Further Simulation Results for Time Error Performance for Transport over an IEC/IEEE 60802 Network

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IEEE 802.1 TSN TG
2020.07.13

Outline

- Introduction
- Assumptions for Simulation Cases
- Results
- Conclusion and Discussion of Next Steps

Introduction - 1

- In the May 2020 IEC/IEEE 60802 virtual meetings, simulation results for dynamic time error for transport over an IEC/IEEE 60802 network were presented [1]
- These were followup results, after initial results had been presented in the March 2020 virtual meetings [2]
- The assumptions for the May meeting simulations [1] were based on previous discussion at the March meeting and at the January 2020 802.1 meeting [3], and also on detailed discussion of the clock models used in 802.1AS, Annex B and the clock model assumptions for IEC/IEEE 60802 [4]
- The simulation results in [2] (March meeting) indicated that the desired objective of max|dTE| of 1 μs over 64 hops (and over 100 hops if possible) cannot be met using the assumptions for the 60802 local clock (± 100 ppm maximum frequency offset and 3 ppm/s maximum frequency drift rate), accumulation of neighborRateRatio to obtain grandmaster (GM) rateRatio, and other assumptions for the various 802.1AS parameters described in [1] (see slide 29 of [1])
- Based on discussion at the March meeting and subsequent email discussion between the March and May meetings, modified assumptions were suggested
  - Consider smaller maximum frequency drift rates (0.1, 0.3, and 1 ppm/s, in addition to the 3 ppm/s initially considered); this is equivalent to using a more stable oscillator
  - Consider measuring the rateRatio relative to the GM using successive Sync messages, rather than accumulating neighborRateRatio measured using Pdelay messages

Introduction - 2

- Simulations using each of these assumptions were run, and the results were presented at the May meeting [1]
- In particular, for the measurement of GM rateRatio using successive Sync messages, the following were considered:
  - Measure a new GM rateRatio on receipt of each Sync message, using the current and previous Sync message
  - Measure a new GM rateRatio on receipt of every 10th Sync message, using that message and the 10th previous Sync message (i.e., jumping window of size 10)
- The May results [1] indicated the following:
  - Depending on the timestamp granularity (i.e., 2 ns and 8 ns were considered), and mean Sync and mean Pdelay message rates (various combinations of 1 message/s and 32 messages/s were considered), it was possible to meet the objective of 1 μs max|dTE| over 64 hops and over 100 hops if possible (leaving sufficient margin for other time error budget components, e.g., cTE) for maximum frequency drift rates of 0.1 ppm/s and 0.3 ppm/s
    - It also was possible to meet this objective for 1 ppm/s, but only for Sync and Pdelay mean rates of 32 messages/s and timestamp granularity of 2 ns
    - The method of measuring frequency offset relative to the GM using successive Sync messages resulted in max|dTE| that exceeded 1 μs over 64 hops in all the cases considered

Introduction - 3

- In the discussions in the May 2020 IEC/IEEE 60802 meeting, and in subsequent email discussion, it was indicated that it might be possible to improve the oscillator stability for some applications, there are other applications where this is not possible (i.e., the resulting cost would be too large)
- It also was indicated that, in measuring GM rateRatio using successive Sync messages, a sliding window should be used rather than a jumping window
  - This would result in better time error performance
- One participant, who had been providing assumptions and requirements for the work so far, indicated he could provide revised assumptions in a presentation, which could then be discussed on the 802.1 email reflector prior to running new simulations
- The presentation was provided, and then revised after subsequent discussion on the reflector; the latest version of the presentation is [5]
- New simulations have been run based on [5] and subsequent email discussion on the 802.1 reflector
  - The assumptions, cases, and results for these simulations are presented here
- Except for describing new models or modifications of existing models, the simulator and models are not described here; they are described in [1] and [2] and the references cited there
- In the following slides, many of the assumptions are highlighted in **bold red** so they can be found easily

Local Clock Noise Generation Model

- The simulations of [2] considered sinusoidal and triangular wave noise generation models that were discussed previously in IEC/IEEE 60802 meetings, as well as a model based on the flicker frequency modulation (FFM) requirement of Annex B/802.1AS; all these models are described in detail in [4]
- It was noted during the presentation of [2] that, for the same maximum frequency offset and drift rate, the triangular wave model is more conservative than the sinusoidal frequency offset model
  - Based on this, it was decided that the next simulations could consider only the triangular wave model local clock noise generation (i.e., local clock stability)
  - It also was decided to focus on, for now, the triangular wave model rather than the FFM model
- The simulations of [1] considered maximum frequency offset of ±100 ppm, and maximum frequency drift rates of 3, 1, 0.3, and 0.1 ppm/s.
  - However, based on [5] and subsequent discussion, it was decided to use the worst case frequency drift rate of **3 ppm/s**, but that a maximum frequency offset of **±50 ppm** would be acceptable
    - In any case, max|dTE| depends mainly on the frequency drift rate; for a rate of 3 ppm/s, max|dTE| for ±50 ppm and ±100 ppm maximum frequency offsets should be approximately the same

Review of Assumptions for HRM - 1

- This slide and the next slide are taken from [1], as the HRM is the same as in [1]
- These assumptions on the HRM are common to all simulation cases
- The HRM is a linear chain that consists of 100 PTP Instances, and therefore with 99 PTP links connecting each successive pair of PTP Instance
  - The first PTP Instance in the chain is the Grandmaster PTP Instance
  - The next 98 PTP Instances are PTP Relay Instances
  - The last PTP Instance is a PTP End Instance
  - The PTP End Instance contains an endpoint filter, through which the transported time is computed

Assumptions for HRM – 2

- The GM and each PTP Relay Instance do not filter the timestamps with an endpoint filter when computing the value of the originTimestamp and correctionField of each transmitted Sync message
  - Rather, these fields are computed using the same fields of the most recently received Sync message, the <syncEventIngressTimestamp> of the most recently received Sync message, the <syncEventEgressTimestamp of the Sync message being transmitted, and the current value of rateRatio (i.e., cumulative rateRatio)
- However, the information at each PTP Relay Instance is used to separately compute a filtered (recovered) time, which could be used, e.g., by a co-located end application
  - This is equivalent to having a PTP End Instance collocated with the PTP Relay Instance

Assumptions for Grandmaster – 1

- This slide and the next two slides are adapted from [1], as the Grandmaster assumptions are the same
- In [1] and [2], the Grandmaster (GM) was assumed to be perfect
  - Both the GM noise generation (i.e., time error of the source of time) and the GM timestamping error were taken to be zero
- This was equivalent to computing dTE relative to the GM output
  - With this approach, the time error of the GM could be considered as a separate budget component (i.e., separate from dTE), to be added later (similar to other budget components, e.g., cTE)
  - Alternatively, the time error of the GM would not be added if this was not considered to be relevant to the application
- In the discussion during the presentation of [2] and in subsequent emails, it was stated that, while it is $\mathrm{dTE}_{\mathrm{R}(k,0)}$ (i.e., relative time error at node *k* relative to the GM) that is important, the effect of the GM phase/time variation on the downstream recovered time should be considered
  - The actual GM noise generation (i.e., not including the effect of timestamp granularity at the GM egress) can be considered to be a triangular wave with $\pm$ 50 ppm maximum frequency offset and maximum frequency drift rate of 3 ppm/s

Assumptions for Grandmaster – 2

- The above means that the GM should be modeled as having noise generation given by a triangular wave with the above characteristics and respective timestamp granularity (the same as for the PTP Relay Instances, i.e., 2 ns or 8 ns)
- The simulator produces absolute time errors (i.e., relative to the reference for the GM), and then time error at each node relative to the GM output is computed
- However, the computation (or measurement) of relative time error can be complicated, because the (ideal) times at which the time errors are computed at a node downstream from the GM are, in general, not the same as the times at which time errors at the GM are computed
    - This is mainly due to an approximation made to speed up the simulation run time
    - A major bottleneck for the run time is the writing of output for each node; the simulation timestep is generally much smaller than the time interval for which output is needed. To reduce the amount of output, the output data is divided into blocks, and the largest and smallest value in each block is written.
    - This does not impact the computation of max|dTE| or MTIE because these are peak and peak-to-peak statistics, respectively. This also has negligible effect on TDEV, because the TDEV computation includes averaging and filtering operations.
    - However, relative time error must be computed using samples taken at the same time; if samples at the same time are not available, interpolation is necessary
        - These issues arose in recent simulation work in ITU-T Q13/15 [6]

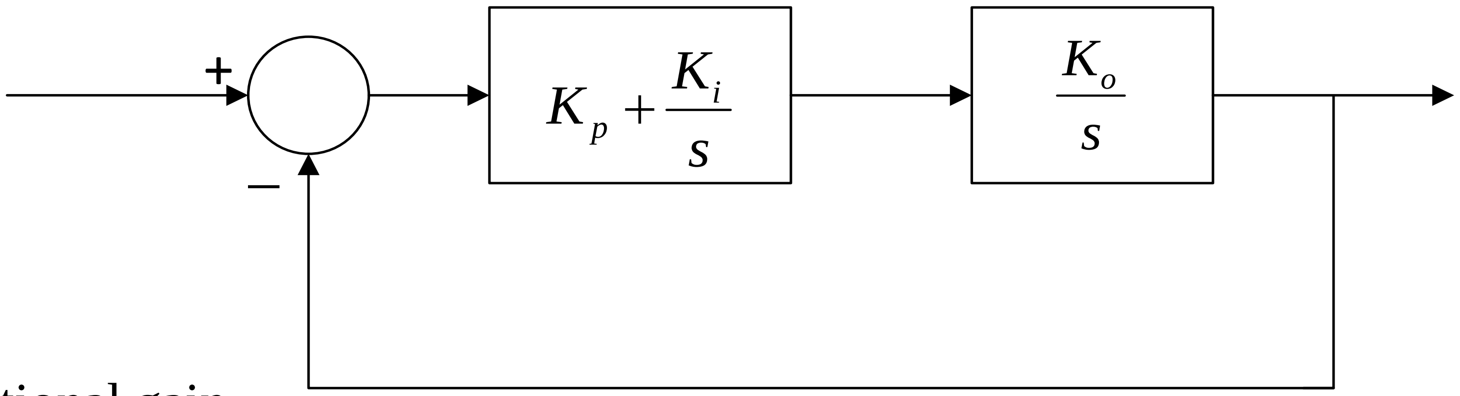
Assumptions for Grandmaster – 3

- However, if the GM frequency offset is a triangular wave with 50 ppm zero-to-peak amplitude and 3 ppm/s drift rate, the period of the variation is (2)(2)(50 ppm/[3 ppm/s]) = 66.7 s.
- The frequency of the variation is 1/66.7 s = 0.015 Hz
- However, the endpoint filter used in the simulations has bandwidth and gain peaking of 3.78 Hz and 1.049 dB, respectively
  - The effect of this filter on the phase variation due to the GM is therefore very small, and the time error at a downstream node relative to the output of the GM noise source will be approximately the same as the time error if the GM noise source is taken to be zero
- Since the results of [1] and [2] show that max|dTE| alone exceeds the desired max|TE| objective of 1 μs by a significant amount, it was decided to omit the effect of the GM noise source for now (it will be included in future simulations after assumptions and parameters that allow the 1 μs objective to be met are decided on)
  - Note that the effect of timestamp granularity at the GM will be included in the simulations

Assumptions Common to All Cases

- These assumptions for the simulations are based on [5] and subsequent discussion on the 802.1 email reflector
  - In addition, some assumptions used previously did not change
- Use **syncLocked mode** (since all ports have same mean Sync interval)
- **Mean Sync Interval: 0.03 s (fixed)**
  - This was indicated in [5]; it was noted in the email discussion that both IEEE Std 1588-2019 and IEEE Std 802.1AS-2020 require mean message intervals to be powers of 2, and the closest power of 2 is 0.03125 s (i.e., 2^{-5} s); however, it was decided to use 0.3 s
    - In addition, the Sync interval is assumed to be fixed; this is relevant only at the GM, as this is the only node that is not in syncLocked mode
- **Mean Pdelay Interval: 1 s**
- **Pdelay turnaround time (i.e., time between receipt of Pdelay_Req and sending of Pdelay_Resp): 10 ms**
- **Timestamp granularity: 2 ns**
- **Window size for GM rateRatio measurement (more on this in a later slide): 8 (current and previous 7 Sync messages)**
- **rateRatio computation granularity: 2.328×10^{-10}**
- Endpoint filter model and assumptions are described on the following slides (adapted from [3]

Endpoint Filter Model and Assumptions - 1



$K_p =$ proportional gain

$K_i =$ integral gain

$K_o =$ VCO/DCO gain

Transfer function:

$$H(s) = \frac{K_p K_o s + K_i K_o}{s^2 + K_p K_o s + K_i K_o} = \frac{2\varsigma\omega_n s + \omega_n^2}{s^2 + 2\varsigma\omega_n s + \omega_n^2}$$

with

$$\omega_n = \sqrt{K_i K_o} \qquad \varsigma = \frac{K_p}{2}\sqrt{\frac{K_o}{K_i}}$$

Endpoint Filter Model and Assumptions - 2

- Often the filter parameters (and requirements) are expressed in terms of 3 dB bandwidth ($f_{3\text{dB}}$) and gain peaking (H_p)
  - These are related to damping ration (ζ) and undamped natural frequency (ω_n) by (see [6] and [7]):

$$f_{3\text{dB}} = \frac{\omega_n}{2\pi}\left[1 + 2\varsigma^2 + \sqrt{\left(1 + 2\varsigma^2\right)^2 + 1}\right]^{1/2}$$

$$H_p(\text{dB}) = 20\log_{10}\left\{\left[1 - 2\alpha - 2\alpha^2 + 2\alpha\sqrt{2\alpha + \alpha^2}\right]^{-1/2}\right\}$$

where

$$\alpha = \frac{1}{4\varsigma^2} = \frac{K_i}{K_p^2 K_o}$$

Endpoint Filter Model and Assumptions – 3

- Modified assumptions for proportional gain and integral gain were given in [5] (these differed from the values given in [1], [2], and [3])
  - However, as before, the VCO gain was folded into the proportional gain and integral gain (this is equivalent to setting the VCO gain to 1)
- Filter assumption:
  - $K_p K_o = 11$, $K_i K_o = 65$
  - **Using the equations on the previous slides, we obtain**
    - ζ **= 0.68219**
    - ω_n **= 15.78 rad/s**
    - H_p **(gain peaking) = 1.28803 dB = (approx) 1.3 dB**
    - f_{3dB} **= 2.6 Hz**
- Note that this filter is underdamped, and has appreciable gain peaking
  - However, the damping ratio (ζ) is close to $1/\sqrt{2}$ = (approx) 0.707); this is often used to obtain a fast response with small overshoot, in cases where the filters are not cascaded (the endpoint filters are not cascaded)

Computation of GM rateRatio using successive Sync messages - 1

- Assume the computation is done every Sync message, using a window of size n (i.e., a sliding window)
  - The computation is done on ingress of a Sync message at a PTP Instance
  - The window size n includes the current Sync message (e.g., a window of size 8 consists of the current Sync message and the previous 7 Sync messages)
- Let C_{kn} be the correctedMasterTime carried by Sync message kn
- Let S_{kn} be the SyncEventIngressTimestamp for Sync message kn
- Then the computed $\mathrm{rateRatio}$ is

$$\mathrm{rateRatio}_{kn} = \frac{C_{kn} - C_{(k-1)n}}{S_{kn} - S_{(k-1)n}}$$

- Note that frequency offset is equal to $\mathrm{rateRatio} - 1$
- The above computation is performed for every Sync message that arrives at a PTP Instance

Computation of GM rateRatio using successive Sync messages - 2

- In addition, the median of the current and previous $n - 1$ computed values of GM rateRatio is obtained
  - The median is computed by sorting the n values from smallest to largest and taking the p^{th} smallest value, where $p = \text{floor}\,(n) + 1$
- For the simulations, we will consider cases:
  - where the median is not computed, i.e., the current value compute using the sliding window is used for GM rateRatio
  - where the median is computed and used for GM rateRatio

