# Comparison of 802.1AS Annex B and 60802 Clock Stability

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# Outline

- Introduction
- 60802 phase and frequency variation
- Background on clock stability and TDEV
- 802.1AS (2011 and 2020) clock stability (measurements)
- Comparison of 60802 and 802.1AS clock stability
- Conclusions

# Introduction - 1

- IEC/IEEE P6802 gives the following requirements for the free-running clock in a PTP Instance:
  - Maximum fractional frequency offset: 100 ppm
  - Maximum rate of change of fractional frequency offset: 3 ppm/s
- In discussions in several 60802 meetings, one or more participants have indicated that previous simulations/analyses they or their colleagues have done assumed either sinusoidal phase and frequency variation or triangular wave phase and frequency variation, both of which meet the above requirements
- IEEE Std 802.1AS-2011, and the soon to be published 802.1AS-2020, have a TDEV requirement for clock stability of a PTP Instance in Annex B, Figure B-1
  - This requirement states that TDEV shall not exceed 5.0*$\tau$ ns, where the observation interval $\tau$ is the range 0.05 s $\leq \tau \leq$ 10 s (Table B-1/802.1AS), when measured using
    - A measurement interval that is at least 120 s (i.e., at least 12 times the longest observation interval),
    - A low-pass filter with 3 dB bandwidth of 10 Hz, first-order characteristic, and 20 dB/decade roll-off, and
    - A sampling interval that does not exceed 1/30 s.

# Introduction - 2

- The TDEV requirement (mask) of Annex B/802.1AS is based on measurements reported in [2]
  - These measurements were made for an inexpensive oscillator, intended for consumer Audio/Video applications
- The purpose of the current presentation is to compare the above 60802 clock requirements with the Annex B/802.1AS TDEV requirement

# 60802 Phase and Frequency Variation - 1

- We will consider two cases:
  - Sinusoidal frequency variation
  - Triangular wave frequency variation
- For each case, we will choose the amplitude and frequency of the variation such that
  - Maximum frequency offset = 100 ppm
  - Maximum rate of change of frequency offset = 3 ppm/s
- First, consider sinusoidal phase variation:

$$x(t) = A\sin(2\pi ft)$$

where

$A$ = amplitude of the variation (units of time)

$f$ = frequency of the variation (Hz)

$x(t)$ = phase (units of time)

# 60802 Phase and Frequency Variation - 2

- Then the frequency ($y(t)$) and rate of change of frequency are:

$$y(t) = \dot{x}(t) = 2\pi f A \cos(2\pi f t)$$

$$\dot{y}(t) = -4\pi^2 f^2 A \sin(2\pi f t)$$

- Then, if $f$ is in Hz and $A$ is in s, the maximum frequency offset and drift rate requirements give

$$2\pi f A = 10^{-4} \text{ (i.e., 100 ppm)}$$

$$4\pi^2 f^2 A = 3\times10^{-6} \text{ s}^{-1} \text{ (i.e., 3 ppm/s)}$$

# 60802 Phase and Frequency Variation - 3

- Solving the above for *f* and *A* gives

$$2\pi fA = 10^{-4} \;\; \text{(i.e., 100 ppm)}$$

$$\frac{4\pi^2 f^2 A}{2\pi fA} = 2\pi f = \frac{3\times 10^{-6}\ \text{s}^{-1}}{10^{-4}} = 0.03\ \text{s}^{-1}$$

- Then

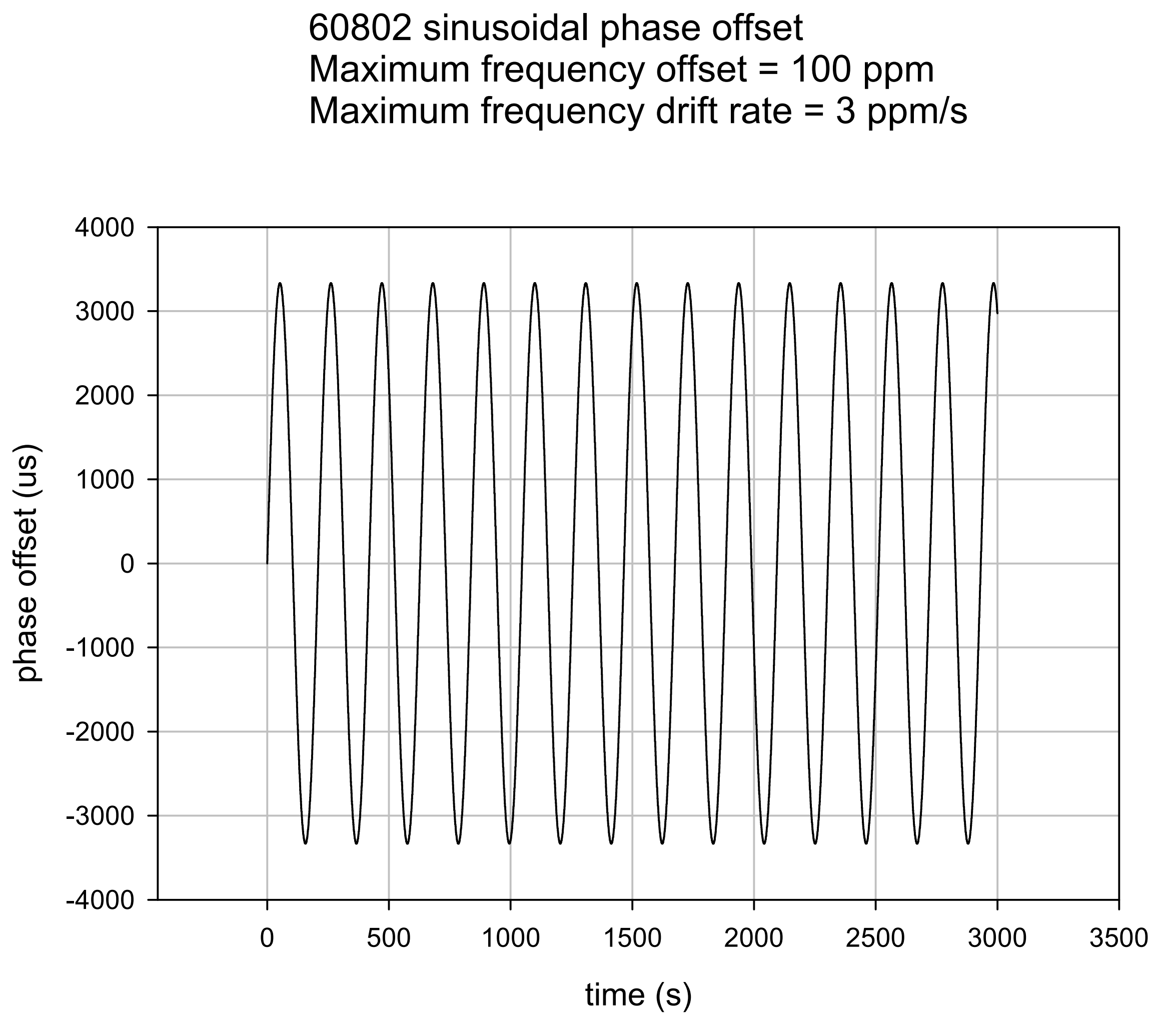
$$f = \frac{0.03}{2\pi}\ \text{Hz} = 4.7746\times 10^{-3}\ \text{Hz} = 4.7746\ \text{mHz}$$

$$2\pi fA = 0.03A = 10^{-4}$$

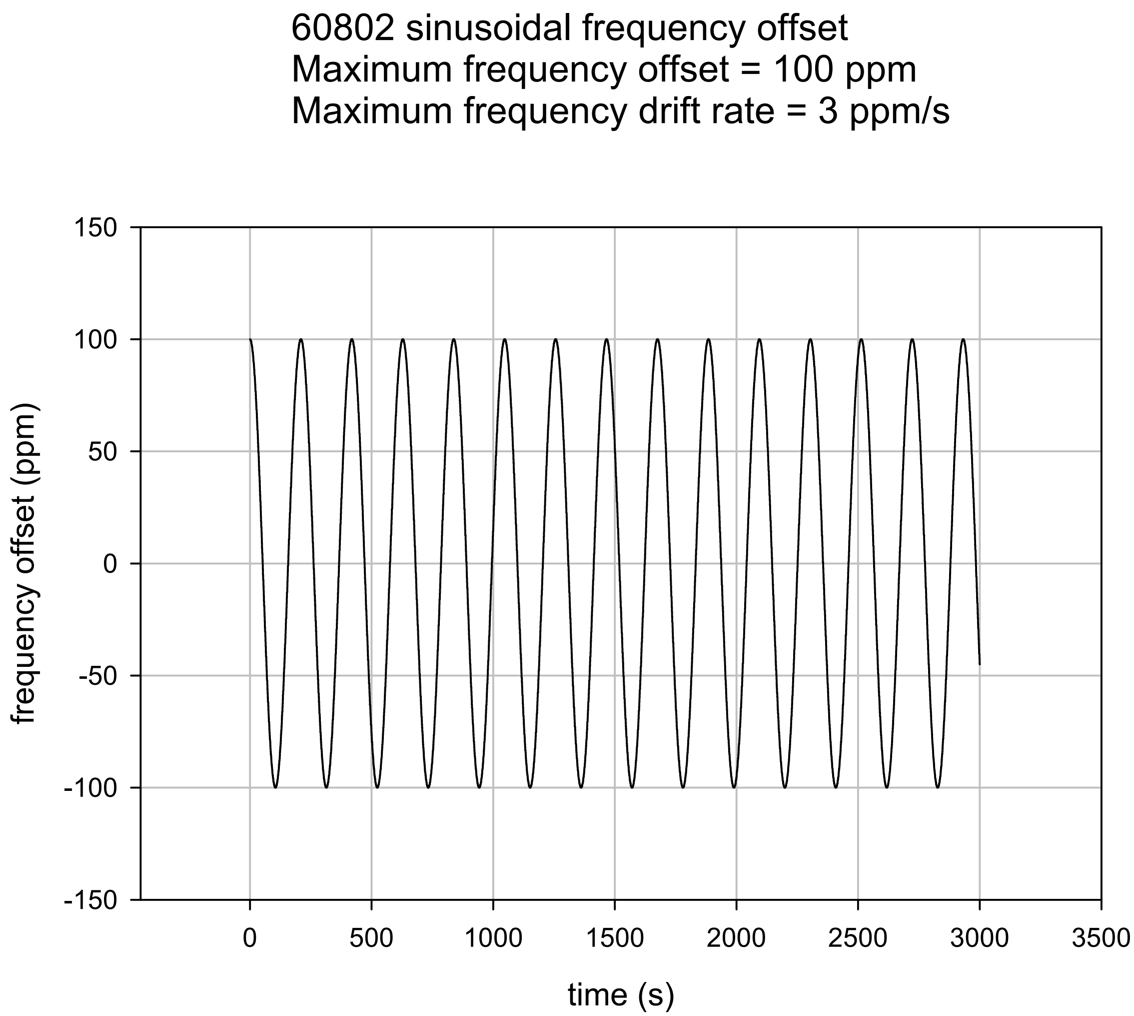
$$A = \frac{10^{-4}}{0.03}\ \text{s} = 0.00333\ \text{s} = 3.33\ \text{ms}$$

