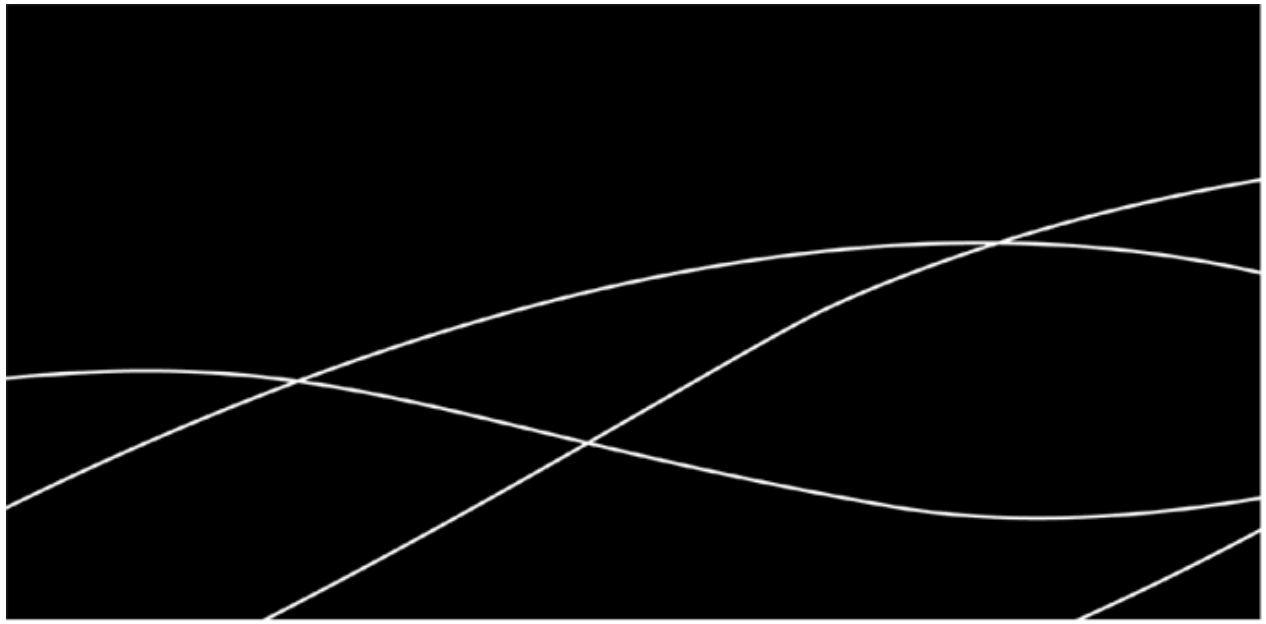
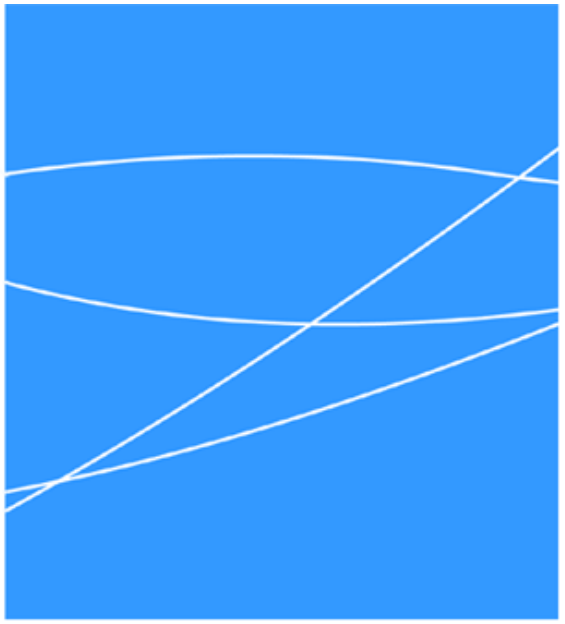
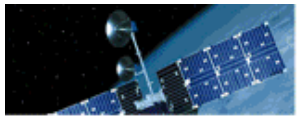
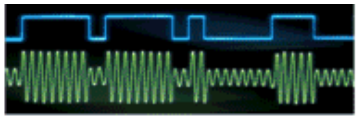








Timing Measurement Fundamentals

ITSF November 2006

Lee Cosart

lcosart@symmetricom.com

Symmetricom®

Measurement & Analysis: Outline

Symmetricom

1. Measurement of Phase 
2. Analysis
3. Measurement Examples

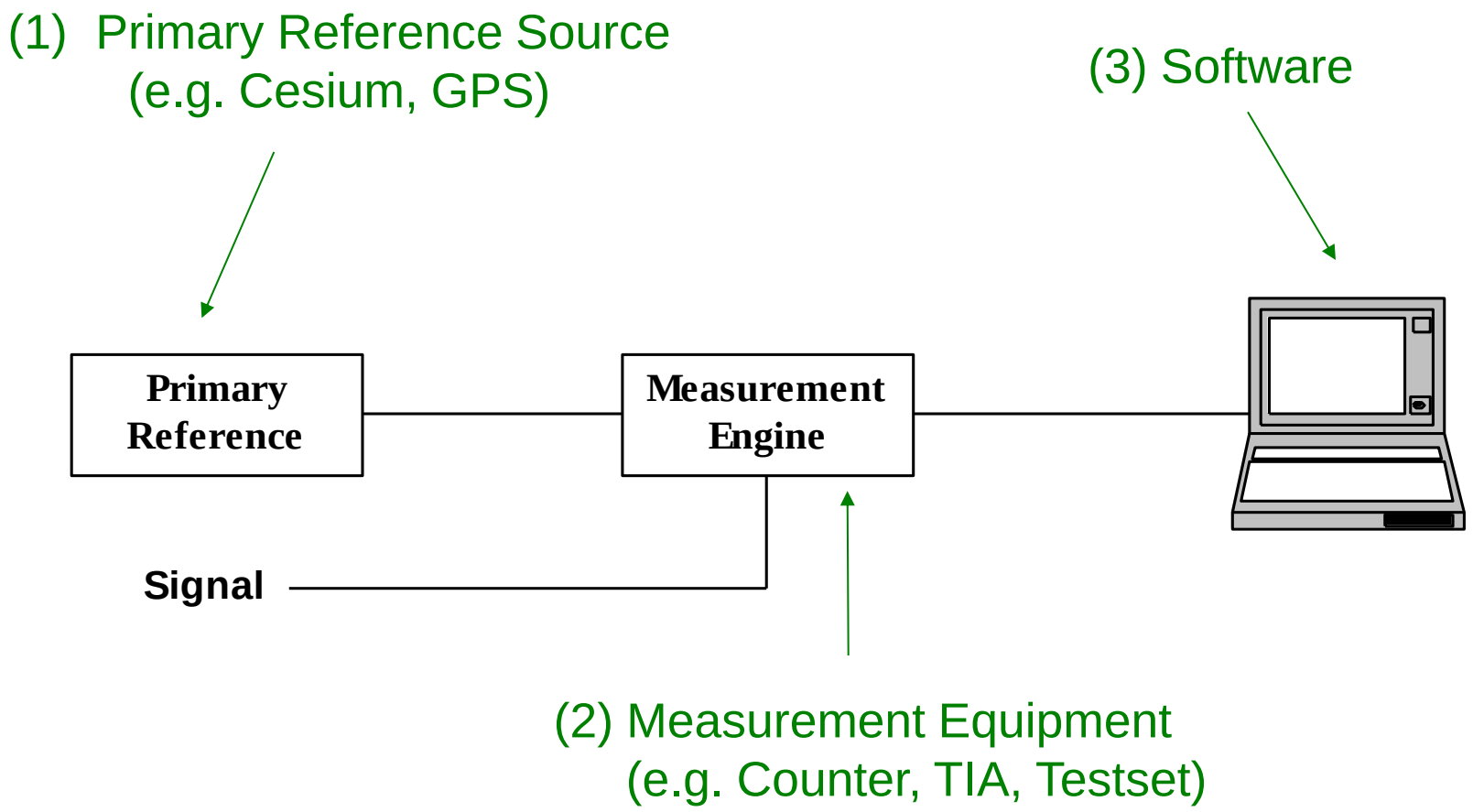
Synchronization Measurement Equipment

Symmetricom

- Some kind of phase detector or phase measurement device is needed

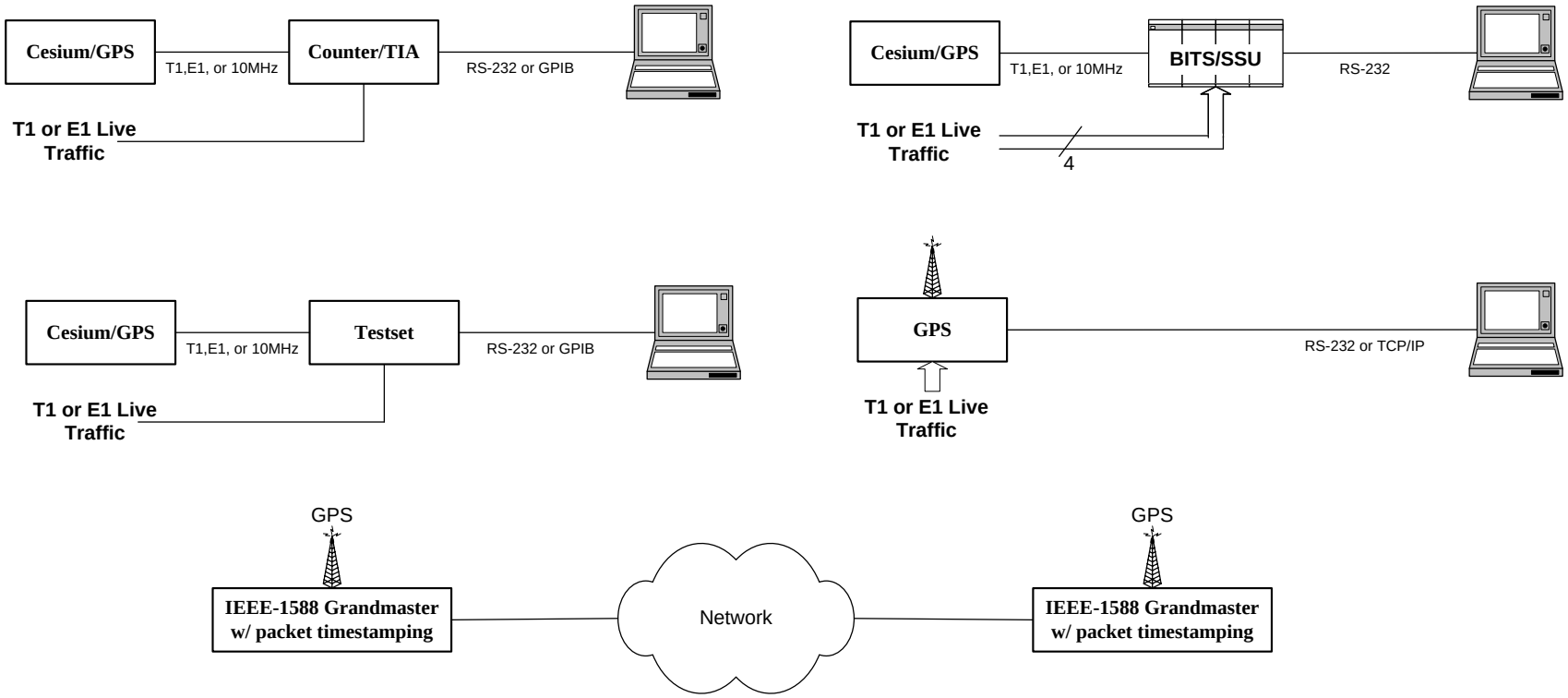
- Phase measurements can be made using:
  - Frequency/time interval counters } Focus for our discussion
  - Time interval analyzers
  - Dedicated testsets
  - BITS/SSU clocks with built-in measurement capability
  - GPS receivers with built-in measurement capability
  - Packet timestamping hardware for PDV (packet delay variation)

Sync Measurement Block Diagram



Sync Measurement Example Configurations

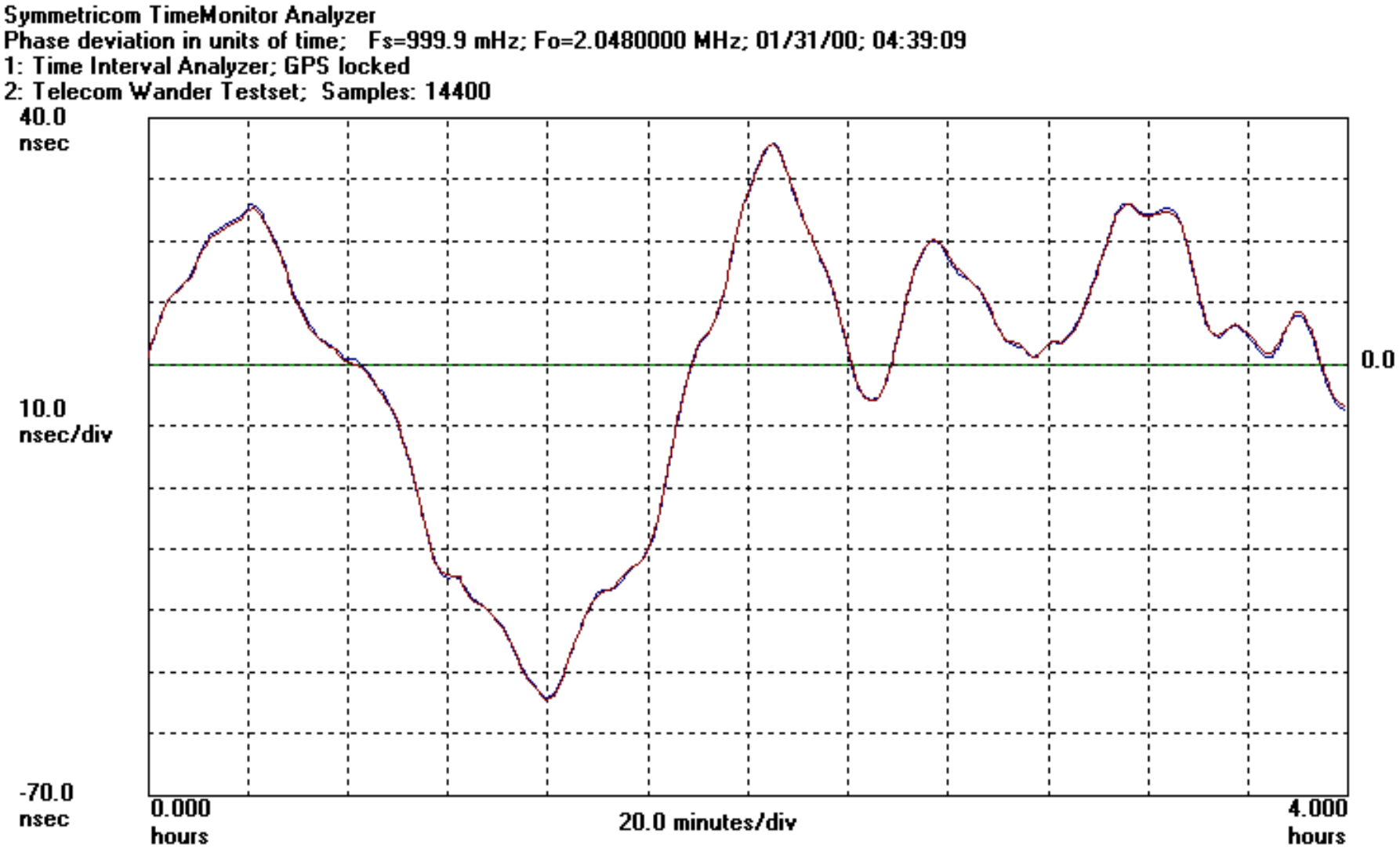
Five Example Measurement Equipment Configurations



Equipment Comparison:
Sync Testset vs. Time Interval Analyzer

Symmetricom

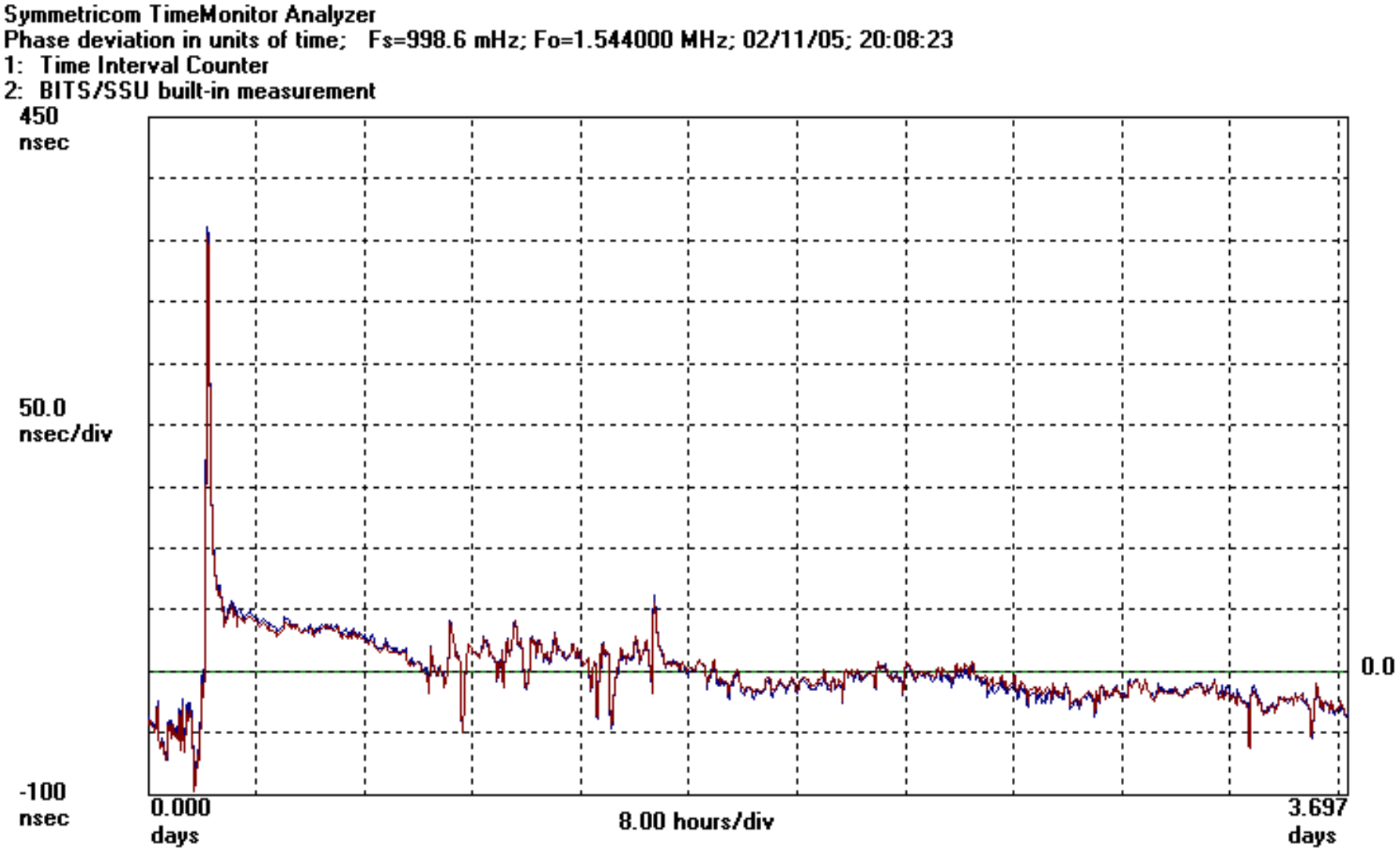
Simultaneous Measurements on GPS Receiver Output



Equipment Comparison: BITS/SSU vs. Counter

Symmetricom

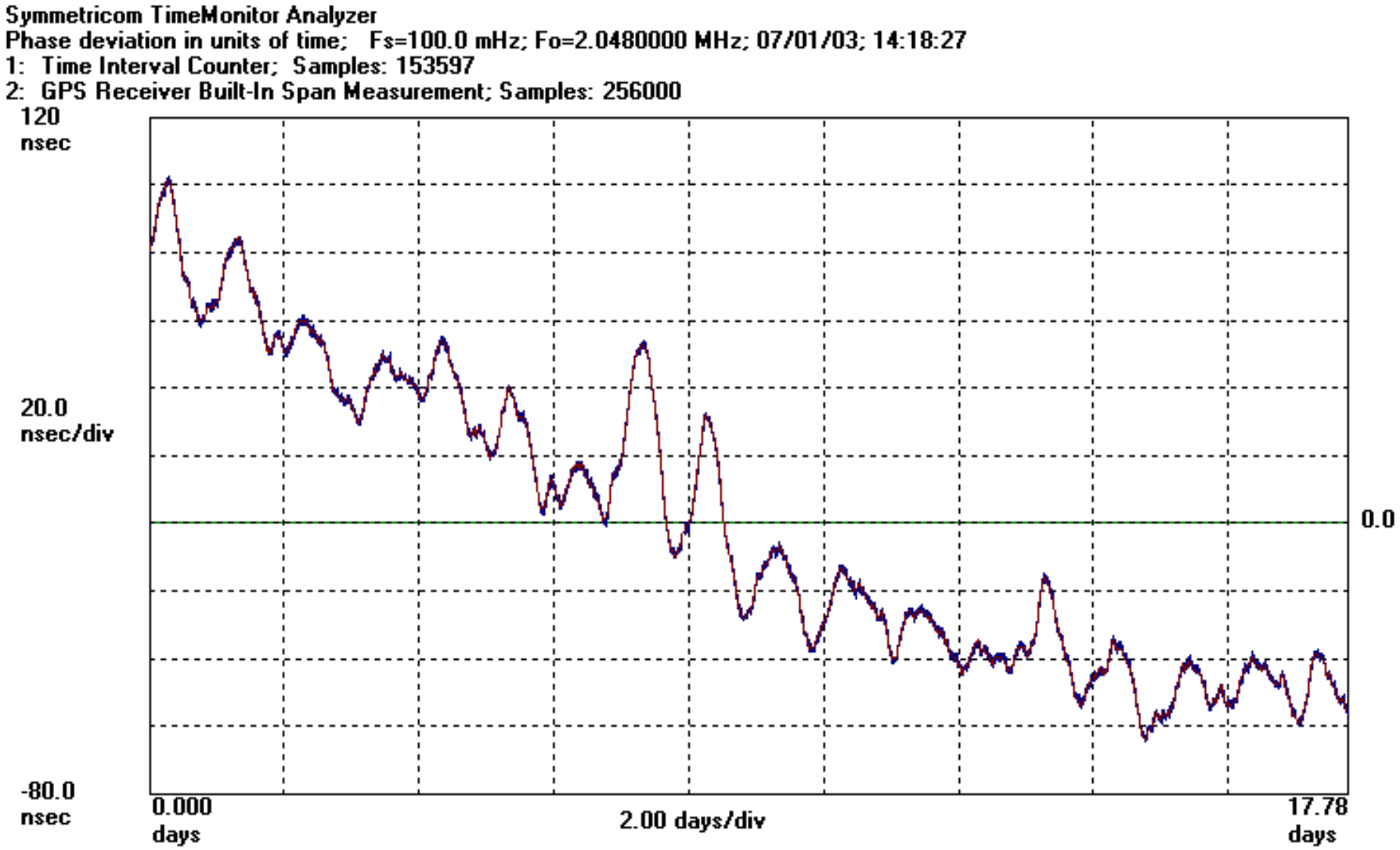
Simultaneous 3.7 Day Measurements on DS1



Equipment Comparison:
GPS Built-in Measurement vs. Counter

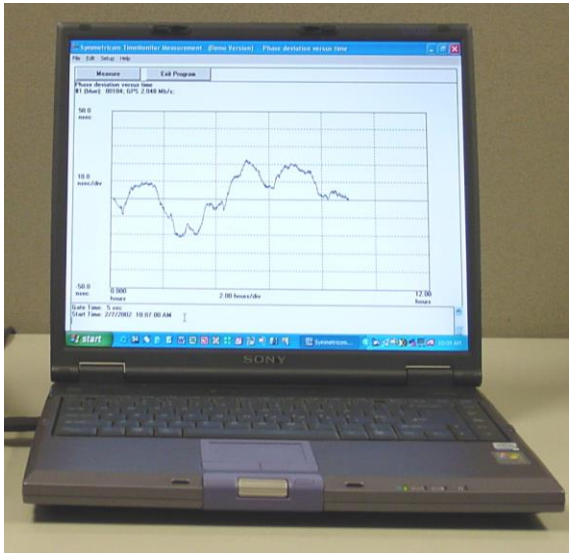
Symmetricom

Simultaneous 18 Day Measurements on Span Line



Measuring Jitter/Wander with a Counter

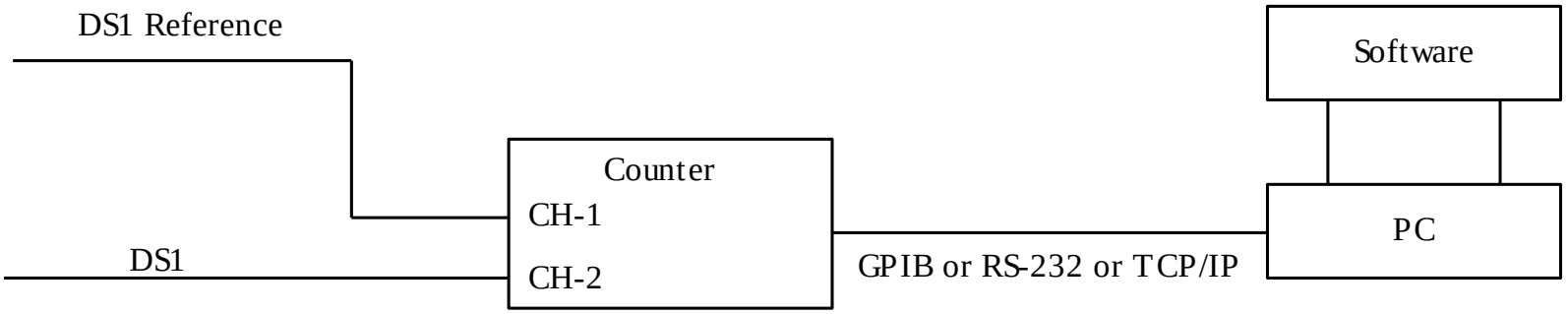
- Jitter & Wander Measurement Setup
  - Computer
  - Software
  - Offtheshelf counter (or counters)



Measuring Jitter/Wander with a Counter

Symmetricom

Counter Jitter/Wander Measurement Basic Block Diagram



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

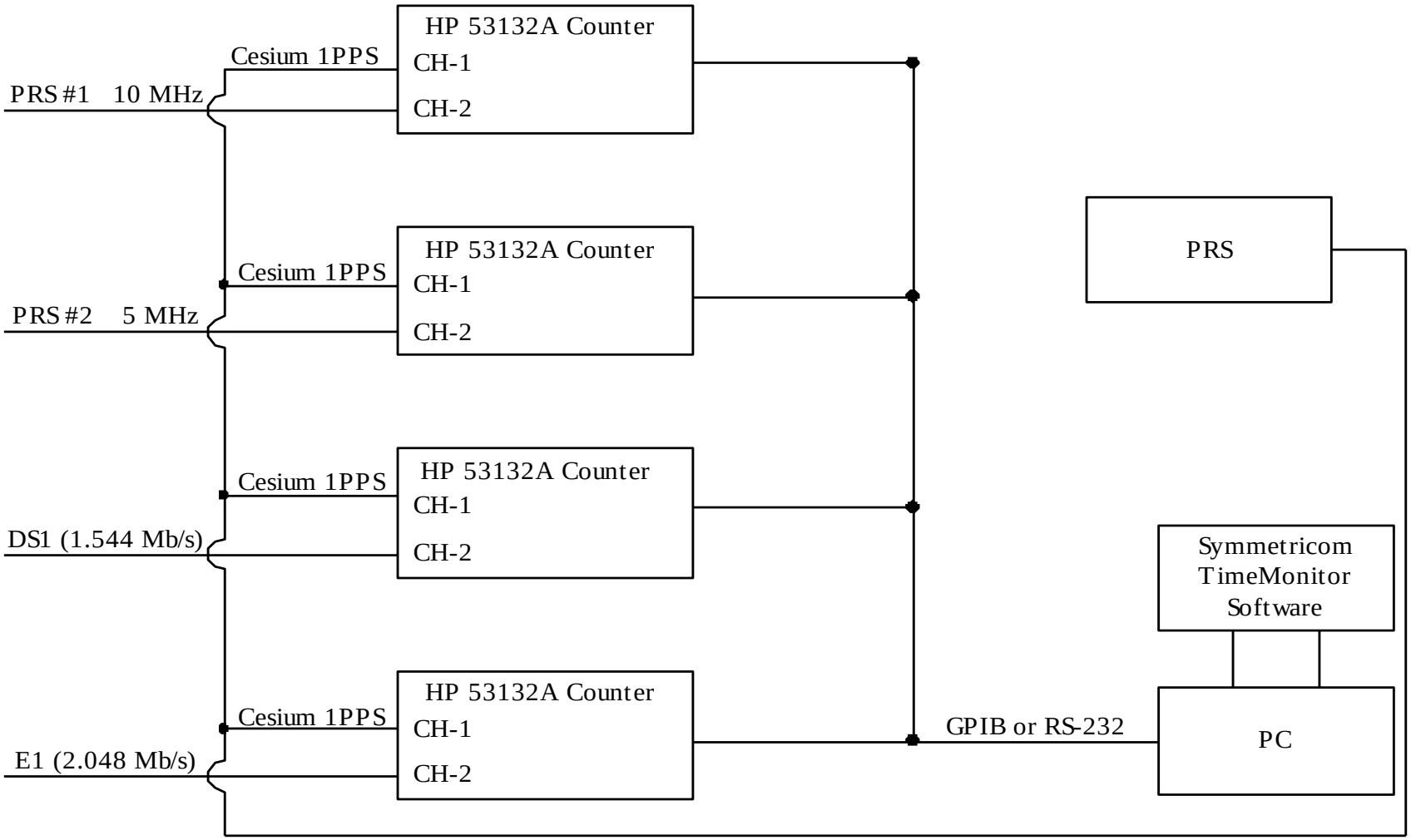
Symmetricom

- 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 DS1s directly.