Residence Times

- Reference [5] indicates that the residence time is 1 ms minimum, 4 ms for the majority of cases, and 10 ms maximum
- In subsequent discussion on the 802.1 email reflector, it was indicated that, for each Sync message arriving at each PTP Relay Instance, the residence time can be chosen randomly from the probability distribution:
  - **Pr(residence time = 1 ms) = 1/3**
  - **Pr (residence time = 4 ms) = 1/3**
  - **Pr (residence time = 10 ms) = 1/3**
- It was decided to run one set of simulation cases with this assumption
- In addition, a set of simulation cases was run for each of the following two assumptions:
  - **Residence time = 4 ms**
  - **Residence time = 1 ms**
  - The case of residence time = 10 ms was not run because results in [1] indicated that the 1 μs time error objective could not be met for this case

Relative Phases of the Triangular Waves

- In [2], simulation cases were considered where:
  - The triangular waves at the successive nodes were in phase (i.e., the relative phases were zero)
  - The phase of each triangular wave (at each node) were chosen randomly at initialization
- **Cases with each of these assumptions will be considered here**

Simulation Time

- The simulation time for all the cases is chosen to include at least several cycles of the triangular waveform
  - The results in [1] and [2] indicated that once steady-state is reached, max|dTE| does not increase appreciably after several cycles
- Period (*T*) for the triangular wave with slope of 3 ppm/s and zero-to-peak amplitude of 50 ppm
  - T = (2)(2)(50 ppm/[3 ppm/s]) = 66.67 s
- In computing max|dTE|, the first 50 s of each simulation time history will be discarded to eliminate any startup transient
- **The simulation time is chosen to be 1050 s** (this includes approximately 15 cycles of the triangular wave after the initial 50 s)

Summary of Simulation Cases – 1

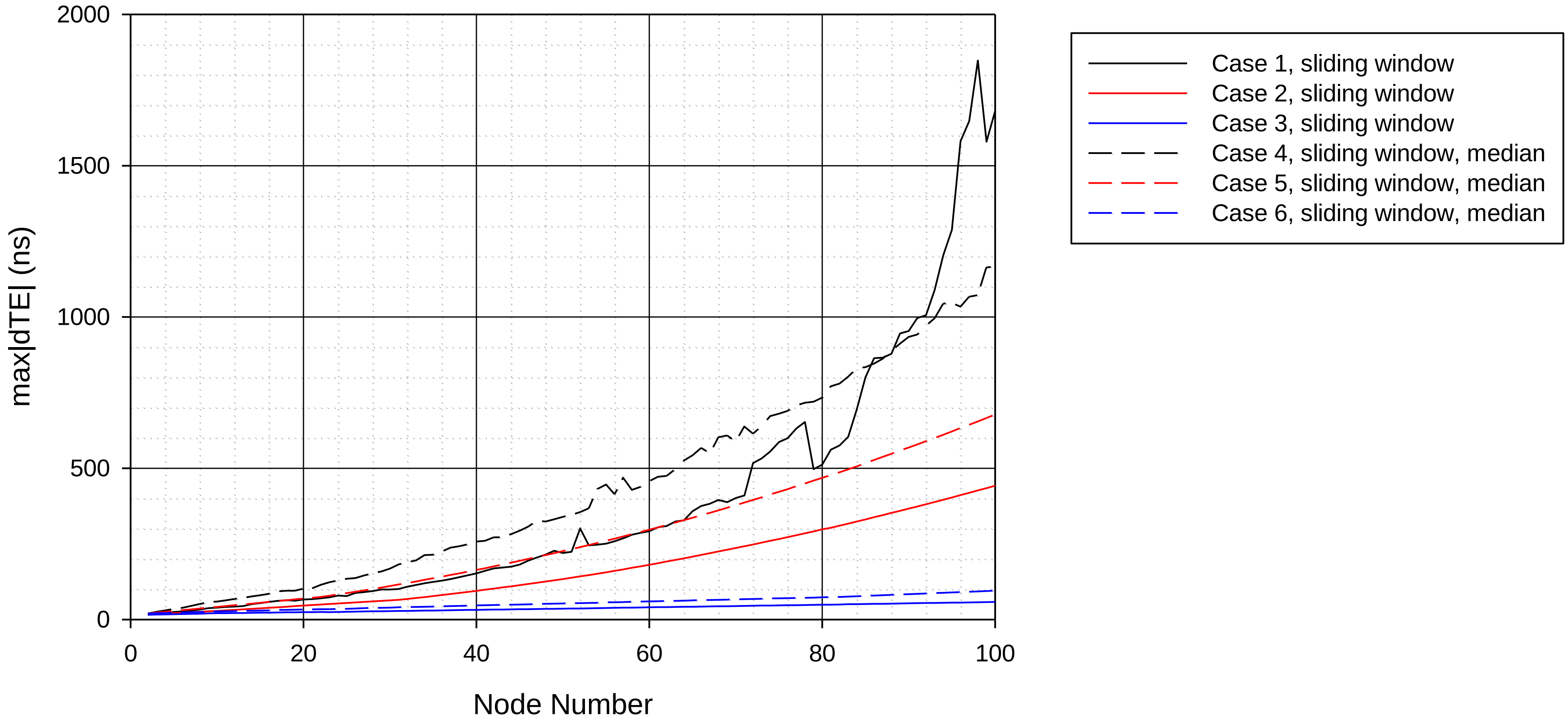
- The simulation cases are summarized in the following tables (the numbering scheme is chosen for convenience of naming directories/folders where the result files are stored; note that the numbering is not always contiguous)
- Parameters not listed are chosen as described in the preceding slides

Summary of Simulation Cases – 2

Obtain GM rateRatio via accumulation of neighborRateRatio			
Case	Residence time (ms)	Compute median for GM rateRatio computation (Yes/No)	Relative phases of triangular waves at each node
1	1, 4, 10 (with equal prob)	No	zero
2	4	No	zero
3	1	No	zero
4	1, 4, 10 (with equal prob)	Yes	zero
5	4	Yes	zero
6	1	Yes	zero
7	1, 4, 10 (with equal prob)	No	random
8	4	No	random
9	1	No	random
10	1, 4, 10 (with equal prob)	Yes	random
11	4	Yes	random
12	1	Yes	random

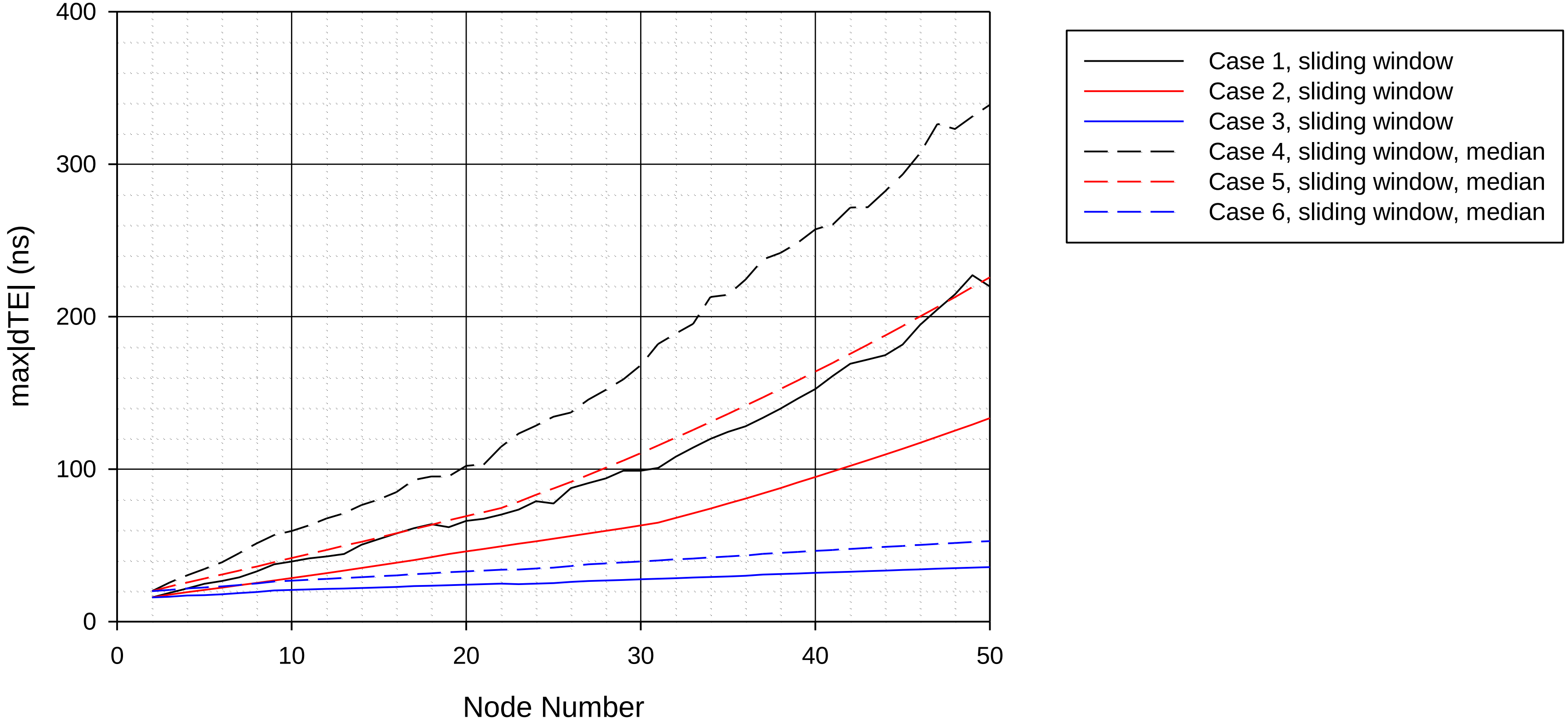
Cases 1 – 6: max|dTE|

Simulation Cases 1 - 6
Single replication of simulation
Clock Model: triangular wave freqeuncy variation
+/- 50 ppm amplitude, 3 ppm/s maximum drift rate, in phase
Cases 1 and 4: 1 ms, 4 ms, 10 ms residence times with equal probability
(chosen independently for each Sync message)
Cases 2 and 5: 4 ms residence time
Cases 3 and 6: 1 ms residence time
Window size is 8 (current plus prev 7 Sync msgs) in all cases,
for computing GM freq offset



Cases 1 - 6: max|dTE|, detail of nodes 1 - 50

Simulation Cases 1 - 6 (detail nodes 1 - 50)
Single replication of simulation
Clock Model: triangular wave freqeuncy variation
+/- 50 ppm amp, 3 ppm/s max drift rate, in phase
Cases 1 and 4: 1 ms, 4 ms, 10 ms residence times with equal probability
(chosen independently for each Sync message)
Cases 2 and 5: 4 ms residence time
Cases 3 and 6: 1 ms residence time
Window size is 8 (current plus prev 7 Sync msgs) in all cases,
for computing GM freq offset



Cases 1 – 6: Discussion of Results – 1

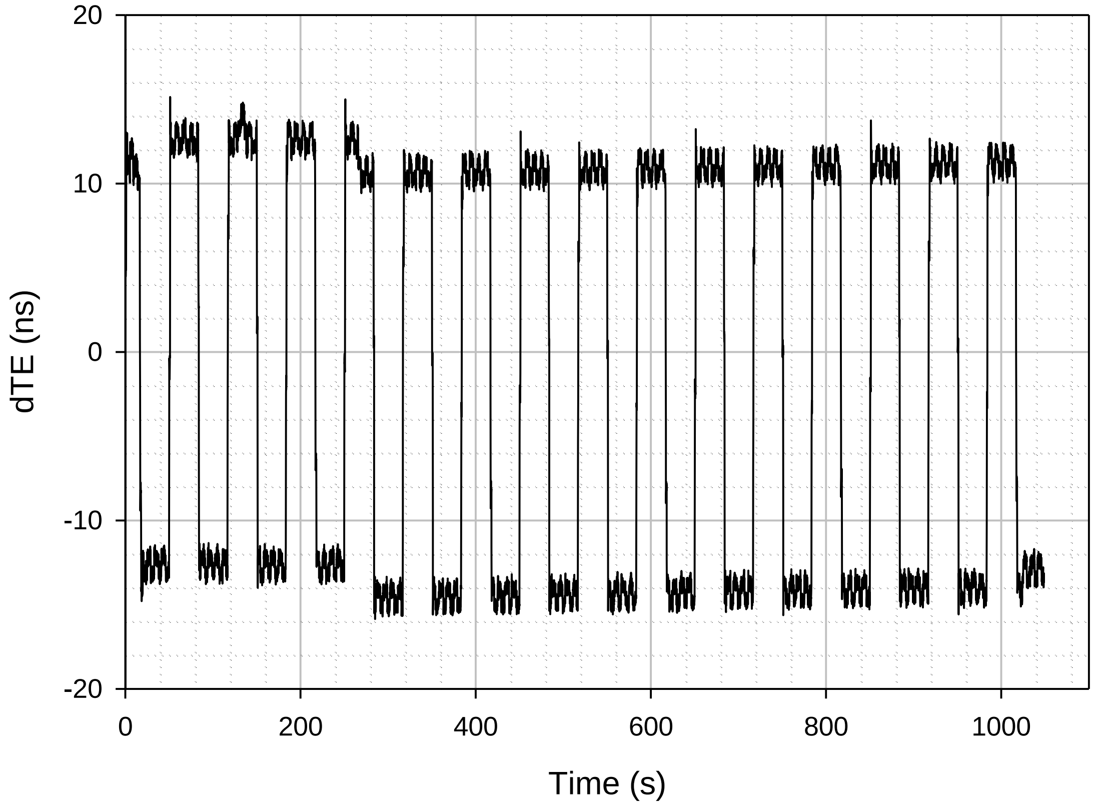
- Cases with 1 ms residence time (cases 3 and 6) have max|dTE| that is less than 100 ns over 100 hops
  - This leaves sufficient margin to meet the max|TE| objective of 1 μs over 64 hops, and over 100 hops if possible (i.e., allowing for other TE budget components, e.g., cTE
- Cases with 4 ms residence time (cases 2 and 5) have max|dTE| of 440 ns after 100 hops and 200 ns after 64 hops if median is not used in rateRatio computation, and max|dTE| of 680 ns after 100 hops and 300 ns after 64 hops if median is used
  - Except possibly for 100 hops and use of median, this likely leaves sufficient margin to meet max|TE| objective of 1 μs
- Cases with distribution of residence times (allowing as much as 10 ms residence time) have max|dTE| that exceeds 1600 ns after 100 hops and 300 ns after 64 hops if median is not used, and exceeds 1100 ns after 100 hops and 500 ns after 64 hops if median is used
  - While it appears that there might be sufficient margin to meet 1 μs objective for max|TE| over 64 hops, additional simulations are needed because the results show some amount of statistical variability due to residence time probability distribution (i.e., non-smoothness of results; must simulate multiple, independent replications)

Cases 1 – 6: Discussion of Results – 2

- In general, cases where GM rateRatio is taken as median of last 10 sliding window values have larger accumulated error than where most recent sliding window value is used
  - This is because the most recent value reflects the latest (and therefore most accurate) GM rateRatio information
  - The value of using the median is to eliminate occasional random errors in measured rateRatio due to bad measurements/data, and such errors are not modeled here
    - Taking the median as the estimate guards against such errors, which might produce transients resulting in large dTE, but at the expense of generally worse performance under normal, steady-state operation
- As will be discussed in later slides, and was discussed in [1], the dTE accumulation with increasing number of hops is due to inherent gain peaking in the transfer function that relates computed GM rate ratio at a PTP Instance and the input syncEventIngressTimestamp, and also in the transfer function that relates computed synchronized time at a PTP Instance and the input syncEventIngressTimestamp

