Symmetricom®

Leading the world in precise time solutions.

Timing Measurements and Metrics for Frequency, Time, and Packet Signals

Lee Cosart

lcosart@symmetricom.com

ITSF 2012

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

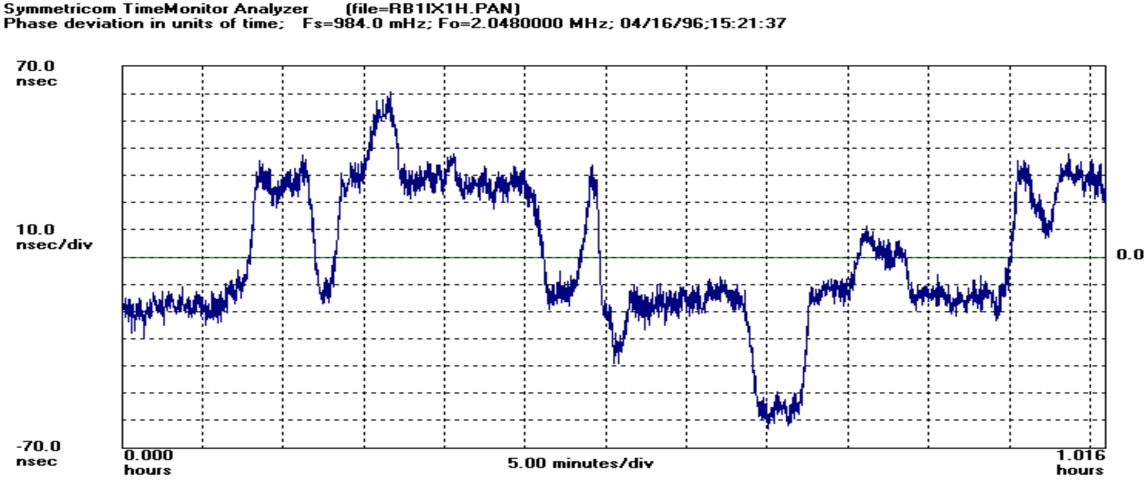
"TIE" vs. "PDV"

- "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
  - Both require (1) PRC/GPS; (2) Precision HW timestamping; (3) PC + SW

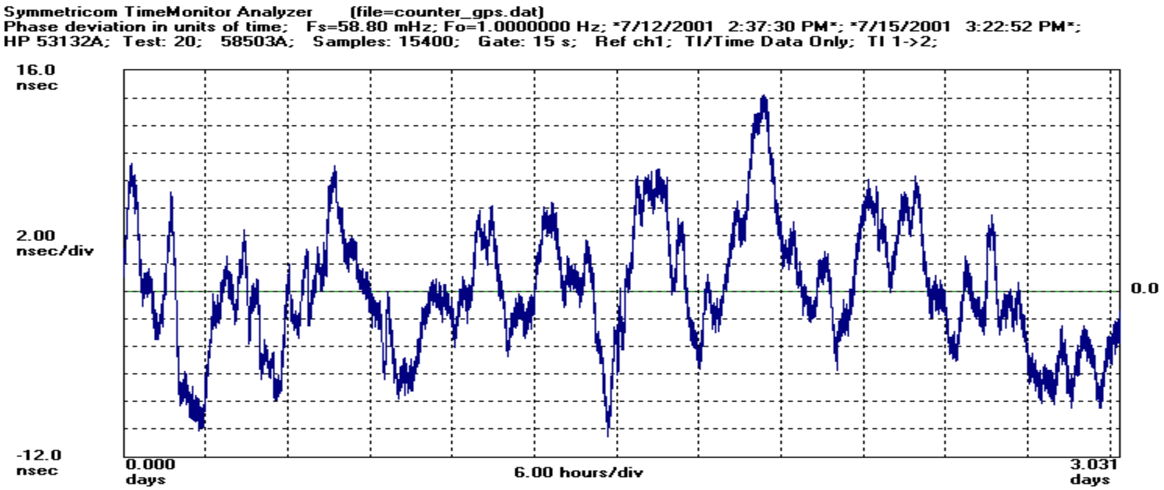
- Measurement equipment:
  - TIE: Counters, TIA's, Test-sets, BITS, SSU, GPS receivers
  - PDV: IEEE 1588 probes, NTP probes, network probes

- TIE measurements are still important in a packet world:
  - 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 Measurements: Network vs. Equipment

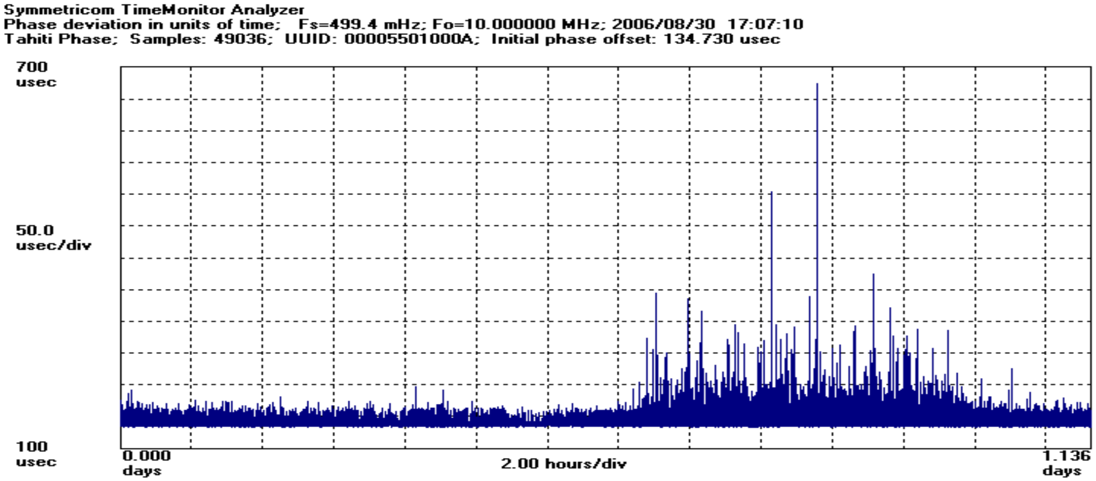


Network TIE

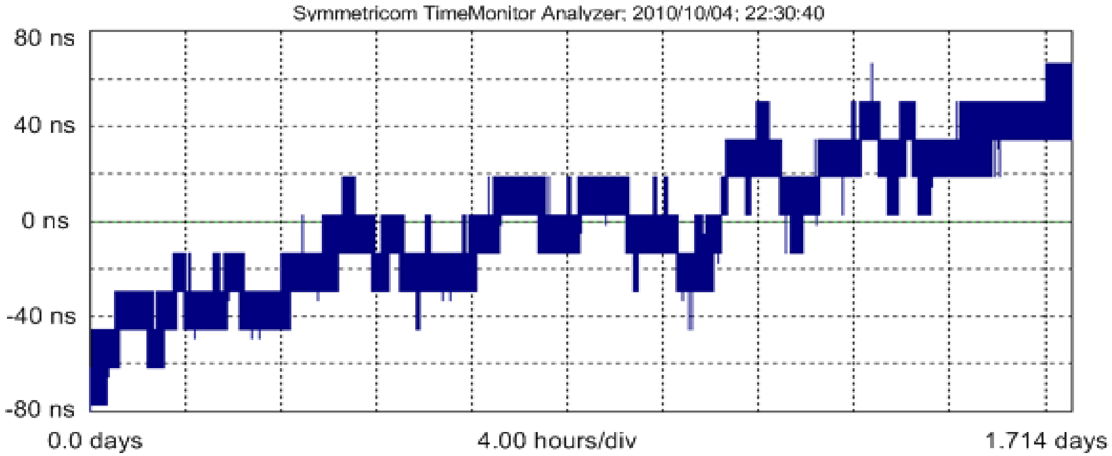


Equipment TIE

PDV Measurements: Network vs. Equipment



Network PDV

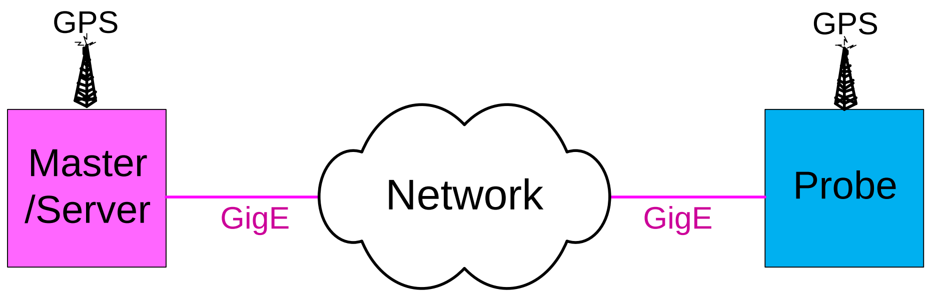


Equipment PDV

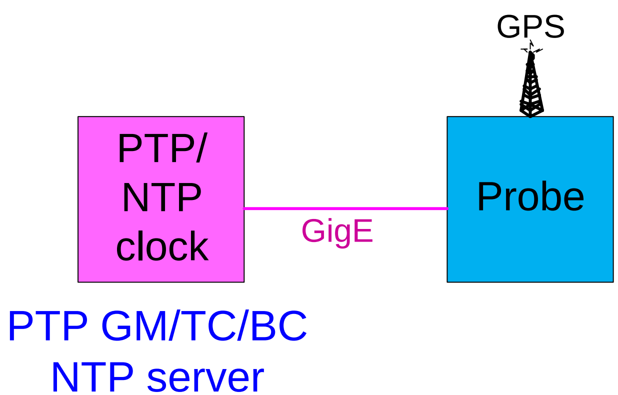
Packet Probe

Symmetricom

Network PDV Measurement

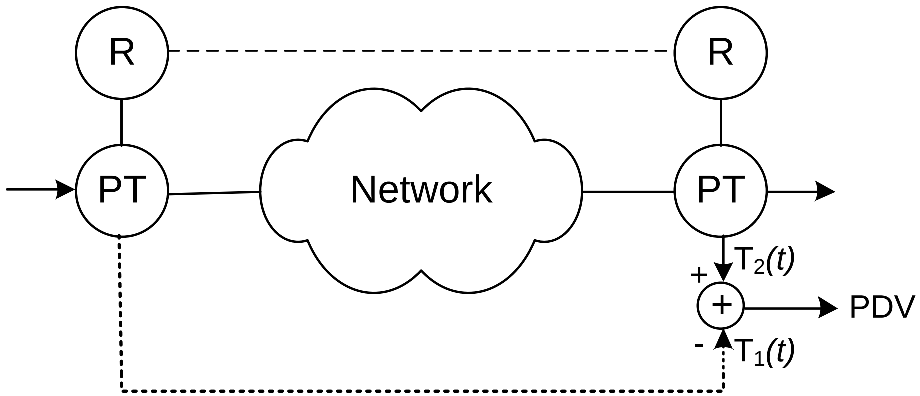


PTP/NTP Equipment Characterization



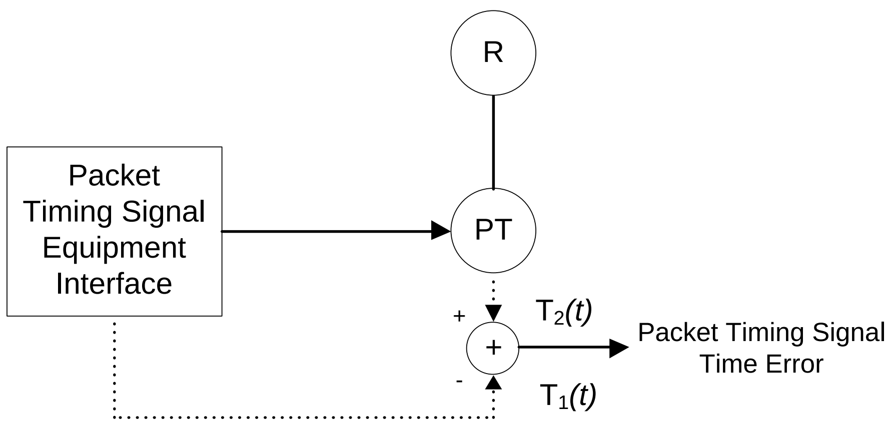
Packet Probe (G.8260 View)

Network PDV Measurement



R	Time or frequency reference
PT	Packet timestamper

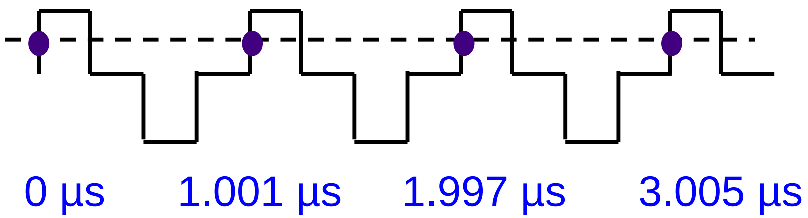
Packet Equipment Characterization

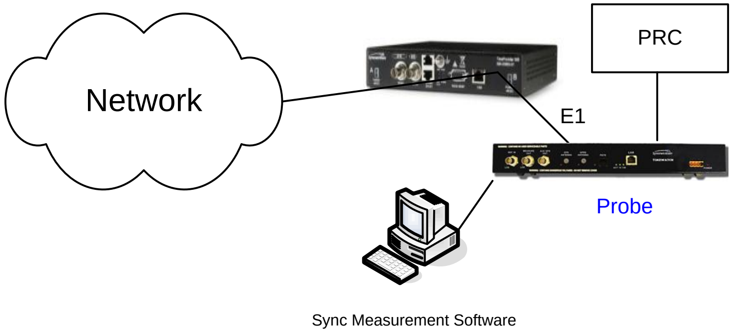


R	Time or frequency reference
PT	Packet timestamper

Frequency signal “TIE” vs. “PDV”

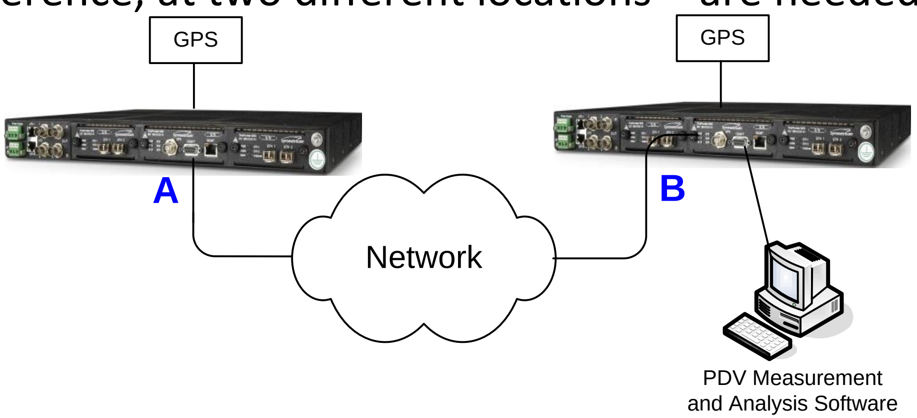
- “TIE” (Single Point Measurement)
  – Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed





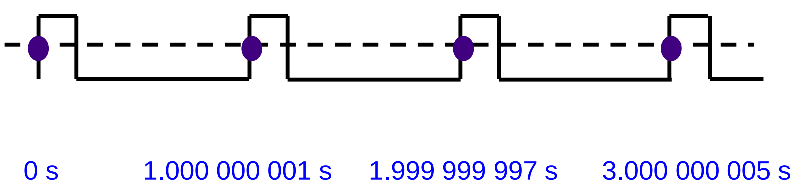
- “PDV” (Dual Point Measurement)
  – Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed