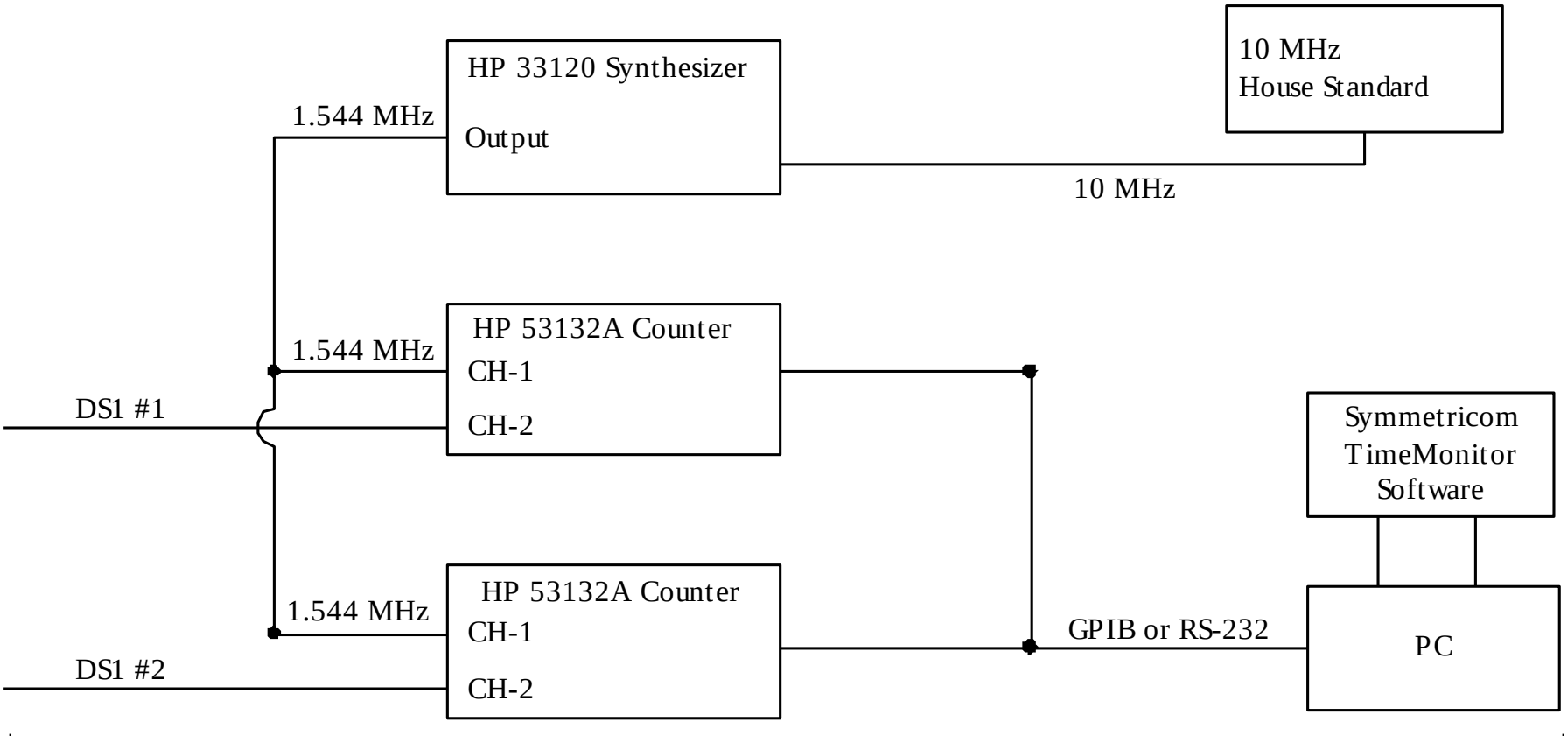
Phase Digitizing with Counter

- 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)
- Clock or data signal (software does data clock recovery): measure DS1, E1, DS3 signals directly

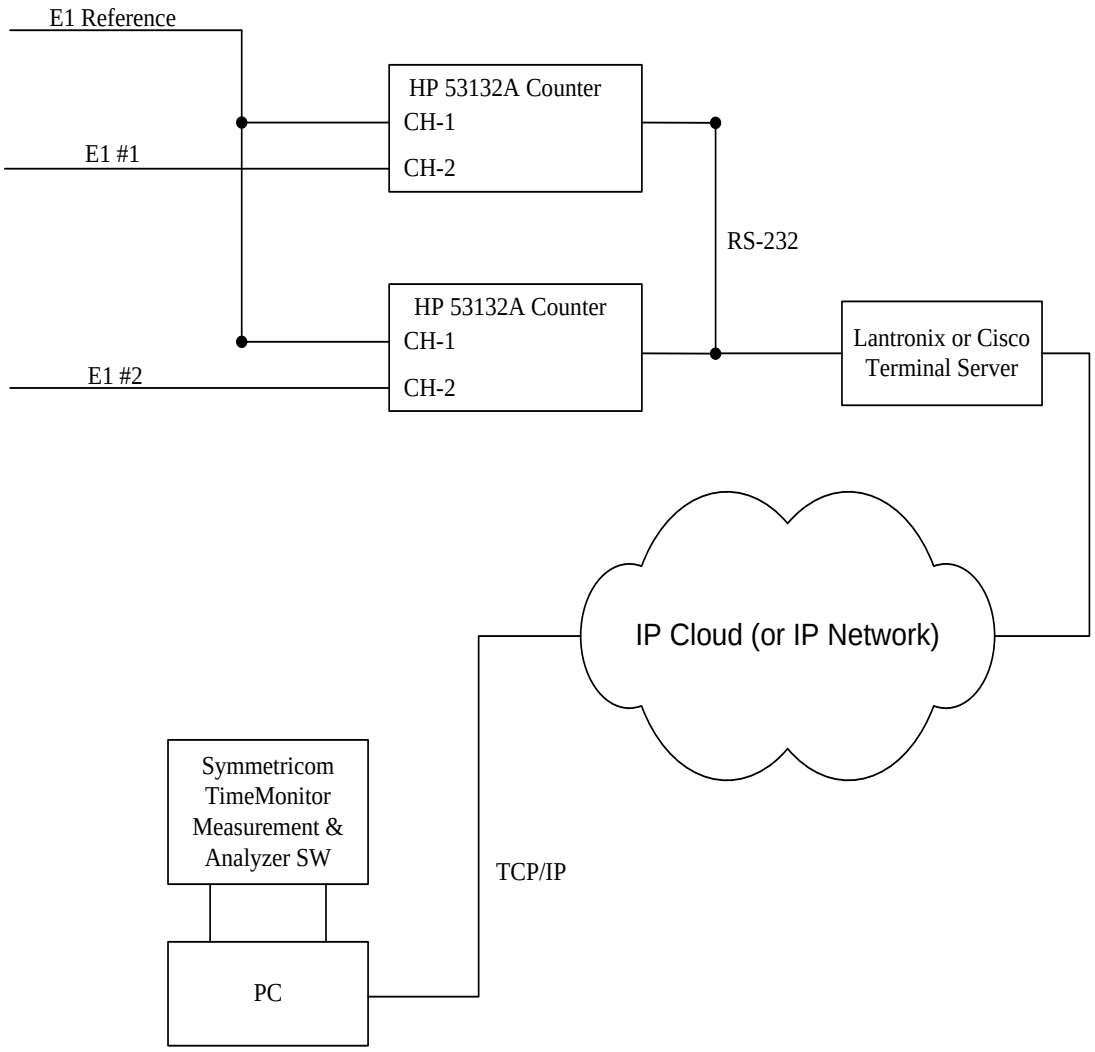
Counter Measurement Block Diagram #1



Counter Measurement Block Diagram #2



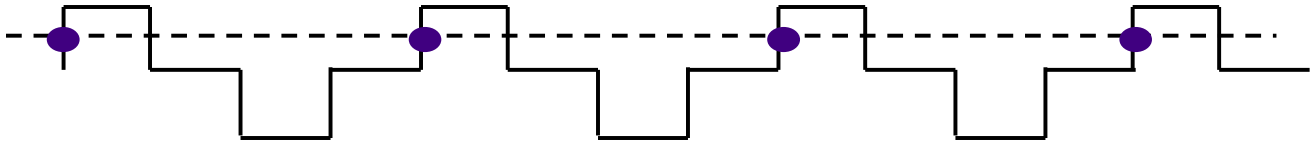
Counter Measurement Block Diagram #3



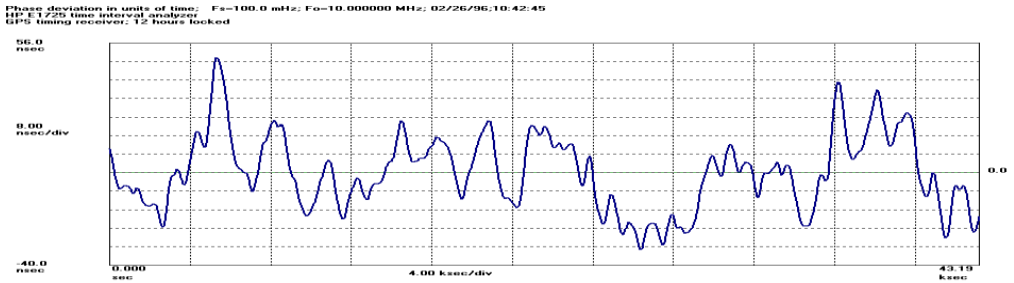
Sync Measurements w/ Phase Digitizing: 3 Step Process

Symmetricom

1. Timestamps

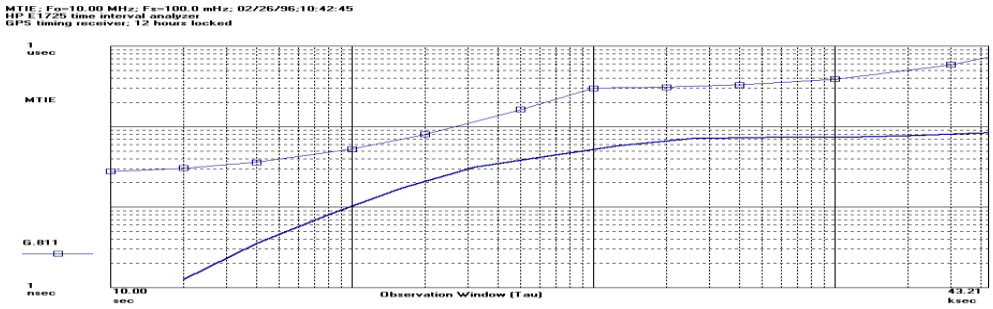


2. Phase



Phase Deviation or TIE

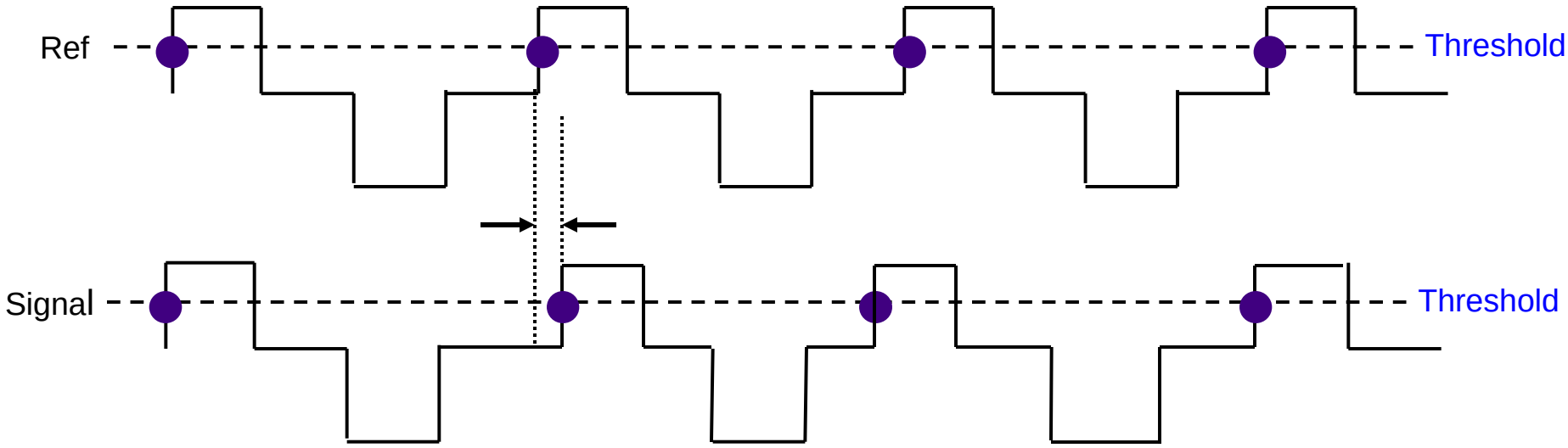
3. Analysis



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

Phase Digitizing with a Time Interval Counter

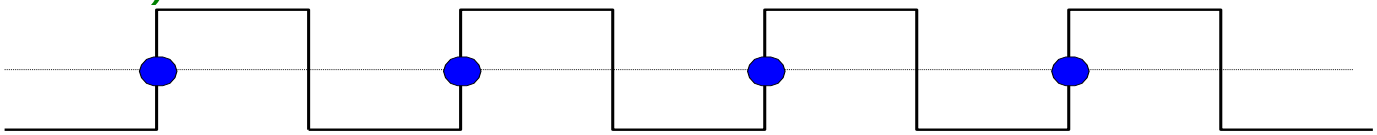
A time interval counter is used to time threshold crossings of a signal very precisely. This process is unaffected by amplitude modulation.



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

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

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

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

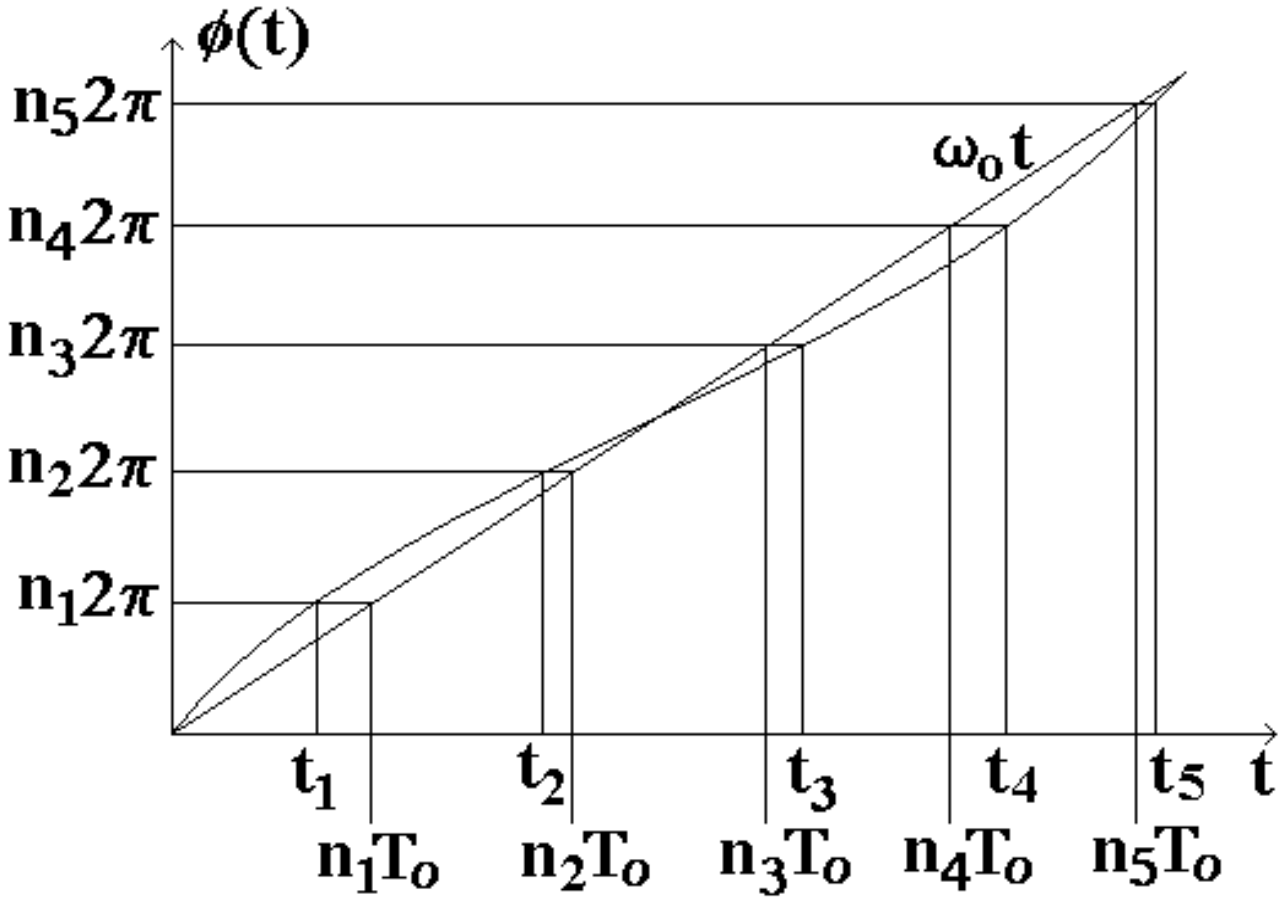
Phase deviation or TIE

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

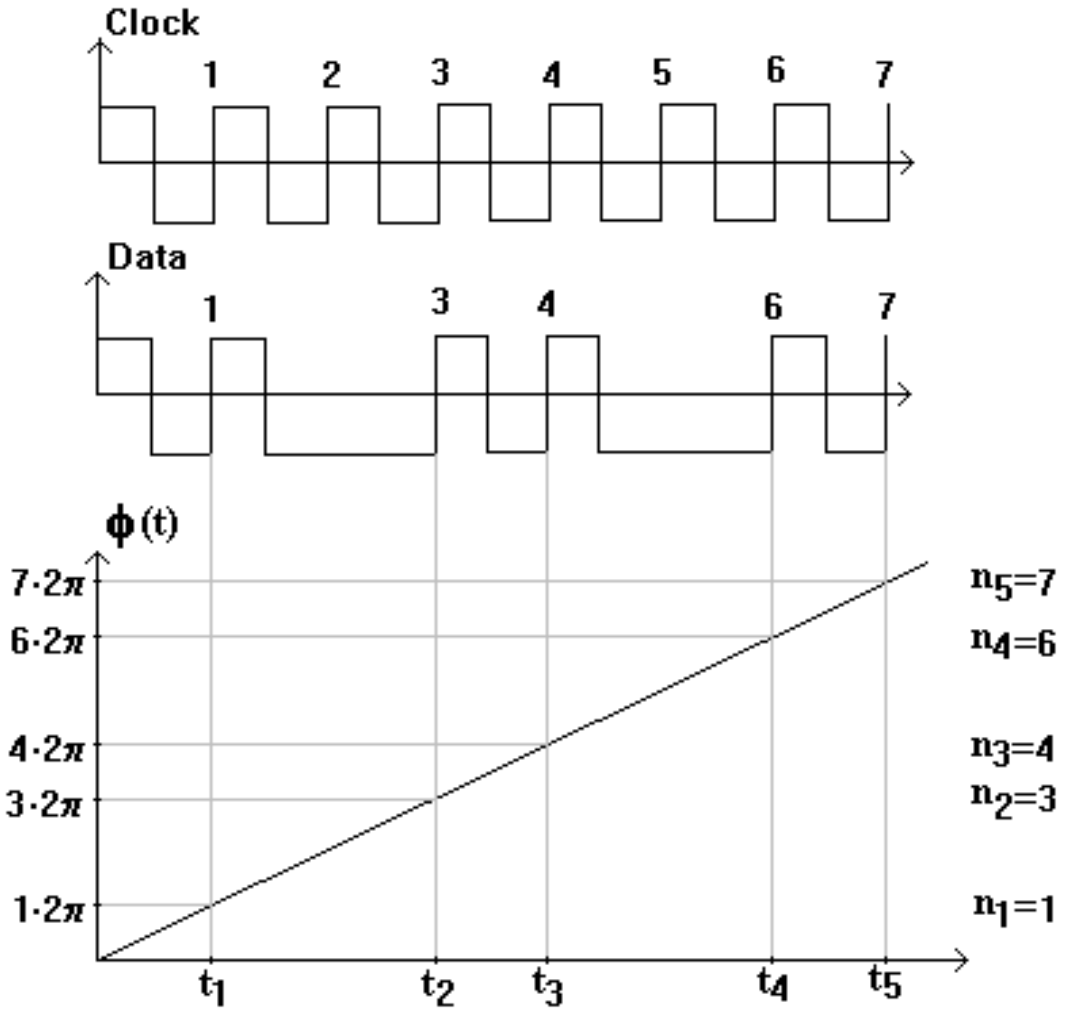
Reference frequency

Phase vs. Time

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



Data Signal Phase vs. Time



Measurement & Analysis: Outline

Symmetricom

1. Measurement of Phase
2. Analysis ←
3. Measurement Examples

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

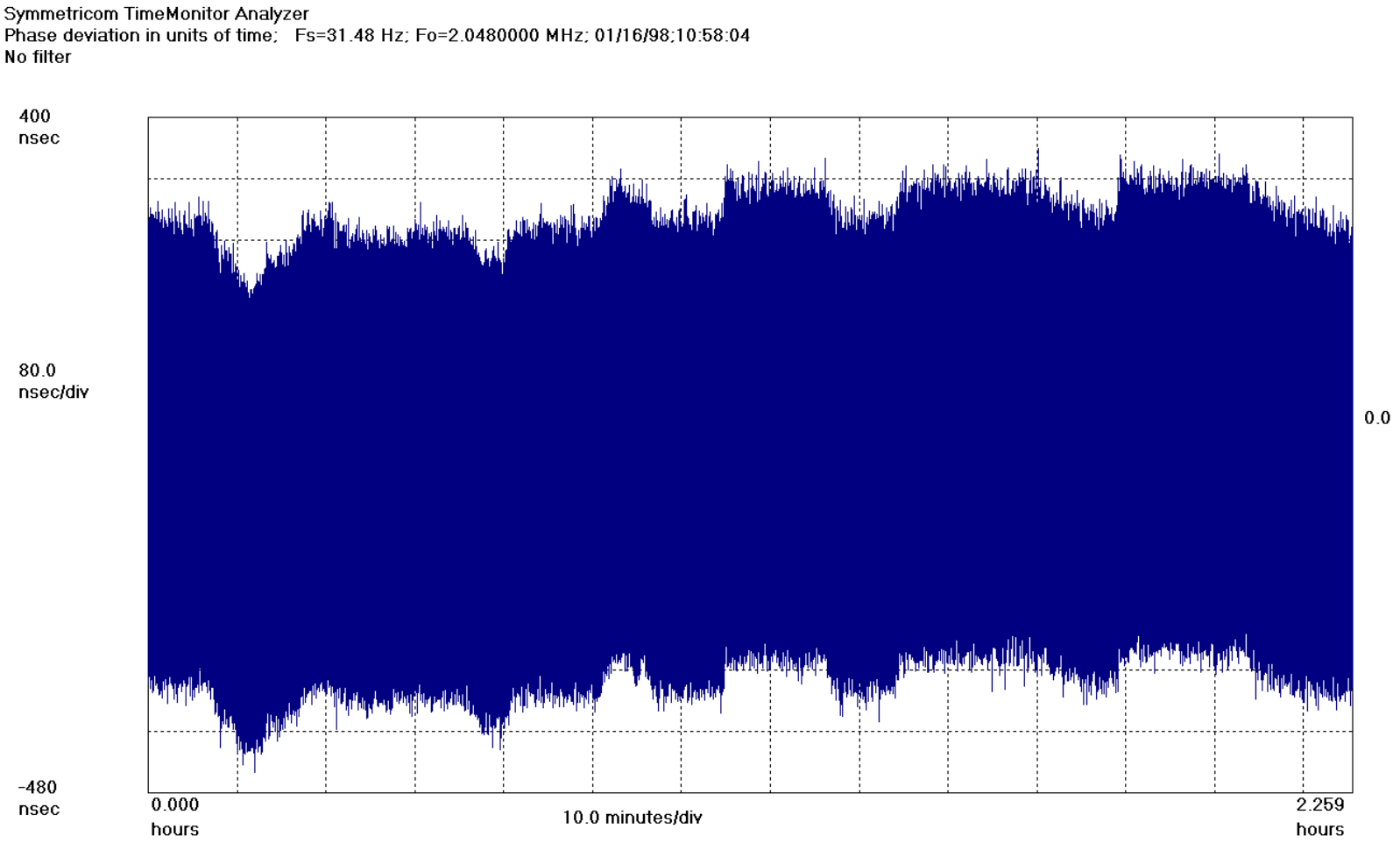
The Importance of Phase (TIE)

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?

- Sync Audit reports: 80% - 90% of the plots are phase plots

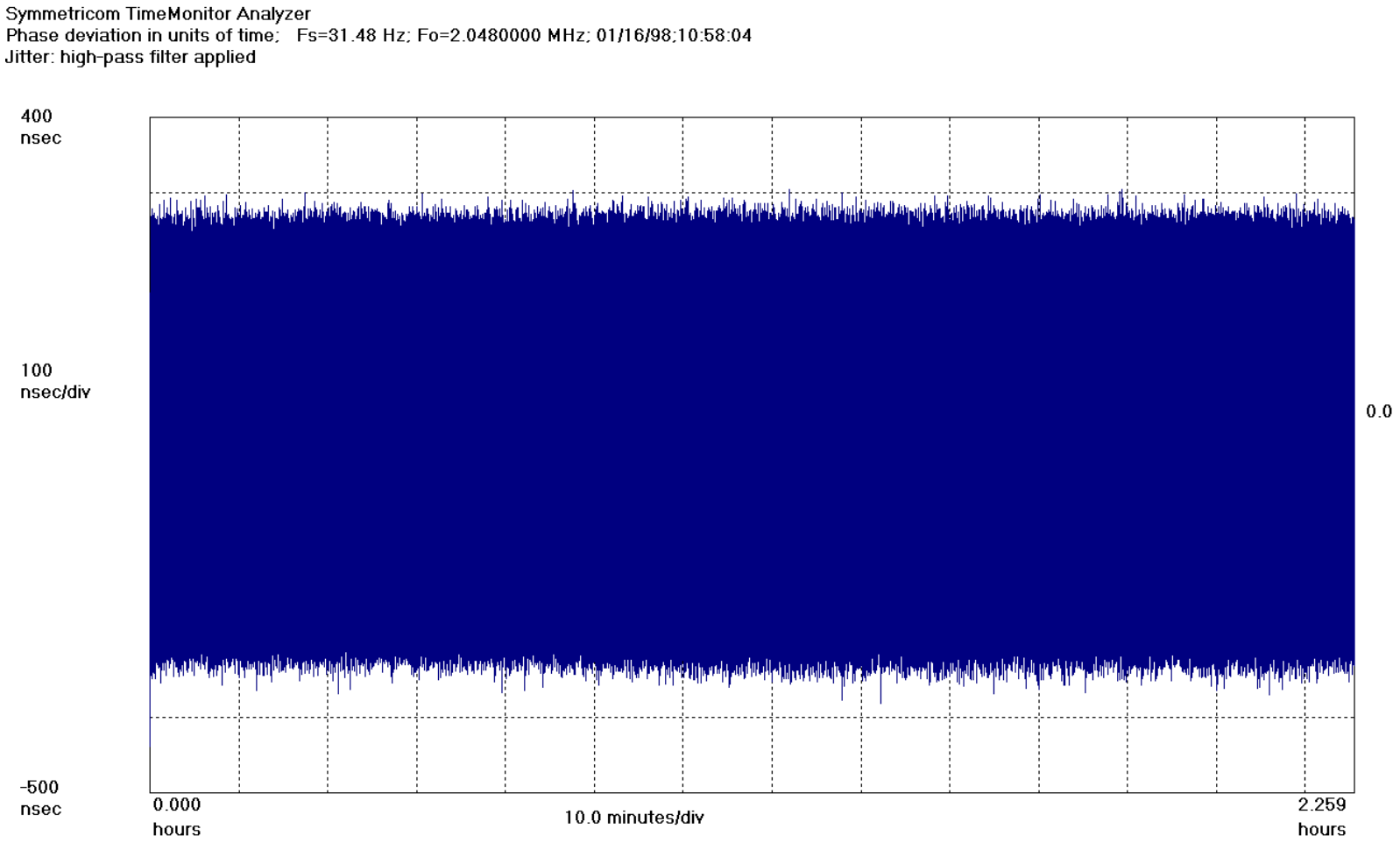
Analysis from Phase: Jitter & Wander

Signal with jitter and wander present



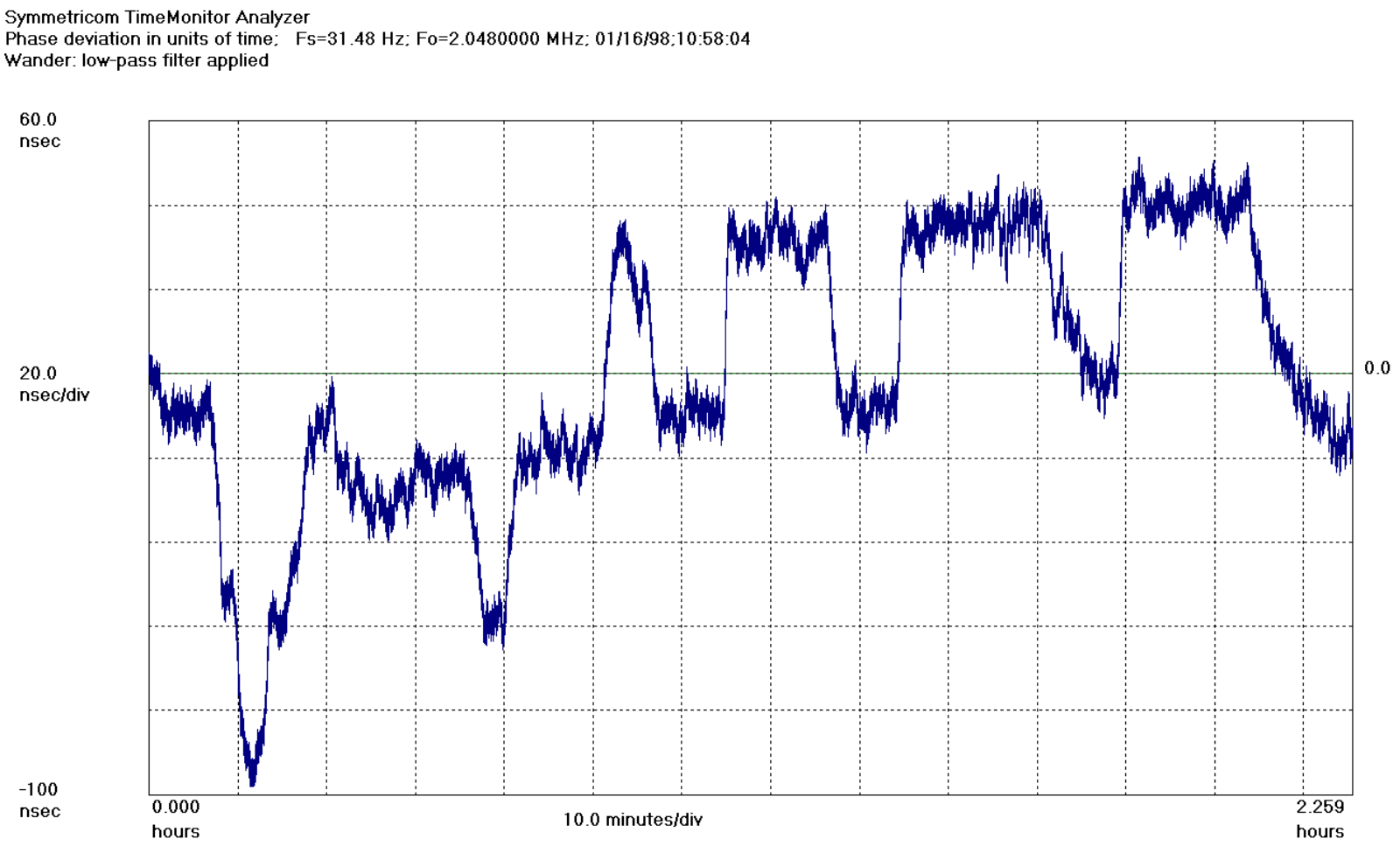
Analysis from Phase: Jitter

Jitter: Filter out low-frequency components with high-pass filter
Jitter = 740 nsec peak-to-peak = 1.52 UI peak-to-peak (E1)



Analysis from Phase: Wander

Wander: Filter out high-frequency components with low-pass filter

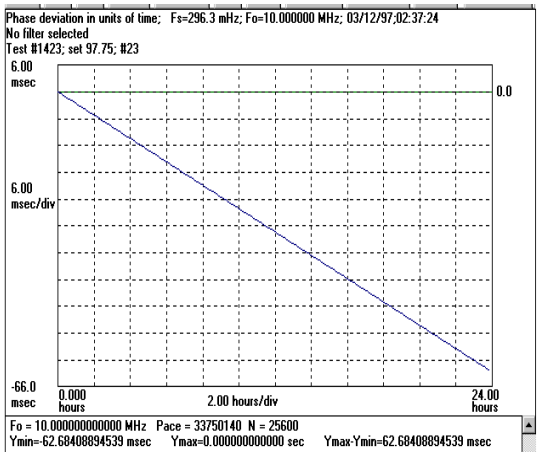


Analysis from Phase: Frequency

- Recall the relationship between frequency and phase:

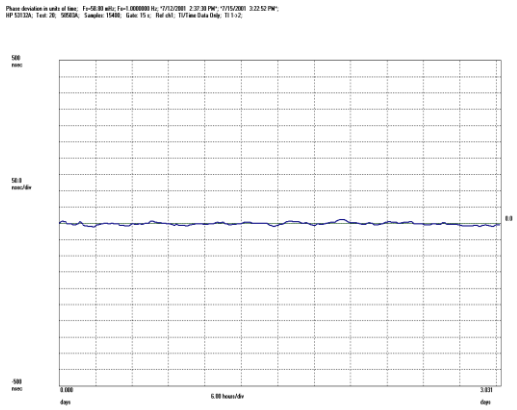
$$\omega = \frac{d\phi}{dt}$$

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



Frequency offset present

No offset: ideal phase plot (flat)



Analysis from Phase: Frequency

Timestamps(μs):	0	1.001	1.997	3.005	4.002	4.999	6.003
ϕ dev (ns):	0	-1	+3	-5	-2	+1	+3

Phase deviation slope

$$\Delta\phi dev = \Delta N \cdot T_o - \Delta t = (\Delta N - f_o \Delta t)/ f_o$$

$$fdev = f - f_o = \Delta N / \Delta t - f_o = (\Delta N - f_o \Delta t)/ \Delta t = \Delta\phi dev \cdot f_o / \Delta t$$

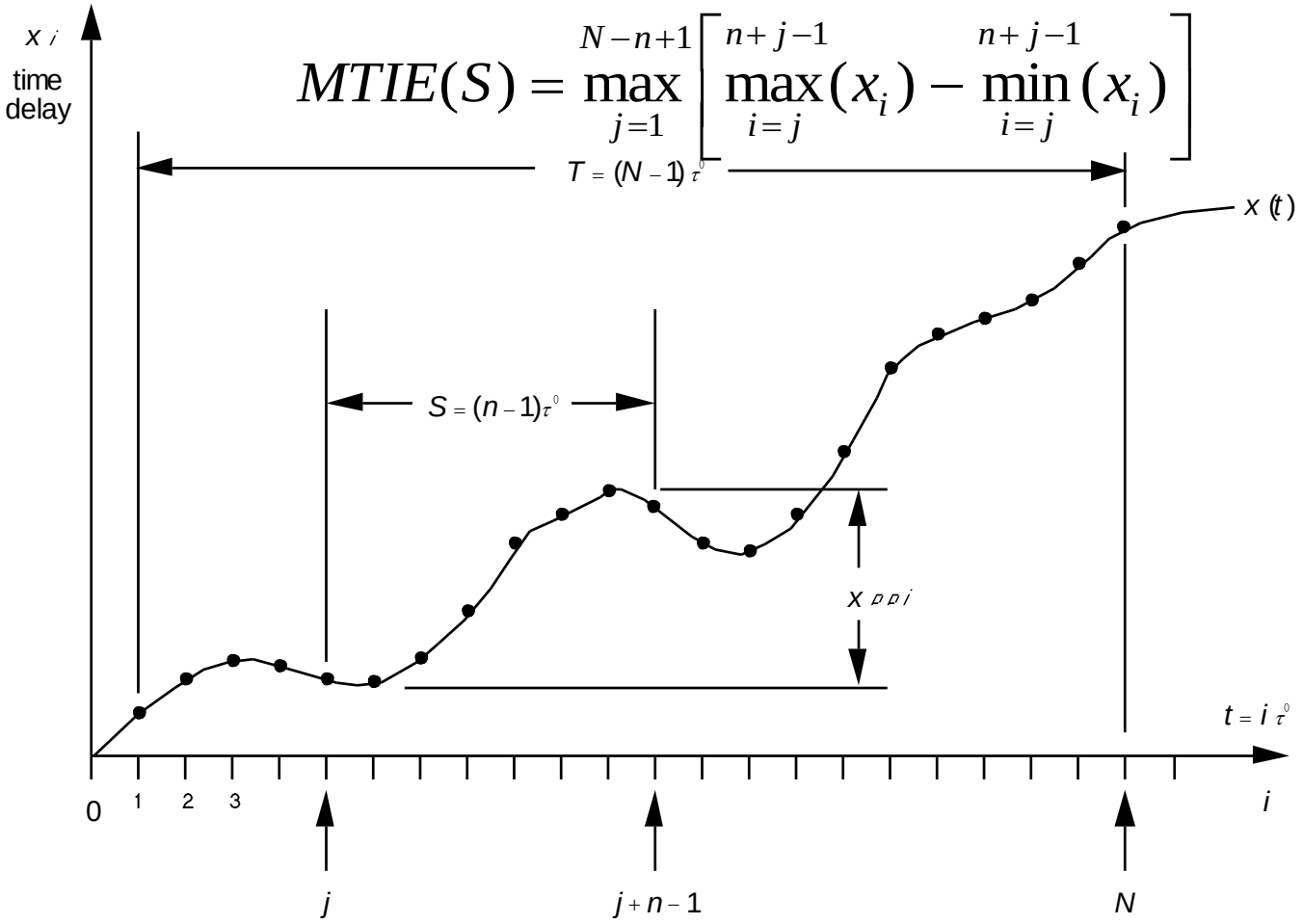
$$ffoff = fdev/f_o$$

For example, take the average fdev over the first 3 cycles:

