Comparison of 802.1AS Annex B and P60802 Clock Stability

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IEEE 802.1 TSN TG
2020.01.20

Outline

- Introduction
- P60802 phase and frequency variation
- Background on clock stability and TDEV
- 802.1AS (2011 and 2020) clock stability (measurements)
- Comparison of P60802 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 P60802 meetings, one or more participants have indicated that previous simulations/analyses they or their colleagues have done assumed sinusoidal phase and frequency variation that 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*τ ns, where the observation interval τ is the range 0.05 s $\le \tau \le$ 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 P60802 clock requirements with the Annex B/802.1AS TDEV requirement

P60802 Phase and Frequency Variation - 1

- We will assume sinusoidal phase variation, and 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
- 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)

P60802 Phase and Frequency Variation - 2

- Then the frequency and rate of change of frequency are:

$$y(t) = \dot{x}(t) = 2\pi fA\cos(2\pi ft)$$

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

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

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

$$4\pi^2 f^2 A = 3\times 10^{-6} \text{ s}^{-1} \text{ (i.e., 3 ppm/s)}$$

P60802 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

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

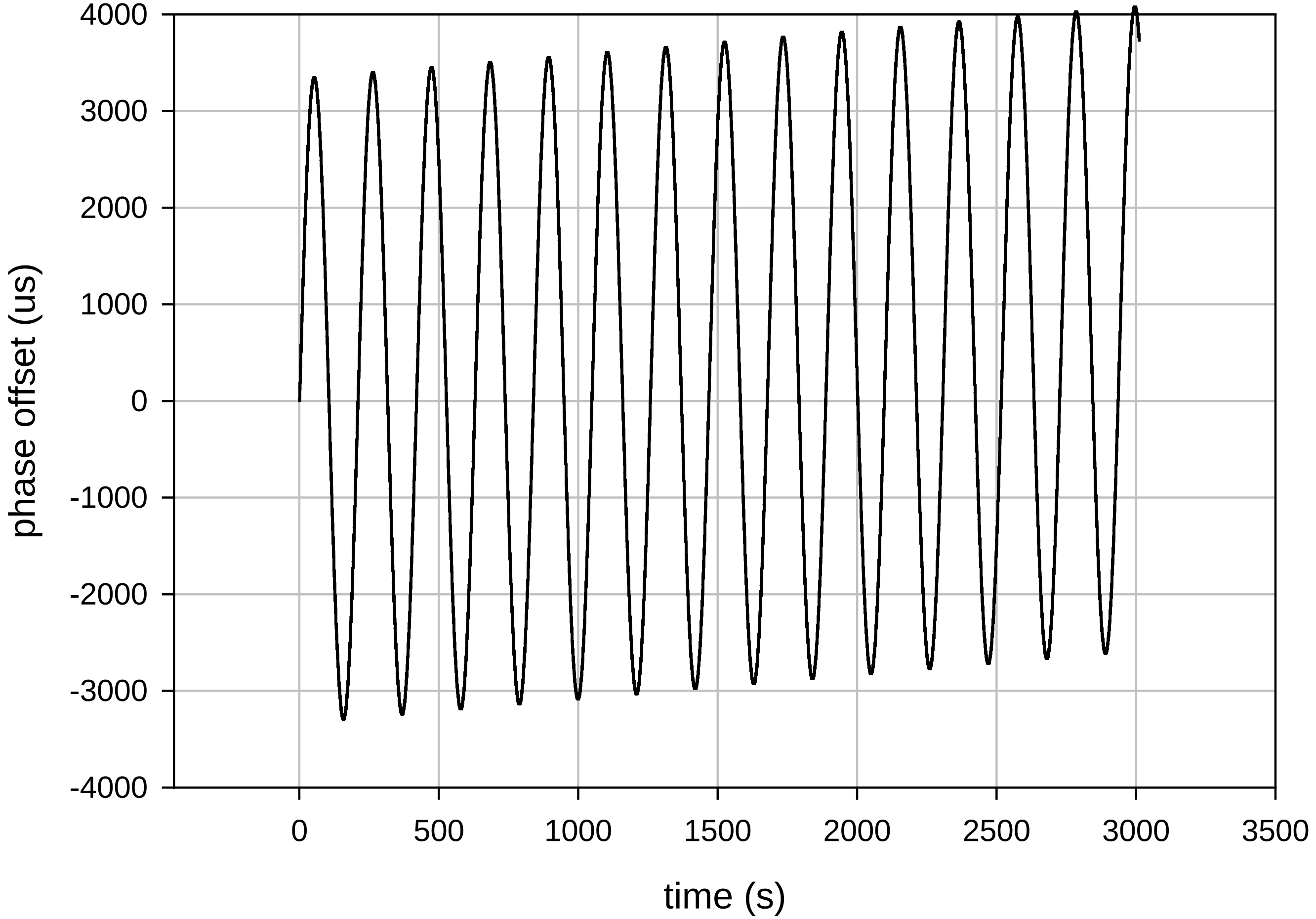
$$2\pi fA = 0.03A = 10^{-4}$$

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

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

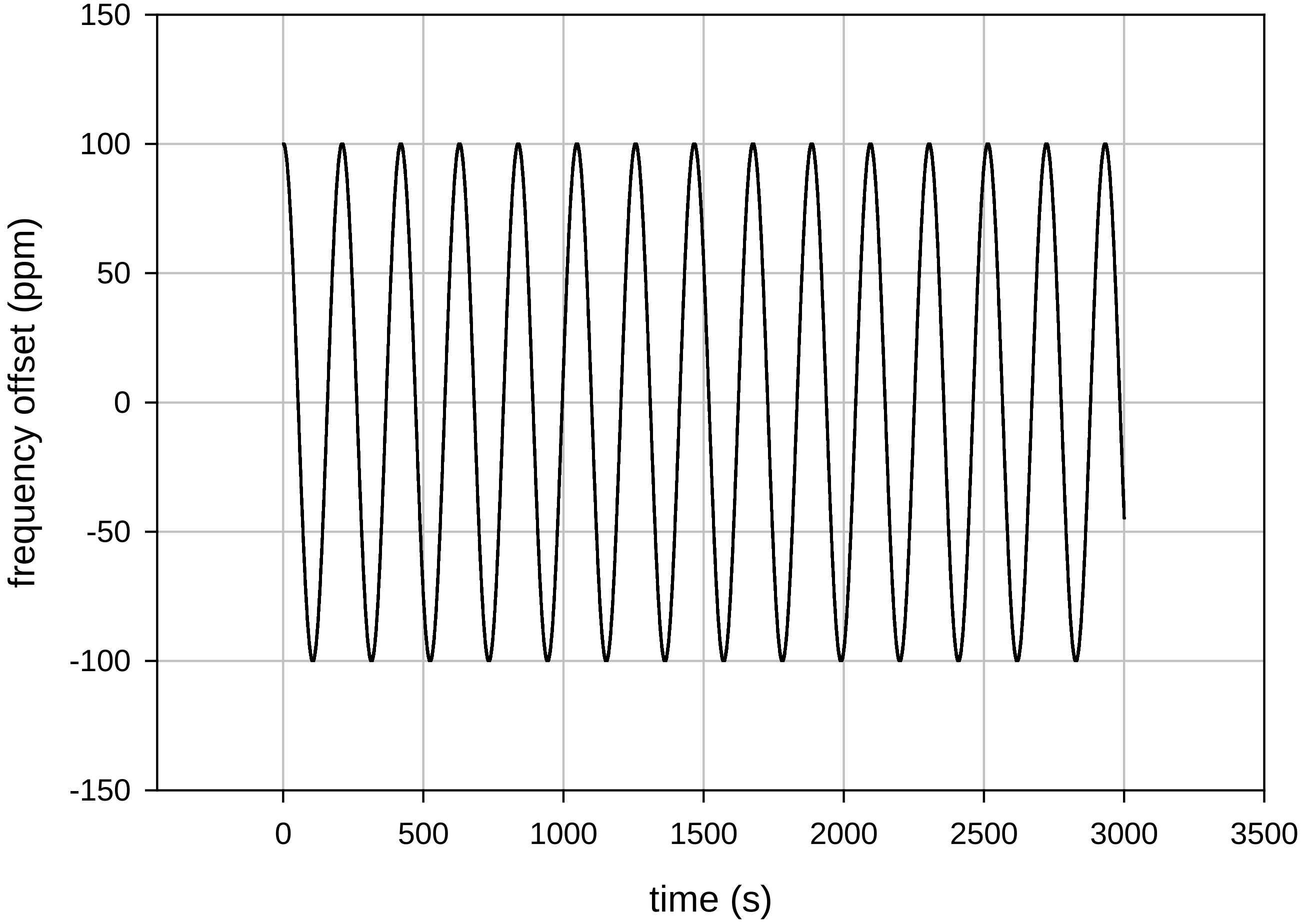
P60802 Phase and Frequency Variation - 4