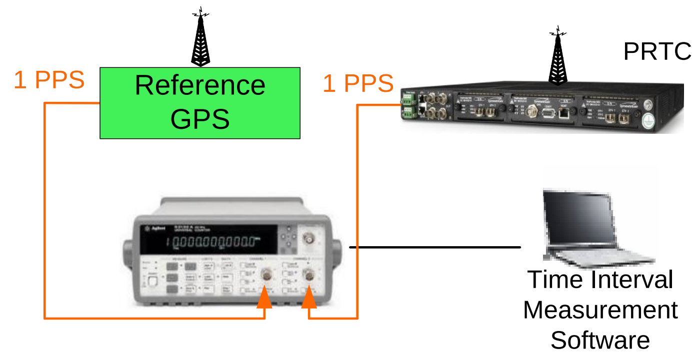
	Timestamp A	Timestamp B
F	1233166476.991204496	1233166476.991389744
R	1233166476.980521740	1233166476.980352932
F	1233166477.006829496	1233166477.007014512
R	1233166476.996147084	1233166476.995977932
F	1233166477.022454496	1233166477.022639568
R	1233166477.011771820	1233166477.011602932



Time signal "Physical" vs. "Packet"

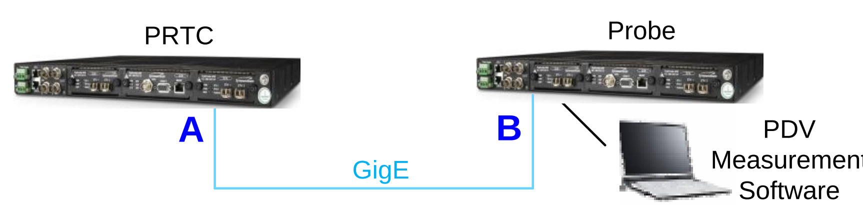
- "1 PPS" (Single Point Measurement)
  - Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed





- "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



"PDV" Measurement Setup Options

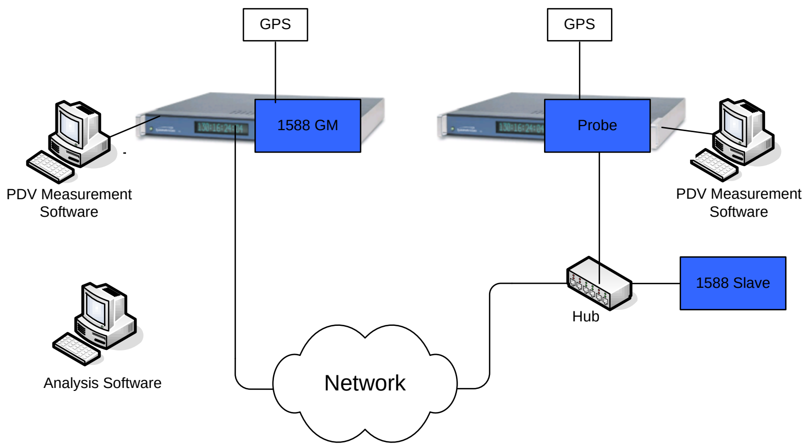
Symmetricom

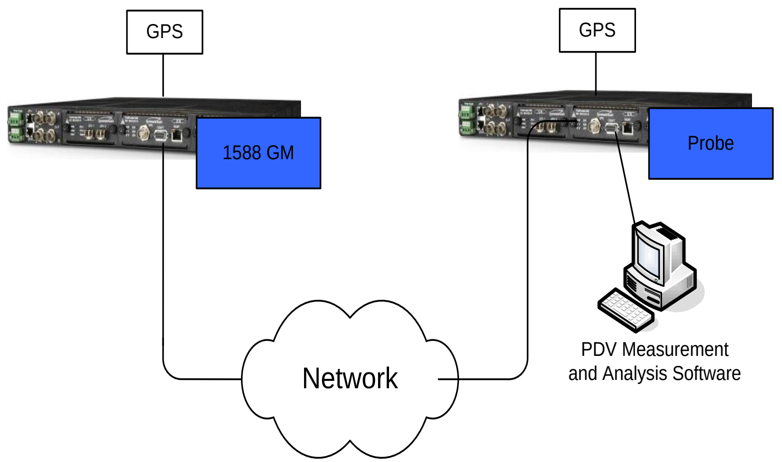
Passive Probe

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

Active Probe

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



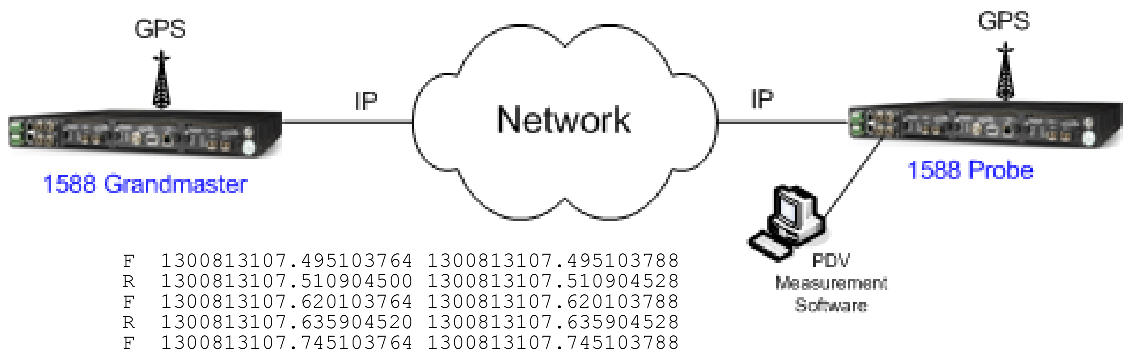


- "PDV"
  - Ideal setup - two packet timestampers with GPS reference so absolute latency can be measured as well as PDV over small to large areas
  - Alternative setup (lab) – frequency (or GPS) locked single shelf with two packet timestampers
  - Alternative setup (field) – frequency locked packet timestampers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

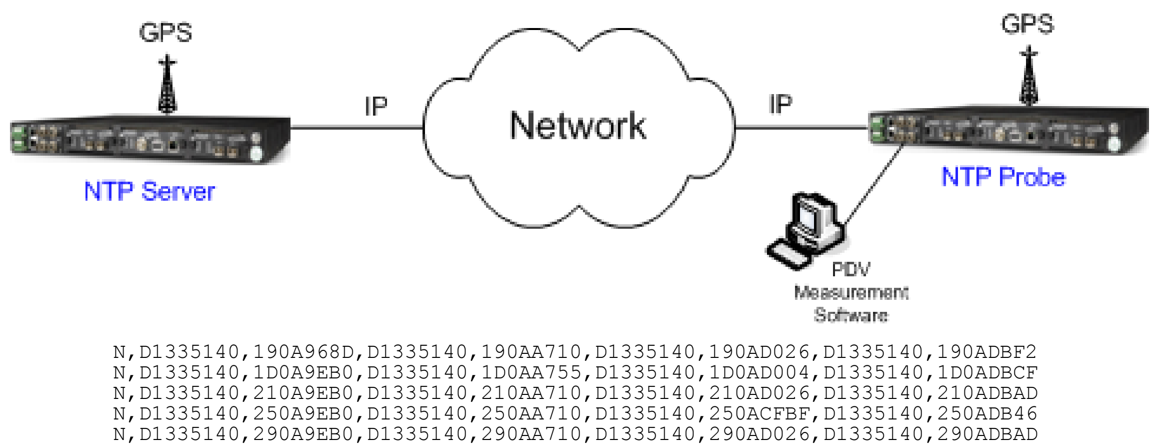
PTP and NTP Probes

Either PTP or NTP packets can be used for probing.

- In some circumstances, one or the other might be more suitable.
- For example, NTP is useful for probing over the public internet because of NAT (network address translation) challenges.



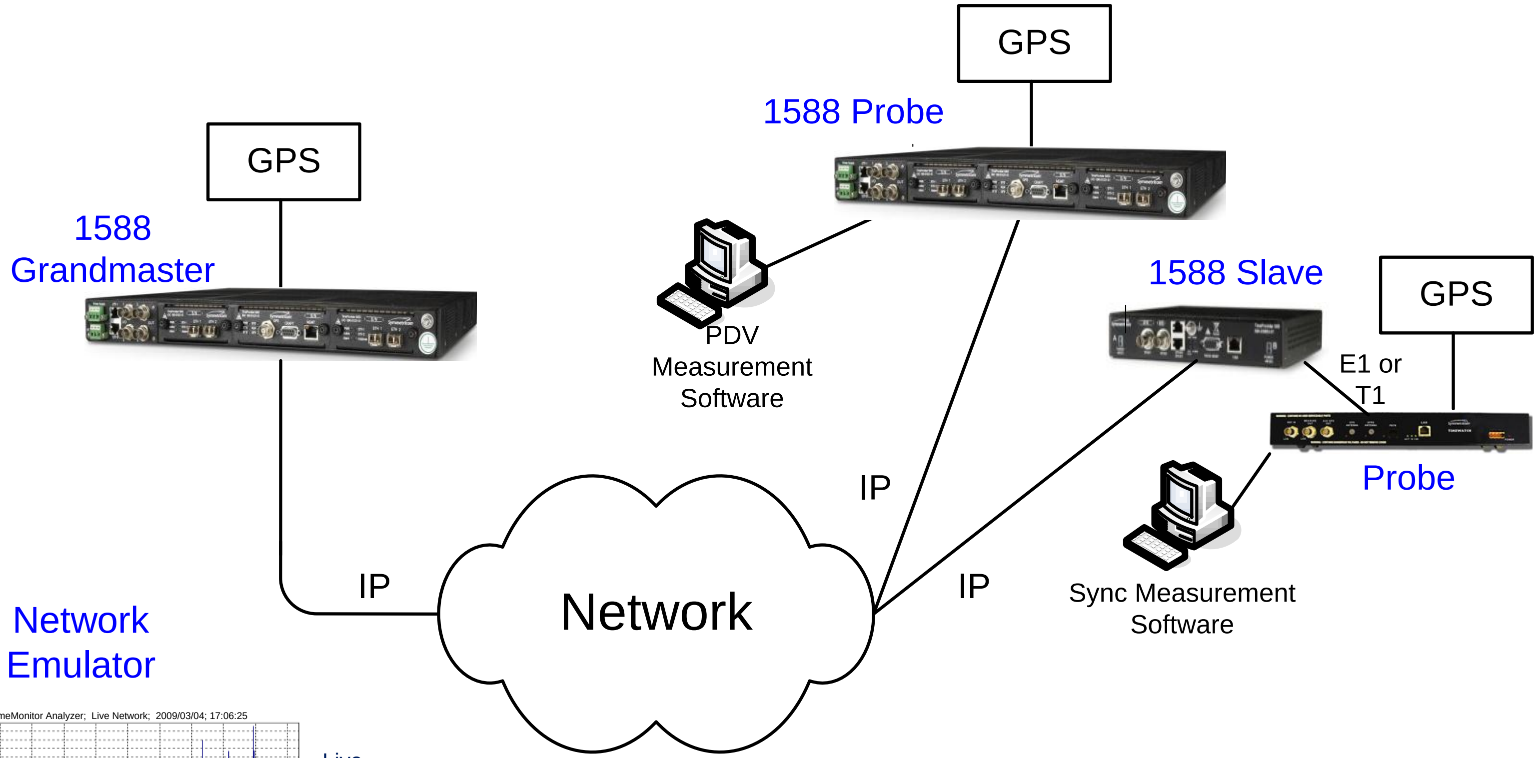
PTP

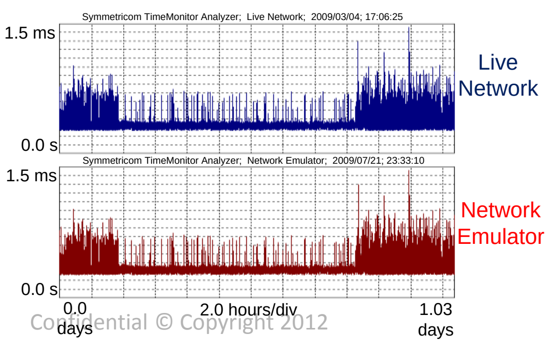


NTP

"TIE" and "PDV"