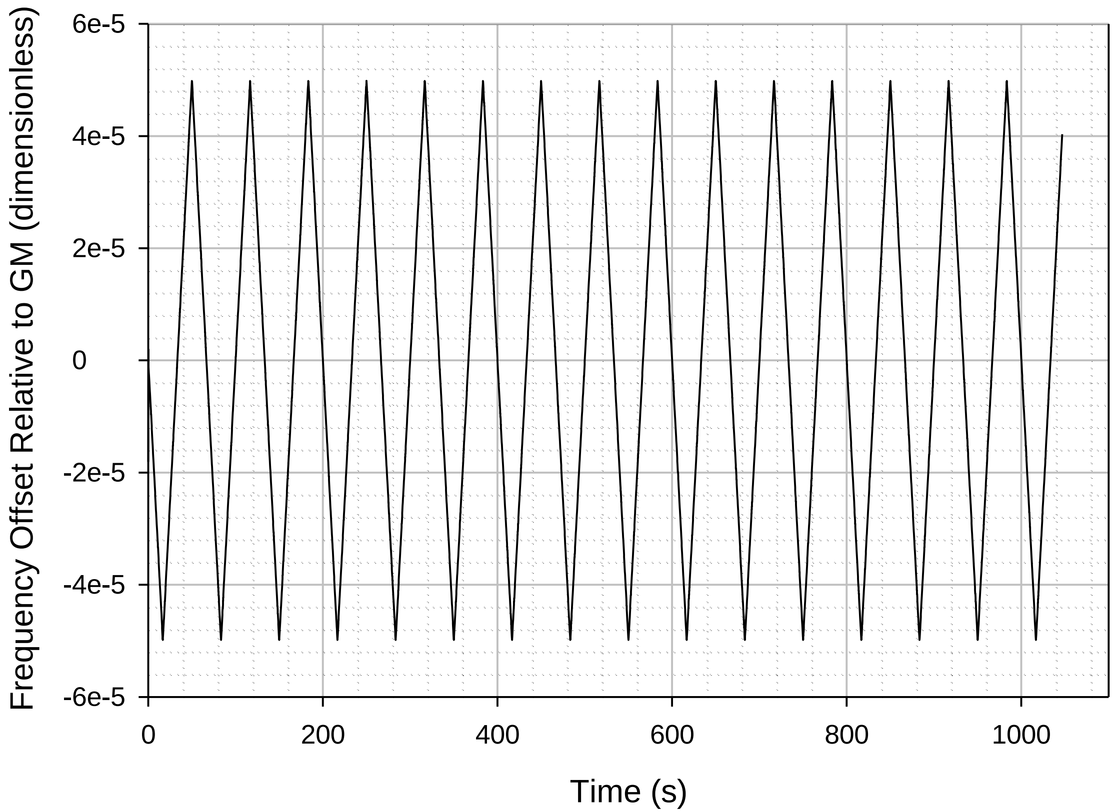
Case 1 – dTE, Node 2

Case 1, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



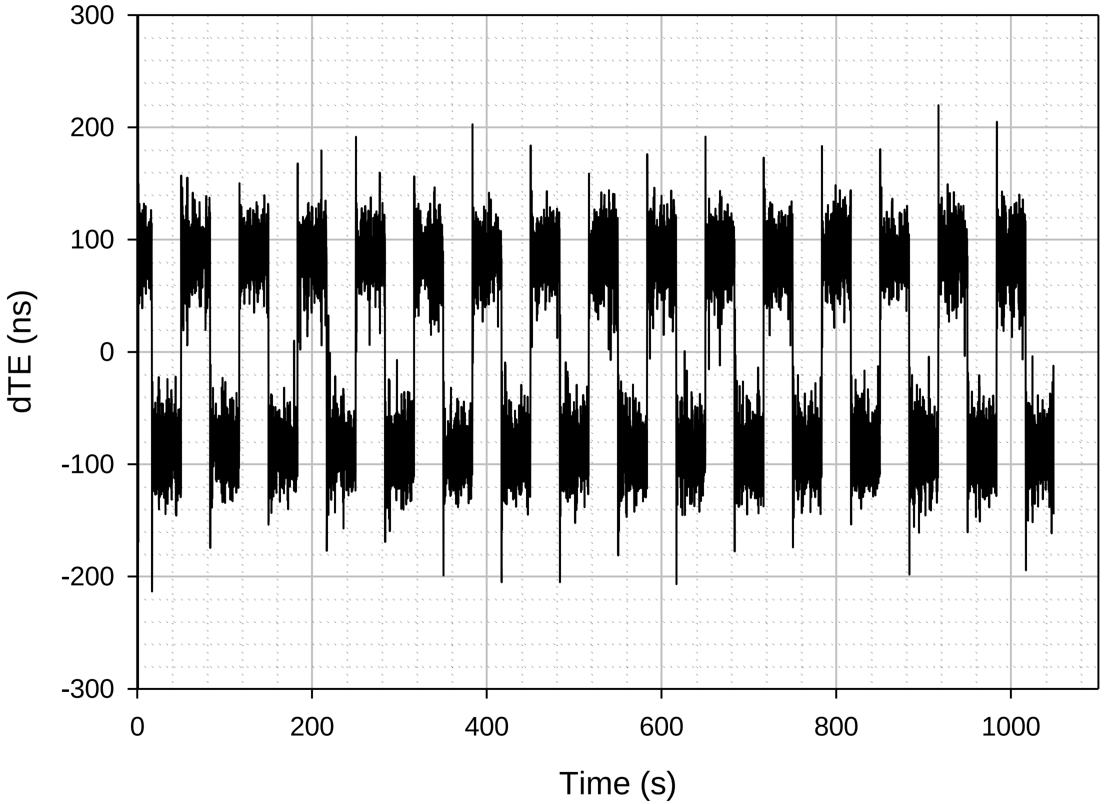
Case 1 – Measured Frequency Offset, Node 2

Case 1, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



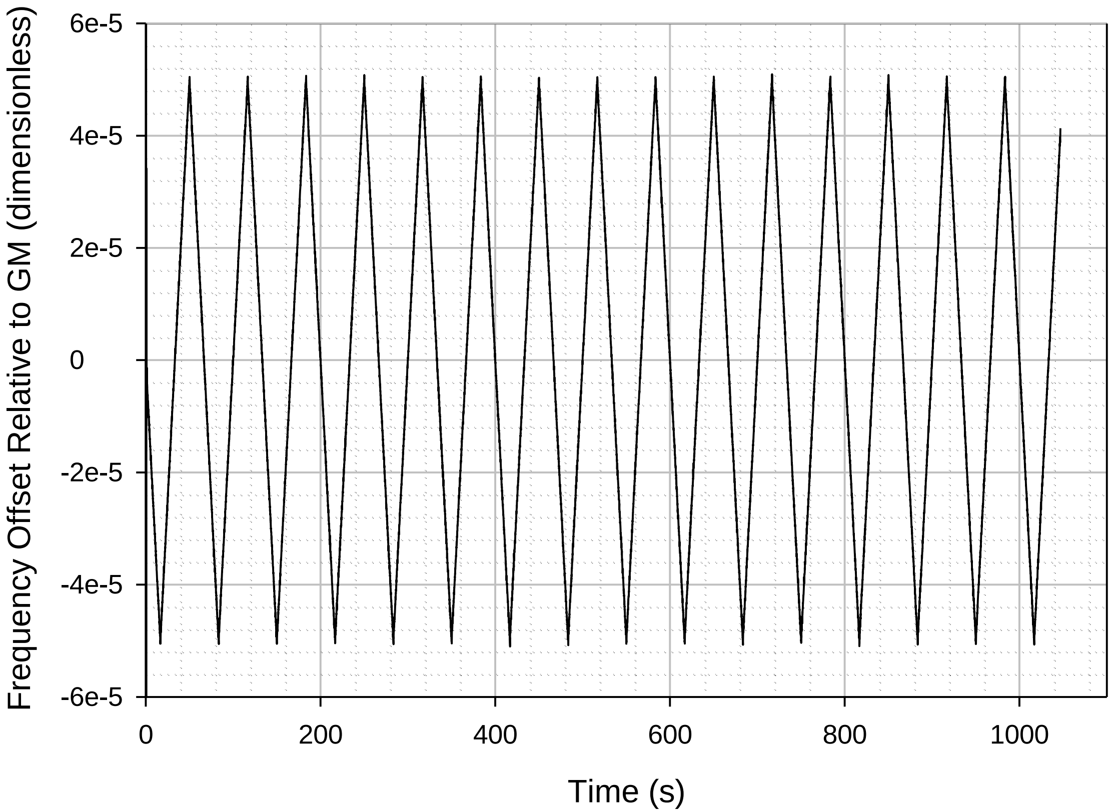
Case 1 – dTE, Node 50

Case 1, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



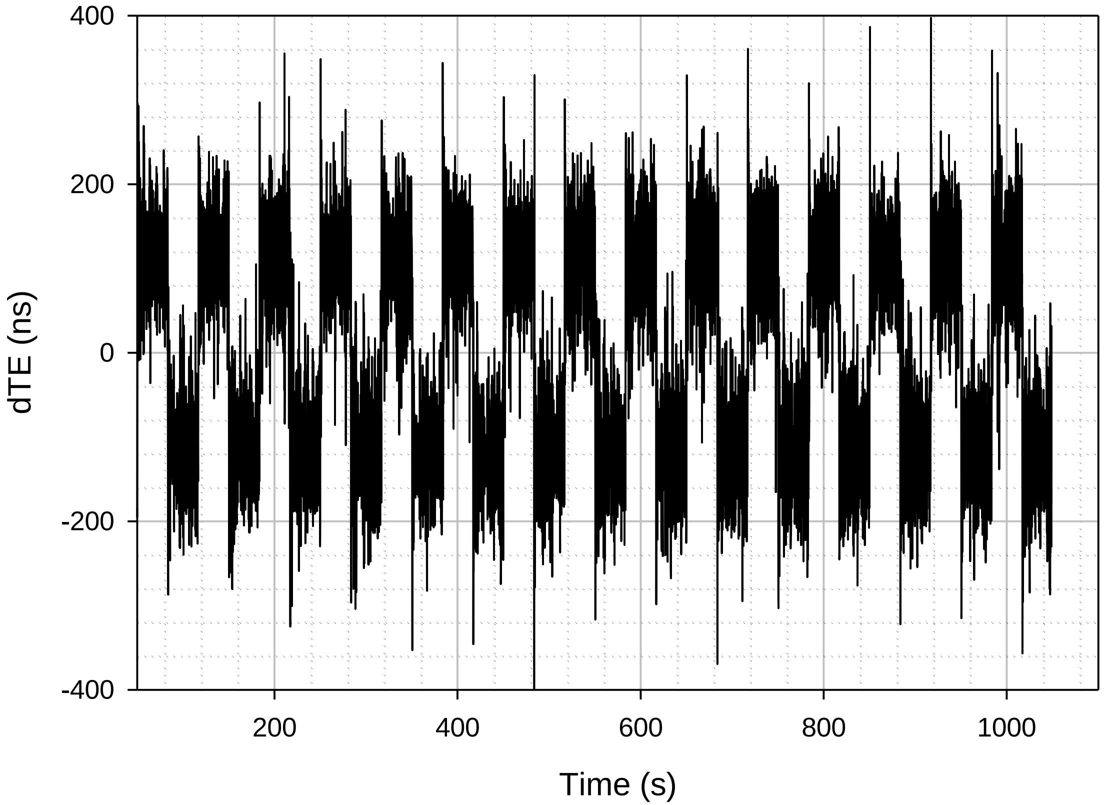
Case 1 – Measured Frequency Offset, Node 50

Case 1, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



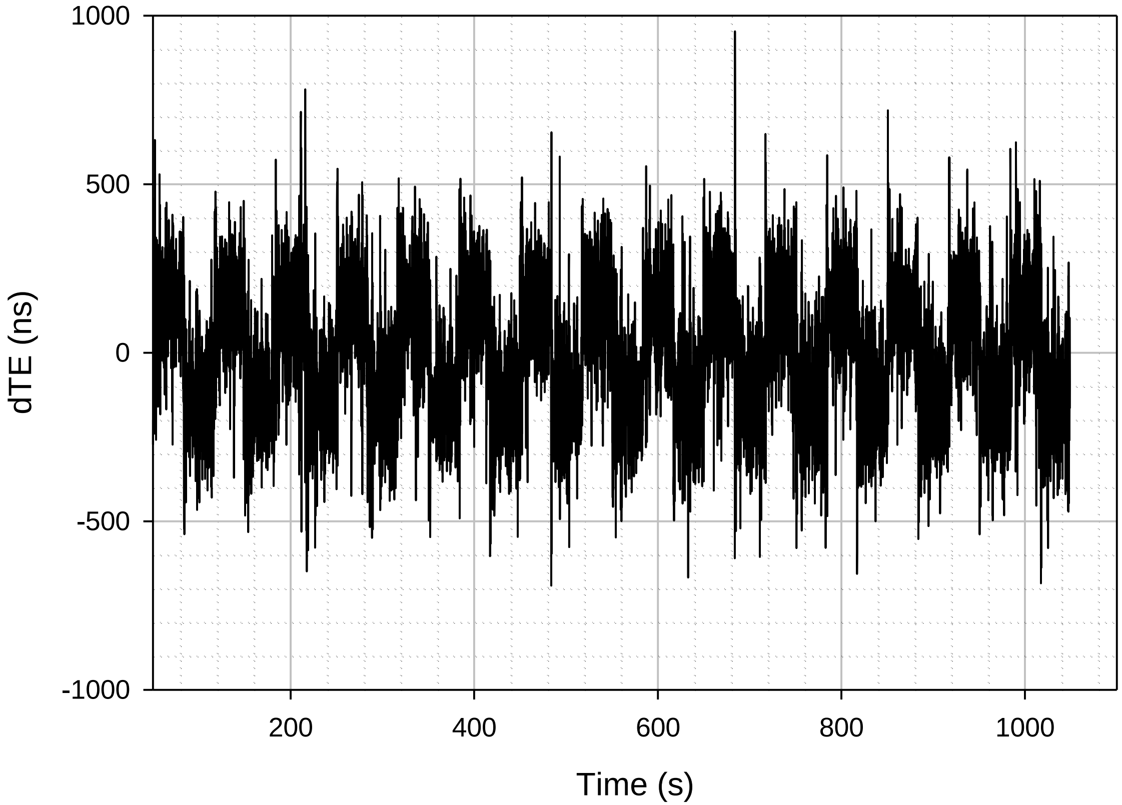
Case 1 - dTE, Node 70

Case 1, PTP Instance (node) 70
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
First 50 s omitted to eliminate any startup transient



