New Simulation Results for dTE for an IEC/IEEE 60802 , Based on New Frequency Stability Model

Geoffrey M. Garner
Huawei (Consultant)

gmgarner@alum.mit.edu

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Introduction

- This presentation contains new simulation results, based on assumptions summarized in [1]
- Included in these assumptions is a new LocalClock phase noise model, based on new frequency stability data presented in [2] and summarized in [3]
- Reference [3] obtained time histories for frequency offset, frequency drift rate, and phase offset for the LocalClock entity, based on the frequency stability versus temperature data of [2] and the periodic temperature profile described in [4]
  - In the assumptions of [1], the temperature profile was modified to shorten the period
- In the following slides, the assumptions are summarized (and the simulation results are presented)
  - The assumptions included 12 simulation cases
  - However, it was found that the 1 μs objective for max|TE| over 64 hops (and 100 hops if possible) was not met
  - Additional simulation cases (for a total of 27 cases) were run, with modified assumptions (the modifications will be described shortly)

Assumptions for Temperature Profile (from [1])

- The temperature history is assumed to vary between – 40°C and +85°C, at a rate of 1°C /s
- When the temperature is increasing and reaches +85°C, it remains at +85°C for 30 s
- The temperature then decreases from +85°C to – 40°C at a rate of 1°C /s; this takes 125 s
- The temperature then remains at – 40°C for 30 s
- The temperature then increases to +85°C at a rate of 1°C /s; this takes 125 s
- The duration of the entire cycle (i.e., the period) is therefore 310 s (5.166667 min)

Assumptions for Frequency Stability due to Temperature Variation

- The dependence of frequency offset on temperature is assumed to be as described in [2] and [3]
  - Specifically, the values a_0, a_1, a_2, and a_3 computed in [3] will be used in the cubic polynomial fit, and the resulting frequency offset will be multiplied by 1.1 (i.e., a margin of 10% will be used).
- The frequency stability data that this polynomial fit is based on is contained in the Excel spreadsheet attached to [3]
  - This data was provided by the author of Reference [2]
- The time variation of frequency offset will be obtained from the cubic polynomial frequency dependence on temperature, and the temperature dependence on time described in the previous slide
  - The time variation of phase/time error at the LocalClock entity will be obtained by integrating the above frequency versus time waveform
  - The time variation of frequency drift rate at the LocalClock entity will be obtained by differentiating the above frequency versus time waveform

- Two types of assumptions will be used for relative time offsets of the phase error histories at each node (separate cases will be run for each assumption):
  - Choose the phase of the LocalClock time error waveform at each node randomly in the range [0,T], at initialization, where T is the period of the phase and frequency variation waveforms (i.e., 310 s, see slide 3)
  - Choose the phase of the LocalClock time error waveform at each node randomly in the range [0, 0.1T], at initialization, where T is the period of the phase and frequency variation waveforms (i.e., 310 s, see slide 3)
    - A uniform probability distribution is used for the random choice
    - 0.1T = 31 s, i.e., any periodic LocalClock time error waveform will be offset from any other such waveform by at most 31 s

Other Assumptions - 1

- Some other assumptions were briefly suggested in email discussion
  - Mean Sync interval: 125 ms
  - Mean Pdelay interval: 31.25 ms
  - Timestamp granularity: 8 ns, 4 ns (both cases)
  - Residence times: 1 ms, 4 ms, 10 ms (all 3 cases)
  - Timestamp error ($\pm$8 ns, each with 0.5 probability)
- The above, along with the two different assumptions for random offsets for phase error waveform implies 12 simulation cases ($2 \times 2 \times 3$)
- Other assumptions can be taken from the most recent simulations [5], and are summarized on the following slides
  - Note that all the simulations here assume GM error of zero; GM error will be added in later simulations, after other assumptions are settled on

Other Assumptions - 2

Assumption/Parameter	Description/Value
Hypothetical Reference Model (HRM), see note following the tables	101 PTP Instances (100 hops; GM, followed by 99 PTP Relay Instances, followed by PTP End Instance
Computed performance results	(a) $\max\lvert dTE_{R(k,\ 0)}\rvert$ (i.e., maximum absolute relative time error between node *k* (*k* > 0) and GM; here, GM time error is 0, so $\max\lvert dTE_{R(k,\ 0)}\rvert = \max\lvert dTE\rvert$) (b) Measured LocalClock rateRatio (frequency offset) relative to GM, for comparison with actual LocalClock frequency offset (results will be plotted for nodes 2, 35, 68, and 101 (where node 2 is the first node after the GM, and the GM is node 1; note that in [1], the GM was node 0, and the above nodes were 1, 34, 67, and 100))
Use syncLocked mode for PTP Instances downstream of GM	Yes
Endpoint filter parameters	$K_pK_o = 11$, $K_iK_o = 65$ ($f_{3dB} = 2.5998$ Hz, 1.288 dB gain peaking, $\zeta = 0.68219$)
Simulation time	(a) For single replication cases: 3150 s; discard first 50 s to eliminate any startup transient before computing $\max\lvert dTE_{R(k,\ 0)}\rvert$ (i.e., 10 cycles of frequency variation after discard) (b) For multiple replication cases, may need to be shorter than 3150 s depending on run times

Other Assumptions - 3

Assumption/Parameter	Description/Value
Number of independent replications, for each simulation case	(a) Single replication cases (i.e. 1) (b) Multiple replication cases (300, subject to acceptable run times; these cases will be run later, after presenting and discussing results for single-replication cases)
GM rateRatio and neighborRateRatio computation granularity	0
Mean link delay	500 ns
Link asymmetry	0
Dynamic timestamp error for event messages (Sync, Pdelay-Req, Pdelay_Resp) due to variable delays within the PHY	±8 ns; for each timestamp taken, a random error is generated. The error is + 8 ns with probability 0.5, and – 8 ns with probability 0.5. The errors are independent for different timestamps and different PTP Instances.
Any variable PHY delay in addition to the dynamic timestamp error described above is assumed to be zero	0

Other Assumptions - 4

- The method described below, using a window and computing the median, for computing neighborRateRatio, was **not** used for cases 1 – 12
  - neighborRateRatio was be computed using the current and most recent Pdelay exchange
- In cases 9 – 11 of [5], which used neighborRateRatio accumulation to measure GM rateRatio, neighborRateRatio was measured using a methodology similar to that used for GM rateRatio via successive Sync messages
- In these cases, a window size of 7 was used, i.e., the difference was taken between respective timestamps of current Pdelay exchange and 7th previous Pdelay exchange
  - In addition, the current estimate of neighborRateRatio was taken as the median of the most recent 7 measurements (including the current measurement)

Other Assumptions - 5

- In cases 12 – 14 of [5], which measured GM rateRatio using successive Sync messages, this same approach was used for both the measurement of GM rateRatio (using Sync messages) and neighborRateRatio (using Pdelay exchanges)
  - neighborRateRatio measurements were needed for compensation of different rates of Pdelay requestor and responder in accounting for Pdelay turnaround time
  - However, in these cases the window size was 11 rather than 7
- The initial results obtained here, for cases 1 – 12, showed that the 1 μs objective for max|TE| over 64 hops (and 100 hops if possible) was exceeded; note that the result for max|dTE| needs to be somewhat less than this to allow for the effects of GM phase variation and cTE

Other Assumptions - 6

- To investigate this further, three cases with 1 ms residence time and initial relative time offsets of the phase error histories at each node chosen randomly over the full period of the LocalClock phase error waveform were run:
  - Timestamp granularity and dynamic timestamp error both zero (case 13)
  - Timestamp granularity = 0; dynamic timestamp error = 8 ns (case 14)
  - Timestamp granularity = 8 ns; dynamic timestamp error = 0 (case 15)
- max|dTE| for case 13 was less than 100 ns for 100 hops
- max|dTE| for case 14 exceeded 1000 ns after 30 hops
- Max|dTE| for case 15 was approximately 730 ns after 100 hops
- These results suggested that dynamic timestamp error is a large contributor to dTE
  - However, since dynamic timestamp error is modeled as being random at each node and uncorrelated in time, it can be reduced by averaging (or, more generally, filtering)
- Therefore, cases 16 – 27 were run; these were analogous to cases 1 – 12, but with neighborRateRatio computed using a window of size 7 and taking the median of the current and most recent 7 measurements
- The 27 cases are summarized on the following slides (note that no averaging is done in computing mean link delay)

Summary of Simulation Cases – 1

Case	Residence time (ms)	Timestamp gran (ns)	Fract of cycle over which initial time error waveforms are randomized (%)	Compute neighborRateRatio averaging over window of size 7 and taking median
1	1	8	100	No
2	4	4	100	No
3	10	8	100	No
4	1	4	100	No
5	4	8	100	No
6	10	4	100	No
7	1	8	10	No
8	4	4	10	No
9	10	8	10	No
10	1	4	10	No
11	4	8	10	No
12	10	4	10	No

Summary of Simulation Cases – 2

Case	Residence time (ms)	Timestamp gran (ns), dynamic timestamp error (ns)	Fract of cycle over which initial time error waveforms are randomized (%)	Compute neighborRateRatio averaging over window of size 7 and taking median
13	1	0, 0	100	No
14	1	0, 8	100	No
15	1	8, 0	100	No

Summary of Simulation Cases – 3

Case	Residence time (ms)	Timestamp gran (ns)	Fract of cycle over which initial time error waveforms are randomized (%)	Compute neighborRateRatio averaging over window of size 7 and taking median
16	1	8	100	Yes
17	4	4	100	Yes
18	10	8	100	Yes
19	1	4	100	Yes
20	4	8	100	Yes
21	10	4	100	Yes
22	1	8	10	Yes
23	4	4	10	Yes
24	10	8	10	Yes
25	1	4	10	Yes
26	4	8	10	Yes
27	10	4	10	Yes

Summary of Simulation Cases - 4

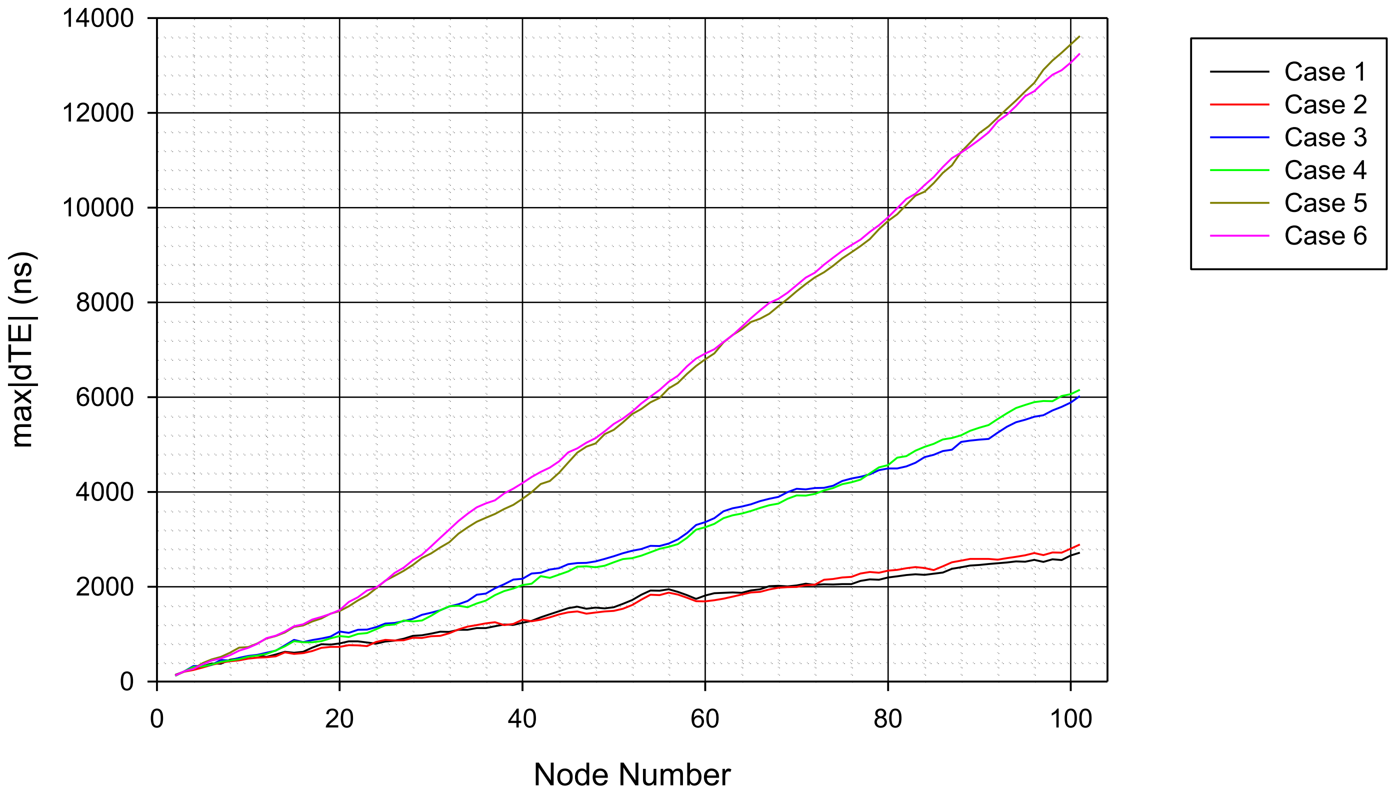
- In cases 1 – 12 and 16 – 27, dynamic timestamp error is as indicated previously (see slide 8):
  - ±8 ns
  - For each timestamp taken, a random error is generated
  - The error is + 8 ns with probability 0.5, and – 8 ns with probability 0.5
  - The errors are independent for different timestamps and different PTP Instances

Cases 1 - 12 Results - 1

- Results for max|dTE| versus node number are summarized on the next two slides, for cases 1 – 6 and 7 – 12, respectively
- Detailed time history results for case 7, nodes 2, 35, 68, and 101 (GM is node 1) follow the max|dTE| results
  - Due to the potentially large number of plots, detailed time history results are not presented for every node of every case; however, results for additional nodes and cases can be supplied if desired

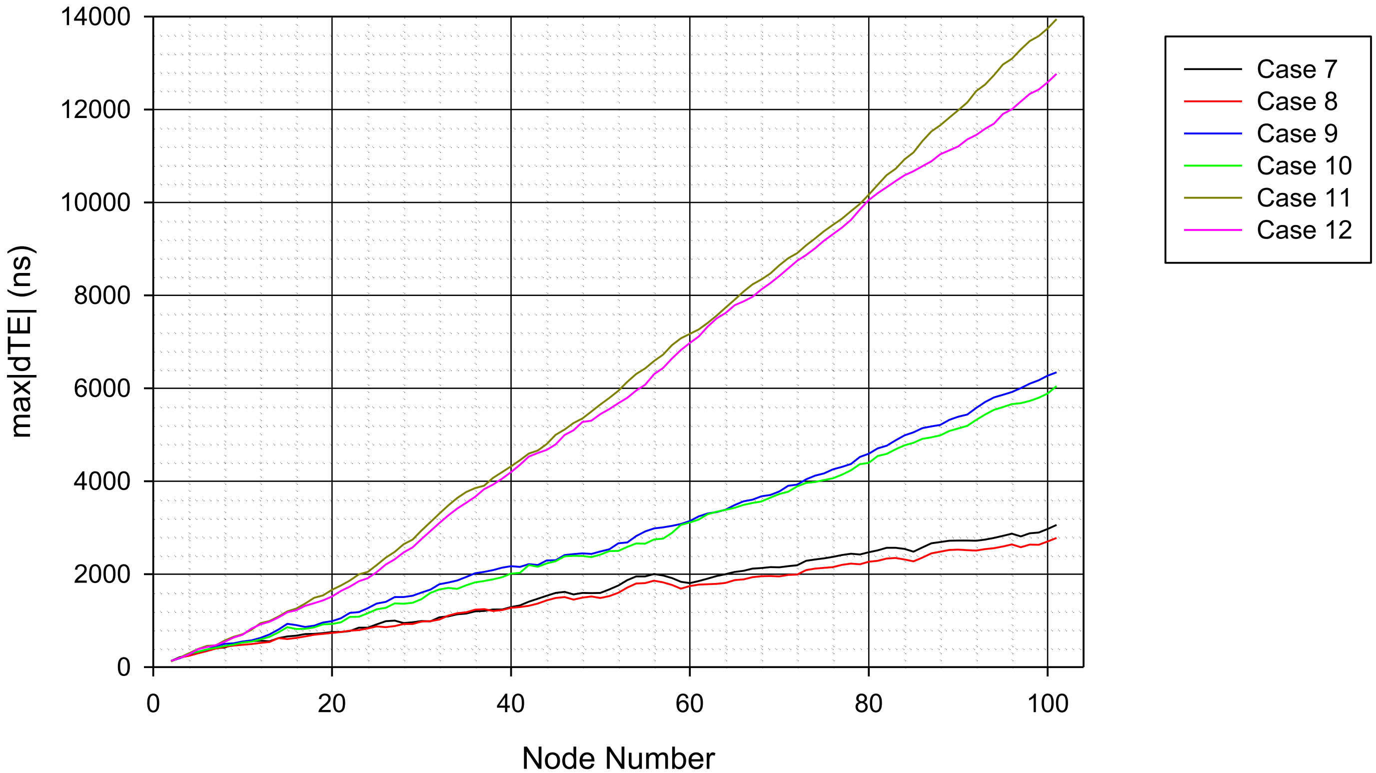
Cases 1 - 12 Results - 2

Simulation Cases 1, 2, 4, 5, 6
Single replication of simulation
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over entire cycle
Residence times: 1 ms (cases 1,2), 4 ms (cases 3,4), 10 ms (cases 5,6)
Timestamp granularities: 8 ns (cases 1,3,5), 4 ns (cases 2,4,6)



Cases 1 – 12 Results - 3

Simulation Cases 7, 8, 9, 10, 11, 12
Single replication of simulation
Clock Model: Frequency vs temperature stability and temperature vs time profile
from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence times: 1 ms (cases 7,8), 4 ms (cases 9,10), 10 ms (cases 11,12)
Timestamp granularities: 8 ns (cases 7,9,11), 4 ns (cases 8,10,12)



Cases 1 - 12 Results - 4

Case	max|dTE|, 64 hops (ns)	max|dTE|, 100 hops (ns)	Case	max|dTE|, 64 hops (ns)	max|dTE|, 100 hops (ns)
1	1924	2717	7	2046	3058
2	1877	2891	8	1871	2777
3	3738	6023	9	3488	6341
4	3597	6155	10	3426	6045
5	7585	13618	11	7904	13942
6	7666	13252	12	7787	12766

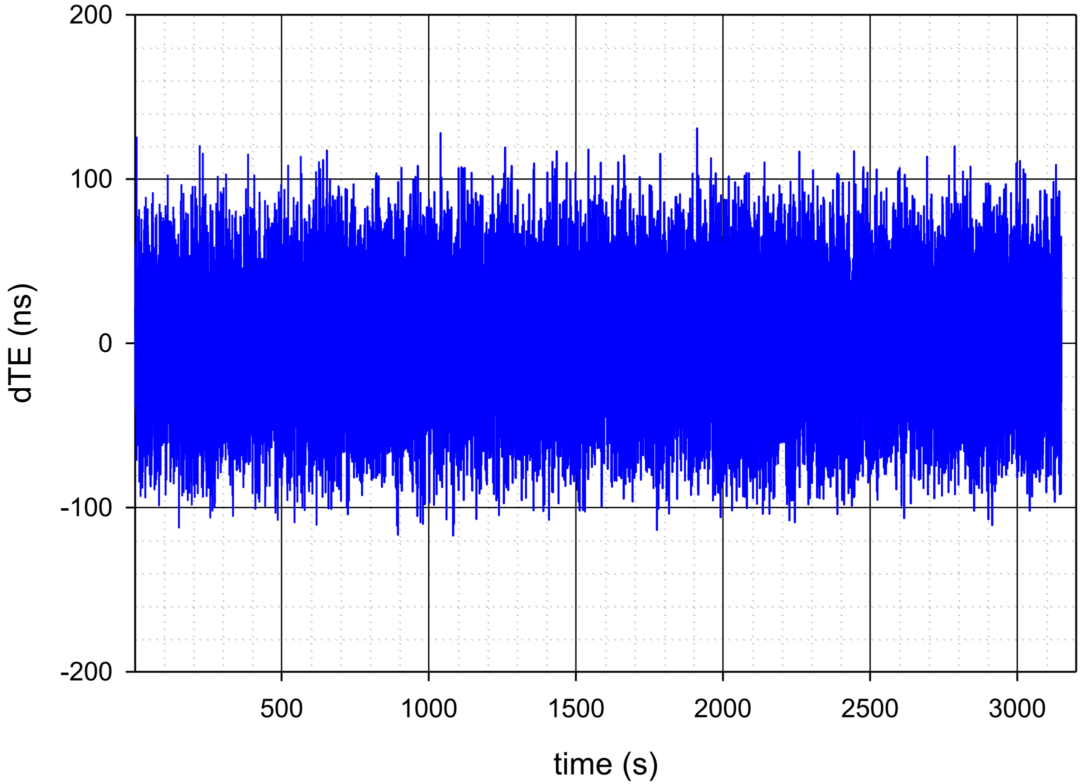
64 hops results are for node 65
100 hops results are for node 101

Cases 1 - 12 Results - 4

- Any lack of smoothness in the results is due to statistical variation, as these results are for a single replication
- The results indicate the following
  - The differences between cases with 8 ns timestamp granularity and 4 ns timestamp granularity (comparing cases 1 and 2, 3 and 4, 5 and 6, 7 and 8, 9 and 10, 11 and 12) are small
  - The differences between cases where the initial LocalClock phase error waveform offsets are chosen randomly over the entire cycle (cases 1 – 6) versus 10% of the cycle (cases 7 – 12) are small
- The 1 μs objective is exceeded after approximately 30 hops for 1 ms residence time, 20 hops for 4 ms residence time, and 12 hops for 10 ms residence time
- The following slides show case 7 results for time histories of dTE, measured and actual frequency offsets at nodes 2, 35, 68, and 101 (GM is node 1), and difference between measured and actual frequency offsets at the same nodes