- Note that the phase variation has relatively large amplitude and low frequency; plots of phase and frequency variation are on the following slides

# 60802 Phase and Frequency Variation - 4

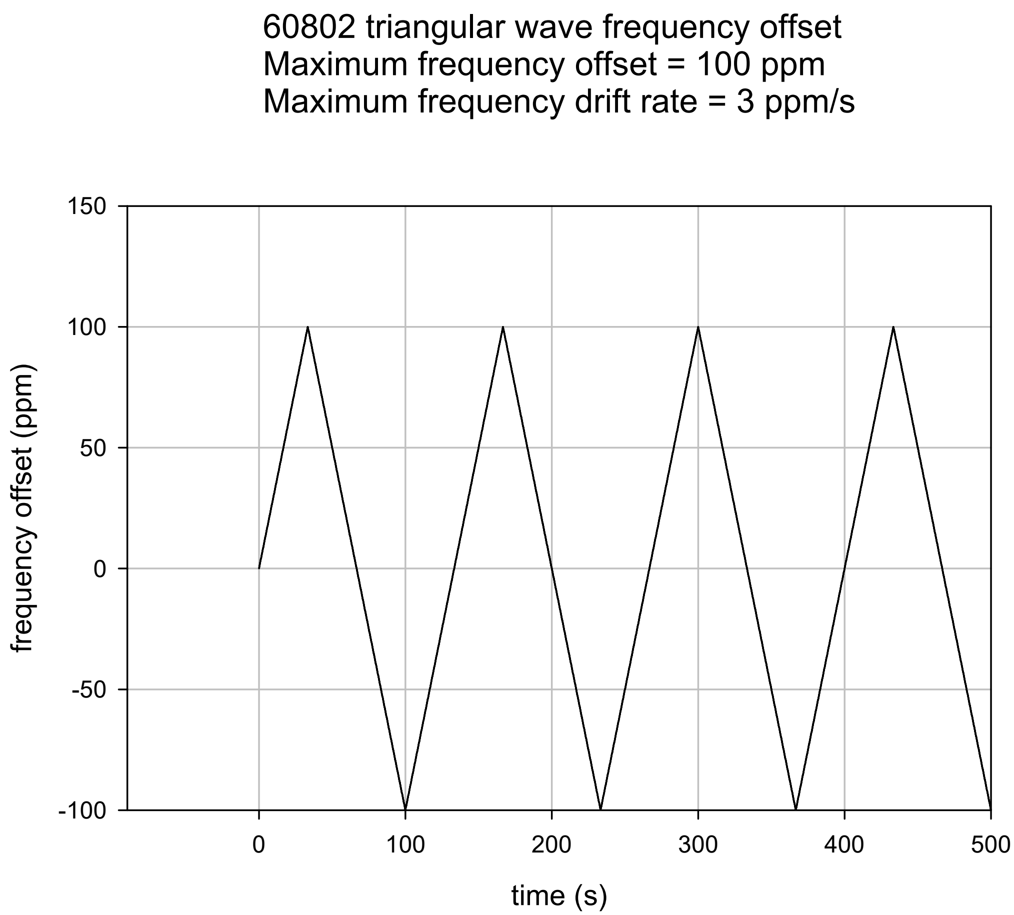


# 60802 Phase and Frequency Variation - 5



# 60802 Phase and Frequency Variation - 6

- Next, consider triangular wave frequency variation:
- The frequency variation is (shown for the first 500 s):



# 60802 Phase and Frequency Variation - 7

- The frequency variation for one period of the triangular wave is given by:

$$y(t) = \begin{cases} mt & 0 \le t \le T_4 \\ A - m(t - T_4) & T_4 < t \le 3T_4 \\ -A + m(t - 3T_4) & 3T_4 < t \le T \end{cases}$$

where

$A =$ amplitude of frequency variation (100 ppm)

$T =$ period of frequency variation ((4)[100 ppm/(3 ppm/s)] = 133.3 s)

$T_4 = T/4 = 33.3$ s

$m = A/T_4 = 3$ppm/s (frequency rate of change)

- The above variation repeats for each cycle
- The phase variation is obtained by integrating the above with respect to time; the result is (see next slide)

# 60802 Phase and Frequency Variation - 8

$$x(t) = \begin{cases} (1/2)mt^2 & 0 \le t \le T_4 \\ mT_4^2 + 2A(t - T_4) - (1/2)mt^2 & T_4 < t \le 3T_4 \\ -4mT_4^2 - 4A(t - 3T_4) + (1/2)mt^2 & 3T_4 < t \le T \end{cases}$$

where

$A =$ amplitude of frequency variation (100 ppm)

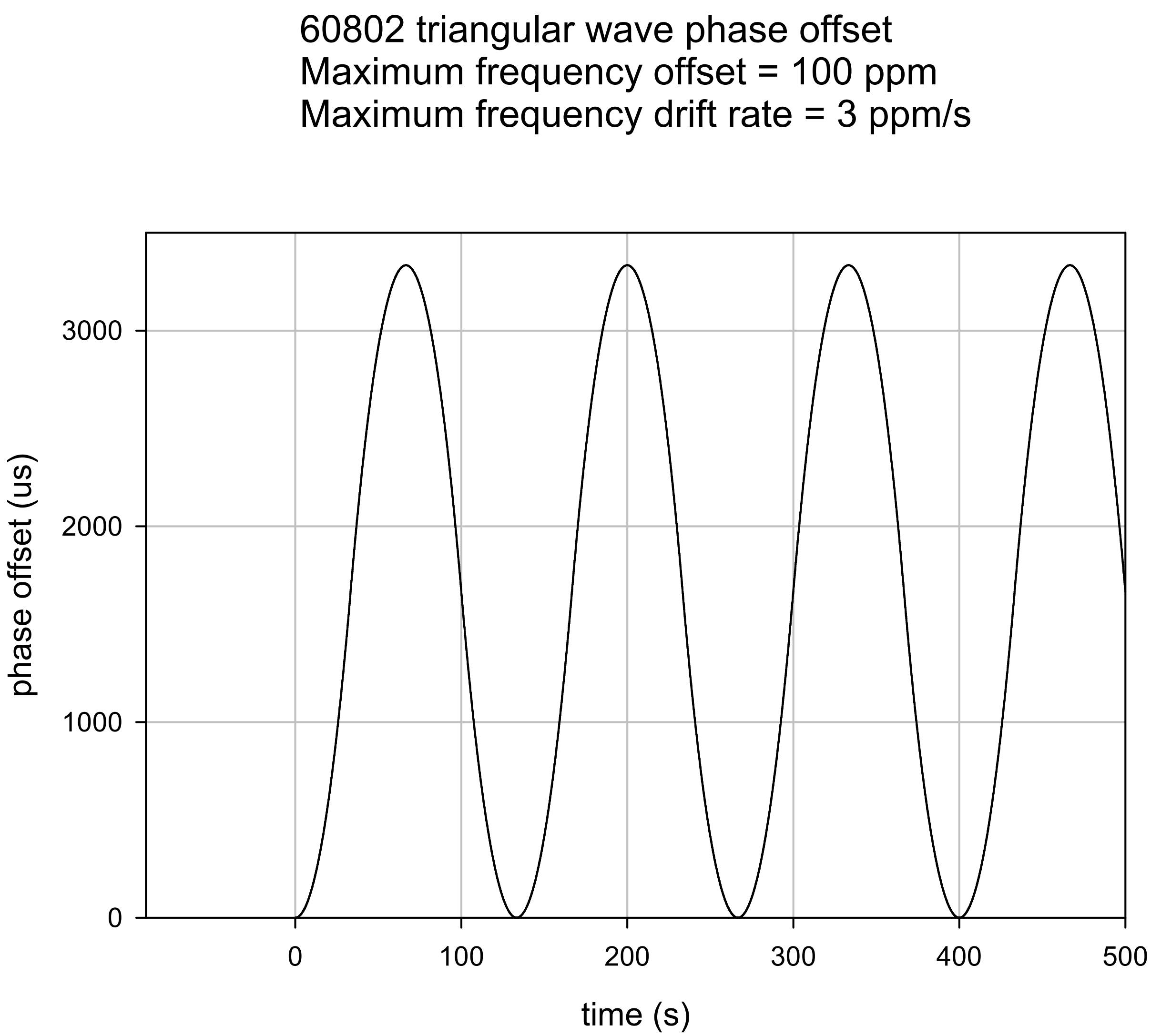
$T =$ period of frequency variation ((4)[100 ppm/(3 ppm/s)] = 133.3 s)

$T_4 = T/4 = 33.3$ s

$m = A/T_4 = 3$ppm/s (frequency rate of change)