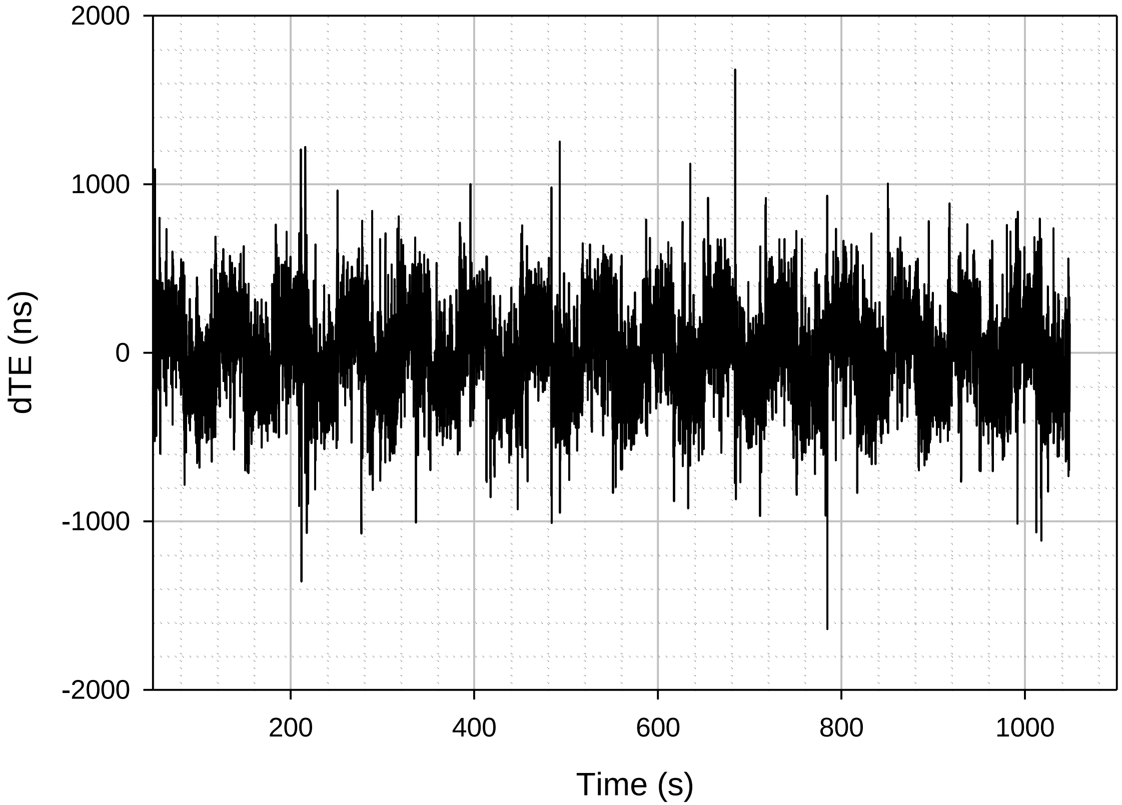
Case 1 - dTE, Node 90

Case 1, PTP Instance (node) 90
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
First 50 s omitted to eliminate any startup transient

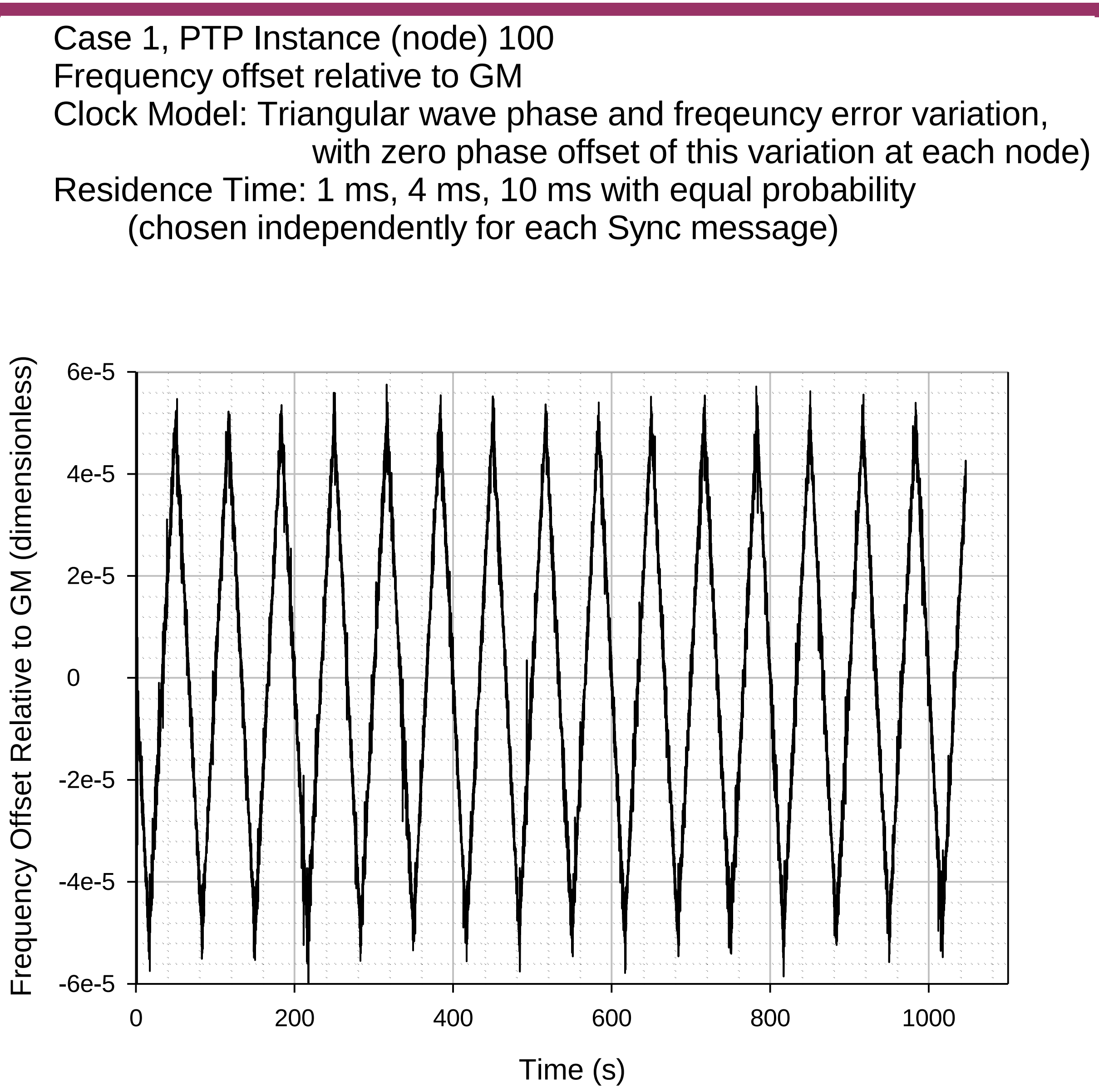


Case 1 - dTE, Node 100

Case 1, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
First 50 s omitted to eliminate any startup transient



Case 1 – Measured Frequency Offset, Node 100

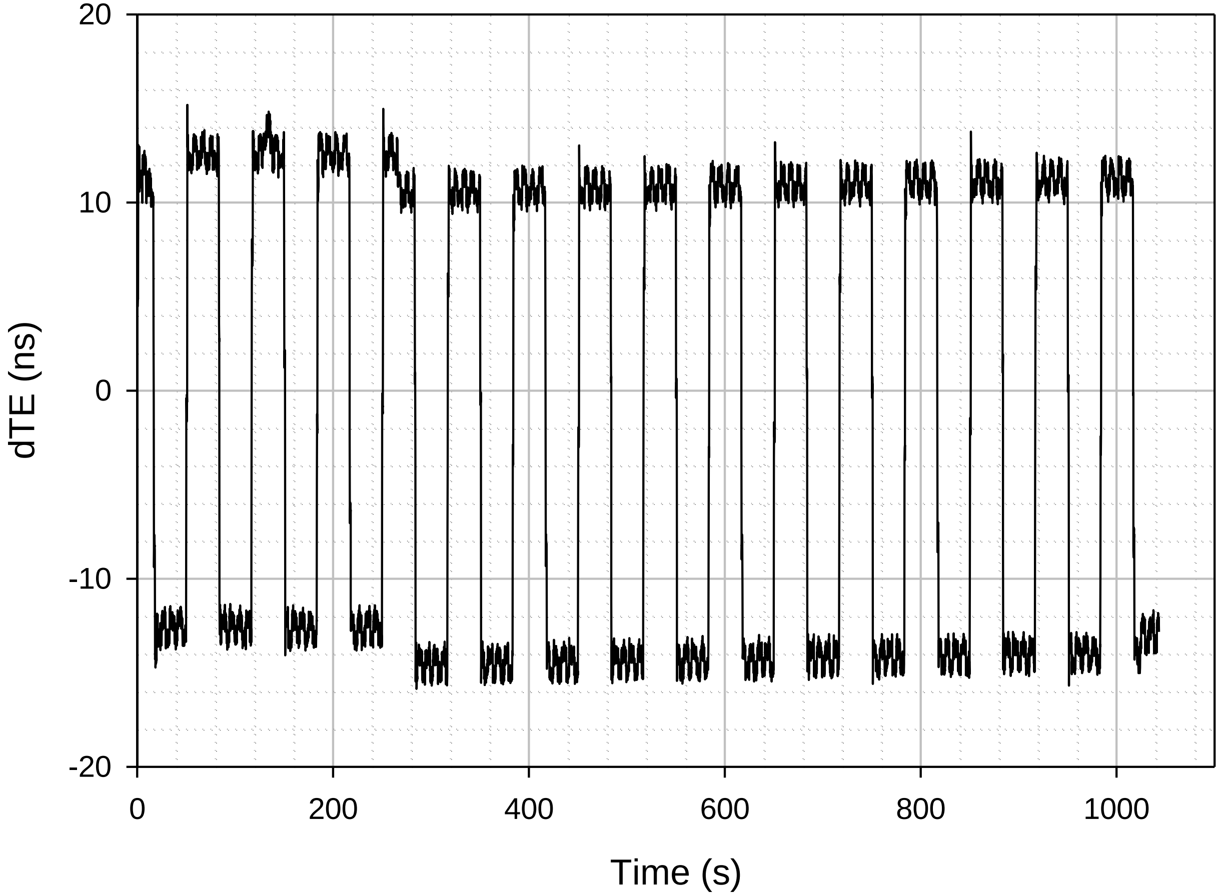


Case 1 – Discussion of Results

- Some of the “jaggedness” (especially in the rateRatio plots) is an artifact of the plotting software
- dTE qualitative shape (square-wave with some variability at the extremities) is consistent with previous results [1], [2]; jumps occur when slope of frequency triangular wave changes
- Node 2 measured GM frequency offset closely matches actual frequency offset triangular wave (50 ppm amplitude and 3 ppm/s slope)
- Later nodes show increasing frequency measurement error, e.g., at node 100, measured frequency offset amplitude approaches 58 ppm at several peaks
- At node 50, dTE shows the approximate square-wave behavior, but now there is overshoot at the transitions due to gain peaking in the rateRatio measurement transfer function
- Later nodes also show dTE accumulation, and continued deviation from square-wave behavior (by node 100, the square pattern has largely disappeared, though the approximate periodic behavior is still visible

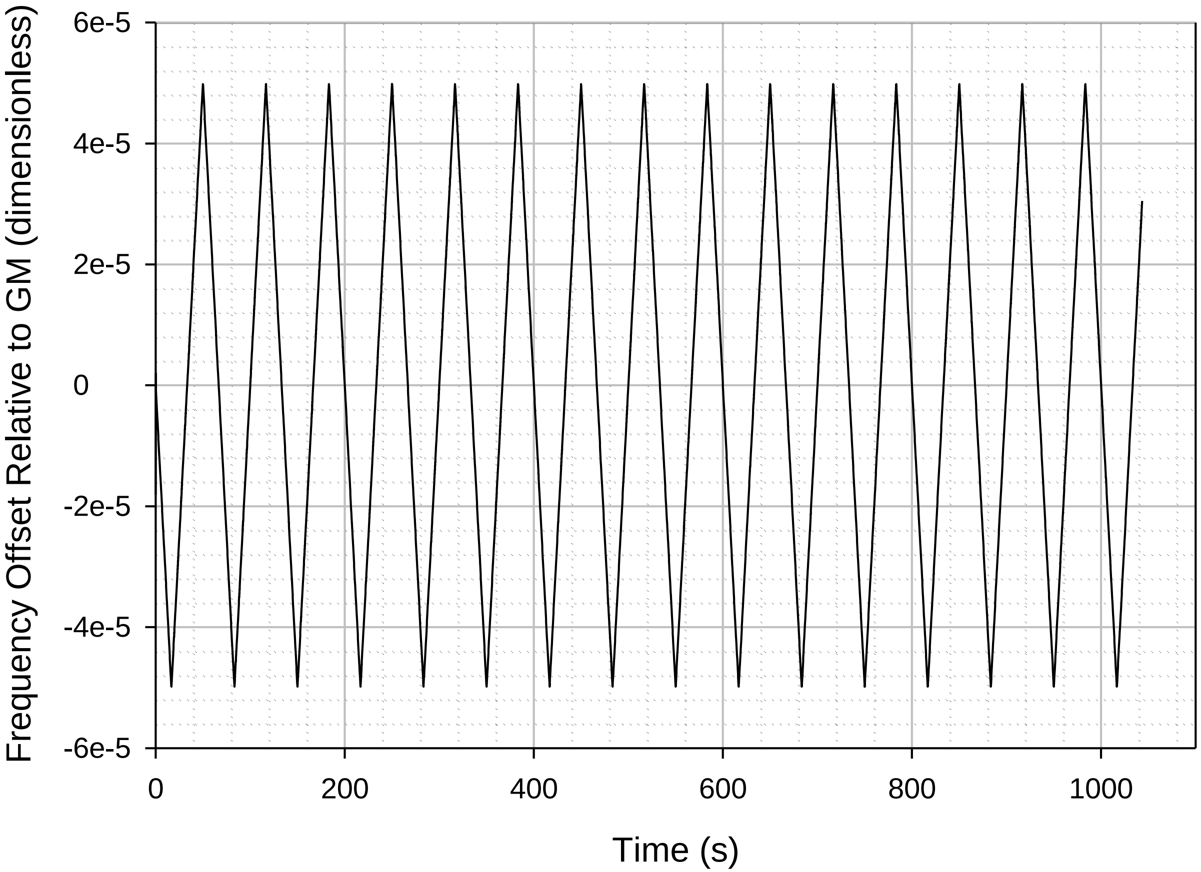
Case 2 - dTE, Node 2

Case 2, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms



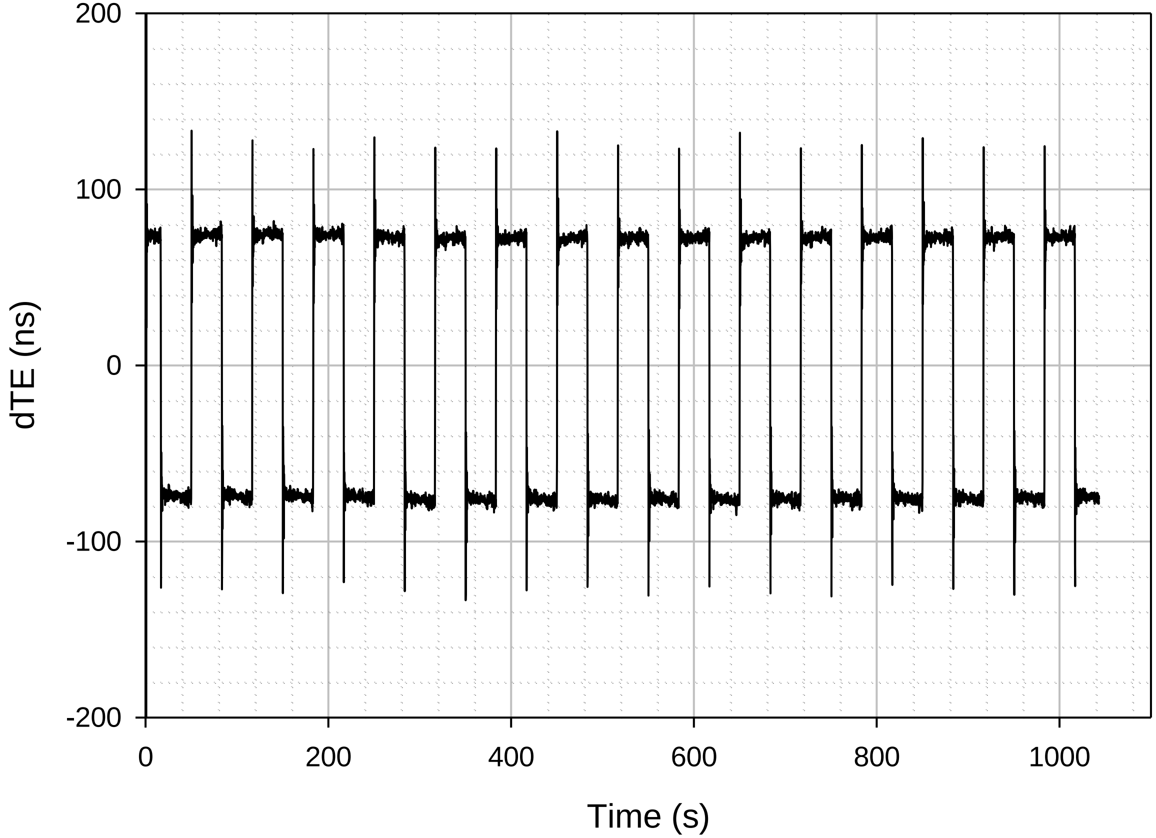
Case 2 - Measured Frequency Offset, Node 2