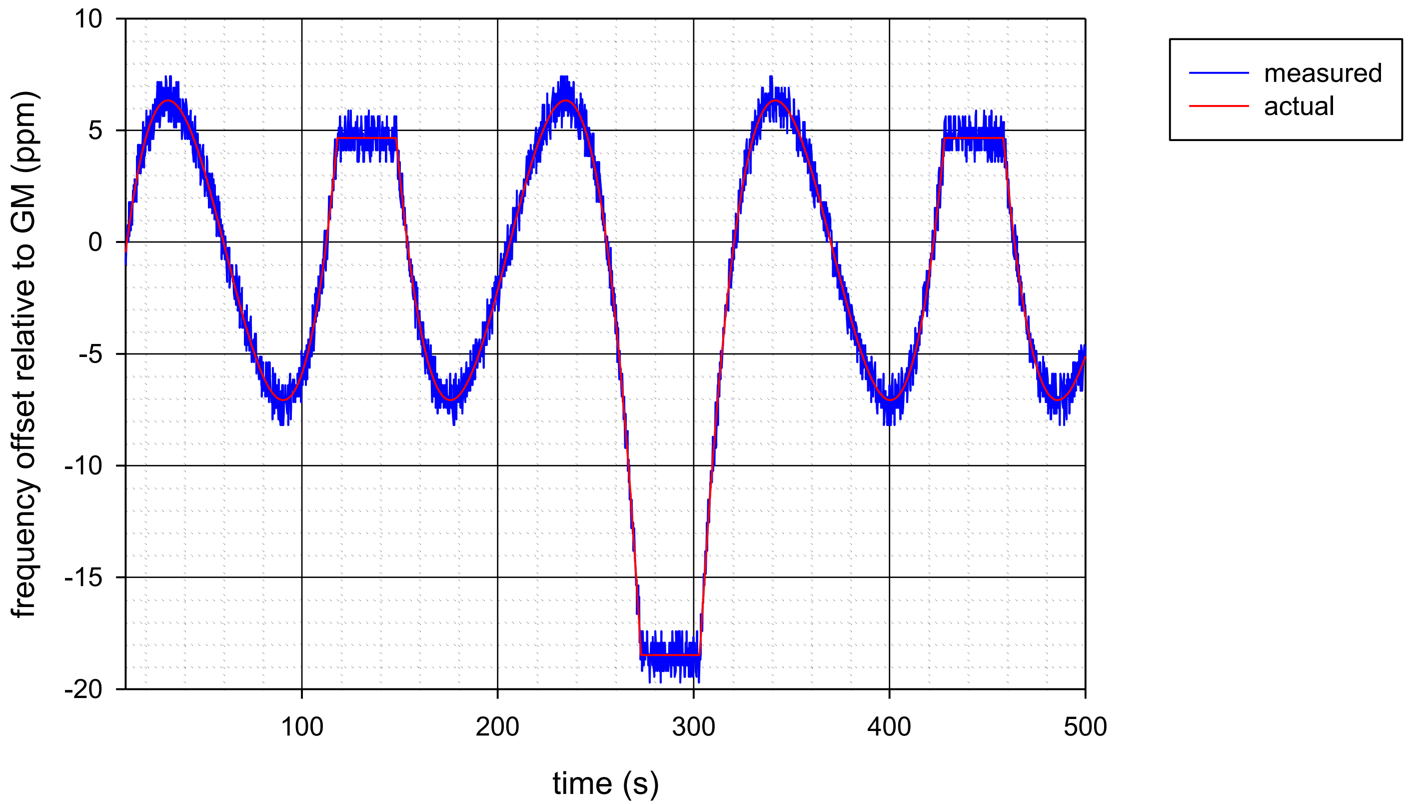
Case 7, Node 2 Detailed Results - 1

Simulation Case 7, Node 2
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



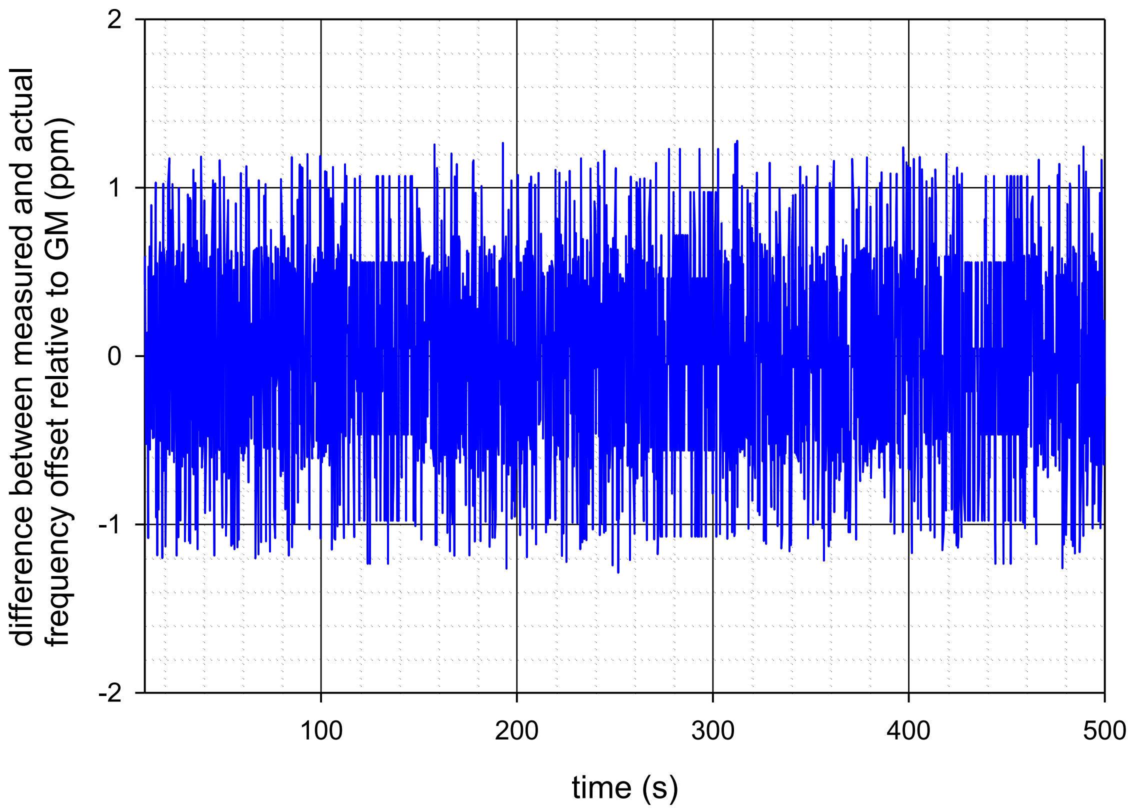
Case 7, Node 2 Detailed Results - 2

Simulation Case 7, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



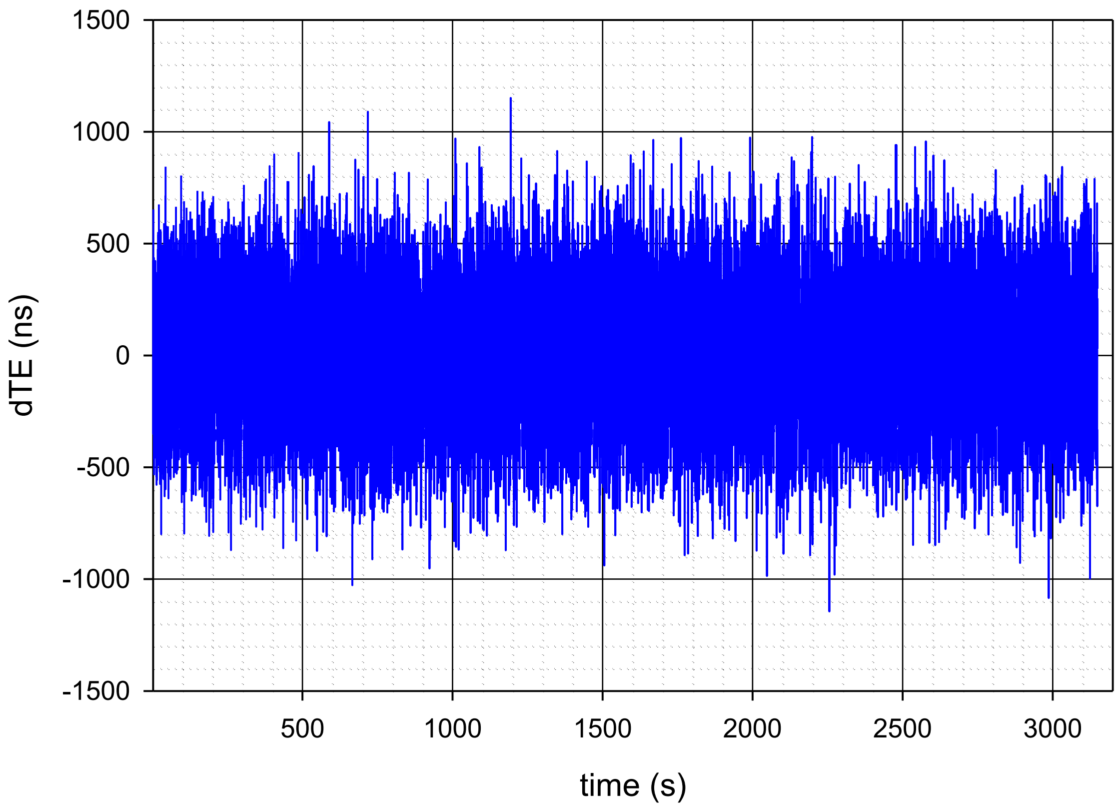
Case 7, Node 2 Detailed Results – 3

Simulation Case 7, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



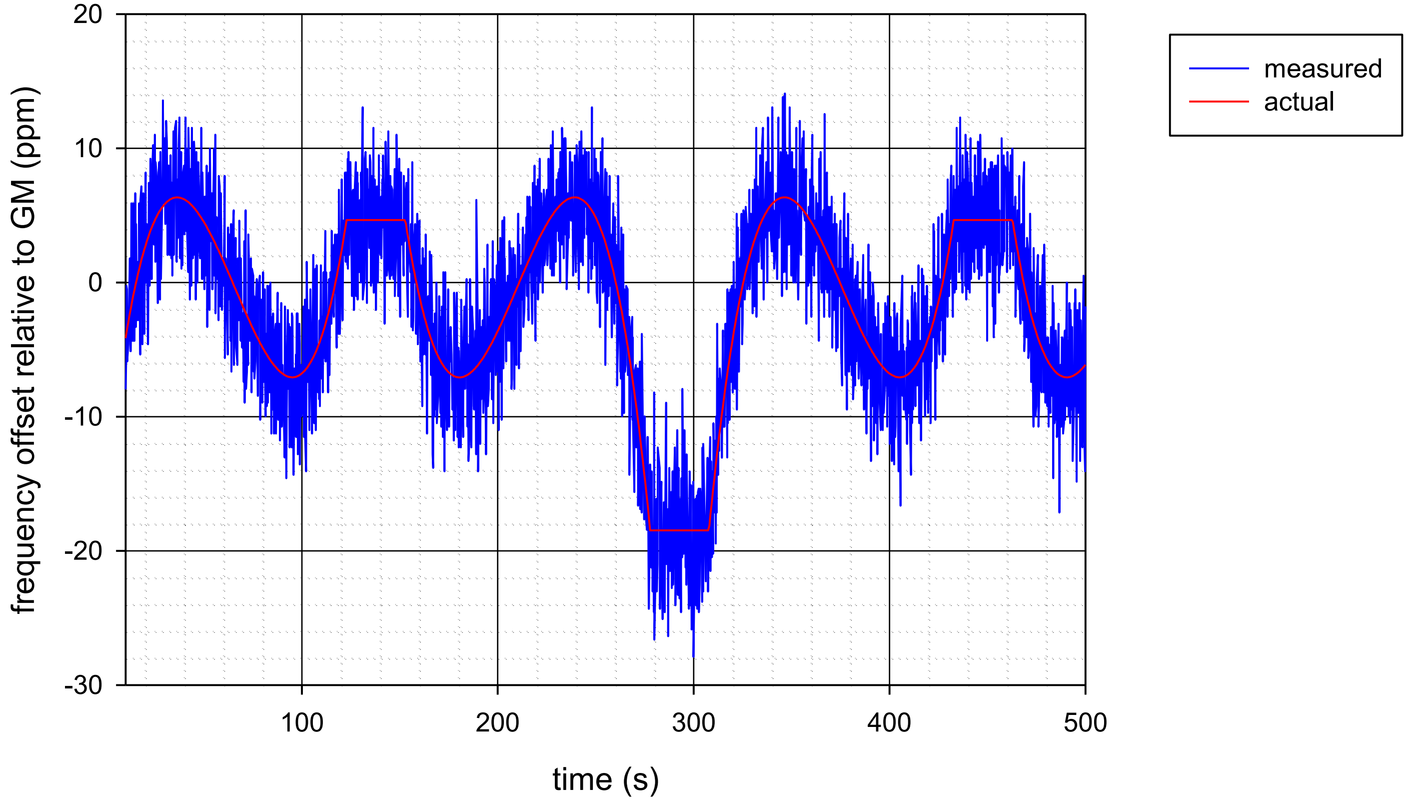
Case 7, Node 35 Detailed Results - 1

Simulation Case 7, Node 35
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



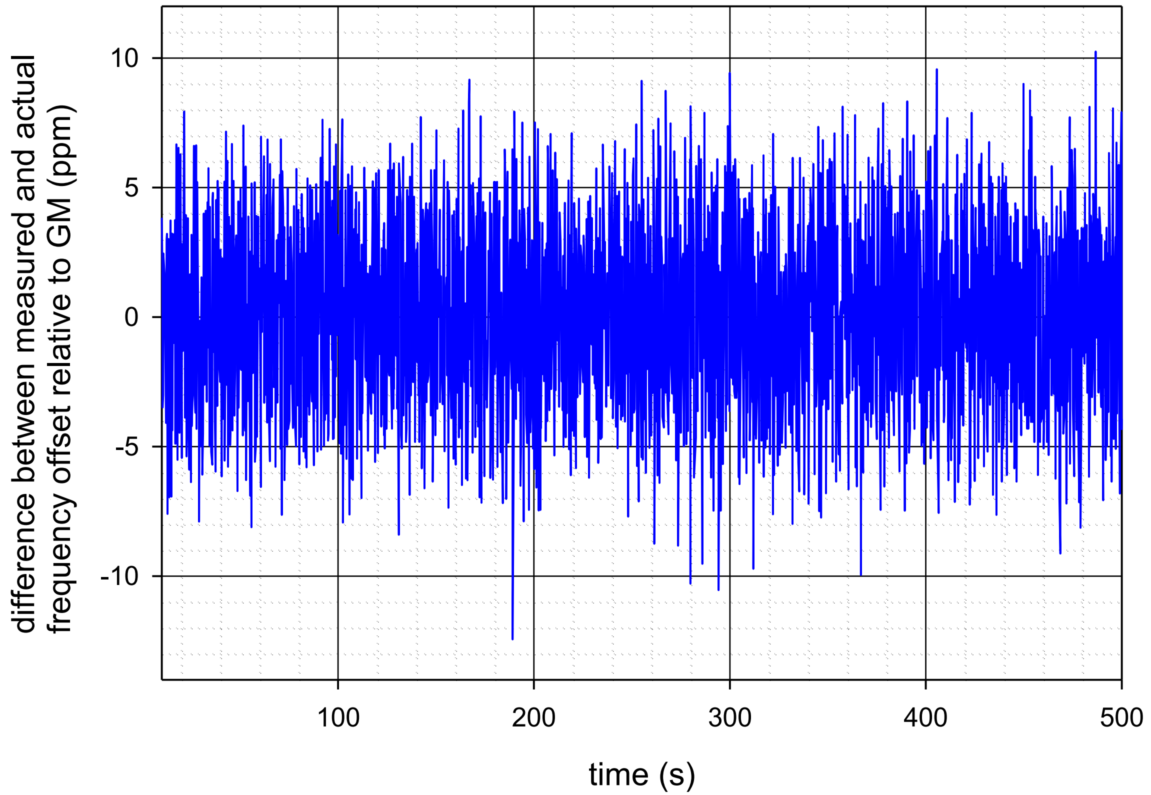
Case 7, Node 35 Detailed Results - 2

Simulation Case 7, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



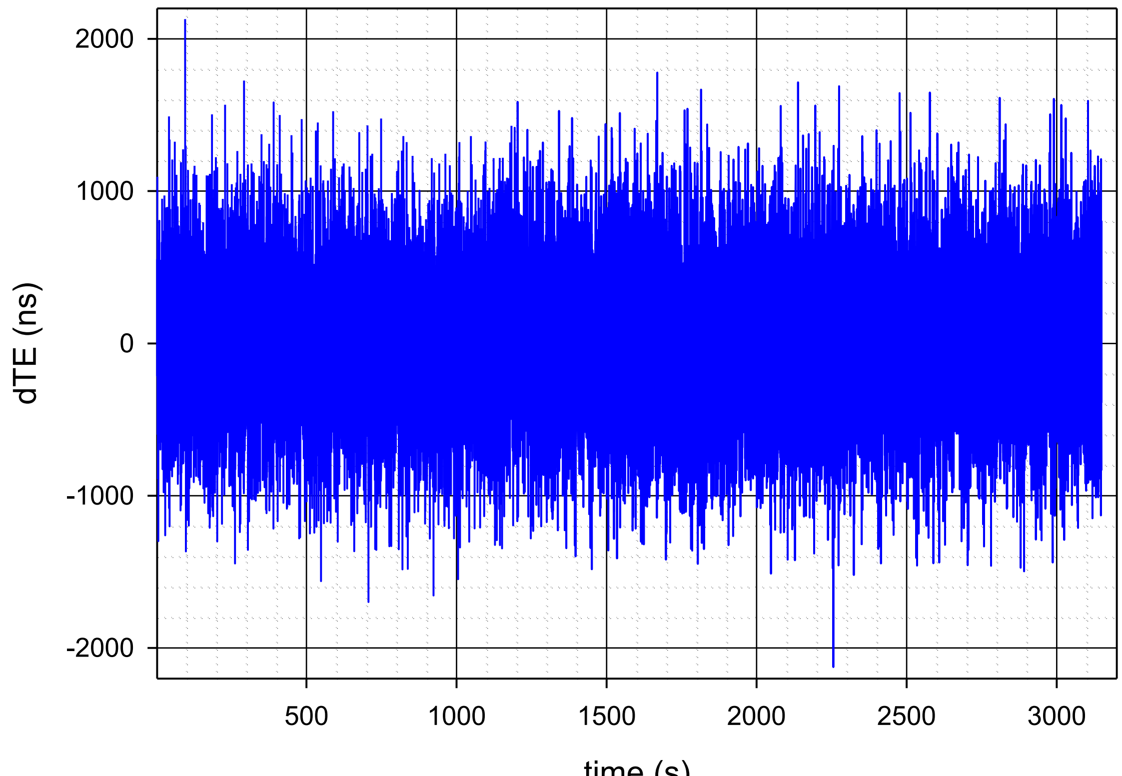
Case 7, Node 35 Detailed Results - 3

Simulation Case 7, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



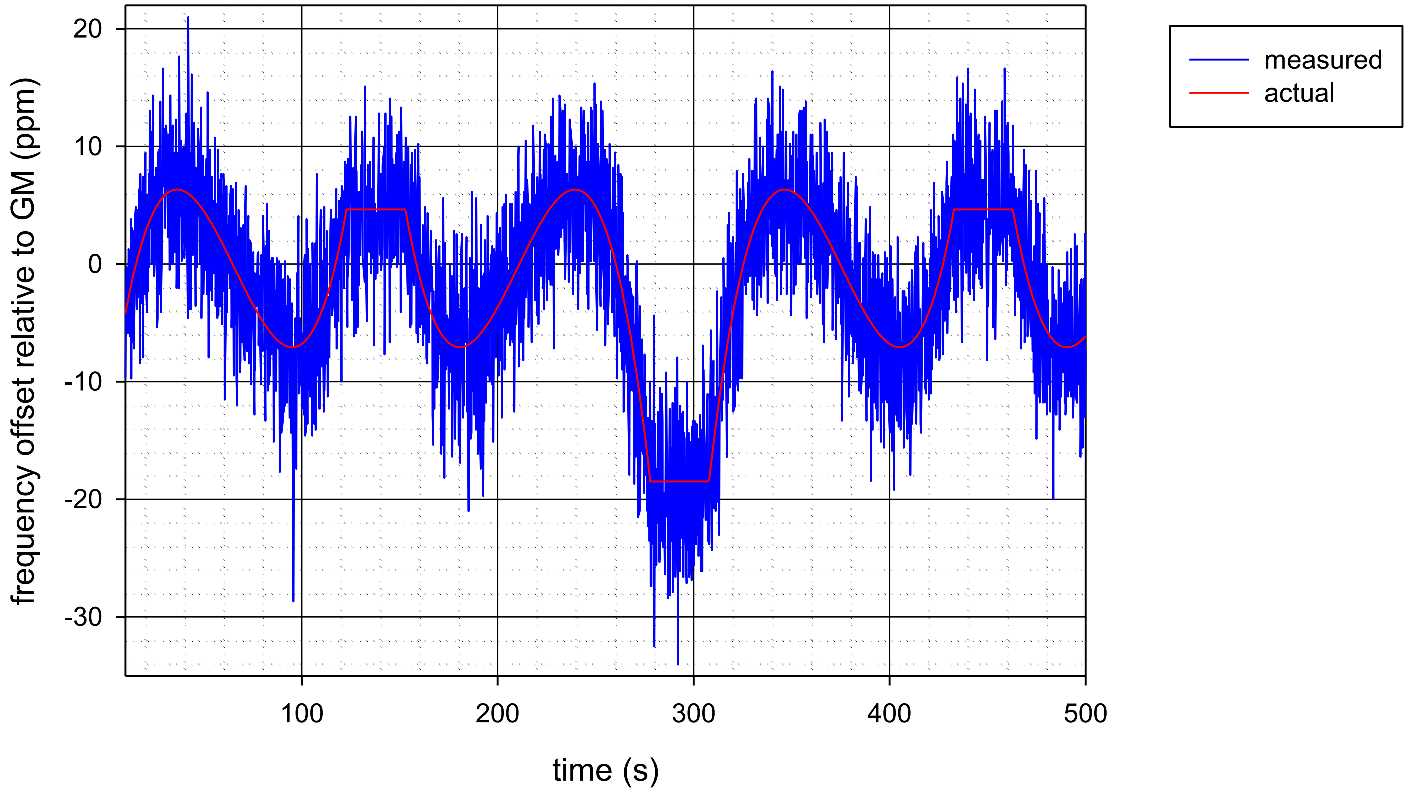
Case 7, Node 68 Detailed Results - 1

Simulation Case 7, Node 68
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



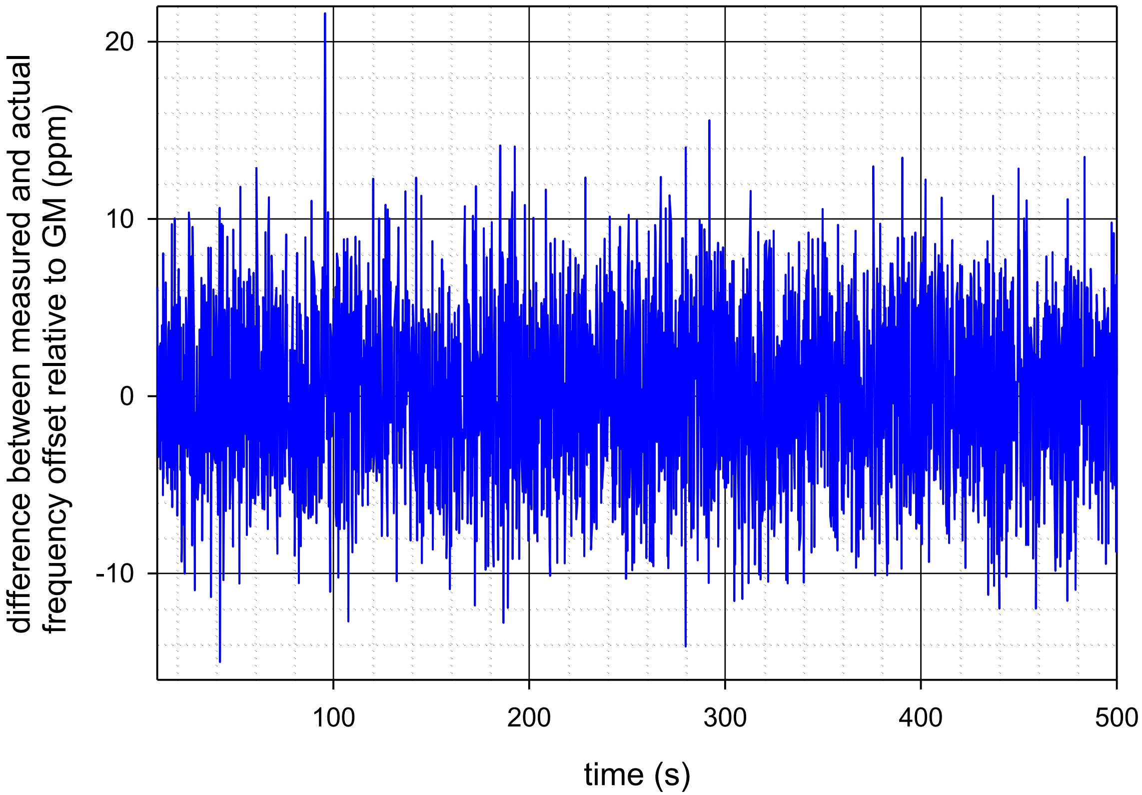
Case 7, Node 68 Detailed Results - 2

Simulation Case 7, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



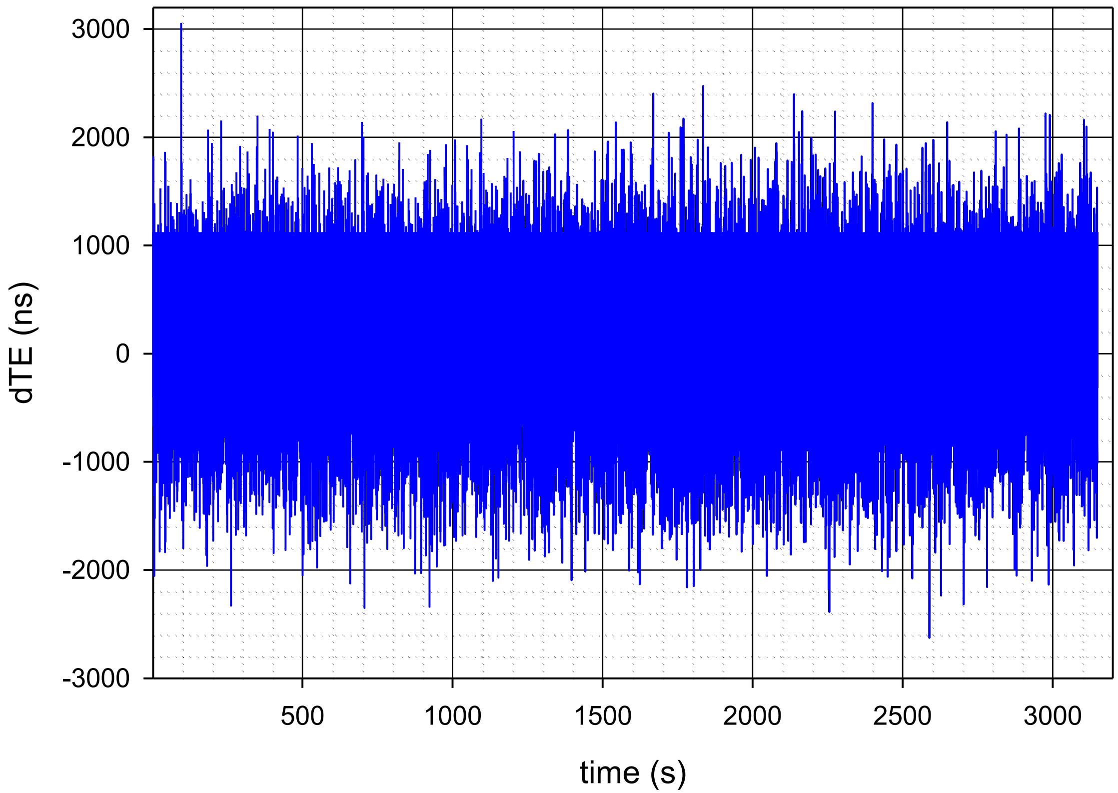
Case 7, Node 68 Detailed Results - 3

Simulation Case 7, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



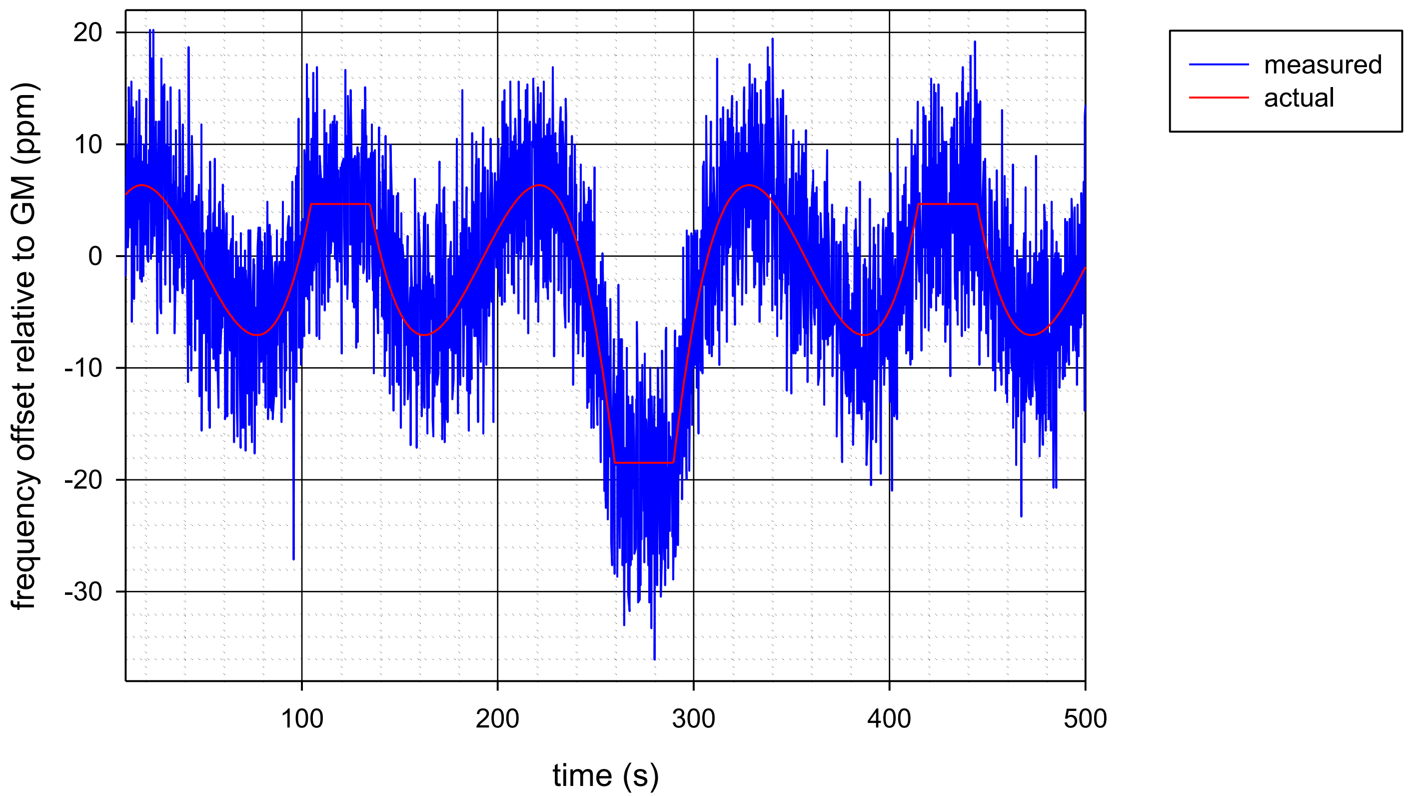
Case 7, Node 101 Detailed Results – 1

Simulation Case 7, Node 101
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



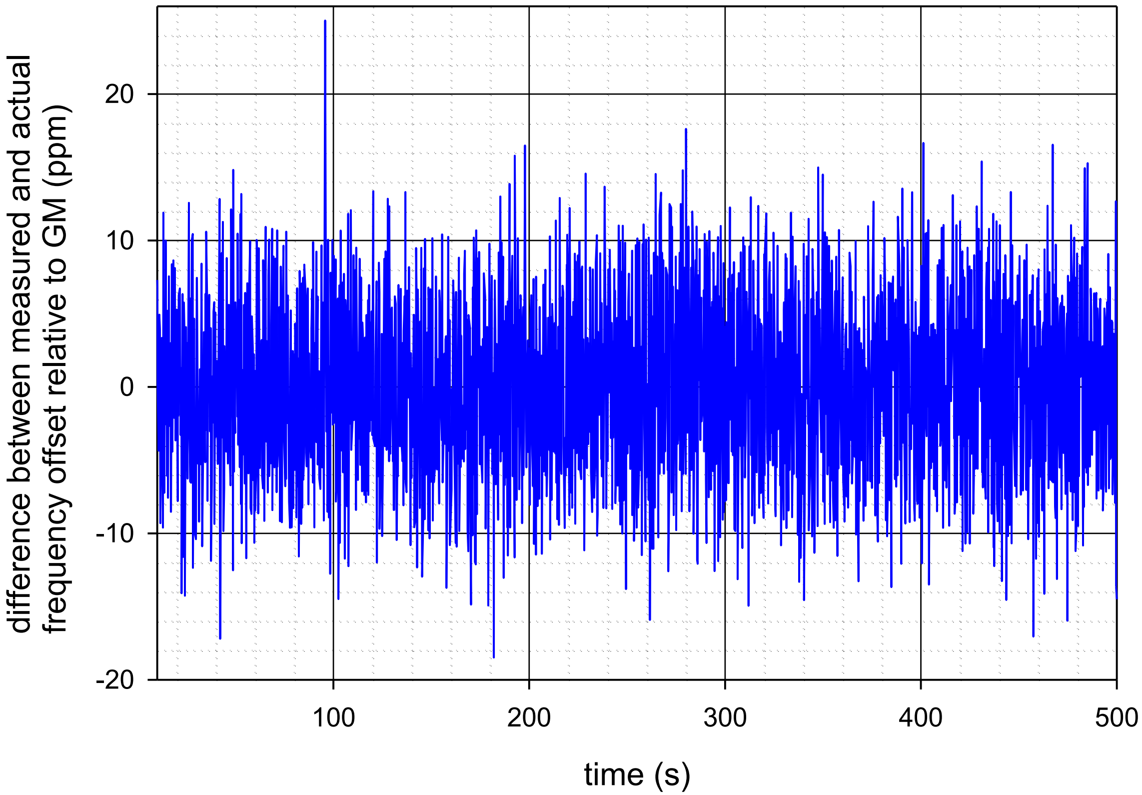
Case 7, Node 101 Detailed Results – 2

Simulation Case 7, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



Case 7, Node 101 Detailed Results – 3

Simulation Case 7, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



Case 7 Detailed Results Summary

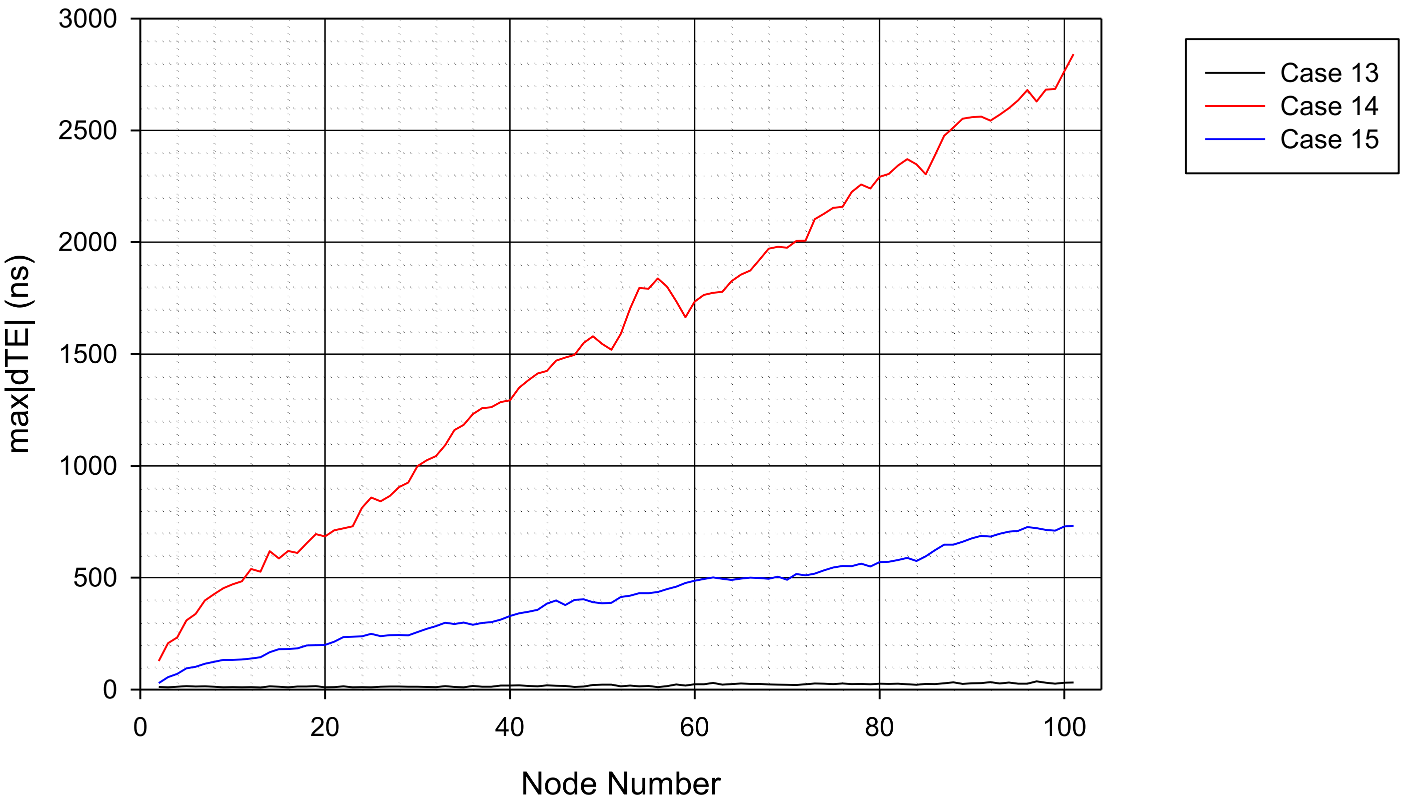
- The maxima of the dTE waveforms for nodes 1, 35, 68, and 101 are approximately 130 ns, 1250 ns, 2100 ns, and 3050 ns, consistent with slide 18
- Slides 21, 24, 27, and 30 show how the measured frequency offset at each node (based on the accumulated neighborRateRatio) follows the actual frequency offset, though with an error that increases with increasing node number
  - The maximum frequency offset error at node 2 (1st node after the GM) is approximately 1.3 ppm
    - The rateRatio measurement at node 2 is equal to neighborRateRatio, because the GM (node 1) is assumed to have zero phase and frequency error
    - The maximum frequency offset measurement error at node 2 is much greater than the requirement of 802.1AS-2020, B.2.4, of ±0.1 ppm
      - B2.4 should likely be clarified to indicate that the requirement is for neighborRateRatio
  - The maximum frequency offset error increases to approximately 13.5 ppm, 22 ppm, and 25 ppm, at nodes 35, 68, and 100, respectively
  - Note that these errors include statistical variability; however, they do indicate the trend