P60802 phase offset
Maximum frequency offset = 100 ppm
Maximum frequency drift rate = 3 ppm/s



P60802 Phase and Frequency Variation - 5

P60802 frequency offset
Maximum frequency offset = 100 ppm
Maximum frequency drift rate = 3 ppm/s



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])
  - α = 0, White Phase Modulation (WPM)
  - α = 1, Flicker Phase Modulation (FPM)
  - α = 2, White Frequency Modulation (WFM)
  - α = 3, Flicker Frequency Modulation (FFM)
  - α = 4, Random-Walk Frequency Modulation (RWFM)
- ❑Can write the PSD, $S_x(f)$ as

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

  - Often express as (ν_0 = nominal clock frequency)

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

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

Background on Clock Stability and TDEV - 3

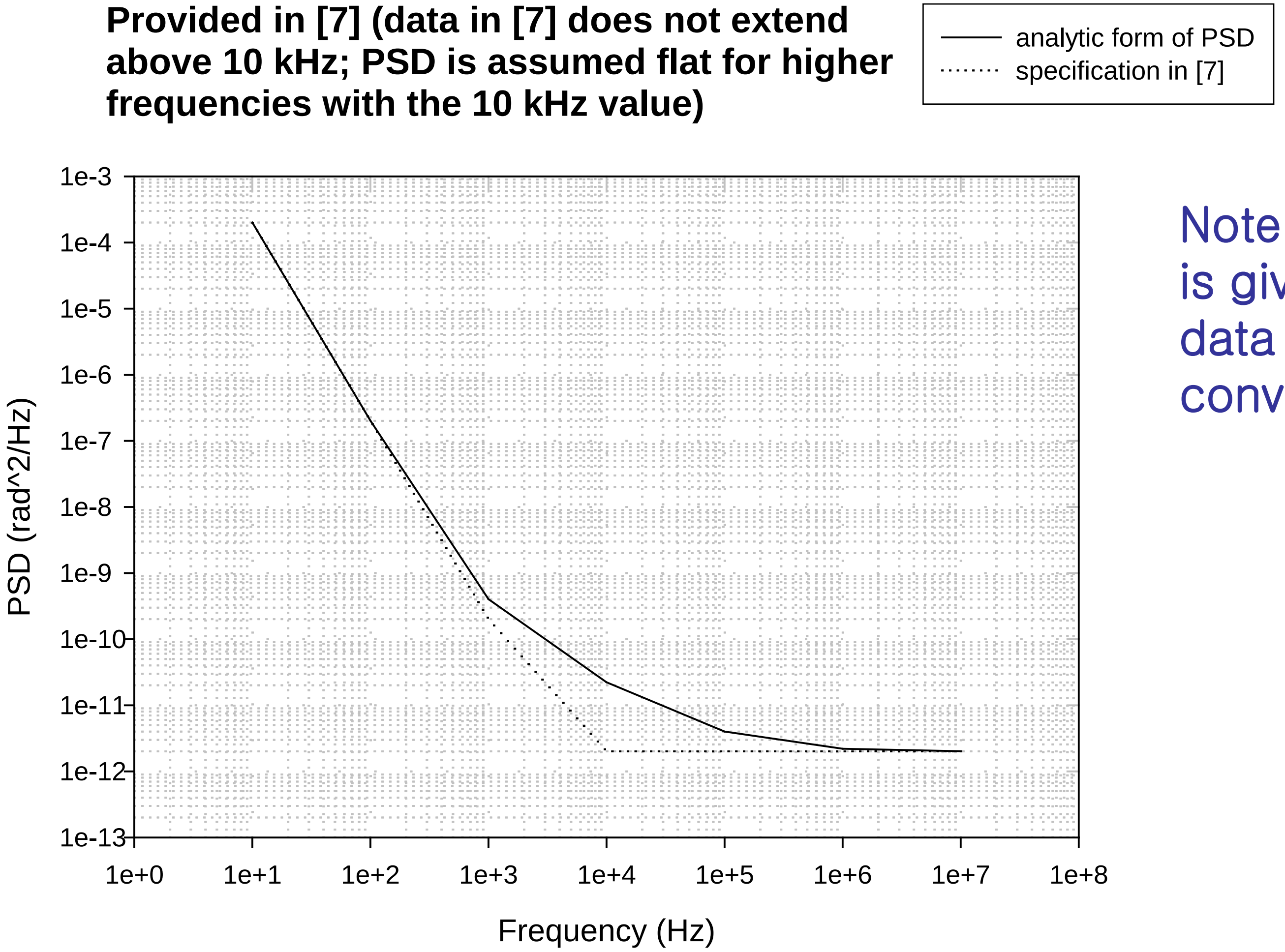
- ❑Often, the one-sided PSD $S_\phi(f)$ is expressed in dBc/Hz, using the conversion

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

  - ▪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 $\mathrm{rad}^2/\mathrm{Hz}$
    - •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)

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

where $E[\cdot]$ denotes expectation,

$\overline{x}$ denotes average over the integration time τ,

and Δ^2 denotes second difference

Background on Clock Stability and TDEV - 6

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

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

where τ_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 τ^β, 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 $S_x(f) = \dfrac{B}{f^3}$ $\mathrm{TVAR}(\tau) = \dfrac{(2\pi)^2 9 \ln 2}{20} B\tau^2$

