1 PPS

Case Studies: Boundary Clocks
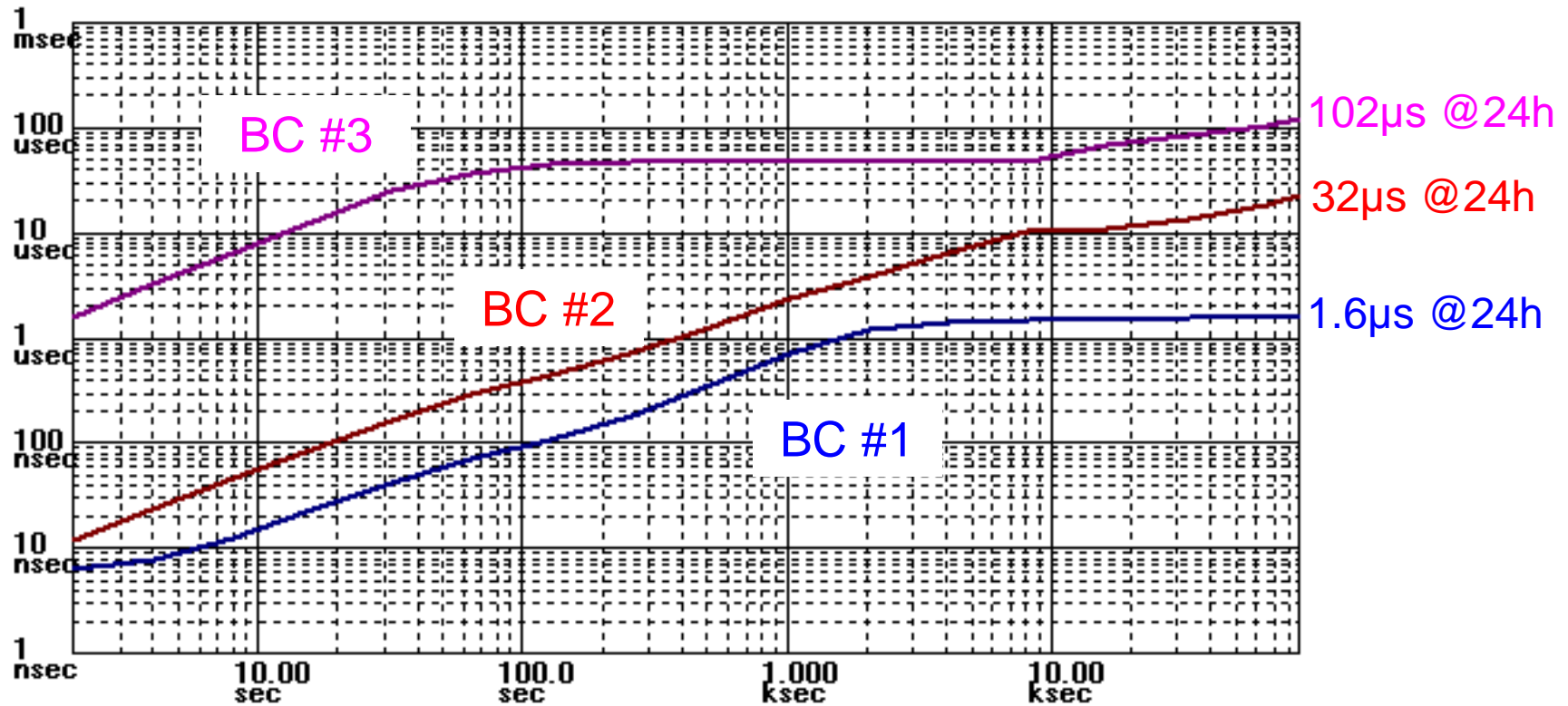
Three boundary clocks from three vendors
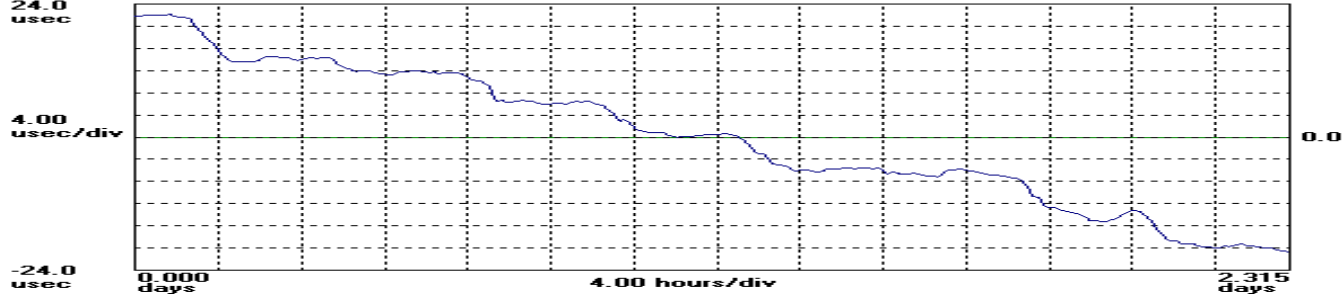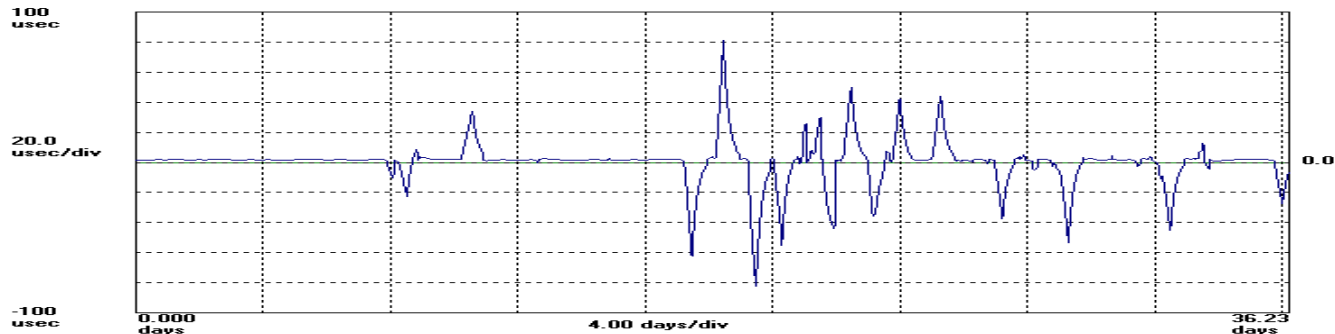
BC Vendor #1