Cases 13 - 15 Results - 1

- The results for cases 1 – 12 suggest that the timestamp granularity and dynamic timestamp error are contributors to the error in measured frequency offset, which in turn causes the error in dTE to be larger
- Therefore, cases 13 – 15 were run; these are similar to case 1, except:
  - Timestamp granularity and dynamic timestamp error both zero (case 13)
  - Timestamp granularity = 0; dynamic timestamp error = 8 ns (case 14)
  - Timestamp granularity = 8 ns; dynamic timestamp error = 0 (case 15)
- The results on the following slide indicate
  - max|dTE| for case 13 is approximately 35 ns for 100 hops
  - max|dTE| for case 14 exceeds 1000 ns after 30 hops and is approximately 2850 ns after 100 hops
  - max|dTE| for case 15 is approximately 730 ns after 100 hops
- These results indicate that dynamic timestamp error contributes more to overall dTE than timestamp granularity, though timestamp granularity does contribute

Cases 13 - 15 Results - 2

Simulation Cases 13, 14, 15
Single replication of simulation
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over entire cycle
Residence time: 1 ms
Timestamp granularity (ns) and Timestamp error (ns): (0,0) case 13; (0,8) case 14; (8,0) case 15



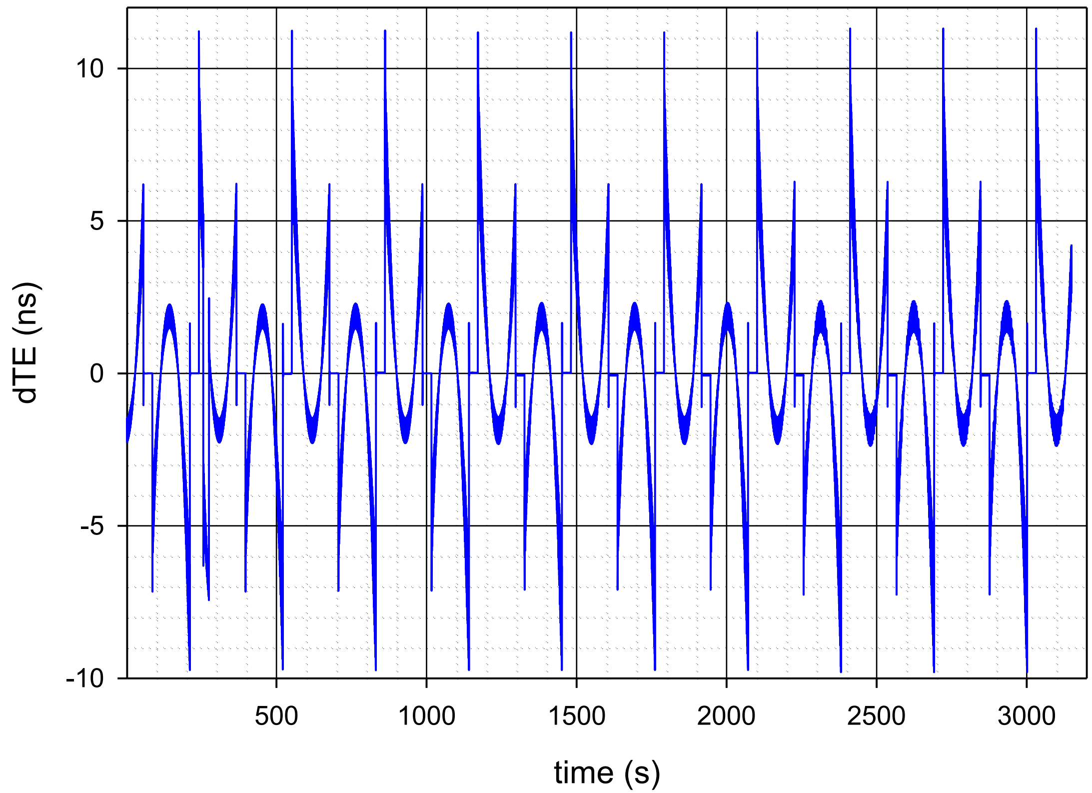
Cases 13 - 15 Results - 3

Case	max|dTE|, 64 hops (ns)	max|dTE|, 100 hops (ns)
13	27	32
14	1855	2841
15	496	733

64 hops results are for node 65
100 hops results are for node 101

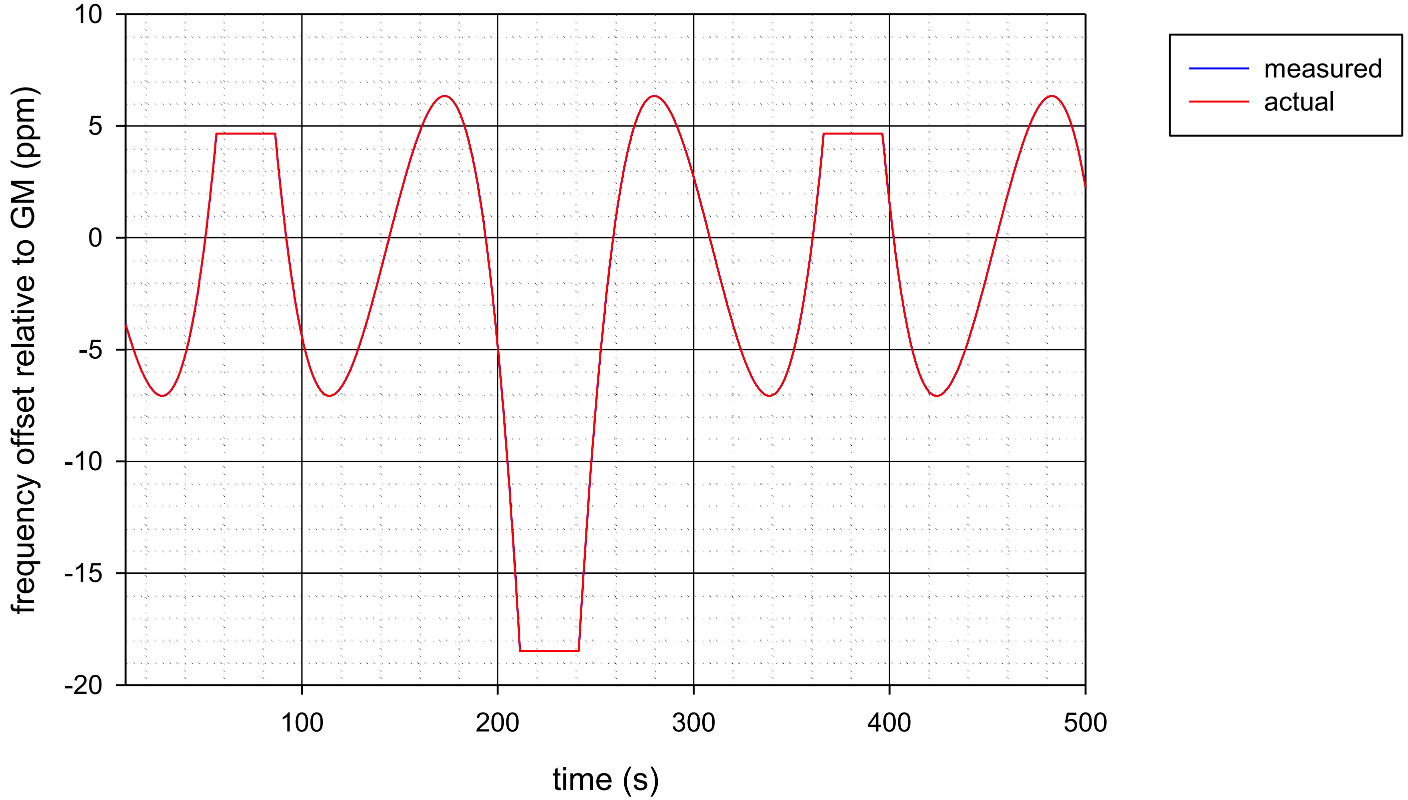
Case 13, Node 2 Detailed Results - 1

Simulation Case 13, Node 2
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



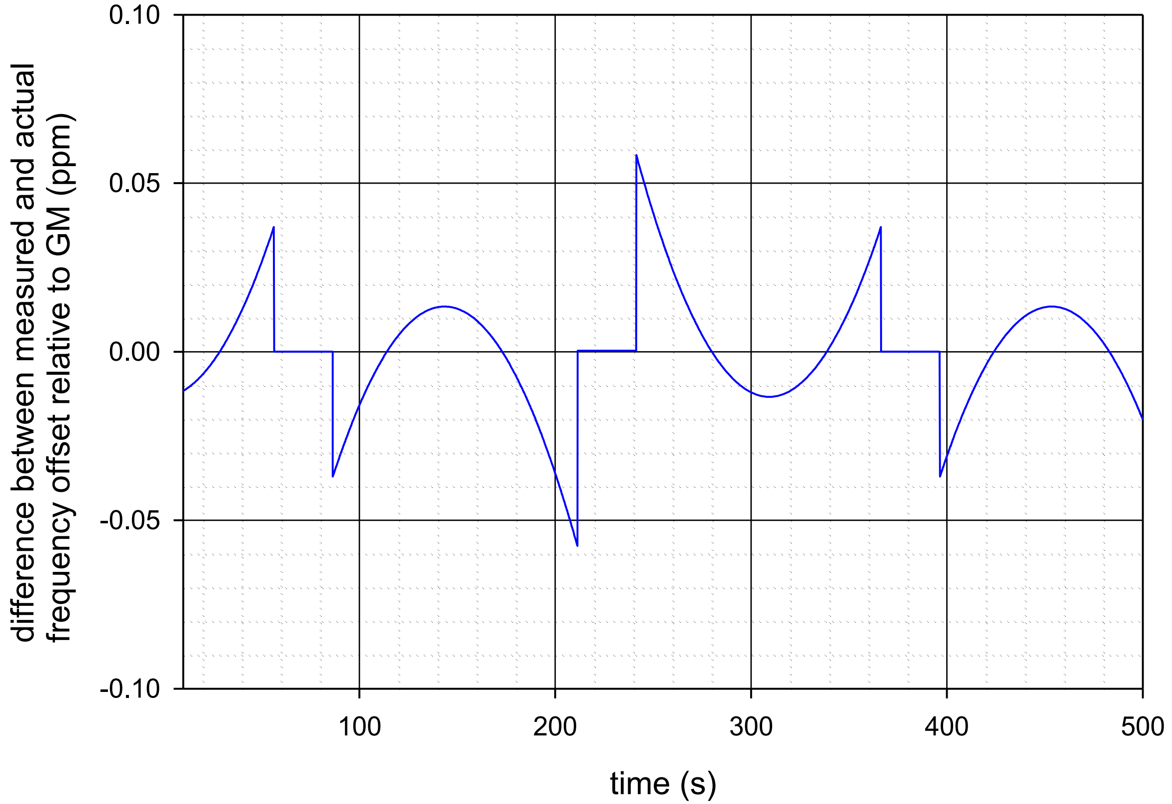
Case 13, Node 2 Detailed Results - 2

Simulation Case 13, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



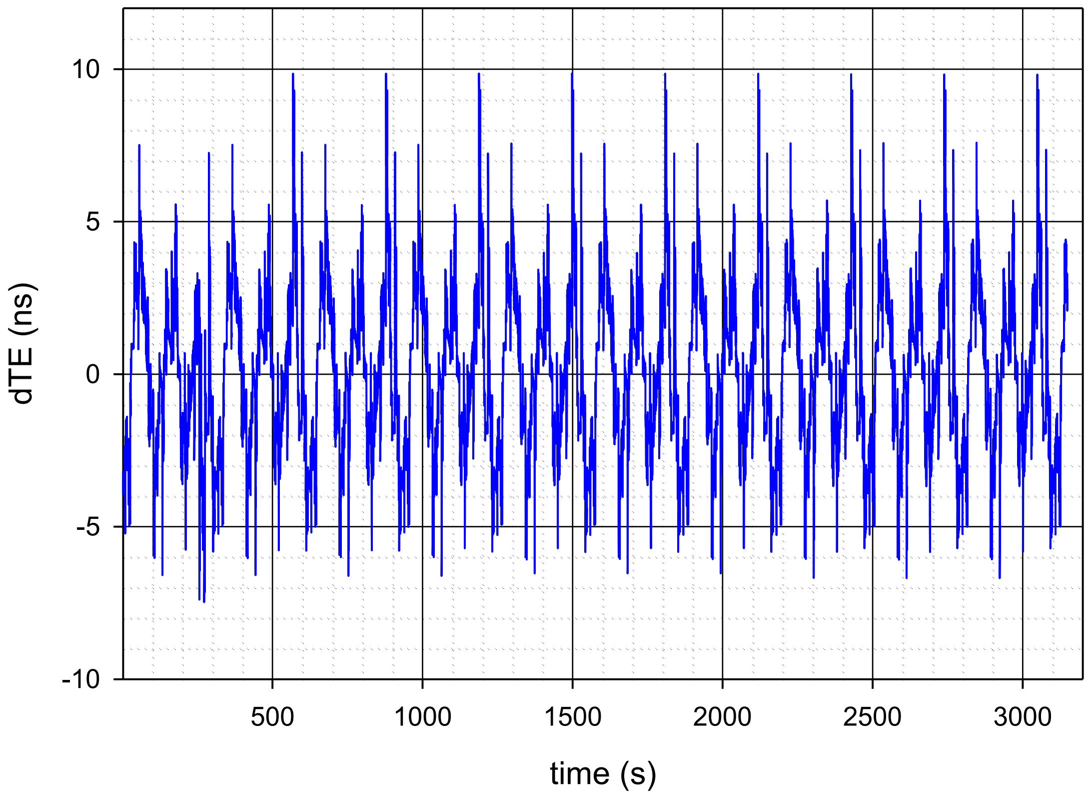
Case 13, Node 2 Detailed Results - 3

Simulation Case 13, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



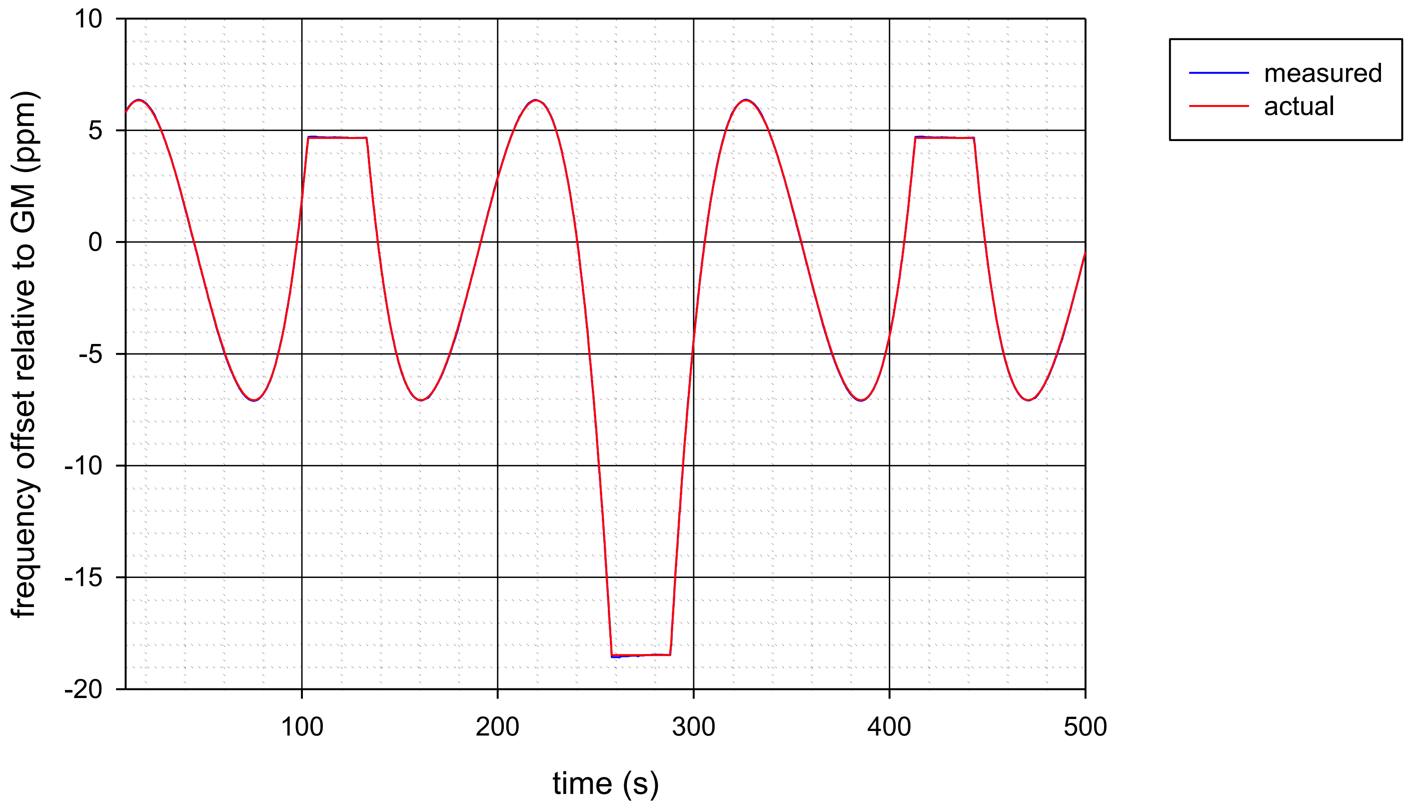
Case 13, Node 35 Detailed Results - 1

Simulation Case 13, Node 35
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



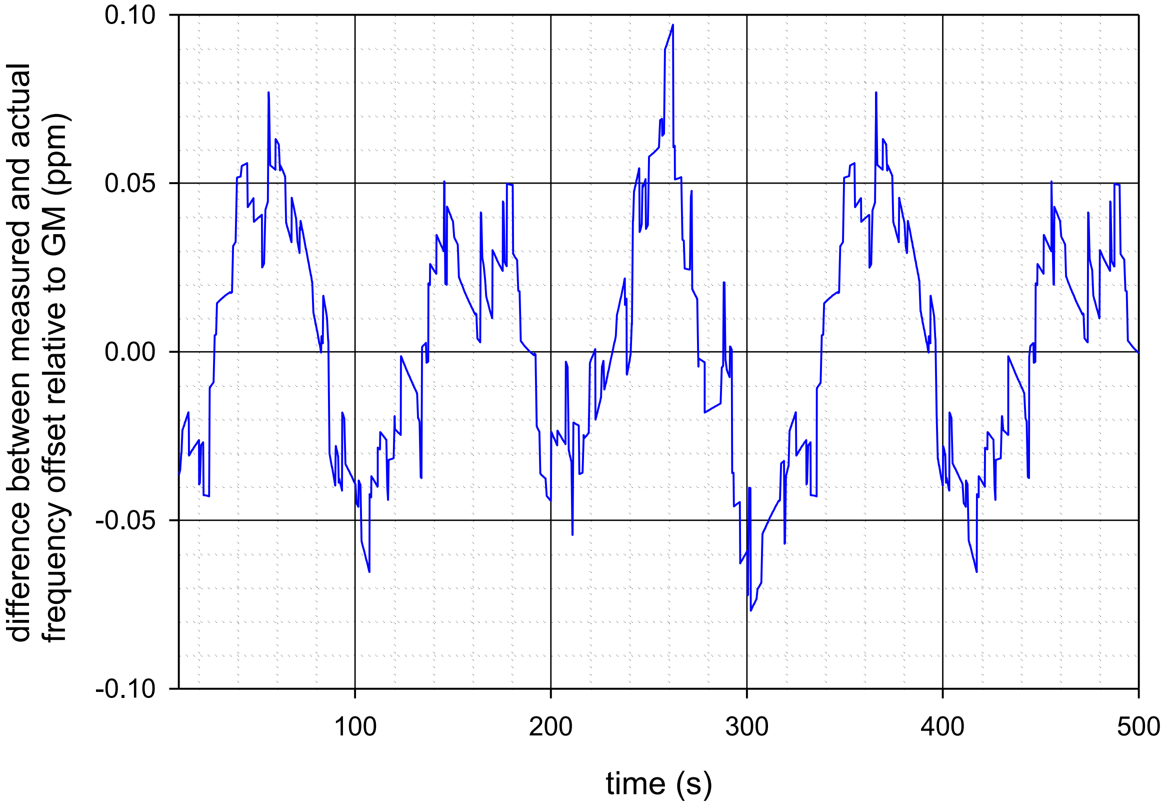
Case 13, Node 35 Detailed Results - 2

Simulation Case 13, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



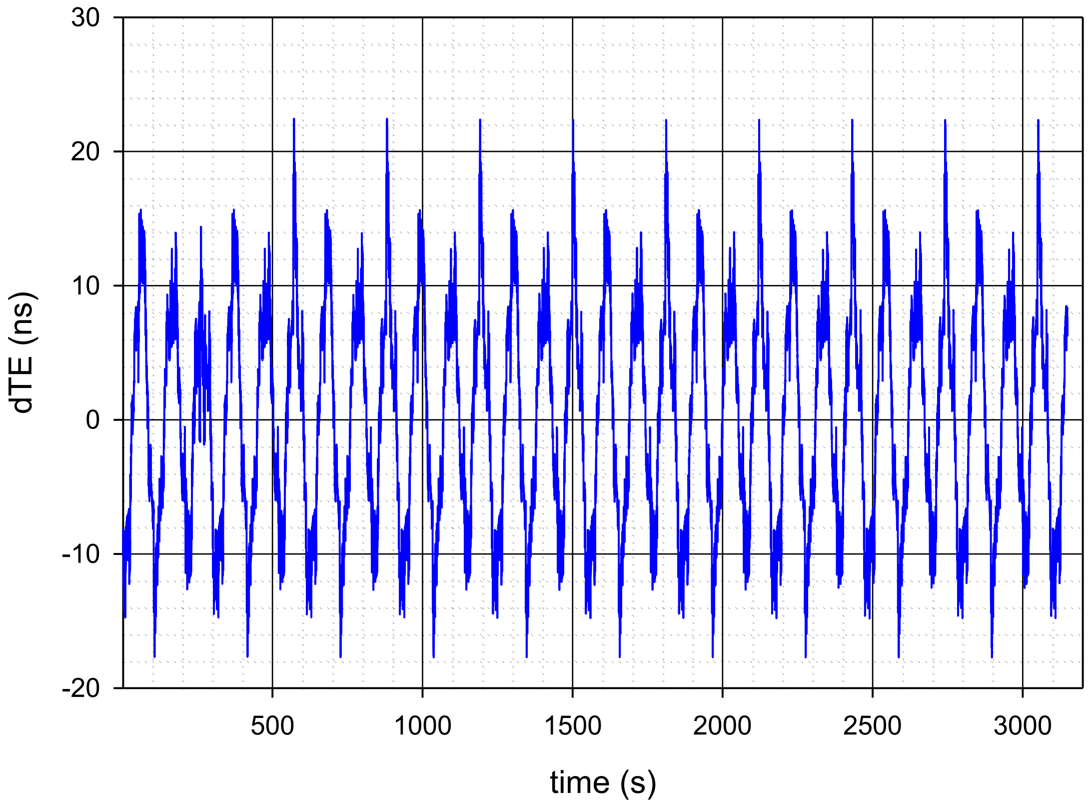
Case 13, Node 35 Detailed Results - 3

Simulation Case 13, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



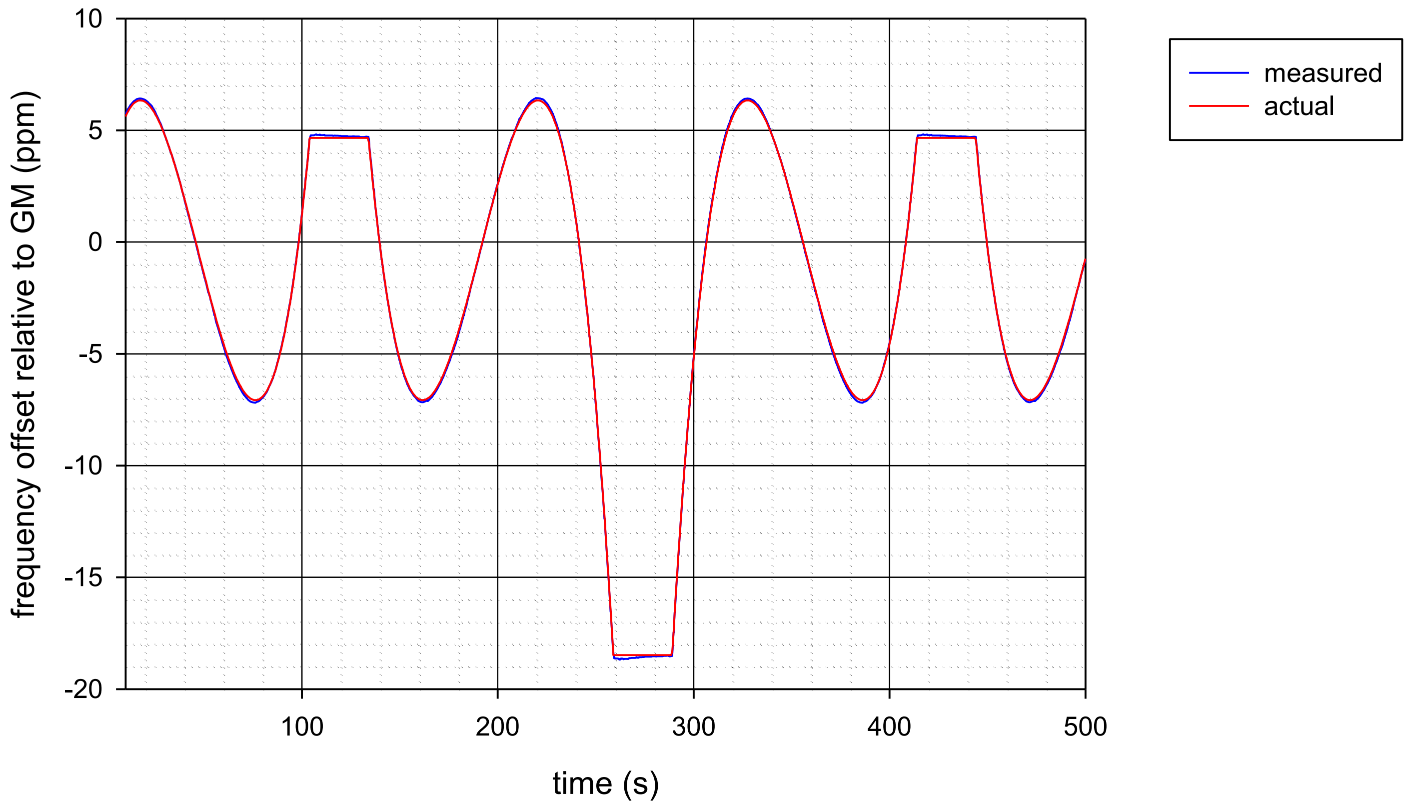
Case 13, Node 68 Detailed Results - 1

Simulation Case 13, Node 68
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile
from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