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

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

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

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

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

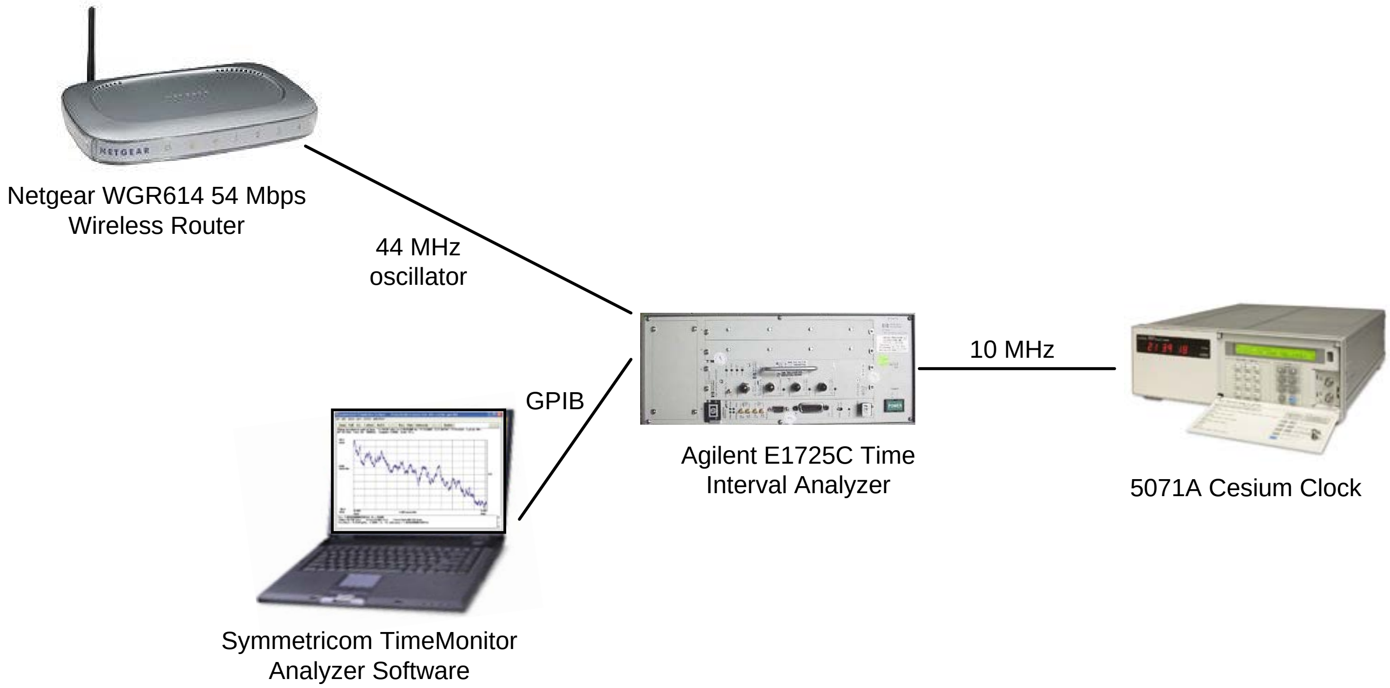
- ❑This section describes the measurements of [2], on which the current Annex B/802.1AS TDEV requirement is based
- ❑The slides are reproduced from [2], with minor modifications (e.g., updating of footers)
- ❑The intent was to measure the wander performance of an inexpensive, oscillator that might be 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*τ ns, rather than 5* τ 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