BC Vendor #2

BC Vendor #3

Loaded 8-node network

Symmetricom TimeMonitor Analyzer
MTIE; Fo=1.000 Hz; Fs=498.9 mHz; 2011/04/09; 09:24:40

BC #3

BC #2

BC #1

102µs @24h

32µs @24h

1.6µs @24h

Characterizing PRTC Accuracy

- A stable and accurate time reference is required. A cesium clock alone will not suffice.

- Possible candidates for such a reference:
  - National metrology lab reference
  - Carefully calibrated "golden" reference GPS receiver

- We need to understand both the accuracy and the stability characteristics of such a reference.

- We need to consider that both the reference and the PRTC under test may deliver different performance under conditions of constant temperature and varying temperature.
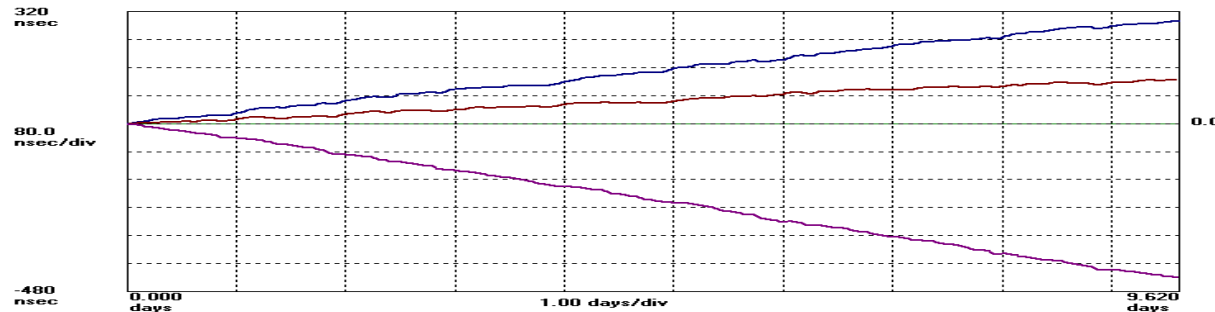
"Golden" Reference GPS Receiver Stability