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





"TIE" Analysis vs. "PDV" Analysis

Symmetricom

"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

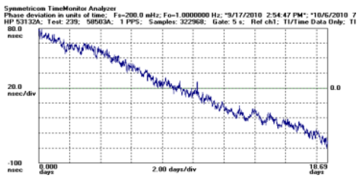
Symmetricom

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

Packet Networks

Analysis from Phase: Frequency

Symmetricom



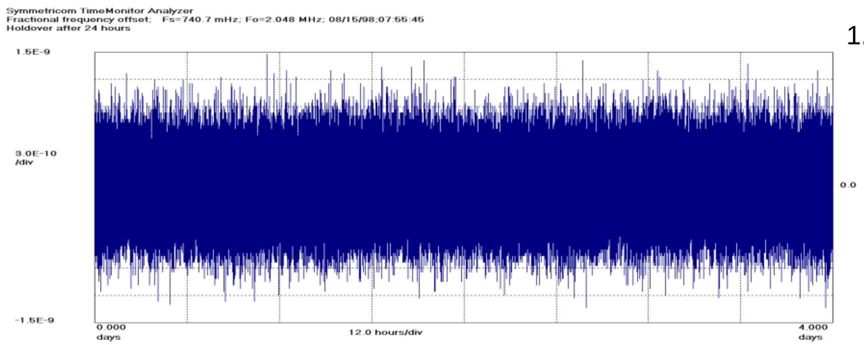
$-8.97 \cdot 10^{-14}$

Frequency Accuracy

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

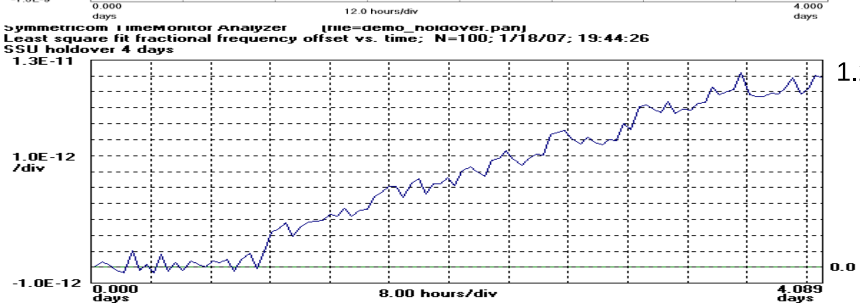
slope/linear: frequency offset

curvature/quadratic: frequency drift



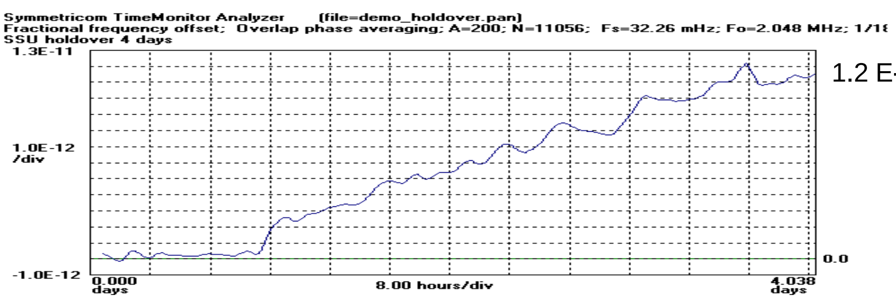
1.5 E-9

Point-by-point



1.2 E-11

Segmented LSF



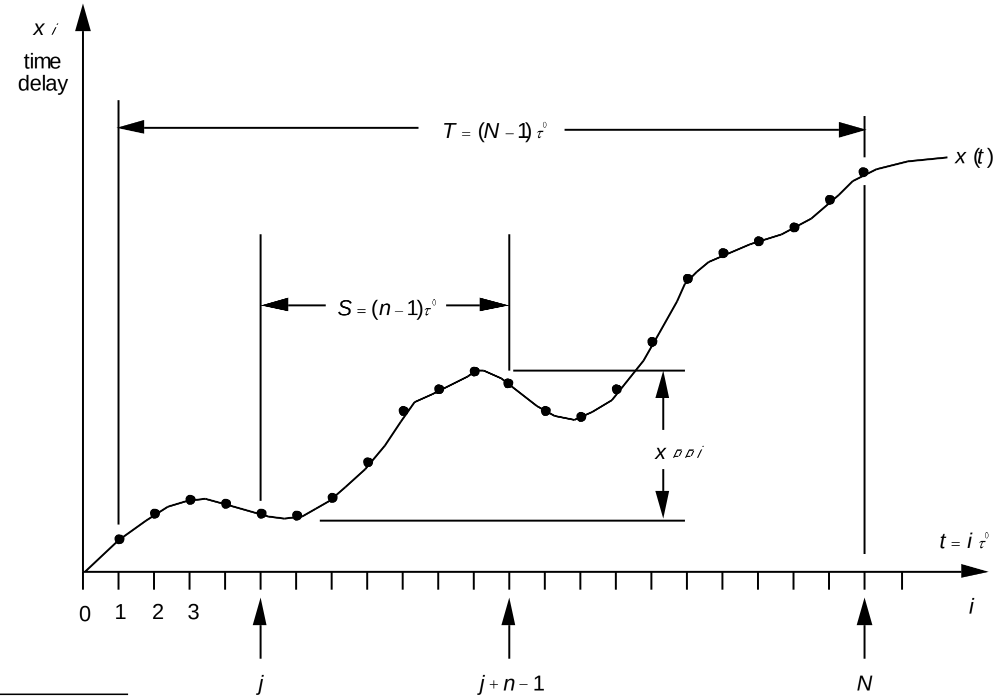
1.2 E-11

Sliding Window Averaging

Analysis from Phase: MTIE/TDEV

Symmetricom

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



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

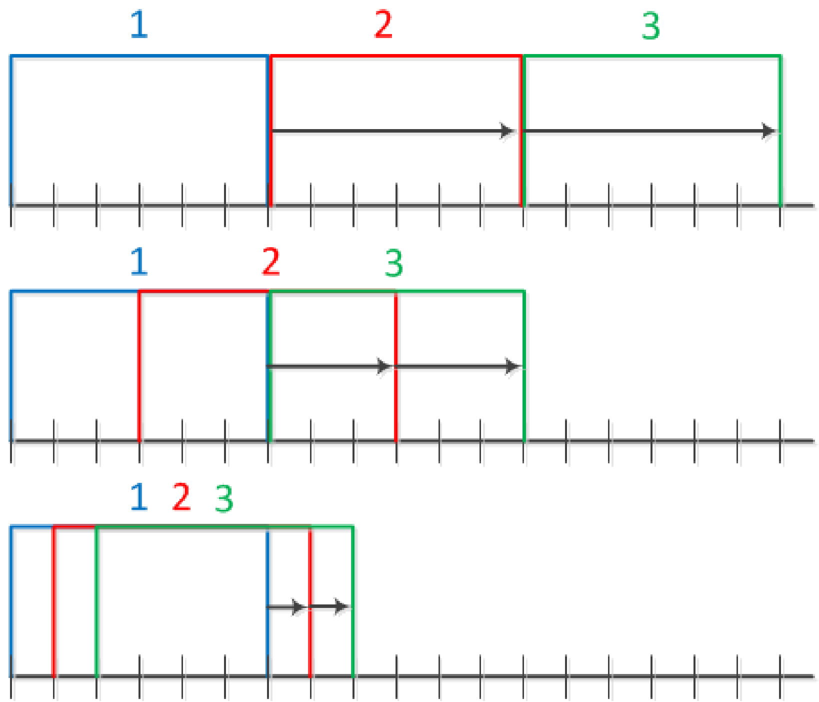
Symmetricom

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

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

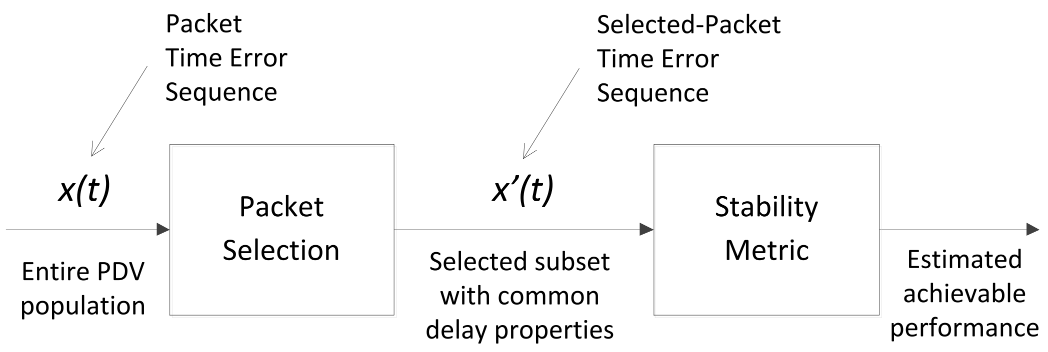


Figure I.3 – Pre-processed packet selection

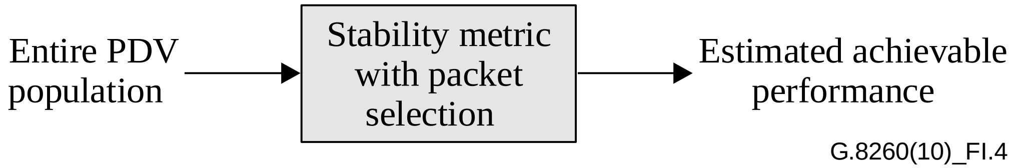
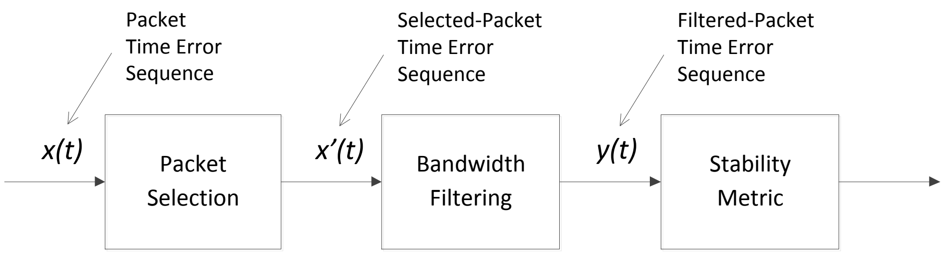


Figure I.4 – Integrated packet selection



Metrics including pre-filtering

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

PDV metrics studying minimum floor delay packet population

Packet Delay Sequence

Symmetricom

Packet Delay Sequence

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

Packet Timestamps

Forward

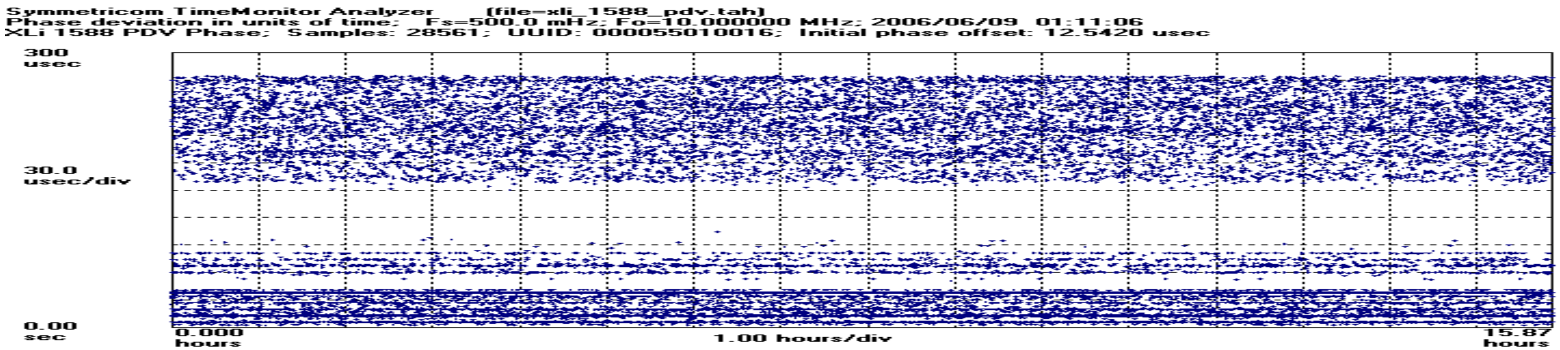
```
#Start: 2009/10/06 15:10:30
0.0000,   2.473E-3
0.0155,   2.330E-3
0.0312,   2.273E-3
0.0467,   2.258E-3
0.0623,   2.322E-3
```

Reverse

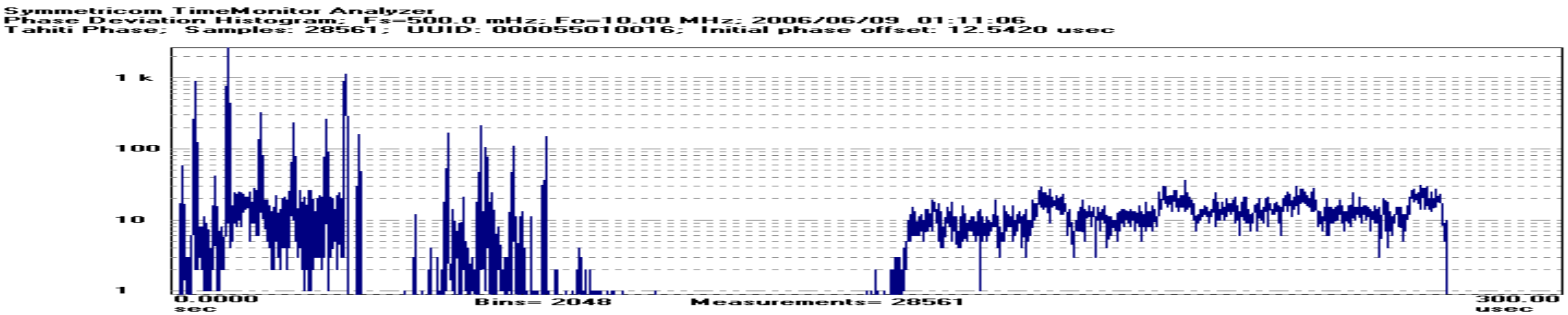
```
#Start: 2009/10/06 15:10:30
0.0000,   3.334E-3
0.0153,   2.913E-3
0.0311,   2.826E-3
0.0467,   2.968E-3
0.0624,   3.065E-3
```