Netgear WGR614 54 Mbps Wireless Router

44 MHz oscillator

GPIB

Agilent E1725C Time Interval Analyzer

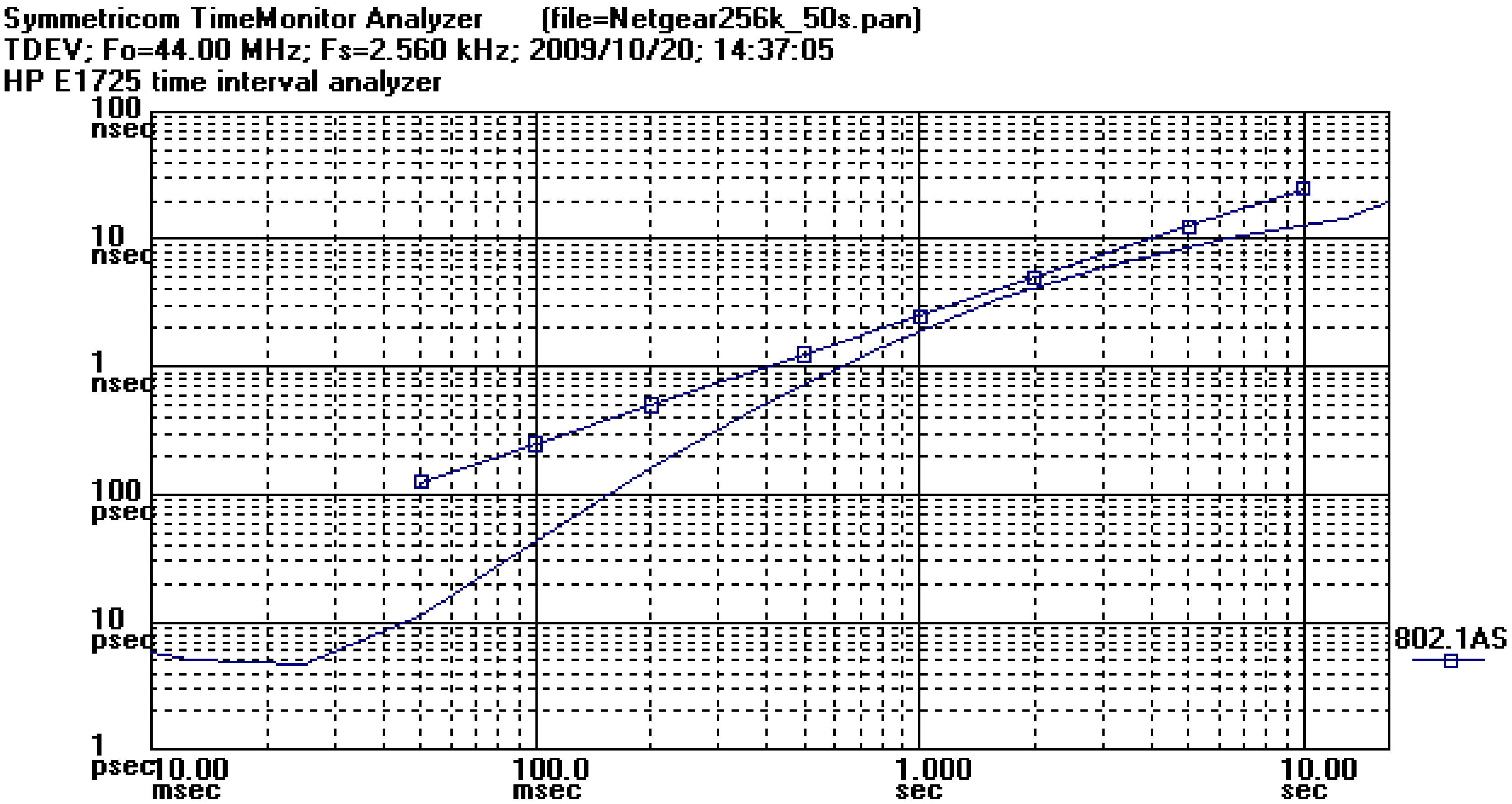
10 MHz

5071A Cesium Clock

Symmetricom TimeMonitor Analyzer Software

Measurement Results – 1

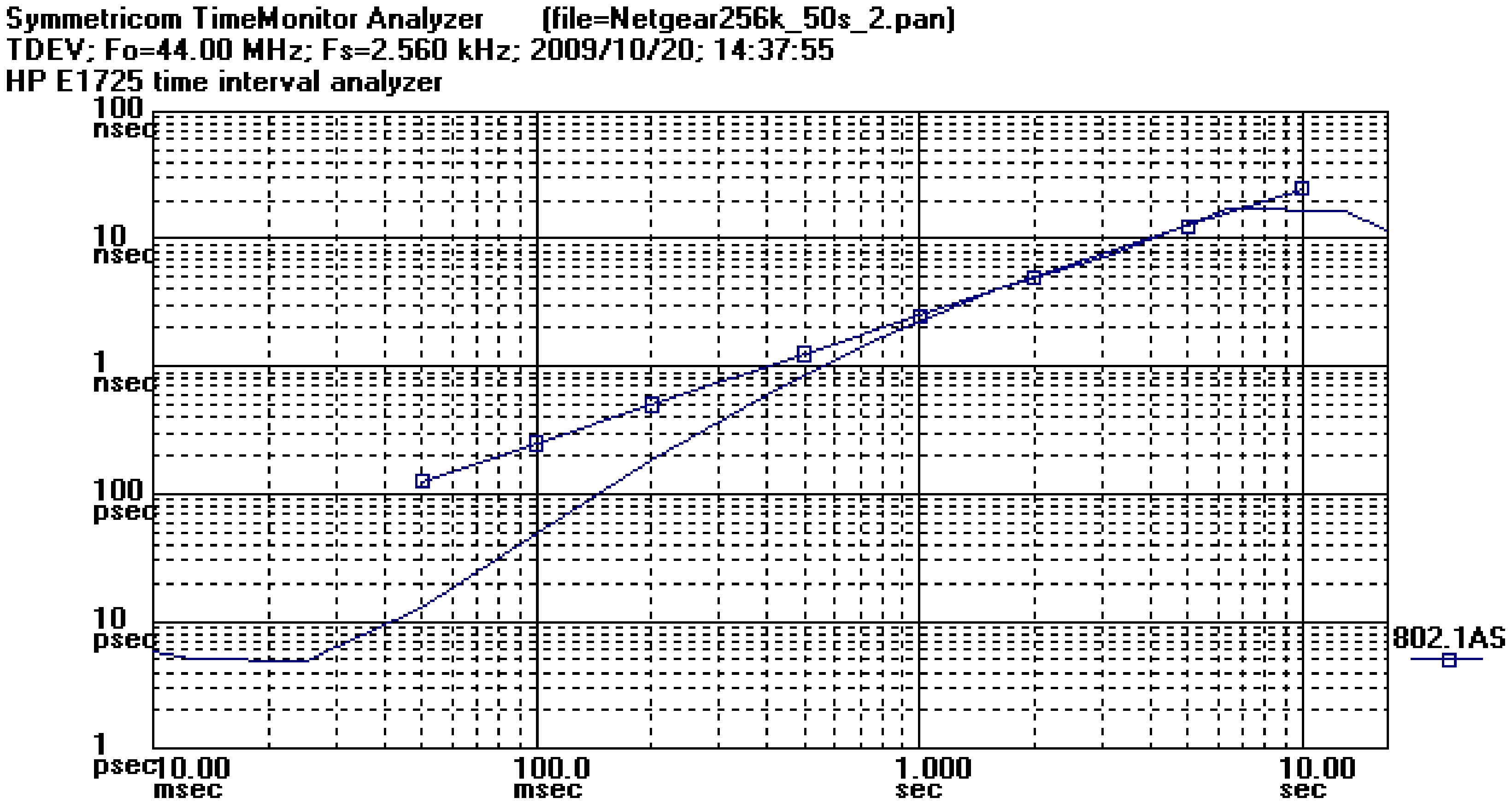
- TDEV result – first 50 s measurement
    - Passes, though not with a large margin



Symmetricom TimeMonitor Analyzer (file=Netgear256k_50s.pan)
TDEV; Fo=44.00 MHz; Fs=2.560 kHz; 2009/10/20; 14:37:05
HP E1725 time interval analyzer

Measurement Results – 2

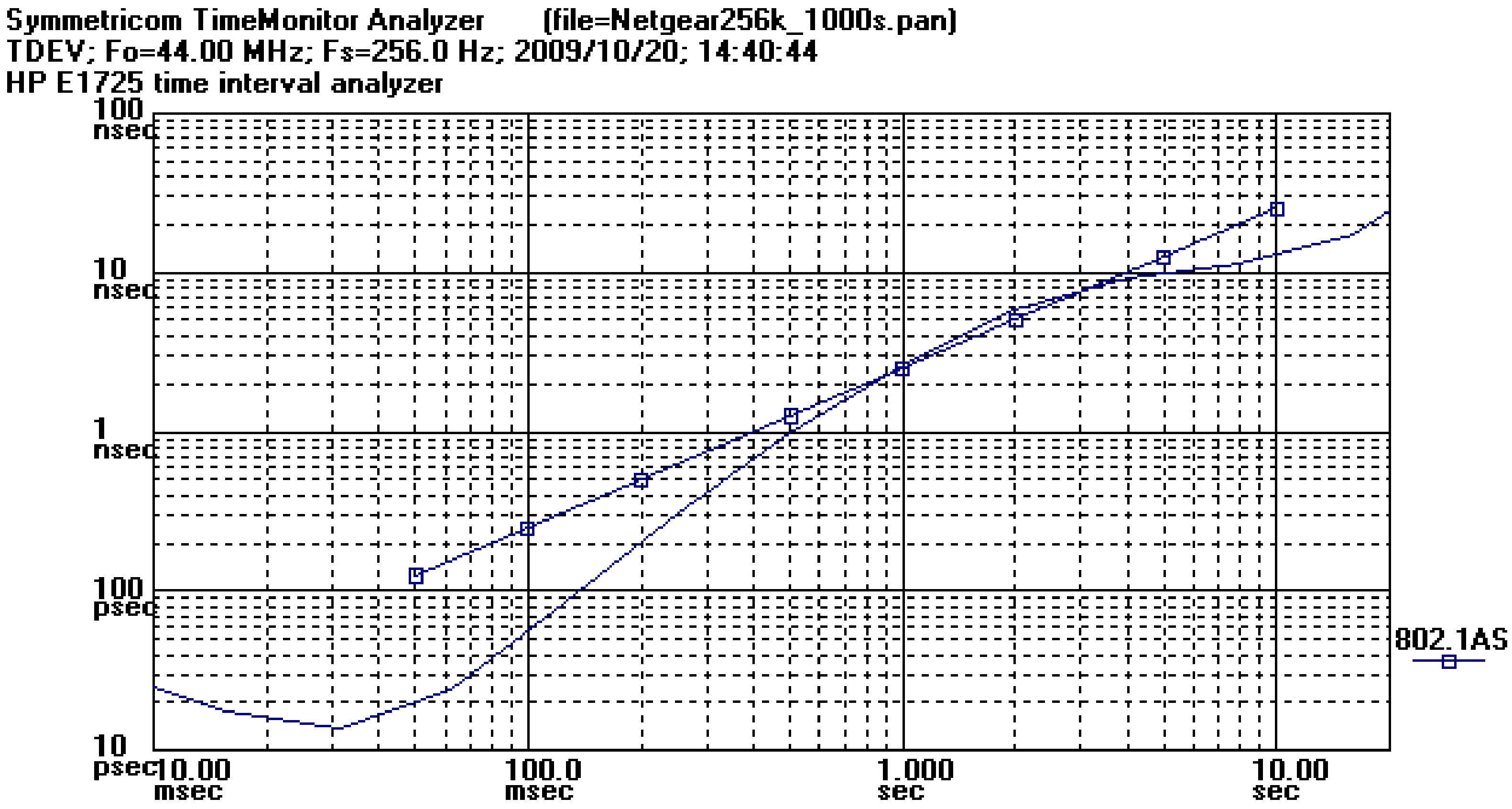
- TDEV result – second 50 s measurement
  - Marginally fails



Symmetricom TimeMonitor Analyzer (file=Netgear256k_50s_2.pan)
TDEV; Fo=44.00 MHz; Fs=2.560 kHz; 2009/10/20; 14:37:55
HP E1725 time interval analyzer