- The above variation repeats for each cycle
- The phase variation is shown on the next slide for the first 500 s
- Note that the phase offset for the sinusoidal and triangular wave cases have similar behavior (with different amplitudes and periods)

# 60802 Phase and Frequency Variation - 9



# Background on Clock Stability and TDEV - 1

- Most of the material in this section (slides 10-30) is taken from [3]
- It is presented here because many current participants of 802.1, and most IEC participants, were not attending 802.1 when [3] was originally presented (in July 2010)
- References [4], [5], and [8] contain a great deal of background material and cite many additional references
- The current presentation does not cover the material in [3] on simulation of power-law noise processes, as that material is needed here
  - That material will be needed for future presentations that present simulations

# Background on Clock Stability and TDEV - 2

- Clock phase noise is typically modeled as a sum of random processes with one-sided power spectral density (PSD) of the form $Af^{-\alpha}$
- In the most general case usually considered in practice, 5 terms are considered (see [4] and [5])
  - $\alpha$ = 0, White Phase Modulation (WPM)
  - $\alpha$ = 1, Flicker Phase Modulation (FPM)
  - $\alpha$ = 2, White Frequency Modulation (WFM)
  - $\alpha$ = 3, Flicker Frequency Modulation (FFM)
  - $\alpha$ = 4, Random-Walk Frequency Modulation (RWFM)
- Can write the PSD, $S_x(f)$ as

$$S_x(f) = \frac{A}{f^4} + \frac{B}{f^3} + \frac{C}{f^2} + \frac{D}{f} + E, \text{ where } S_x(f) \text{ has units of } \text{ns}^2/\text{Hz}$$

  - Often express as ($\nu_0$ = nominal clock frequency)

$$S_\phi(f) = (2\pi\nu_0)^2 S_x(f), \text{ where units of } S_\phi(f) \text{ are } \text{rad}^2/\text{Hz}$$

- The above processes are non-stationary; background on PSD for non-stationary processes is given in [8]

# Background on Clock Stability and TDEV - 3

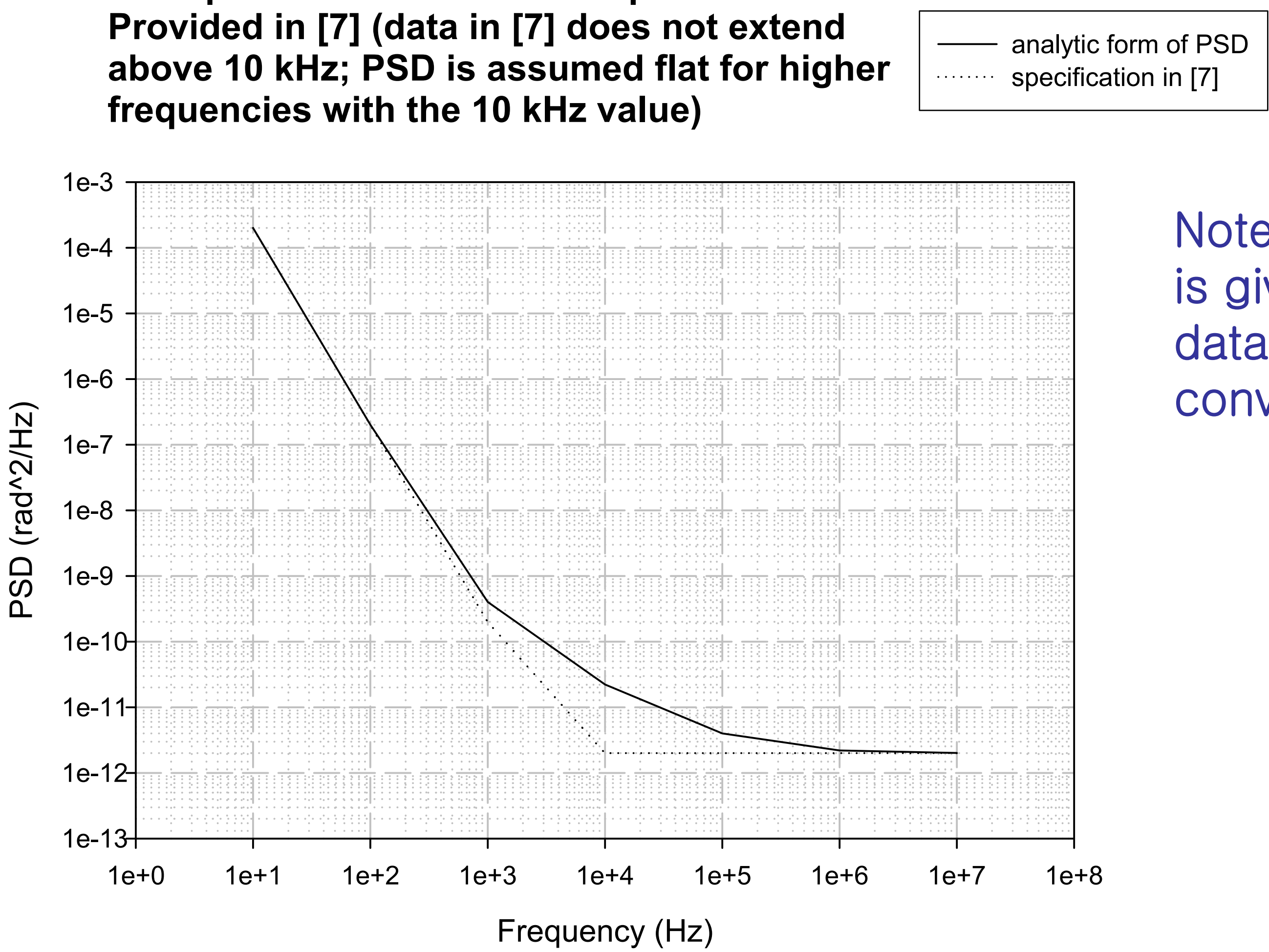
- Often, the one-sided PSD $S_\phi(f)$ is expressed in dBc/Hz, using the conversion

$$S_\phi(f)\ [\text{dBc/Hz}] = 10\log_{10}\{S_\phi(f)\ [\text{rad}^2/\text{Hz}]\}$$

  - Must be careful on whether the PSD is one-sided or two-sided; respective equations will contain additional factors of 2 in converting between them
  - An example PSD specification is given in Figure 12 of [7], and reproduced on the next slide (note that a similar example is given in Figure 2 of [6])
    - Data in [7] is given in dBc/Hz; data has been converted to $\text{rad}^2$/Hz
    - Data in [7] is given only for frequencies below 10 kHz; here, we assume the PSD is flat above 10 kHz
    - Dotted curve on the next slide is the converted data of [7]; solid line is a conservative fit of the above power law sum
- The above example specification contains WPM, FPM, and FFM terms
  - In the wander region ($f \le 10$ hz), the FFM term ($B/f^3$) dominates
  - The 802.1AS wander generation specification is base on FFM behavior

# Background on Clock Stability and TDEV - 4

**Example Clock Phase Noise Specification Provided in [7] (data in [7] does not extend above 10 kHz; PSD is assumed flat for higher frequencies with the 10 kHz value)**




Note: Data in [7] is given in dBc/Hz; data has been converted to rad$^2$/Hz

# Background on Clock Stability and TDEV - 5

- Another measure for clock noise, which is more convenient because it is a time domain parameter, is Time Variance (TVAR) [4], [5]
  - Time Deviation (TDEV) is the square root of TVAR
- TVAR is 1/6 times the expectation of the square of the second difference of the phase error averaged over an interval
  - TVAR is related to Modified Allan Variance (MVAR) (see next slide), which is in turn a generalization of Allan Variance (AVAR)

$$\mathrm{TVAR}(\tau) = \frac{1}{6} E\left[\left(\Delta^2 \bar{x}\right)^2\right]$$

where $E[\cdot]$ denotes expectation,

$\bar{x}$ denotes average over the integration time $\tau$,

and $\Delta^2$ denotes second difference

# Background on Clock Stability and TDEV - 6

- TVAR may be estimated from measured or simulated data using [5]

$$\text{TVAR}(n\tau_0) = \frac{1}{6n^2(N-3n+1)} \sum_{j=1}^{N-3n+1} \left[ \sum_{i=j}^{n+j-1} (x_{i+2n} - 2x_{i+n} + x_i) \right]^2, \quad \text{n} = 1, 2, \ldots, \text{integer part}(N/3)$$

where $\tau_0$ is the sampling interval and $\tau = N\tau_0$

- TVAR is equal to $\tau^2/3$ multiplied by the Modified Allan Variance
- For power-law noises with PSD proportional to $f^{-\alpha}$, TVAR is proportional to $\tau^\beta$, where $\beta = \alpha - 1$
- Note also that PTP Variance in 1588 (from which offsetScaledLogVariance is obtained) is equal to $\tau^2/3$ multiplied by the Allan Variance

# Background on Clock Stability and TDEV - 7

- The magnitude of TVAR may be related to the magnitude of PSD for power-law noises; see [4] and [5] for details

  - FFM $S_x(f) = \frac{B}{f^3}$ $\quad \mathrm{TVAR}(\tau) = \frac{(2\pi)^2 9 \ln 2}{20} B\tau^2$

  - WFM $S_x(f) = \frac{C}{f^3}$ $\quad \mathrm{TVAR}(\tau) = \frac{(2\pi)^2}{12} C\tau$

  - FPM (result is from [4]; a more exact expression is given in [5])