Measurement Setup
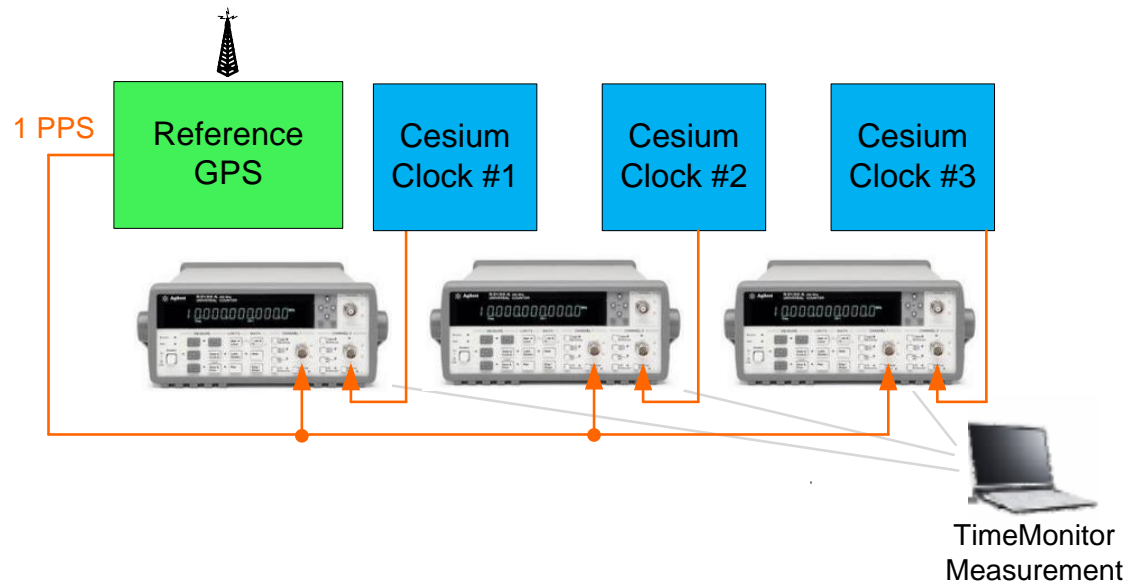
Note: Measurements conducted at constant room temperature.
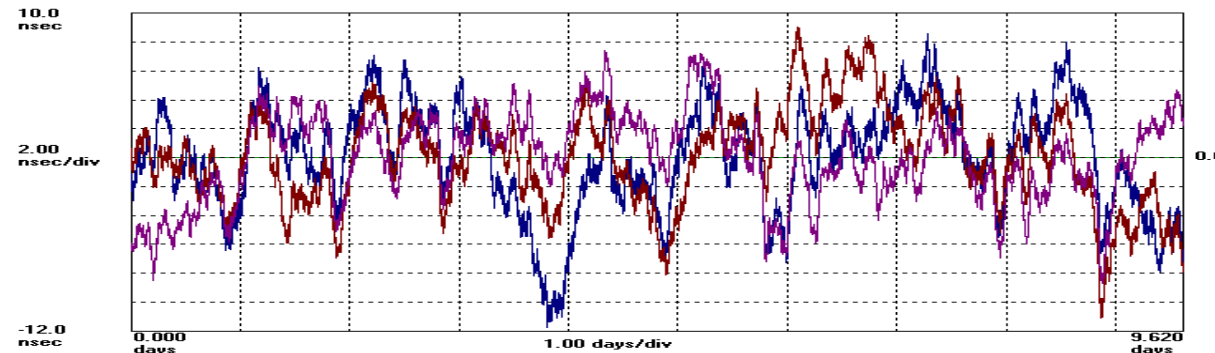
"Golden" Receiver Stability Performance