Measurement Results – 3

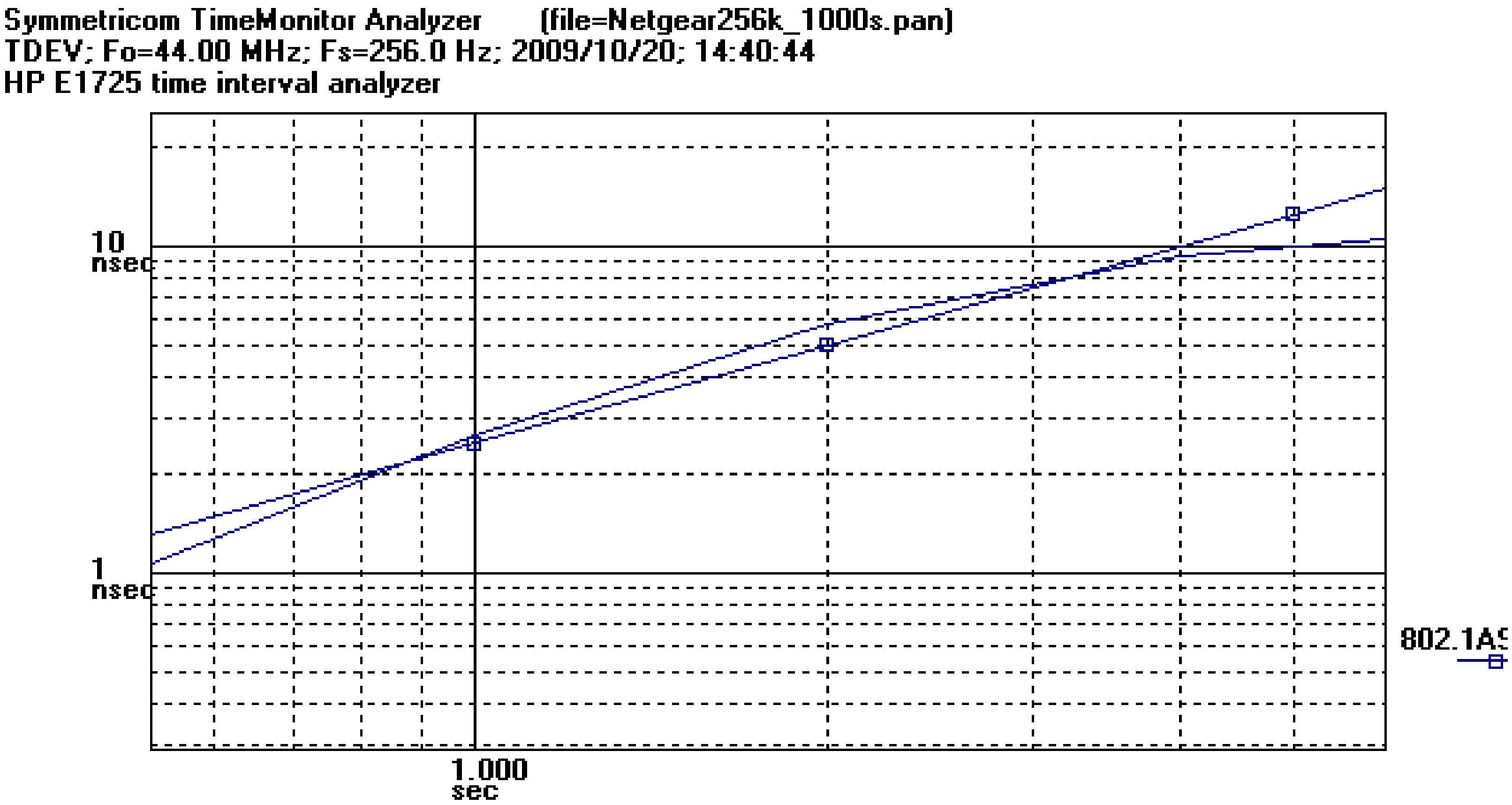
- TDEV result – 1000 s measurement
  - Marginally fails



Symmetricom TimeMonitor Analyzer (file=Netgear256k_1000s.pan)
TDEV; Fo=44.00 MHz; Fs=256.0 Hz; 2009/10/20; 14:40:44
HP E1725 time interval analyzer

Measurement Results – 4

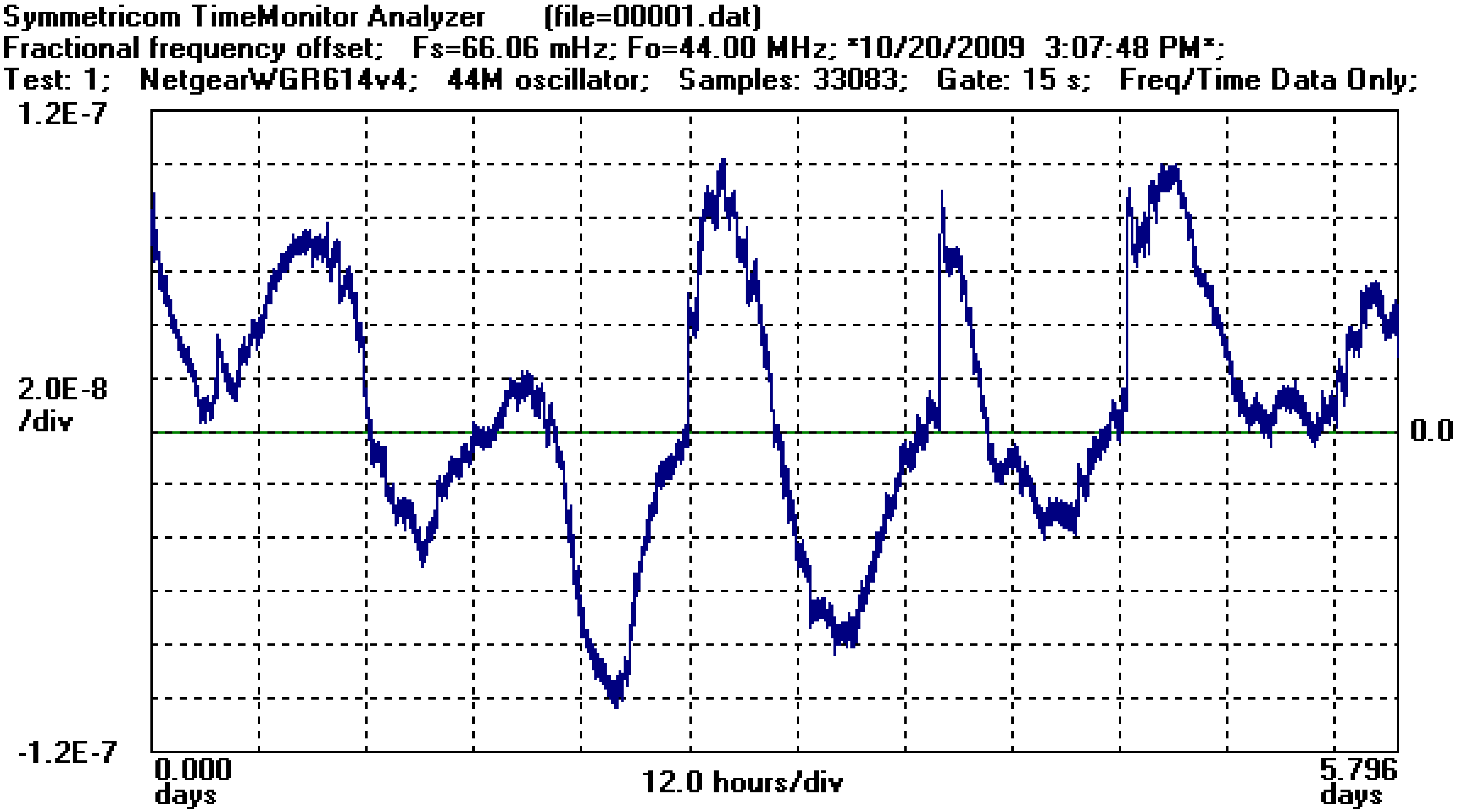
- ❑TDEV result – 1000 s measurement, region of marginal failure
  - ▪Mask is exceeded by approximately 16%, at 2 s observation interval