Frequency Deviation = - 5nsec · 10^6Hz/3.005μsec = -1.7 kHz

Fractional Frequency Offset = -1.7 kHz/1MHz = -1.7 parts per thousand

Analysis from Phase: MTIE

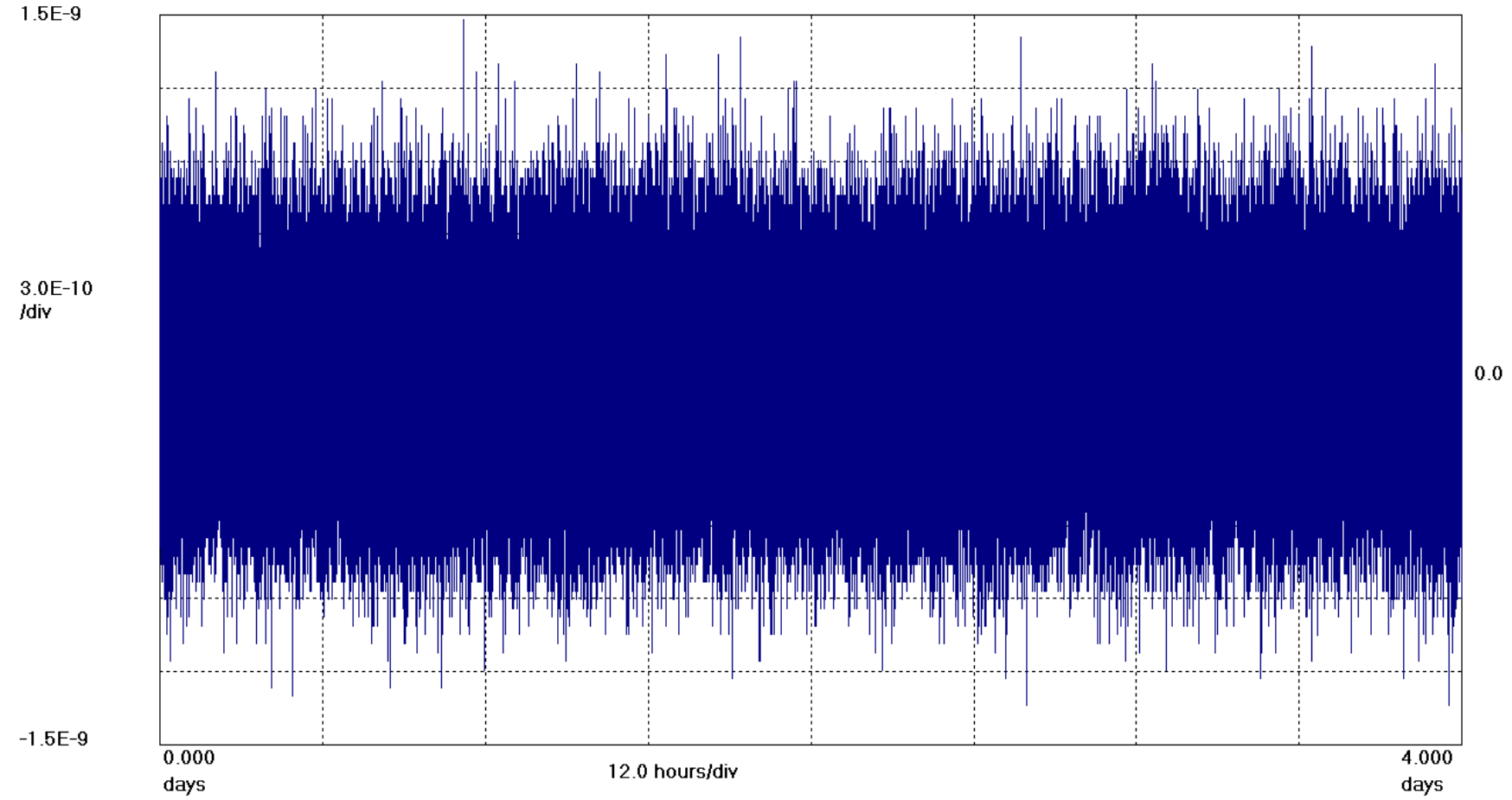


Measurement Analysis: Frequency

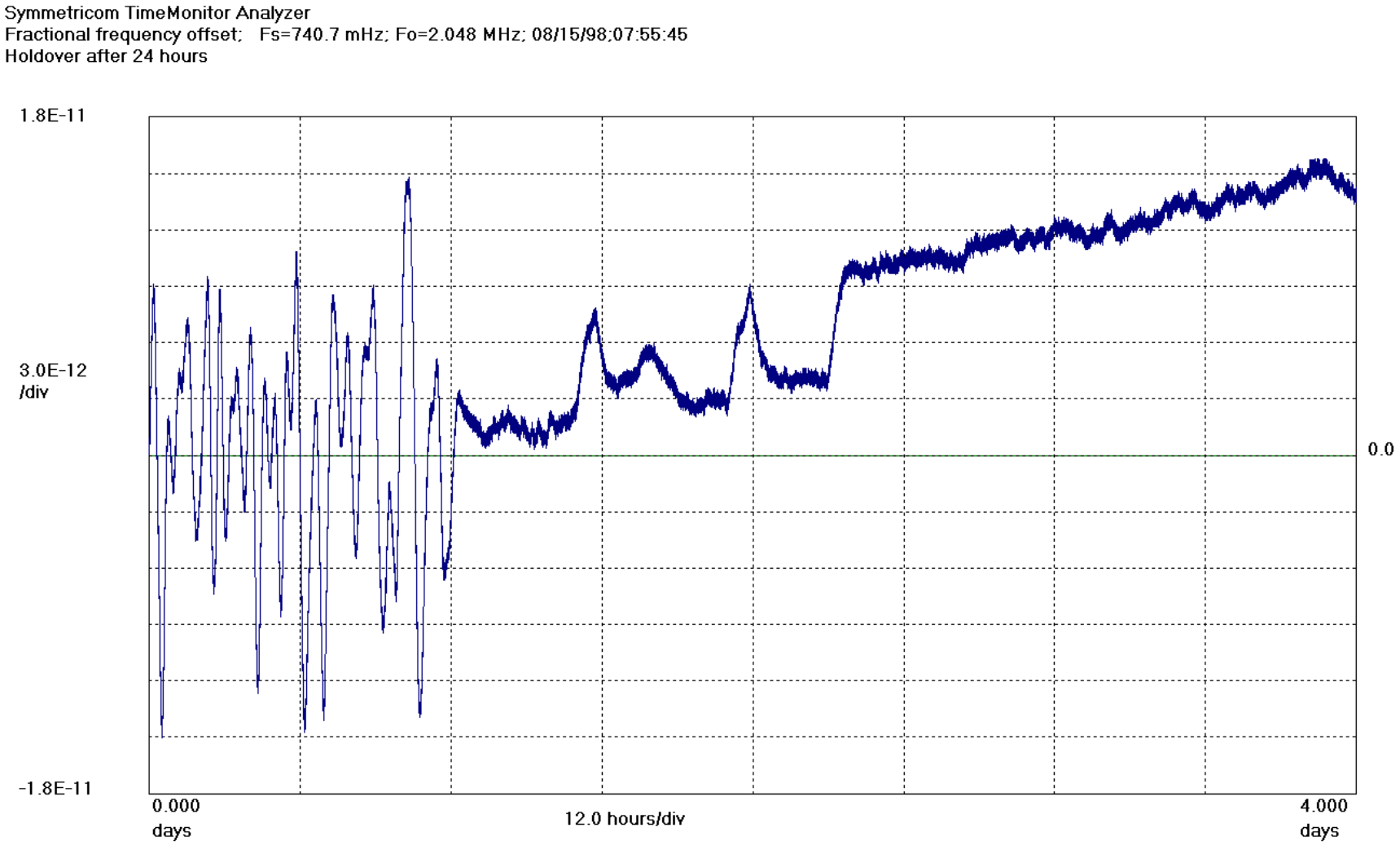
Symmetricom

- 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 (leastsquarefit)
  - Example: PRS 1 part in 10^{11} requirement
- To sum up: a tradeoff exists between precision of frequency result and pinpointing when it occurred

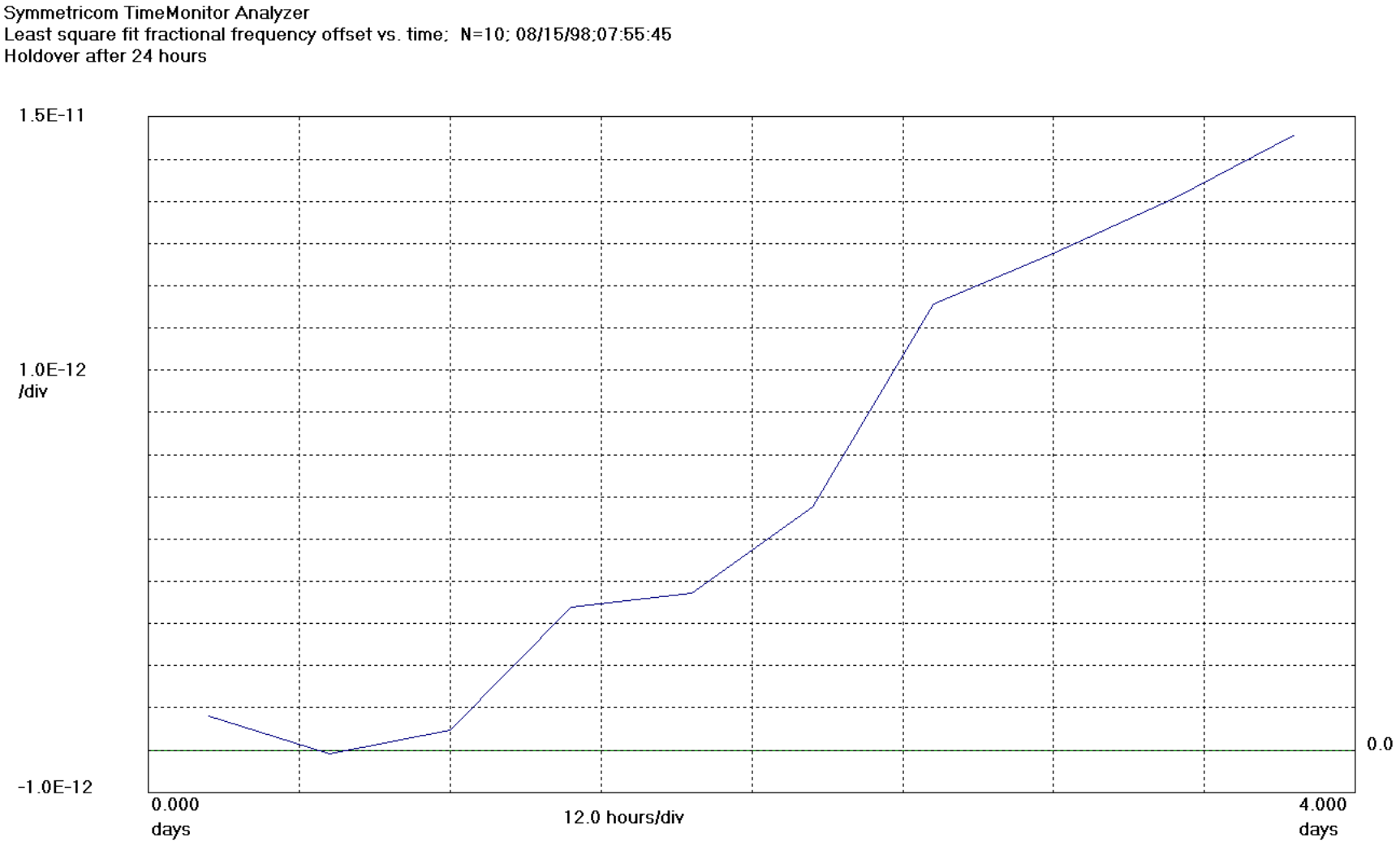
Frequency: Point-by-point



Frequency: w/ Low Pass Filter



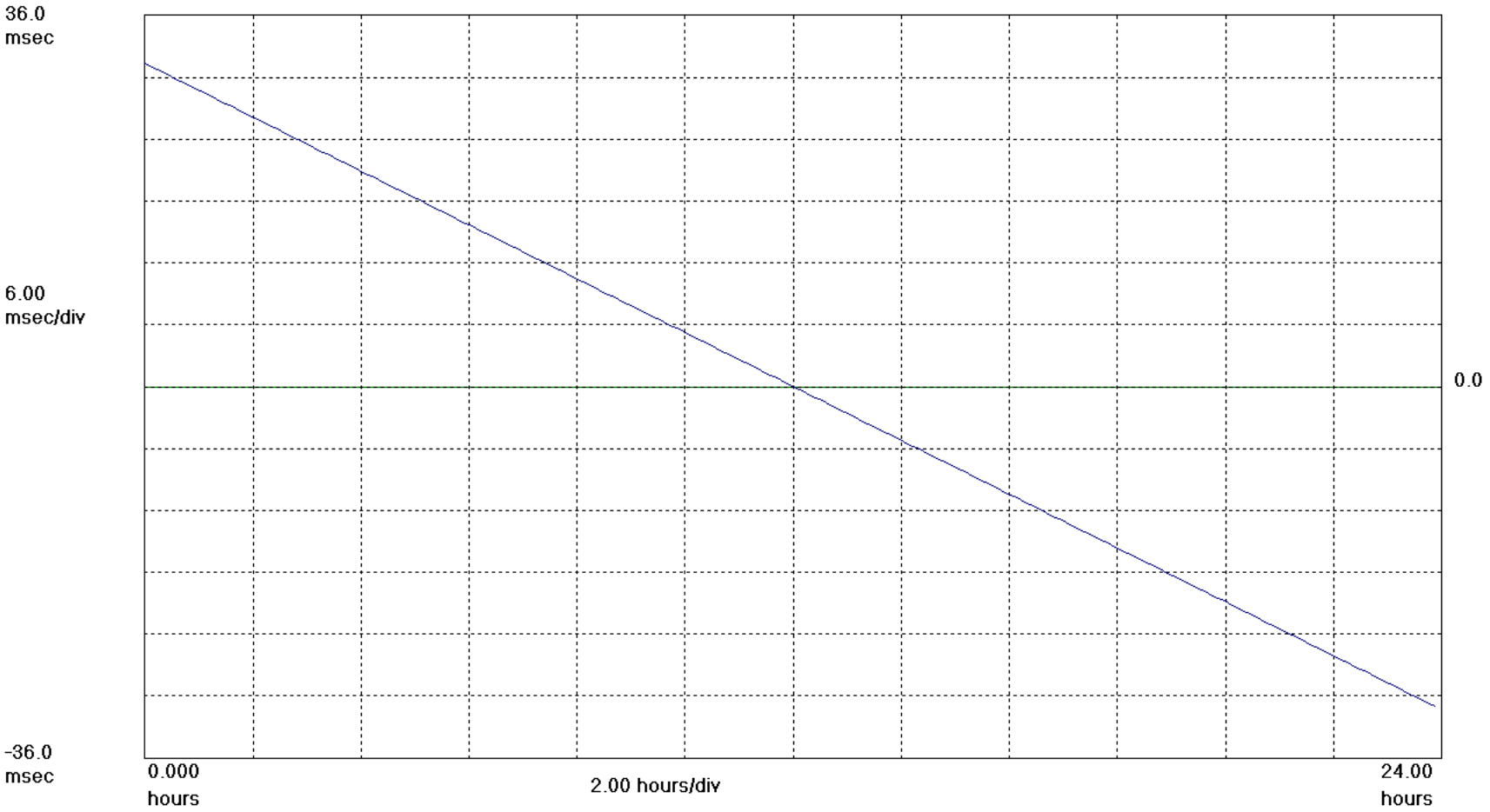
Frequency: Segmented LSF



Frequency: Offset Present

0.7 ppm on double oven quartz oscillator

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=296.3 mHz; Fo=10.000000 MHz; 03/12/97;02:37:24
Test #1423; set 97.75; #23; Fo offset = -7.255E-7; Fo reference = 10.000000000000 MHz

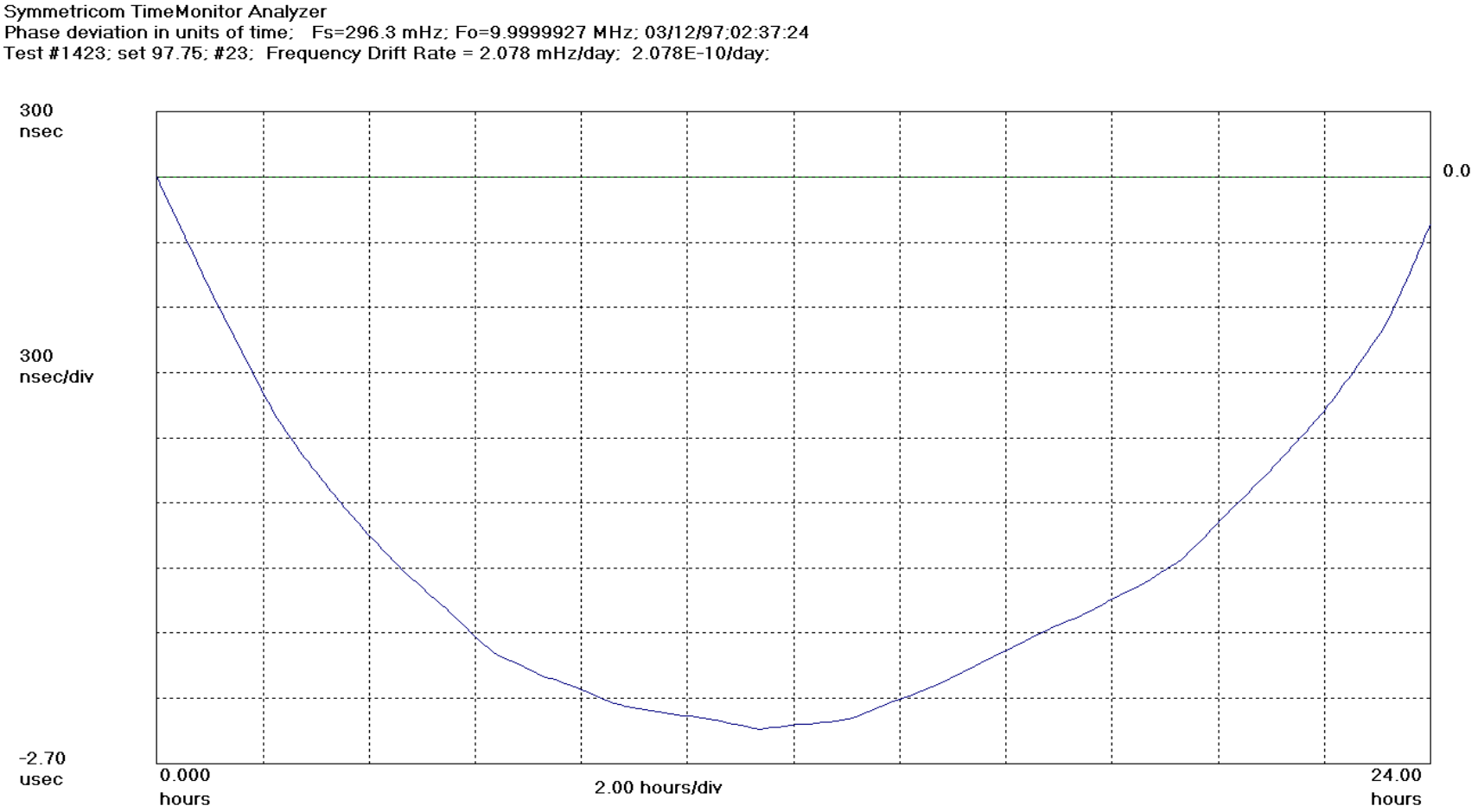


Frequency: Offset Removed

Frequency offset removed

Phase deviation quadratic shape shows presence of linear frequency drift

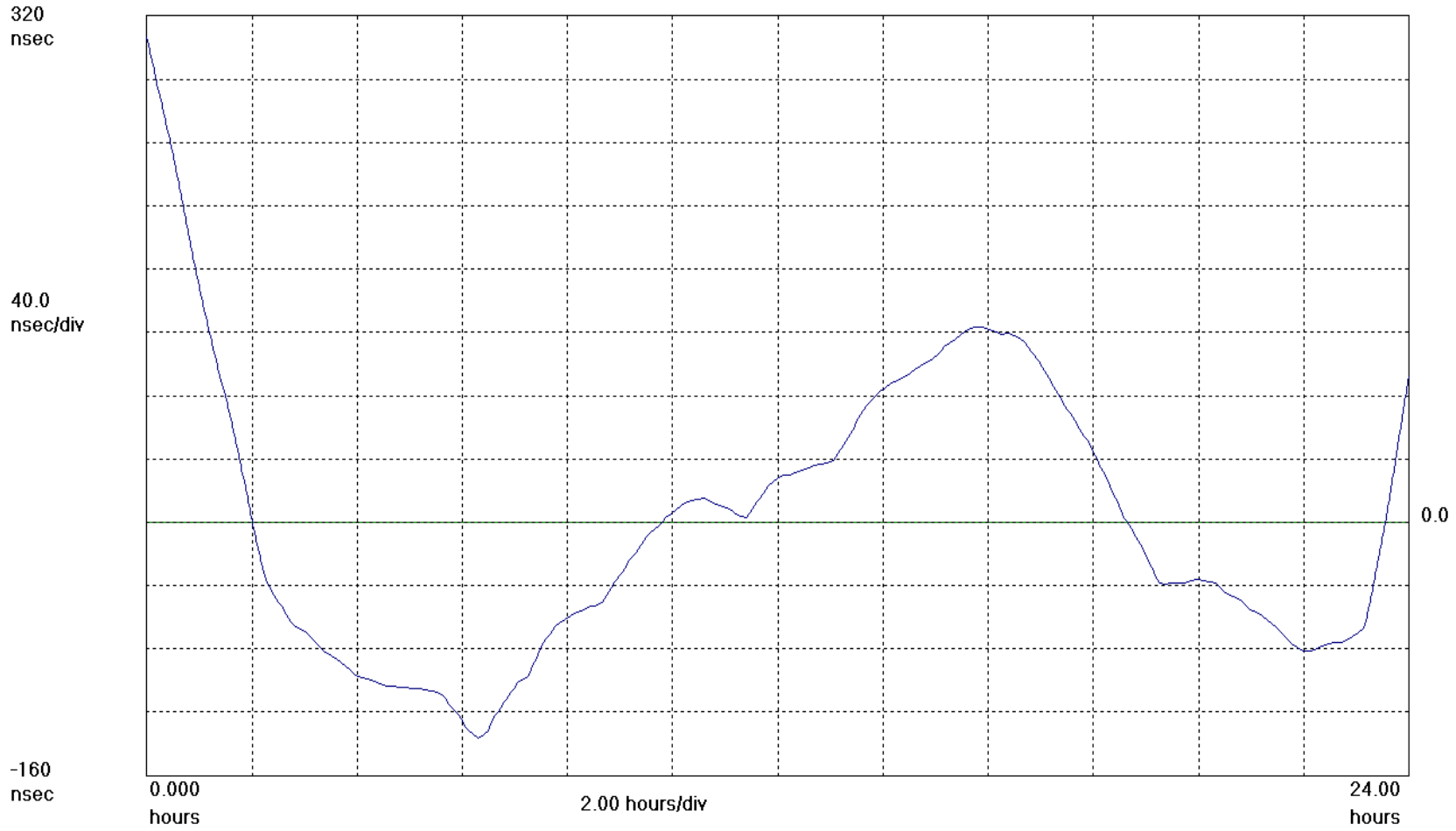
Frequency drift is 2 mHz per day or $2 \cdot 10^{-10}$ per day



Frequency: Drift Removed

Phase deviation fit to quadratic shows residual phase movement

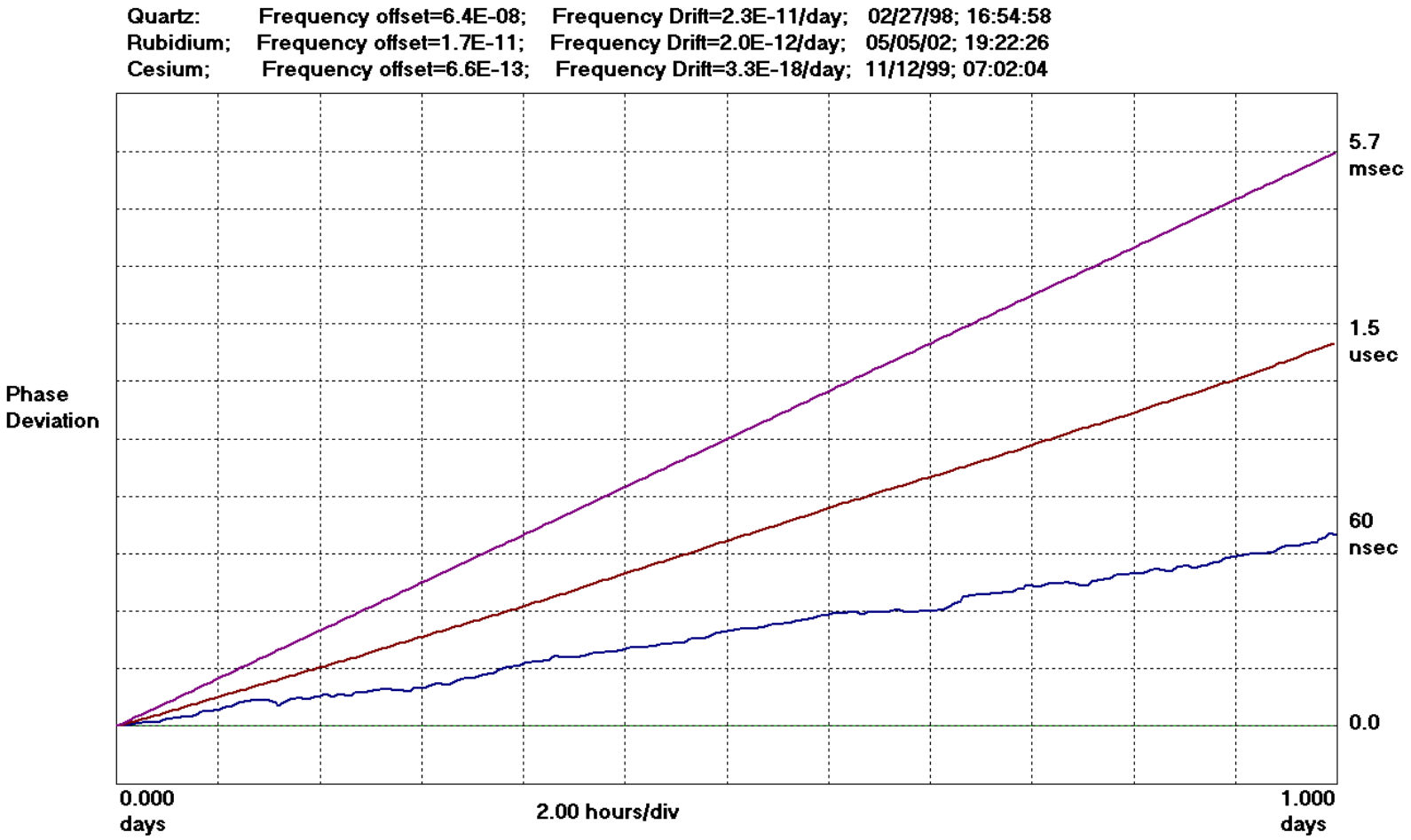
Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=296.3 mHz; Fo=9.9999927 MHz; 03/12/97;02:37:24
Test #1423; set 97.75; #23; Frequency Drift Rate = 2.078 mHz/day; 2.078E-10/day;