Packet Delay Distribution

Symmetricom



Packet Delay Sequence



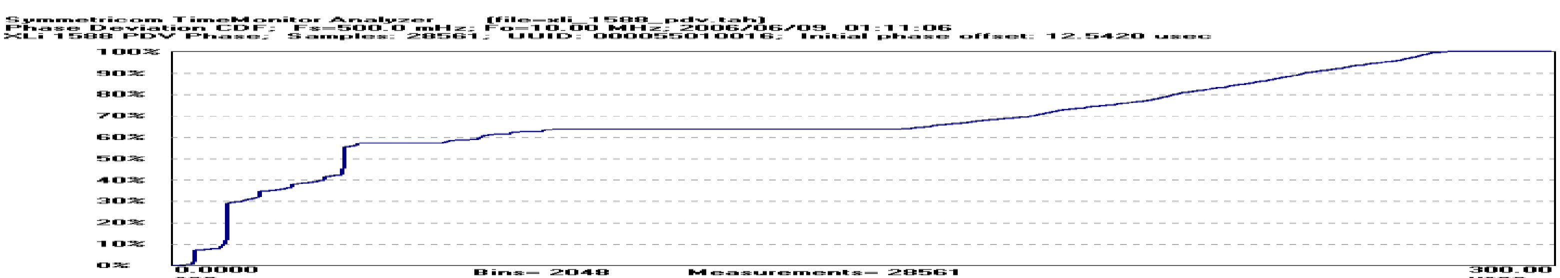
PDF

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.%

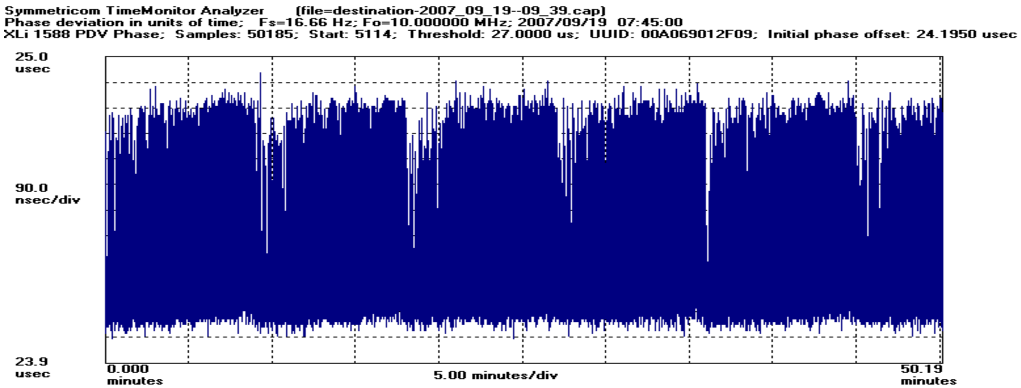
Statistics



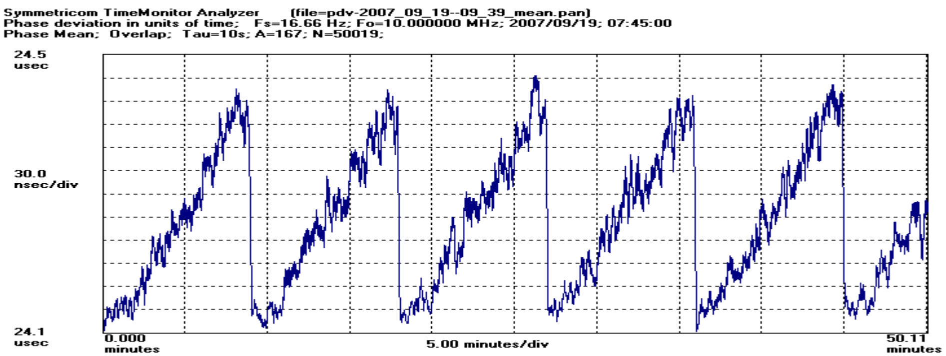
CDF

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

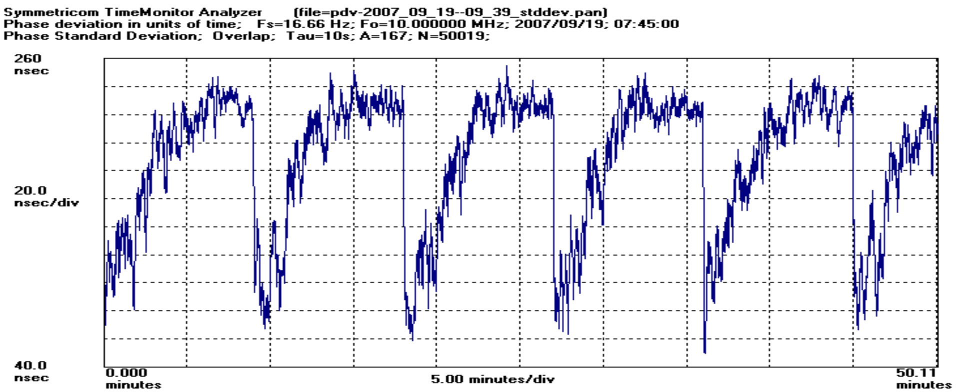
Tracked Packet Delay Statistics



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

minTDEV, bandTDEV, MATIE, MAFE

TDEV

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

minTDEV

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

bandTDEV

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

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

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

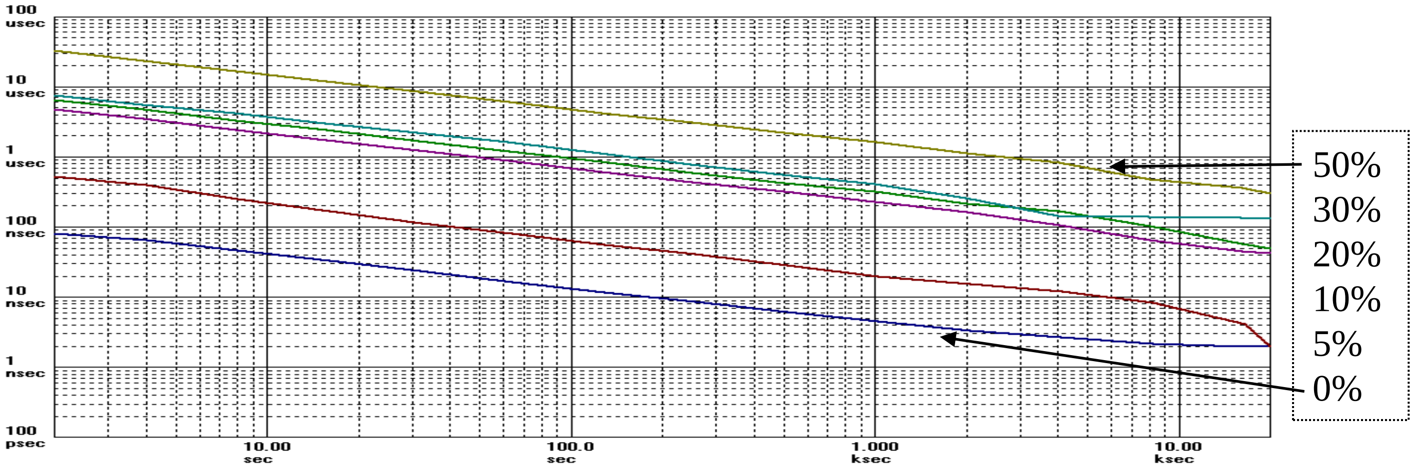
where n = 1, 2, ..., integer part (N/2) and where

$$x_{\min}(i) = \min\lfloor x_j \rfloor for(i <= j <= i+n-1)$$

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.

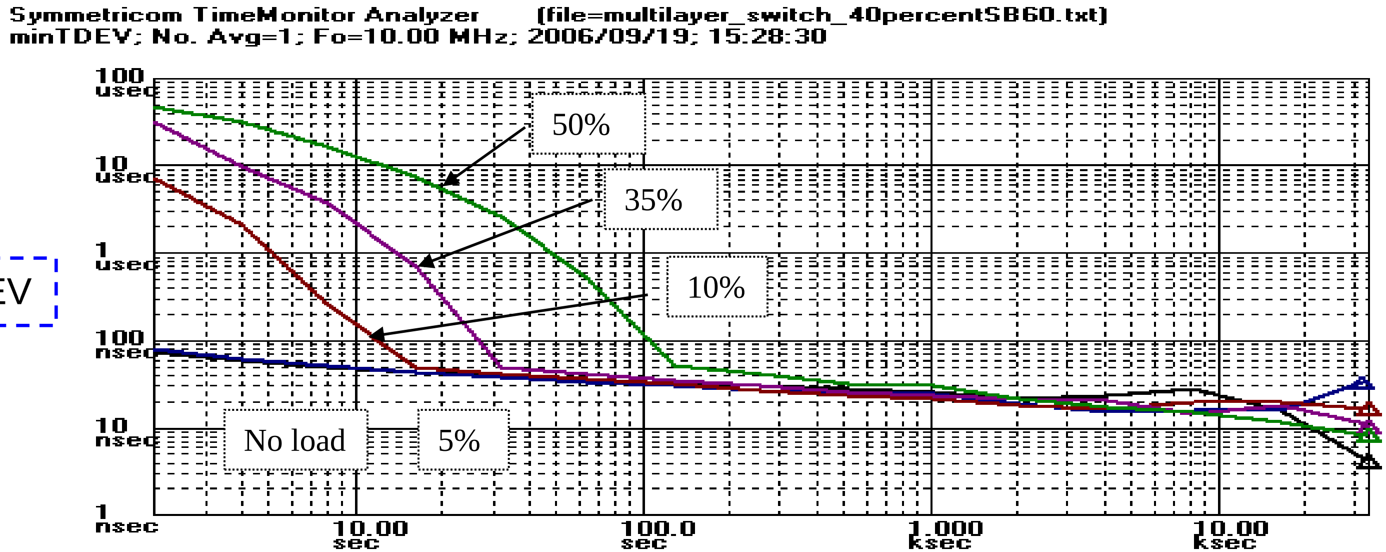
TDEV & minTDEV with Traffic

TDEV



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

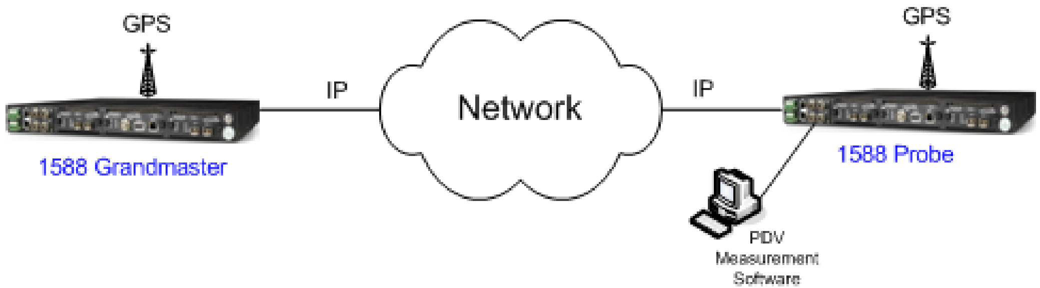
minTDEV

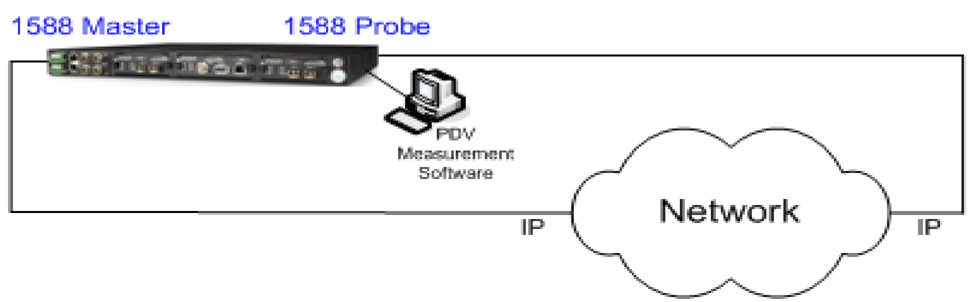


Packet Time Transport

“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

Two-way Data Set

#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

Minimum Search Sequence

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		

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

Metrics: Time Transport

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

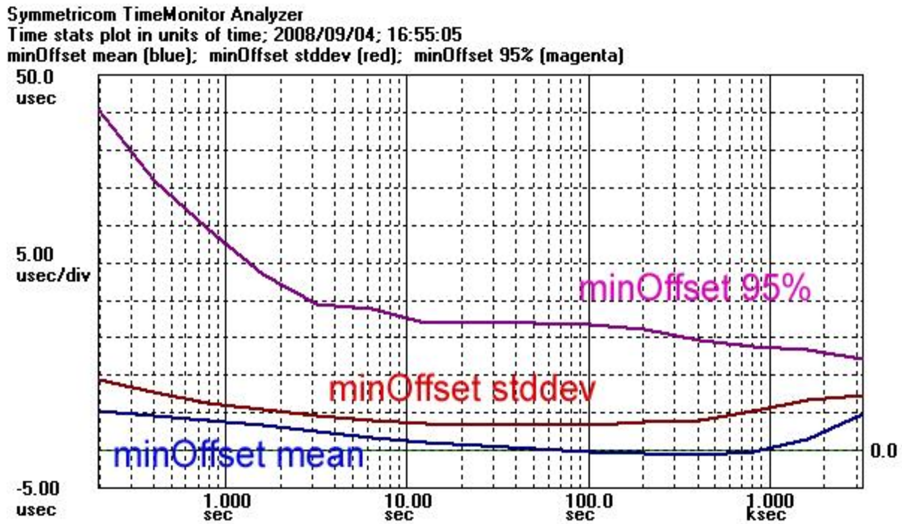
minOffset statistics: minOffset statistic such as mean, standard deviation, or 95 percentile plotted as a function of time window tau

Metrics: Time Transport

Symmetricom

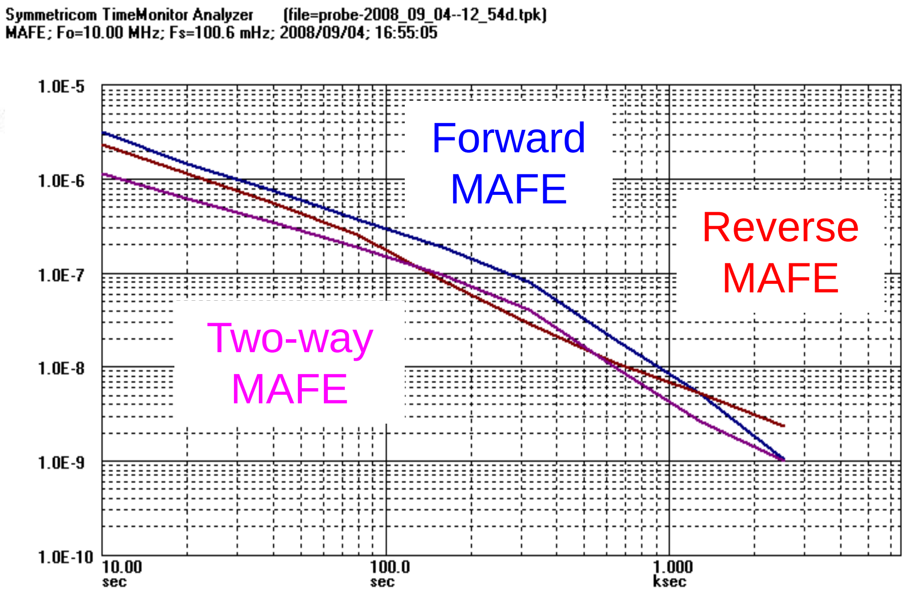
minOffset Statistics

(Two-way minimum offset statistics vs. τ)



Two-way MAFE

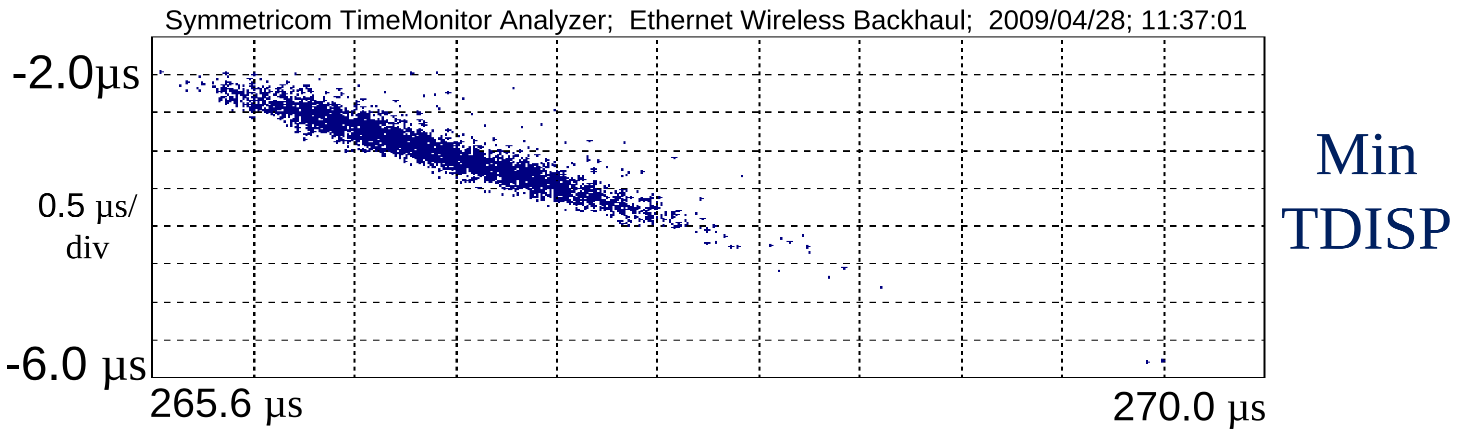
(MAFE of minOffset)