Symmetricom TimeMonitor Analyzer (file=Netgear256k_1000s.pan)
TDEV; Fo=44.00 MHz; Fs=256.0 Hz; 2009/10/20; 14:40:44
HP E1725 time interval analyzer

Measurement Results – 5

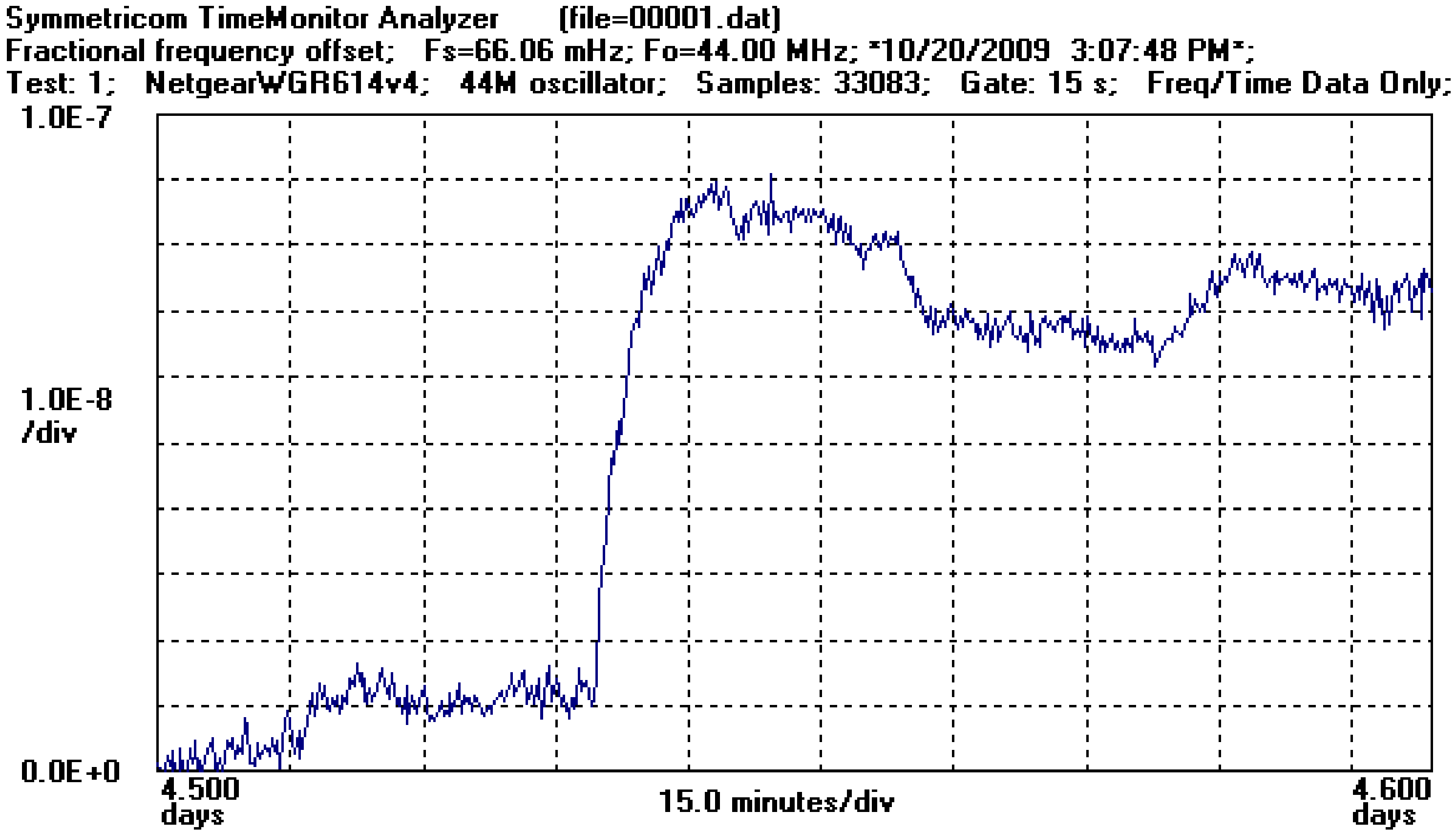
- ❑Frequency measurement over 6 days (note diurnal cycle)



Symmetricom TimeMonitor Analyzer (file=00001.dat)
Fractional frequency offset; Fs=66.06 mHz; Fo=44.00 MHz; "10/20/2009 3:07:48 PM";
Test: 1; NetgearWGR614v4; 44M oscillator; Samples: 33083; Gate: 15 s; Freq/Time Data Only;