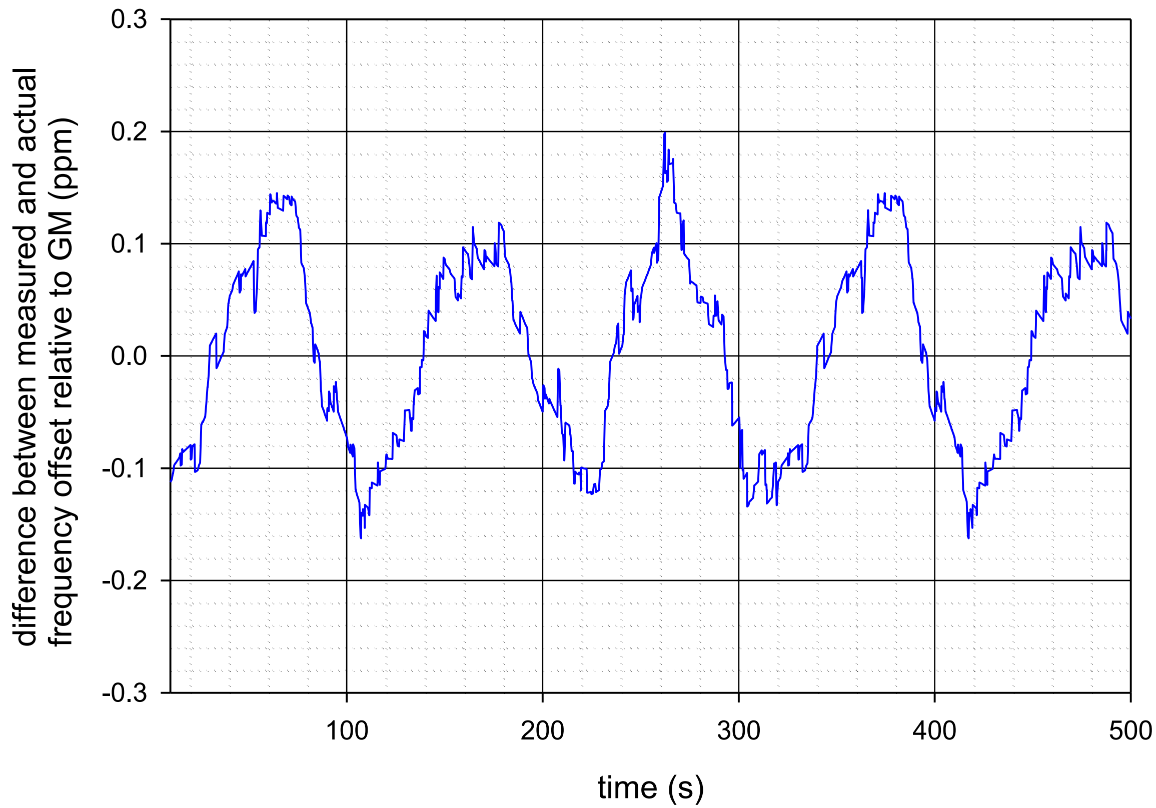
Case 13, Node 68 Detailed Results - 2

Simulation Case 13, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



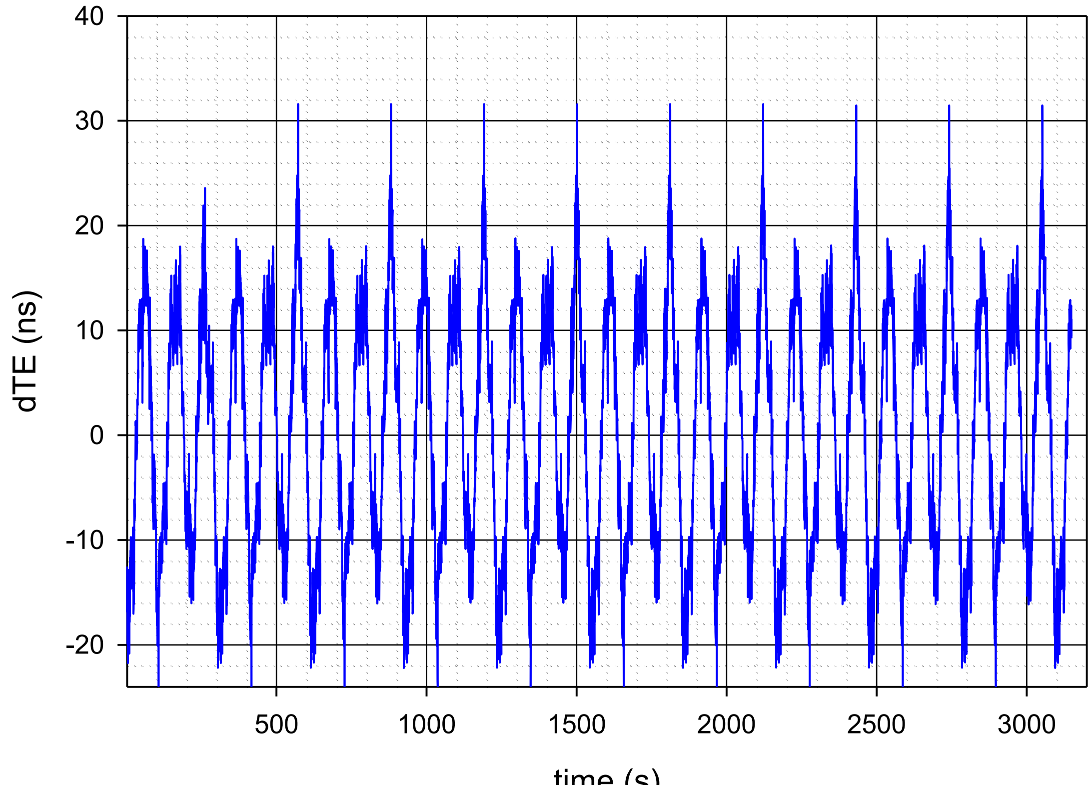
Case 13, Node 68 Detailed Results - 3

Simulation Case 13, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



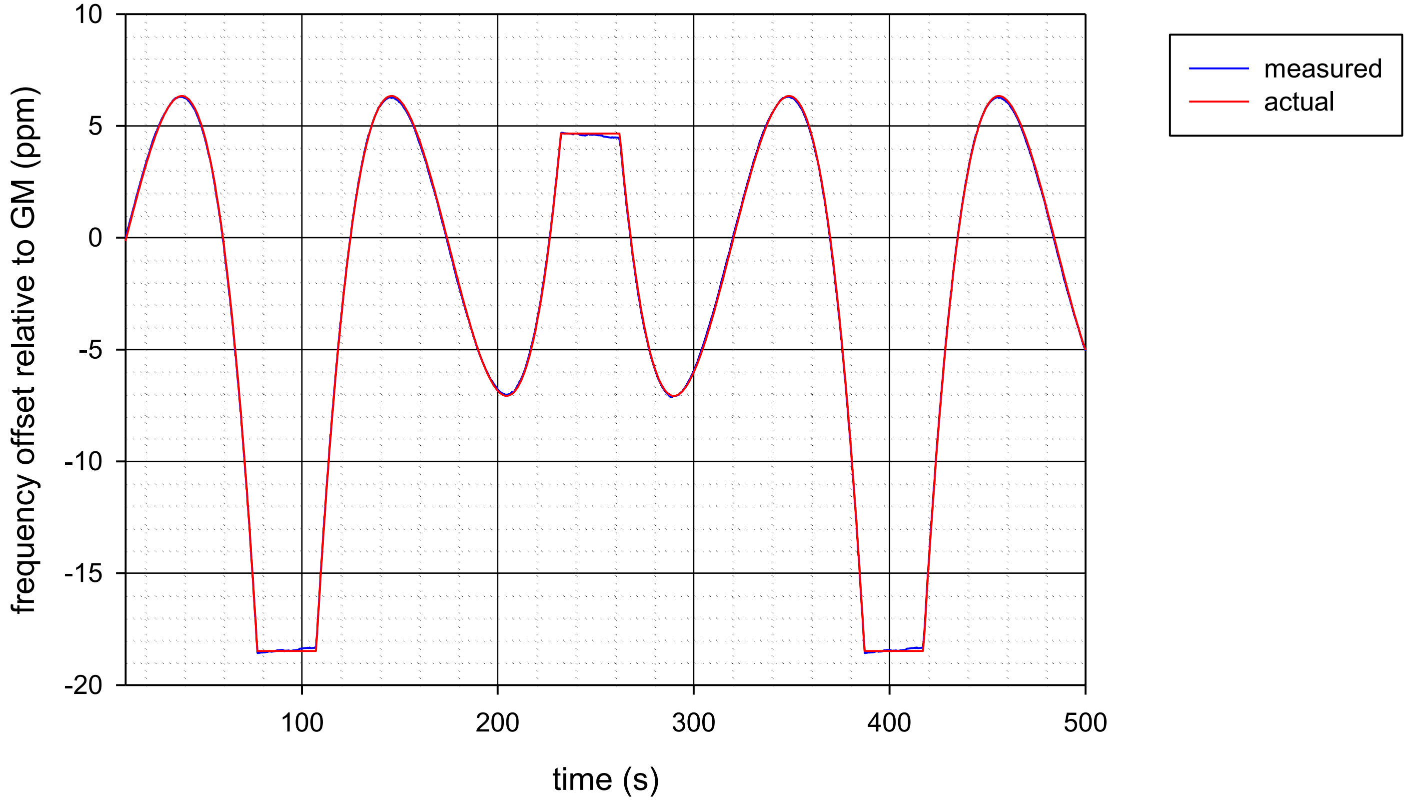
Case 13, Node 101 Detailed Results - 1

Simulation Case 13, Node 101
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



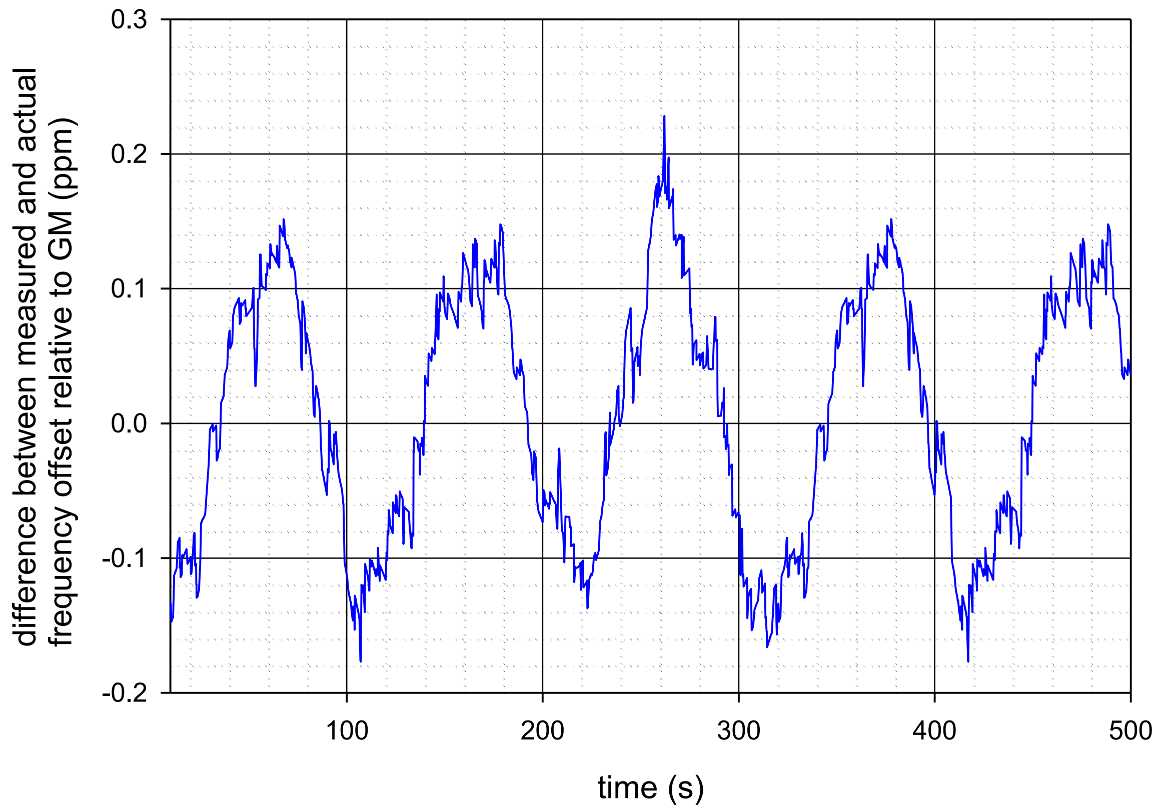
Case 13, Node 101 Detailed Results - 2

Simulation Case 13, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



Case 13, Node 101 Detailed Results - 3

Simulation Case 13, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



Case 13 – Detailed Results Summary

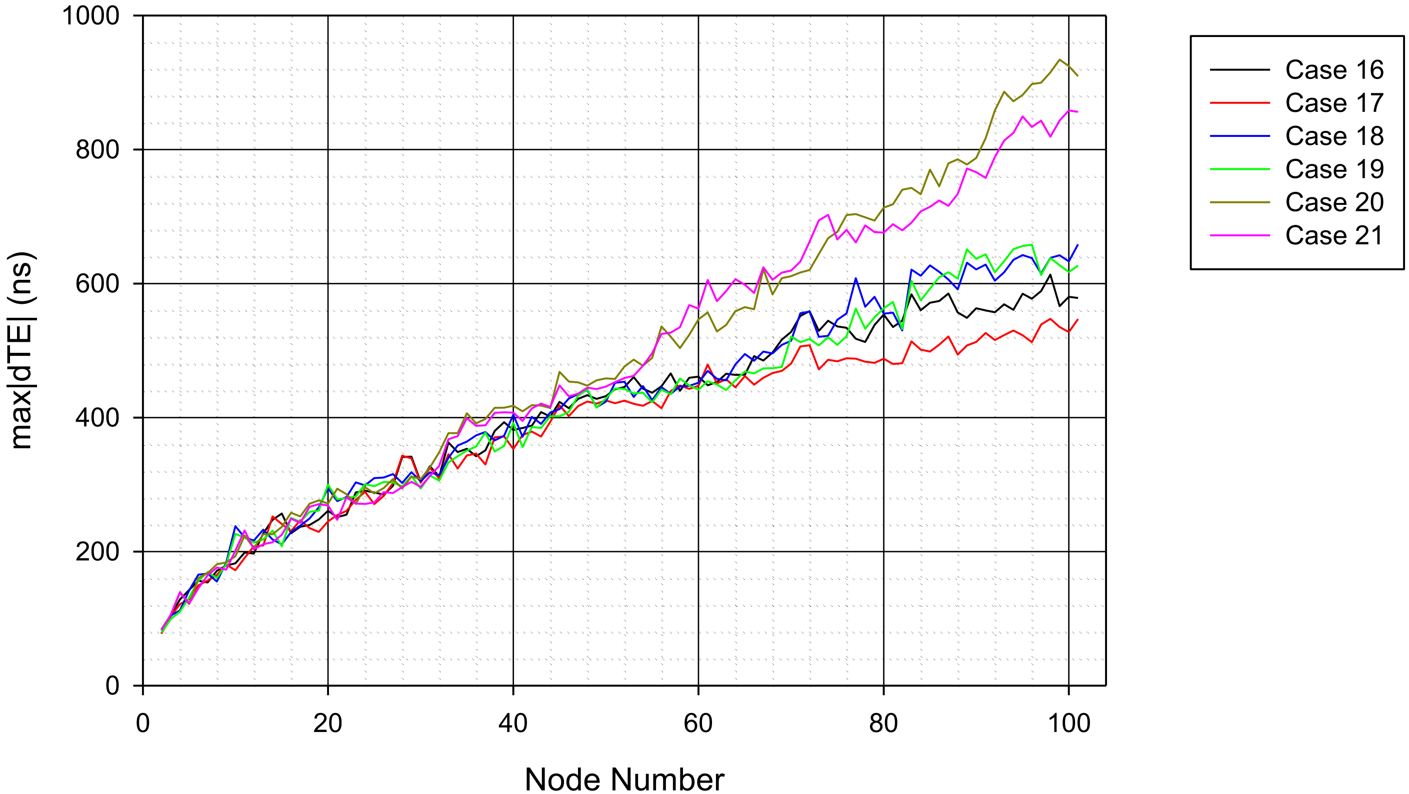
- The maximum dTE for nodes 2, 35, 68, and 101 is 11 ns, 10 ns, 22 ns, and 32 ns, respectively, consistent with max|dTE| results in slide 34 (the fact that maximum dTE for node 35 is slightly less than for node 2 is due to statistical variation)
- The error in measured frequency offset, compared to actual frequency offset, for nodes 2, 35, 68, and 101 is 0.06 ppm, 0.1 ppm, 0.2 ppm, and 0.23 ppm, respectively
  - The maximum frequency offset measurement error for node 2 is less than the requirement of 802.1AS-2020, B.2.4, of ±0.1 ppm

Cases 16 - 27 Results - 1

- The results for cases 13 – 15 suggest that it might be possible to reduce max|dTE| in cases where the timestamp granularity and dynamic timestamp error are as assumed in cases 1 – 12 by computing neighborRateRatio using the current and most recent *N* values
- This gives rise to cases 16 – 27, which are the same as cases 1 – 12, respectively, except that neighborRateRatio is computed at each node by:
    1. Taking the difference between the current correctedResponderEventTimestamp (see 11.2.19.2.2 of 802.1AS-2020) and the correctedResponderEventTimestamp of the N^{th} most recent Pdelay exchange
    2. Taking the difference between the current responseOriginTimestamp and the responseOriginTimestamp of the N^{th} most recent Pdelay exchange
    3. Dividing the result of 1. by the result of 2., and saving the most recently computed *N* values of this quotient (including the current value)
    4. Taking the median of the saved values as the current measured neighborRateRatio value
- For cases 16 – 27, the window size is taken to be 7 (i.e., $N = 7$)

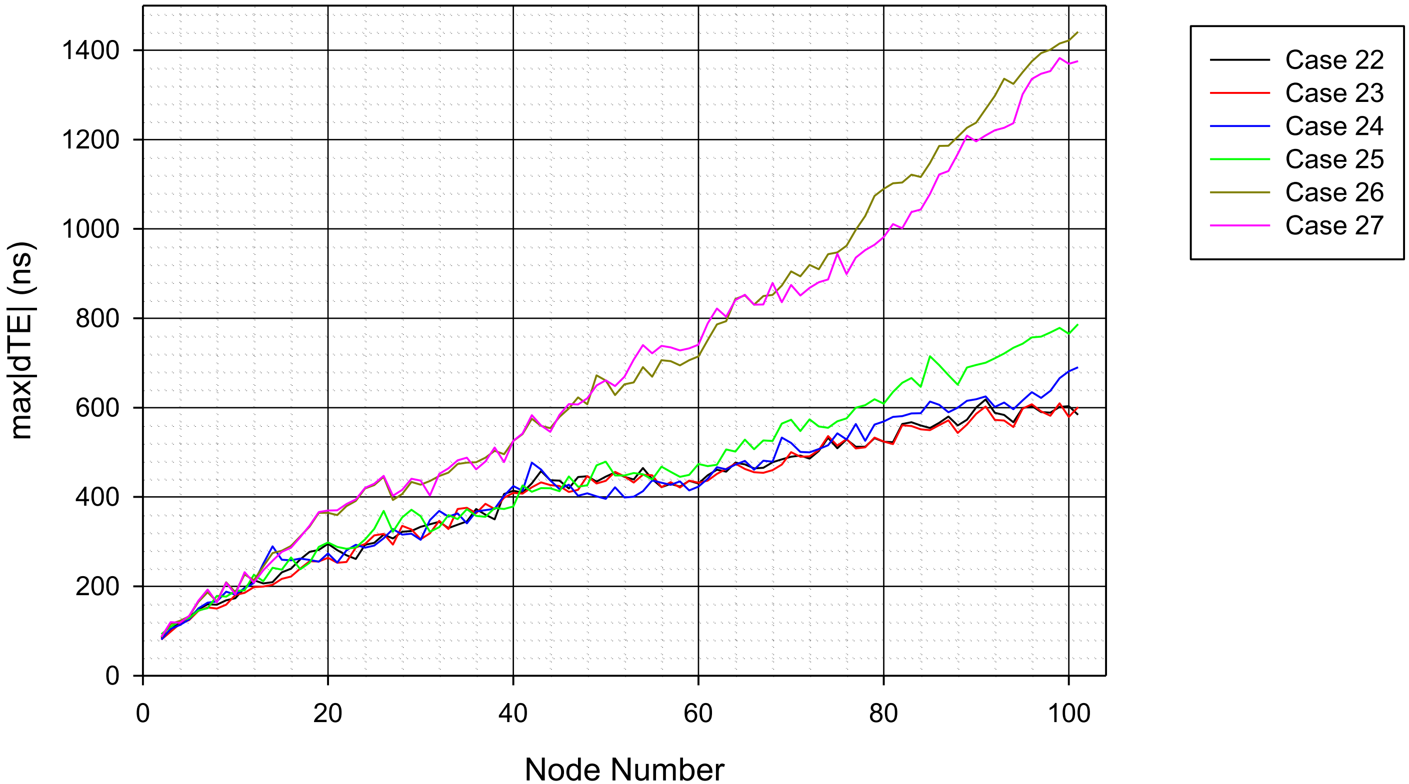
Cases 16 - 27 Results - 2

Simulation Cases 16, 17, 18, 19, 20, 21
Single replication of simulation
Clock model: stability and temp vs time profile from [1]
Accumulate neighborRateRatio; measure using size 10 window and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over entire cycle
Residence times: 1 ms (cases 16,17), 4 ms (cases 18,19), 10 ms (cases 20,21)
Timestamp granularities: 8 ns (cases 16,18,20), 4 ns (cases 17,19,21)



Cases 16 – 27 Results – 3

Simulation Cases 22, 23, 24, 25, 26, 27
Single replication of simulation
Clock model: stability and temp vs time profile from [1]
Accumulate neighborRateRatio; measure using size 10 window and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence times: 1 ms (cases 22,23), 4 ms (cases 24,25), 10 ms (cases 26,27)
Timestamp granularities: 8 ns (cases 22,24,26), 4 ns (cases 23,25,27)



Cases 16 – 27 Results – 4

- Any lack of smoothness in the results is due to statistical variation, as these results are for a single replication
- The results indicate the following
  - The differences between cases with 8 ns timestamp granularity and 4 ns timestamp granularity (comparing cases 1 and 2, 3 and 4, 5 and 6, 7 and 8, 9 and 10, 11 and 12) are small
    - To the extent that there are differences, it appears that the 4 ns cases have smaller accumulated time error
  - The cases where the initial LocalClock phase error waveform offsets are chosen randomly over the entire cycle (cases 16 – 21) tend to have smaller accumulate time error than the cases where the offsets are chosen randomly over 10% of the cycle (cases 22 – 27); this is most pronounced for the cases with 10 ms residence time
- The 1 μs objective is exceeded only for the cases with 10 ms residence time and where the waveform offsets are chosen randomly over 10% of the cycle (cases 26 and 27), after approximately 80 hops

Cases 16 - 27 Results - 5

- The following slides show results for cases 16, 22, and 27, for time histories of dTE, measured and actual frequency offsets at nodes 2, 35, 68, and 101 (GM is node 1), and difference between measured and actual frequency offsets at the same nodes

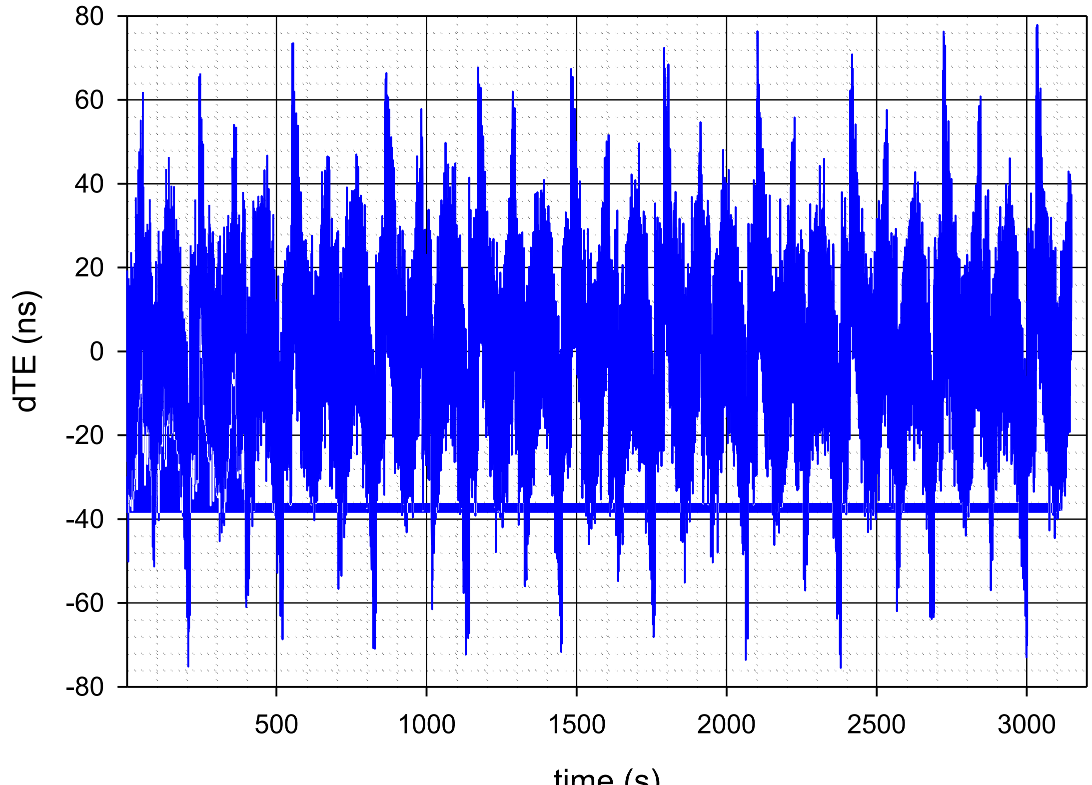
Cases 16 - 27 Results - 6

Case	max|dTE|, 64 hops (ns)	max|dTE|, 100 hops (ns)	Case	max|dTE|, 64 hops (ns)	max|dTE|, 100 hops (ns)
16	464	579	22	473	584
17	462	547	23	463	601
18	495	658	24	480	690
19	469	627	25	528	787
20	565	909	26	851	1441
21	598	856	27	853	1376