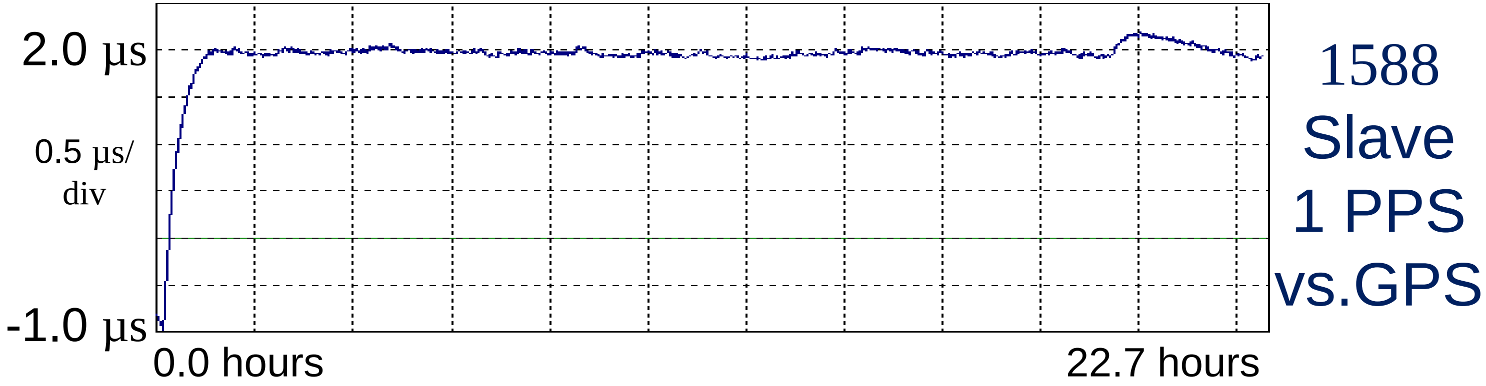


Case Studies: Networks

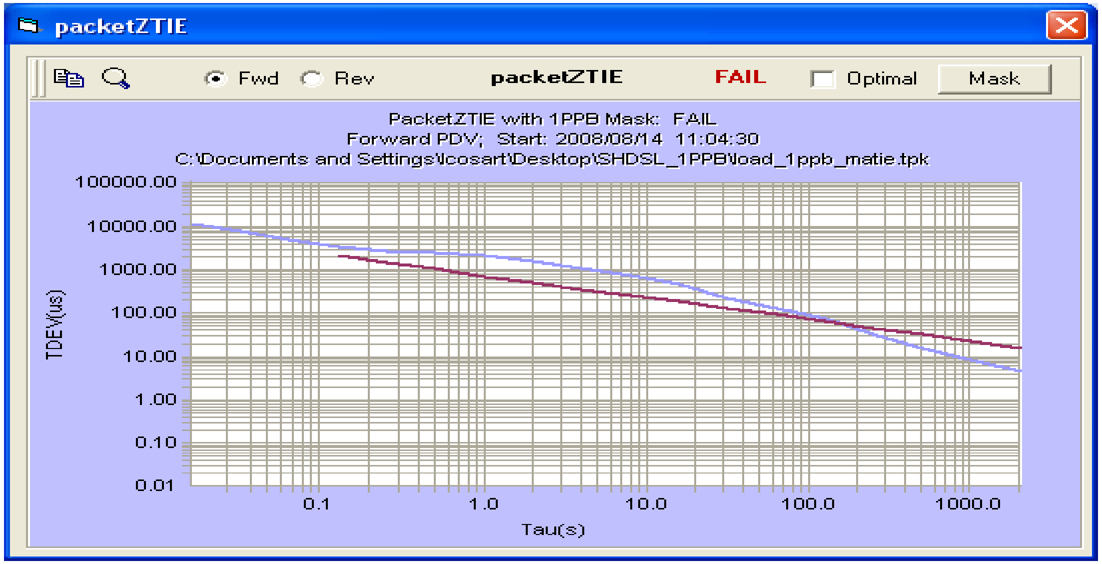
Asymmetry in Wireless Backhaul

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



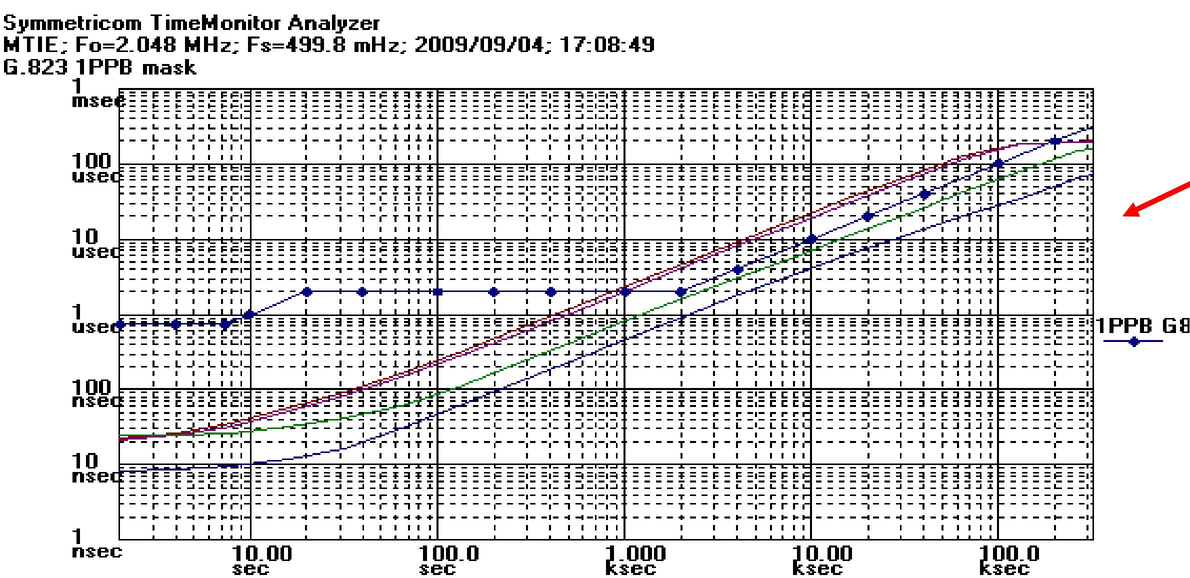


Case Studies: Networks



Packet measurement

Packet data analysis: 1PPB offset predicted

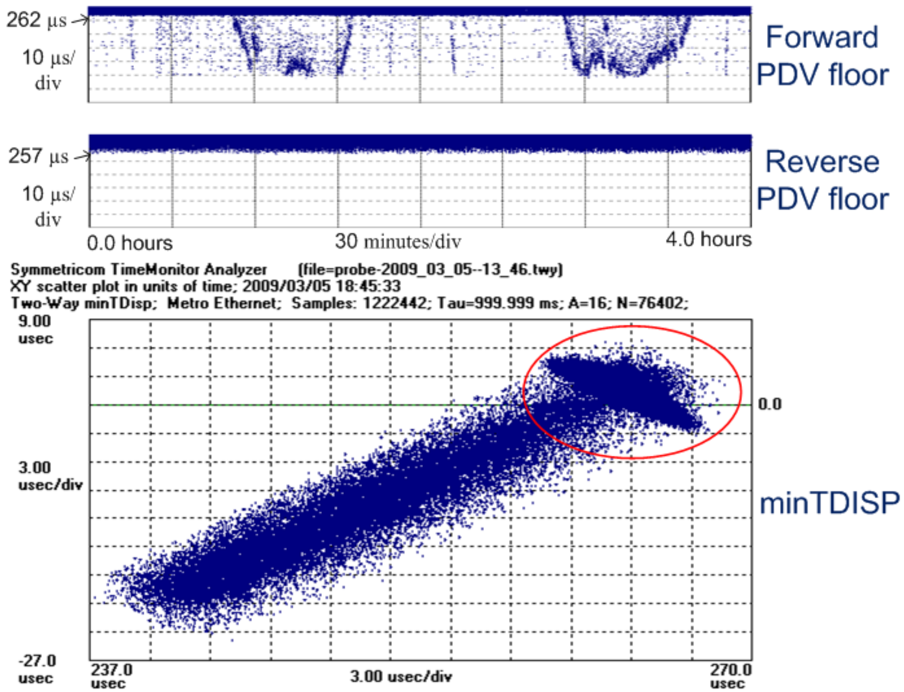


Sync measurement

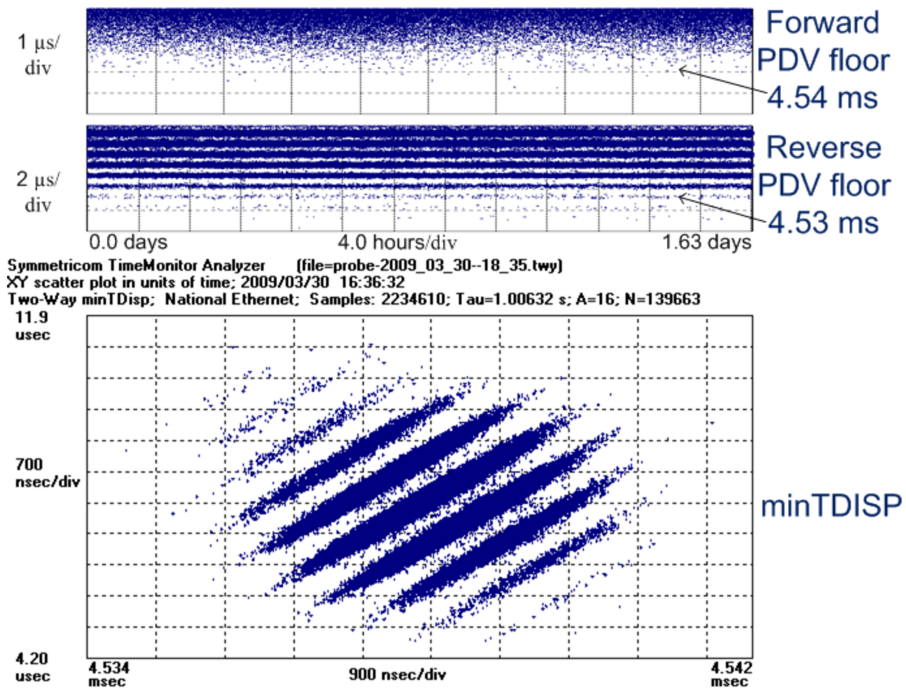
1588 slave performance: 1 PPB offset measured

Case Studies: Networks

Metro Ethernet Network



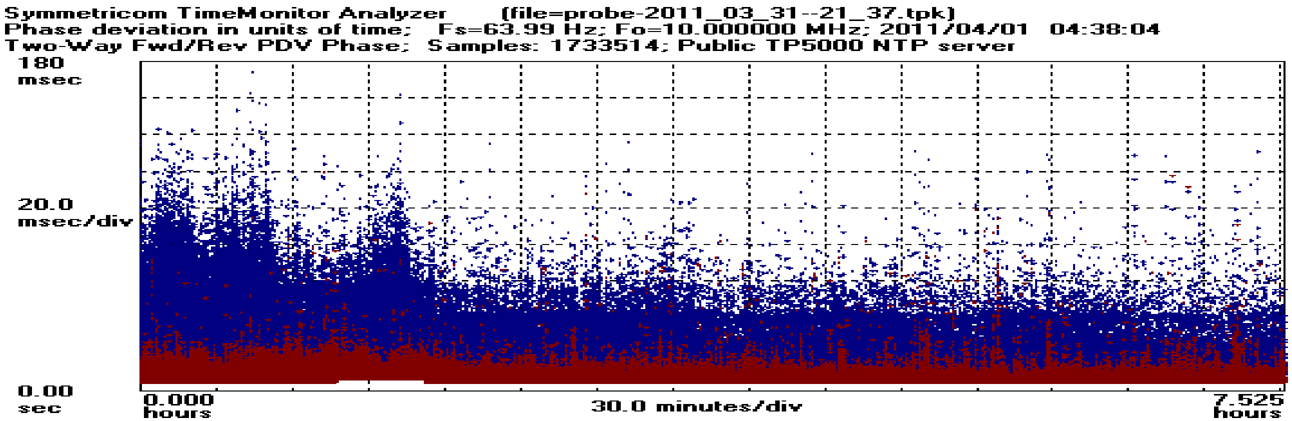
National Ethernet Network



Forward and reverse packet delay sequences with zooms into the respective floors and minTDISP

Case Studies: Networks

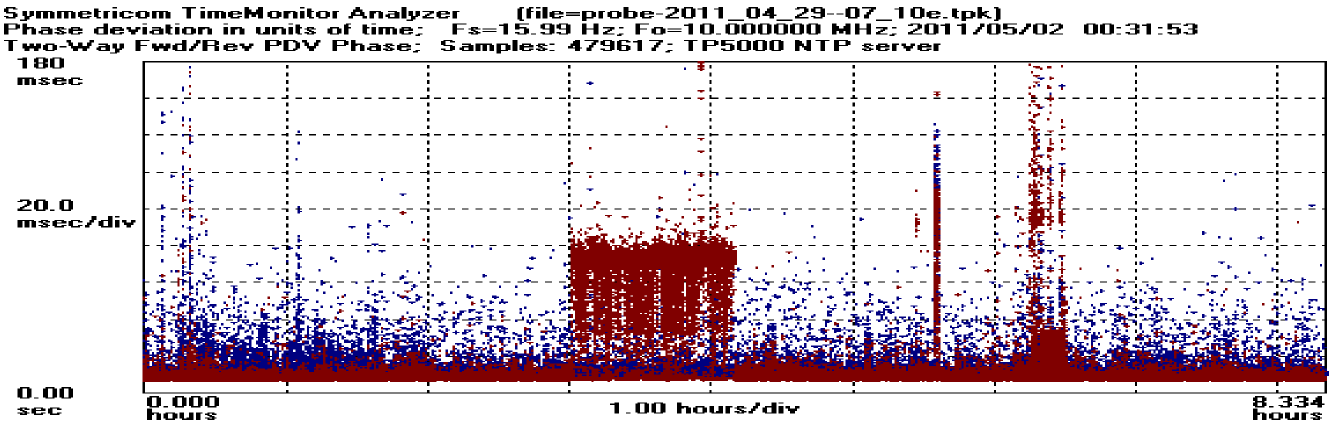
Public Internet w/ Cable Modem Access (NTP probe)



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)



Downstream typically 9.0 msec minimum

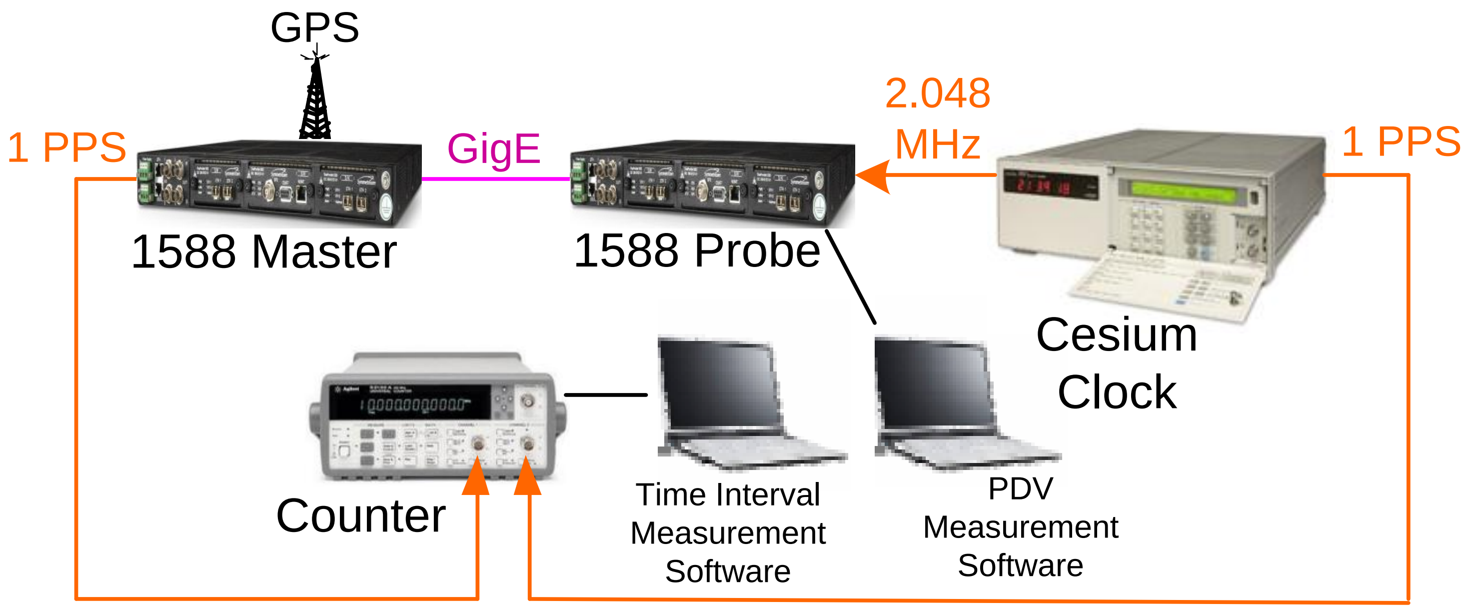
Upstream typically 6.7 msec minimum, steps to 70 msec for 1 hour