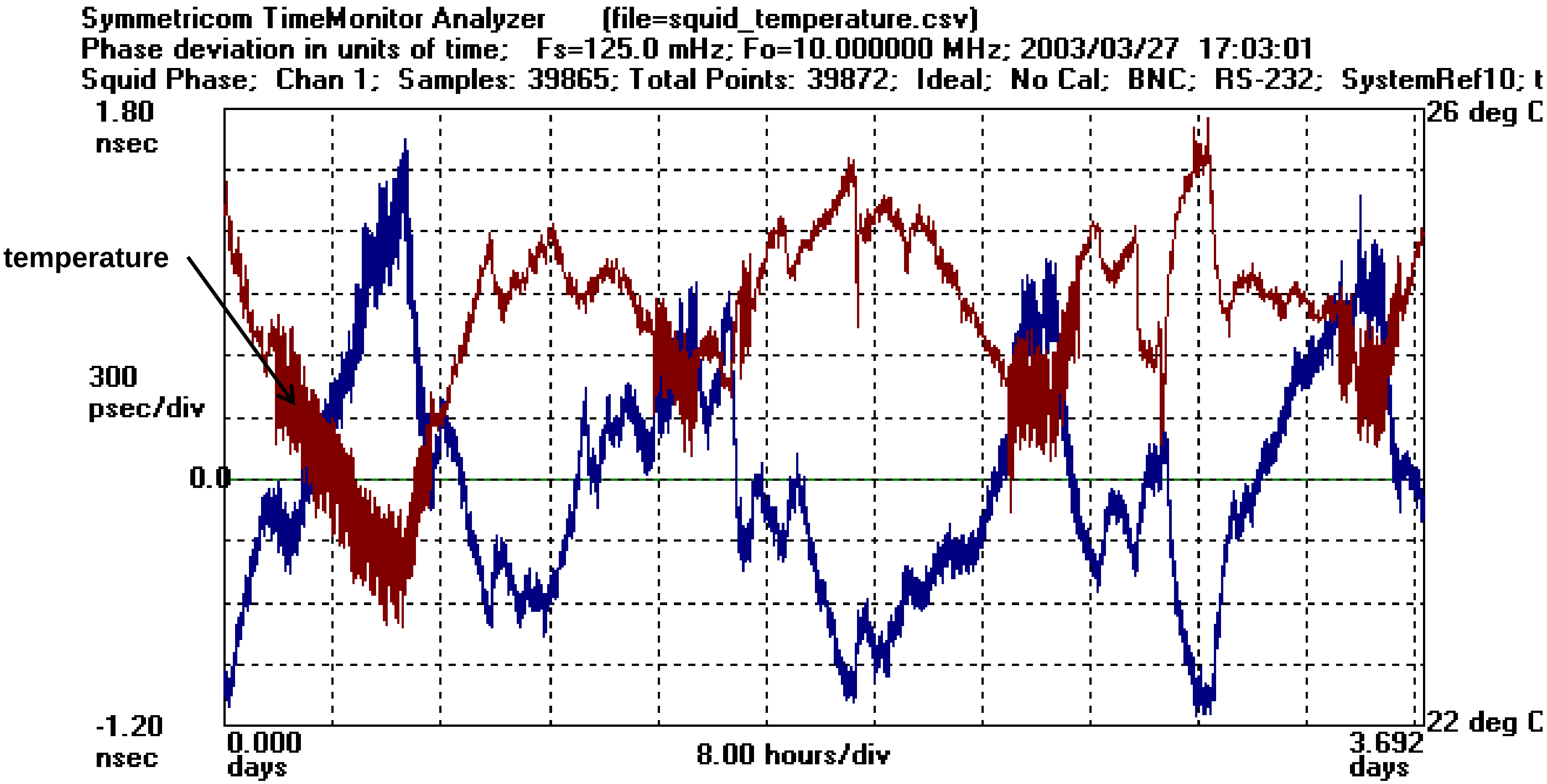
Measurement Results – 6

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



Measurement Results – 7

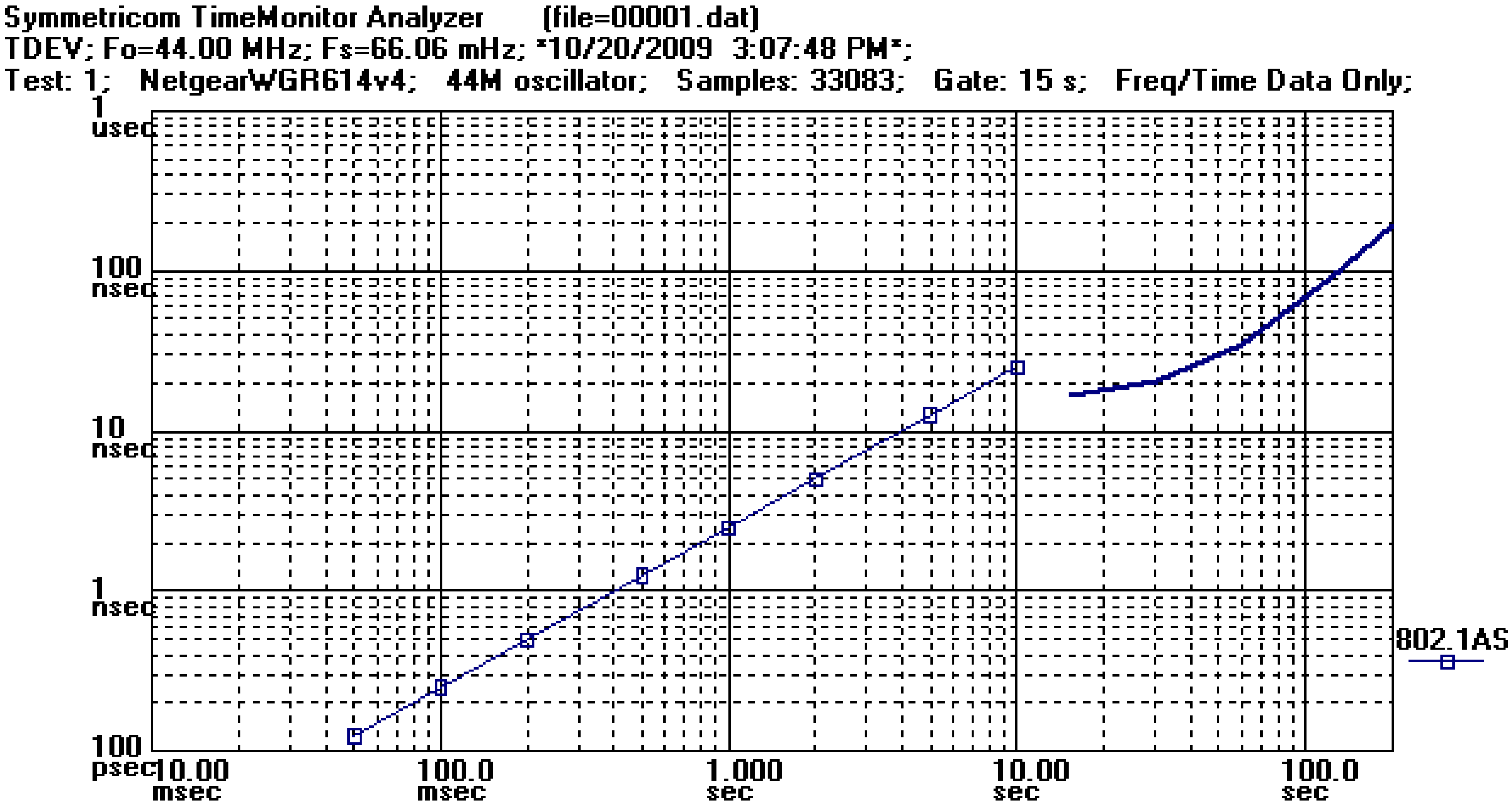
- ❑ Sample temperature (ambient room temperature) and phase error history (red plot is temperature, blue plot is phase error)
  - ▪ Temperature variation is representative of conditions in lab for previous measurements (temperature does not change by more than 3 – 4 deg C)



Symmetricom TimeMonitor Analyzer (file=squid_temperature.csv)
Phase deviation in units of time; Fs=125.0 mHz; Fo=10.000000 MHz; 2003/03/27 17:03:01
Squid Phase; Chan 1; Samples: 39865; Total Points: 39872; Ideal; No Cal; BNC; RS-232; SystemRef10; t