64 hops results are for node 65
100 hops results are for node 101

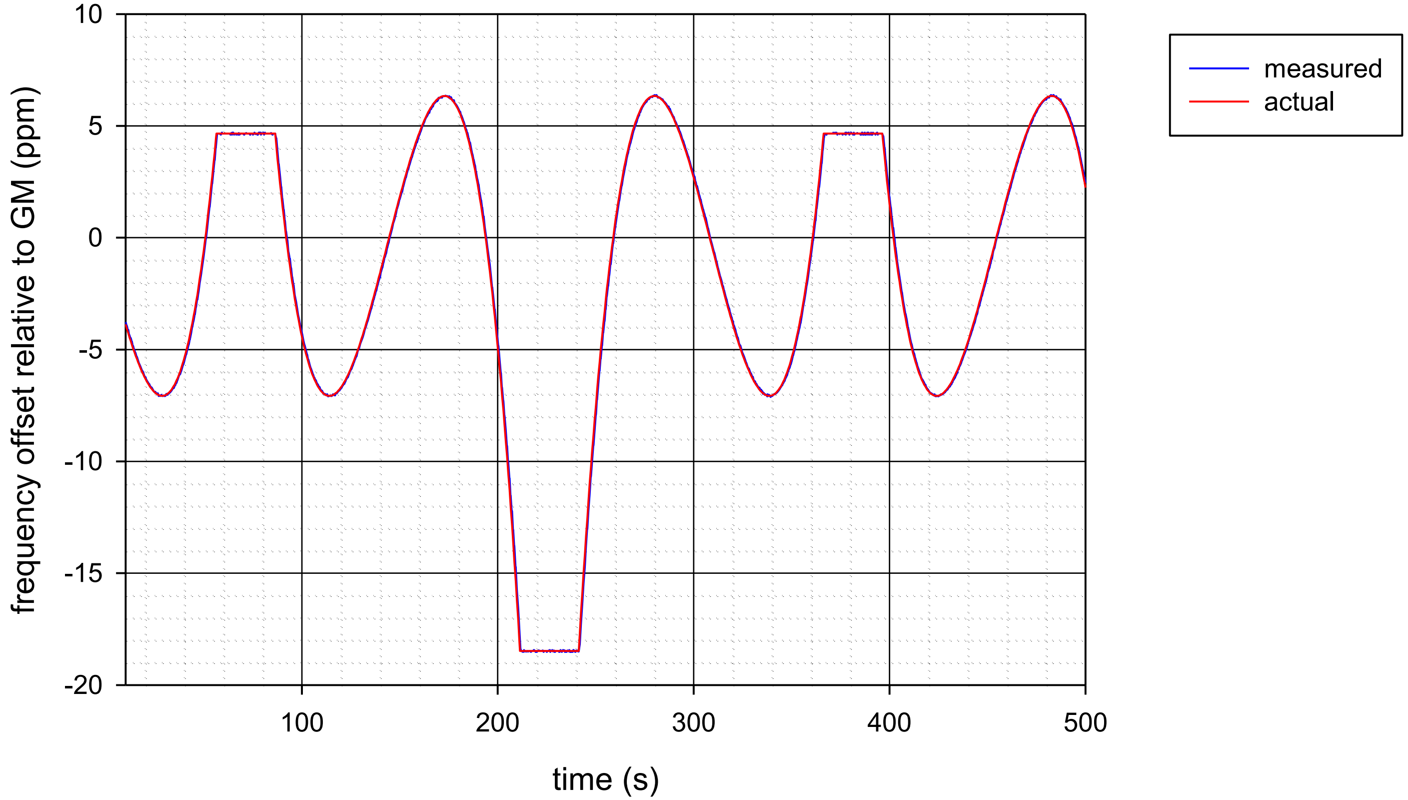
Case16, Node 2 Detailed Results - 1

Simulation Case 16, Node 2
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile
from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



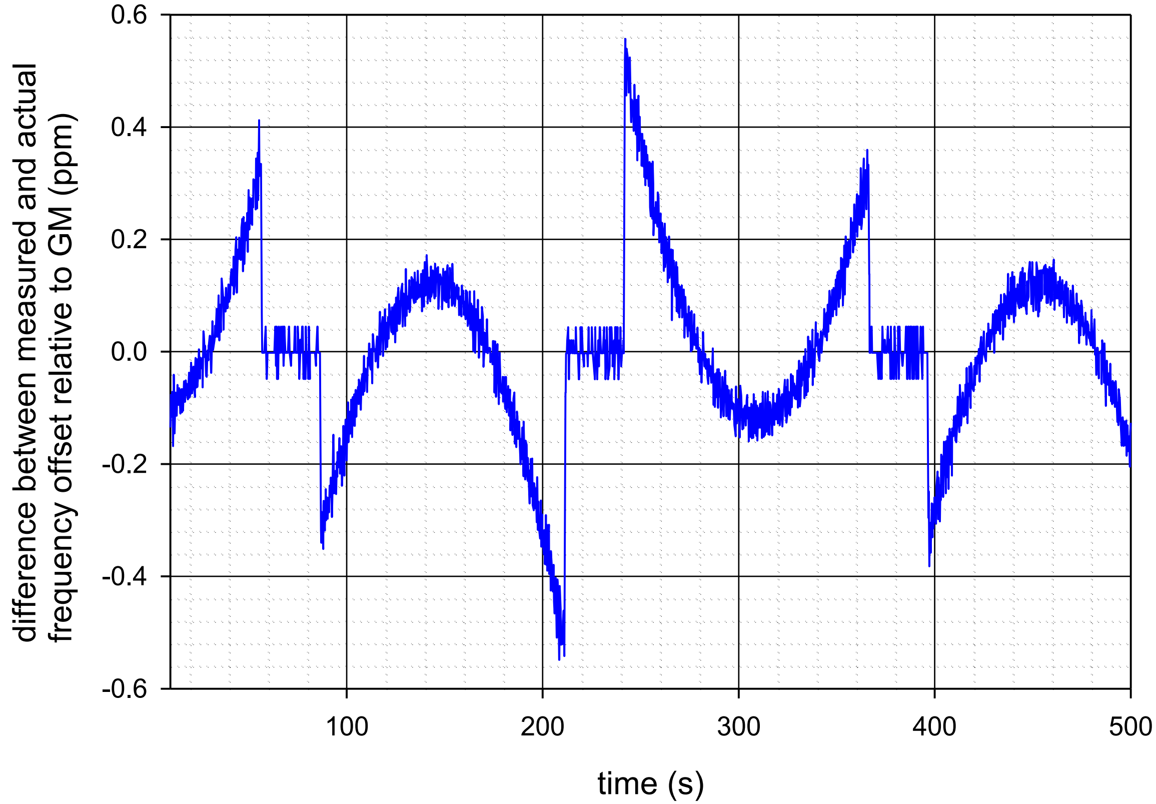
Case16, Node 2 Detailed Results - 2

Simulation Case 16, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



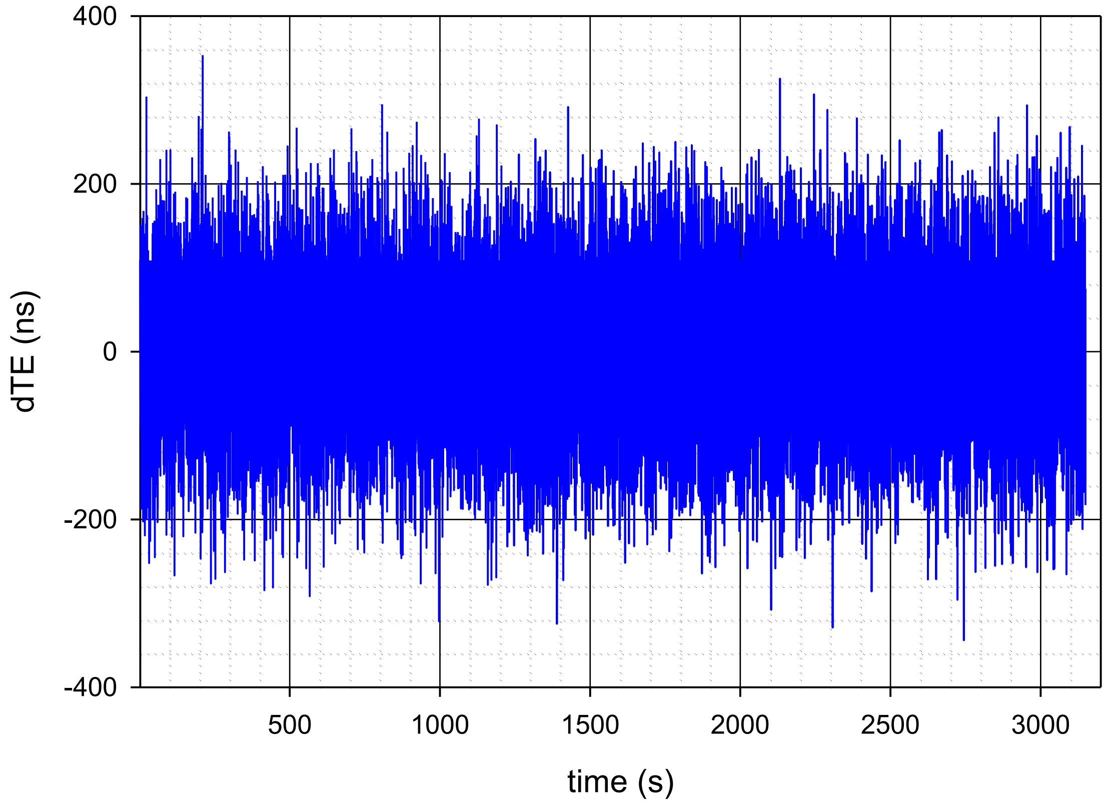
Case16, Node 2 Detailed Results – 3

Simulation Case 16, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



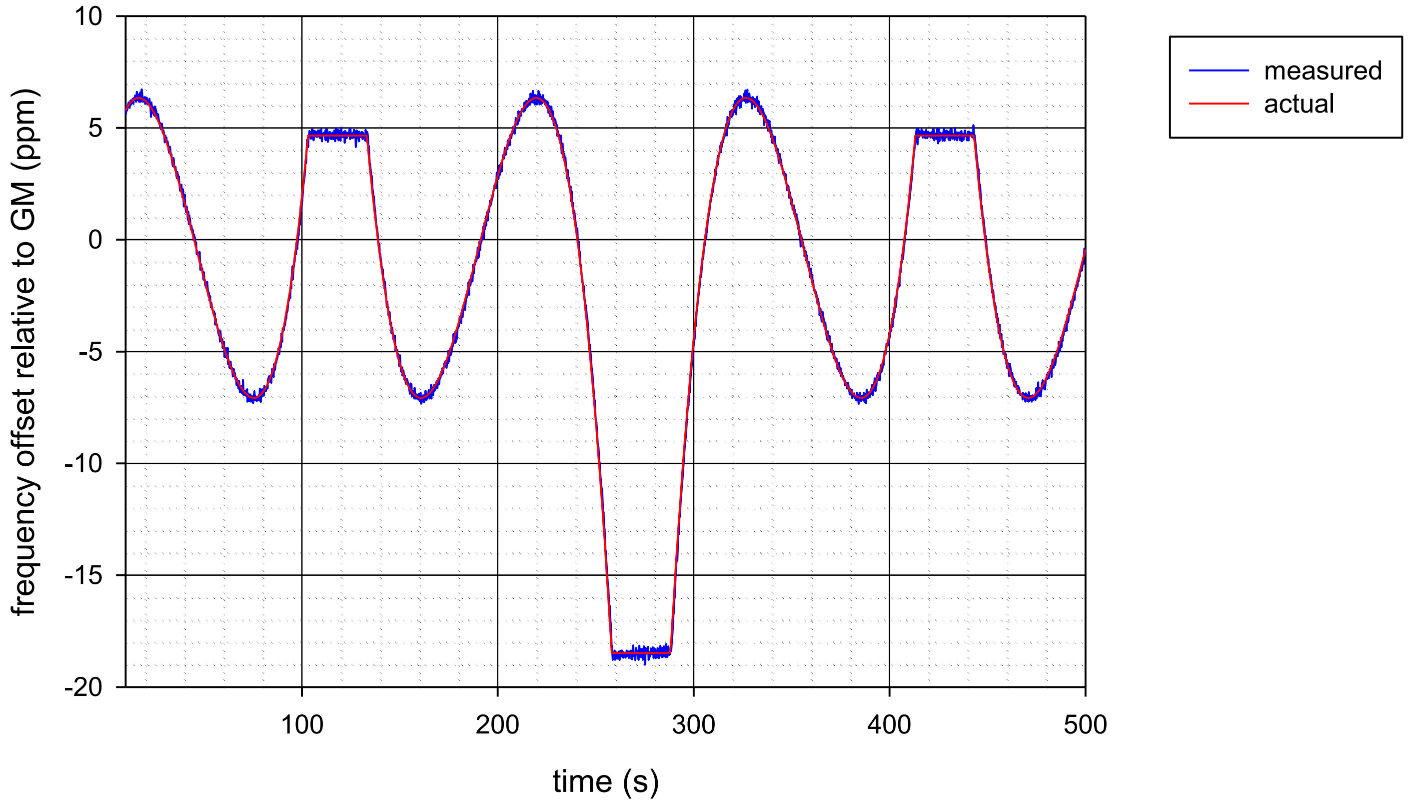
Case16, Node 35 Detailed Results - 1

Simulation Case 16, Node 35
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



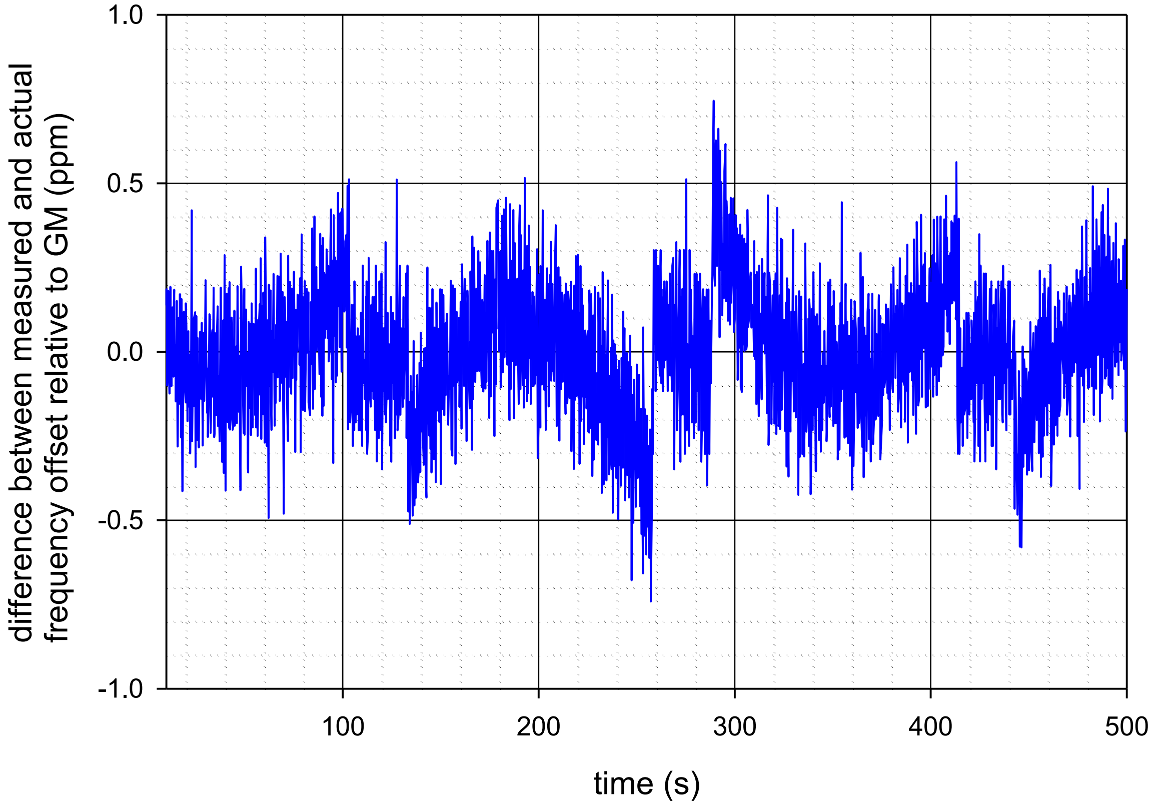
Case16, Node 35 Detailed Results – 2

Simulation Case 16, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



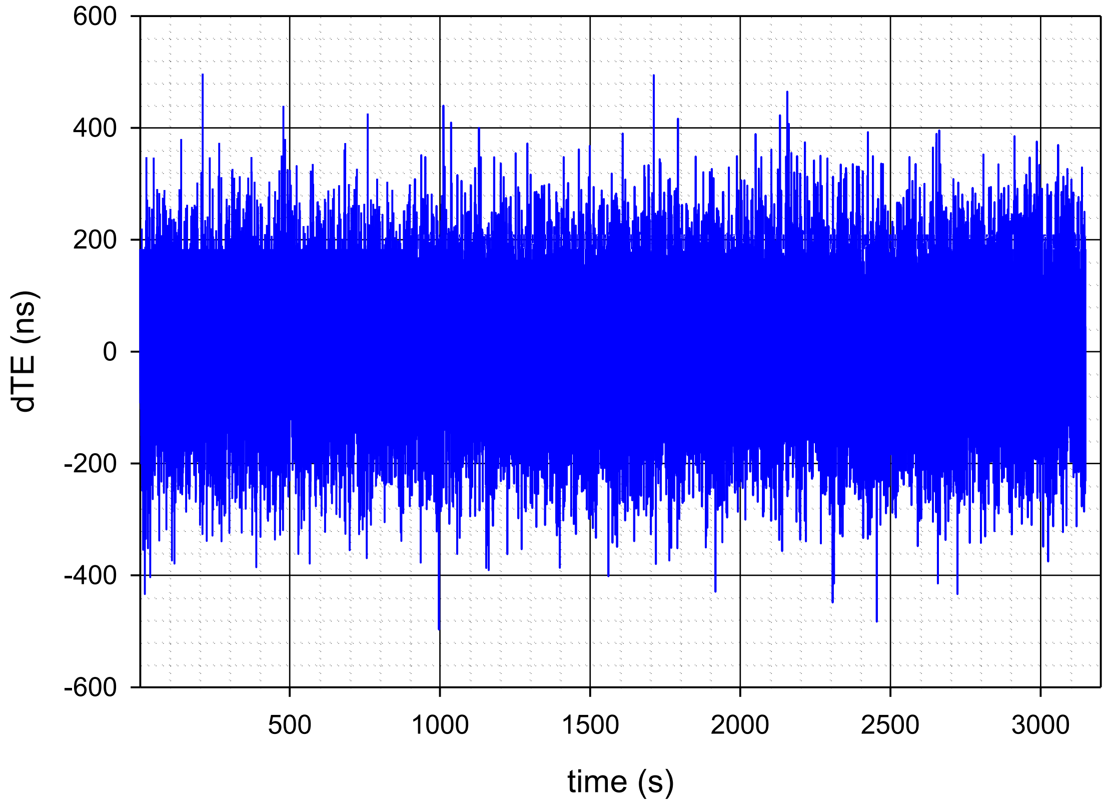
Case16, Node 35 Detailed Results – 3

Simulation Case 16, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



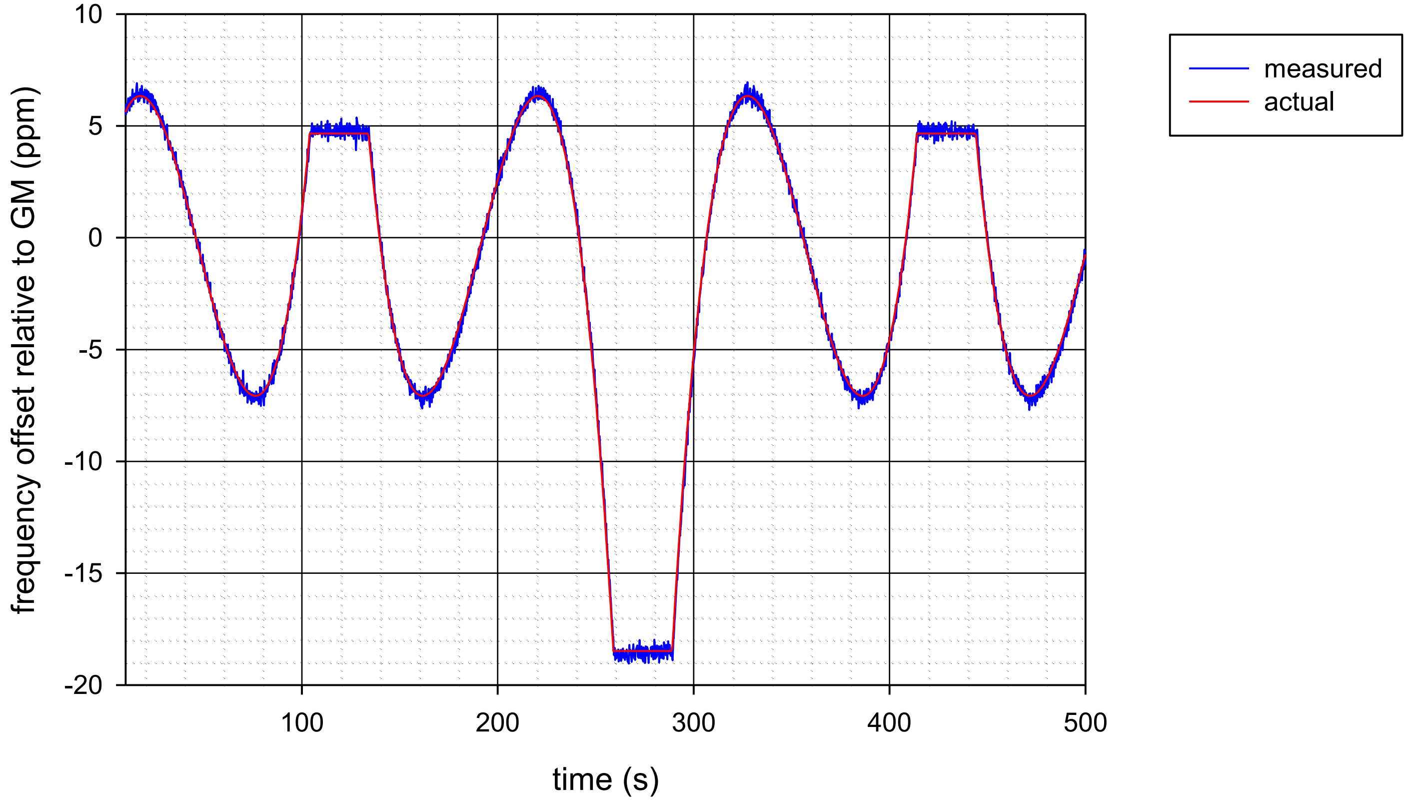
Case16, Node 68 Detailed Results - 1

Simulation Case 16, Node 68
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



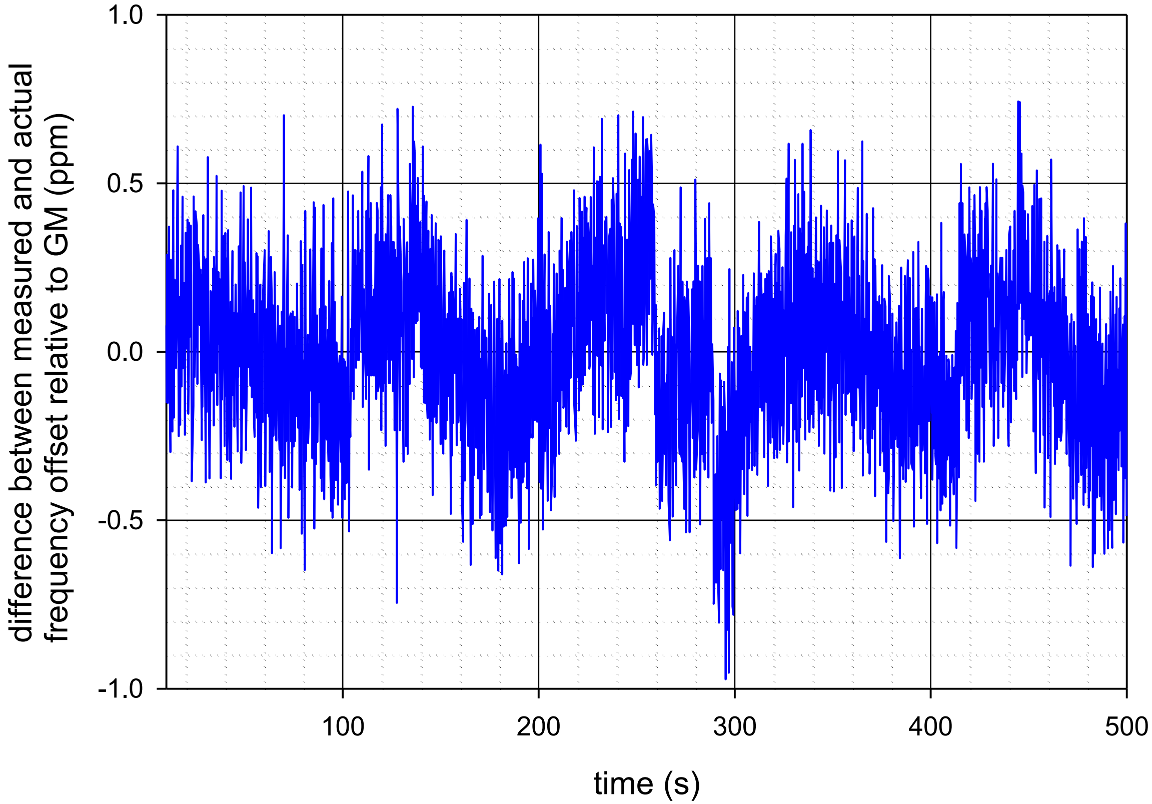
Case16, Node 68 Detailed Results – 2

Simulation Case 16, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



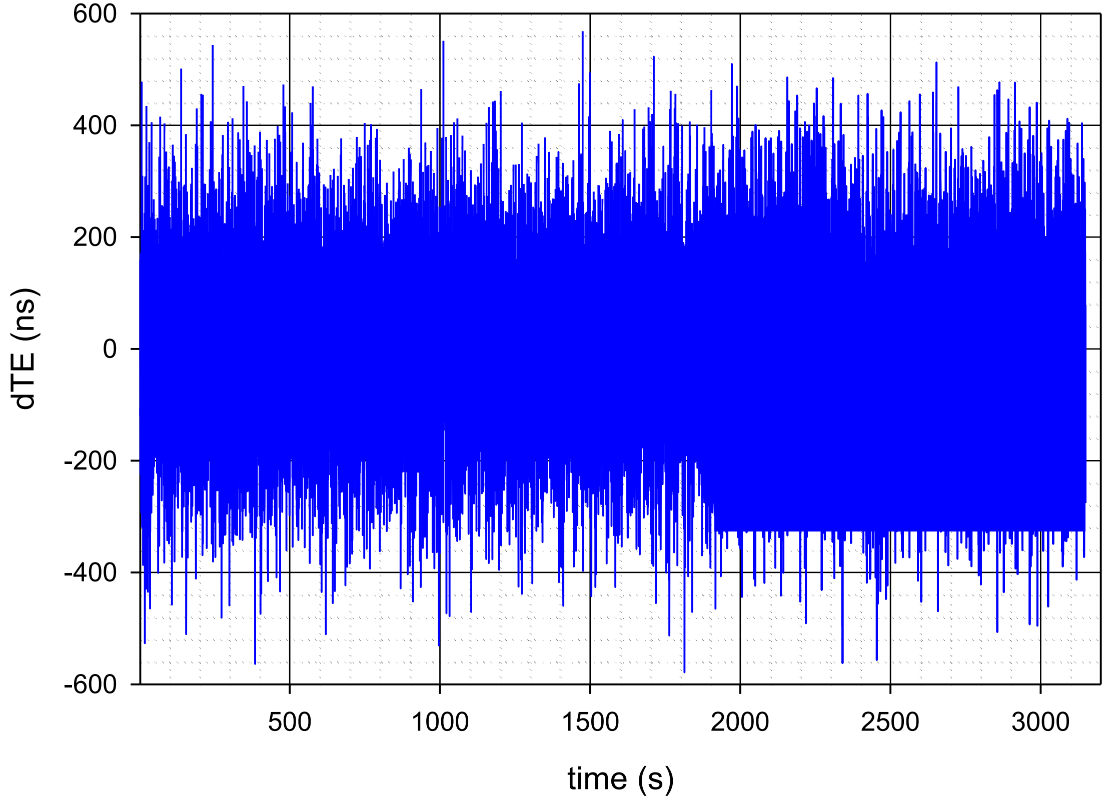
Case16, Node 68 Detailed Results – 3

Simulation Case 16, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



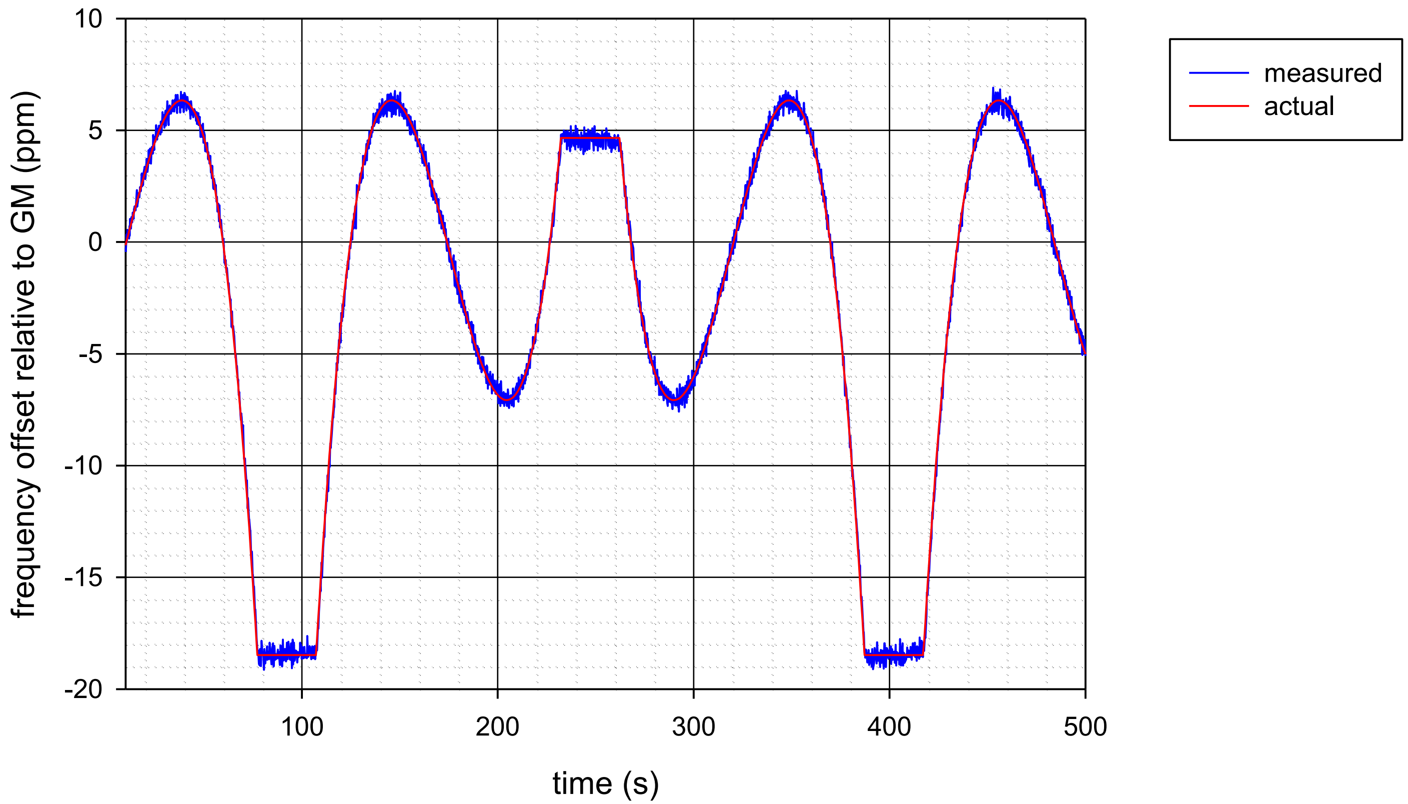
Case16, Node 101 Detailed Results - 1

Simulation Case 16, Node 101
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