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time;   Fs=1.000 Hz; Fo=1.0000000 Hz; 2012/02/03; 15:35:09

Raw results vs. 3 cesium clocks

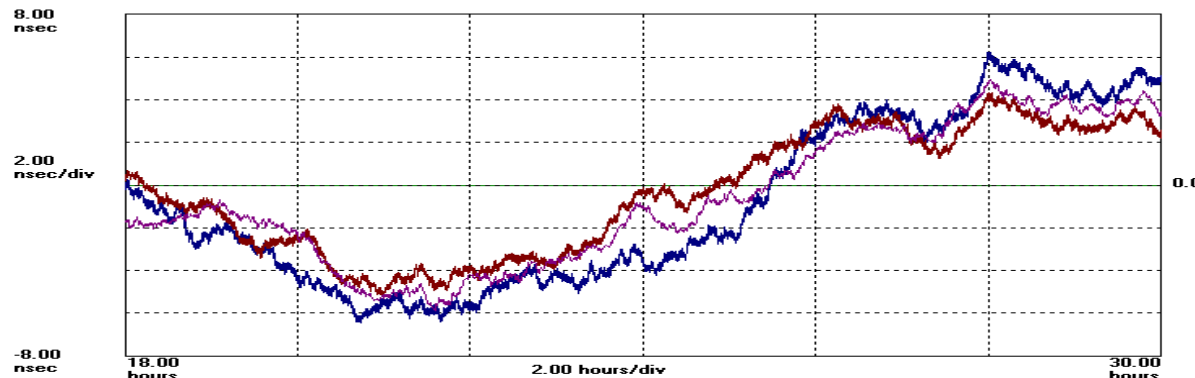Cesium 1 (blue):   3.573E-13
Cesium 2 (red):   1.579E-13
Cesium 3 (violet): -5.428E-13