Not shown: delays as much as several seconds

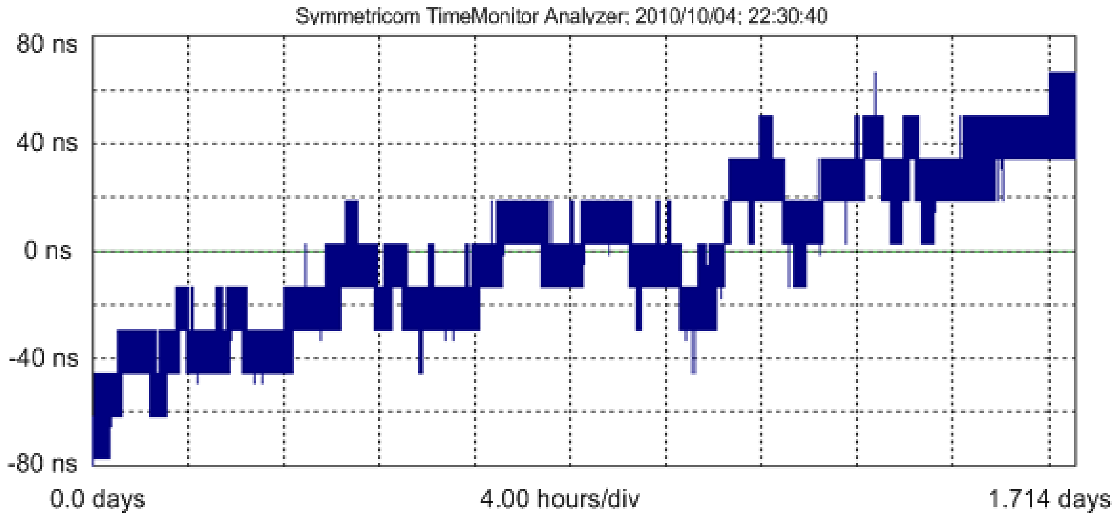
Case Studies: Grandmaster Clock

Symmetricom

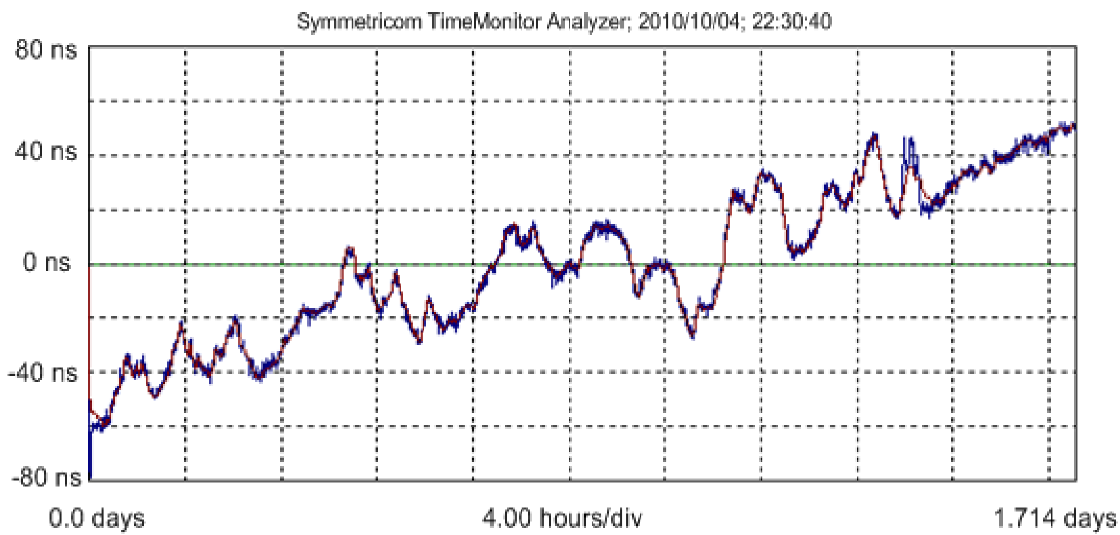
Grandmaster Measurement Setup



Case Studies: Grandmaster Clock



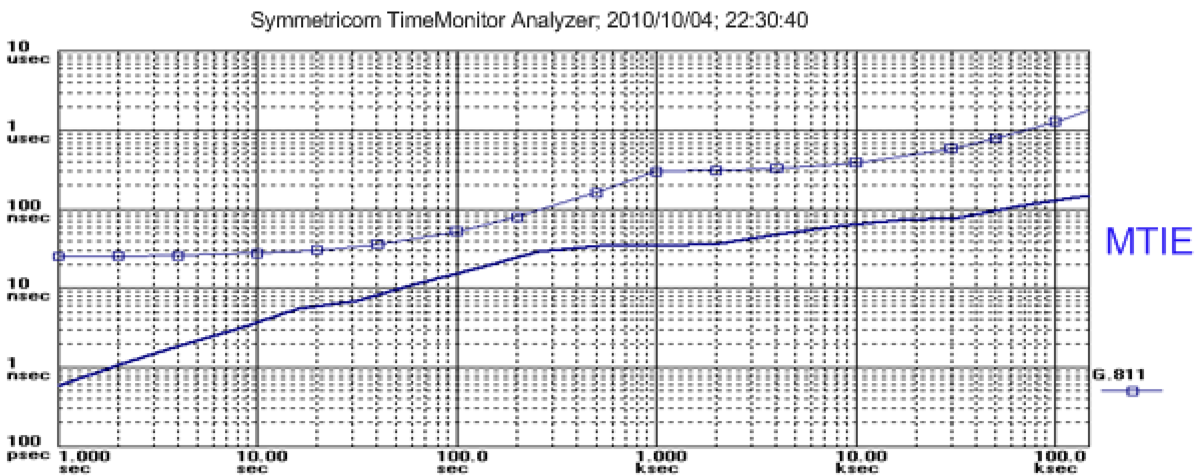
Raw unfiltered probe measurement



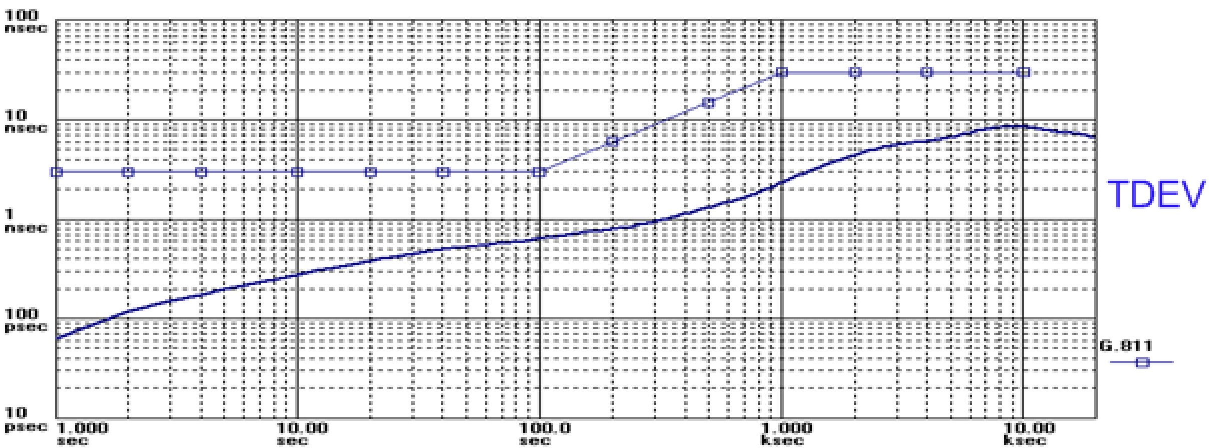
Overlay of filtered probe and 1PPS measurement