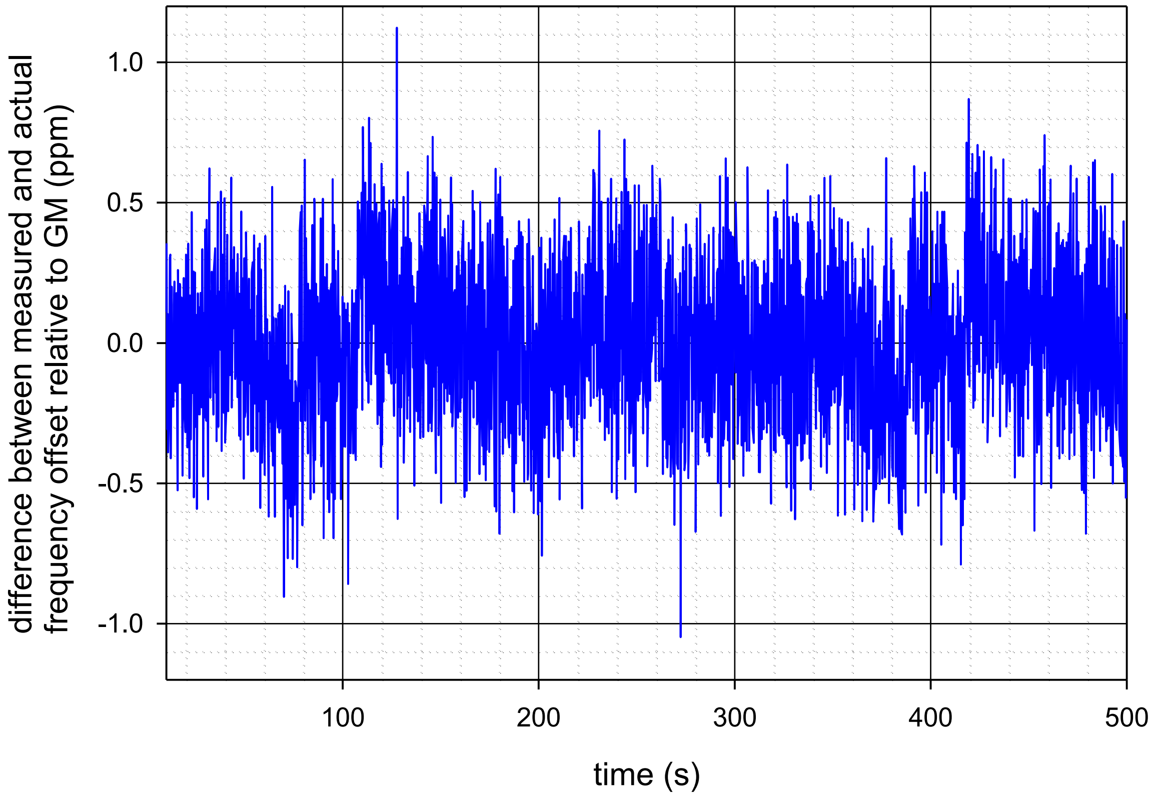
Case16, Node 101 Detailed Results - 2

Simulation Case 16, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



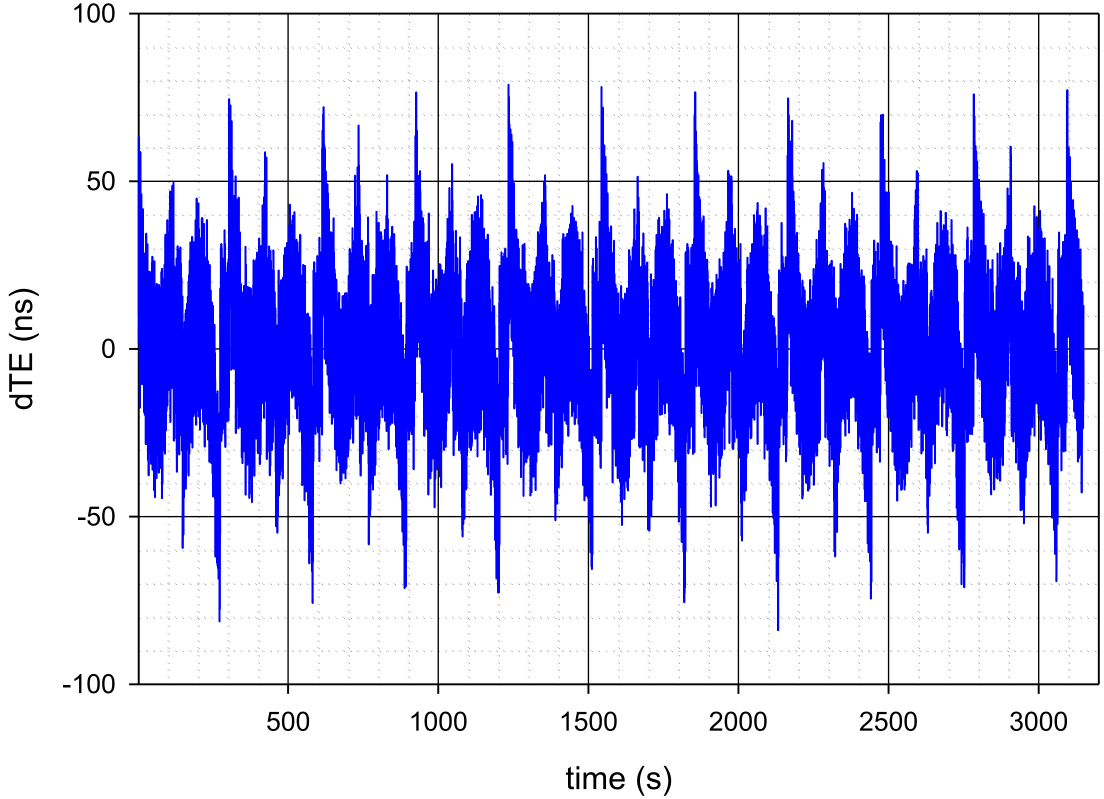
Case16, Node 101 Detailed Results - 3

Simulation Case 16, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



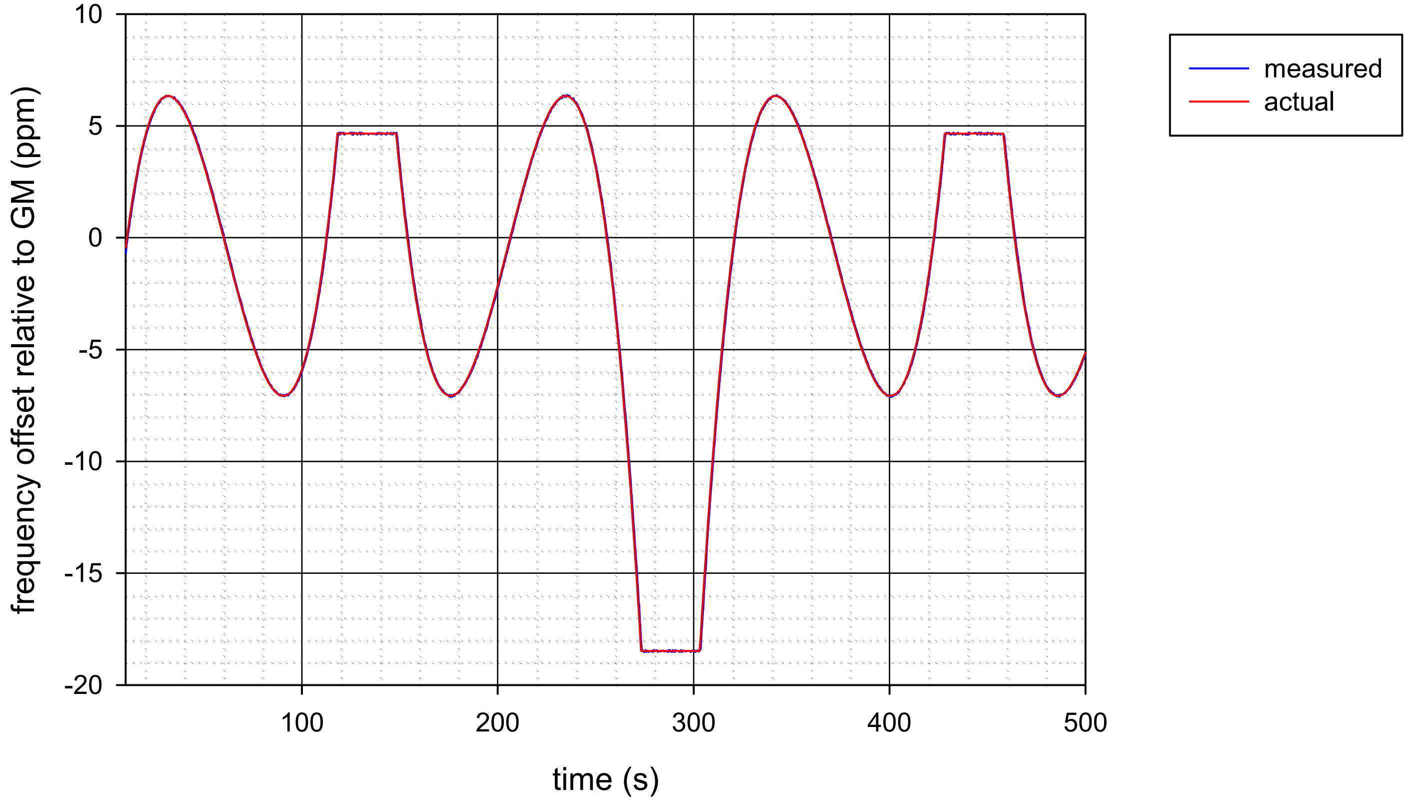
Case22, Node 2 Detailed Results - 1

Simulation Case 22, Node 2
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



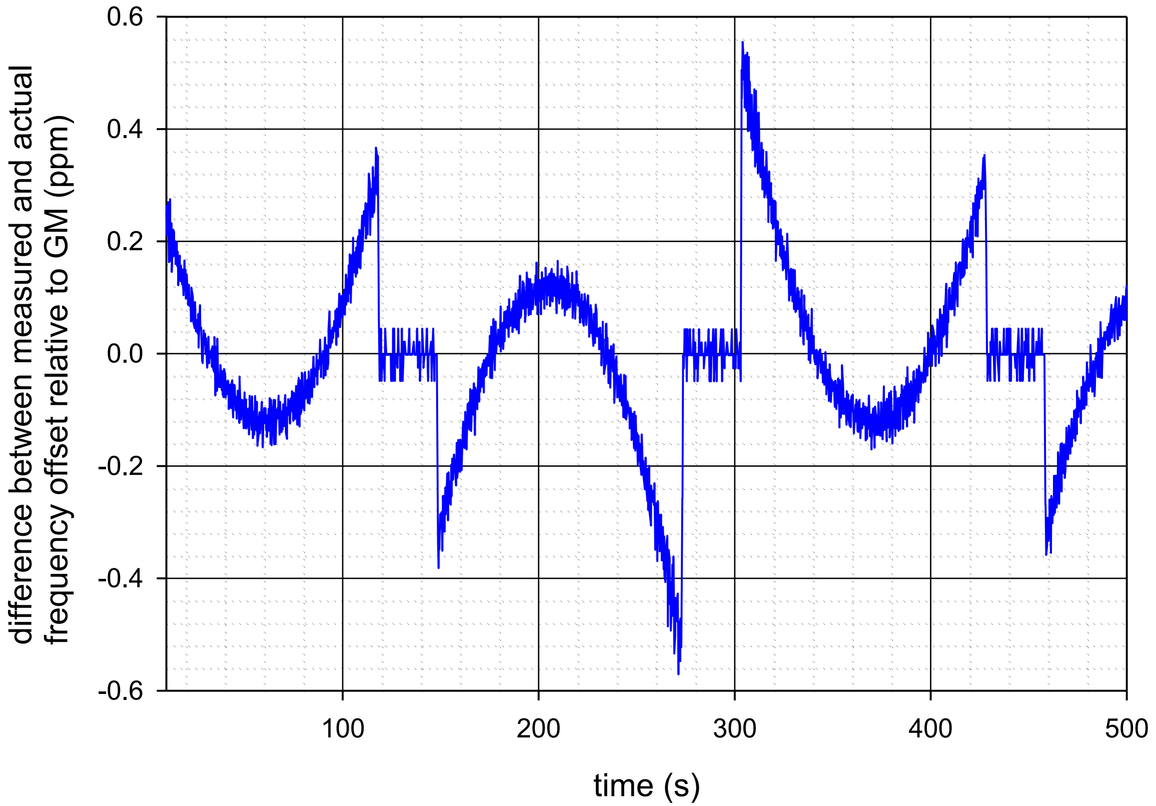
Case22, Node 2 Detailed Results - 2

Simulation Case 22, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



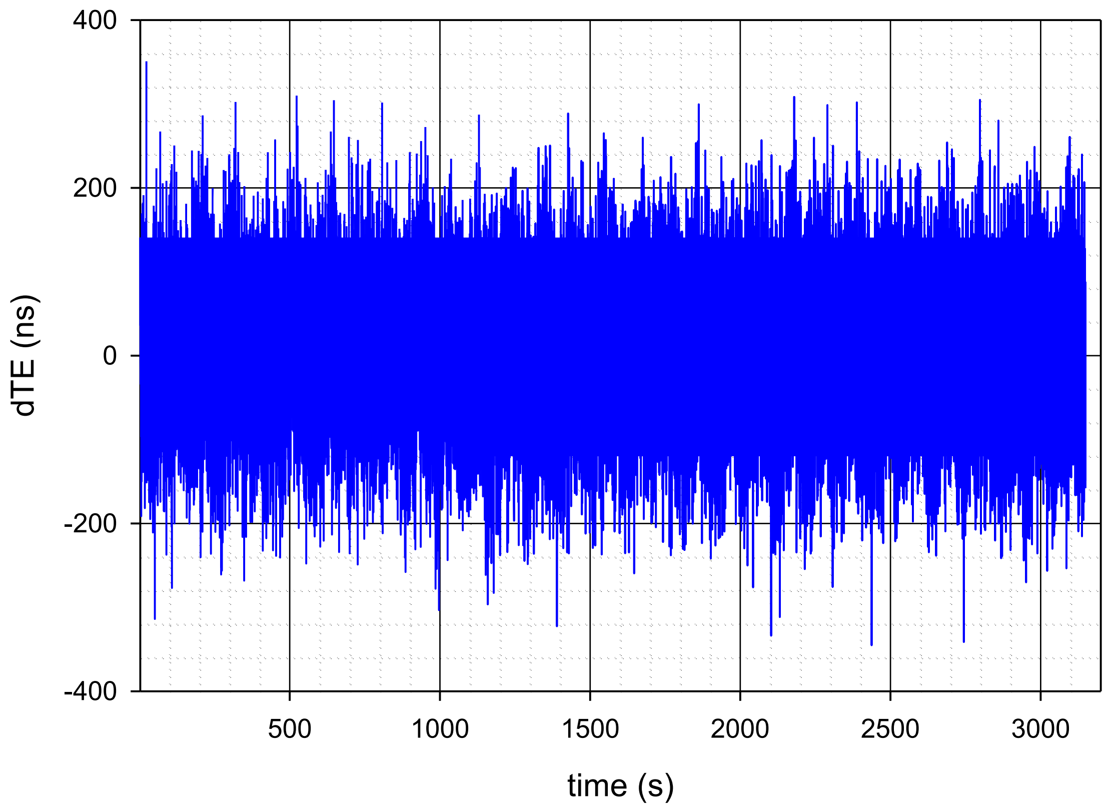
Case22, Node 2 Detailed Results – 3

Simulation Case 22, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



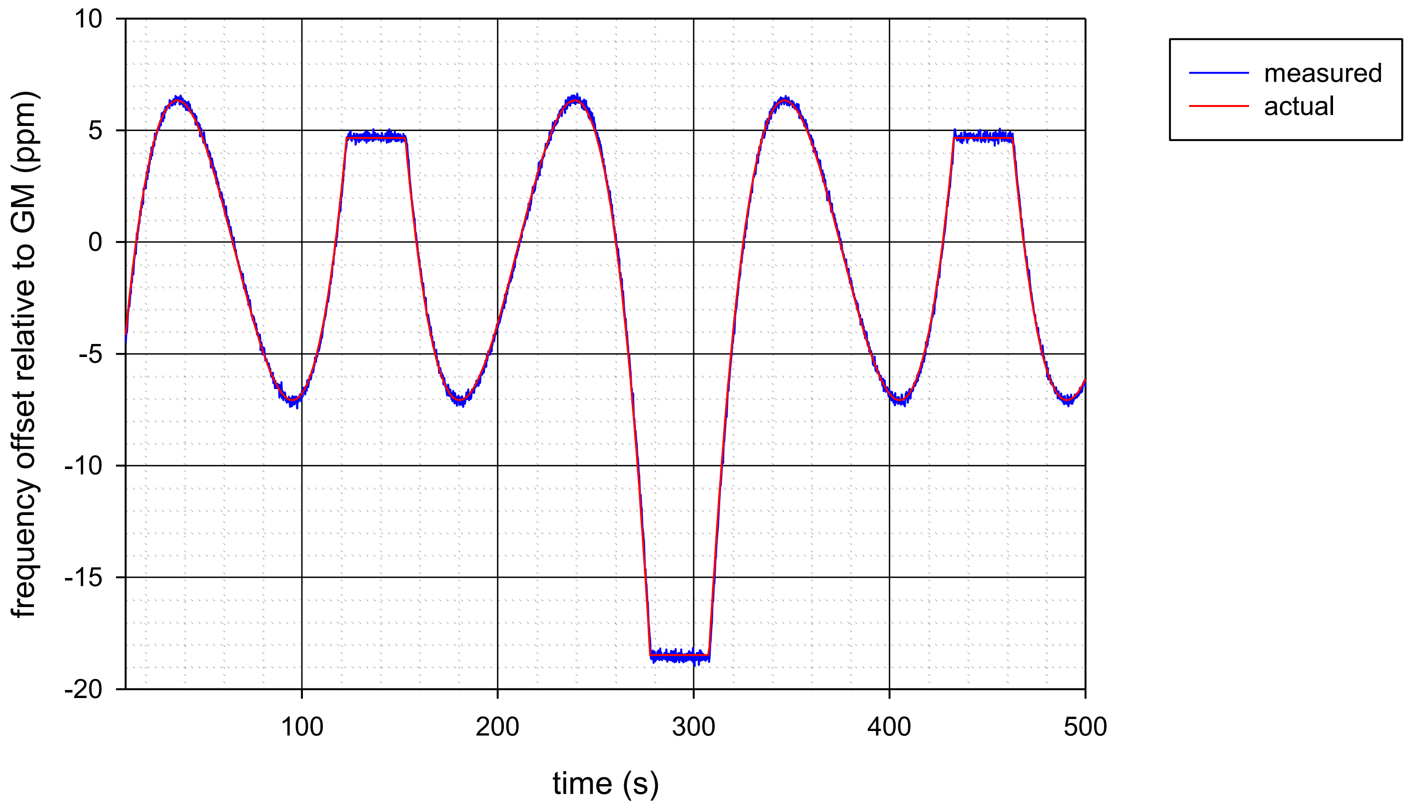
Case22, Node 35 Detailed Results – 1

Simulation Case 22, Node 35
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



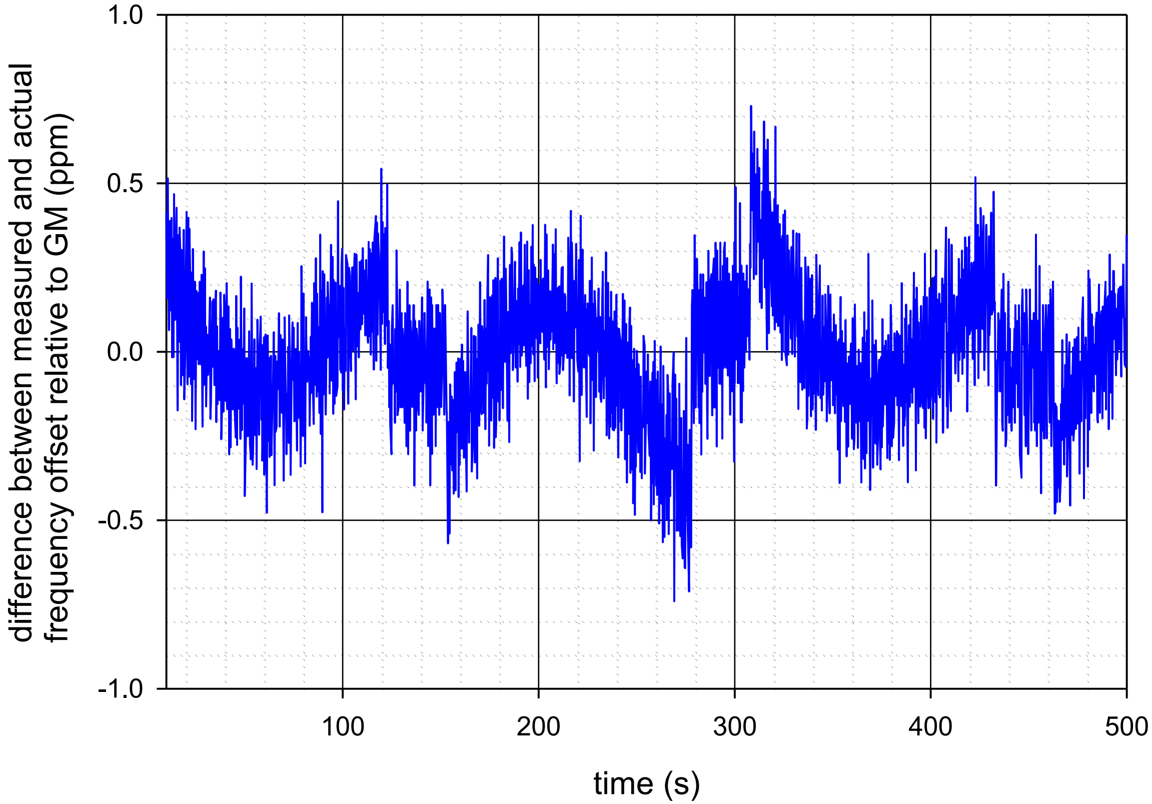
Case22, Node 35 Detailed Results - 2

Simulation Case 22, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



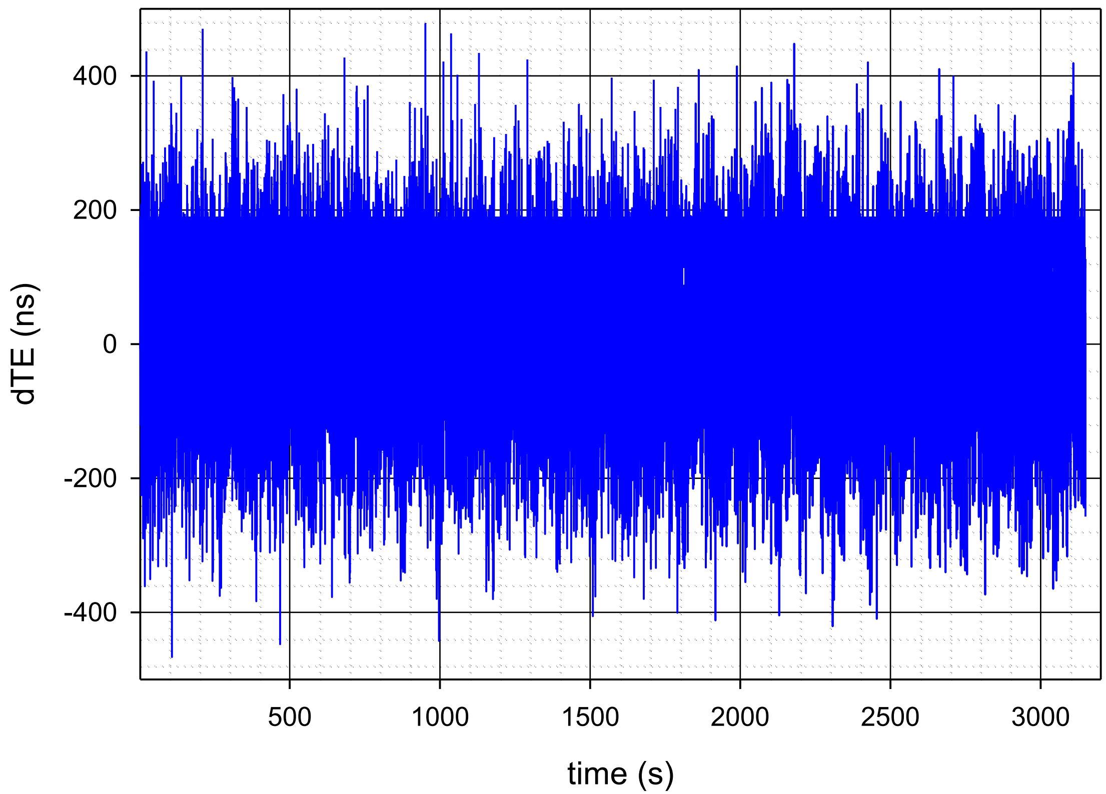
Case22, Node 35 Detailed Results – 3

Simulation Case 22, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



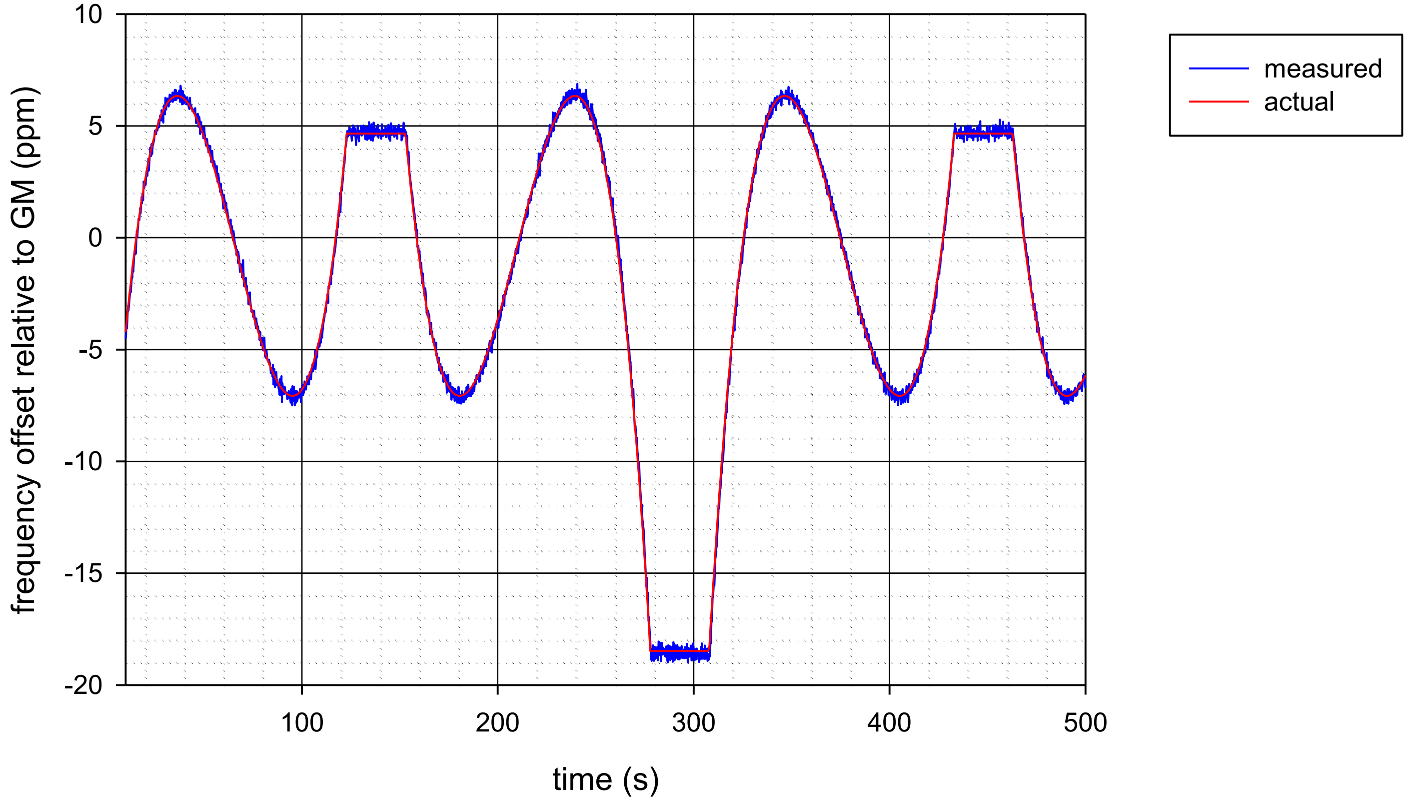
Case22, Node 68 Detailed Results - 1

Simulation Case 22, Node 68
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile
from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