Results with respective cesium offsets removed

Zoom into 12 hour section of 10-day measurement

"Golden" Receiver Stability Performance
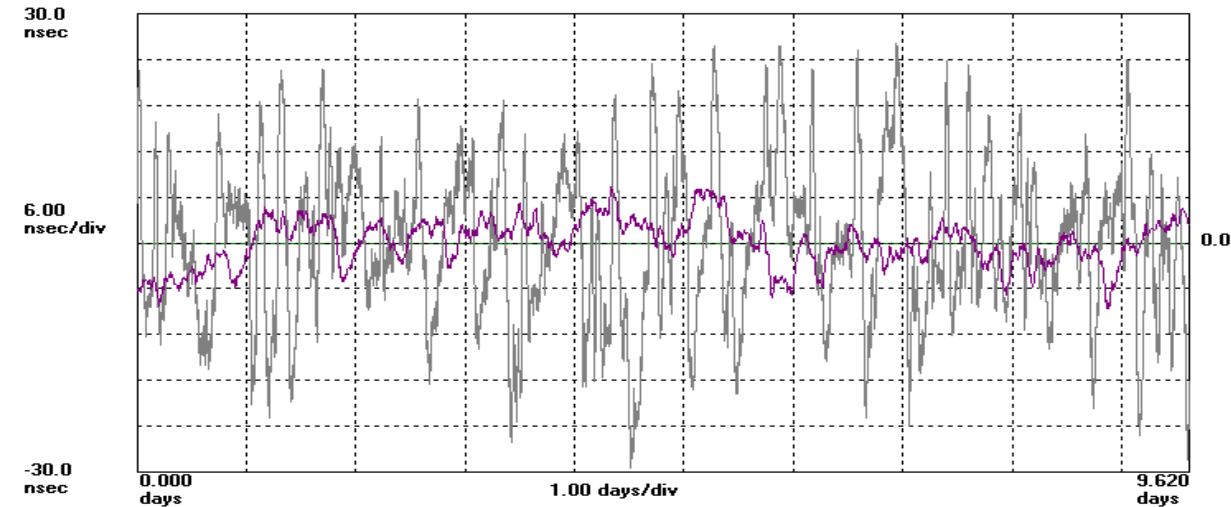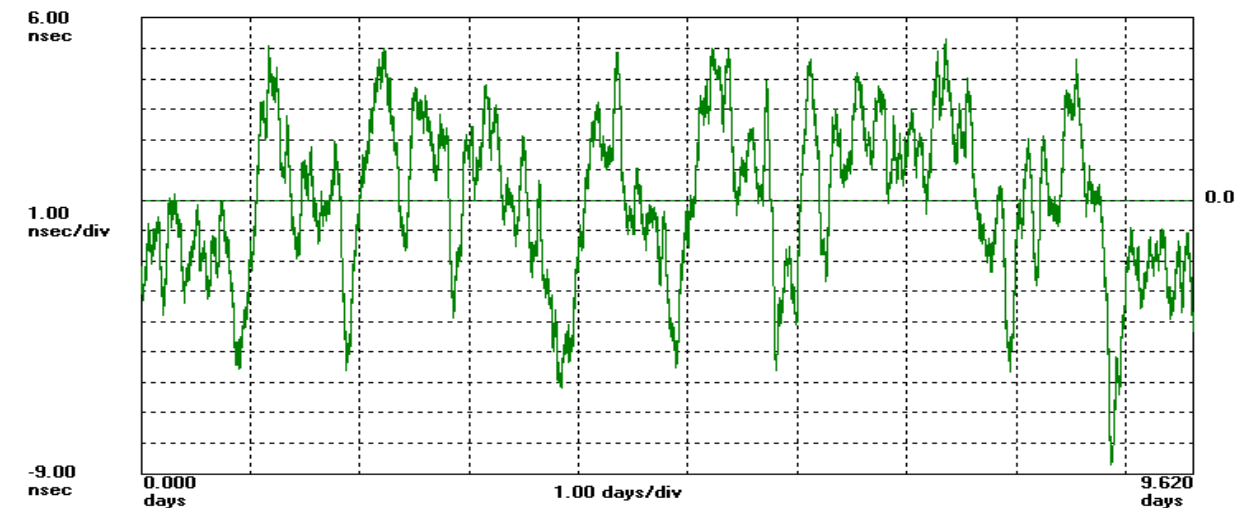

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=1.000 Hz; Fo=1.0000000 Hz; 2012/02/03; 15:35:09
RefGPS (violet) and GM (gray) measured against cesium

"Golden" vs. conventional GPS receiver

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=1.000 Hz; Fo=1.0000000 Hz; 2012/02/03; 15:35:09
4 (green): Phase; Samples: 831170; HP 53132A; Avg 74/75/76 9.6 days; 2012/02/03; 15:35:09

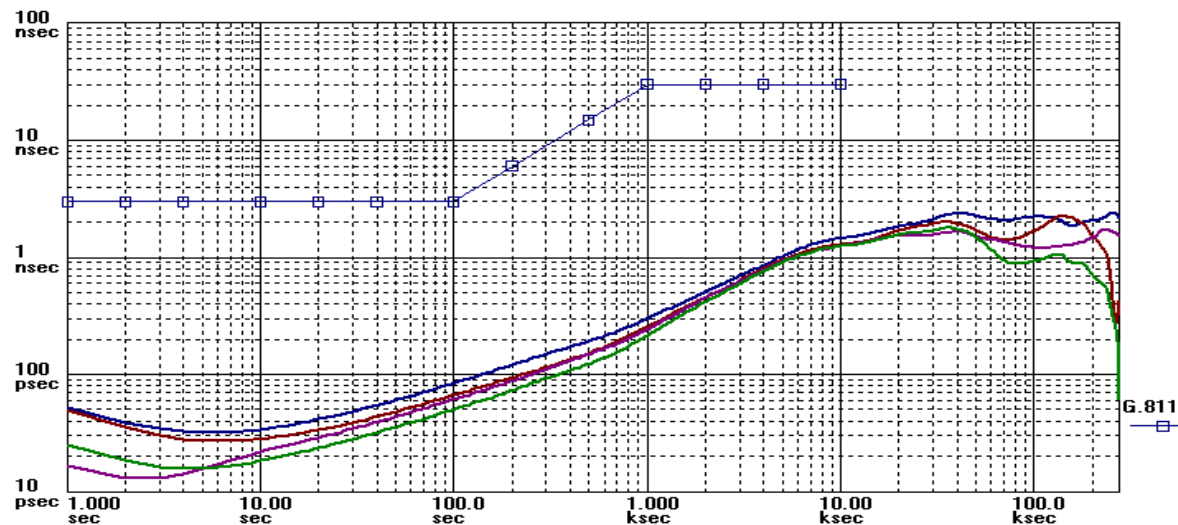Three "Golden" measurements averaged together