Case 2, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms



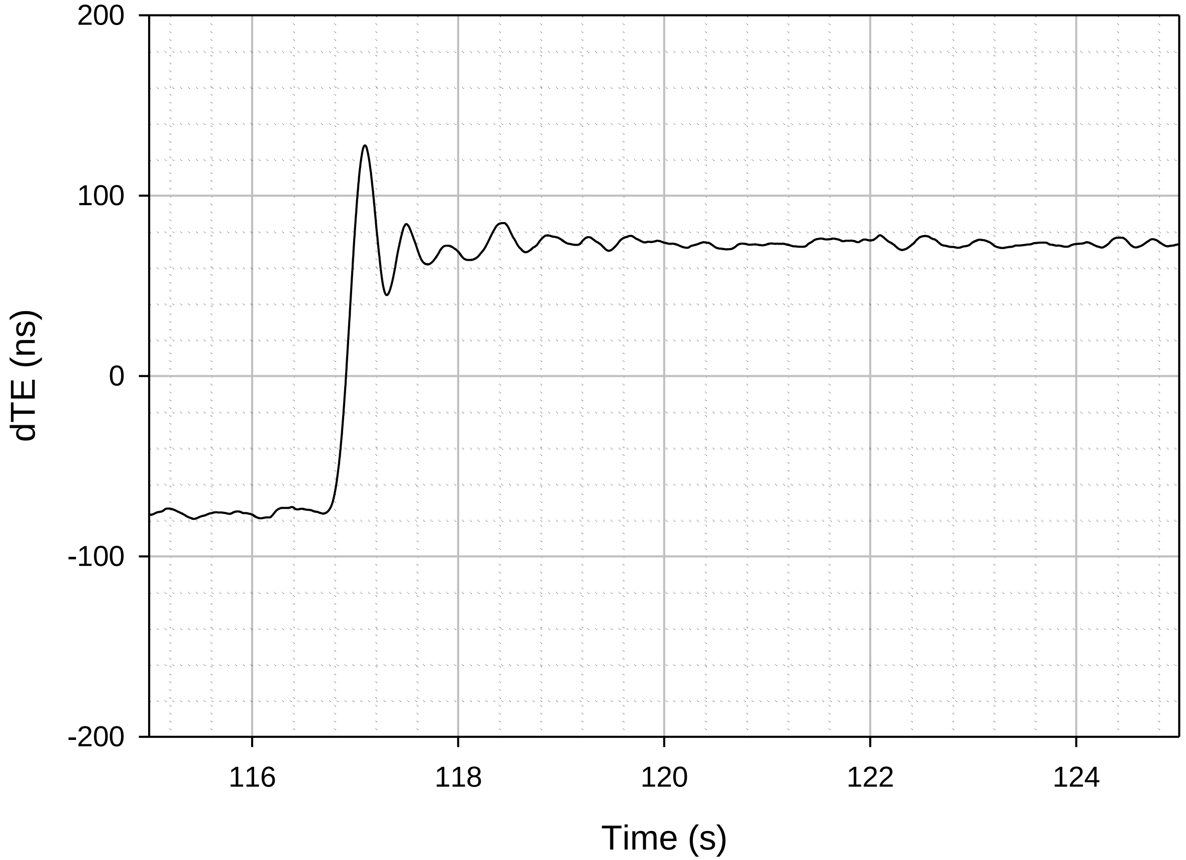
Case 2 - dTE, Node 50

Case 2, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms

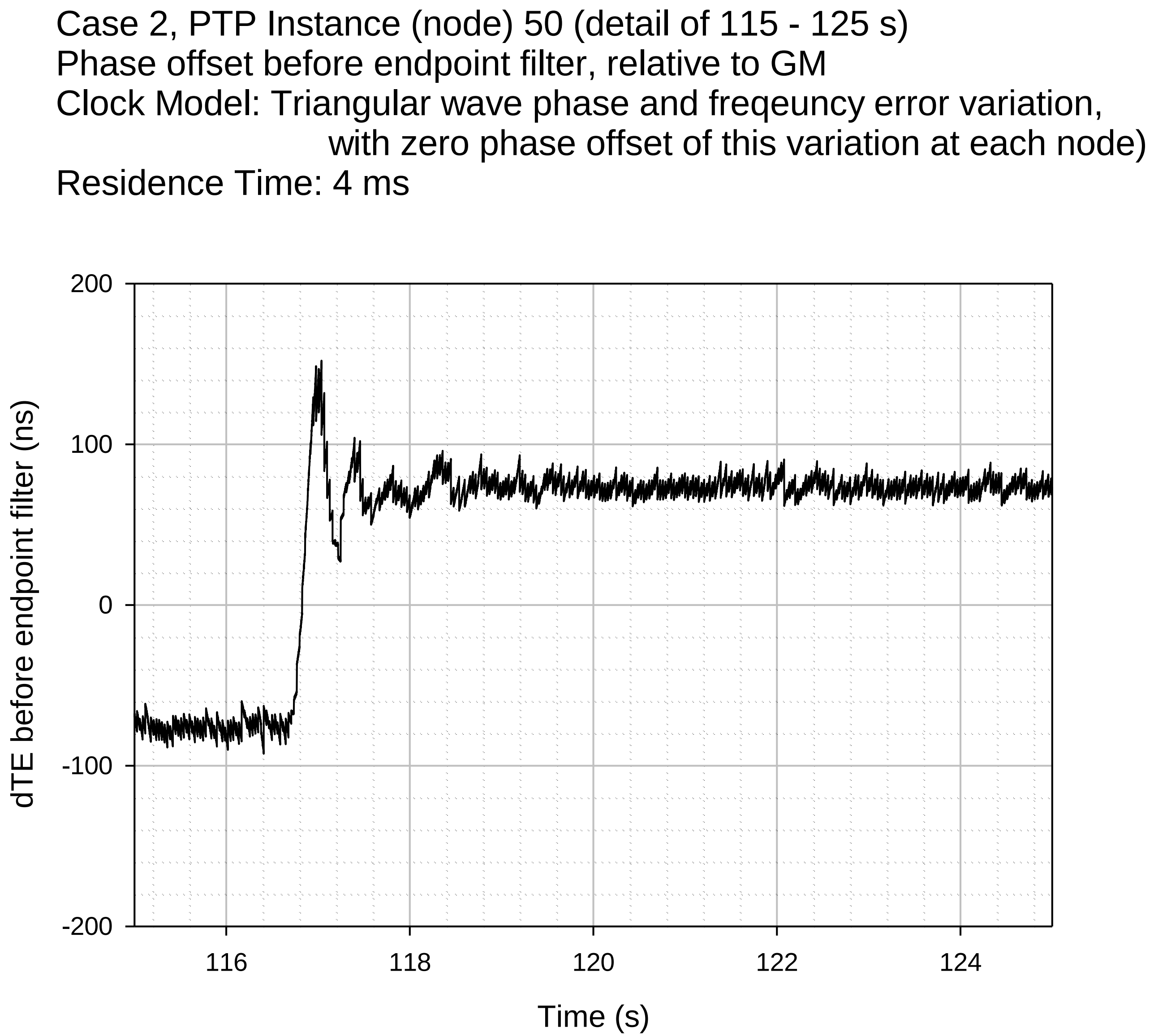


Case 2 - dTE, Node 50 (detail of 115 - 125 s)

Case 2, PTP Instance (node) 50 (detail of 115 - 125 s)
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms

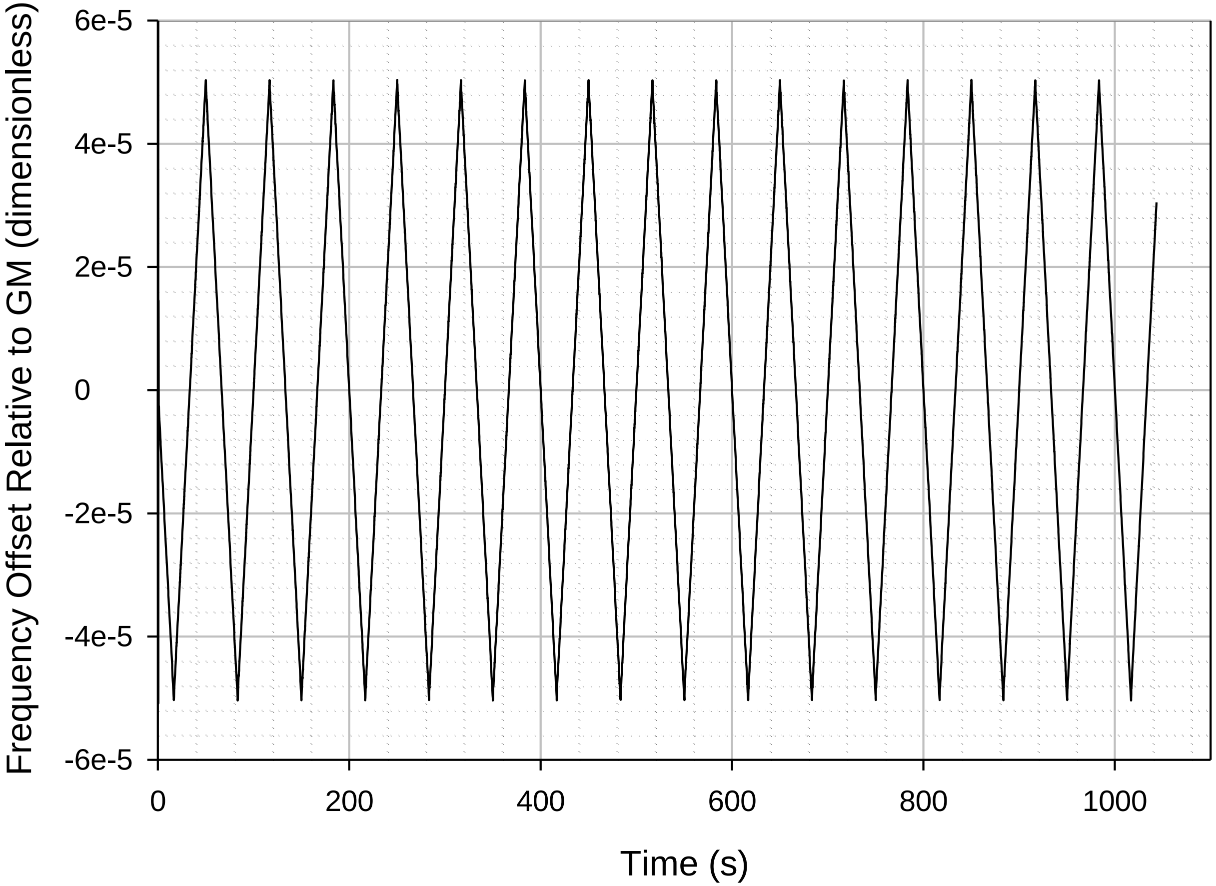


Case 2 - dTE before Endpoint Filtering, Node 50 (detail of 115 - 125 s)



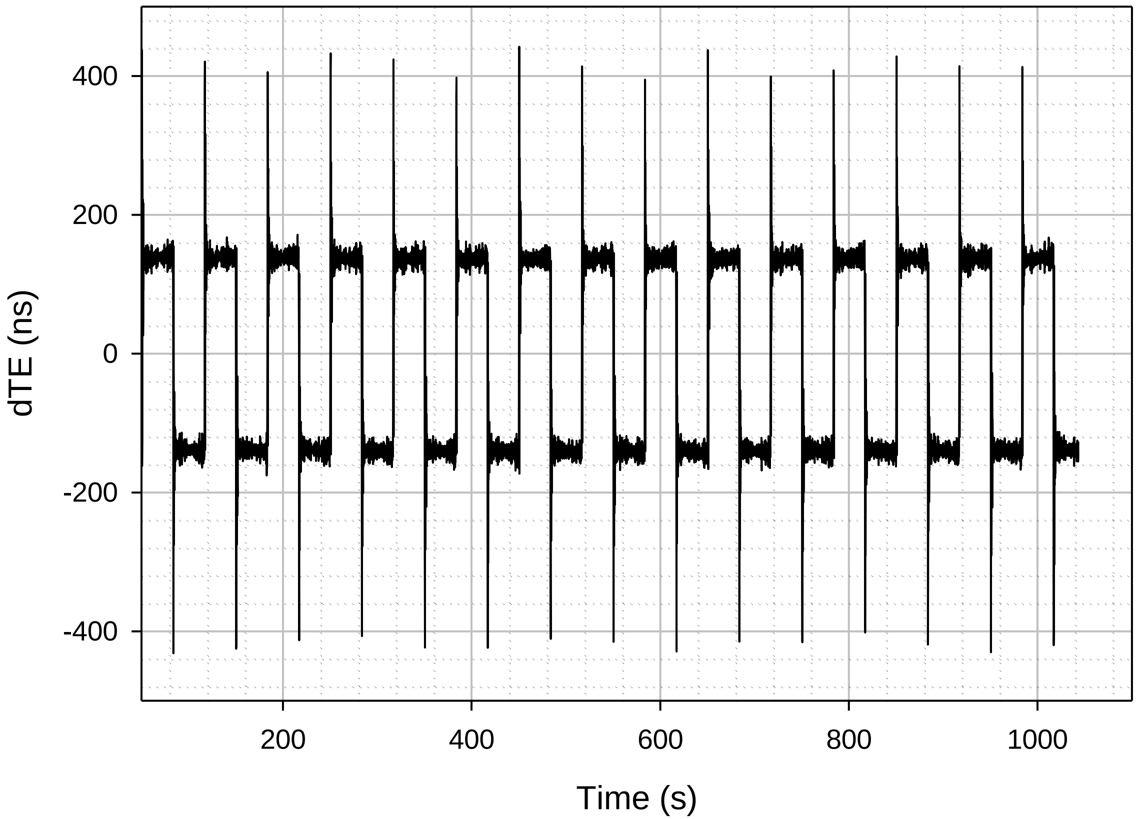
Case 2 – Measured Frequency Offset, Node 50