    $S_x(f) = \frac{D}{f}$ $\quad \mathrm{TVAR}(\tau) = \frac{3.37}{3} D$

  - WPM $S_x(f) = E$ $\quad \mathrm{TVAR}(\tau) = \frac{\tau_0 f_h}{\tau} E$

$f_h$ = noise bandwidth

# Background on Clock Stability and TDEV - 8

- TVAR and TDEV (or Allan Variance or Modified Allan Variance) are used to characterized phase noise in oscillators rather than classical variance
  - The time-domain estimator for classical variance diverges for some power-law noise processes
  - The time-domain estimators for TVAR, Allan Variance, and Modified Allan Variance converge for all power-law noise processes
- For the 802.1AS Annex B, Figure B-1 TDEV mask

$$\mathrm{TDEV}(\tau) = 5\times 10^{-9}\tau \qquad 0.05\,\mathrm{s} \le \tau \le 10\,\mathrm{s}$$

$$\frac{(2\pi)^2 9\ln 2}{20} B = (5\times 10^{-9})^2$$

$$B = \frac{(5\times 10^{-9})^2 (20)}{(2\pi)^2 9\ln 2} \quad \mathrm{s}^2/\mathrm{Hz} = 2.0302\times 10^{-18} \quad \mathrm{s}^2/\mathrm{Hz}$$

$$B = 2.0302 \quad \mathrm{ns}^2/\mathrm{Hz}$$

# 802.1AS Clock Stability

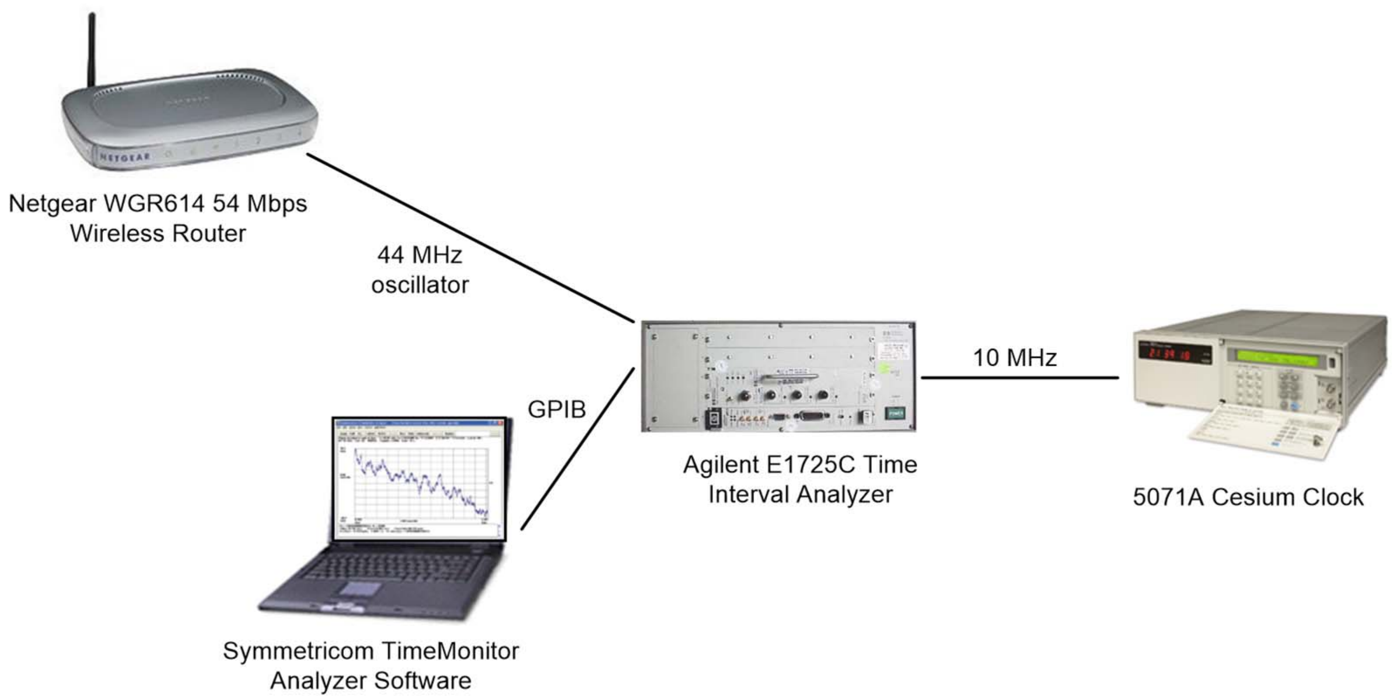
- This section describes the measurements of [2], on which the current Annex B/802.1AS TDEV requirement is based
- The slides are reproduced from [2], with minor modifications (e.g., updating of footers)
- The intent was to measure the wander performance of an inexpensive, oscillator that might be used in a consumer-grade product (in this case a consumer-grade wireless router)
- Note that at the time the measurements were made, the draft 802.1AS TDEV requirement (mask) was one-half its current value, i.e., its level was 2.5*$\tau$ ns, rather than 5* $\tau$ ns (i.e., it was more stringent)
  - As a result of these measurements, the mask level was doubled, i.e., the requirement was made less stringent
  - Subsequent simulations were run using the new mask
- The author of the current presentation would like to acknowledge Lee Cosart (the first author of [2]), who made the measurements

# Measurement Setup – 1

- The measurement was made using an Agilent E1725C Time Interval Analyzer
  - Measurement data collected and analyzed using Symmetricom TimeMonitor Analyzer software
  - E1725C has a single shot timing resolution of 50 ps, more than adequate for this test
- A 10 MHz reference was supplied to the time interval analyzer from a 5071A Cesium clock
- The measured oscillator was contained in a consumer-grade wireless router product – the Netgear WGR614 54 Mbps Wireless Router
  - 802.11g wireless
  - 4 10/100 Mbit/s Ethernet LAN ports
  - 1 10/100 Mbit/s Ethernet WAN port
  - The measurements were made on one sample device (i.e., one unit)
- The oscillator was accessed by removing the top of the wireless router and using an oscilloscope probe

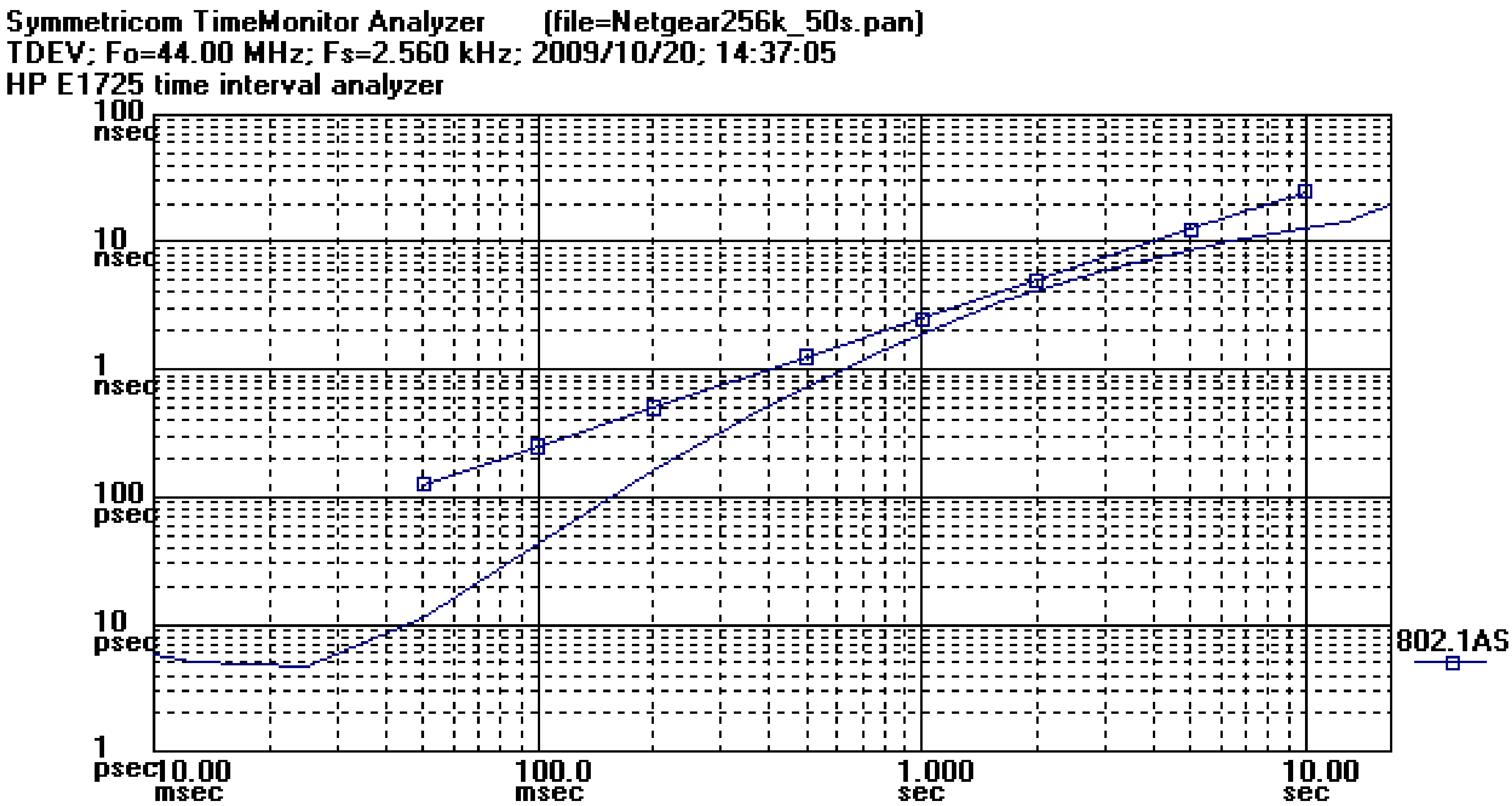
# Measurement Setup - 2

- Initially, samples were collected over 50 s at a rate of 2.5 kHz
  - Later test used 1000 s measurement interval
- Timestamps were converted to phase deviation, for the TDEV calculation
- The measured oscillator frequency was approximately 44 MHz