Case Studies: Grandmaster Clock

Traditional Metrics Applied to Filtered Probe Measurement



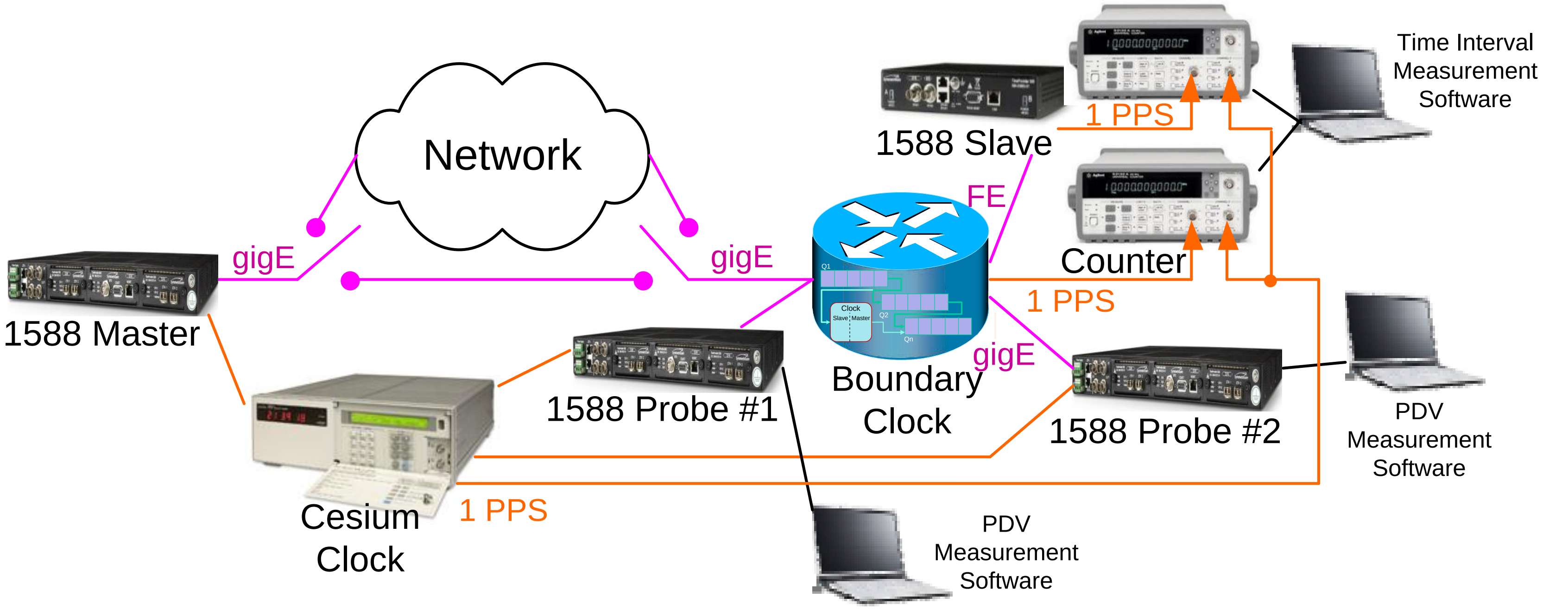
MTIE below G.811 PRC mask



TDEV below G.811 PRC mask

Case Studies: Boundary Clocks

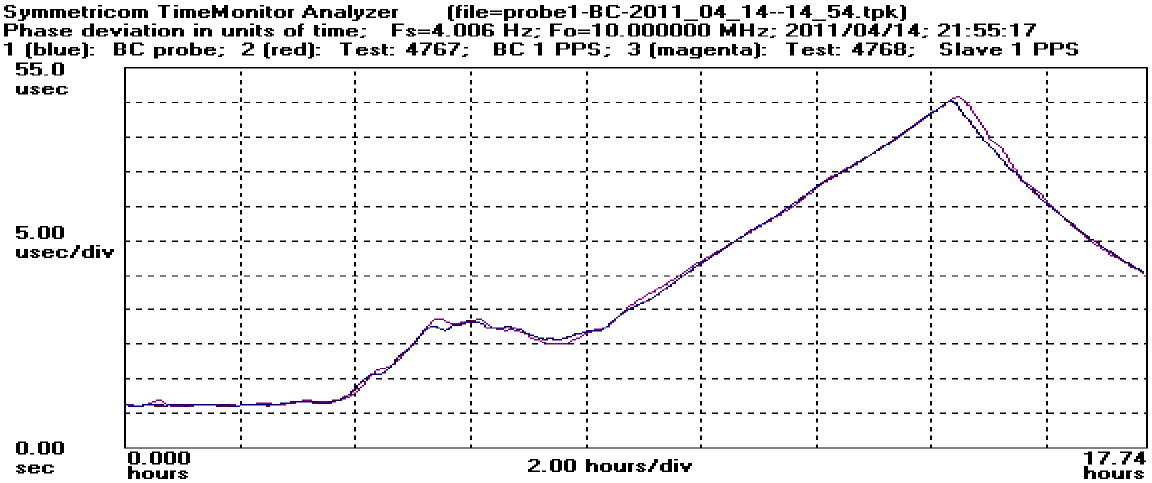
Boundary Clock Measurement Setup

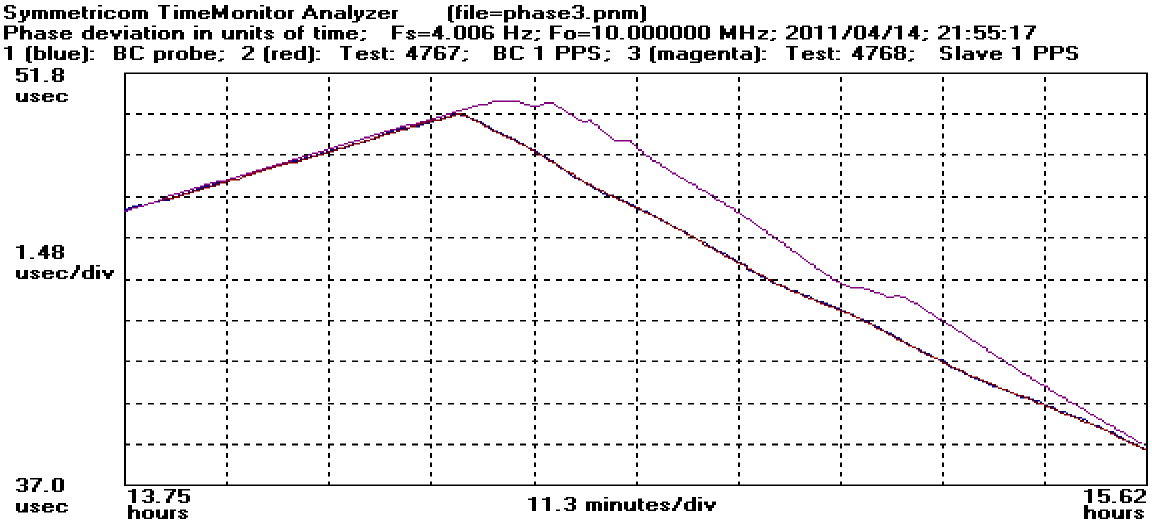


Case Studies: Boundary Clocks

Boundary Clock Measurement: 3 Approaches

(1) Packet probe; (2) BC 1PPS; (3) Connected slave 1PPS

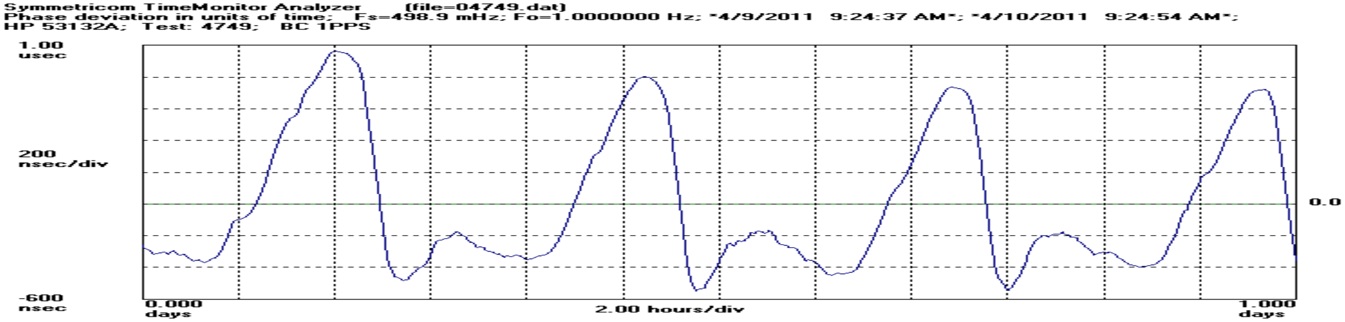




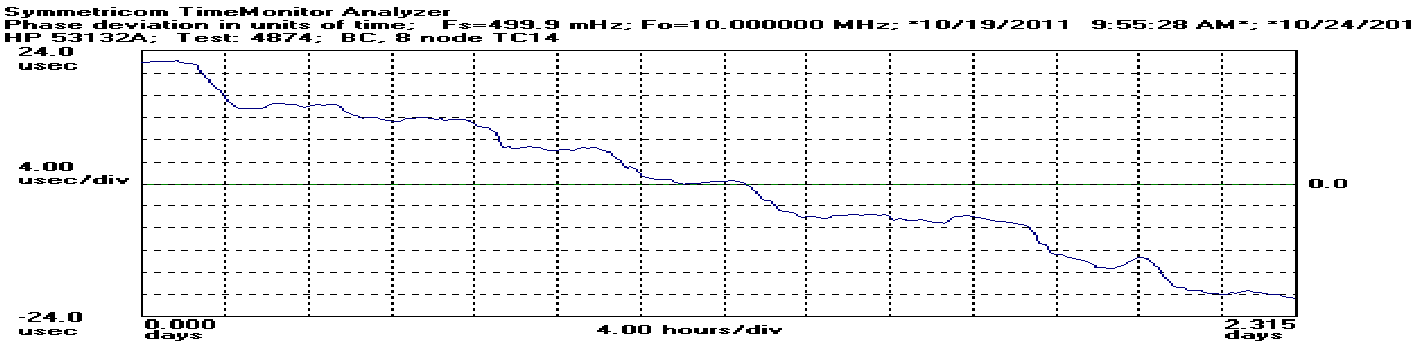
Case Studies: Boundary Clocks

Symmetricom

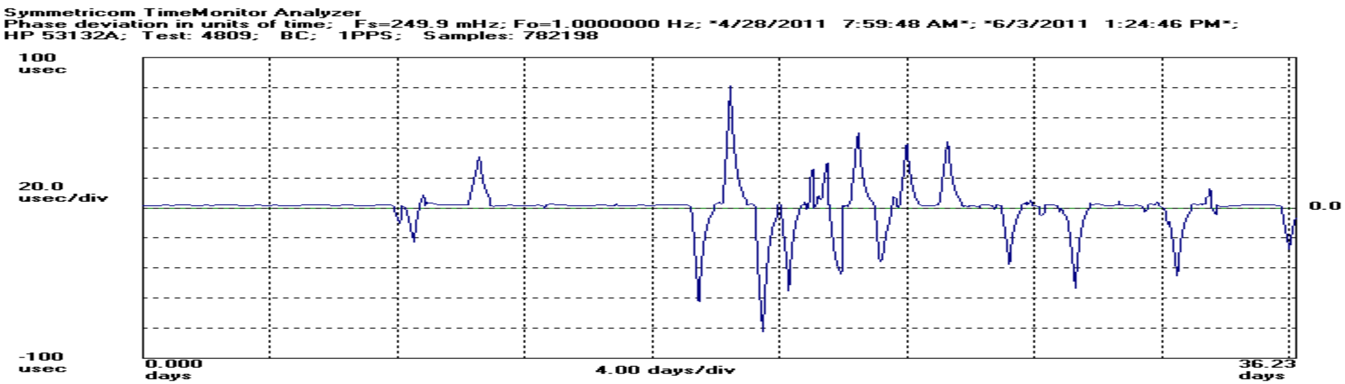
Three boundary clocks from three vendors



BC Vendor #1



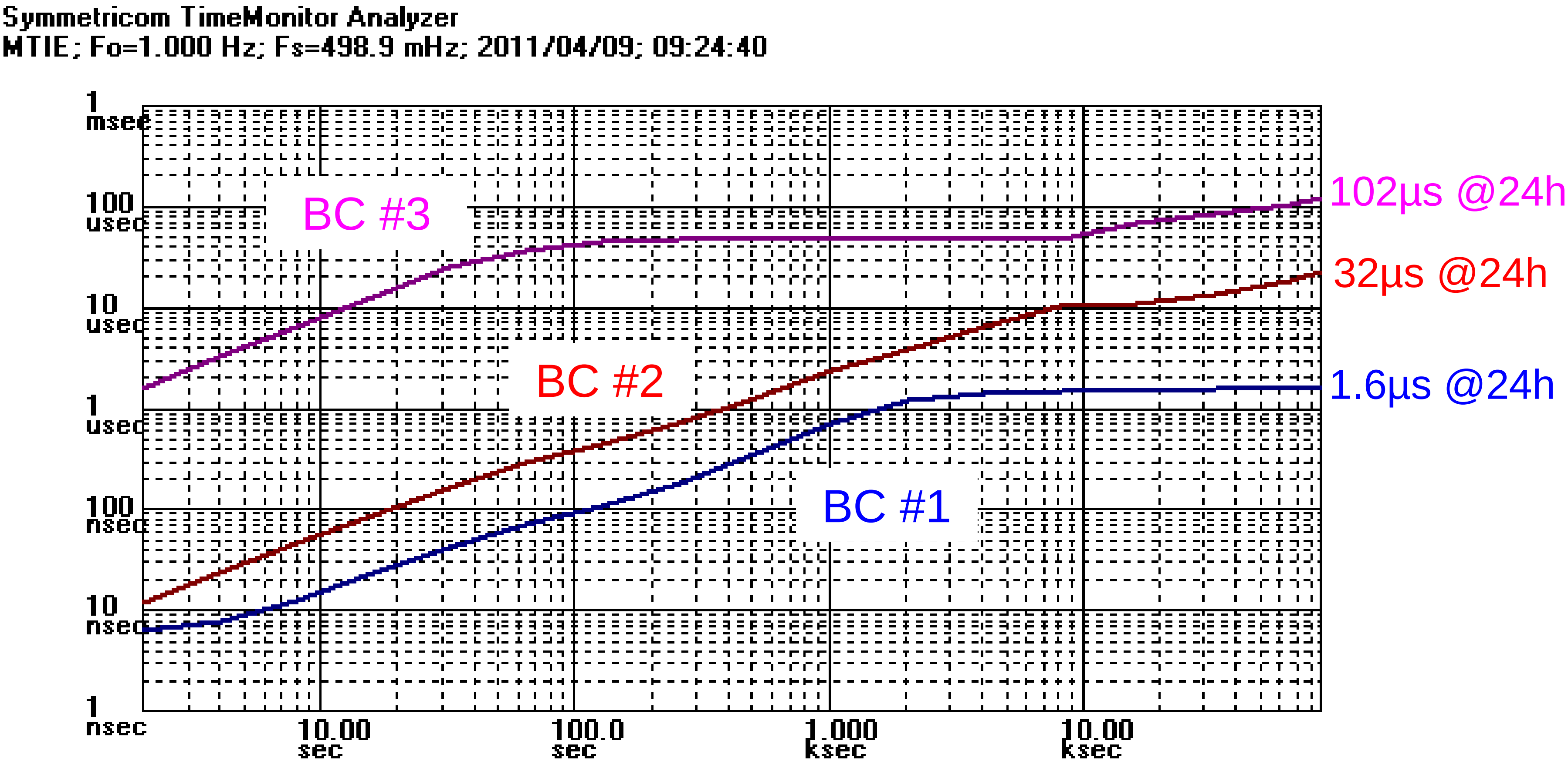
BC Vendor #2



BC Vendor #3

Case Studies: Boundary Clocks

Loaded 8-node network

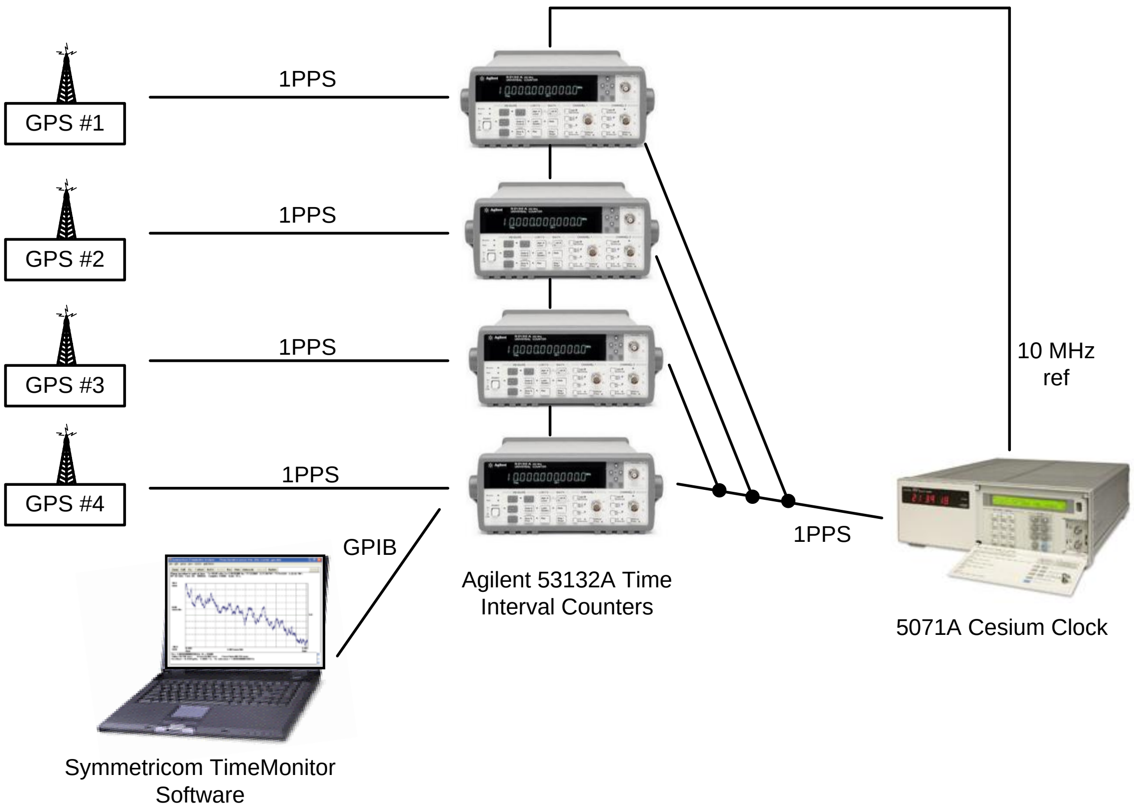


Case Studies: Four GPS Receivers

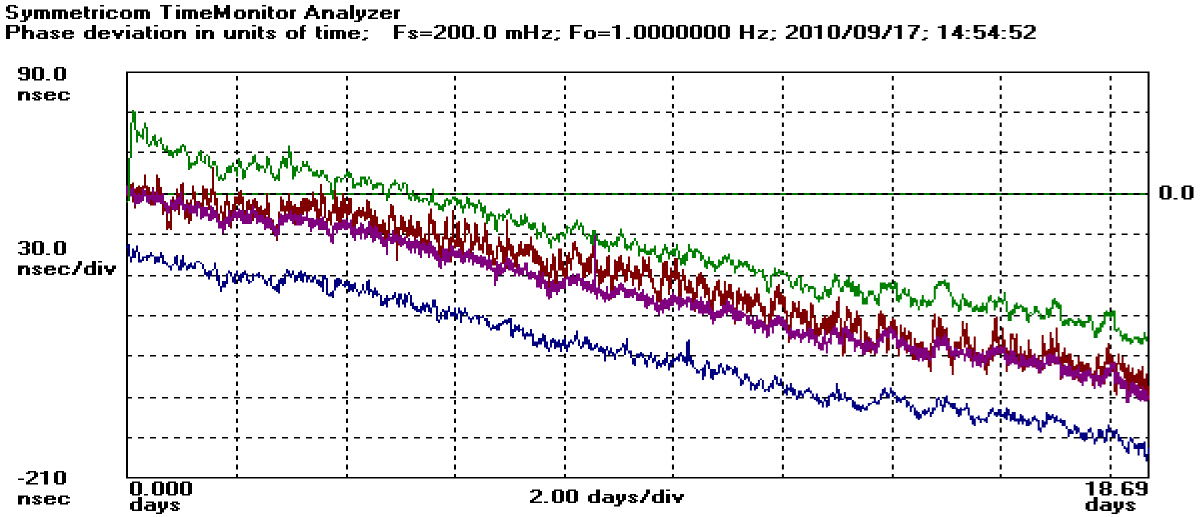
Symmetricom

Measurement Setup

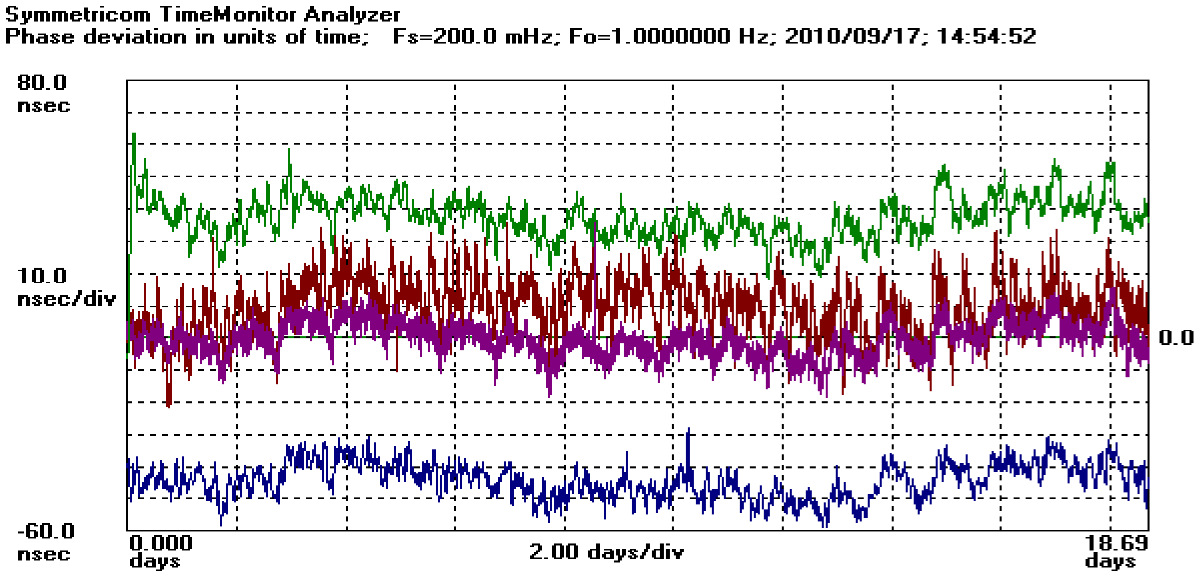
GPS receivers share the same antenna



Case Studies: Four GPS Receivers



Raw GPS vs. cesium 1PPS



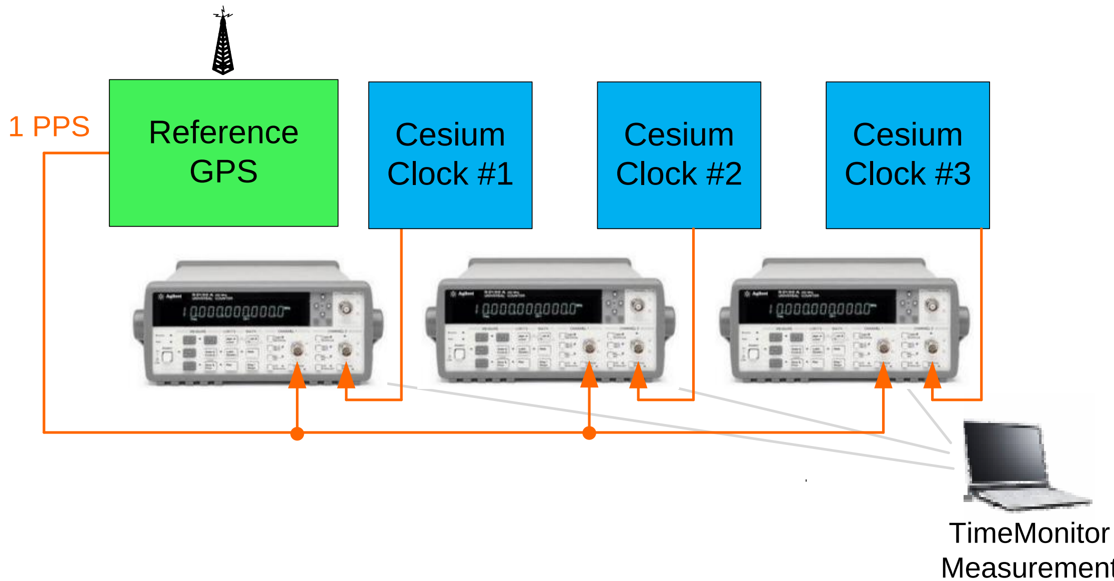
GPS measurements with cesium offset removed