Frequency Accuracy and Stability

Symmetricom

Quartz, Rubidium, and Cesium



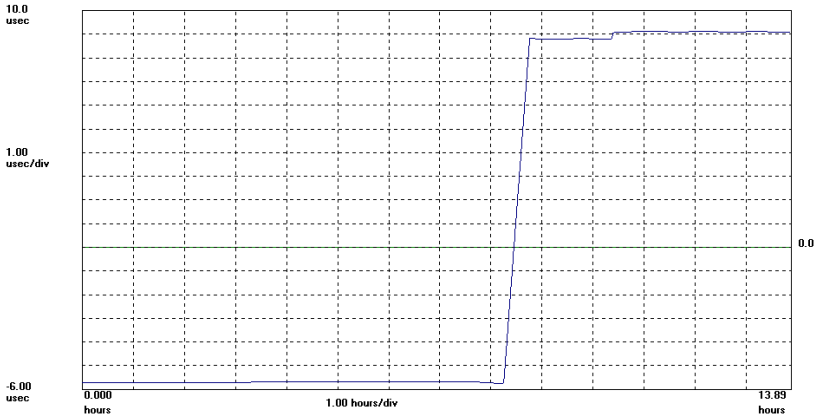
Synchronization Measurements

Symmetricom

- 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

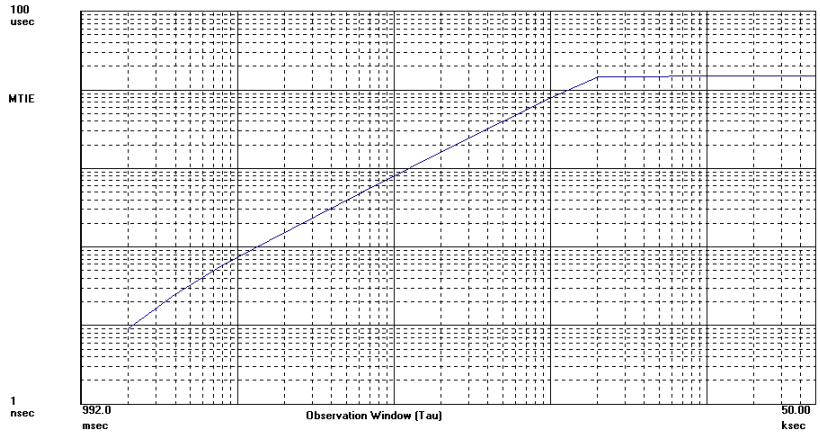
MTIE: shows a step in phase

Phase



Phase steps upwards 15 µsec about 8 hours into the measurement

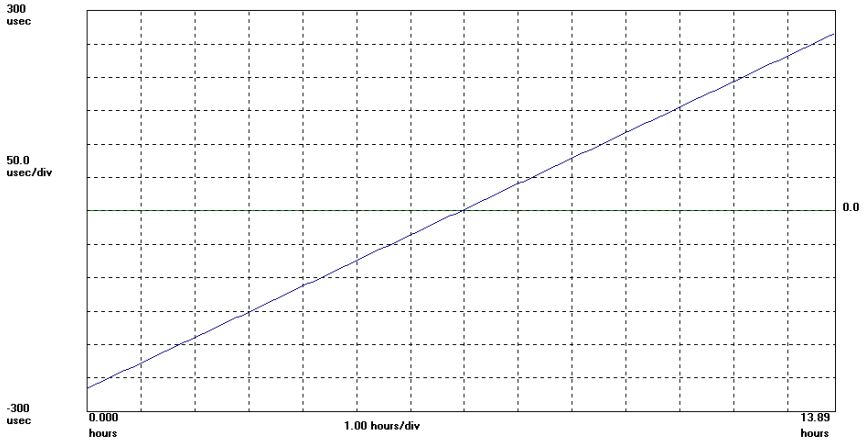
MTIE



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

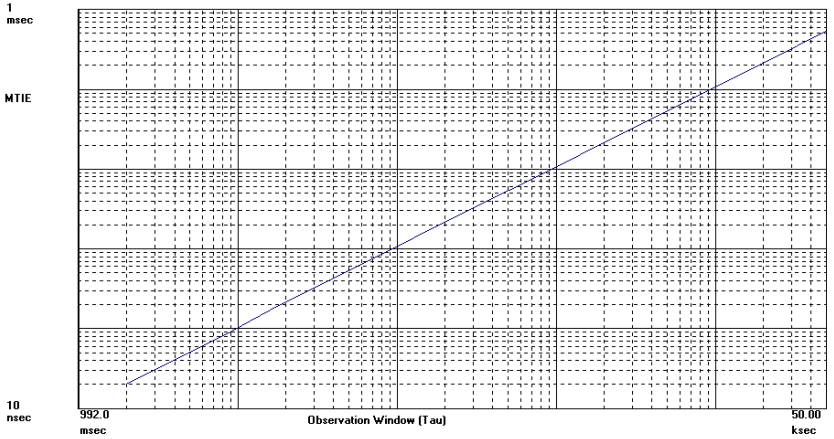
MTIE: shows a frequency offset

Phase



A frequency offset is seen as a constant slope in phase

MTIE

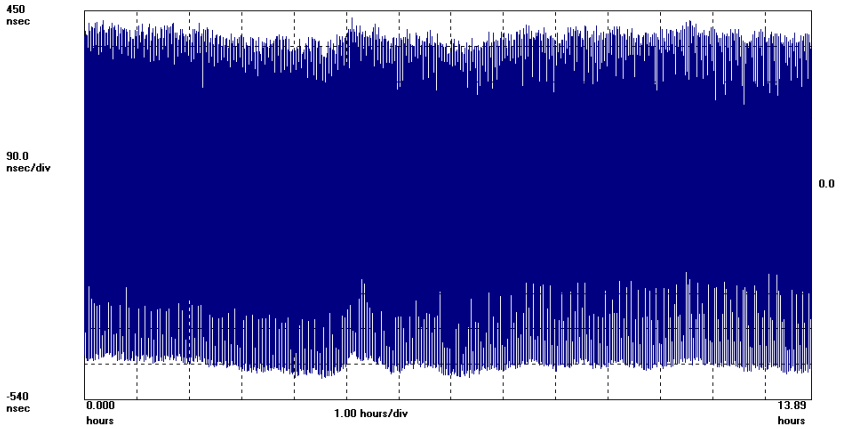


MTIE constantly increases with increasing observation time

TDEV: shows a phase modulation consistent throughout measurement

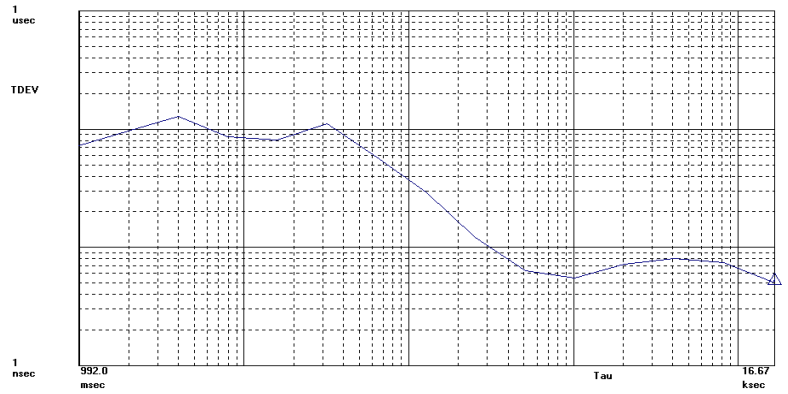
Symmetricom

Phase



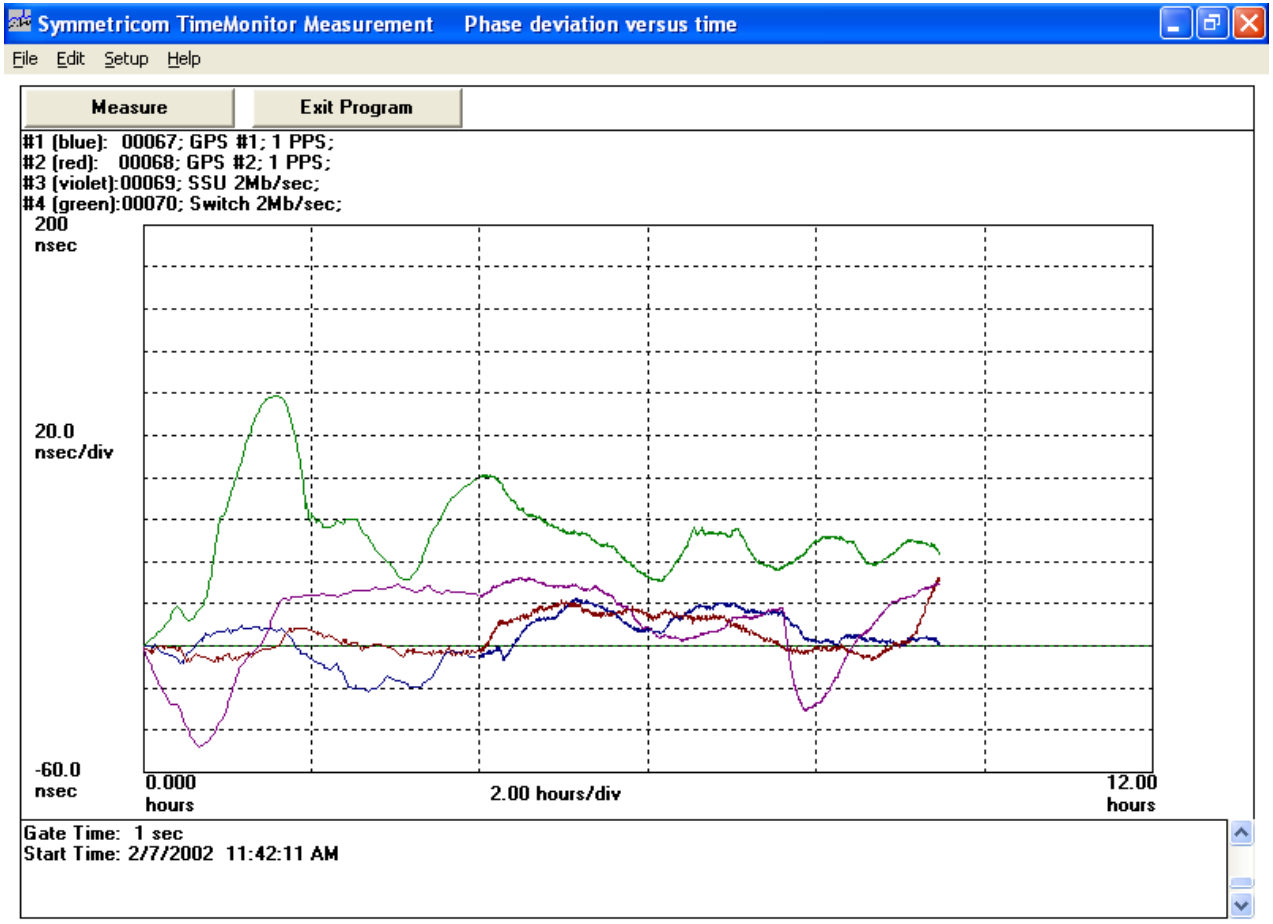
Phase shows large swings in the short term but is flat in the long term

TDEV



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

Measurement Demo



Measurement & Analysis: Outline

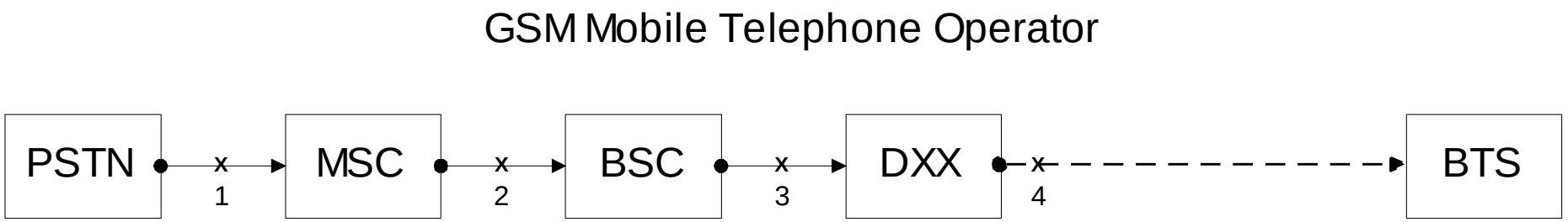
Symmetricom

1. Measurement of Phase
2. Analysis from Phase
3. Measurement Examples ←

Sync Measurement #1: Network Element Cascading

Symmetricom

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

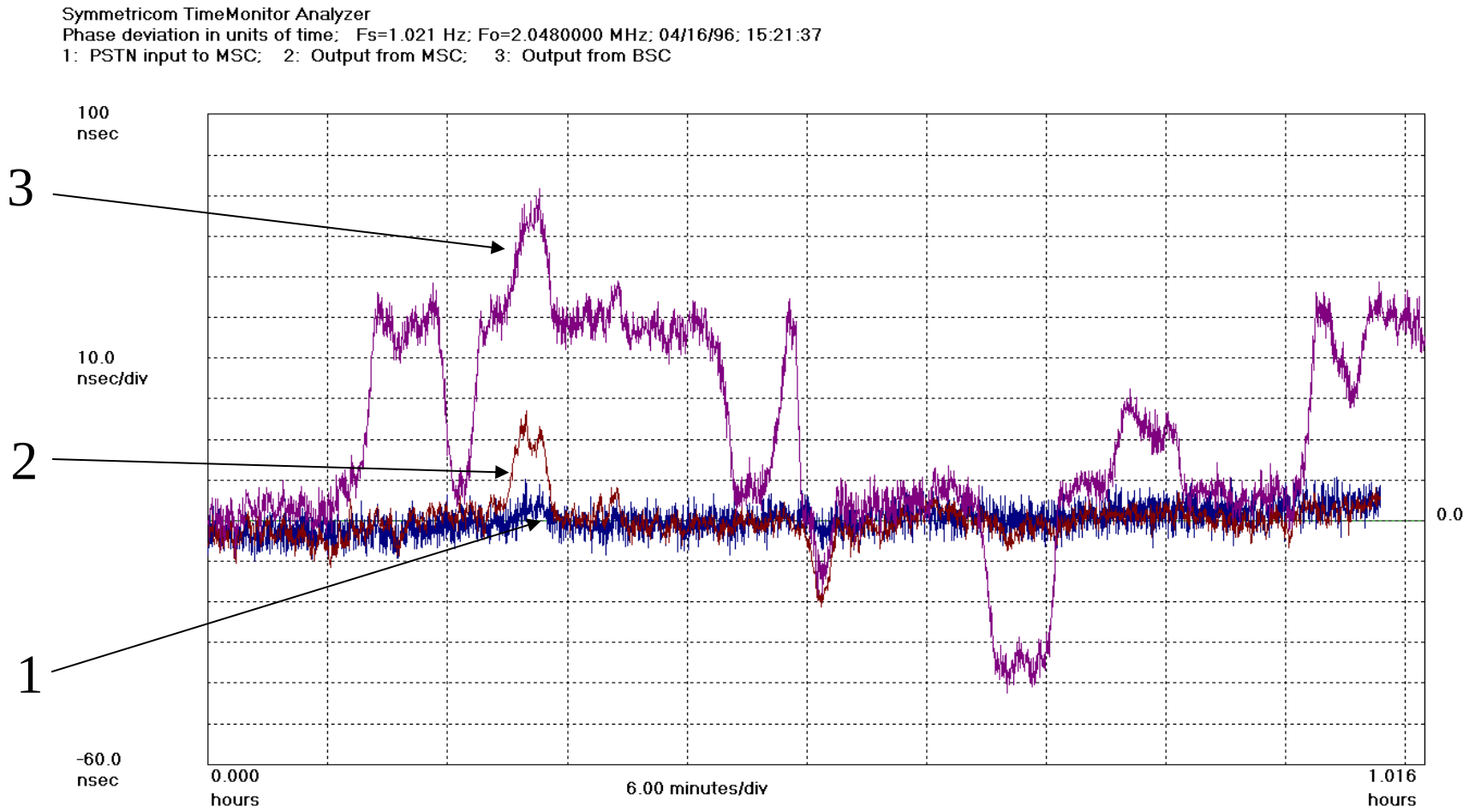


x: measurement points

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

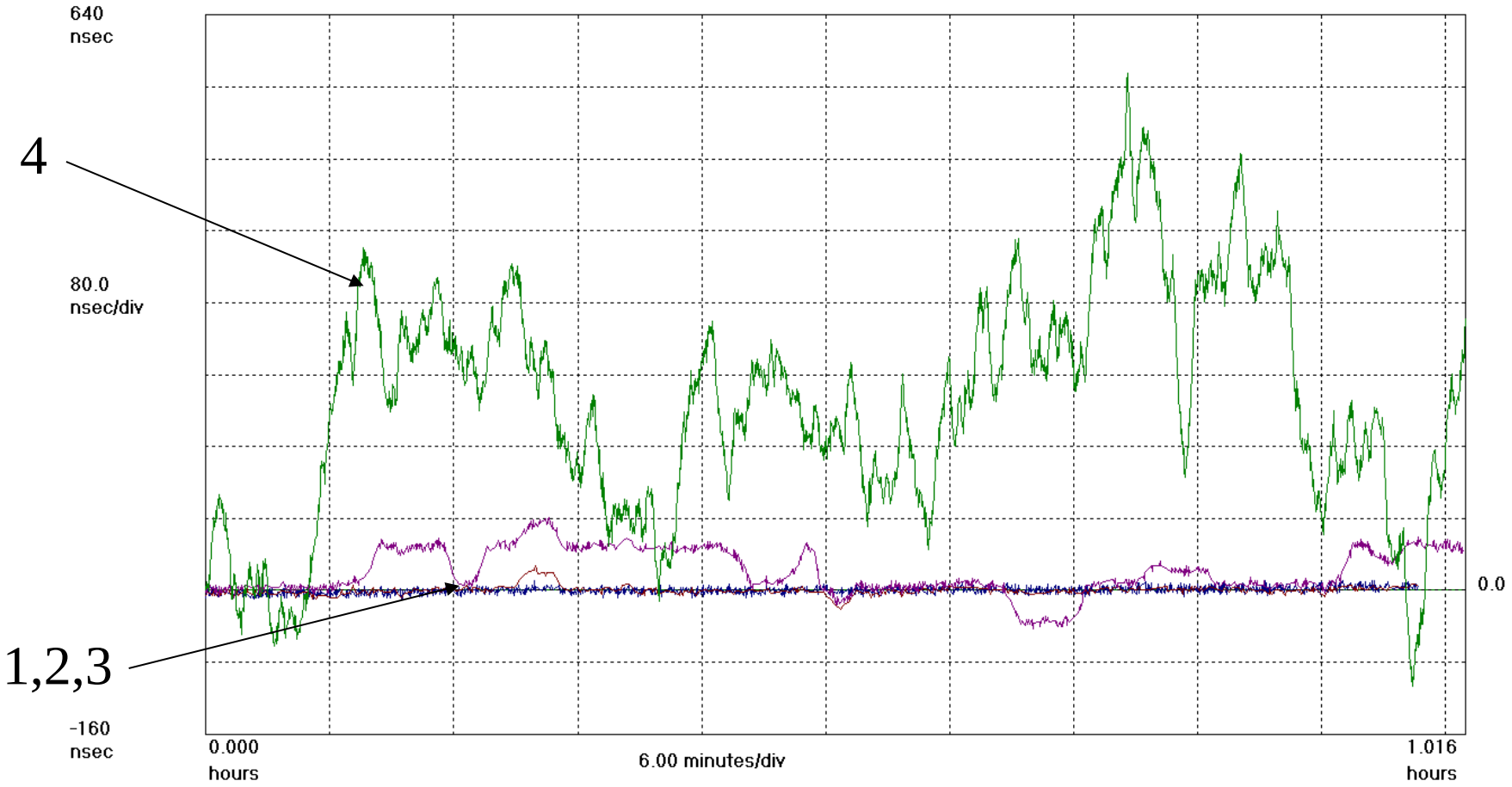


Sync Measurement #1: Network Element Cascading

Symmetricom

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

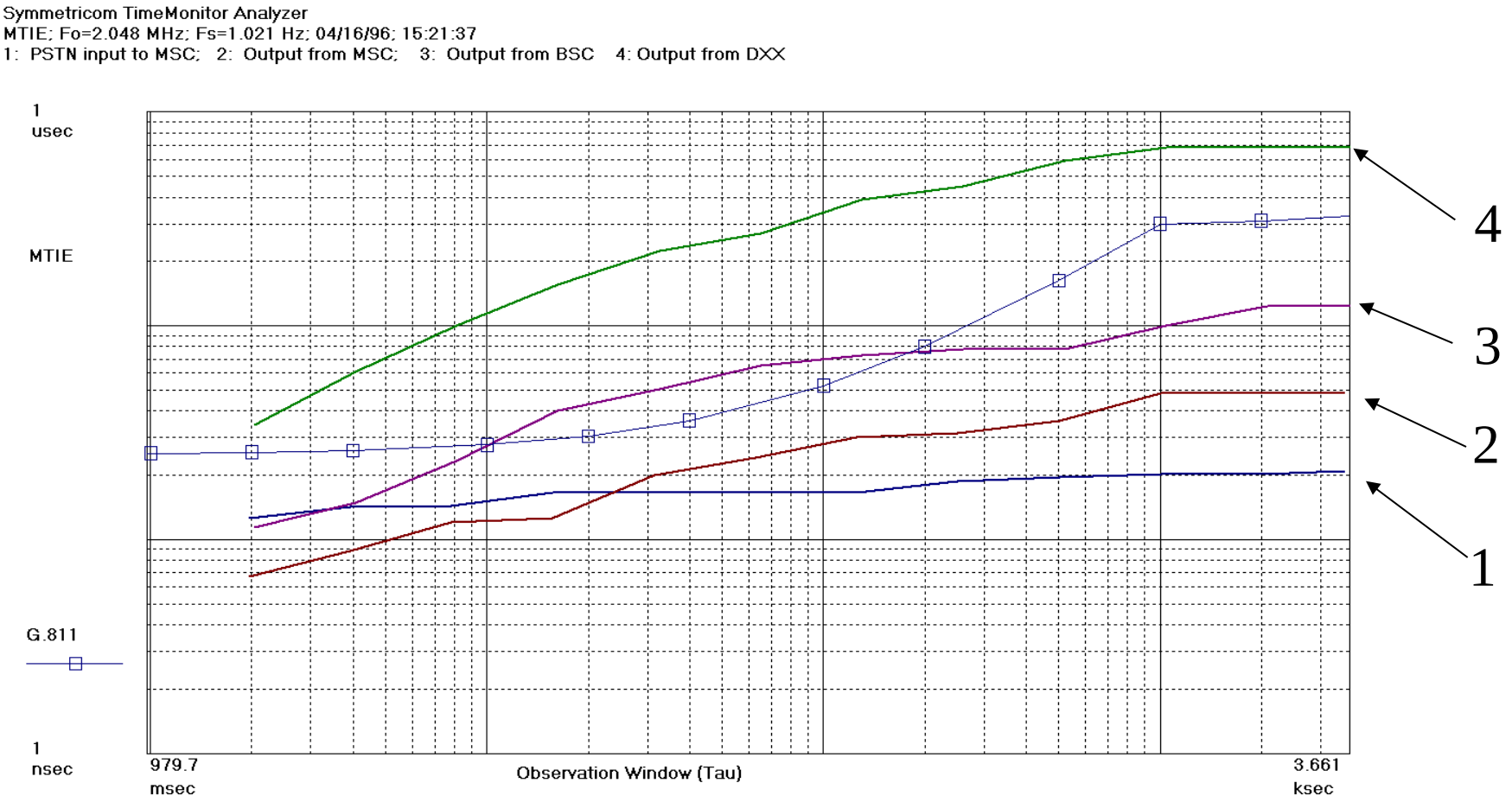
Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=1.021 Hz; Fo=2.0480000 MHz; 04/16/96; 15:21:37
1: PSTN input to MSC; 2: Output from MSC; 3: Output from BSC 4: Output from DXX



Sync Measurement #1: Network Element Cascading

Symmetricom

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

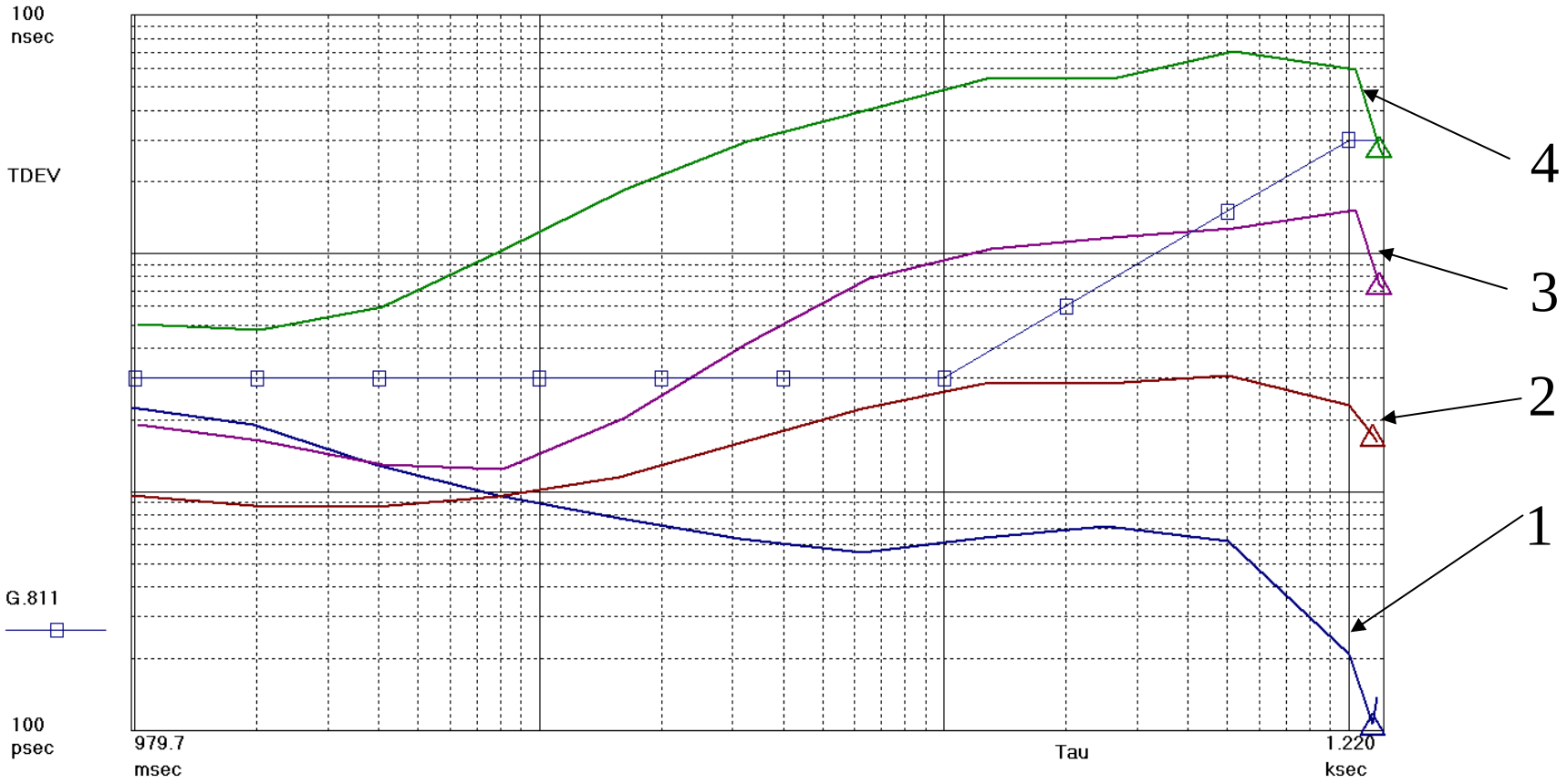


Sync Measurement #1: Network Element Cascading

Symmetricom

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

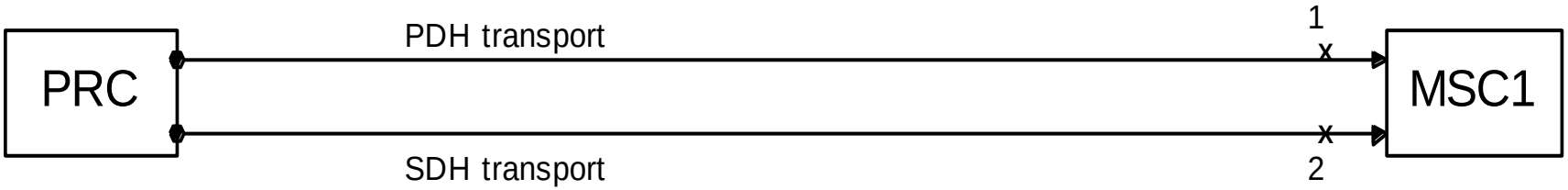
Symmetricom TimeMonitor Analyzer
TDEV; No. Avg=1; Fo=2.048 MHz; Fs=1.021 Hz; 04/16/96; 15:21:37
1: PSTN input to MSC; 2: Output from MSC; 3: Output from BSC; 4: Output from DXX