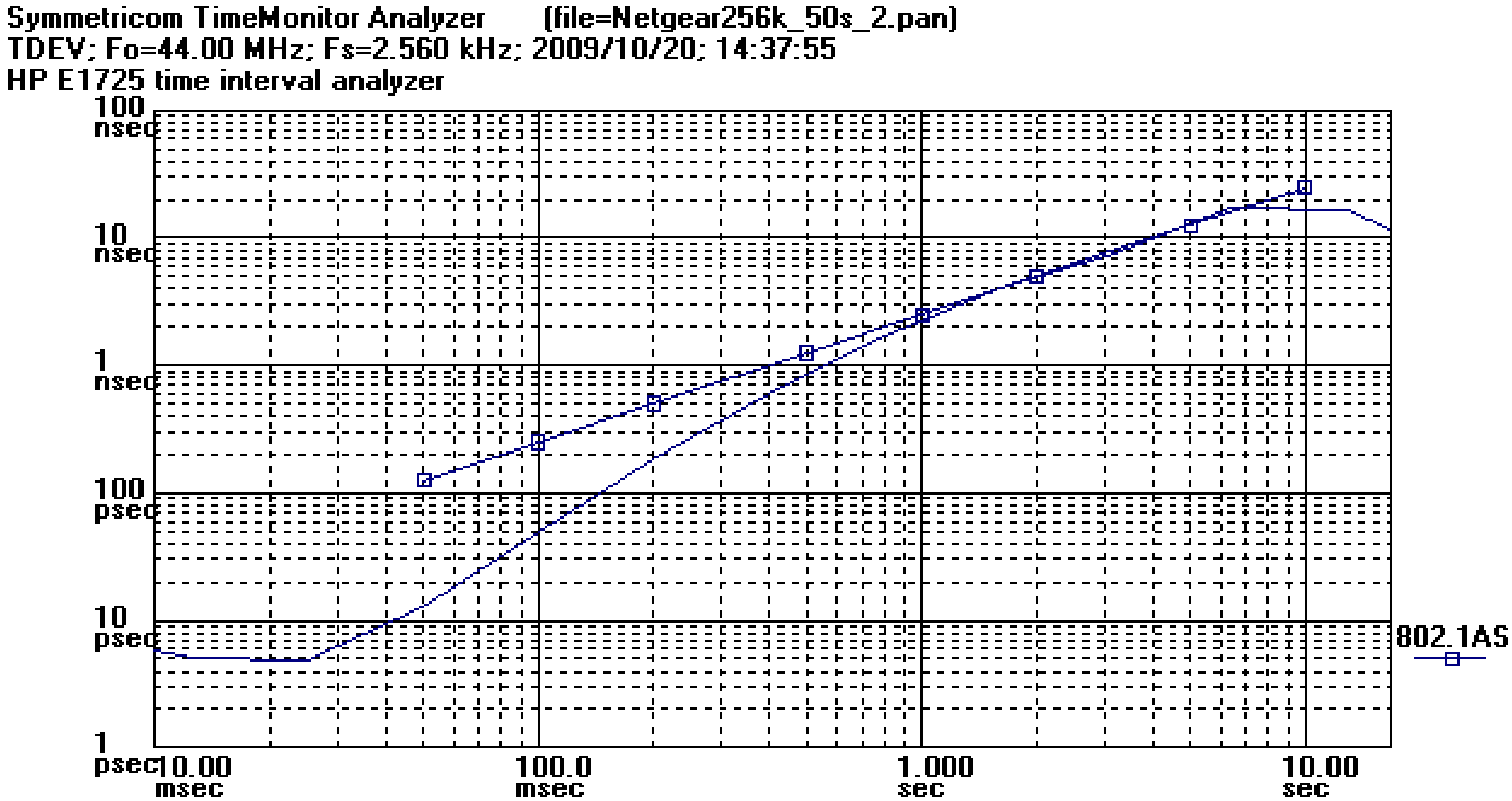
# Measurement Results – 1

- TDEV result – first 50 s measurement
  - Passes, though not with a large margin



# Measurement Results - 2

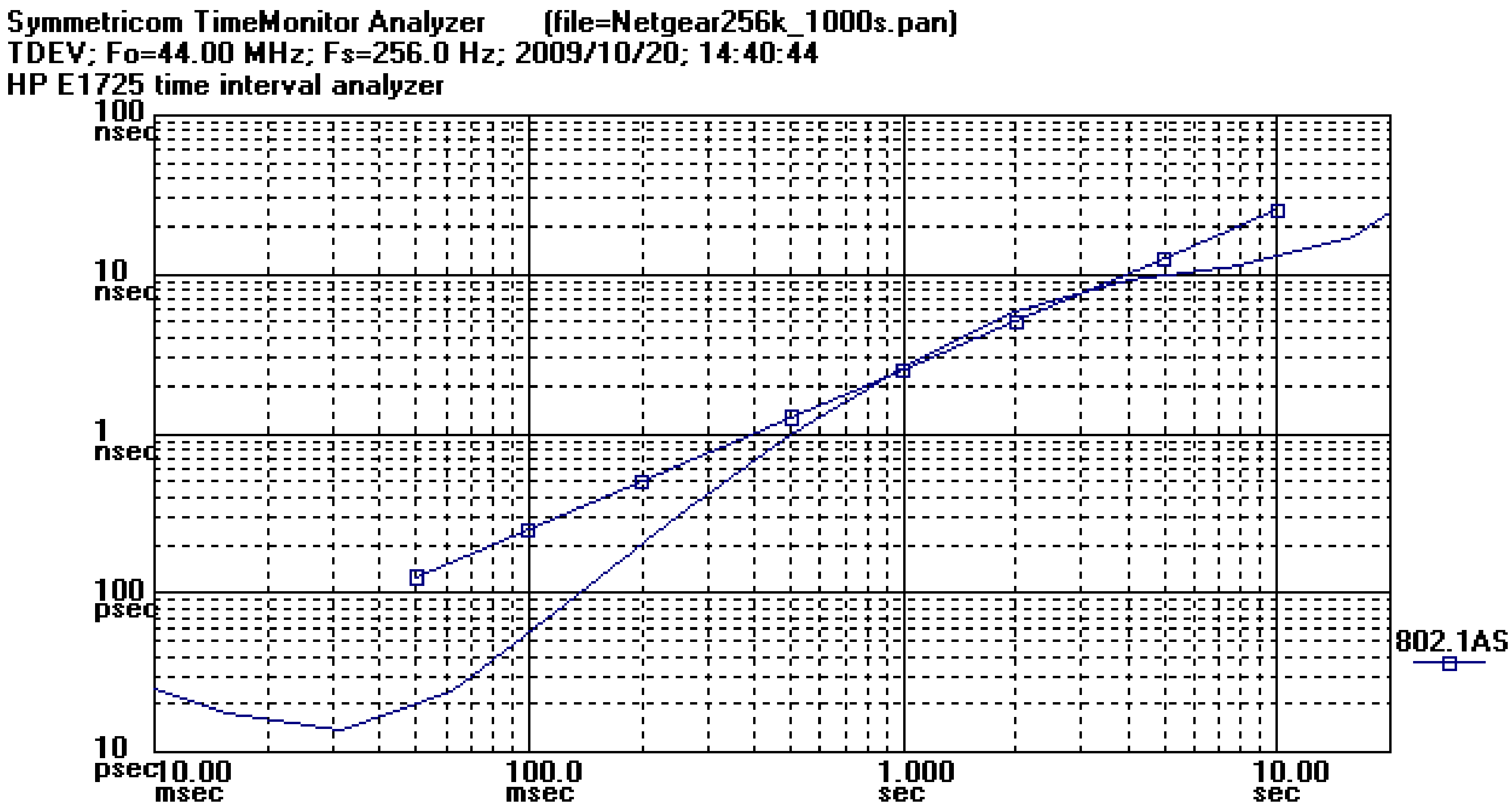
- TDEV result – second 50 s measurement
  - Marginally fails