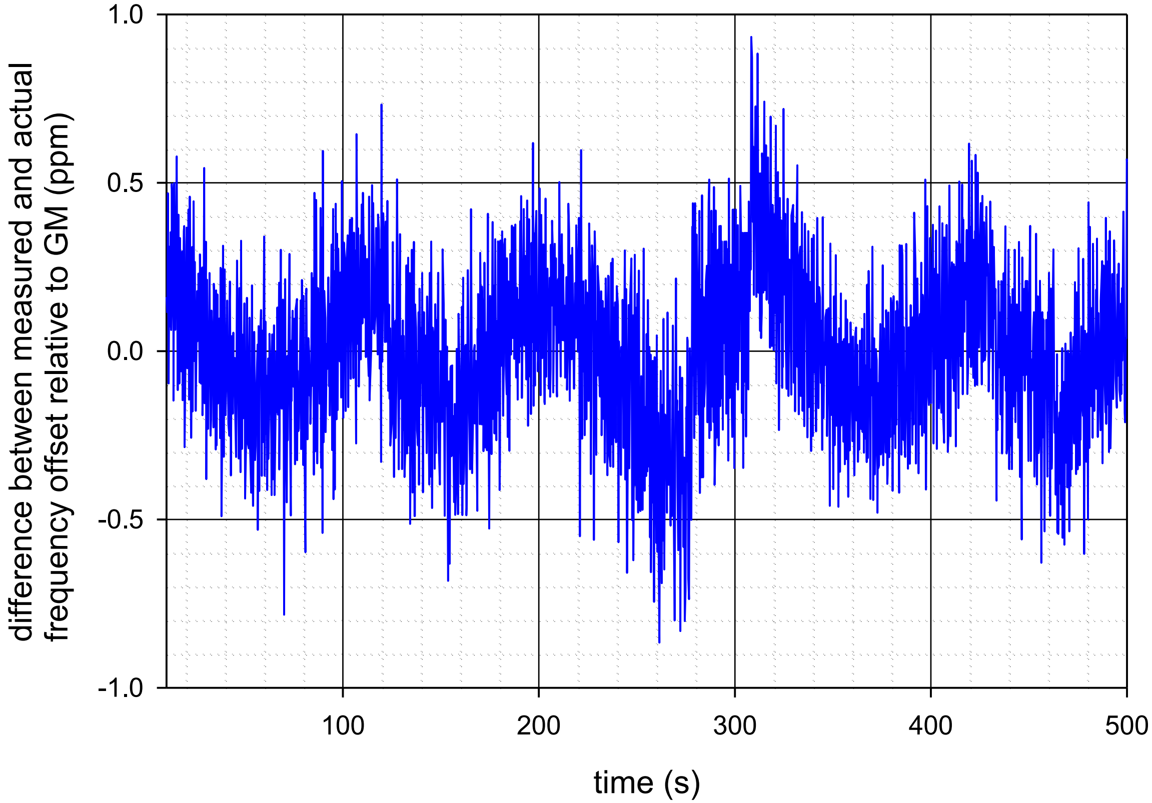
Case22, Node 68 Detailed Results – 2

Simulation Case 22, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



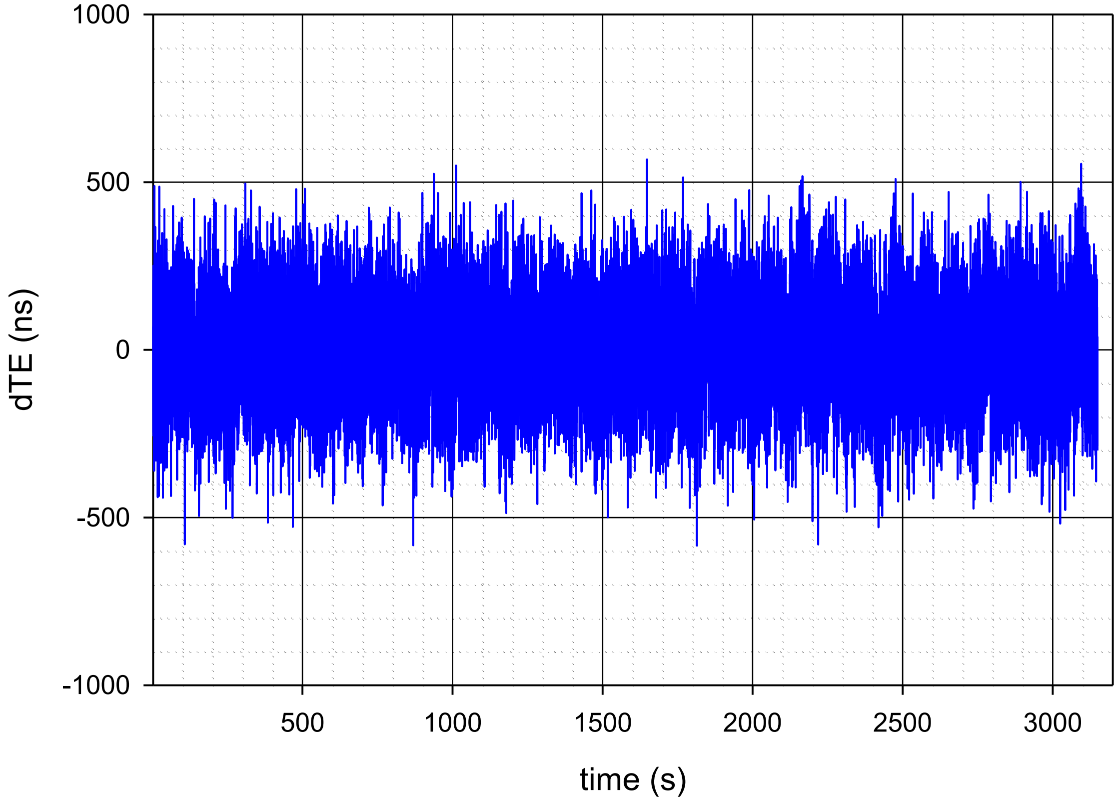
Case22, Node 68 Detailed Results – 3

Simulation Case 22, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



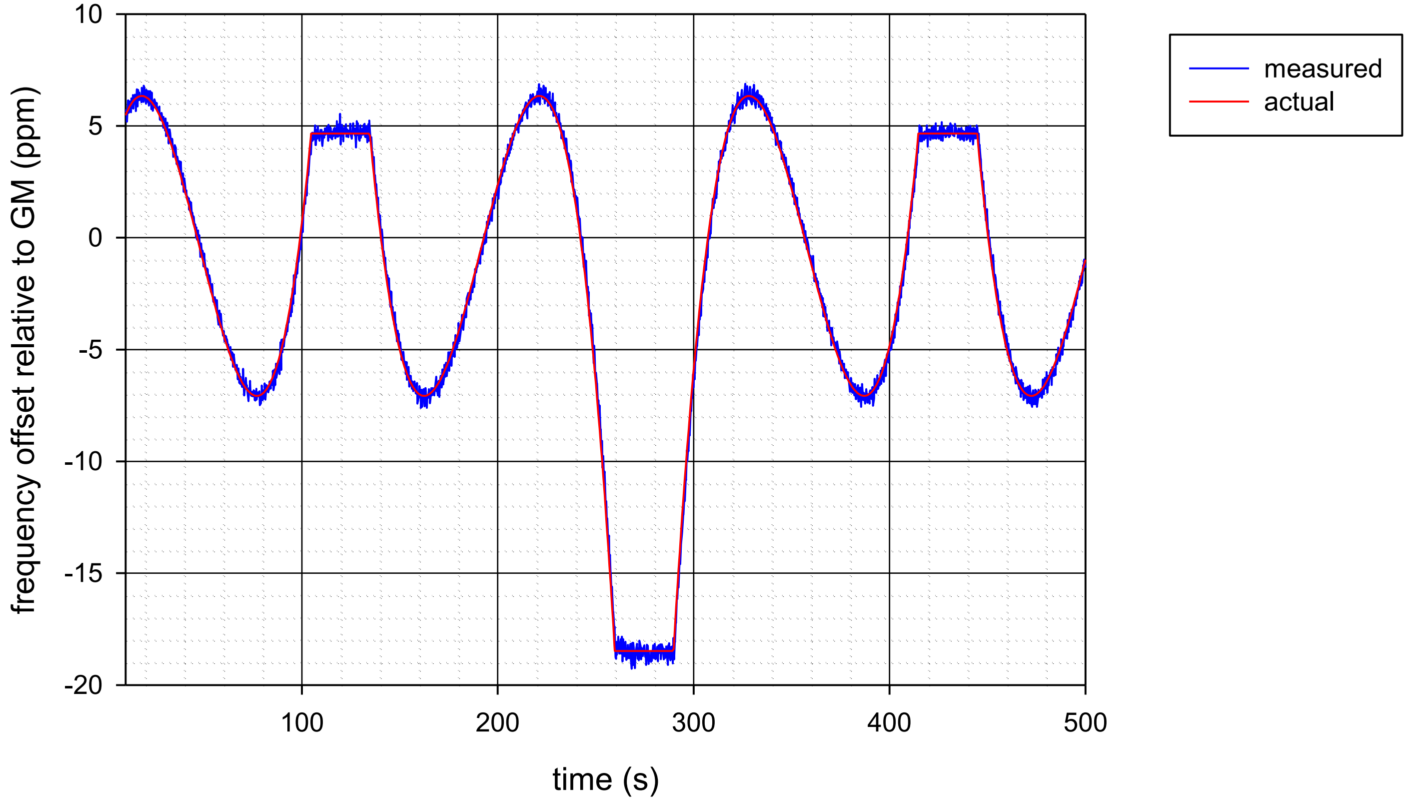
Case22, Node 101 Detailed Results - 1

Simulation Case 22, Node 101
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



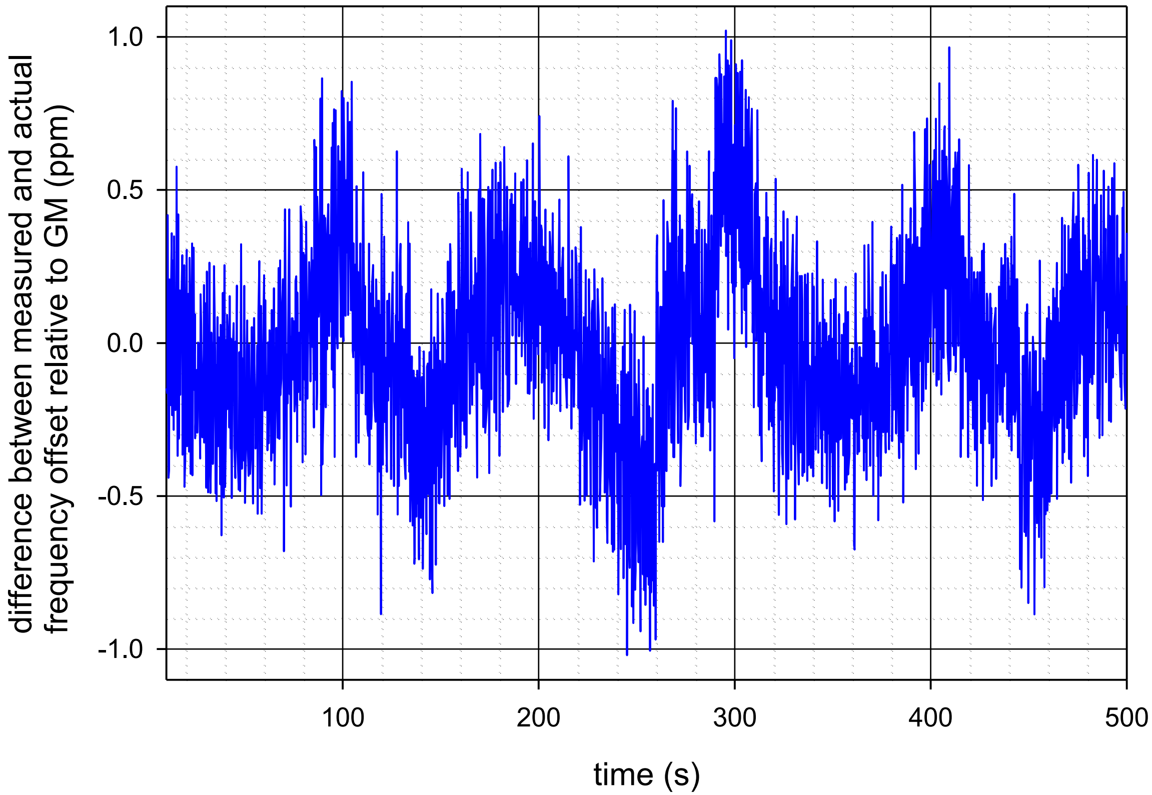
Case22, Node 101 Detailed Results - 2

Simulation Case 22, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



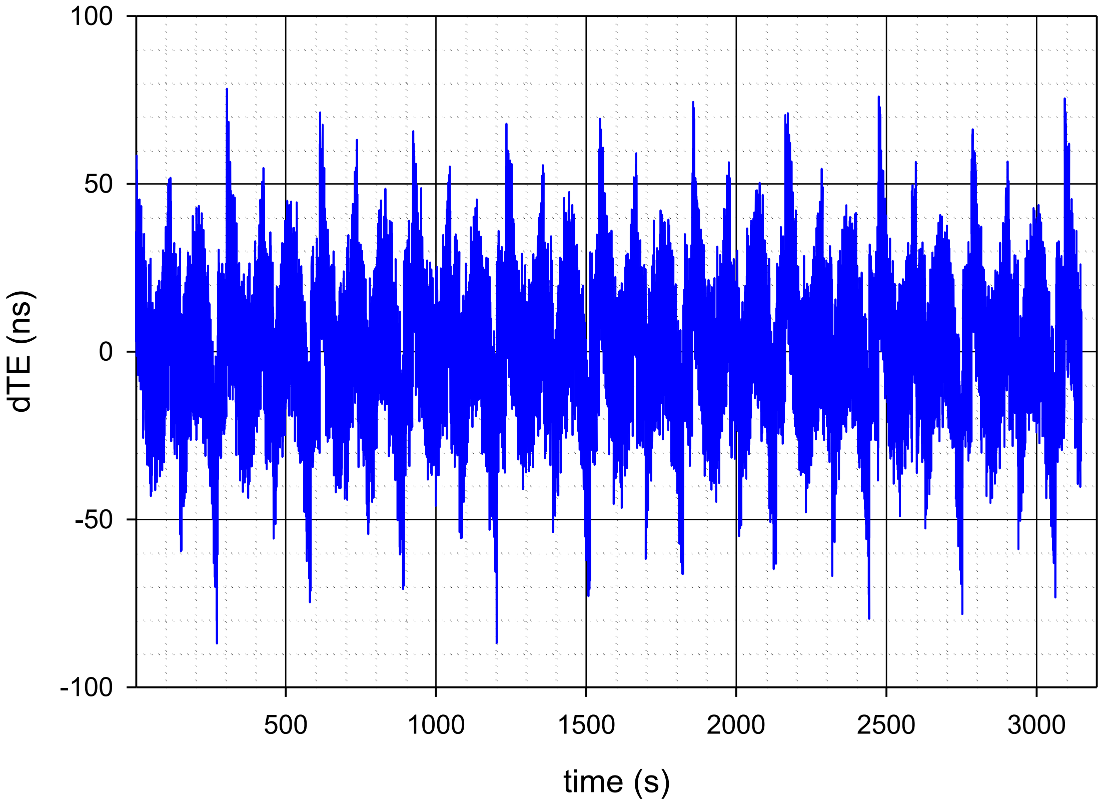
Case22, Node 101 Detailed Results - 3

Simulation Case 22, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



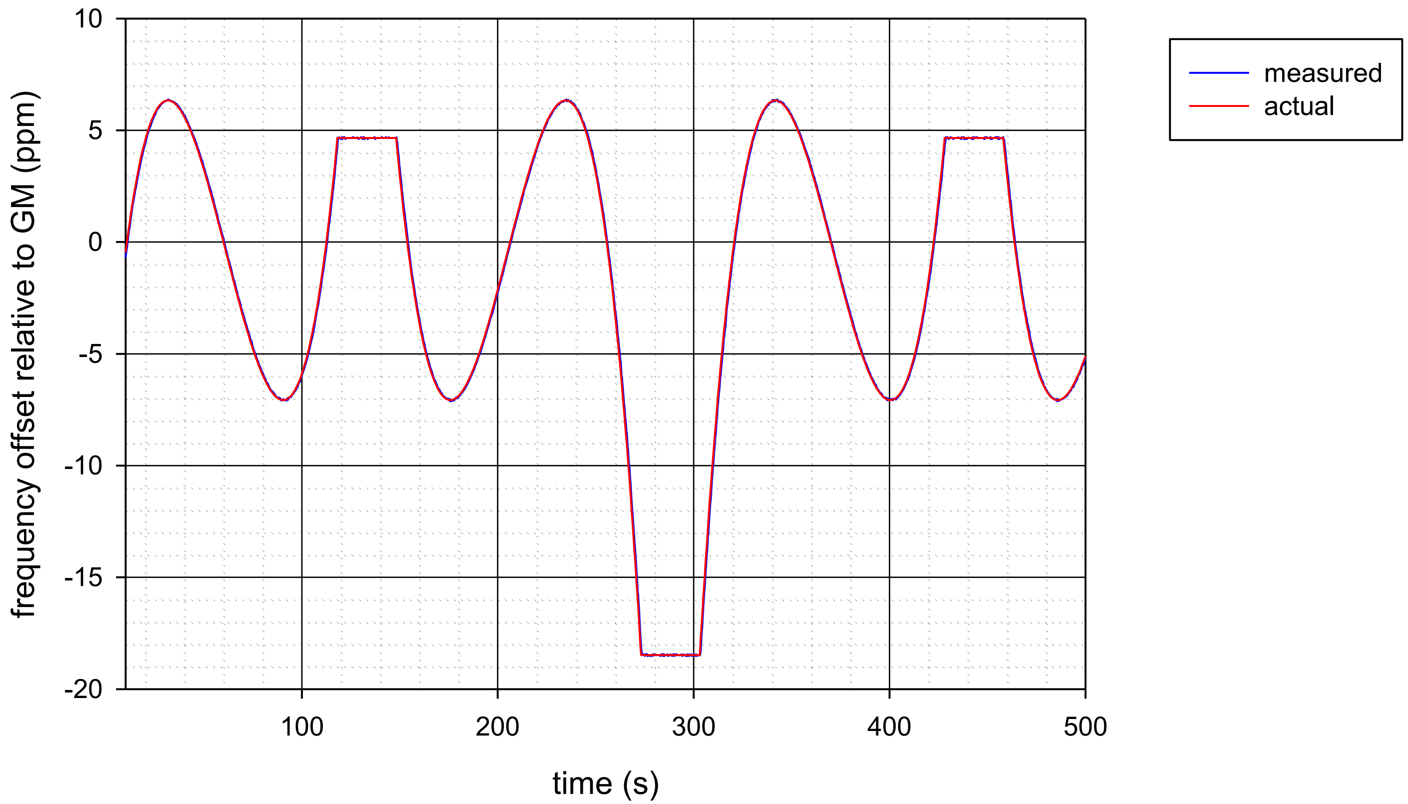
Case27, Node 2 Detailed Results – 1

Simulation Case 27, Node 2
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile
from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



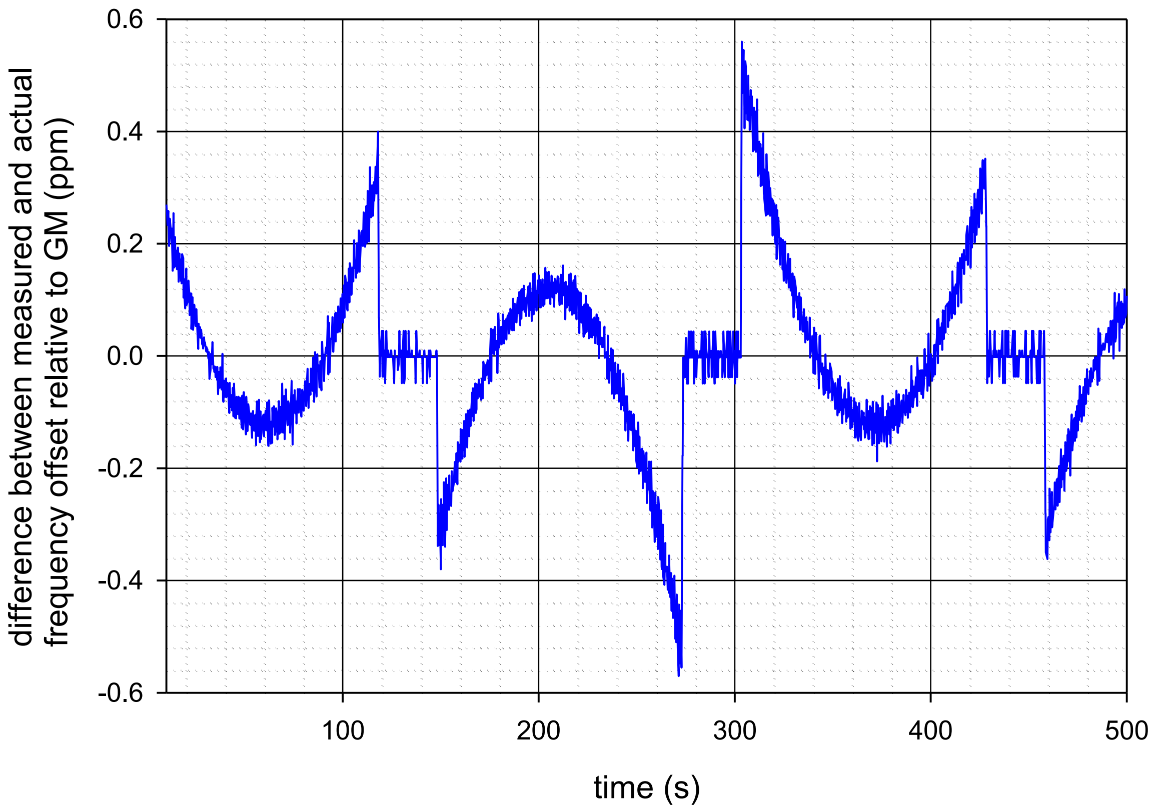
Case27, Node 2 Detailed Results - 2

Simulation Case 27, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



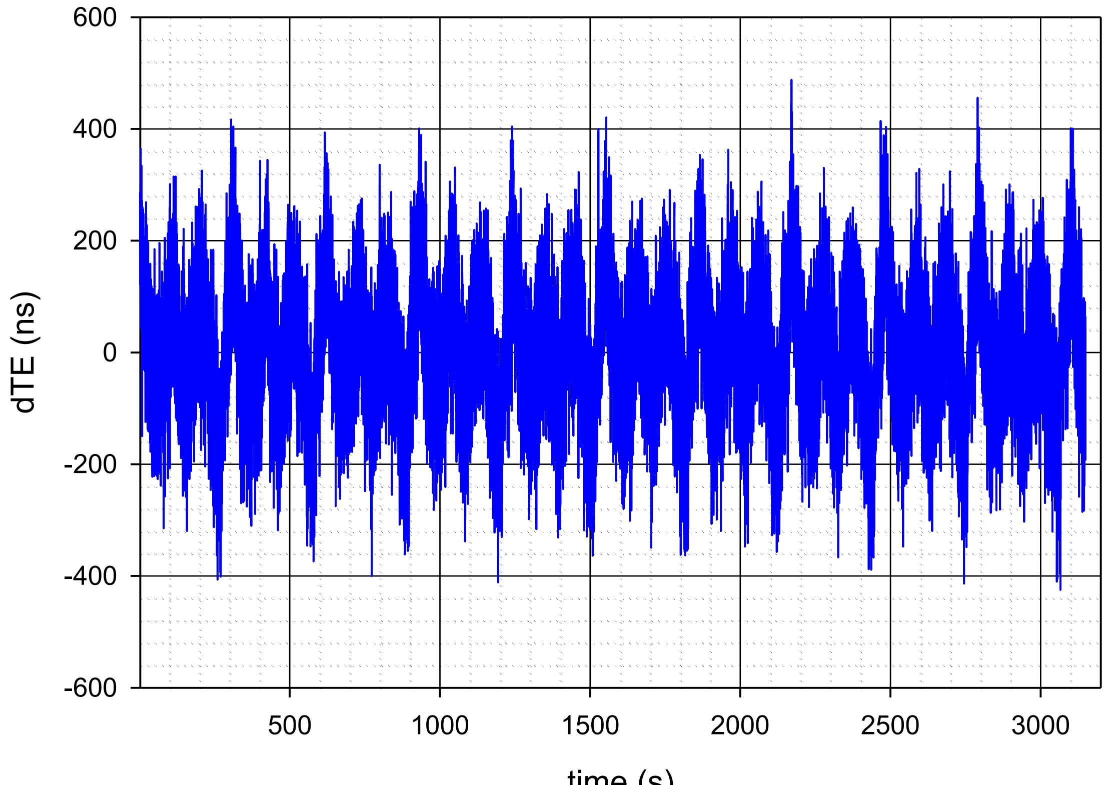
Case27, Node 2 Detailed Results - 3

Simulation Case 27, Node 2
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



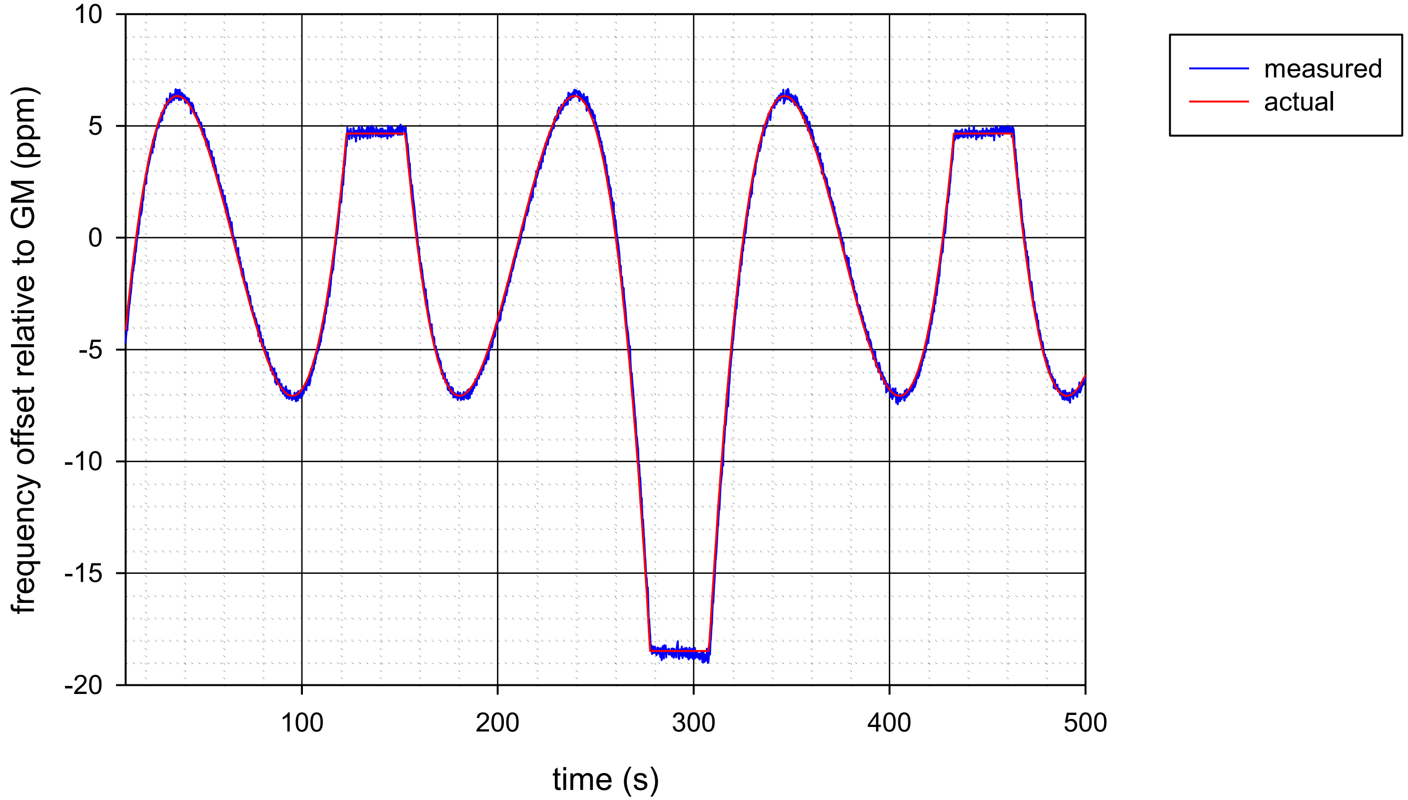
Case27, Node 35 Detailed Results – 1

Simulation Case 27, Node 35
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