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

Symmetricom

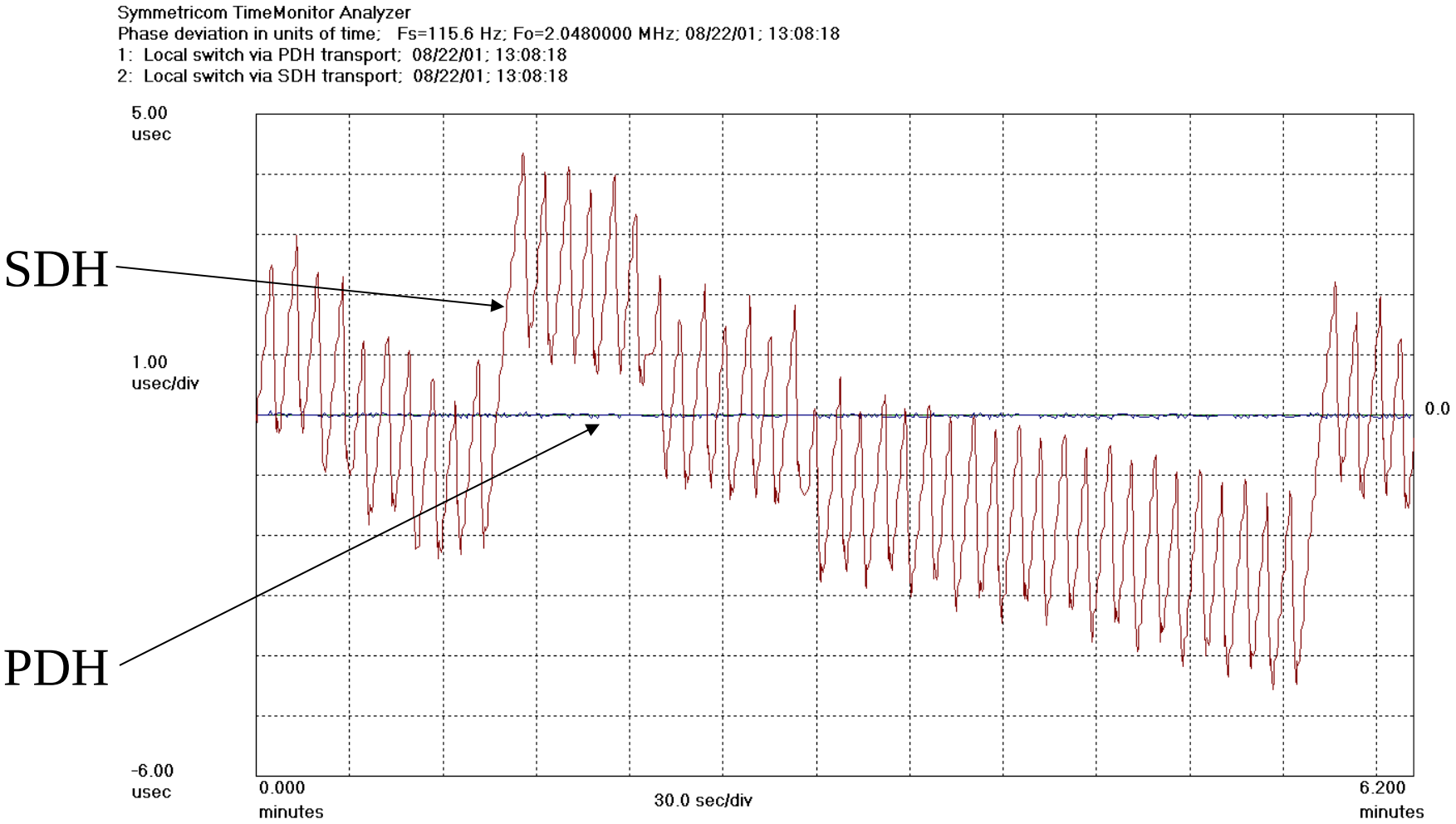
MSC PSTN timing: PDH vs. SDH transport



x: measurement points

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

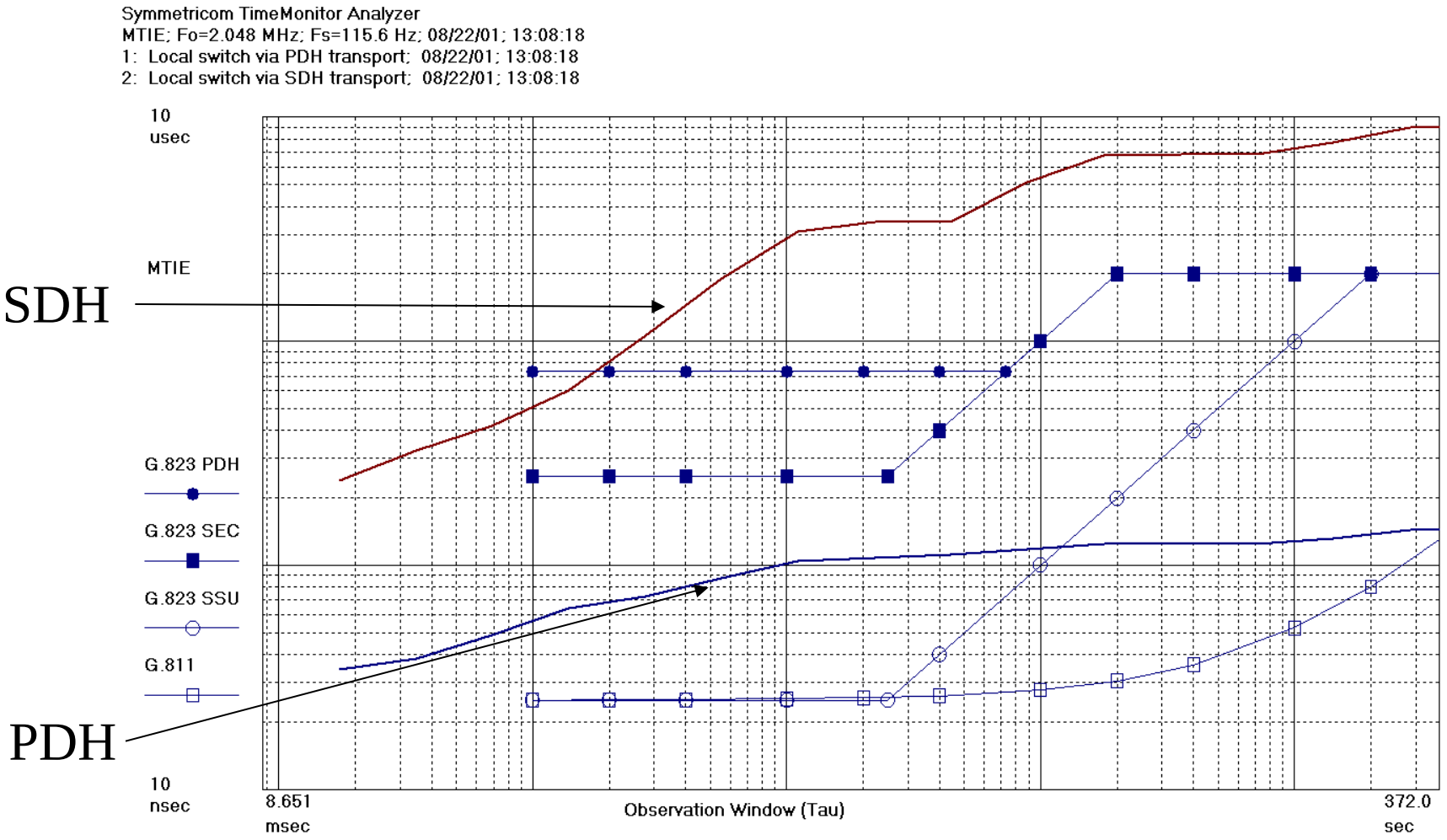
PDH vs. SDH transport



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

Symmetricom

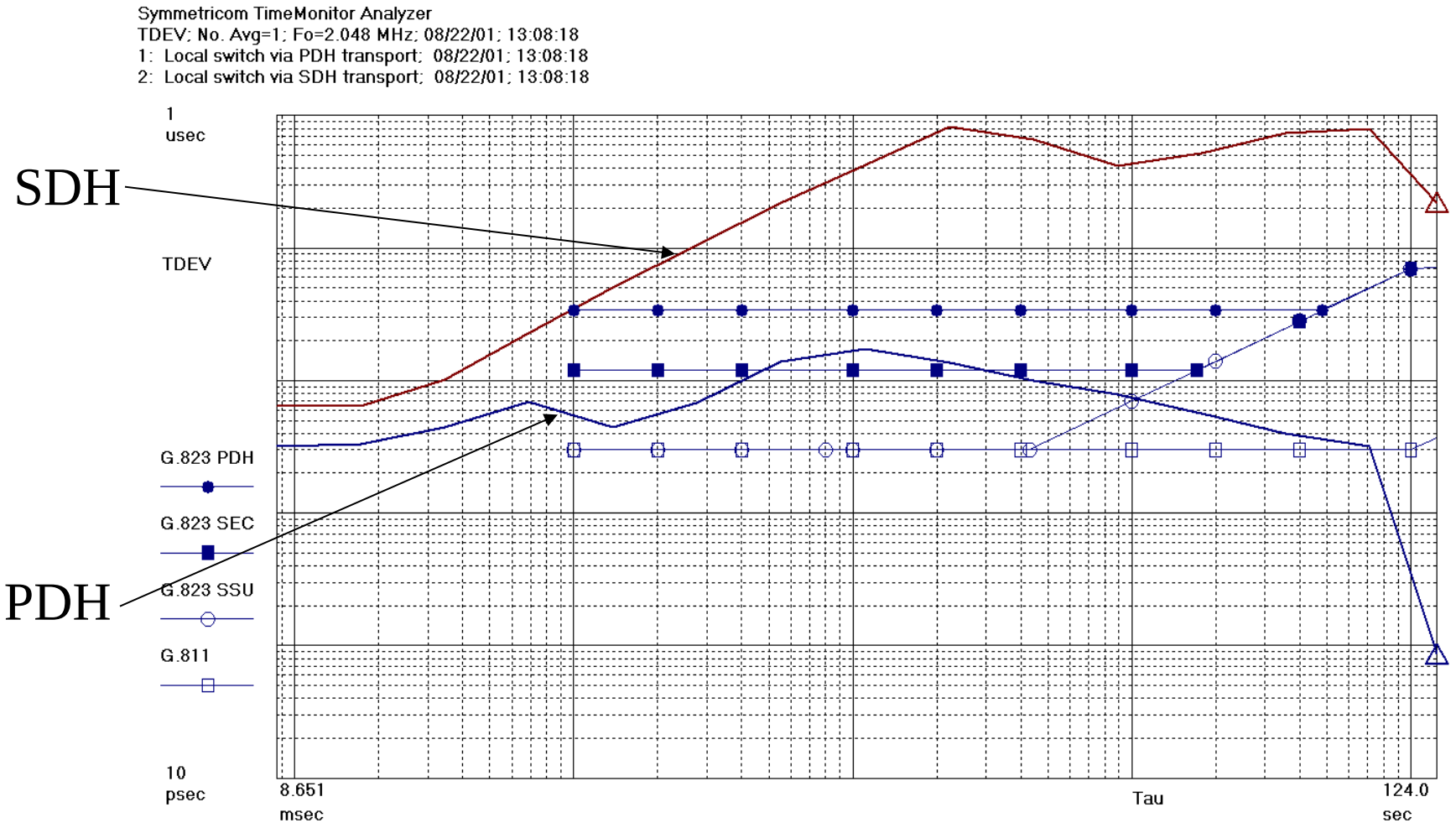
PDH vs. SDH transport



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

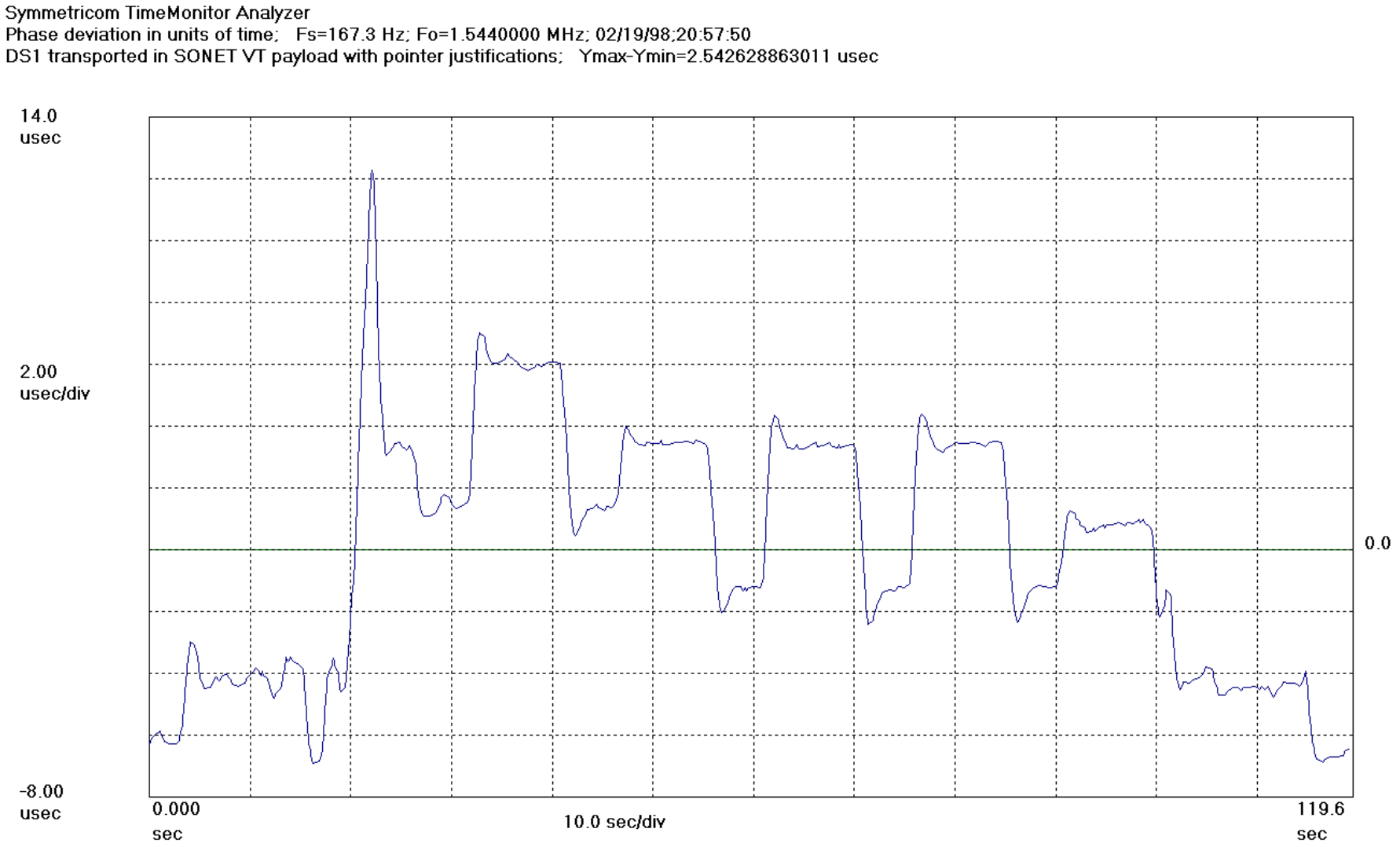
Symmetricom

PDH vs. SDH transport



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

SONET pointer justifications on DS1

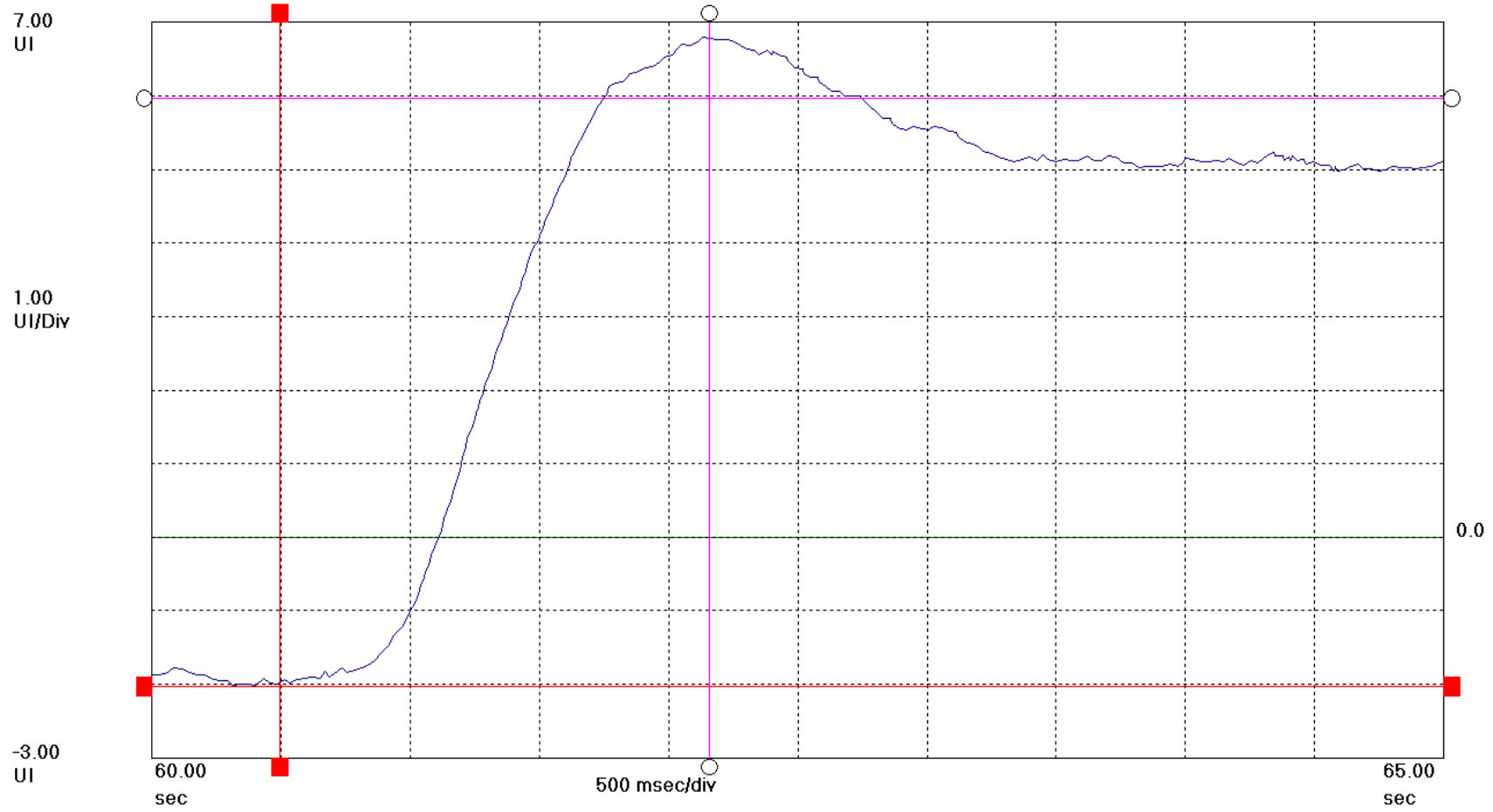


Sync Measurement #2: SONET/SDH vs. PDH Transport

Symmetricom

SONET pointer justifications on DS1
Zoom into 8UI phase movement

Symmetricom TimeMonitor Analyzer
Phase shift in unit intervals; Fs=167.3 Hz; Fo=1.5440000 MHz; 02/19/98;20:57:50
DS1 transported in SONET VT payload with pointer justifications; MRK1to2> Dtime=1.662 sec; DPhase=8.001 UI; 5.182 us

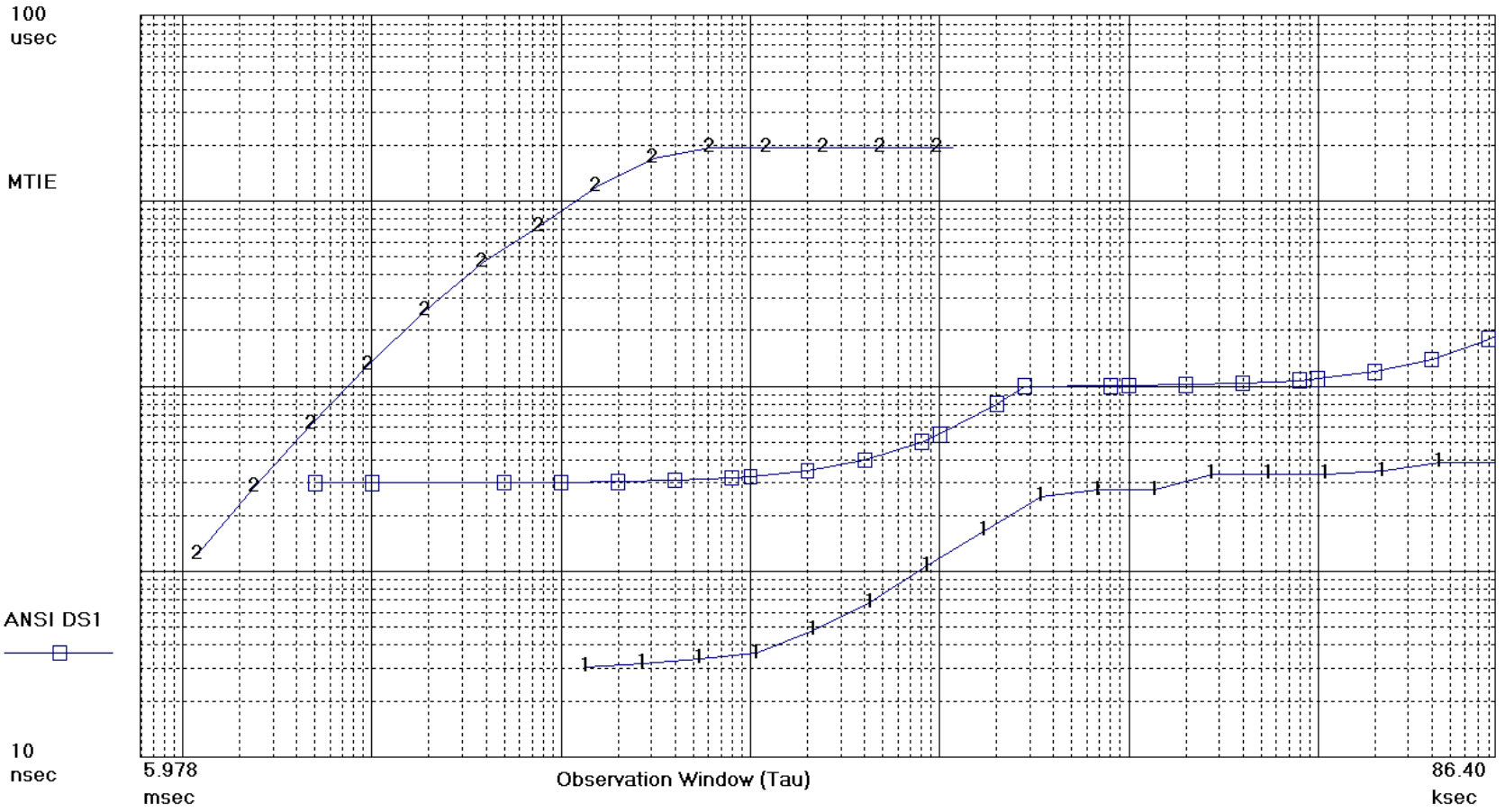


Sync Measurement #2: SONET/SDH vs. PDH Transport

Symmetricom

SONET pointer justifications on DS1
SONET vs. PDH transport MTIE comparison

Symmetricom TimeMonitor Analyzer
MTIE; Fo=1.544 MHz; Fs=1.481 Hz; 10/13/97; 14:40:33
1: PDH transport; 10/13/97; 14:40:33; 2: SONET transport; 02/19/98; 20:57:50



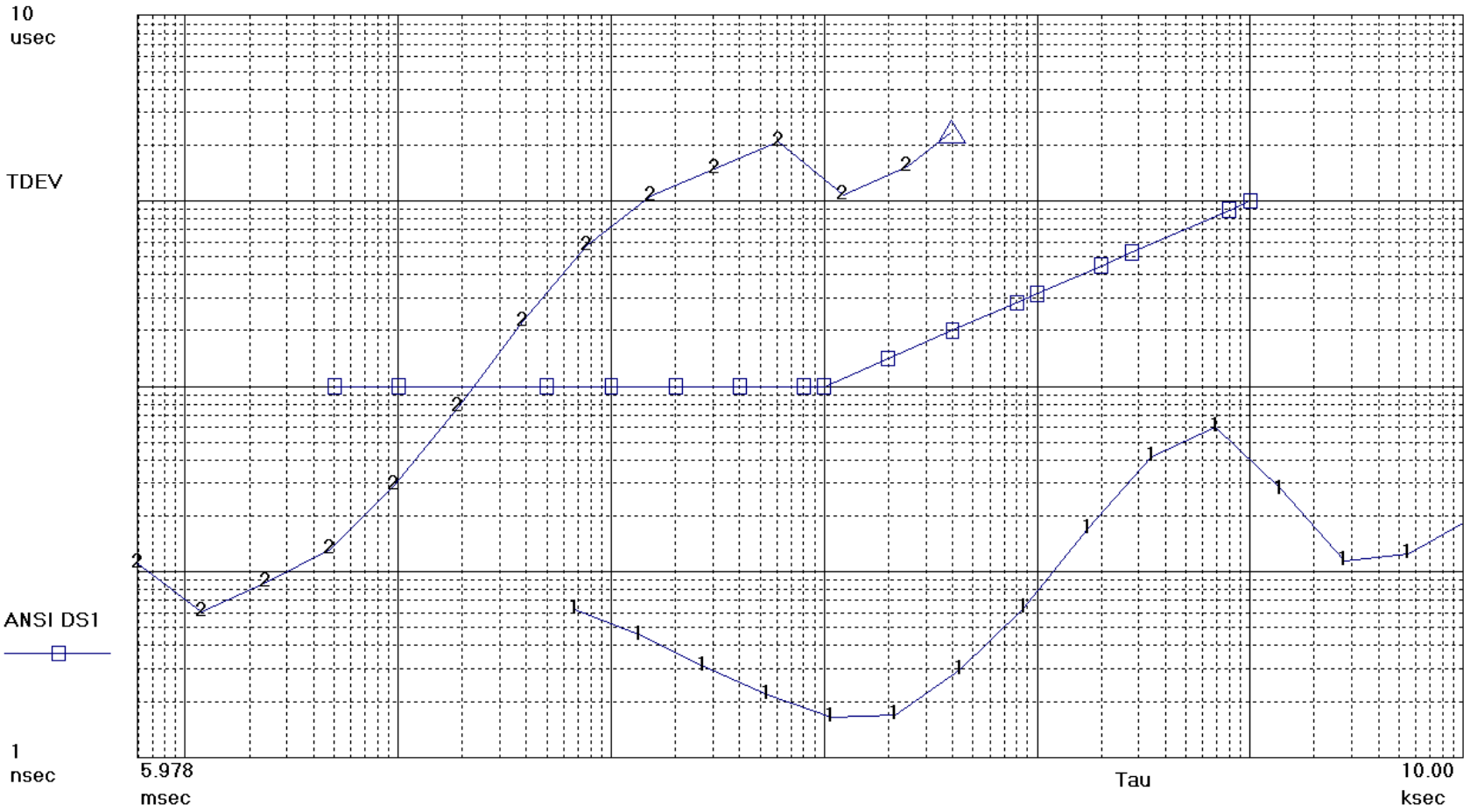
Sync Measurement #2: SONET/SDH vs. PDH Transport

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

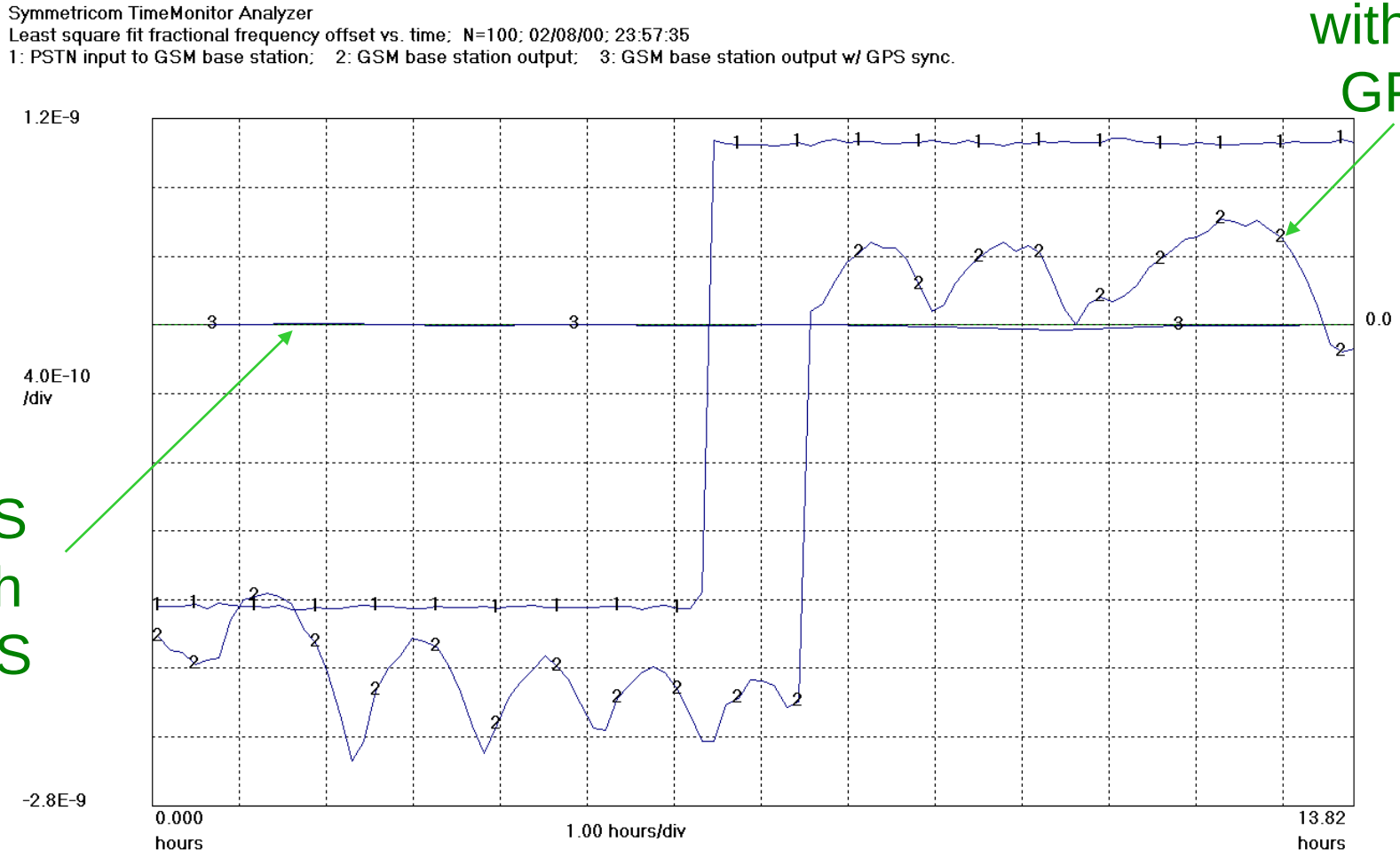


Sync Measurement #3:
GSM BTS: GPS vs. PSTN timing

Symmetricom

Frequency jump from PSTN at GSM base station

BTS without GPS

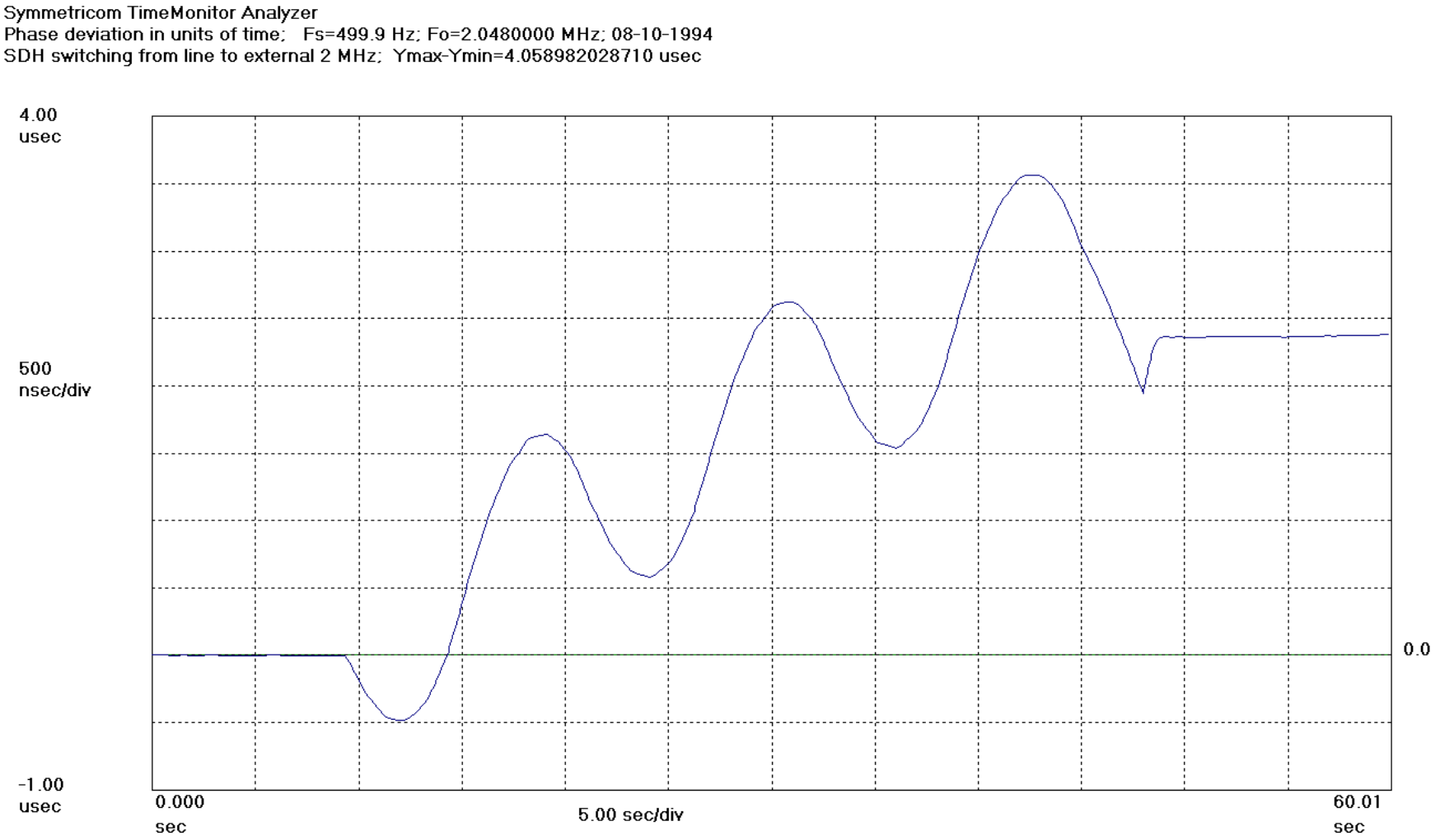


BTS with GPS

Sync Measurement #4: NE Reference Switching

Reference switching

Phase deviation ringing and overall phase shift of 2.4 µsec

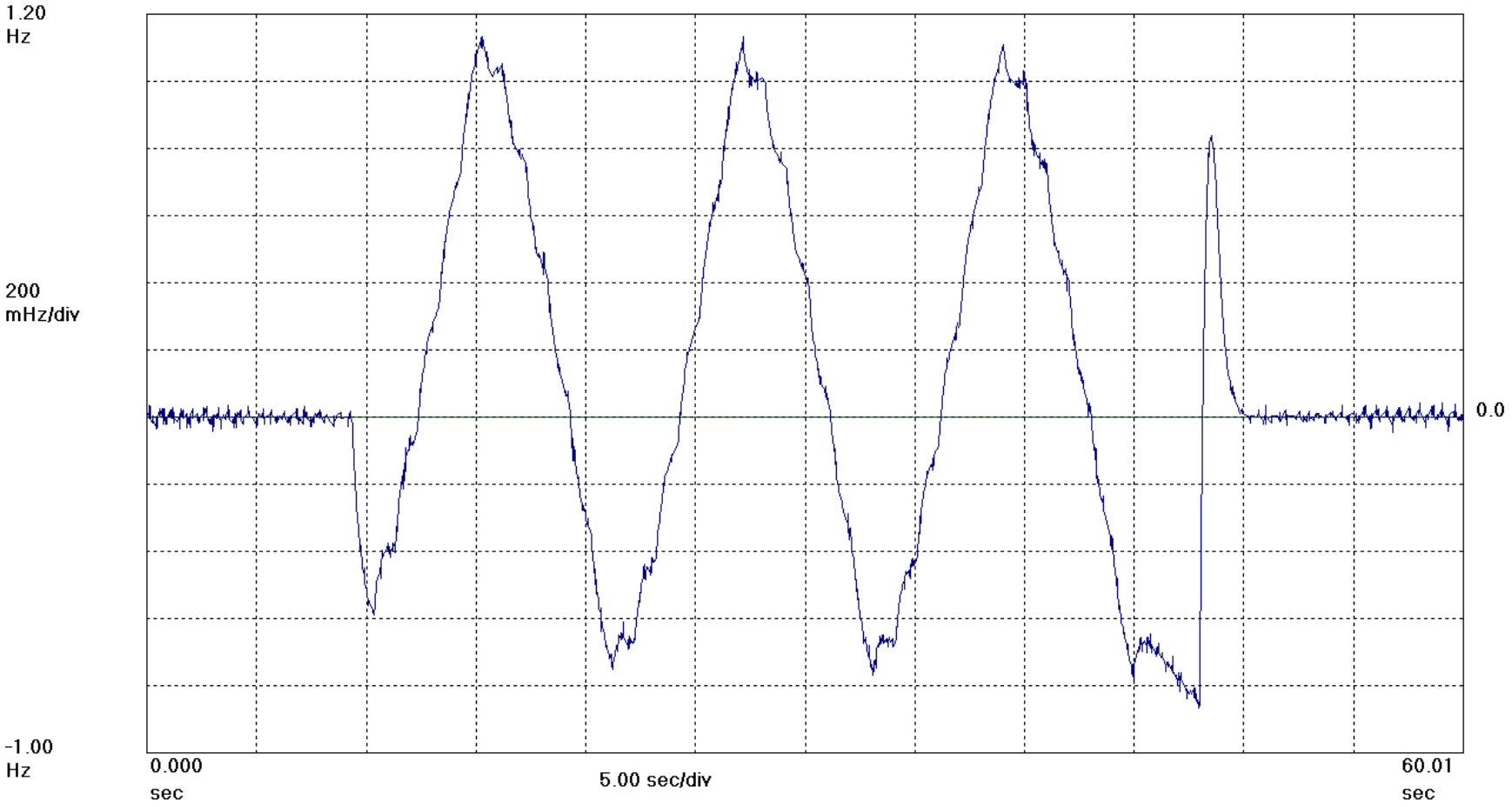


Sync Measurement #4: NE Reference Switching

Reference switching

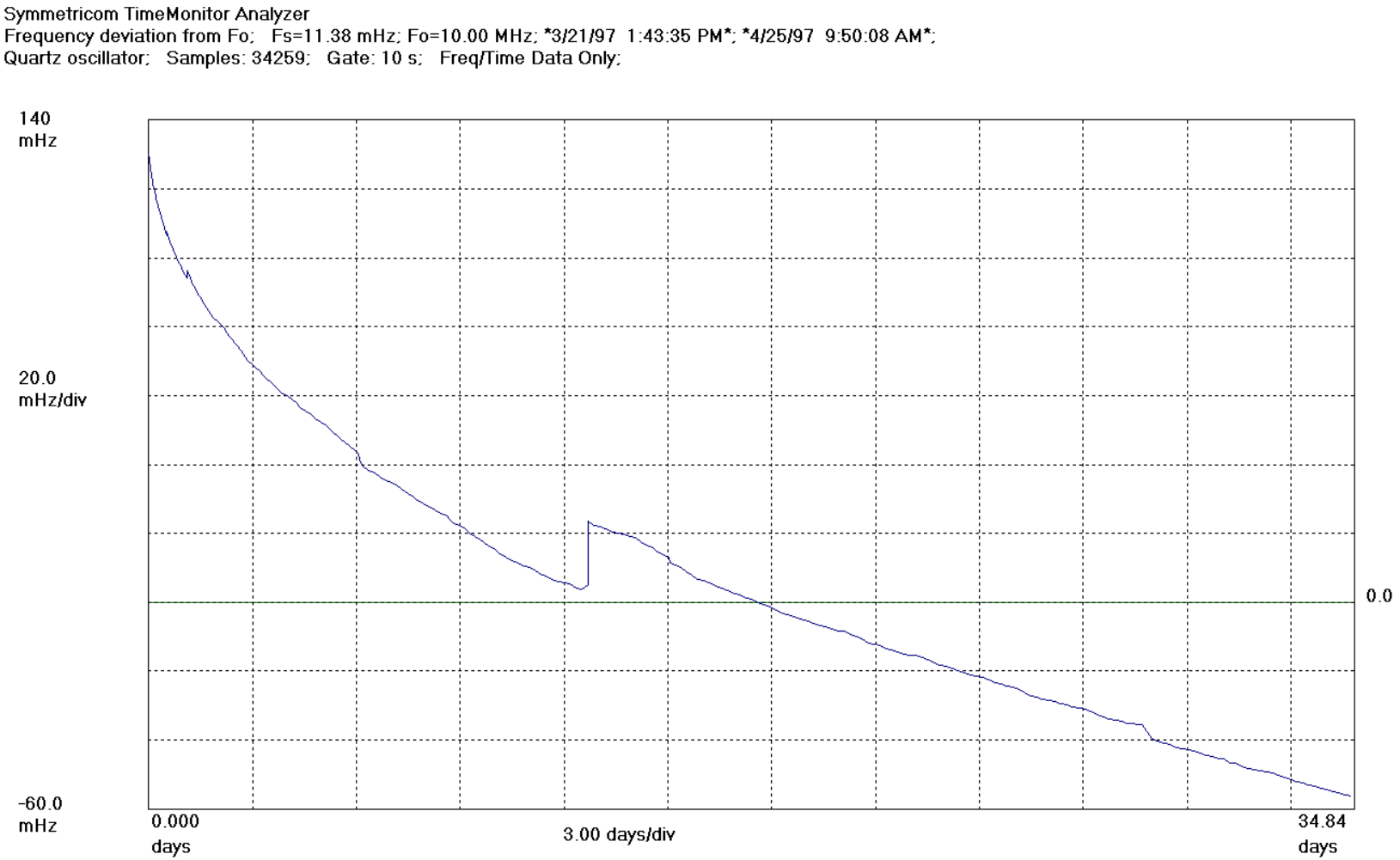
Frequency movement +/- 1 Hz

Symmetricom TimeMonitor Analyzer
Frequency deviation from Fo; Fs=499.9 Hz; Fo=2.048 MHz; 08-10-1994
SDH switching from line to external 2 MHz; Ymax-Ymin=2.005233108997 Hz