# Measurement Results – 3

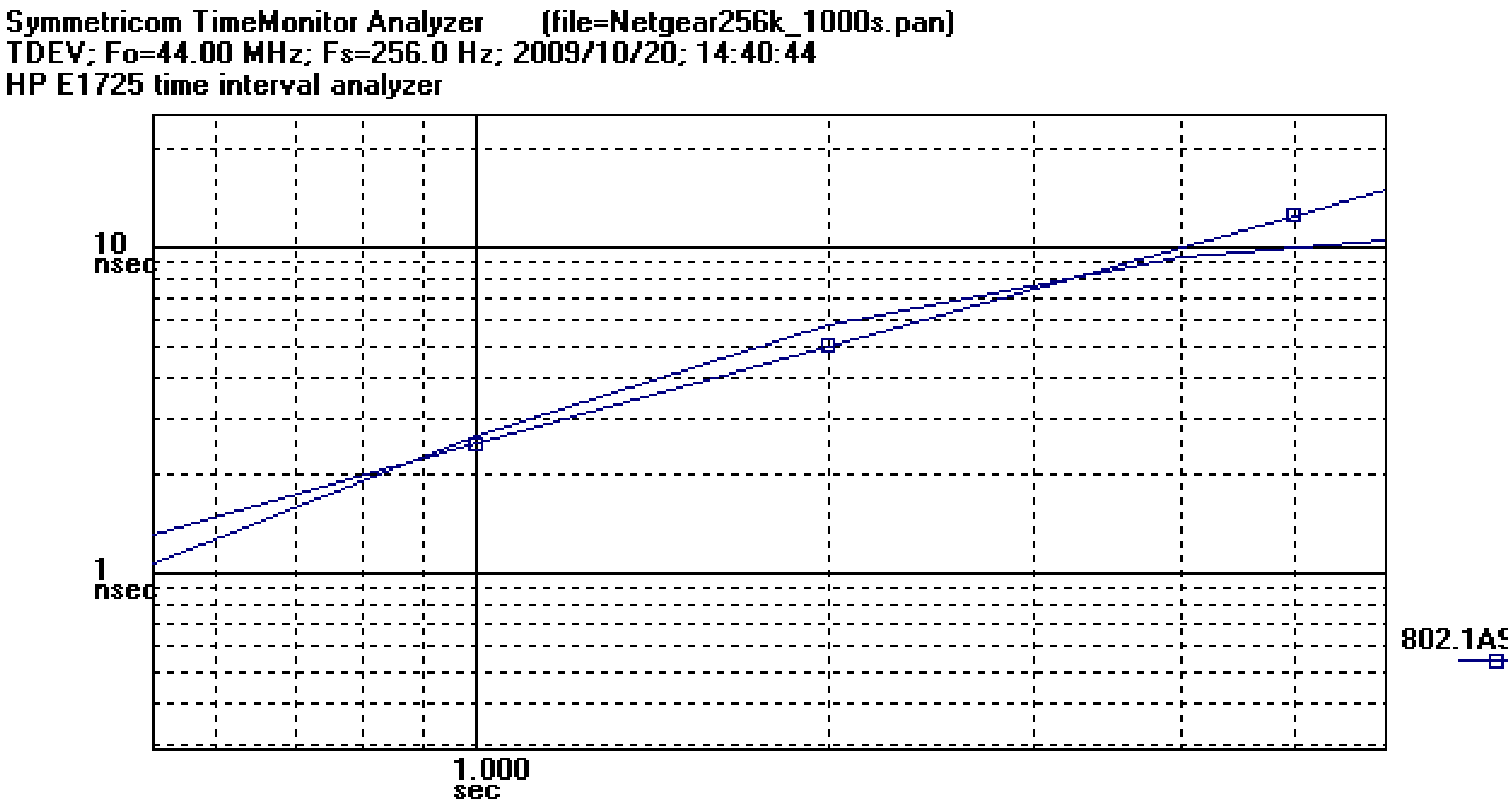
❑TDEV result – 1000 s measurement

- Marginally fails



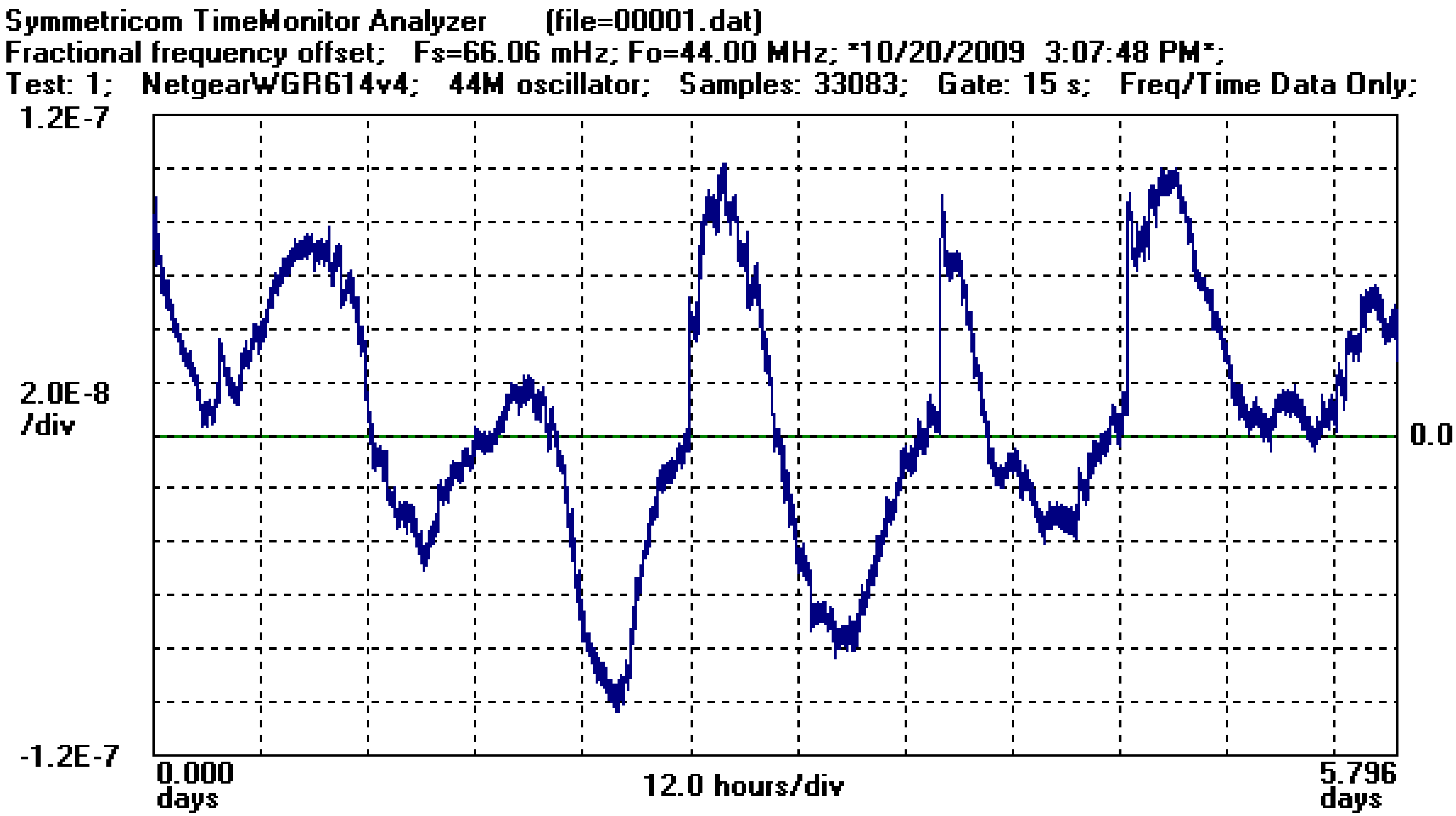
# Measurement Results - 4

- TDEV result – 1000 s measurement, region of marginal failure
  - Mask is exceeded by approximately 16%, at 2 s observation interval



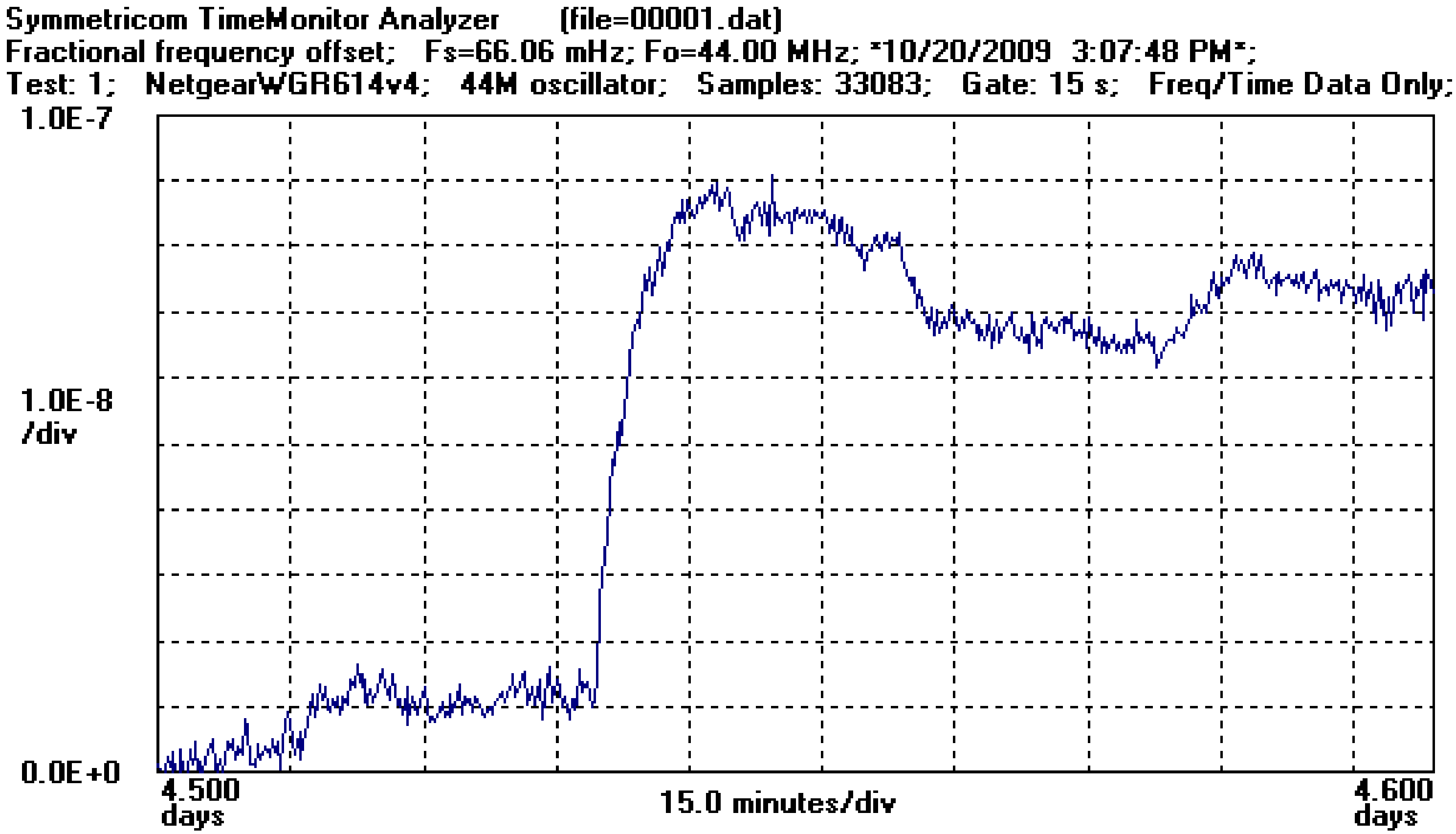
# Measurement Results – 5

- Frequency measurement over 6 days (note diurnal cycle)