"Golden" Receiver Stability Performance

Symmetricom TimeMonitor Analyzer
MTIE; Fo=1.000 Hz; Fs=1.000 Hz; 2012/02/03; 15:35:09
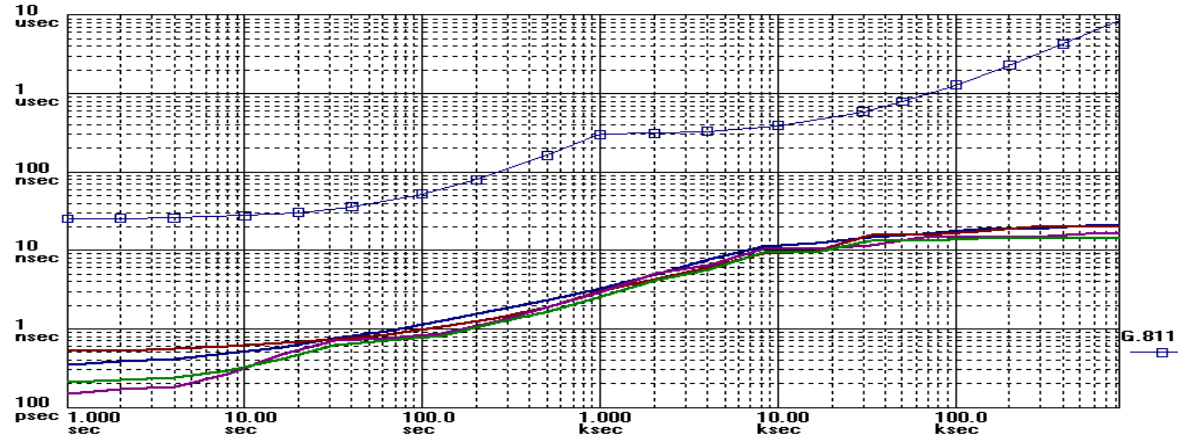
"Golden" receiver
MTIE performance

Symmetricom TimeMonitor Analyzer
TDEV; Fo=1.000 Hz; Fs=1.000 Hz; 2012/02/03; 15:35:09

"Golden" receiver
TDEV performance

Summary

- Types of measurements
  - Frequency, Time, and Packet Signals
  - "TIE" vs. Packet "PDV"
  - Network vs. Equipment
  - Packet probes: passive vs. active, PTP vs. NTP

- Clock and Packet Analysis
  - TIE analysis methods inform approach to PDV analysis
  - Stability metrics (1) Preprocessed or (2) Integrated packet selection
  - Frequency transport metrics
  - Time transport metrics

- Measurement Case Studies
  - Networks
    - Wireless backhaul: frequency and asymmetry
    - Metro/National Ethernet (PTP probe)
    - ADSL/Cable modem access (NTP probe)
  - Equipment
    - IEEE 1588 GM & BC (measurements on physical signal or packet signal)
    - PRTC: Four GPS receiver comparison (common antenna and common measurement reference)
    - PRTC: "Golden" receiver stability

Thank You

Lee Cosart

Senior Technologist

lcosart@symmetricom.com

Phone: +1-408-428-6950

Symmetricom, Inc.
2300 Orchard Parkway
San Jose, CA 95131-1017
Tel: +1 408-428-7907
Fax: +1 408-428-6960

www.symmetricom.com