Sync Measurement #5: Oscillator Frequency Jump

Oscillator frequency jump: effect on holdover

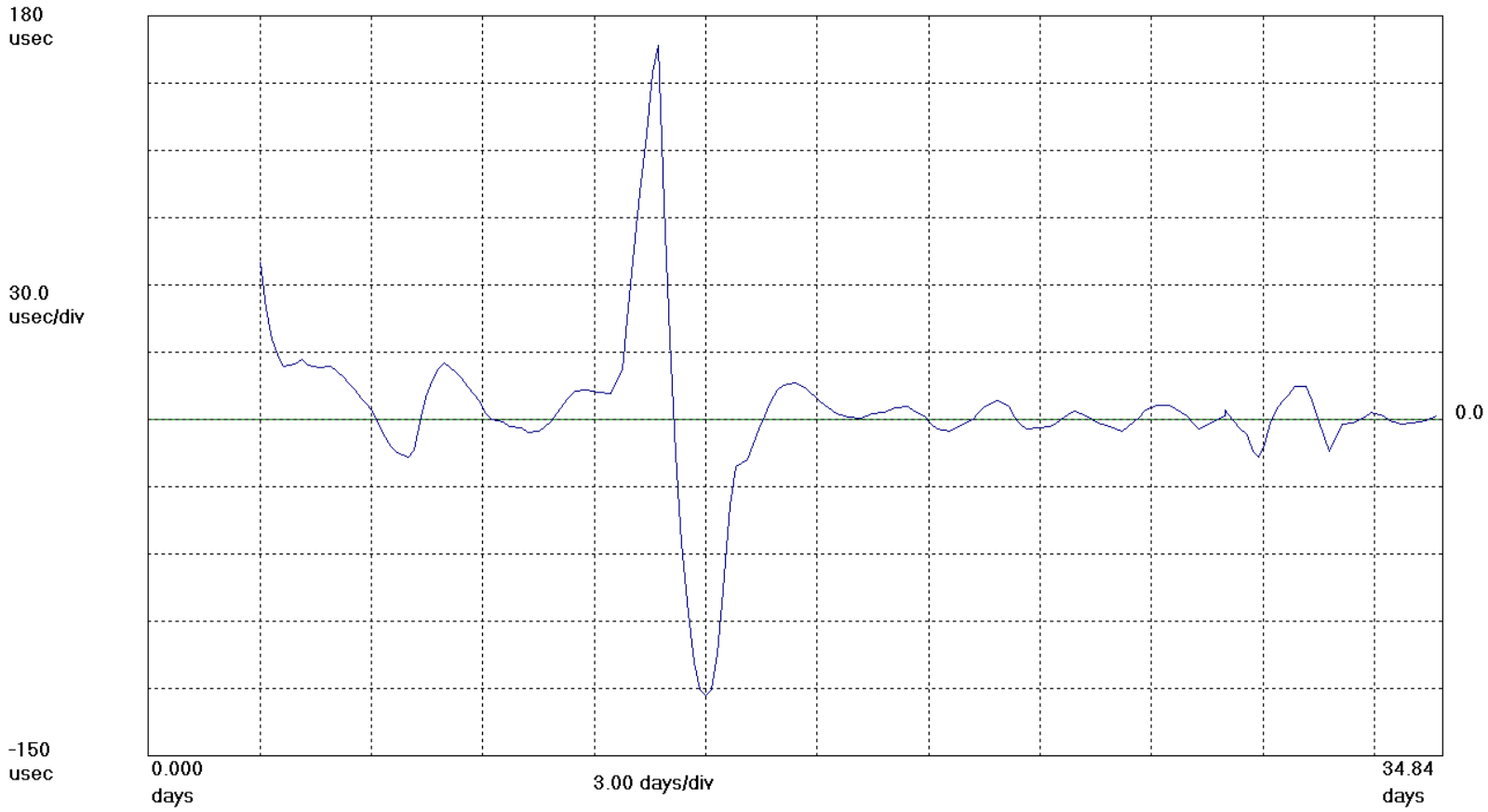


Sync Measurement #5: Oscillator Frequency Jump

Symmetricom

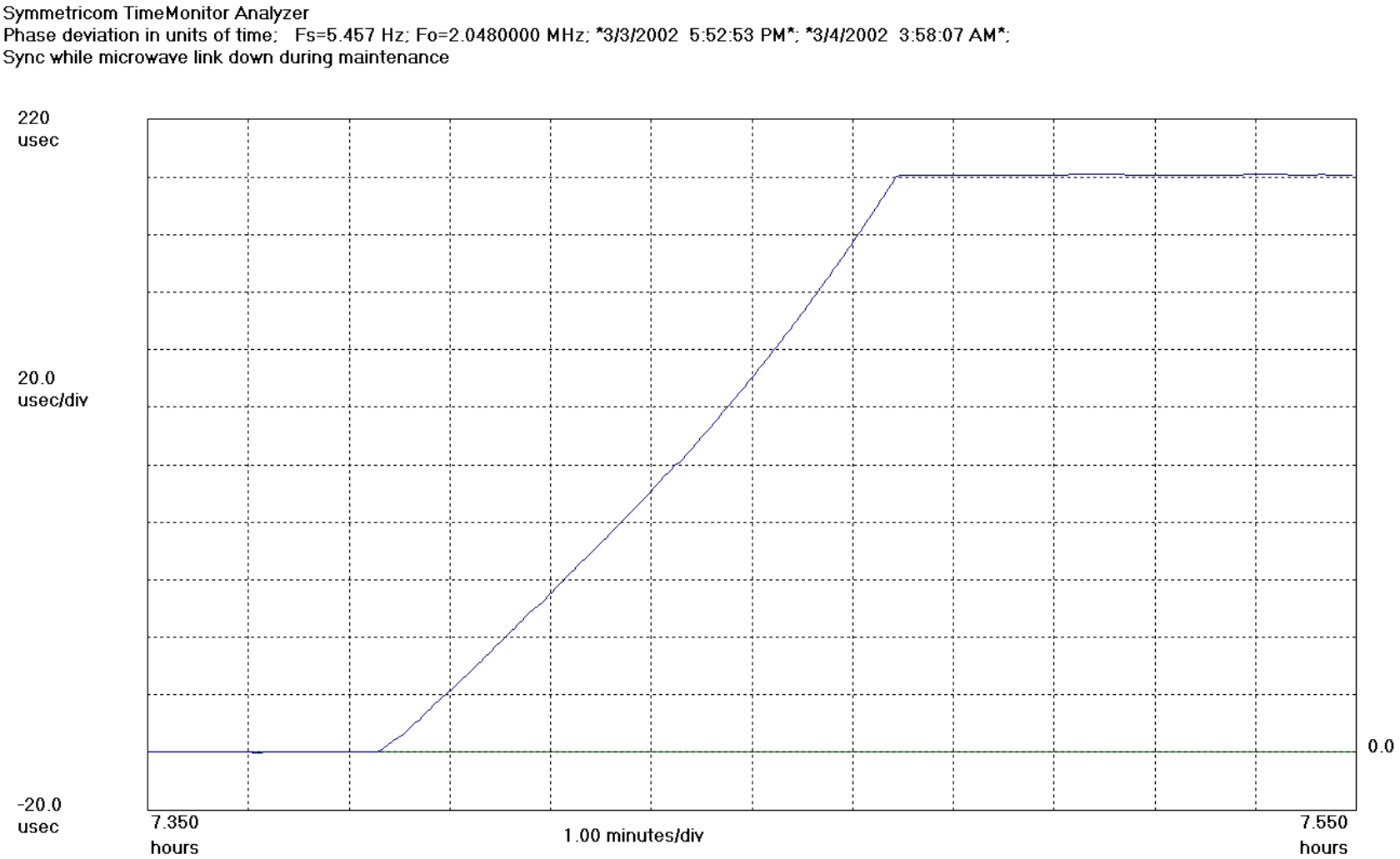
Oscillator frequency jump: effect on holdover
> 150 µsec rather than 1 to 10 µsec

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

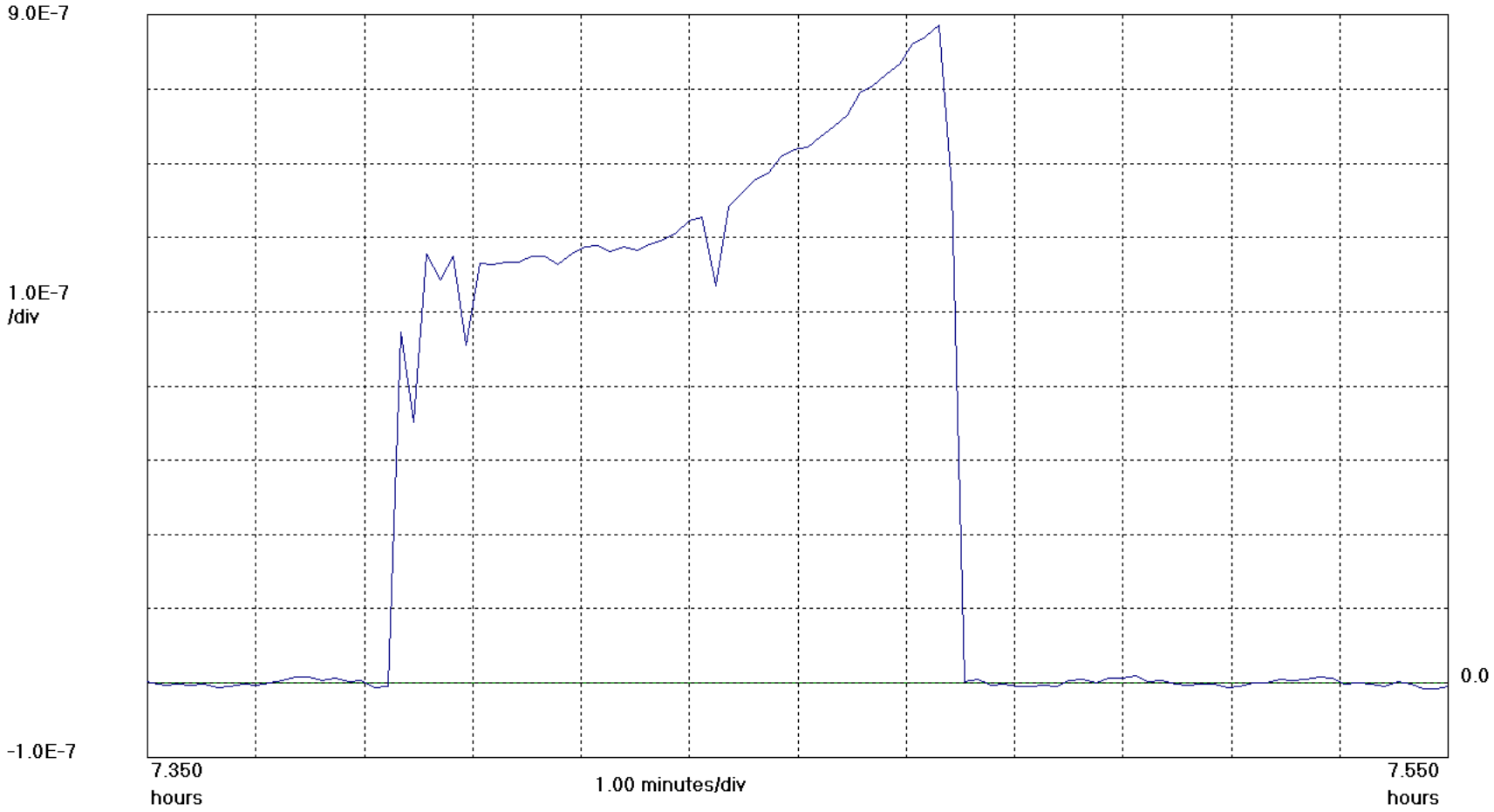
Microwave link down: 200 µsec over 5 minutes



Sync Measurement #6: Microwave Link Down

Microwave link down: Frequency offset reaches 1 ppm

Symmetricom TimeMonitor Analyzer
Least square fit fractional frequency offset vs. time; N=5000; *3/3/2002 5:52:53 PM*; *3/4/2002 3:58:07 AM*;
Sync while microwave link down during maintenance

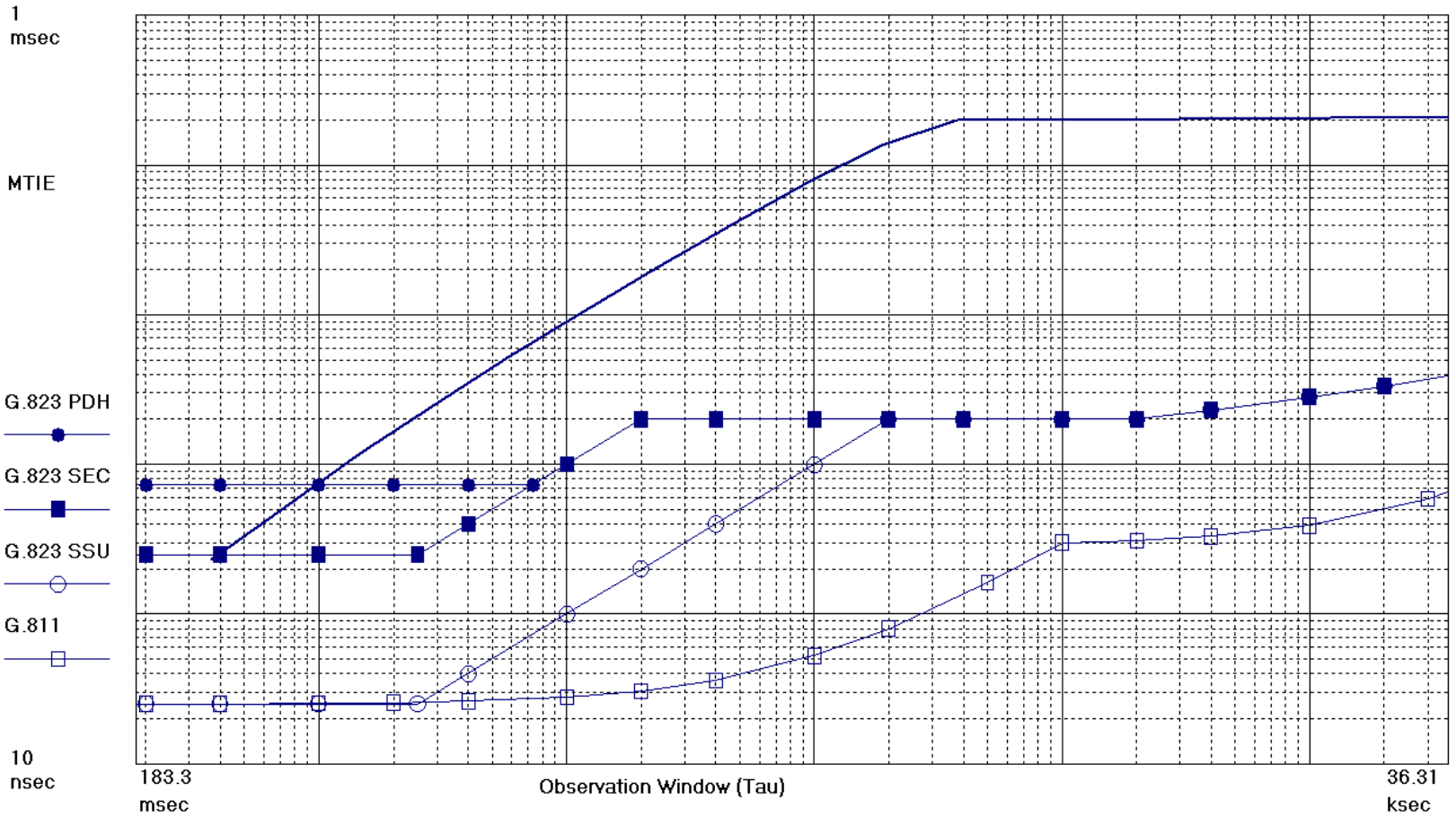


Sync Measurement #6: Microwave Link Down

Symmetricom

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

Symmetricom TimeMonitor Analyzer
MTIE; Fo=2.048 MHz; Fs=5.457 Hz; *3/3/2002 5:52:53 PM*; *3/4/2002 3:58:07 AM*;
Sync while microwave link down during maintenance

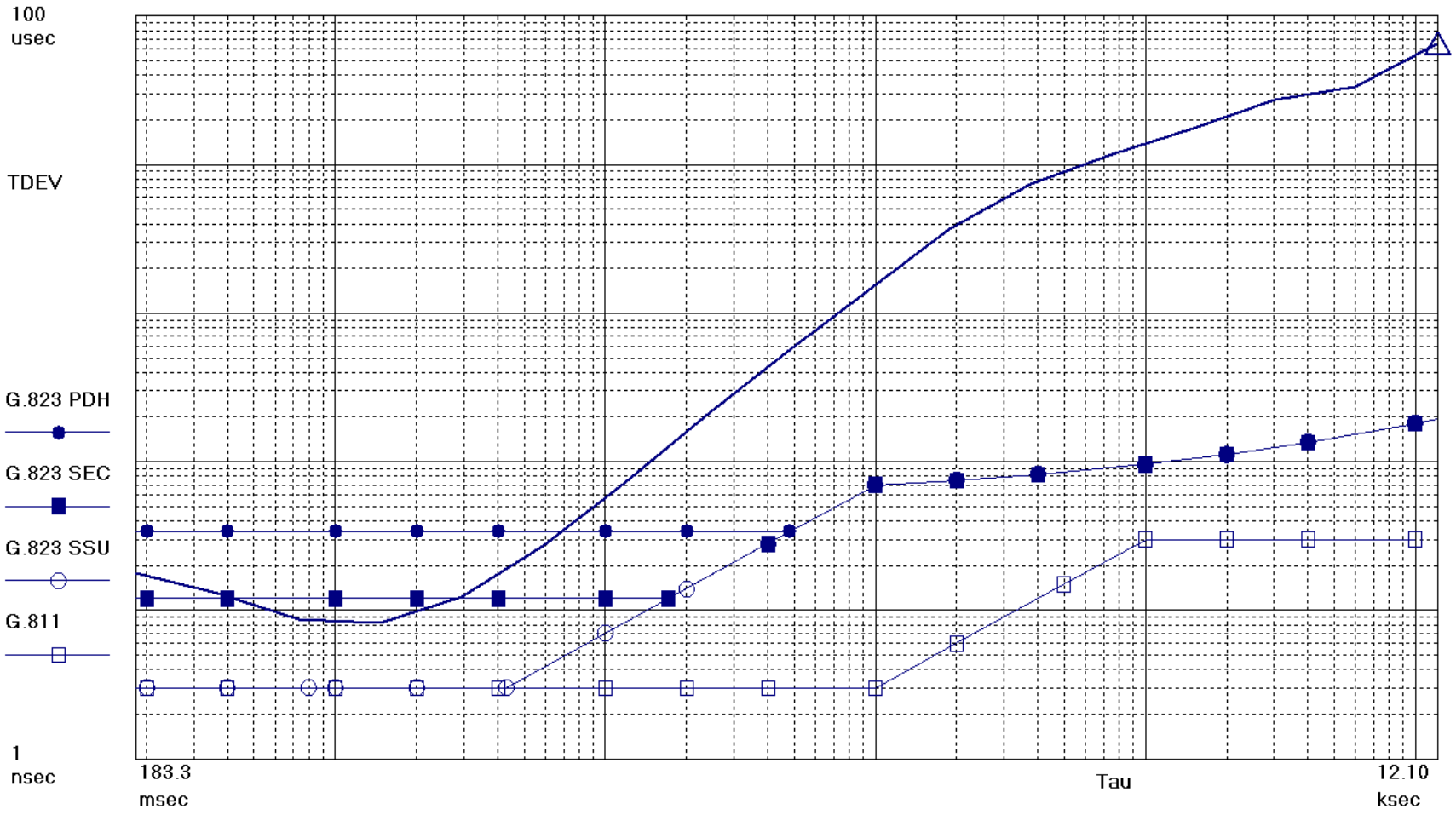


Sync Measurement #6: Microwave Link Down

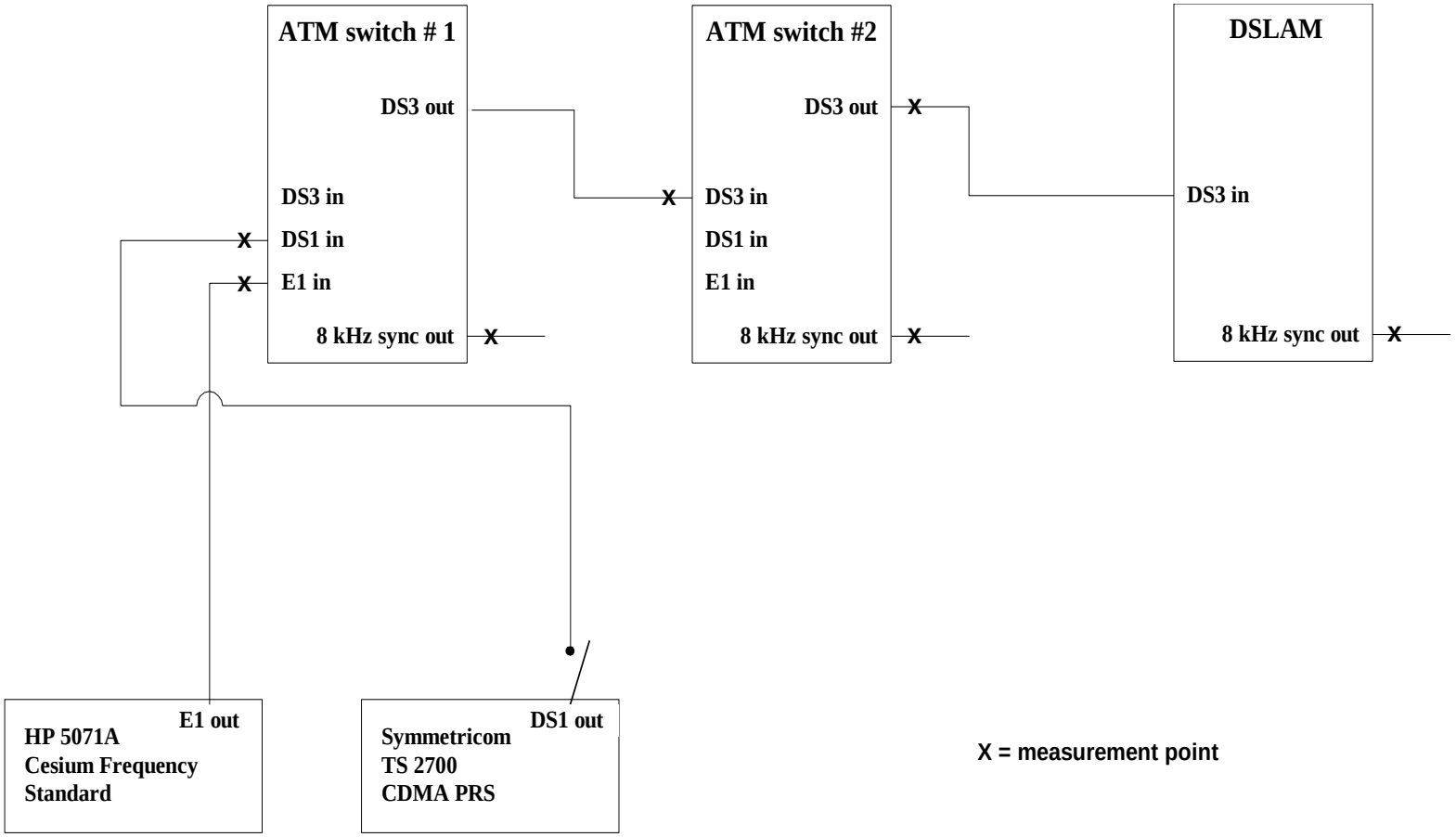
Symmetricom

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

Symmetricom TimeMonitor Analyzer
TDEV; No. Avg=1; Fo=2.048 MHz; *3/3/2002 5:52:53 PM*; *3/4/2002 3:58:07 AM*;
Sync while microwave link down during maintenance



Sync Measurement #7: DSL Synchronization

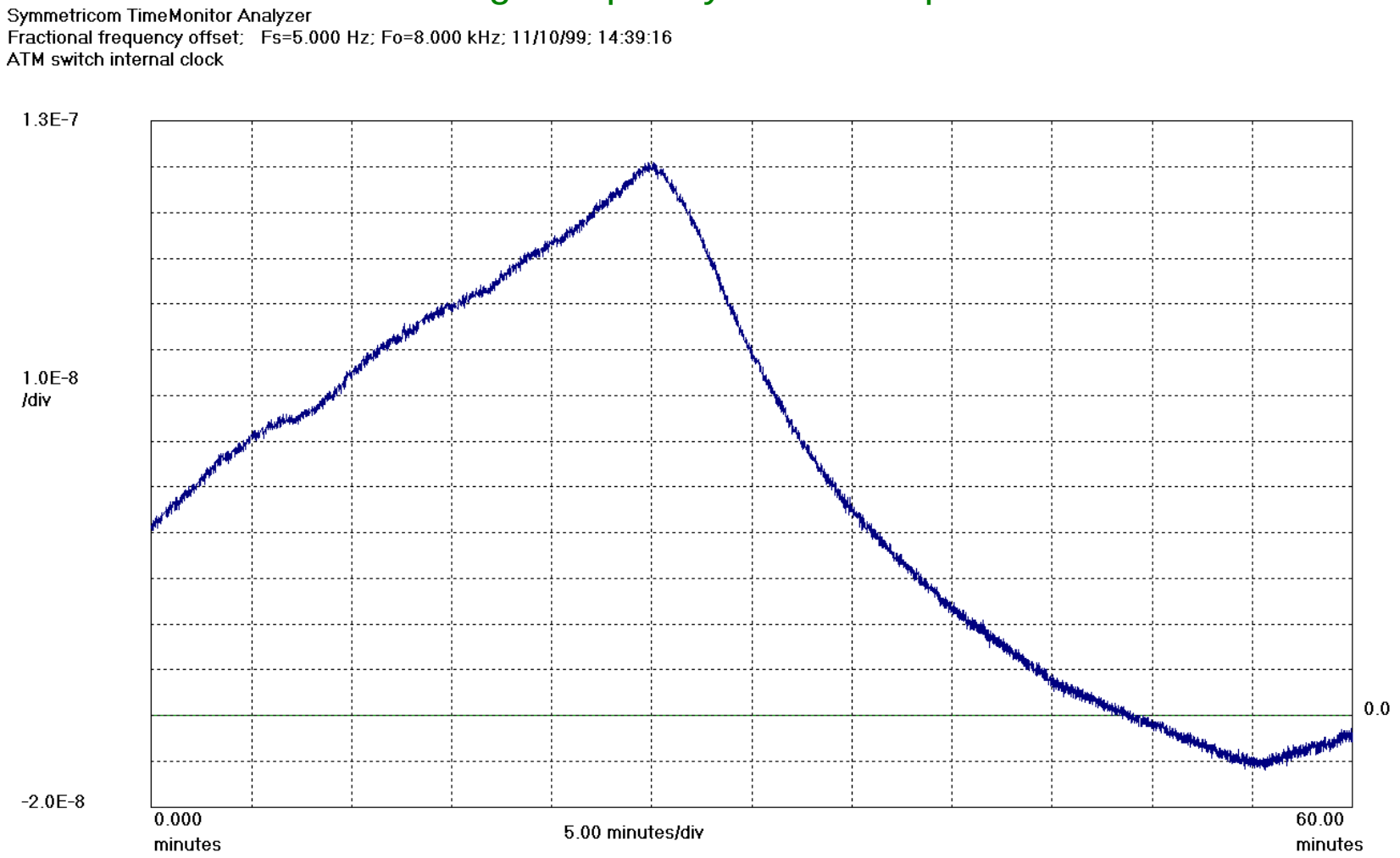


Sync Measurement #7: DSL Synchronization

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

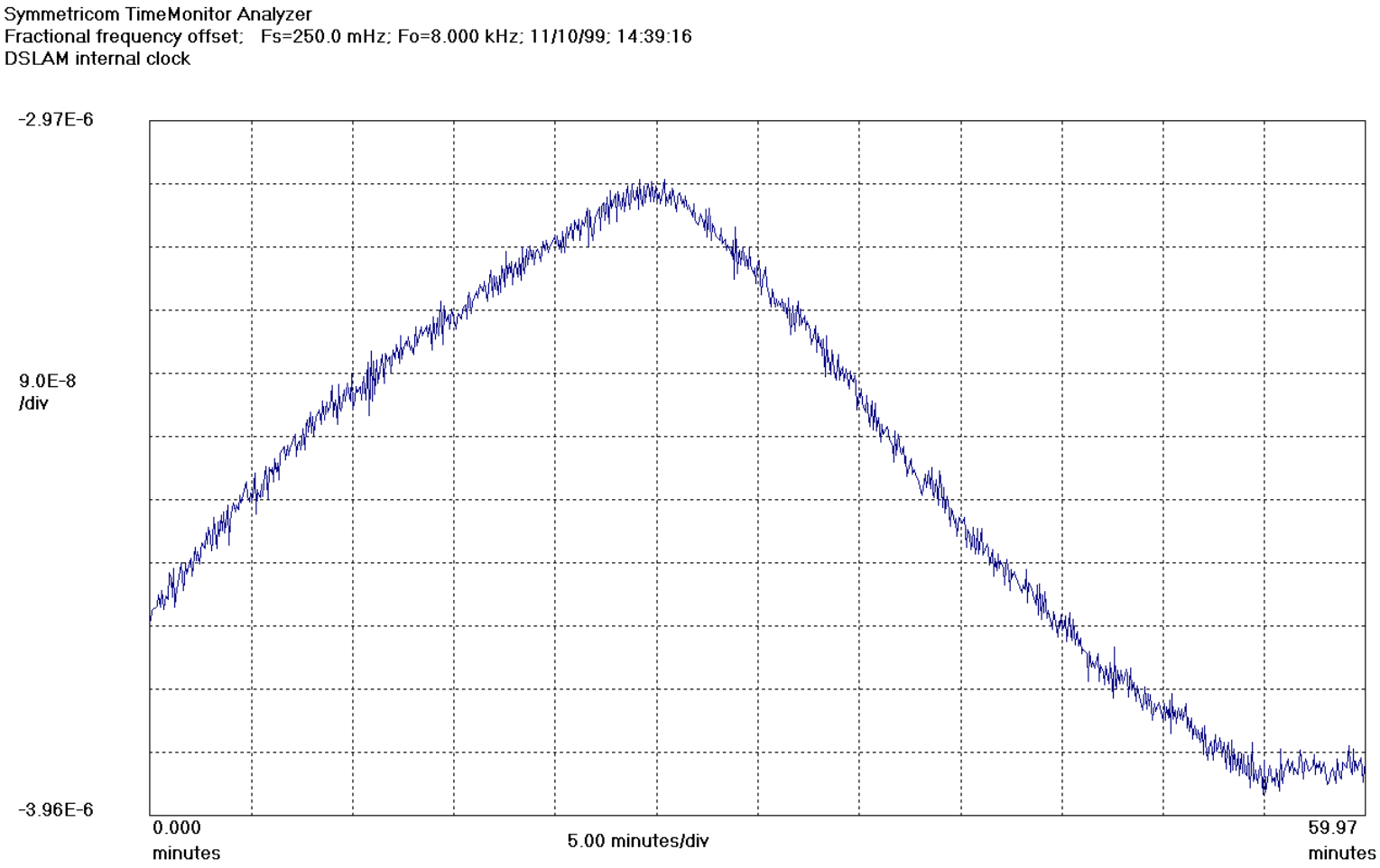


Sync Measurement #7: DSL Synchronization

DSLAM internal oscillator

Frequency drifting between –3 and –4 parts in 10^6 over 1 hour

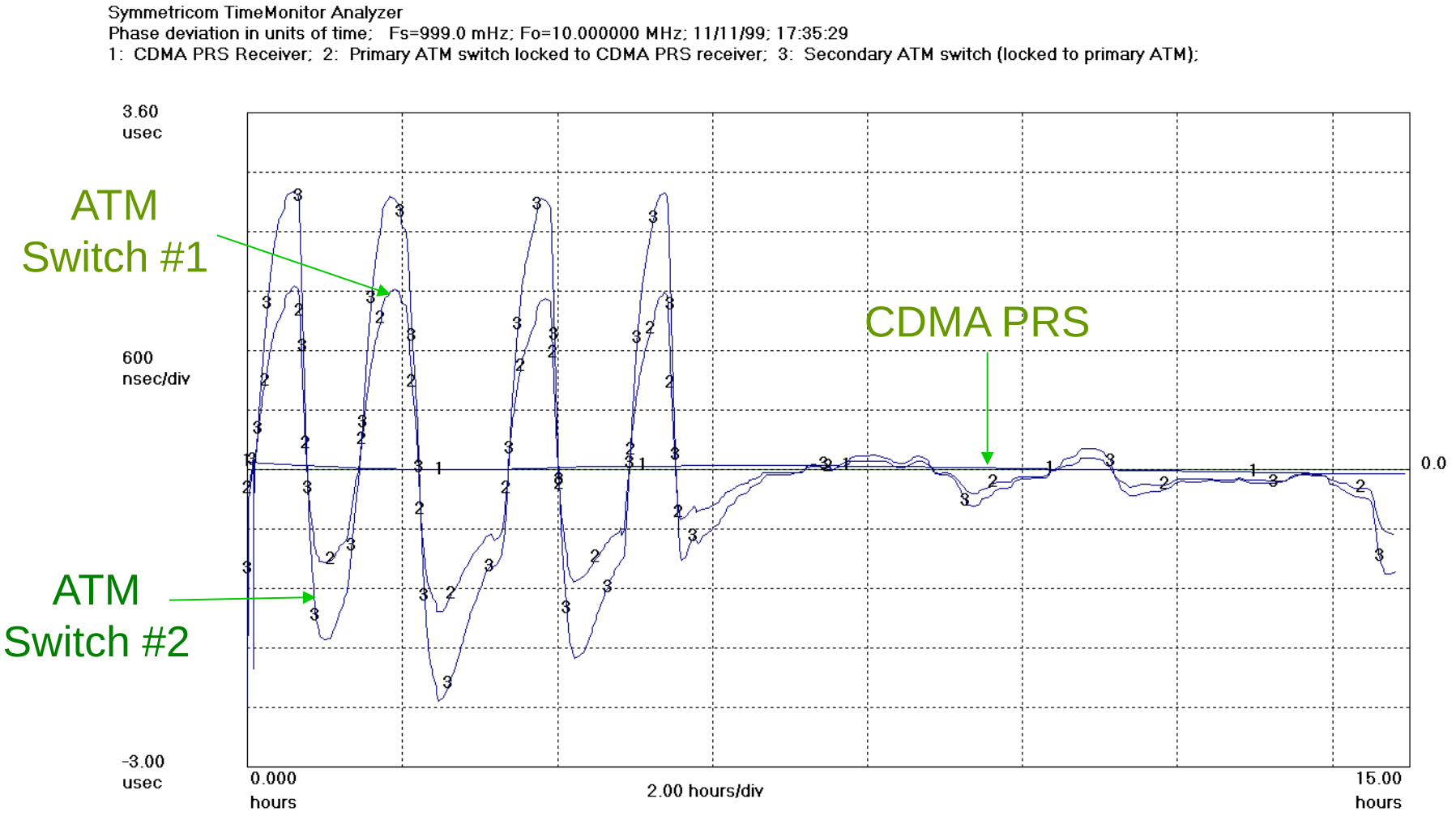
Average frequency offset: -3.4 parts in 10^6