Case 2, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms



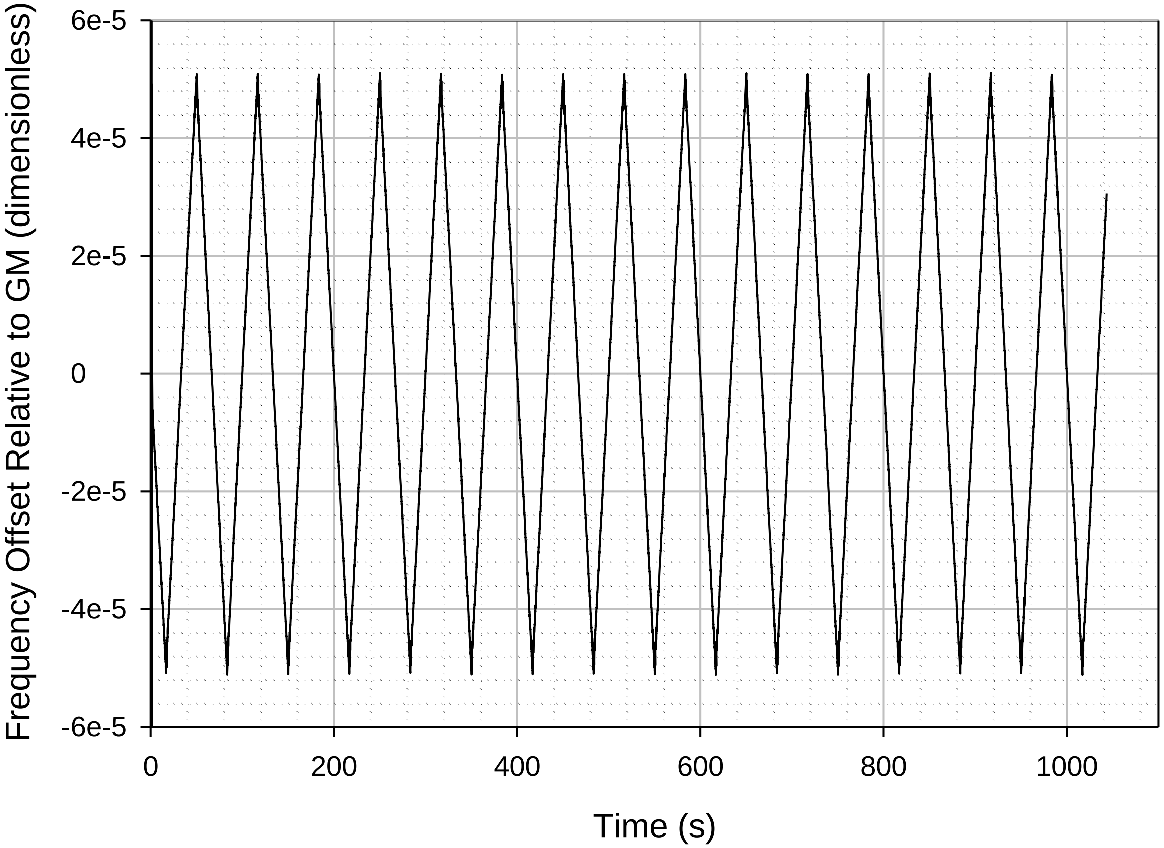
Case 2 – dTE, Node 100

Case 2, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms
First 50 s omitted to eliminate any startup transient



Case 2 – Measured Frequency Offset, Node 100

Case 2, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms



Case 2 – Discussion of Results – 1

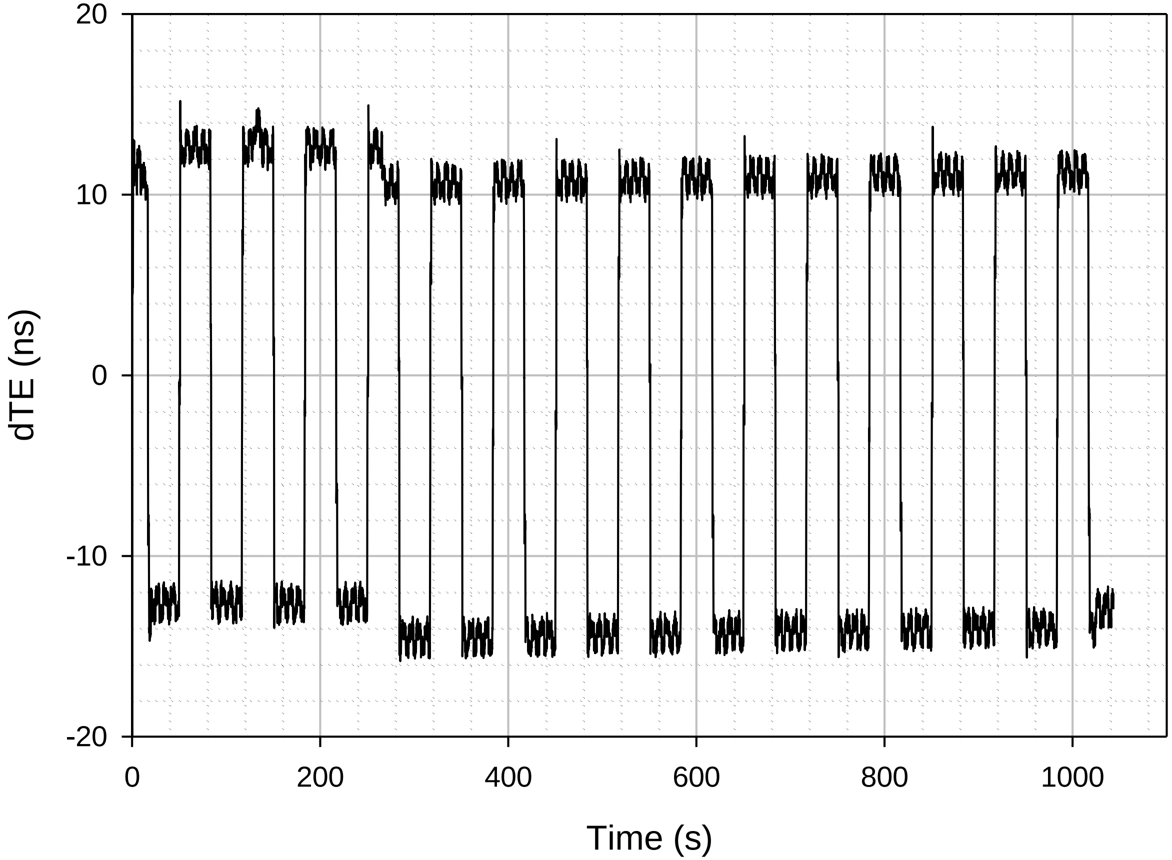
- As in case 1, dTE accumulates with increasing number of hops, though now the square-wave pattern remains visible due to fixed residence time and smaller gain peaking
- Also as in case 1, error in measured frequency offset increases with increasing hop number, though error is less than in case 1; maximum measured frequency offset is approximately 51 ppm after 100 hops
- Results at node 2 are almost the same as in case 1; this is because cases 1 and 2 differ in the residence time, which has no impact at the node 2 ingress

Case 2 - Discussion of Results - 2

- Overshoot in dTE at square-wave transitions is evident after 50 hops, and even more so at 100 hopes
- dTE detail for 115 – 125 s, at node 50, clearly shows overshoot and ringing (i.e., damped oscillations) at square-wave transition
    - This implies that the effective damping ratio for the transfer function that relates computed synchronized time at a PTP Instance and the input syncEventIngressTimestamp, due to the rateRatio measurement, is less than 1 (and likely less than 0.5, though analysis is needed to determine its exact value)
    - The gain peaking is ***not*** due to the endpoint filter; comparison of the results for dTE before and after the endpoint filter shows that the endpoint filter smooths the shorter-term noise, but has negligible effect on the longer-term ringing oscillations
    - The endpoint filter bandwidth is 2.6 Hz, which corresponds to a time constant of approximately 0.06 s, while the ringing oscillations have a period that exceeds 0.4 s, i.e., almost 10 times as large as the endpoint filter time constant

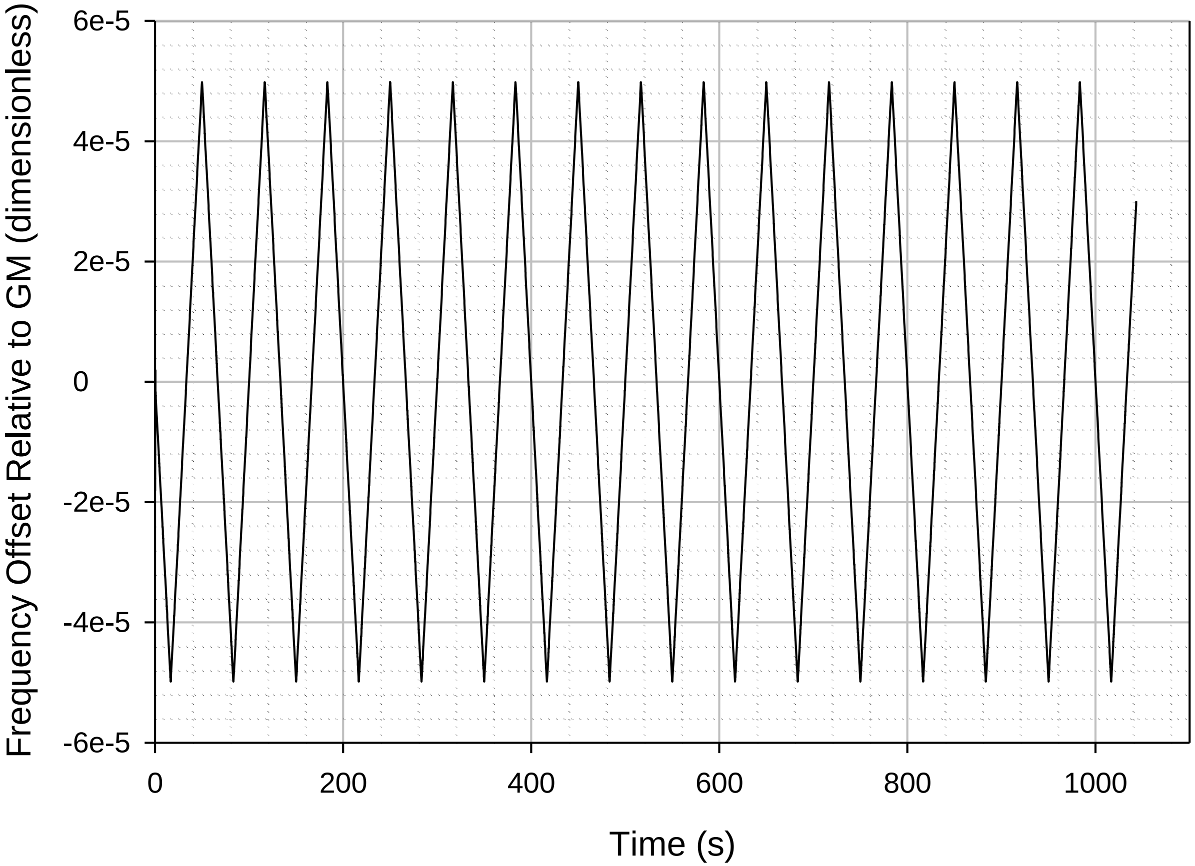
Case 3 - dTE, Node 2

Case 3, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms



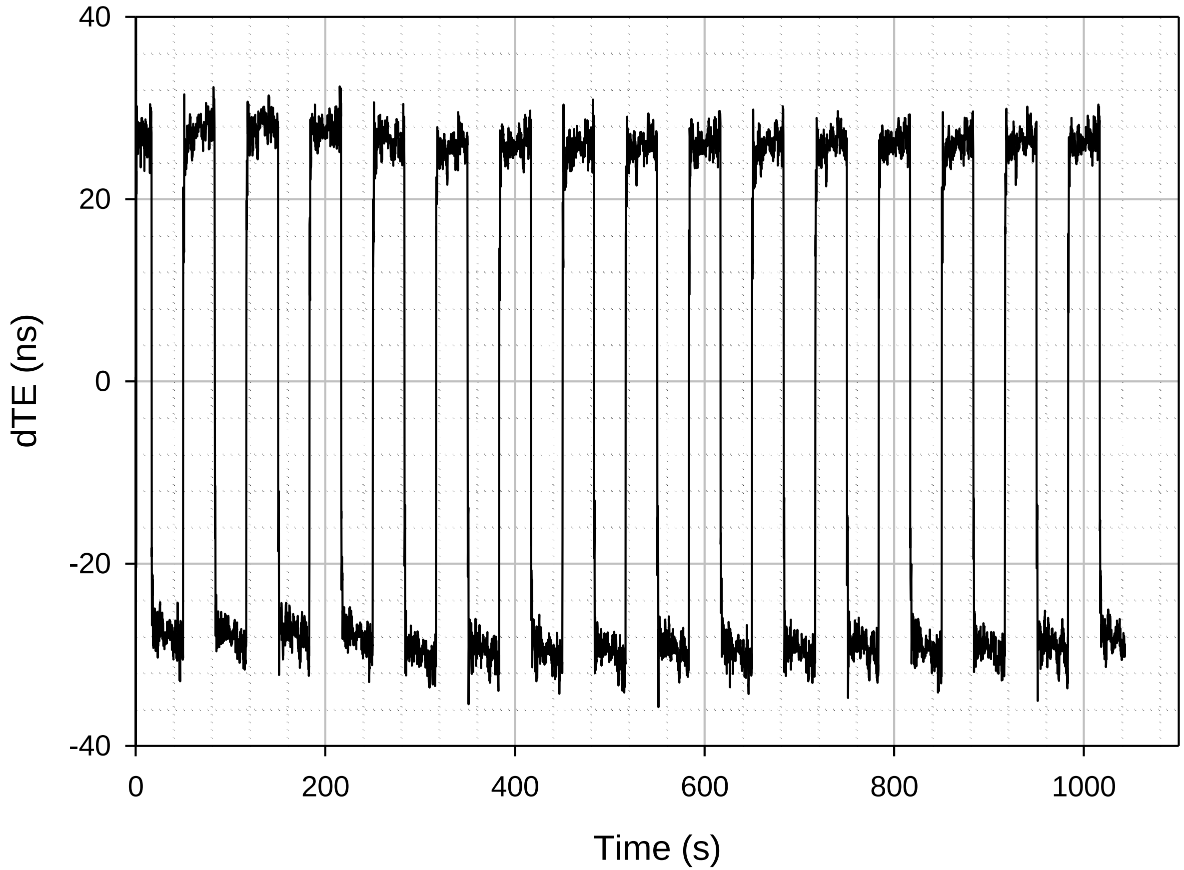
Case 3 - Measured Frequency Offset, Node 2