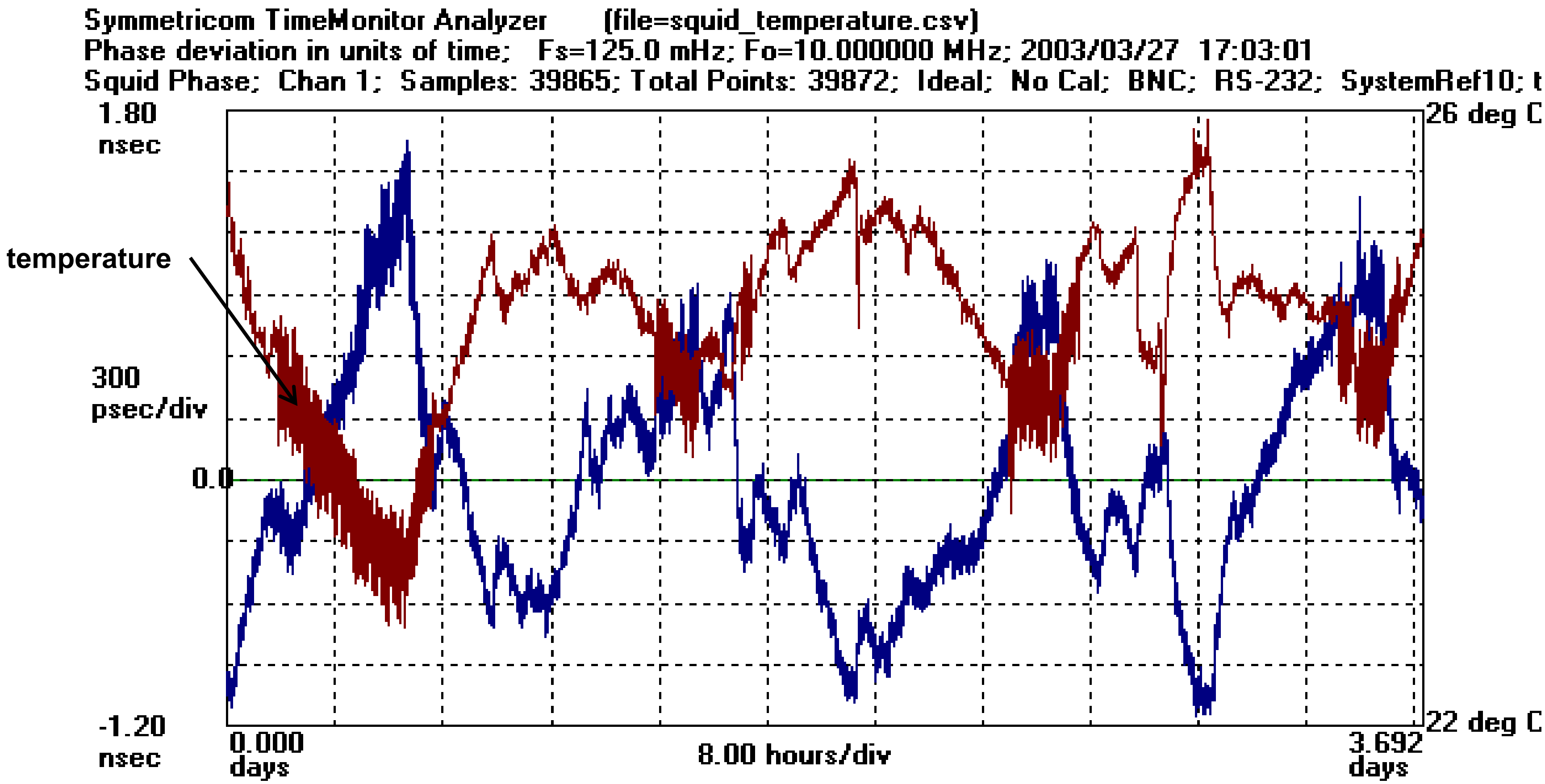
# Measurement Results - 6

- Frequency measurement over 6 days, detail of final steep increase
  - Maximum rate of frequency change is on the order of $1.2\times10^{-8}$ /1 min = $2\times10^{-10}$ /s = 0.0002 ppm/s



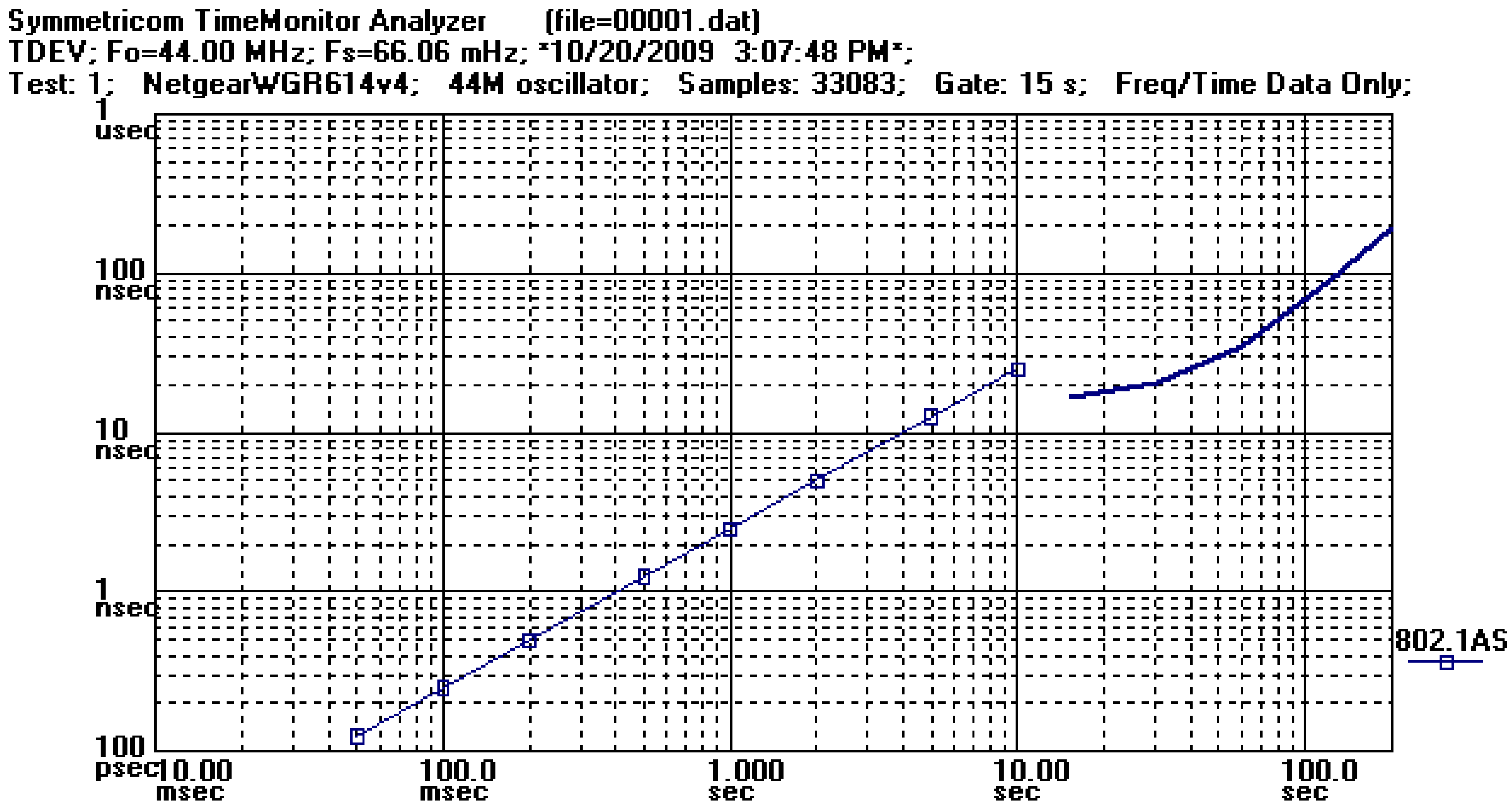
# Measurement Results - 7

- Sample temperature (ambient room temperature) and phase error history (red plot is temperature, blue plot is phase error)
  - Temperature variation is representative of conditions in lab for previous measurements (temperature does not change by more than 3 – 4 deg C)