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

Sync Measurement #7: DSL Synchronization

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

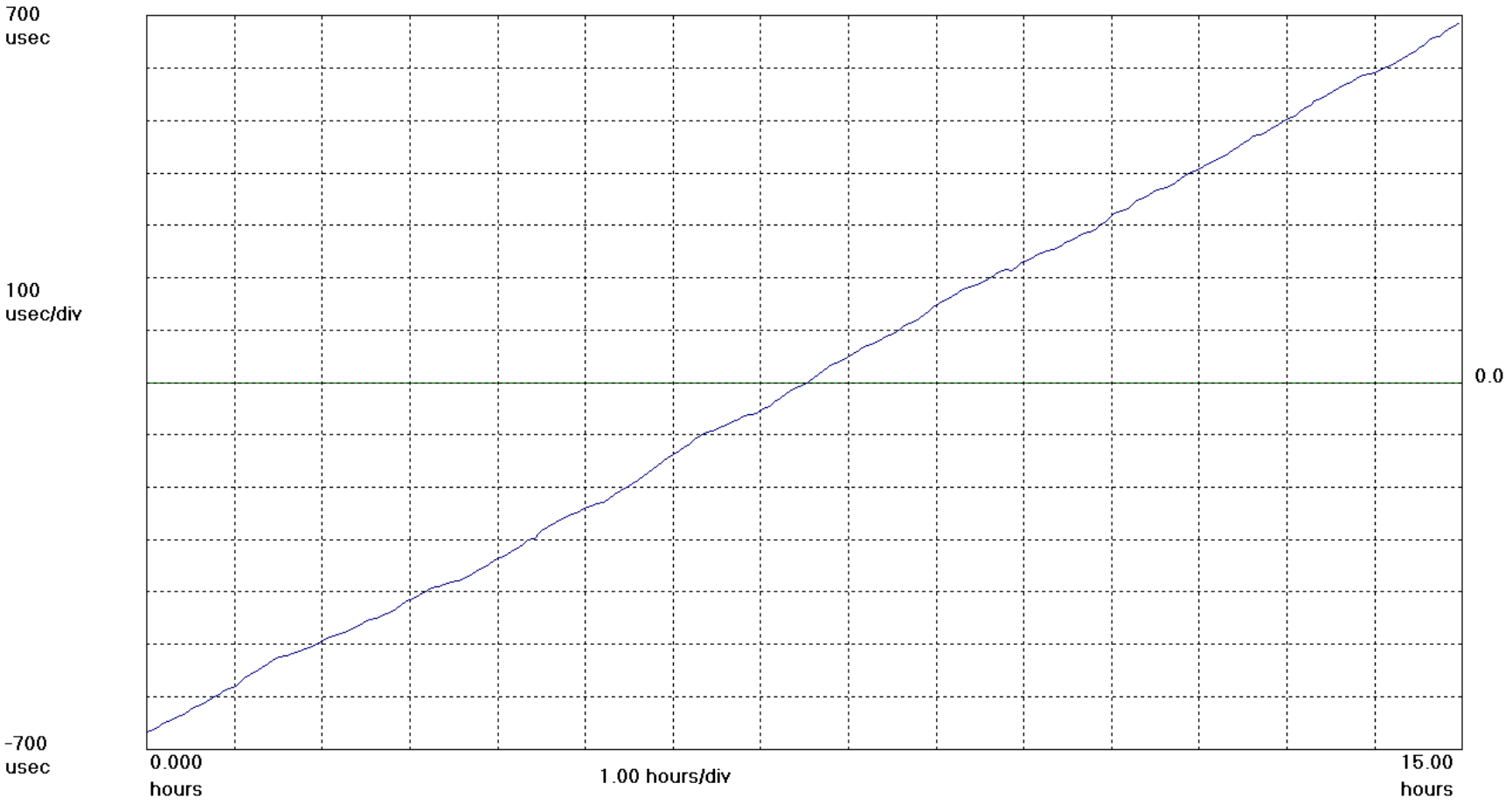


Sync Measurement #7: DSL Synchronization

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

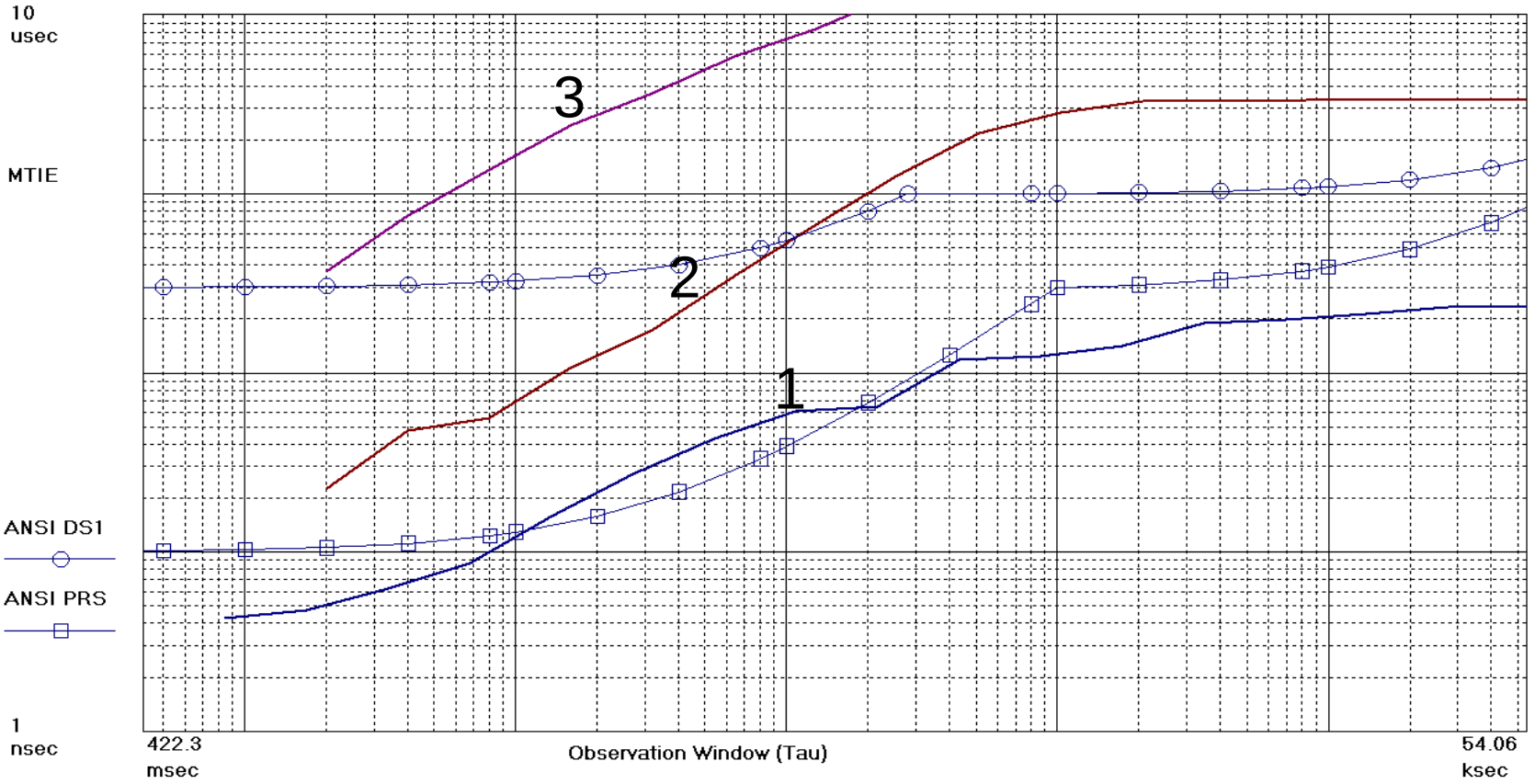


Sync Measurement #7: DSL Synchronization

Symmetricom

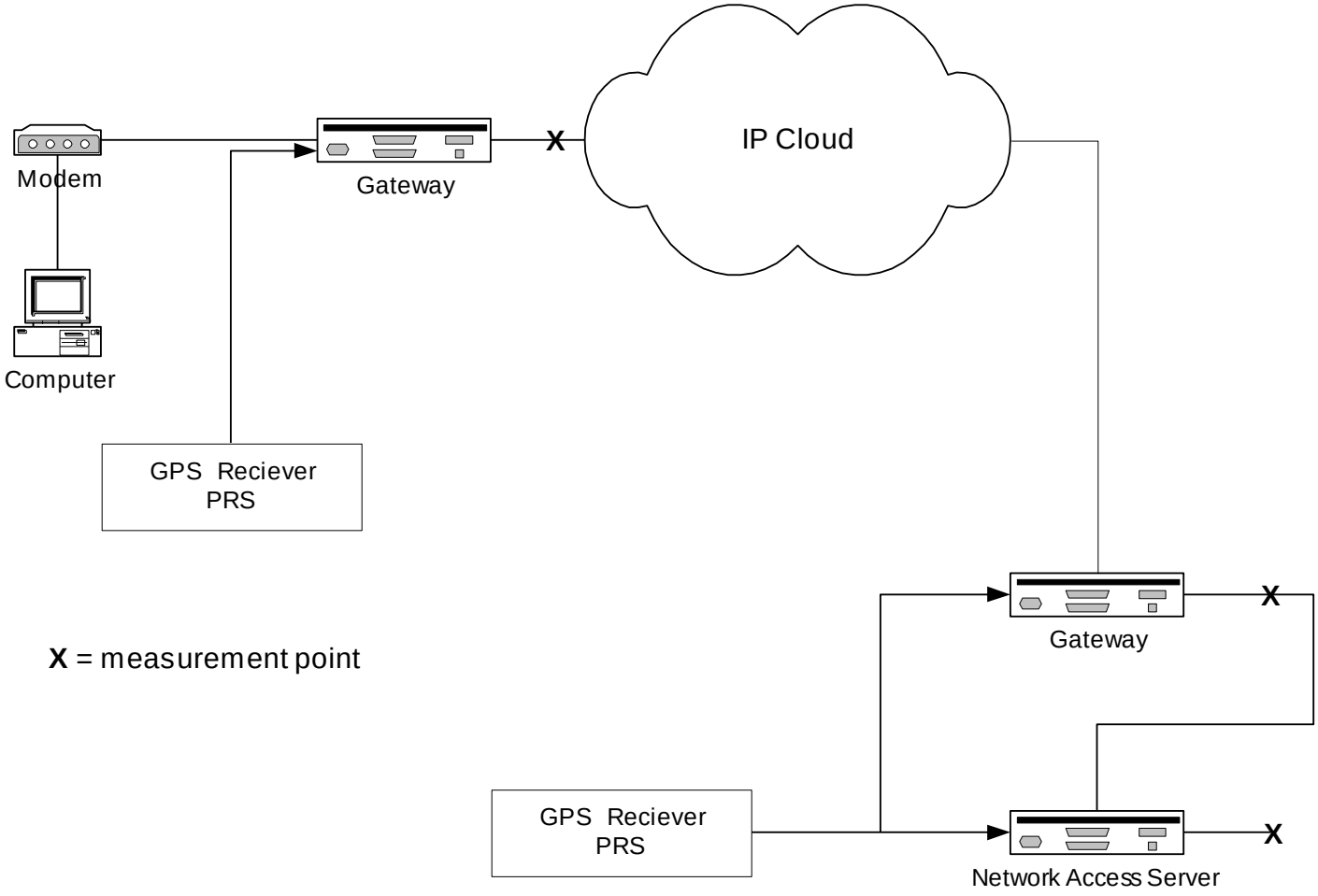
ATM vs. ATM Δ T vs. DSLAM

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

Modem over IP fails without synchronization

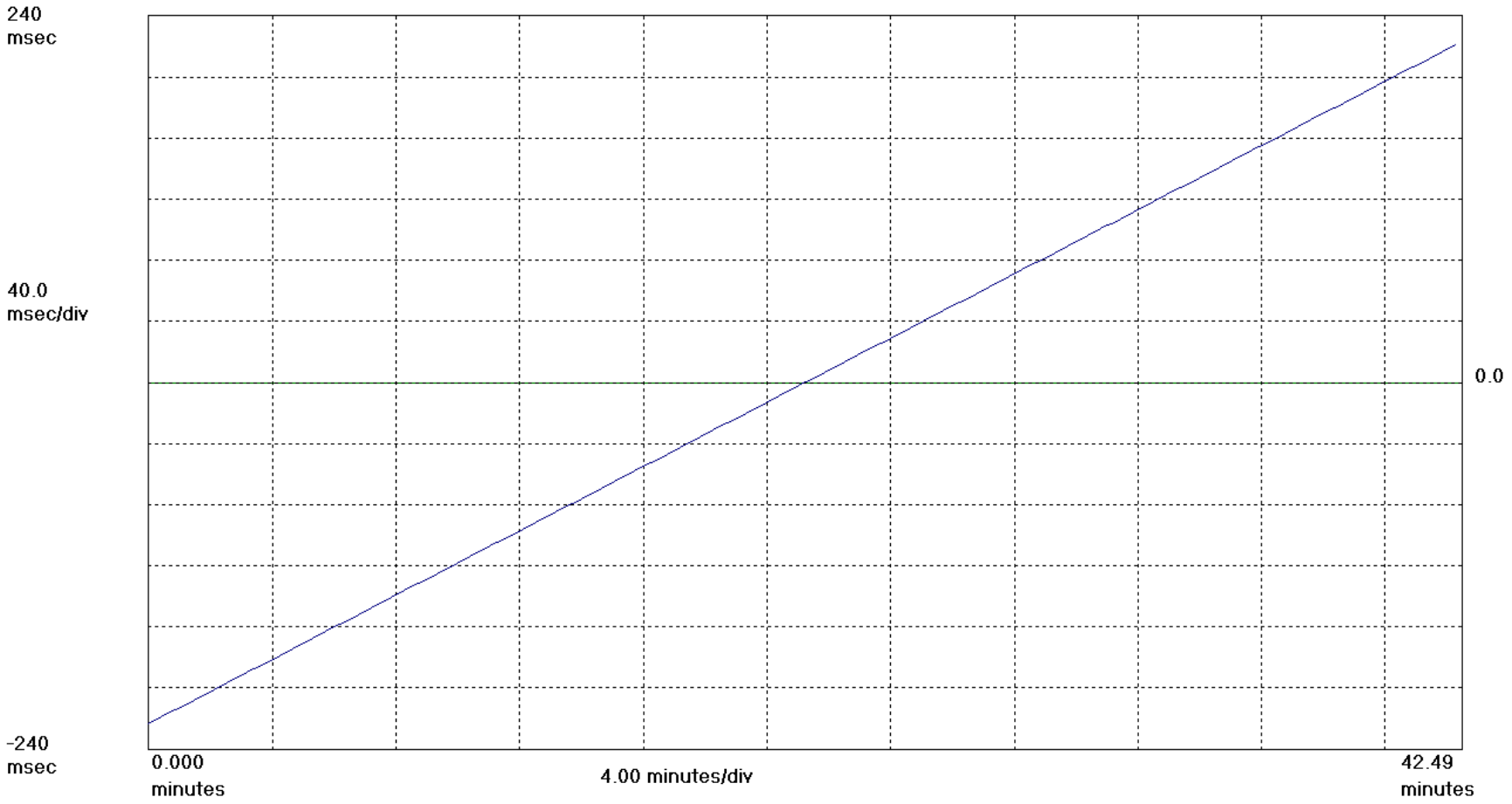


Sync Measurement #8: IP Synchronization

IP network access server internal oscillator

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

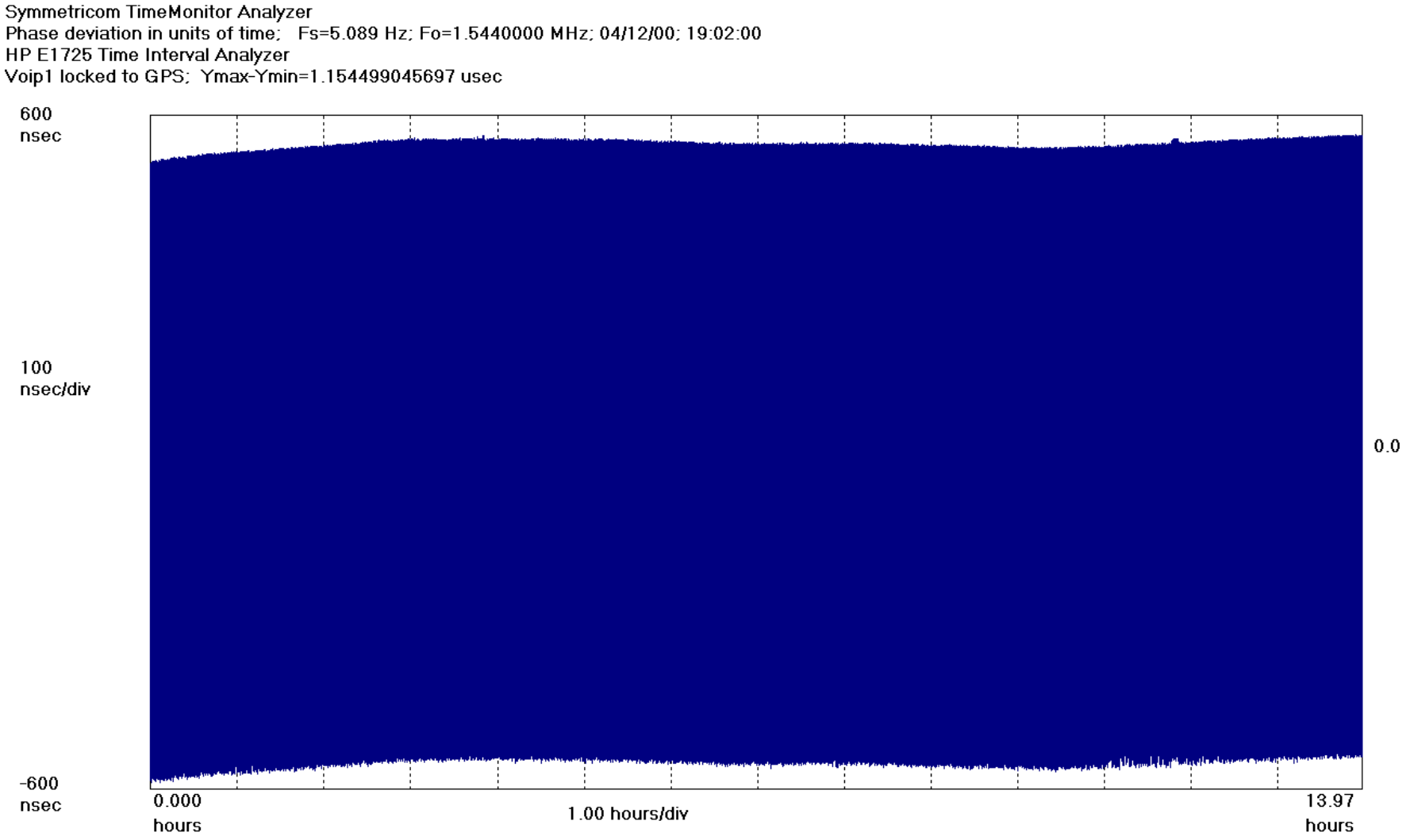
Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=10.04 Hz; Fo=1.5440000 MHz; 04/10/00; 12:40:54
NAS free-run; Fo offset = 270.6 Hz; 1.752E-4; Fo reference = 1.5440000000000 MHz



Sync Measurement #8: IP Synchronization

IP network access server locked to external PRS reference

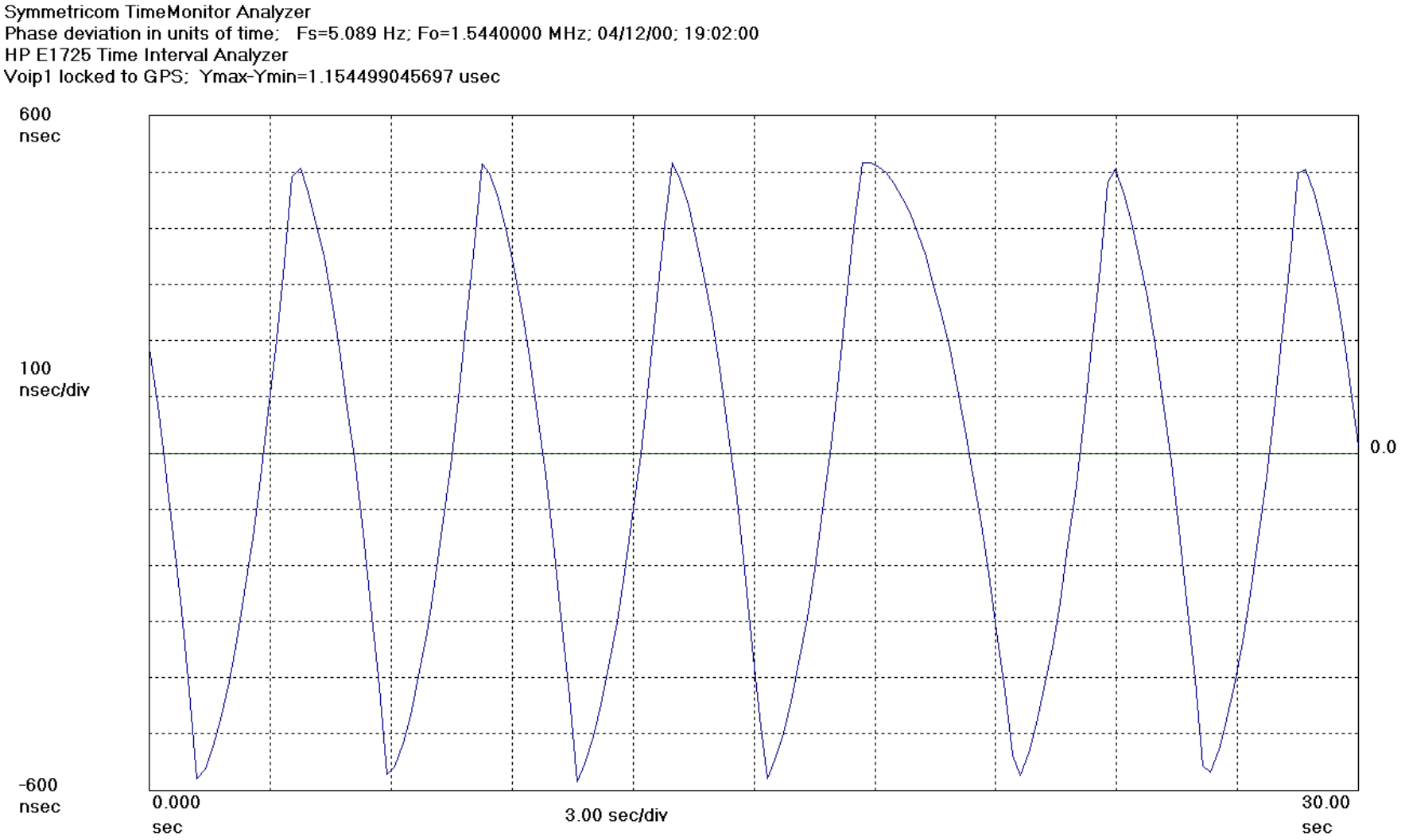
Short-term wander at 1.15 µsec peak-to-peak



Sync Measurement #8: IP Synchronization

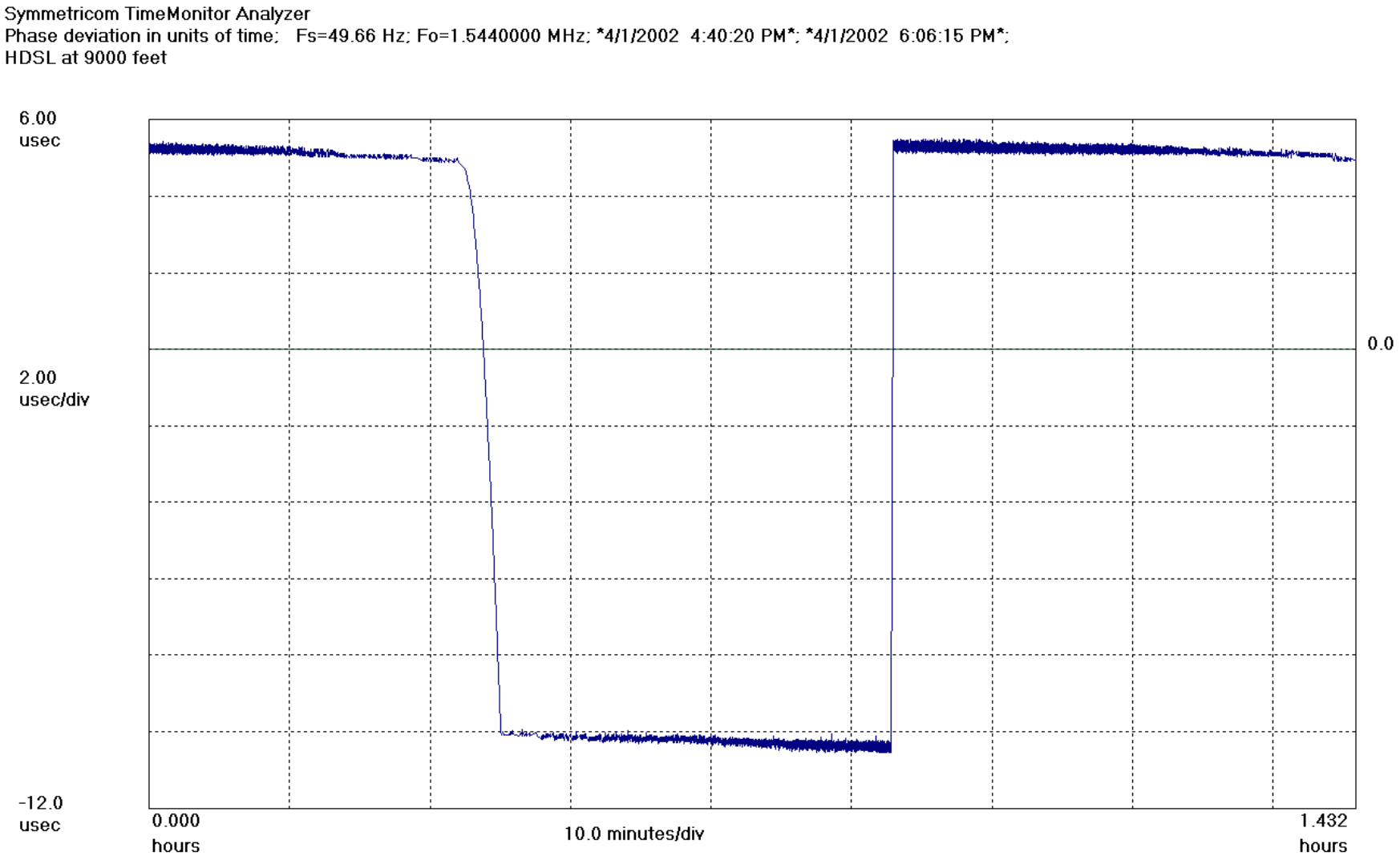
IP network access server locked to external PRS reference