Case 3, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms



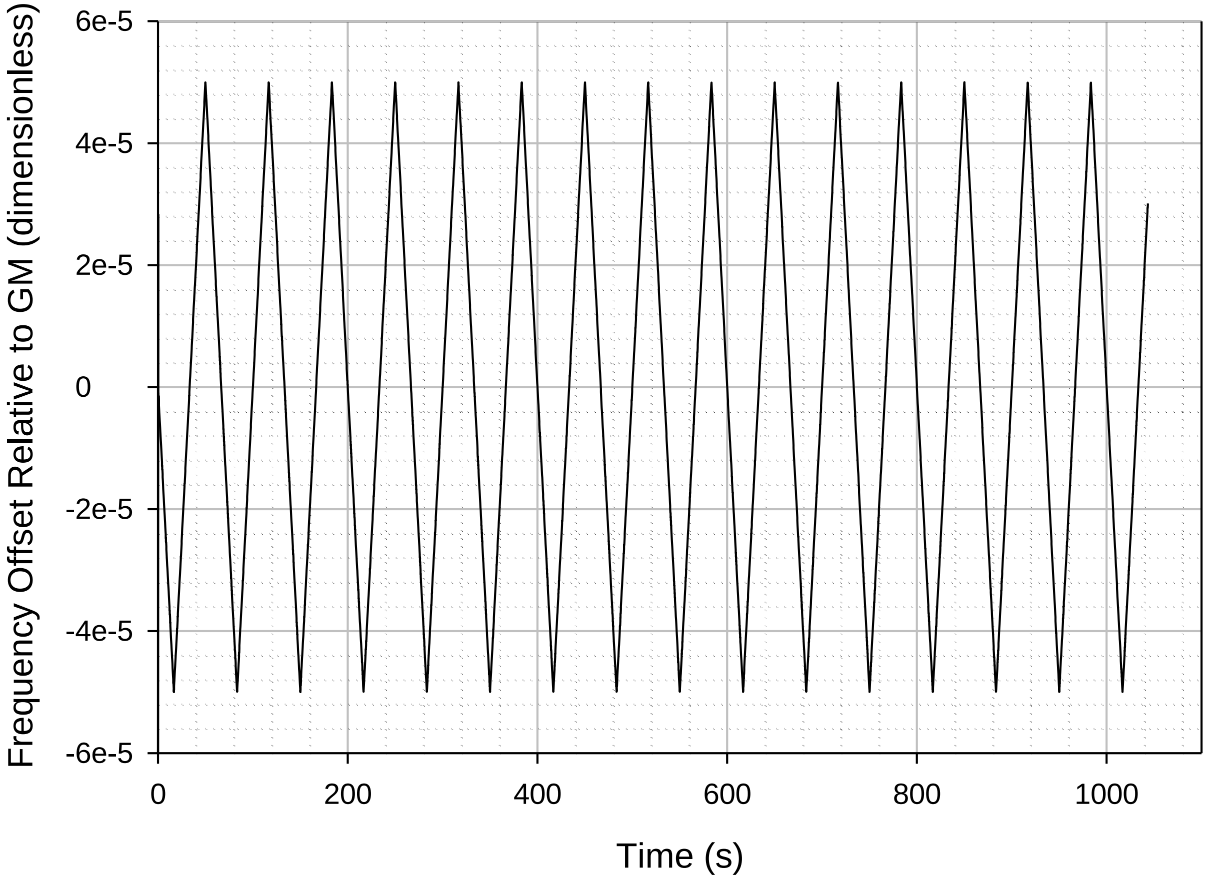
Case 3 - dTE, Node 50

Case 3, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms

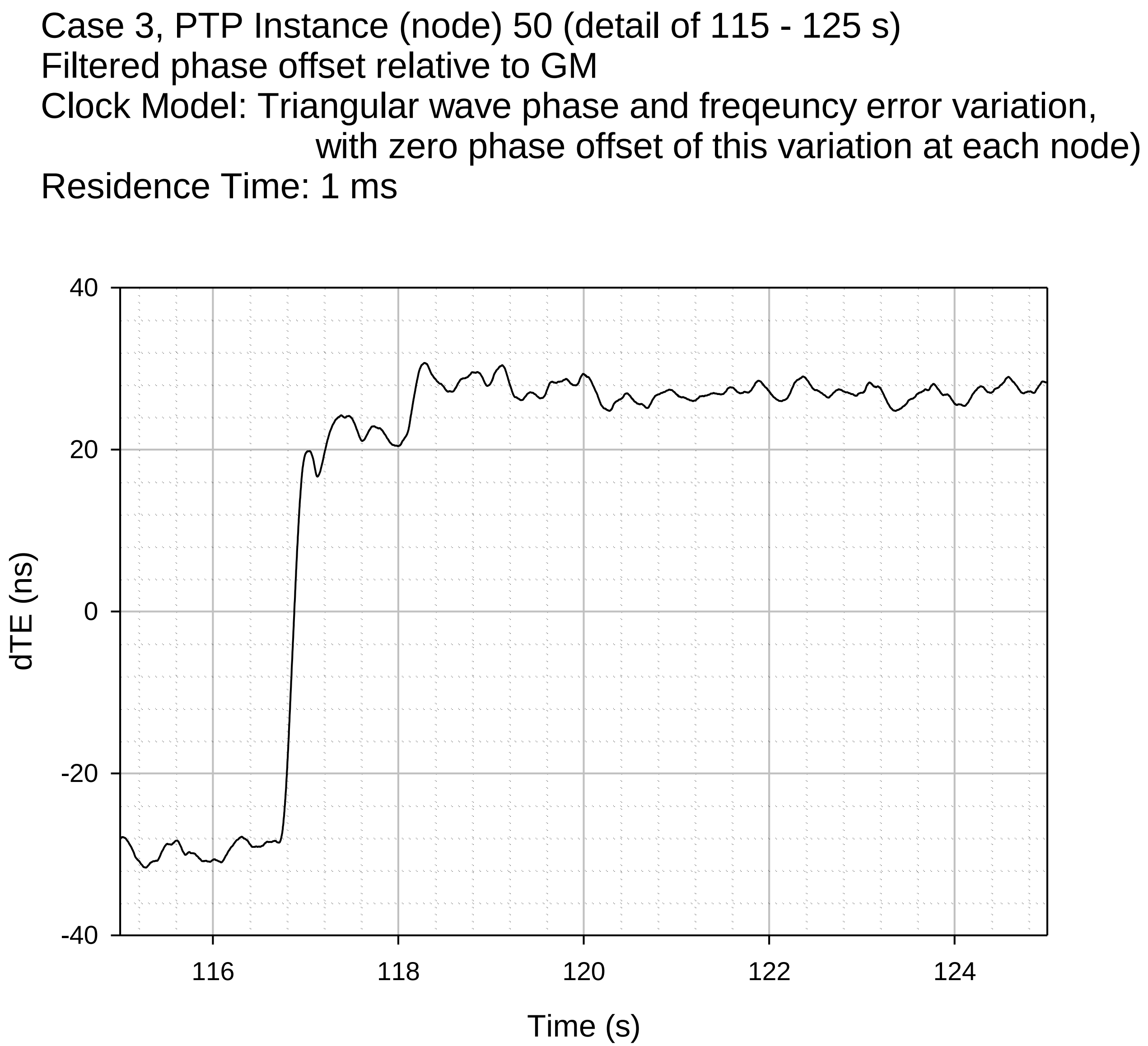


Case 3 - Measured Frequency Offset, Node 50

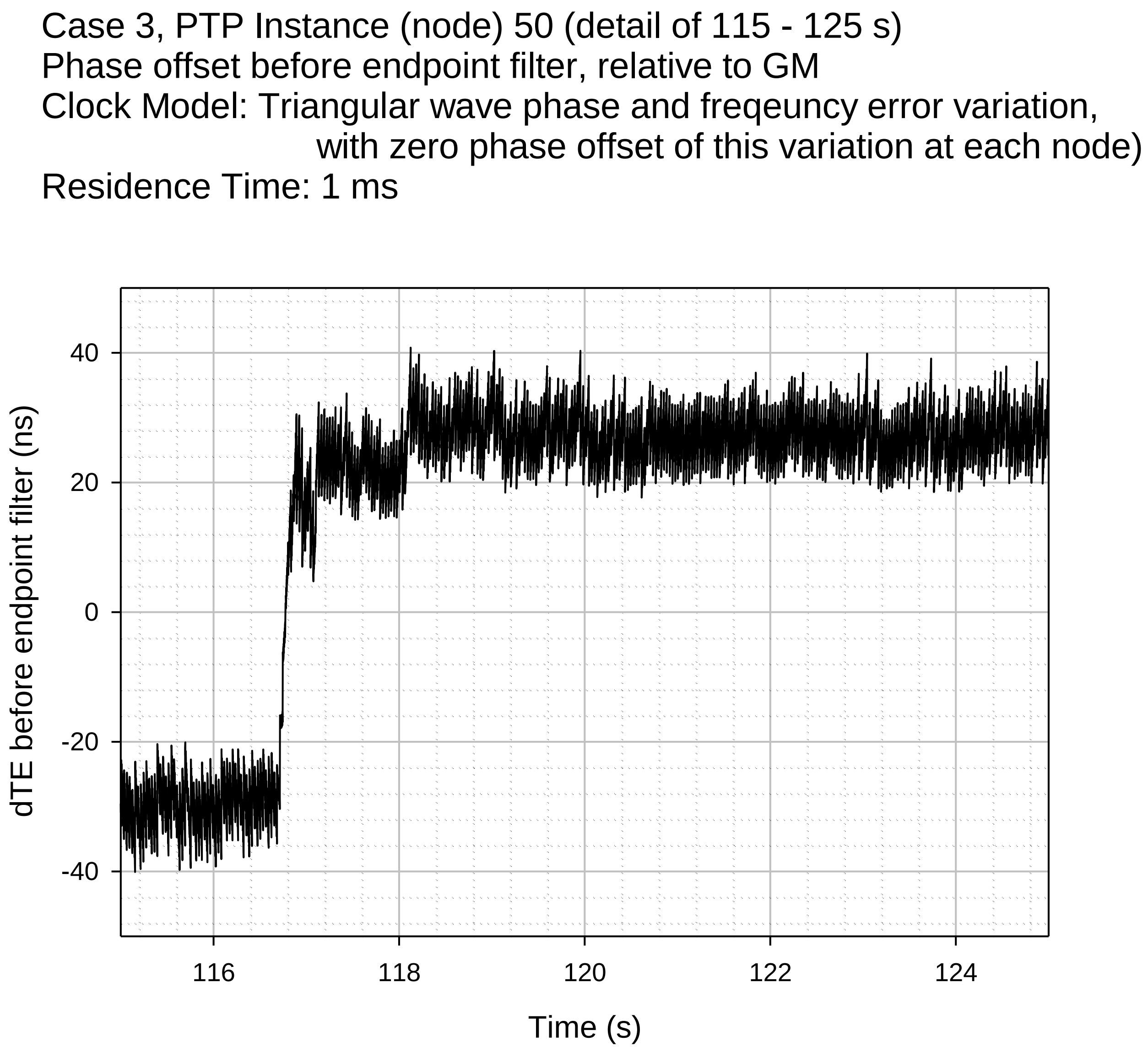
Case 3, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms



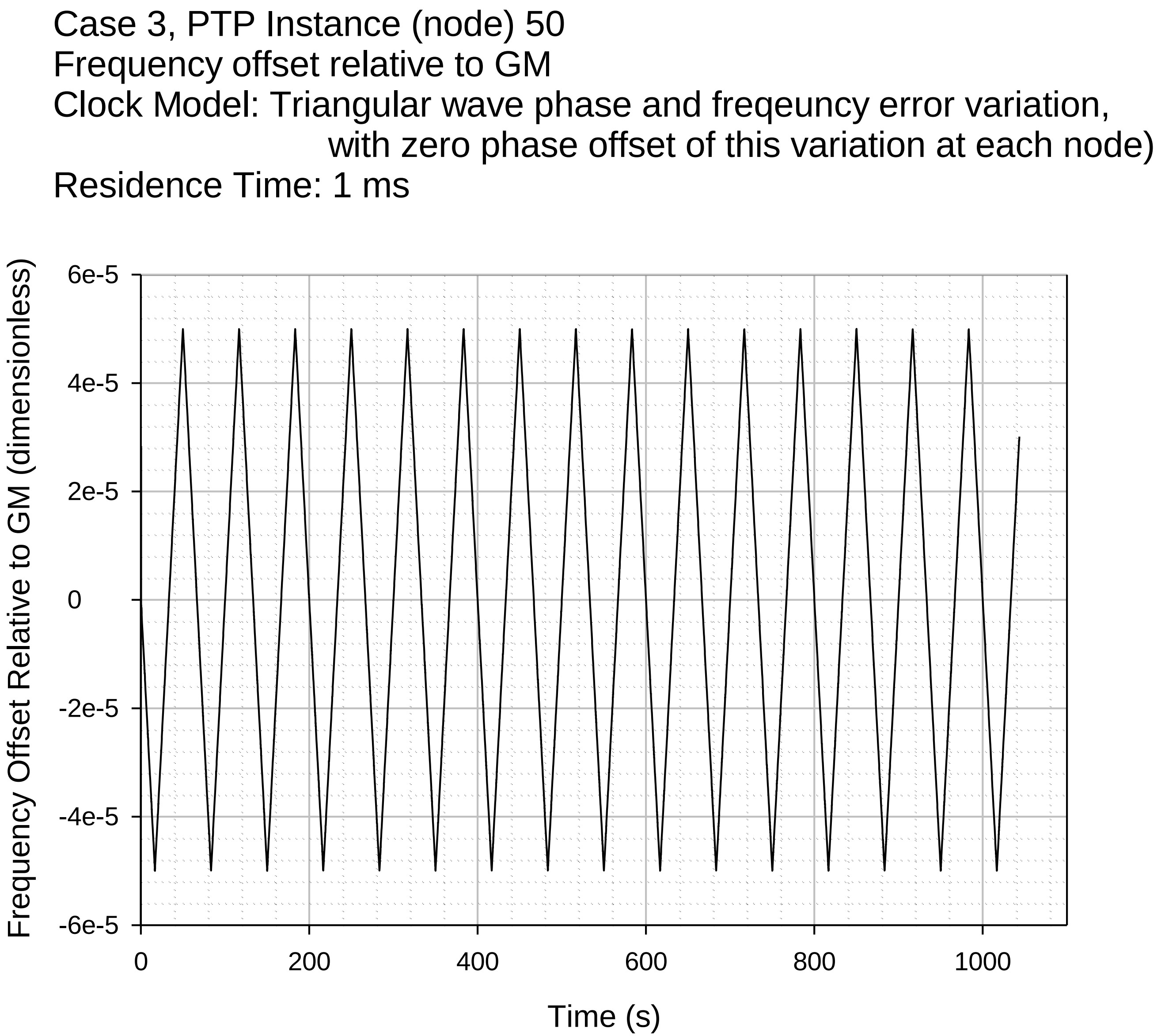
Case 3 - dTE, Node 50 (detail of 115 - 125 s)



Case 3 – dTE before Endpoint Filtering, Node 50 (detail of 115 - 125 s)