Measurement Results – 8

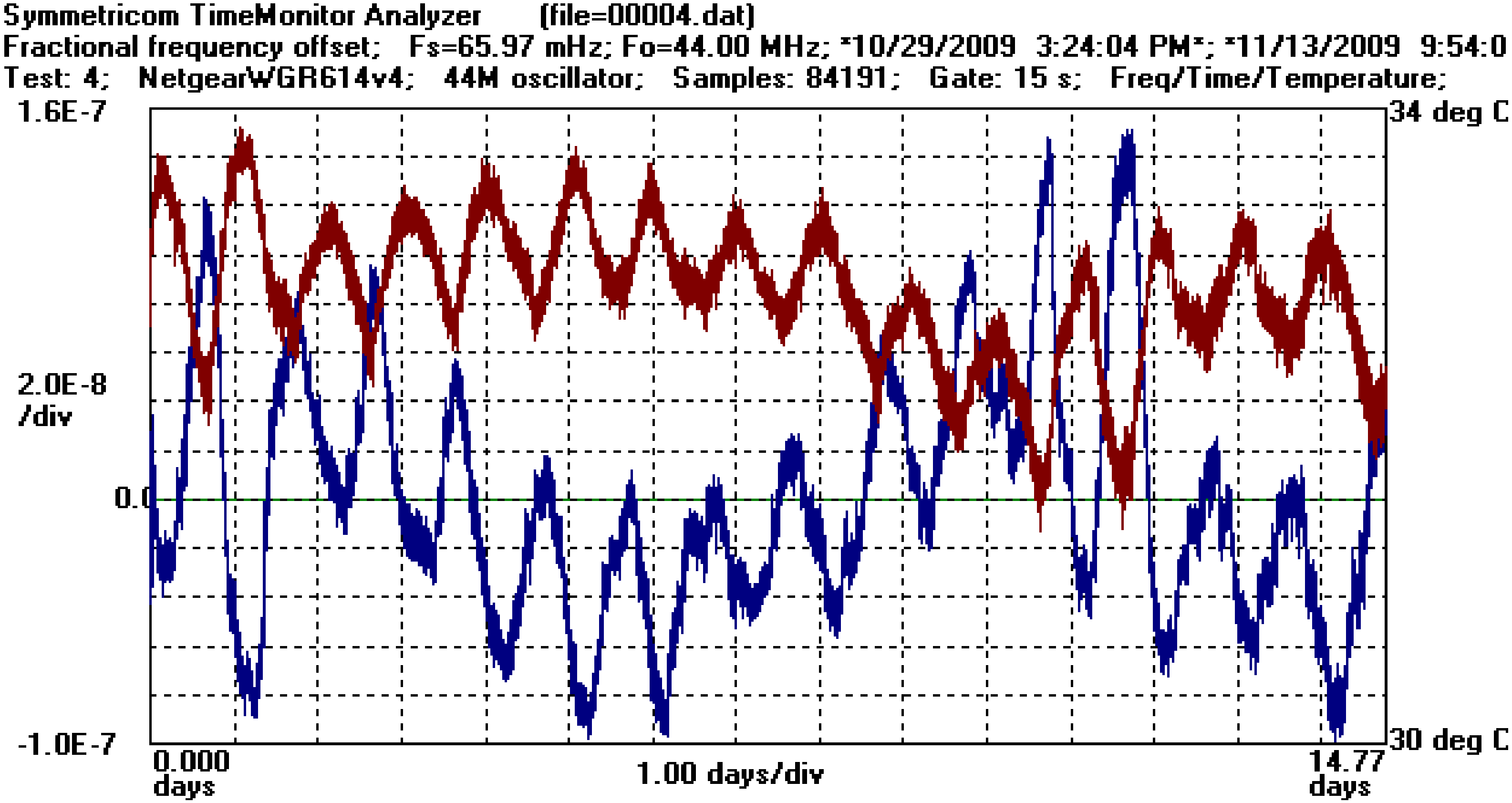
- ❑TDEV result – 6 day measurement interval (observation interval ranged from approximately 15 s to 200 s)
  - ▪TDEV is within an extrapolation of the requirement



Symmetricom TimeMonitor Analyzer (file=00001.dat)
TDEV; Fo=44.00 MHz; Fs=66.06 mHz; *10/20/2009 3:07:48 PM*;
Test: 1; NetgearWGR614v4; 44M oscillator; Samples: 33083; Gate: 15 s; Freq/Time Data Only;

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

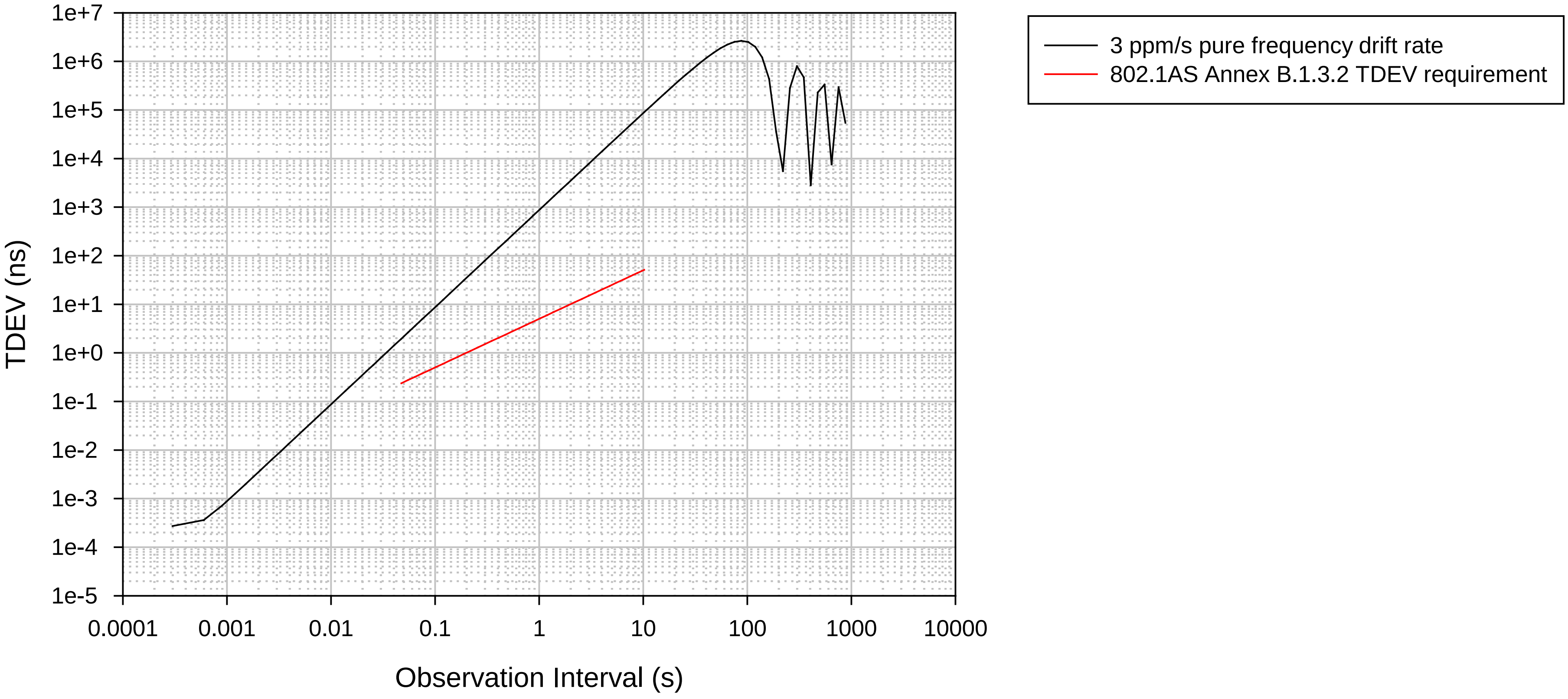
- ❑Measured TDEV is either very close to the mask or marginally fails for observation intervals in the range of approximately 1 – 3 s
- ❑For observation intervals less than 0.5 s, measured TDEV is well within the mask
- ❑For temperature conditions in the lab (slide 27), maximum rate of frequency change 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 P60802 and 802.1AS clock stability

- ❑TDEV was computed for the P60802 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 P60802 and 802.1AS clock stability

Comparison of TDEV for P60802 frequency drift rate (3 ppm/s)
and 802.1AS-2020 TDEV requirement of Annex B.1.3.2
Assumes sinusoidal phase and frequency variation, with maximum
frequency offset of 100 ppm



Comparison of P60802 and 802.1AS clock stability

- TDEV for the P60802 phase variation increases linearly (on a log-log scale) up to approximately 100 s
  - This is approximately ½ the period of the phase variation (i.e., 0.5*(2π/0.03 rad/s) = 105 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 P60802 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 P60802 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, P60802 does not state a temperature range or requirement
- ❑In any case, the most important consideration is the dTE that results from the P60802 frequency stability and from the Annex B/802.1AS frequency stability
- ❑Both the P60802 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