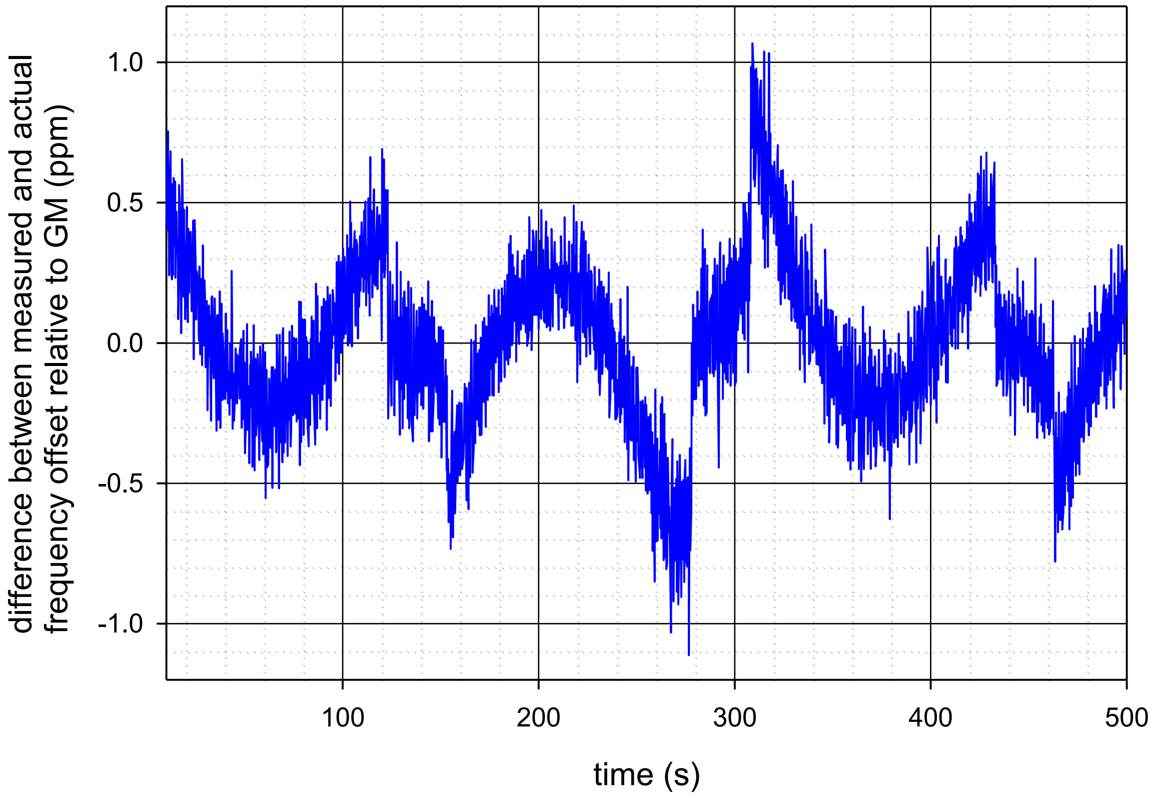
Case27, Node 35 Detailed Results - 2

Simulation Case 27, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



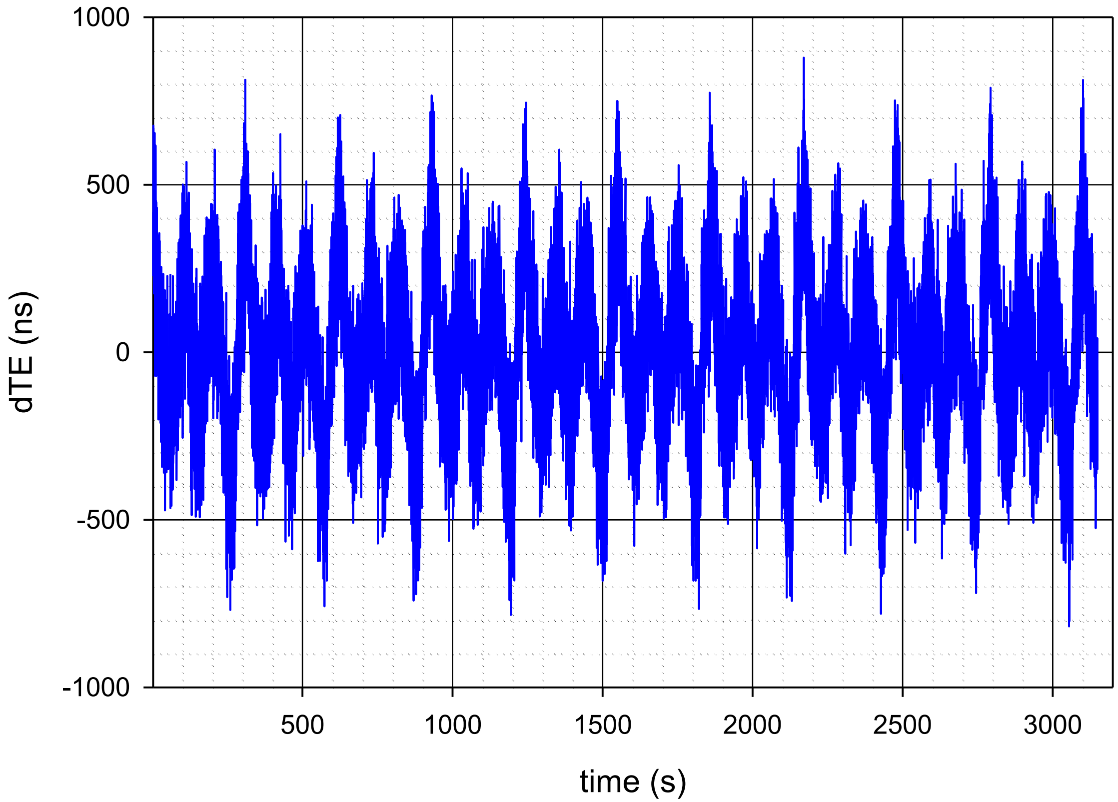
Case27, Node 35 Detailed Results – 3

Simulation Case 27, Node 35
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



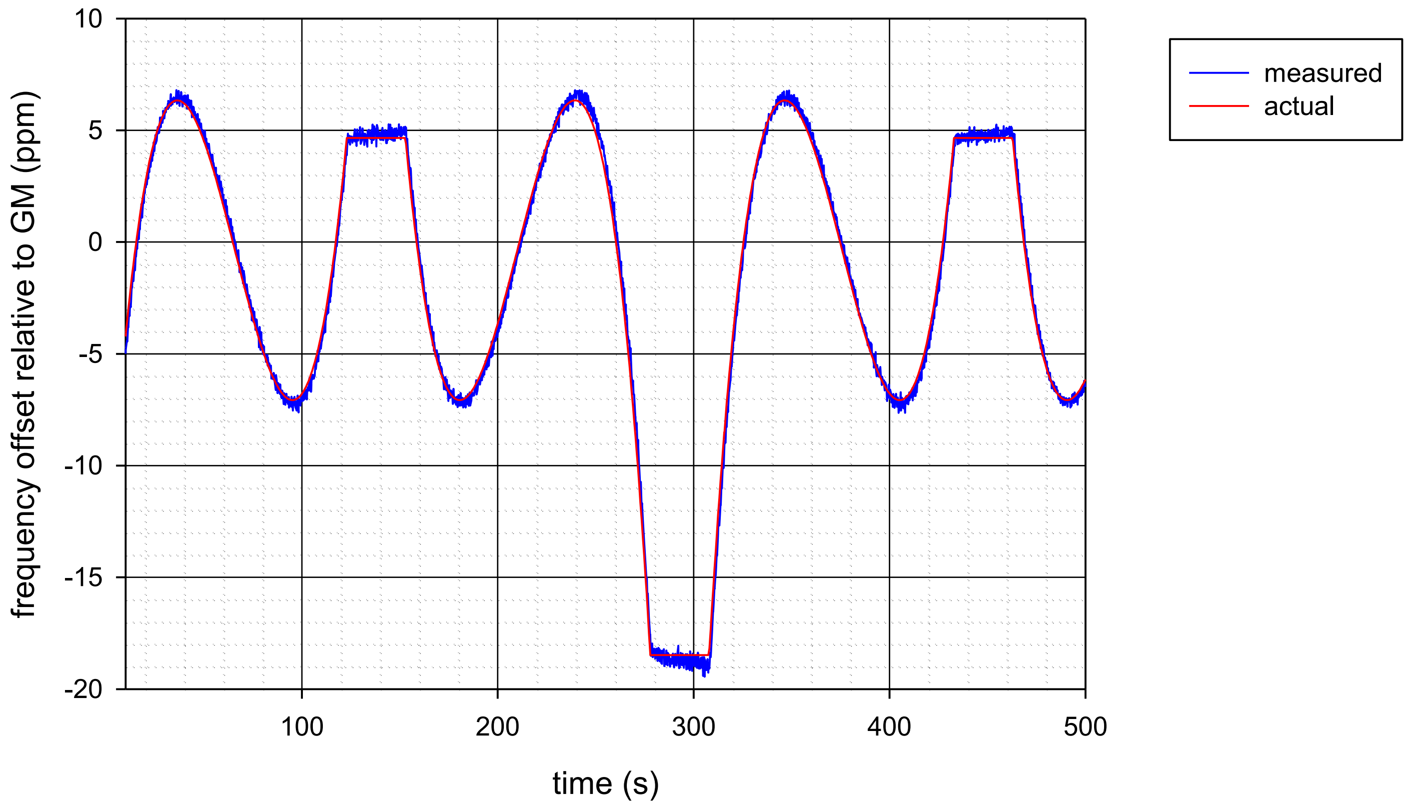
Case27, Node 68 Detailed Results – 1

Simulation Case 27, Node 68
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



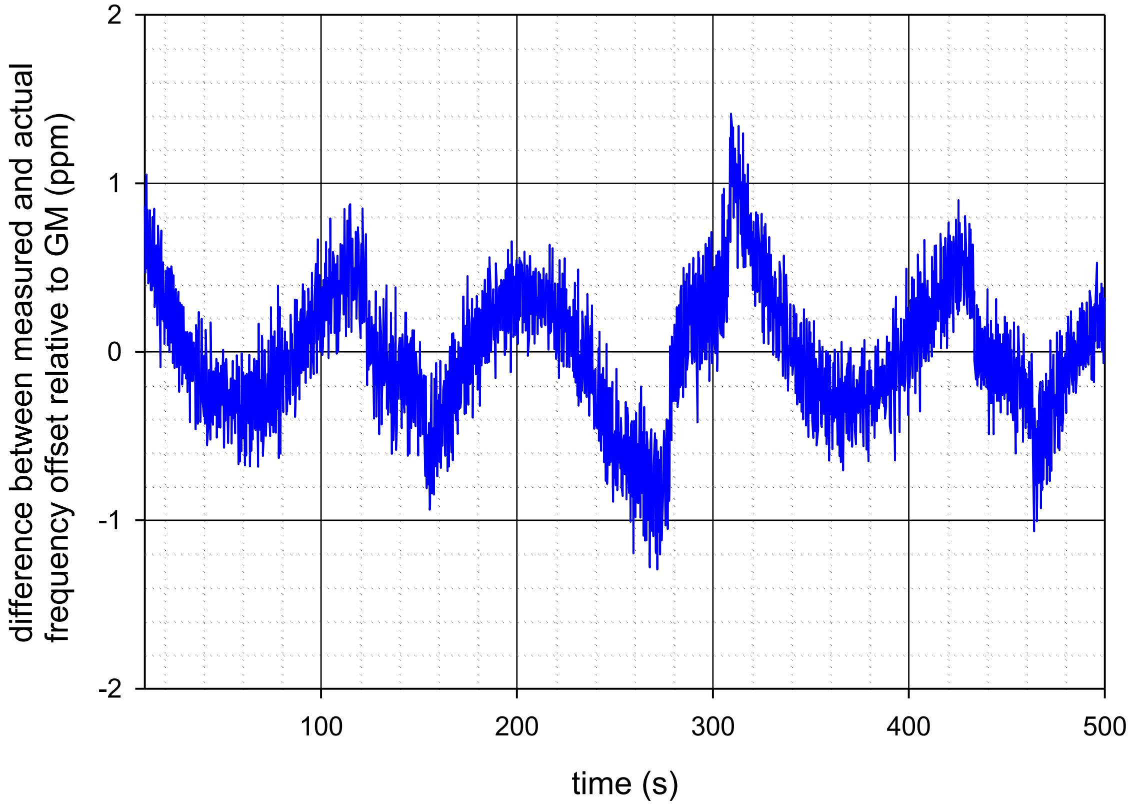
Case27, Node 68 Detailed Results – 2

Simulation Case 27, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



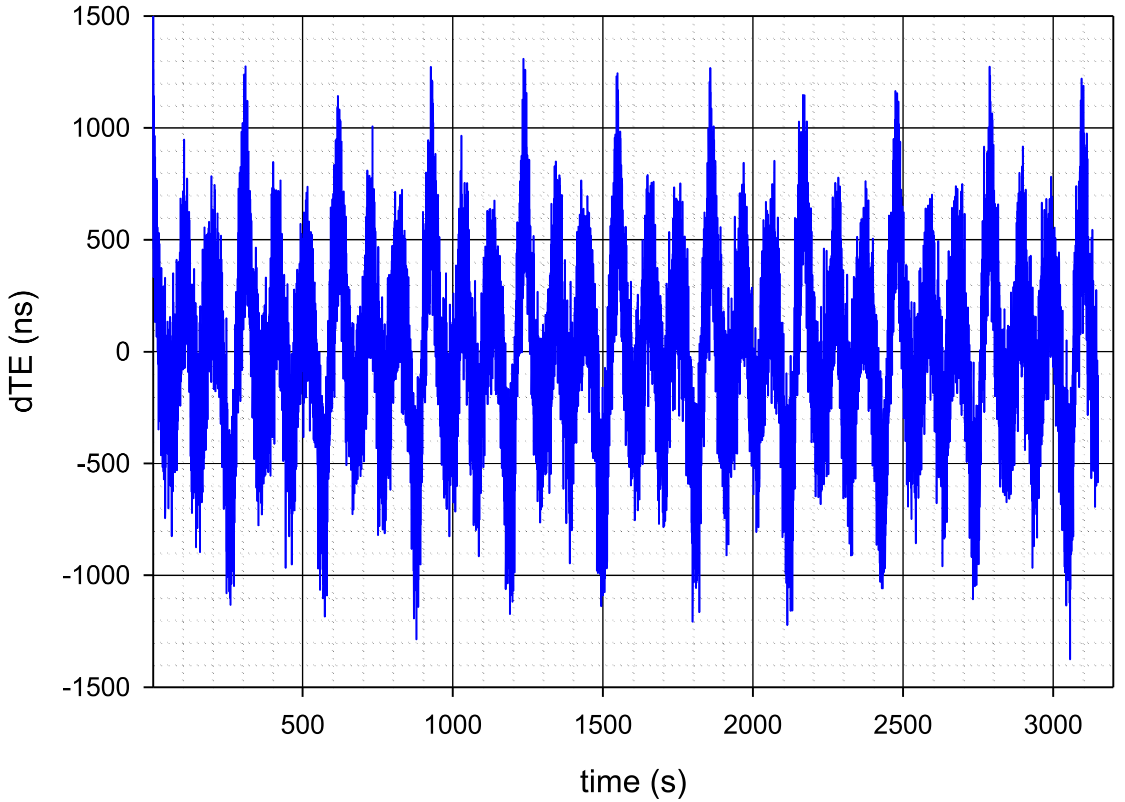
Case27, Node 68 Detailed Results – 3

Simulation Case 27, Node 68
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



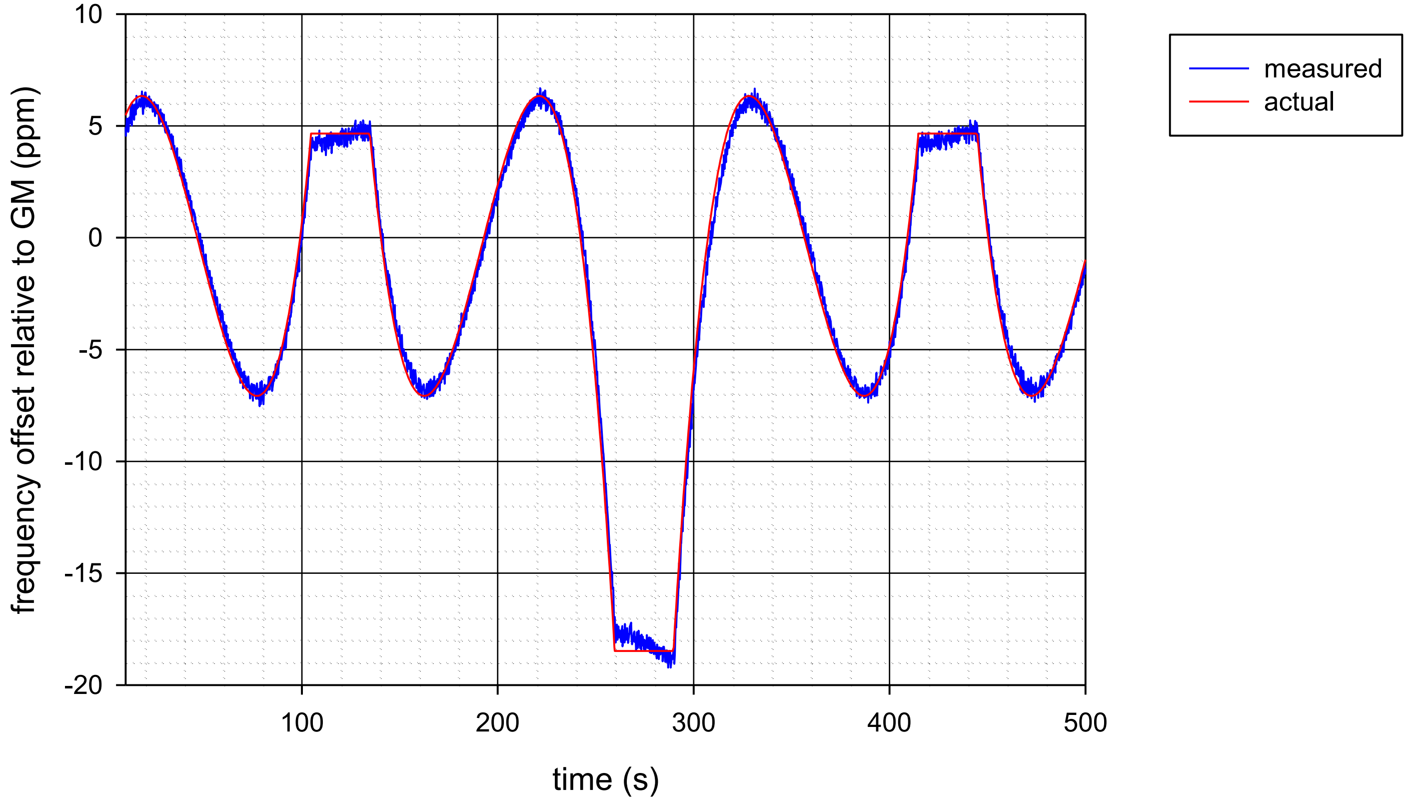
Case27, Node 101 Detailed Results – 1

Simulation Case 27, Node 101
Single replication of simulation, 2 - 3150 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



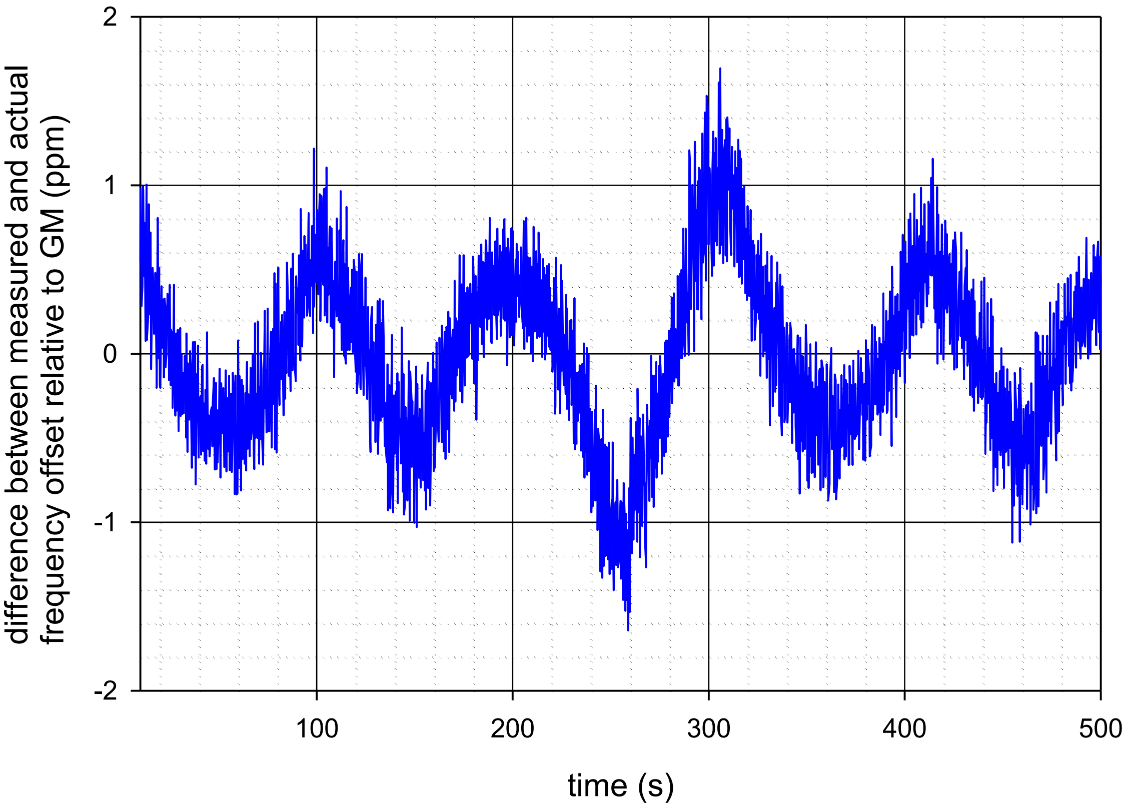
Case27, Node 101 Detailed Results - 2

Simulation Case 27, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



Case27, Node 101 Detailed Results – 3

Simulation Case 27, Node 101
Single replication of simulation, detail of 10 - 500 s
Clock Model: Frequency vs temperature stability and temperature vs time profile from [1]
Accumulate neighborRateRatio
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 10% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns



Cases 16, 22, 27, Detailed Results Summary

- The maxima of the dTE waveforms are consistent with the summary results on slides 51 and 52
- All the results for measured and actual frequency offset show that the former follows the latter, with added noise that increases with node number (see slides 57, 60, 63, 66, 69, 72, 75, 78, 81, 84, 87, and 90)
  - The maximum frequency offset error at node 2 (1st node after the GM) is approximately 0.56 ppm, for cases 16, 22, and 27
    - The rateRatio measurement at node 2 is equal to neighborRateRatio, because the GM (node 1) is assumed to have zero phase and frequency error
    - The maximum frequency offset measurement error at node 2 is much greater than the requirement of 802.1AS-2020, B.2.4, of ±0.1 ppm
      - B2.4 should likely be clarified to indicate that the requirement is for neighborRateRatio
  - The maximum frequency offset error at node 35 is approximately 0.75 ppm, 0.75 ppm, and 1.2 ppm, for cases 16, 22, and 27, respectively
  - The maximum frequency offset error at node 68 is approximately 0.98 ppm, 0.95 ppm, and 1.4 ppm, for cases 16, 22, and 27, respectively
  - The maximum frequency offset error at node 101 is approximately 1.1 ppm, 1.0 ppm, and 1.7 ppm, for cases 16, 22, and 27, respectively
  - Note that these errors include statistical variability; however, they do indicate the trend

Conclusions

- It appears that it is possible to meet the max|TE| objective of 1 μs over 64 hops, and over 100 hops if possible, if neighborRateRatio is measured over a window of size 7, with the median of the 7 values taken as the measurement
  - Timestamp granularity is assumed to be 8 ns
    - Reducing timestamp granularity to 4 ns has small impact
  - Dynamic timestamp error is assumed to be $\pm$8 ns, each with 0.5 probability
  - max|dTE| results for 100 hops range from 550 – 600 ns for 1 ms residence time, 630 – 790 ns for 4 ns residence time, and 850 – 1450 ns for 10 ms residence time
  - The results for 1 ms, and possibly 4 ms, appear to have margin for
    - Increase when multiple replications are run
    - Effect of GM time error variation
    - Constant time error (cTE)
- If the current assumptions for timestamp granularity, dynamic timestamp error, and residence time are retained, the focus should be narrowed to 8 ns timestamp granularity, and 1 ms and possibly 4 ms residence time (with the current dynamic timestamp error assumption and measurement of neighborRateRatio using window of size 7 and median

Possible Next Steps - Simulations

- 300 multiple replications of simulations, with the effect of GM time error variation added
  - Assume the GM has the same time error model as the LocalClock entities of the other PTP Instances, i.e., based on the temperature profile of [1] and the frequency stability versus temperature of [2] and [3] (see slides 3 and 4)
  - Compute relative dynamic time error (dTE_R) relative to GM, using interpolation (see [5] for details)
  - 8 ns timestamp granularity and dynamic timestamp error of ±8ns, each with 0.5 probability
  - Focus on 1 ms and 4 ms residence times
  - Consider initial offsets of LocalClock phase error waveform at each node to be random over full cycle and random over 10% of cycle
- The above imply 4 cases, based on the following cases here:
  - Cases 16, 18, 22, 24

Possible Next Steps - Consideration of Requirements and Compliance - 1

- The model for measurement of neighborRateRatio based on a window of size 7 and computation of the median is one of many ways that neighborRateRatio can be measured
- The particular way in which it is measured is implementation specific
- The IEC/IEEE 60802 profile should allow any measurement scheme, as long as respective requirements are met
  - In the case here, the requirement is that the error in the measurement of neighbor frequency offset (i.e., neighborRateRatio – 1) not exceed a specified limit
  - The exact limit cannot be finalized until the multiple replication simulations are run and the end-to-end time error budget is finalized; however, the results here suggest that the limit of 802.1AS-2020, B.2.4, of ±0.1 ppm, could give acceptable results because the results obtained in cases 16 – 27 had maximum neighbor frequency offset of 0.56 ppm
- Since the Follow_Up Information TLV carries accumulated rateRatio, it should be possible to test a single PTP Instance with a test set both serving as the GM and measuring the result

Possible Next Steps - Consideration of Requirements and Compliance - 2

- Limits on timestamp granularity and dynamic timestamp error also must be specified
  - These are both equipment requirements, and tolerance requirements when the accuracy of the neighborRateRatio measurement is tested
  - In such a test, the test set would need to add both the specified timestamp granularity and dynamic timestamp error to the PTP event messages sent to the equipment under test, because the scheme used in the neighborRateRatio measurement would need to tolerate these errors
- A more detailed description of these considerations can be given in a future presentation, after the future simulations are completed

Thank you

References - 1

[1] Geoffrey M. Garner, *Summary of Assumptions for Next Simulations, based on Presentation and Subsequent Discussion of [1], Revision 1*, IEC/IEEE 60802 presentation, March 11, 2021 (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-summary-of-assumptions-next-simulations-0321-v01.pdf)

[2] Chris McCormick, *Crystal Fundamentals & State of the Industry*, IEC/IEEE 60802 presentation, February 22, 2021 call (available at https://www.ieee802.org/1/files/public/docs2021/60802-McCormick-Osc-Stability-0221-v01.pdf)

[3] Geoffrey M. Garner, *Phase and Frequency Offset, and Frequency Drift Rate Time History Plots Based on New Frequency Stability Data*, IEC/IEEE 60802 presentation, March 8, 2021 call (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-temp-freqoffset-plots-based-on-new-freq-stabil-data-0321-v00.pdf)

References - 2

[4] Jordan Woods, *Concerns regarding the clock model used in 60802 time synchronization simulations*, Revision 1, IEC/IEEE 60802 presentation, December 21, 2020 call (available at https://www.ieee802.org/1/files/public/docs2020/60802-woods-ClockModel-1220-v02.pdf)

[5] Geoffrey M. Garner, *Further Simulation Results for Dynamic Time Error Performance for Transport over an IEC/IEEE 60802 Network Based on Updated Assumptions*, Revision 2, December 14, 2020 call (available at https://www.ieee802.org/1/files/public/docs2020/60802-garner-further-simulation-results-time-sync-transport-1120-v02.pdf)