Zoom into first 30 seconds: wander pattern observed



Sync Measurement #9:
HDSL: Unsuitable for Sync Transport

HDSL DS1: 15 µsec phase steps every 30 minutes

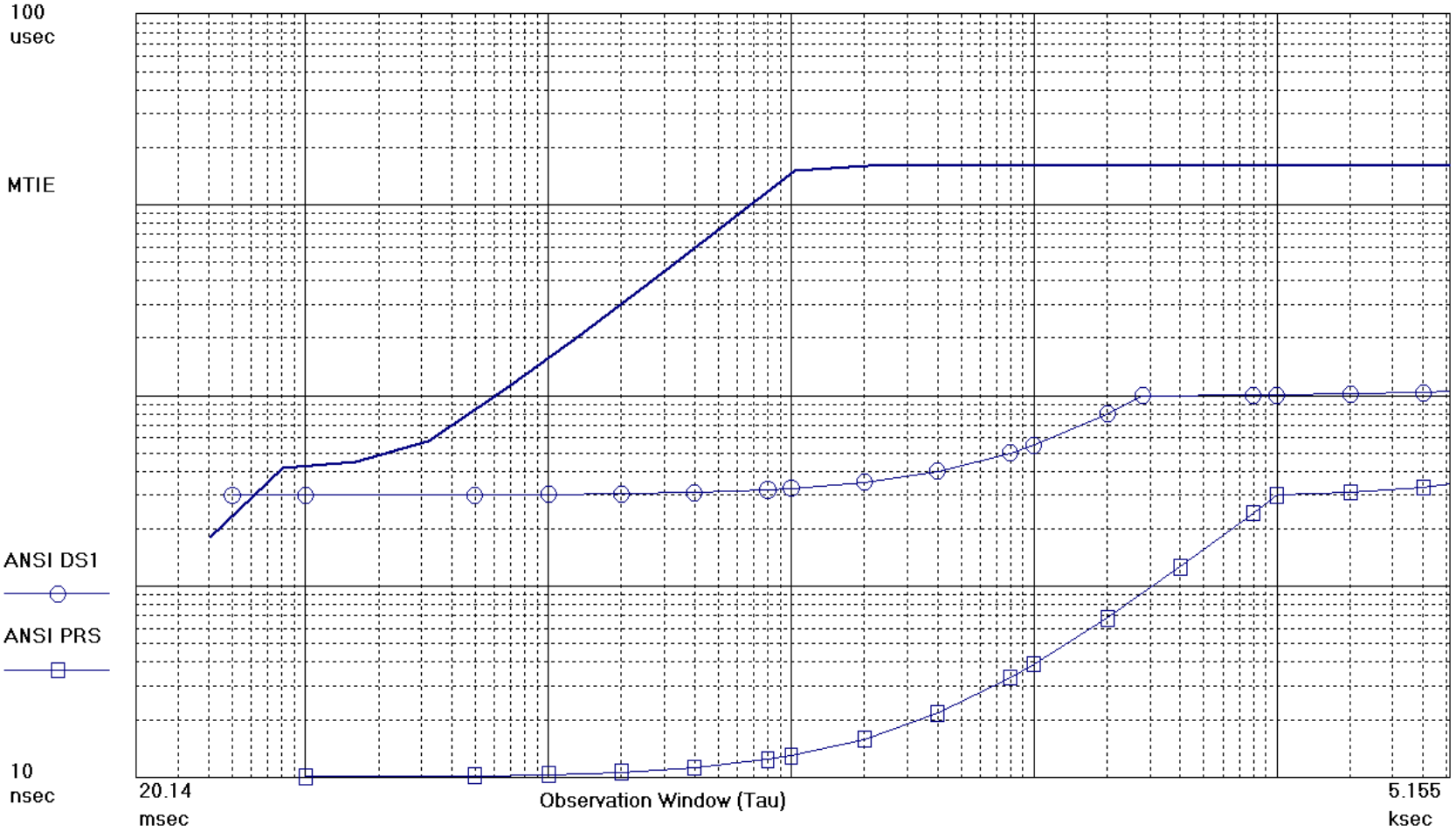


Sync Measurement #9:
HDSL: Unsuitable for Sync Transport

Symmetricom

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

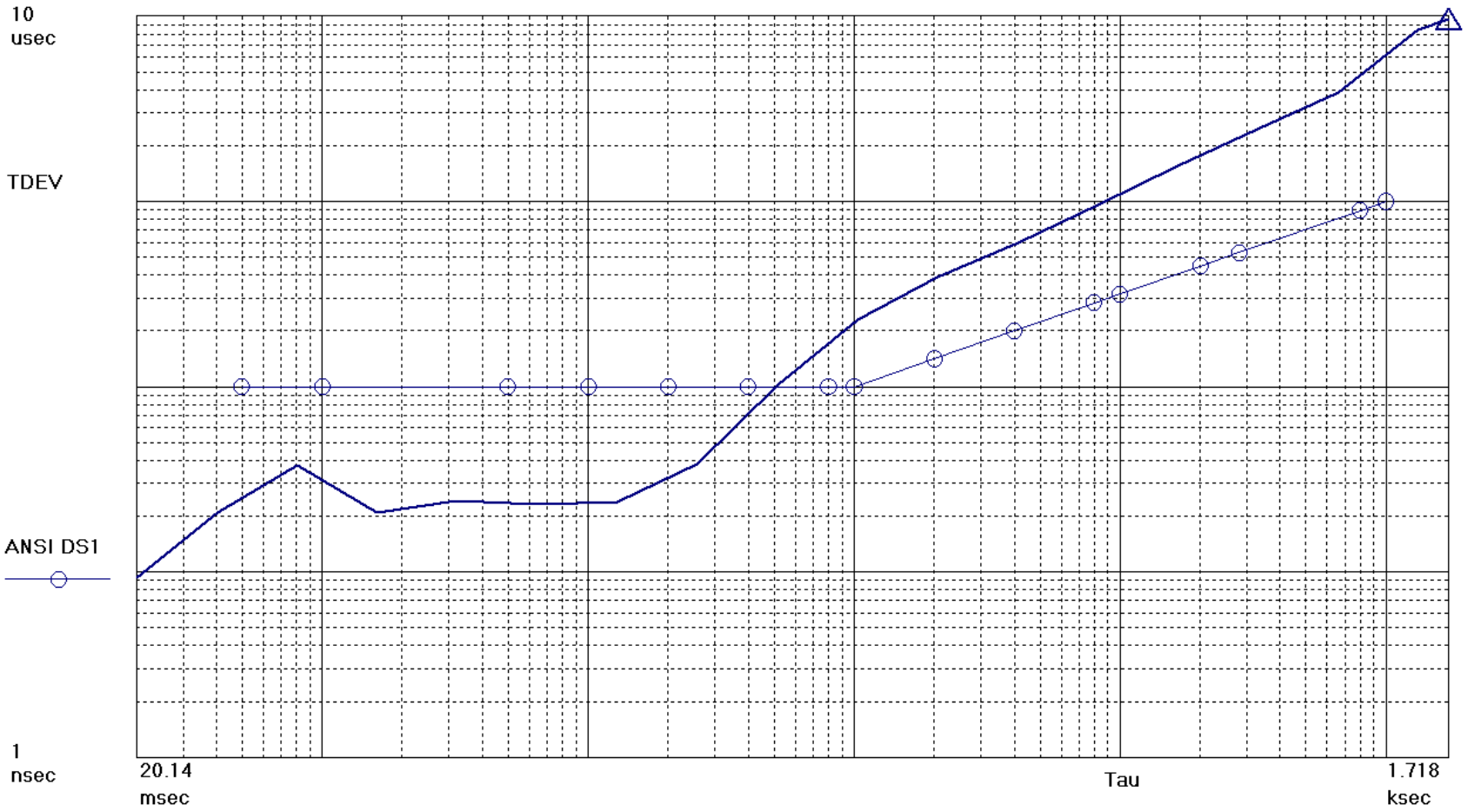


Sync Measurement #9:
HDSL: Unsuitable for Sync Transport

Symmetricom

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

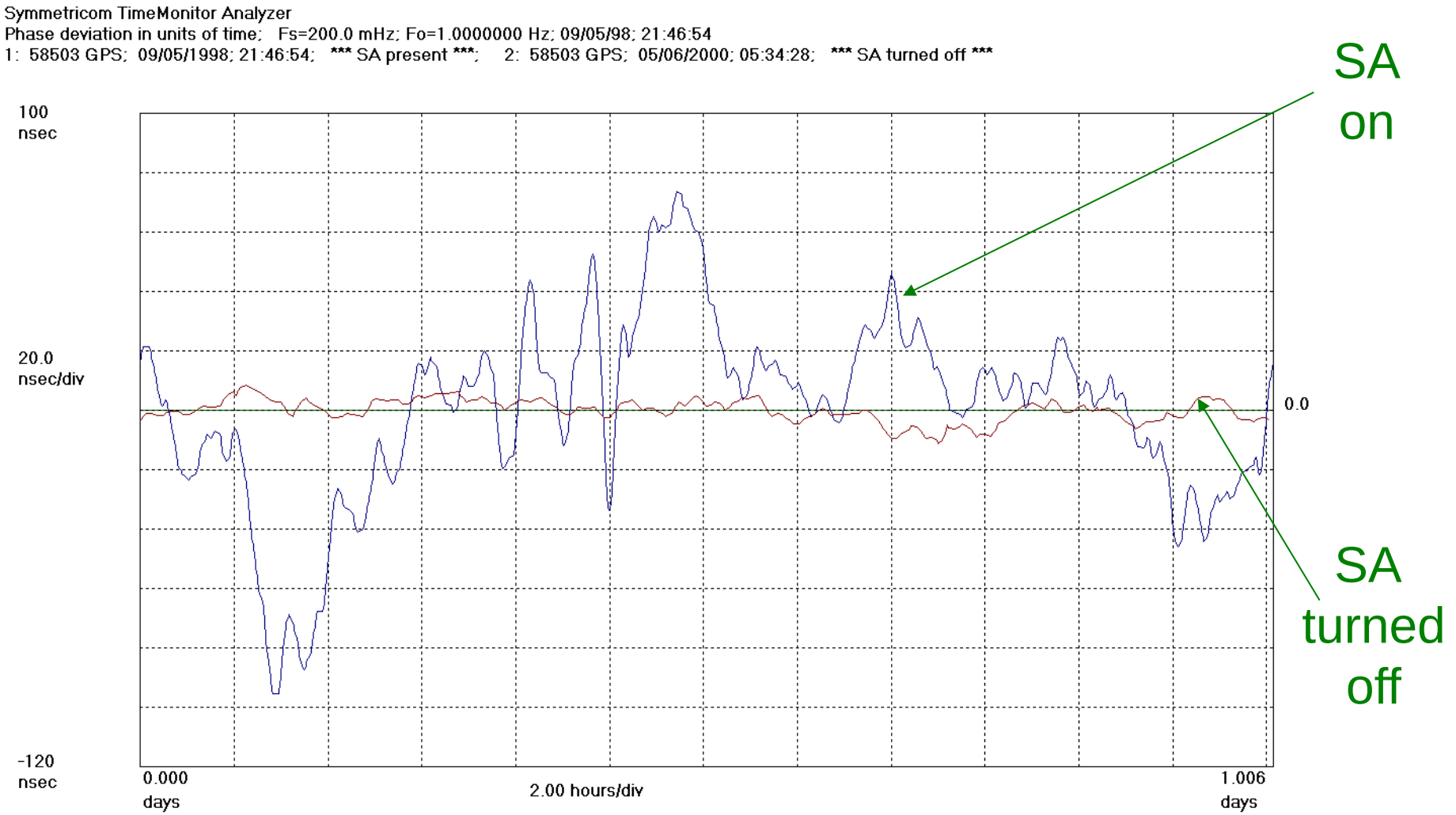
Symmetricom TimeMonitor Analyzer
TDEV; No. Avg=1; Fo=1.544 MHz; *4/1/2002 4:40:20 PM*; *4/1/2002 6:06:15 PM*;
HDSL at 9000 feet



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

Symmetricom

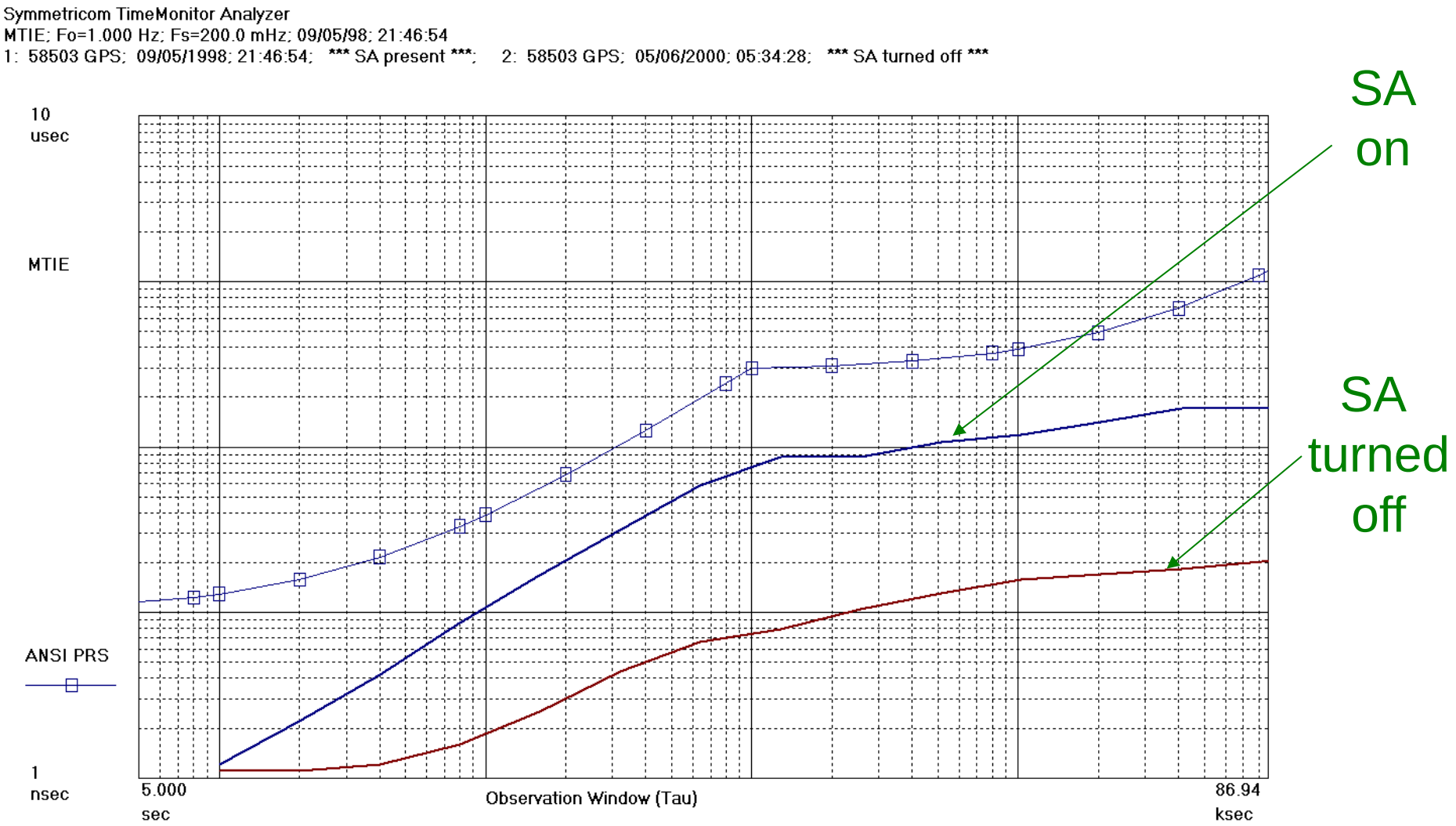
Effect of turning off SA on GPS receivers



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

Symmetricom

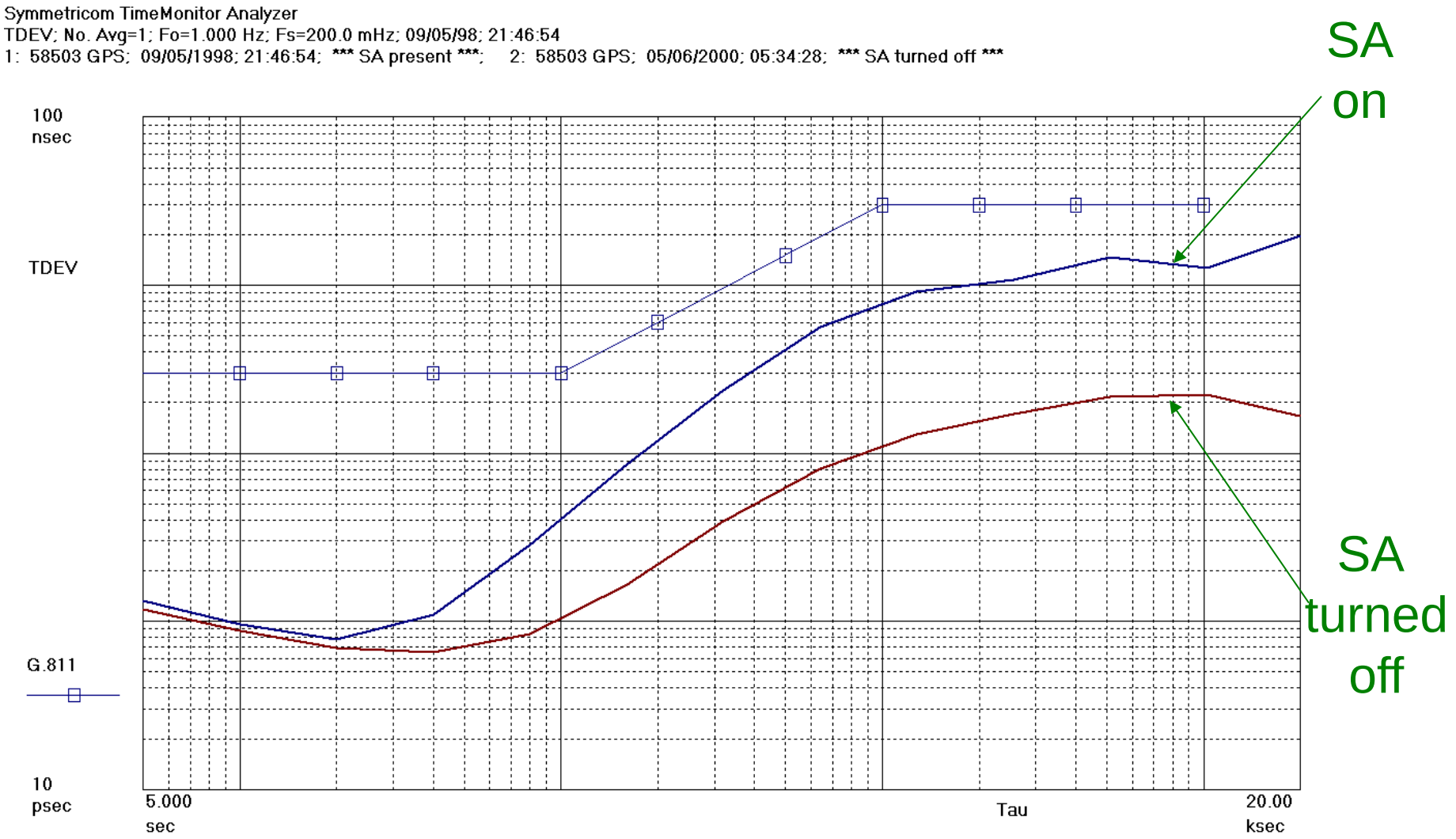
Effect of turning off SA on GPS receivers: MTIE



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

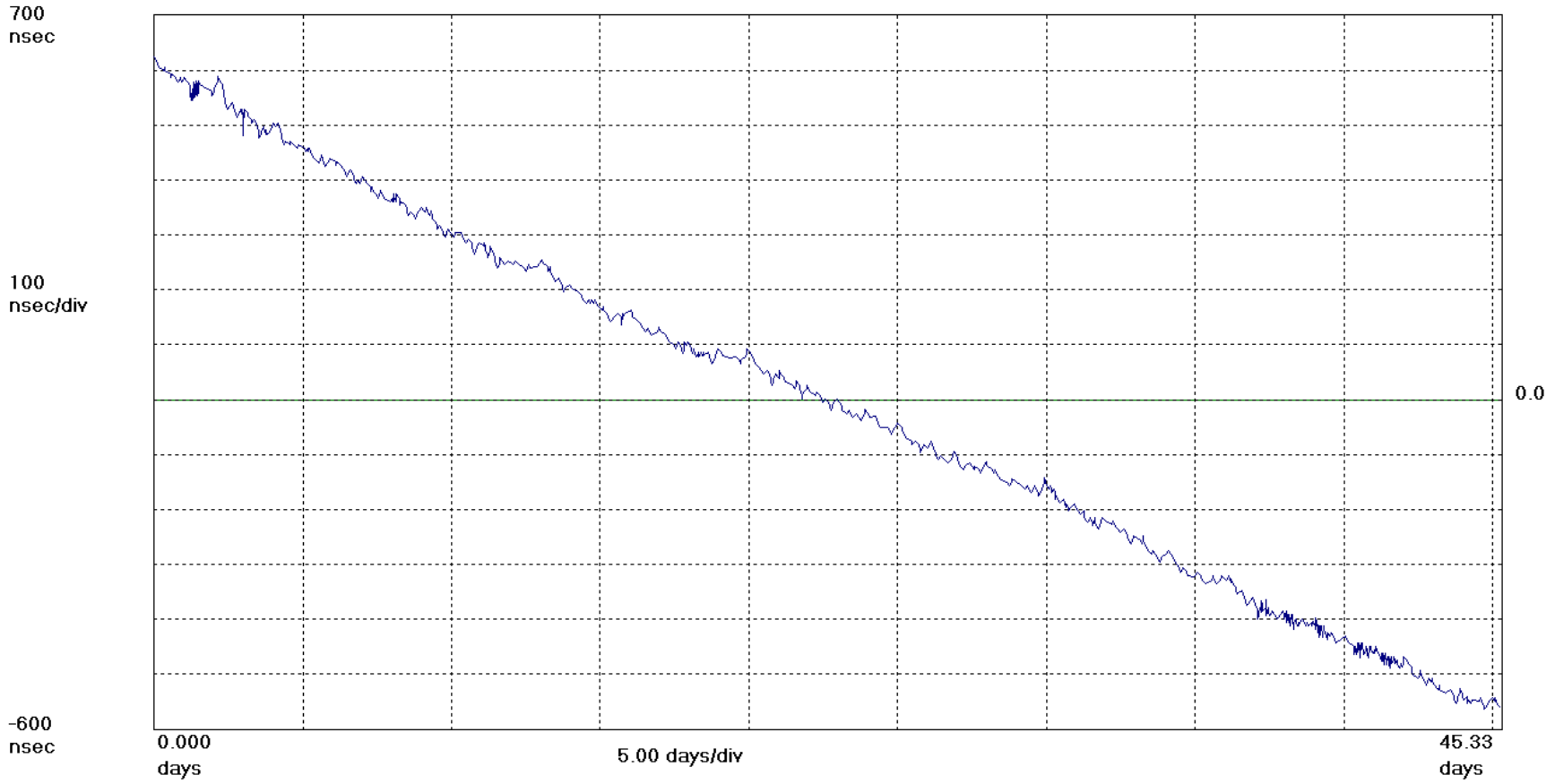
Symmetricom

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

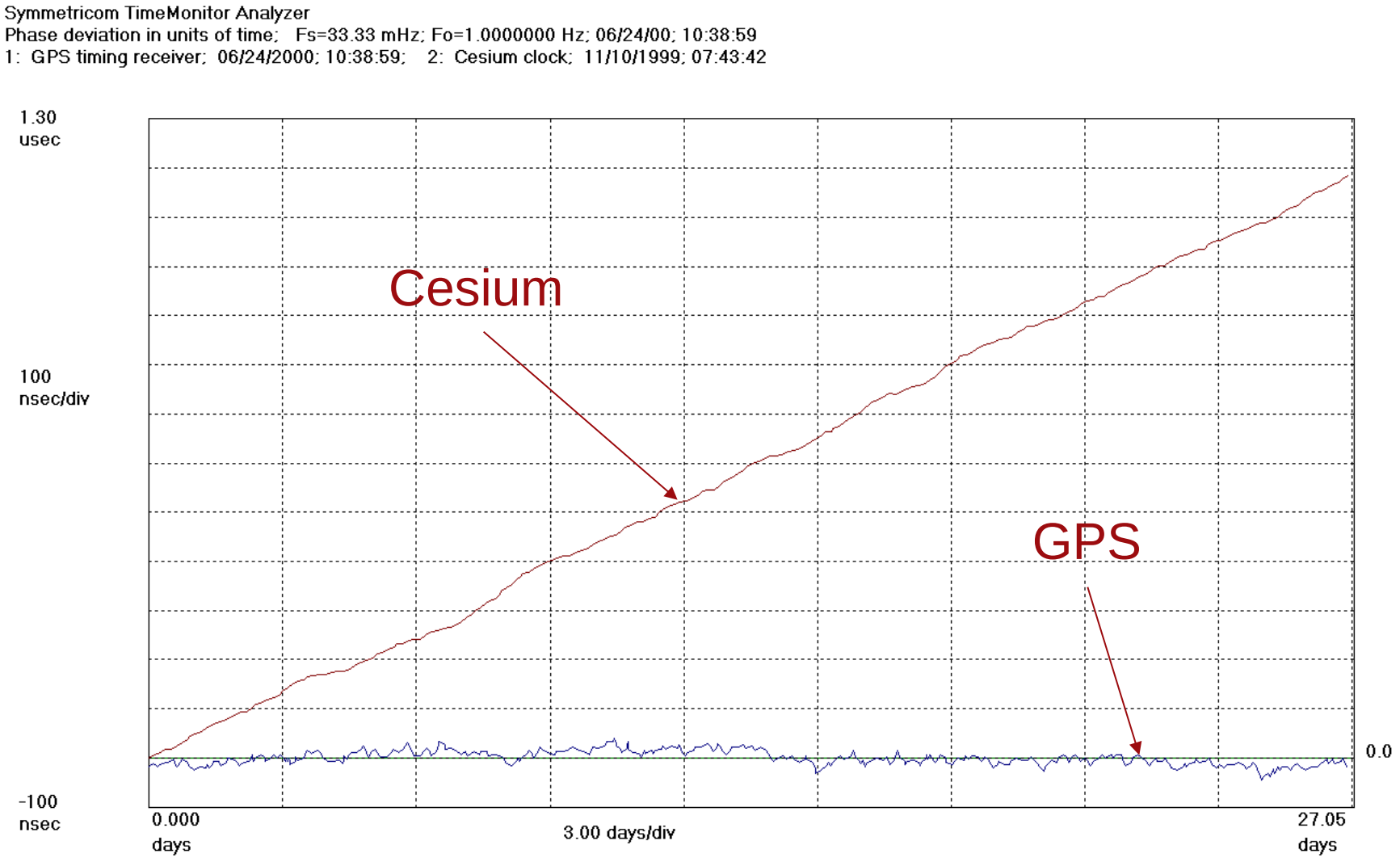
24 hour measurement: cesium can be used to measure GPS

45 day measurement: GPS can be used to measure cesium

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=33.33 mHz; Fo=1.0000000 Hz; *6/19/2000 11:09:59 AM*; *8/3/2000 7:07:14 PM*;
HP 53132A time interval counter; GPS receiver measured vs. cesium clock 45 days



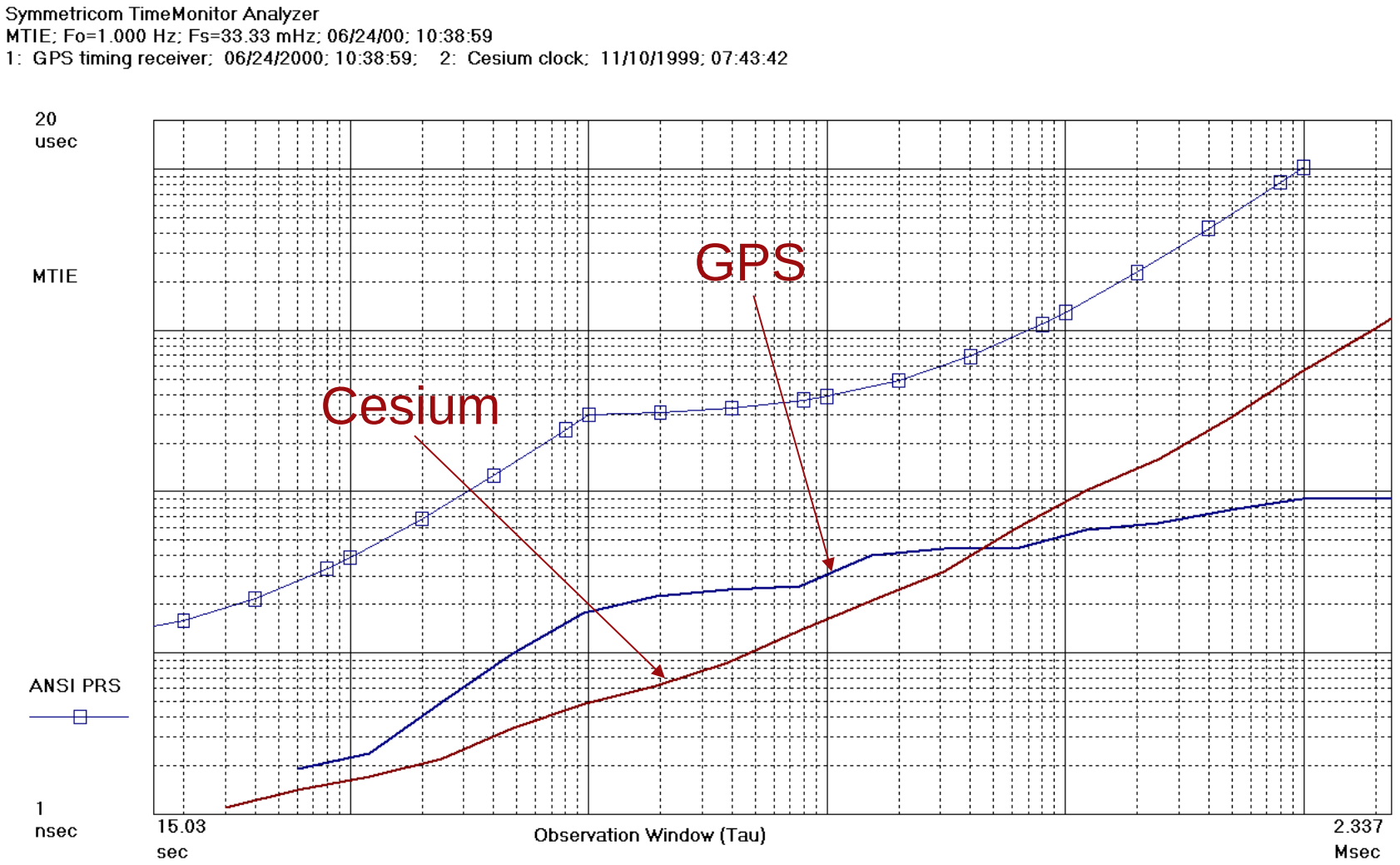
Sync Measurement #11: GPS vs. Cesium



Sync Measurement #11: GPS vs. Cesium

Intersect point at 12.7 hours

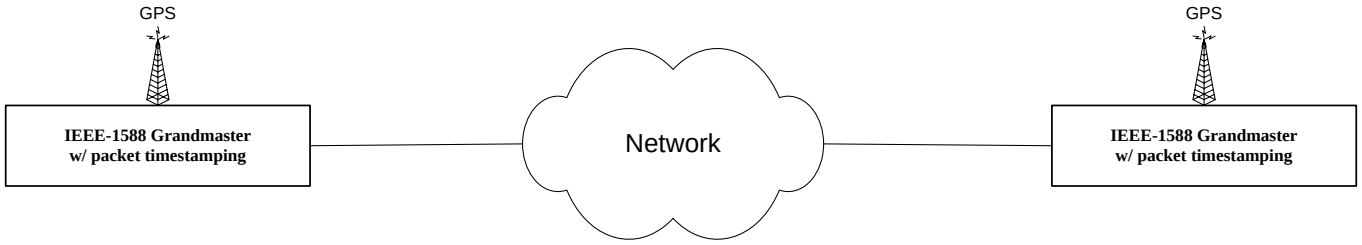
Both meet PRS requirements by a large margin



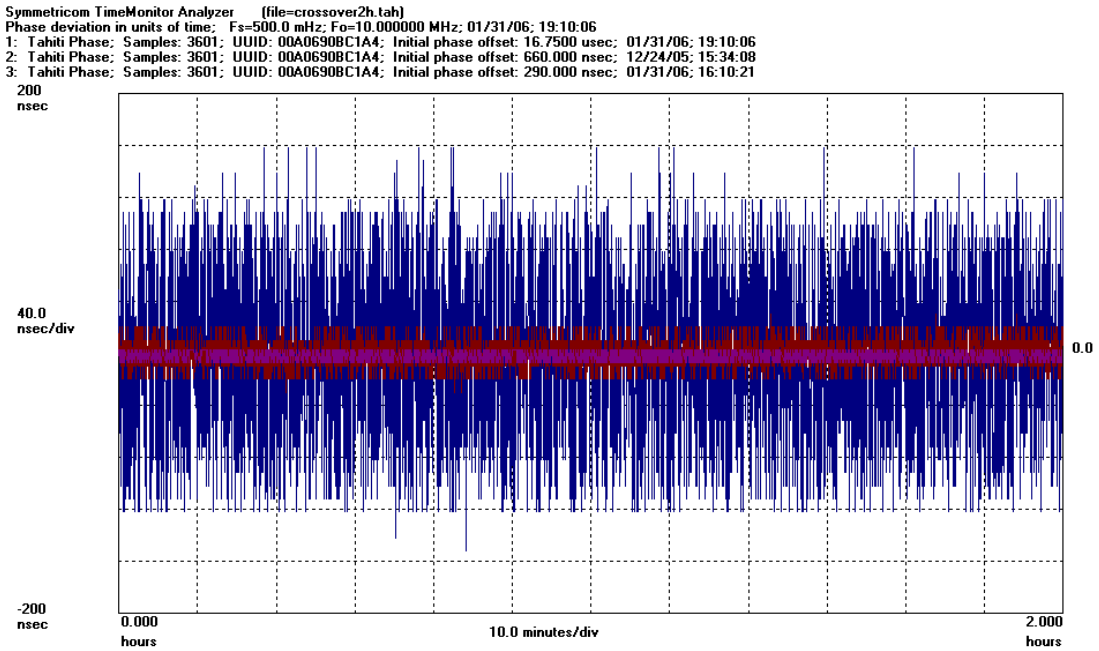
Sync Measurement #12: Packet Delay Variation Measurements

Symmetricom

PDV from timestamping at both ends of a network



Crossover cable vs. hub vs. switch



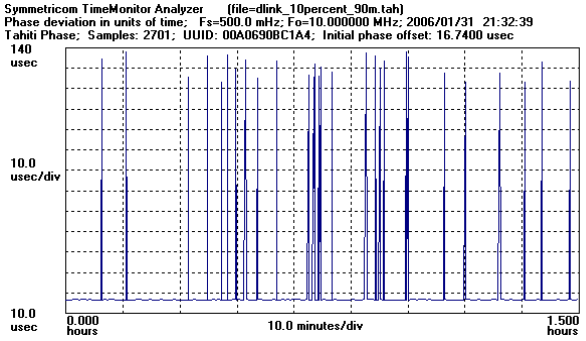
Sync Measurement #12: Packet Delay Variation Measurements

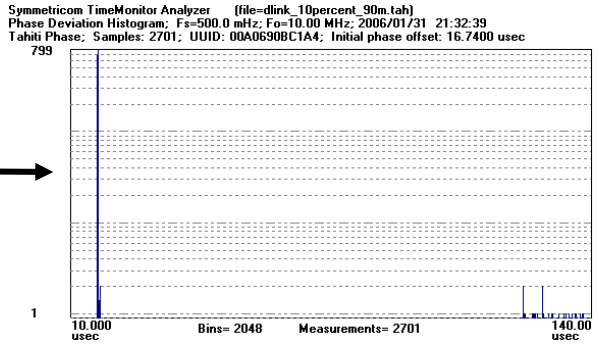
Symmetricom

Phase

With traffic

Stats





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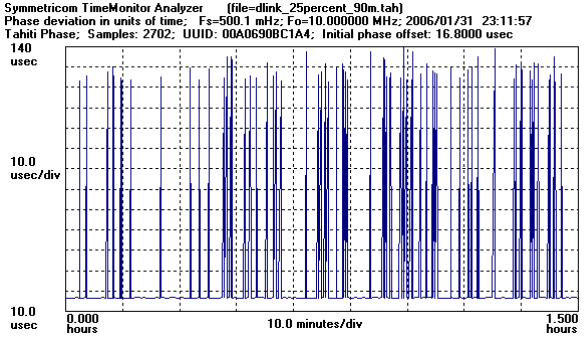

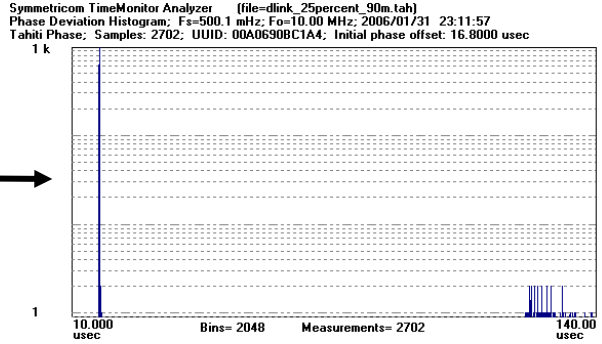

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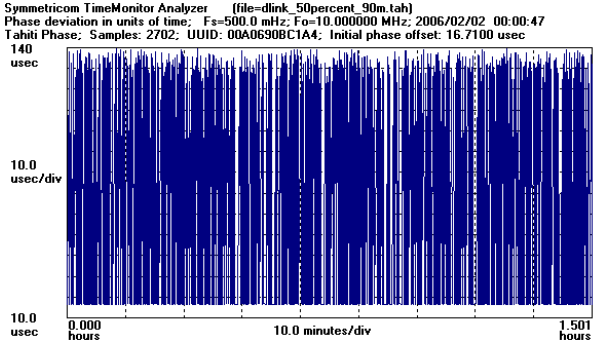

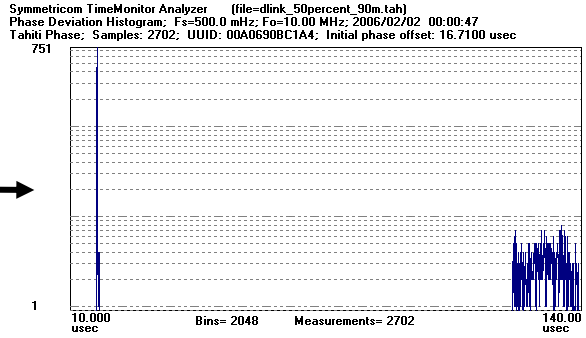

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Sync Measurement #12: Packet Delay Variation Measurements

Symmetricom

TDEV comparison