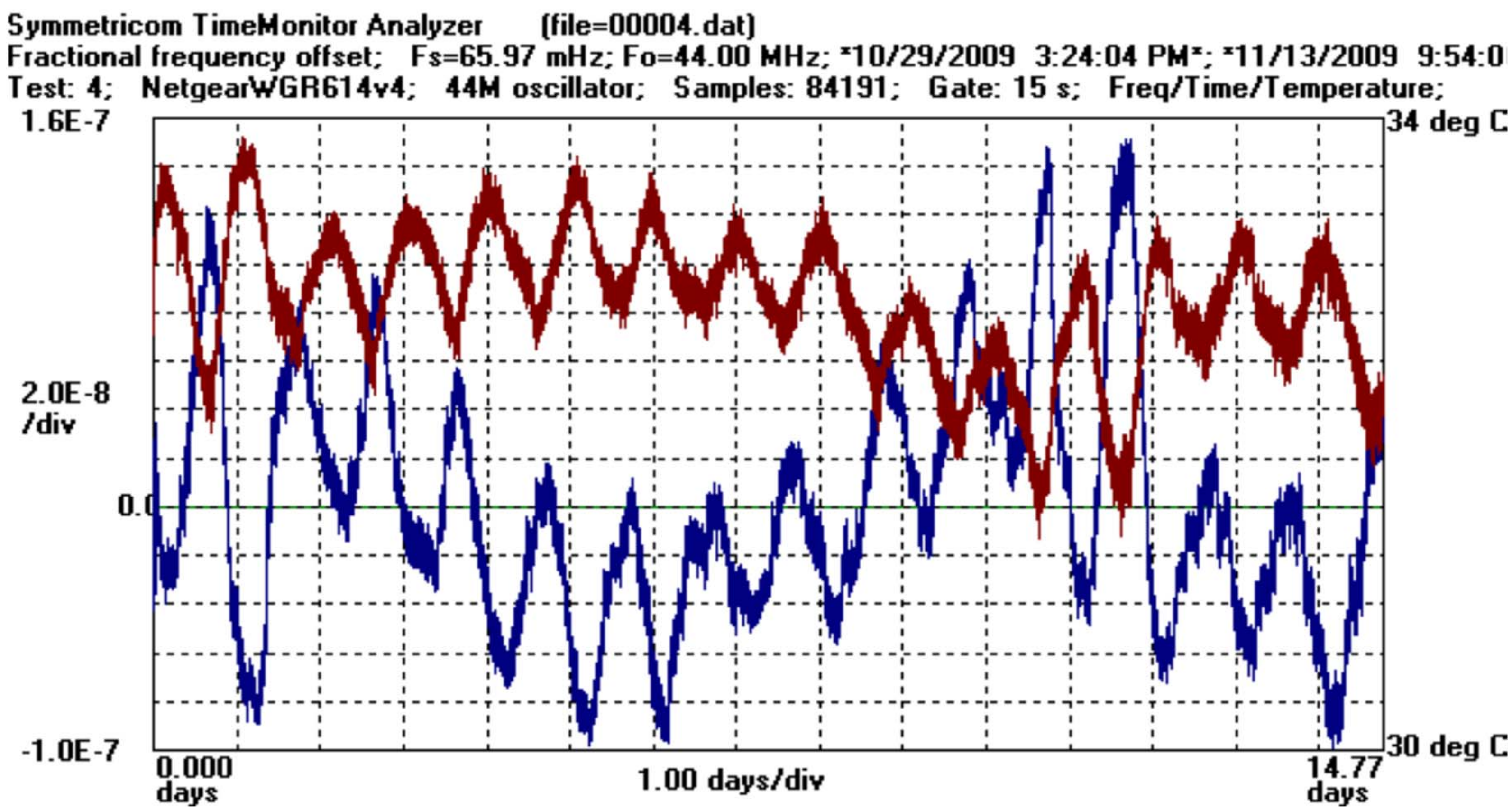
# Measurement Results – 8

- TDEV result – 6 day measurement interval (observation interval ranged from approximately 15 s to 200 s)
  - TDEV is within an extrapolation of the requirement



# Measurement Results – 9

- Frequency and temperature measurement over 14 days (red plot is temperature, blue plot is frequency)
  - Temperature measurement is at oscillator (it is higher than slide 16 temperature because that is ambient room temperature)
  - Results are qualitatively similar to 6-day results; note diurnal cycle



# Conclusions

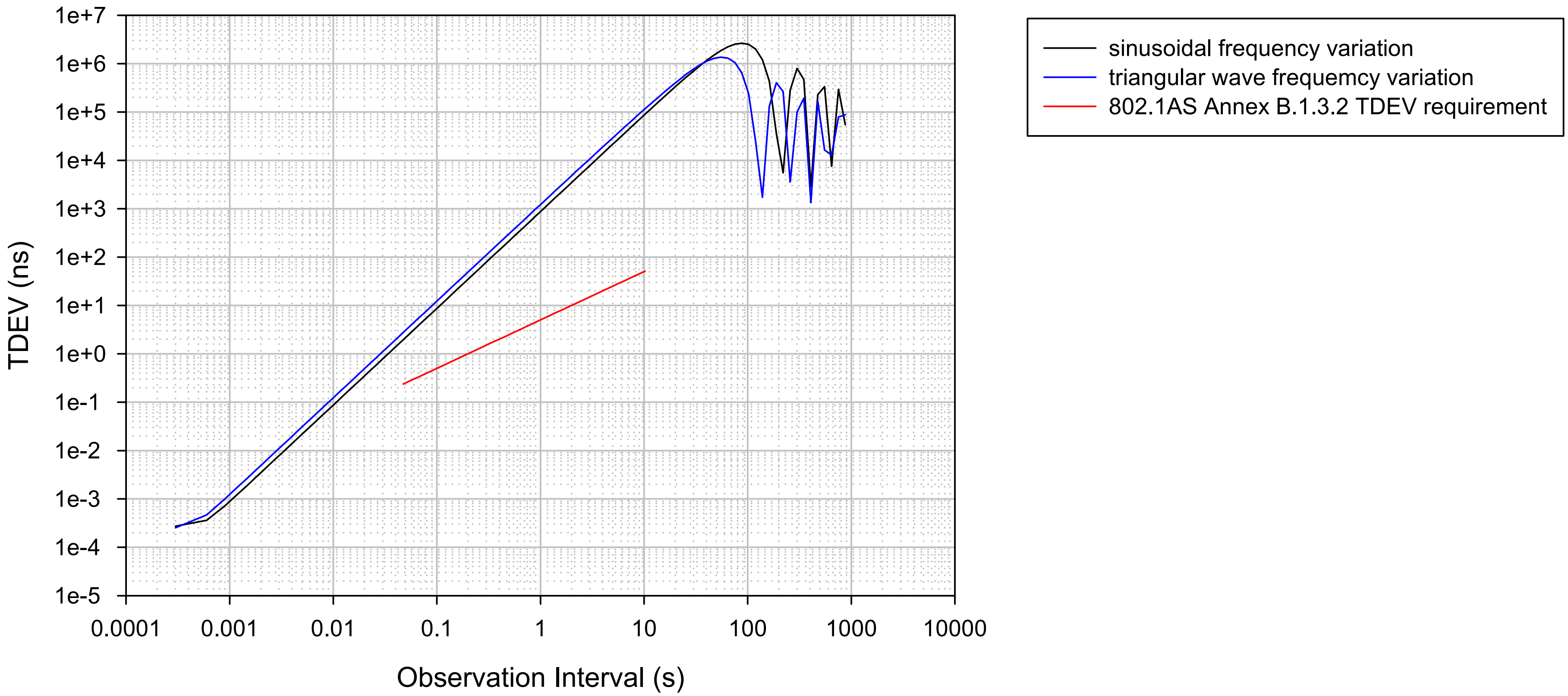
- Measured TDEV is either very close to the mask or marginally fails for observation intervals in the range of approximately 1 – 3 s
- For observation intervals less than 0.5 s, measured TDEV is well within the mask
- For temperature conditions in the lab (slide 27), maximum rate of frequency change is on the order of 0.0002 ppm/s
  - This indicates that the current 802.1AS assumption of 4 ppm/s or 1 ppm/s (assumption 9 of Annex Z) is extremely conservative
- Frequency variation over 14 days is qualitatively similar to variation over 6 days
- The results are very promising, but indicate that the present TDEV requirement should be increased to allow for margin for observation intervals in the range 1 – 3 s
  - It appears an increase in the mask by a factor of 2 would suffice, providing the performance for timing transport is acceptable (this must be checked via simulation)

# Comparison of 60802 and 802.1AS clock stability

- TDEV was computed for the 60802 phase offset (slide 8), and compared with the current Annex B/802.1AS TDEV mask
- Due to the fact that the frequency of the phase variation, i.e., 4.7746 mHz (see slide 7), is much less than 10 Hz, the 10 Hz low-pass measurement filter (see slide 3) was omitted
- Note that the other bullet items on slide 3 are met:
  - A measurement interval that is at least 120 s (i.e., at least 12 times the longest observation interval),
  - A sampling interval that does not exceed 1/30 s.
- Results are on the next slide

# Comparison of 60802 and 802.1AS clock stability

Comparison of TDEV for 60802 frequency drift rate (3 ppm/s)
and 802.1AS-2020 TDEV requirement of Annex B.1.3.2
Assumes sinusoidal and triangular wave phase and frequency variation,
with maximum frequency offset of 100 ppm



# Comparison of 60802 and 802.1AS clock stability

- TDEV for the 60802 phase variation increases linearly (on a log-log scale) up to approximately 100 s
  - This is approximately ½ the period of the sinusoidal phase variation case (i.e., $0.5*(2\pi/0.03$ rad/s) = 105 s ), and 2/3 the period of the triangular wave phase variation case (i.e., 2/3 of 133 s)
- Then TDEV shows oscillatory behavior (this would be with decreasing amplitude if the measurement interval were longer)
- The slope of TDEV in the linear (on a log-log scale) region is 2
- The 60802 TDEV exceeds the Annex B/802.1AS mask by approximately a factor of 10 at 0.05 s observation interval, and more than a factor of 1000 at 10 s observation interval
- This is consistent with the measurement results of [2], which showed much smaller rates of frequency change (e.g., 0.0002 ppm/s maximum, see slide 30)

# Conclusions

- The allowable 60802 frequency variation is considerably larger, i.e., by 1 to 3 orders of magnitude, than the variation allowed by the Annex B/802.1AS TDEV mask
  - Note that, for the measurements, the temperature variation in the lab was within 3°C
  - It is likely that larger temperature variation would have resulted in larger TDEV
  - However, 60802 does not state a temperature range or requirement
- In any case, the most important consideration is the dTE that results from the 60802 frequency stability and from the Annex B/802.1AS frequency stability
- Both the 60802 and Annex B/802.1AS frequency stability requirements will be considered, for the simulation cases that are planned

# References - 1

[1] IEC/IEEE 60802 - Time-Sensitive Networking Profile for Industrial Automation/D1.1, September 2019

[2] Lee Cosart and Geoffrey M. Garner, *Wander TDEV Measurements for Inexpensive Oscillator*, Symmetricom and Samsung presentation to IEEE 802.1, November 2, 2009.

[3] Geoffrey M. Garner, *Simulation Results for 802.1AS Synchronization Transport with Clock Wander Generation and Updated Residence and Pdelay Turnaround Times*, Samsung presentation to IEEE 802.1, July 12, 2010.

[4] David W. Allan, Marc A. Weiss, and James L. Jespersen, *A Frequency Domain View of Time Domain Characterization of Clocks and Time and Frequency Distribution Systems*, Forty-Fifth Annual Symposium on Frequency Control, Los Angeles, CA, May 29 – 31, 1991, pp. 667 – 678.

[5] Stefano Bregni, *Synchronization of Digital Telecommunications Networks*, Wiley, 2002.

# References - 2

[6] *Phase Noise*, Vectron International, Application Note, available at http://www.vectron.com.

[7] *Jitter and Signal Noise in Frequency Sources*, Raltron, Application Note, available at http://www.raltron.com/

[8] N. Jeremy Kasdin, *Discrete Simulation of Colored Noise and Stochastic Processes and* $1/f^{\alpha}$ *Power Law Noise Generation*, Proceedings of the IEEE, Vol. 83, No. 5, May 1995

Thank you