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

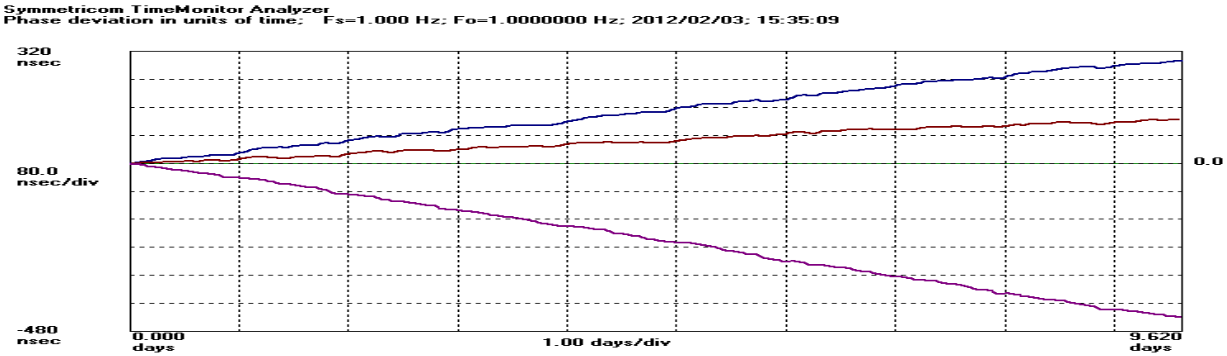
Measurement Setup



Note: Measurements conducted at constant room temperature.

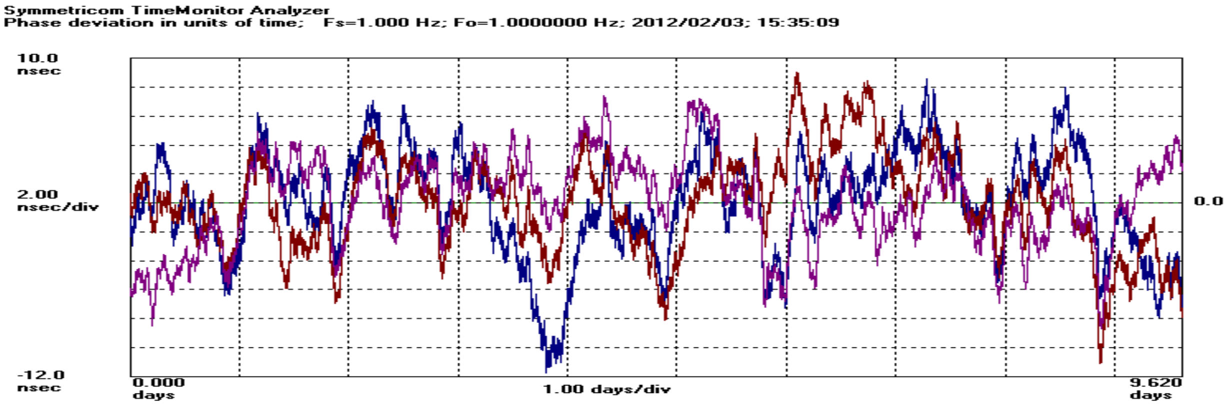
“Golden” Receiver Stability Performance

Symmetricom

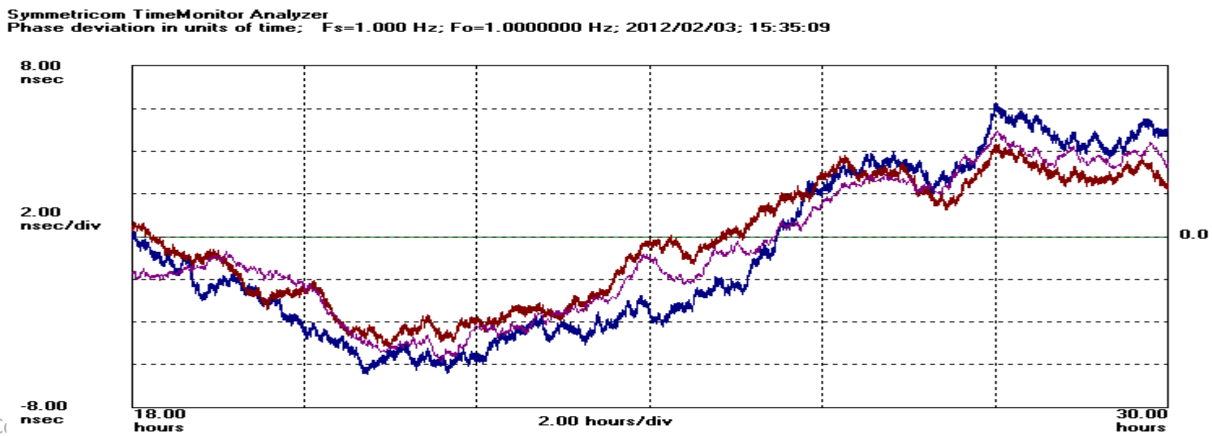


Raw results vs. 3 cesium clocks

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

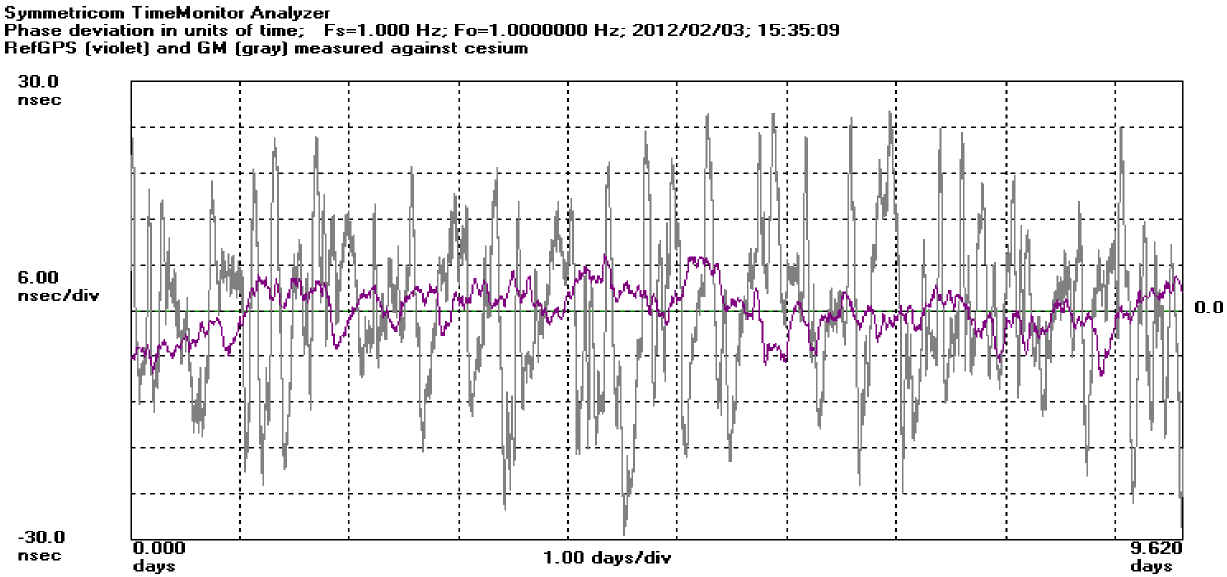


Results with respective cesium offsets removed

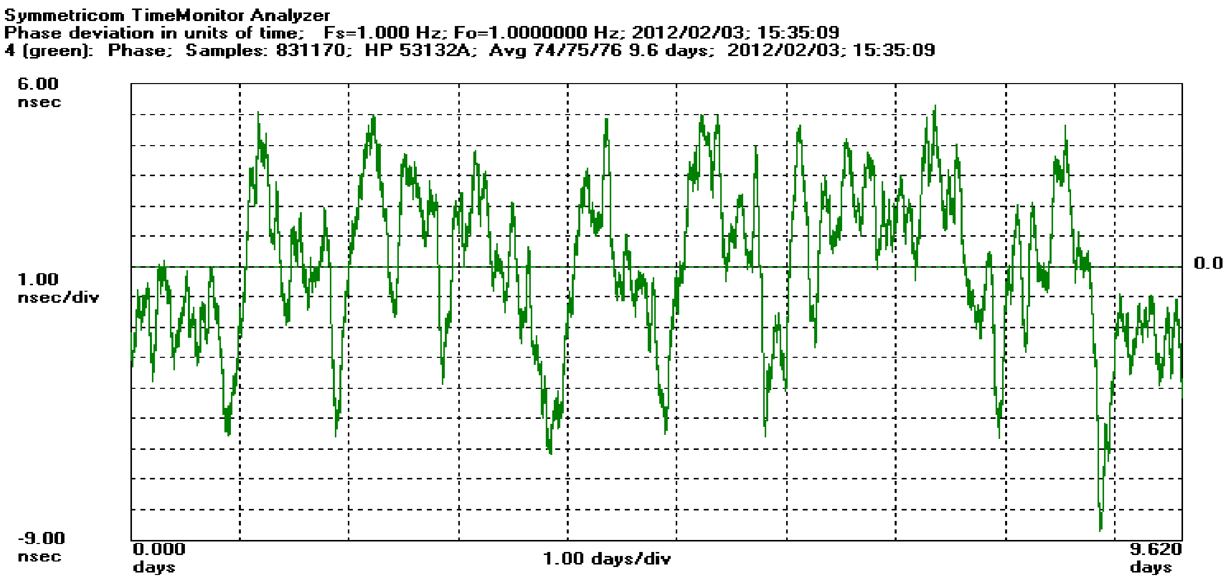


Zoom into 12 hour section of 10-day measurement

“Golden” Receiver Stability Performance

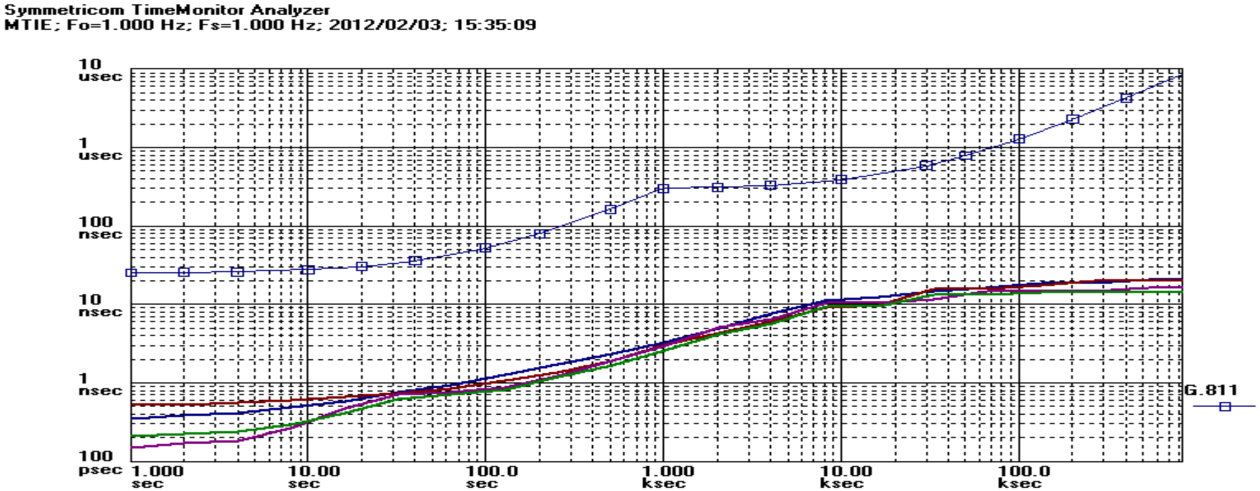


“Golden” vs. conventional GPS receiver

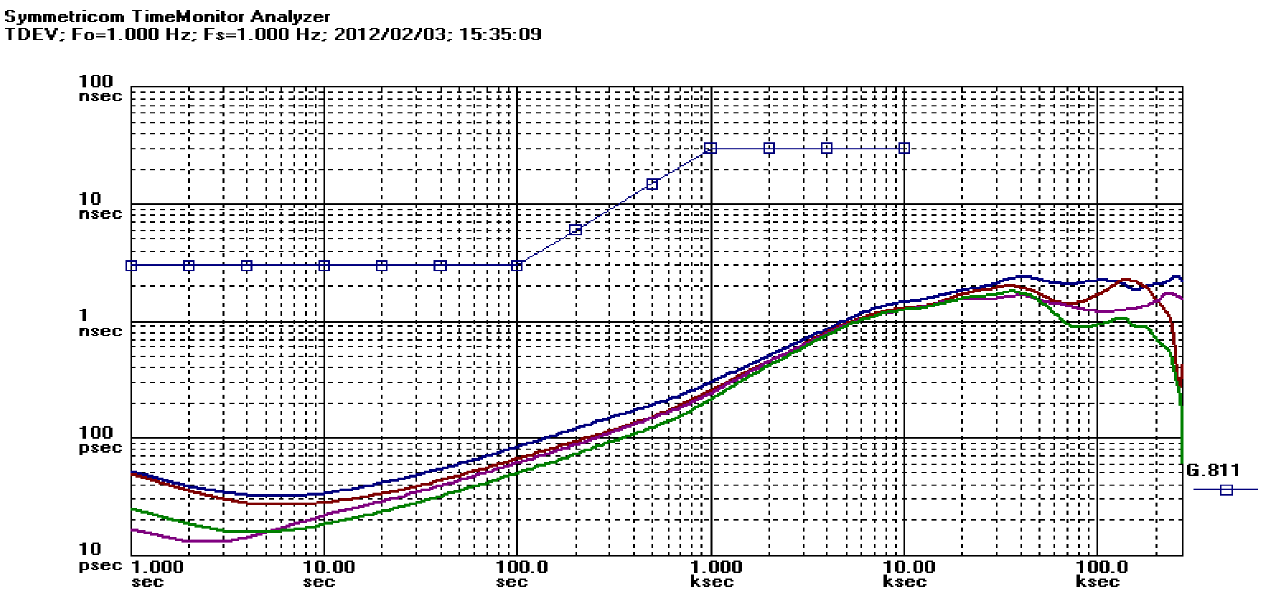


Three “Golden” measurements averaged together

“Golden” Receiver Stability Performance



“Golden” receiver MTIE performance



“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