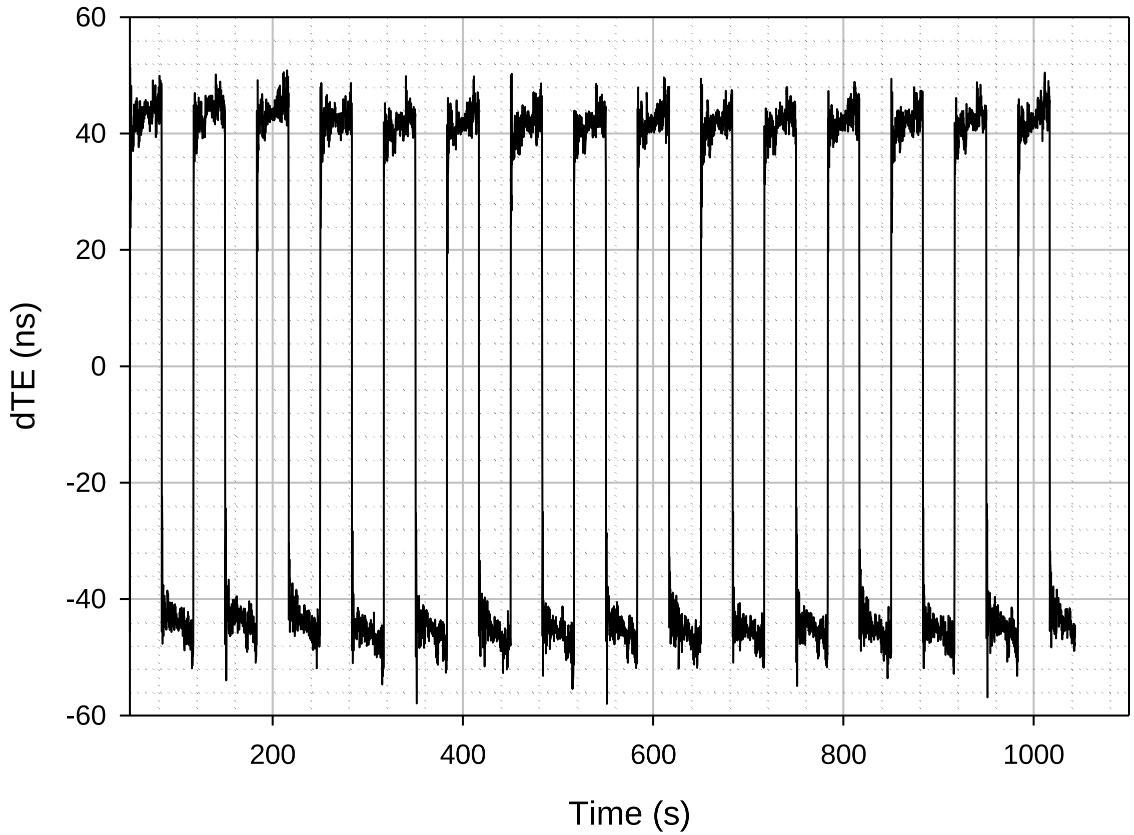


Case 3 – Measured Frequency Offset, Node 50



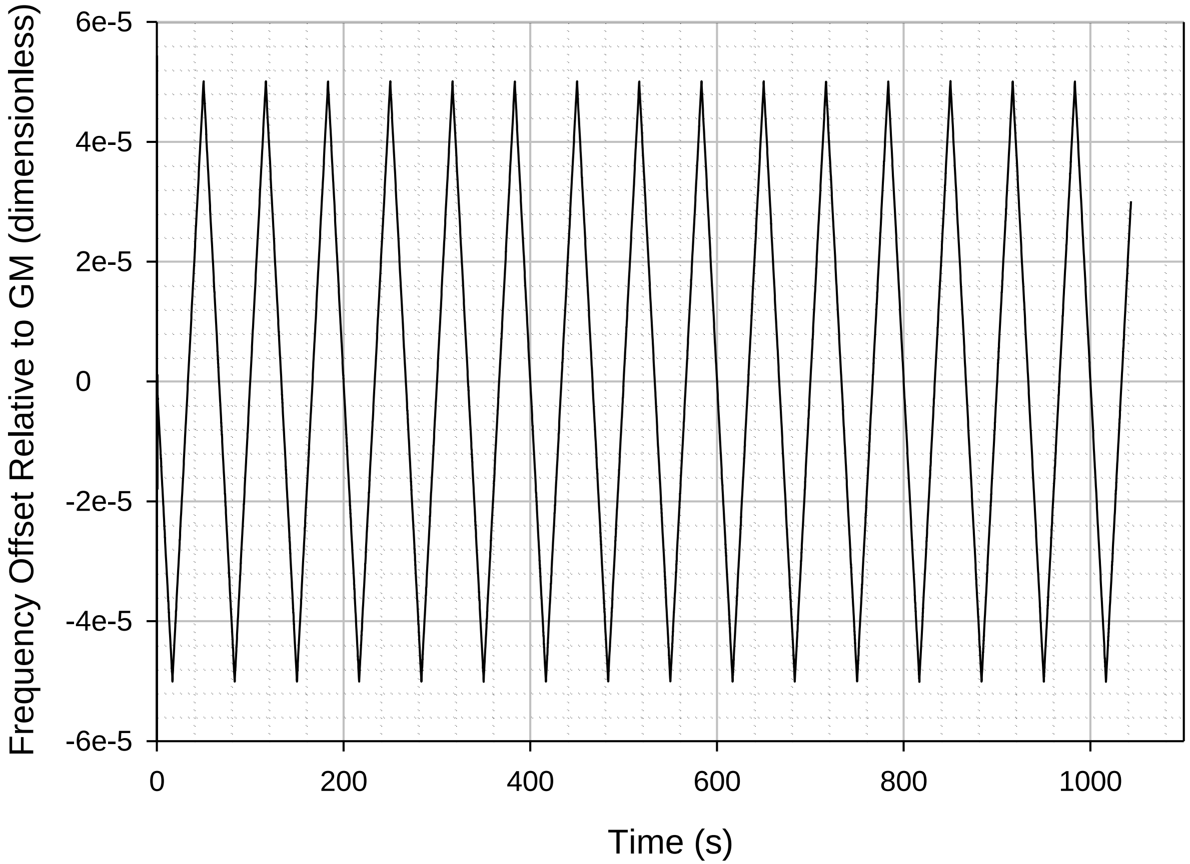
Case 3 – dTE, Node 100

Case 3, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms
First 50 s omitted to eliminate any startup transient



Case 3 - Measured Frequency Offset, Node 100

Case 3, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms

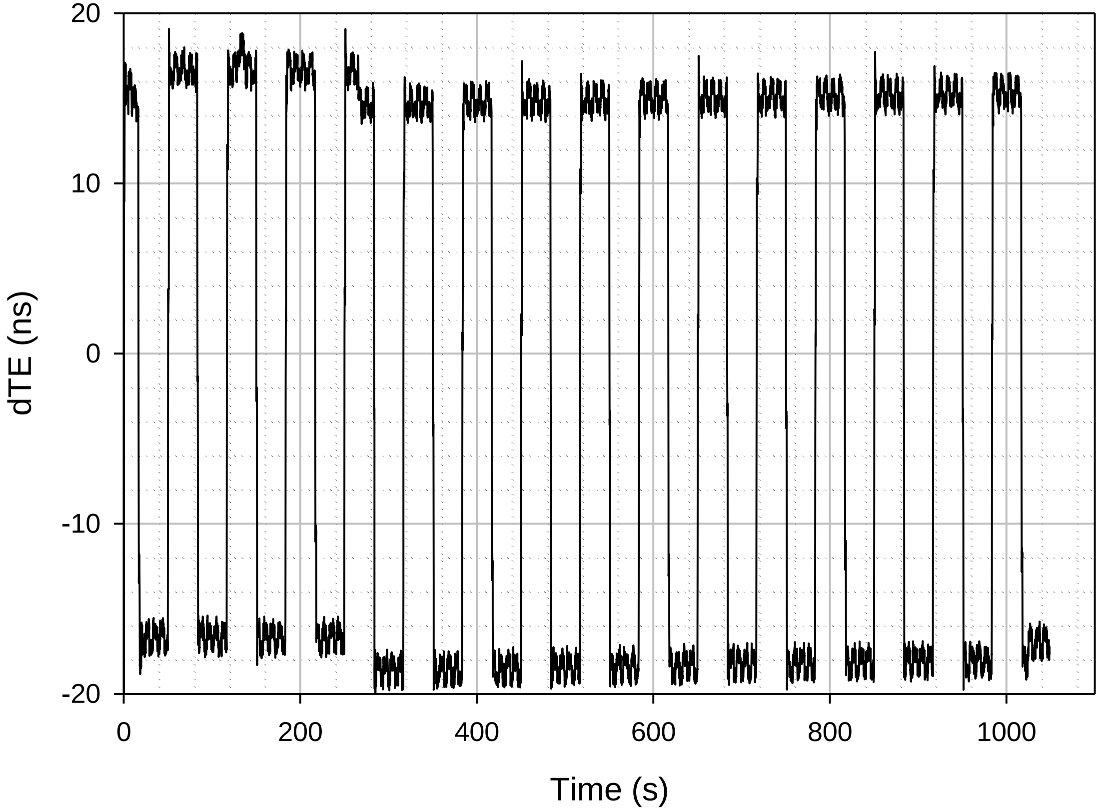


Case 3 - Discussion

- As in cases 1 and 2, dTE accumulates with increasing number of hops, though now the square-wave pattern remains more visible and smaller overshoot due to fixed residence time and still smaller gain peaking
  - As in case 2, detail of 115 – 125 s shows that endpoint filter smooths the shorter-term noise, but has negligible effect on the longer-term ringing oscillations
- Any accumulated error in frequency measurement is not discernable on the scale of the plots
- Results at node 2 are almost the same as in cases 1 and 2; this is because cases 1, 2, and 3 differ in the residence time, which has no impact at the node 2 ingress

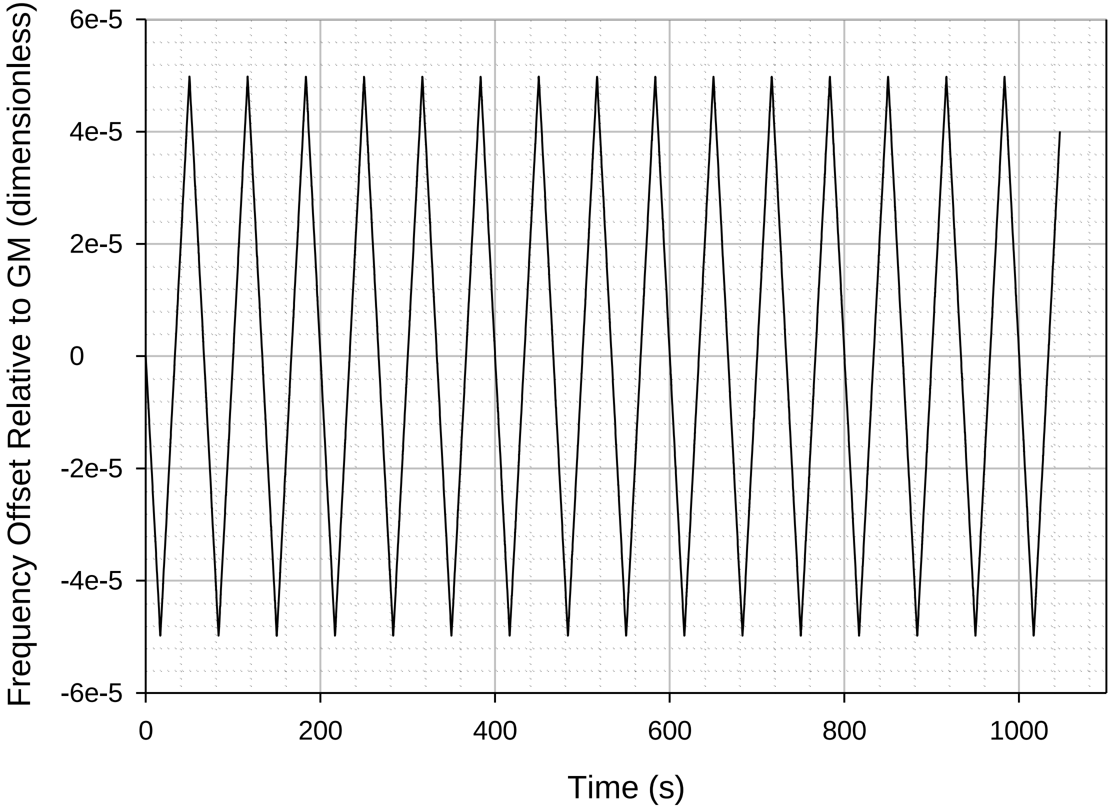
Case 4 - dTE, Node 2

Case 4, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median



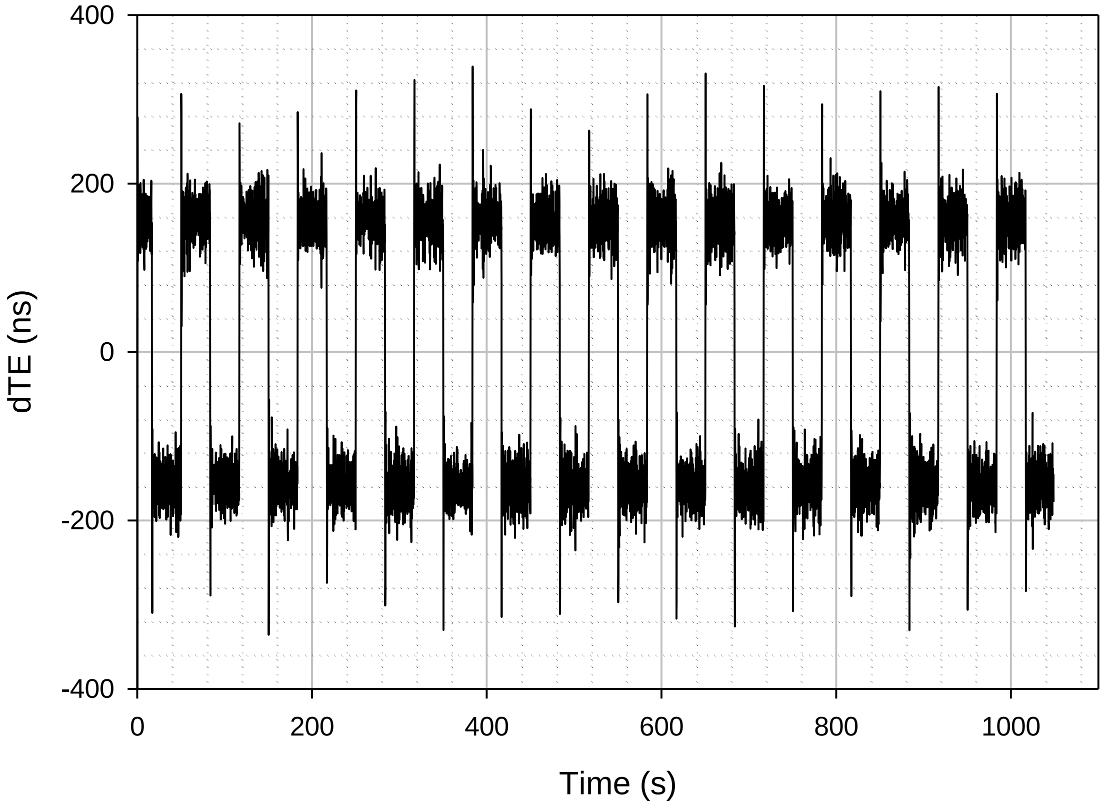
Case 4 – Measured Frequency Offset, Node 2

Case 4, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median



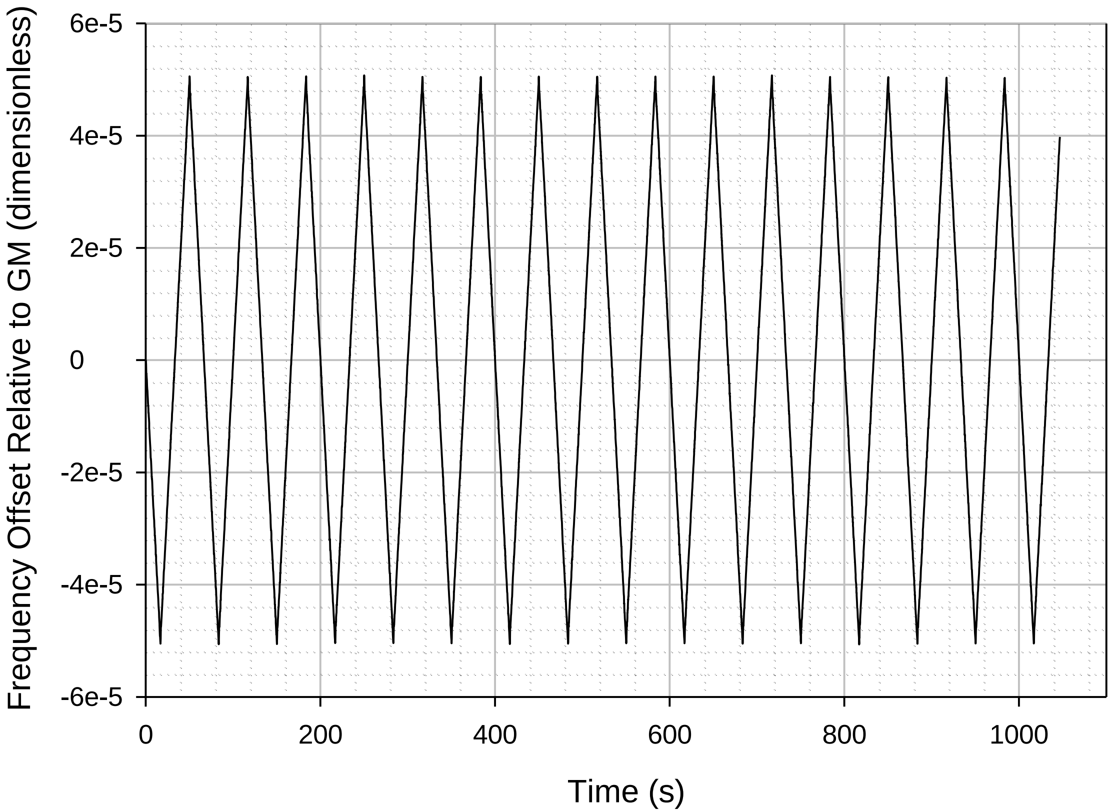
Case 4 – dTE, Node 50

Case 4, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median

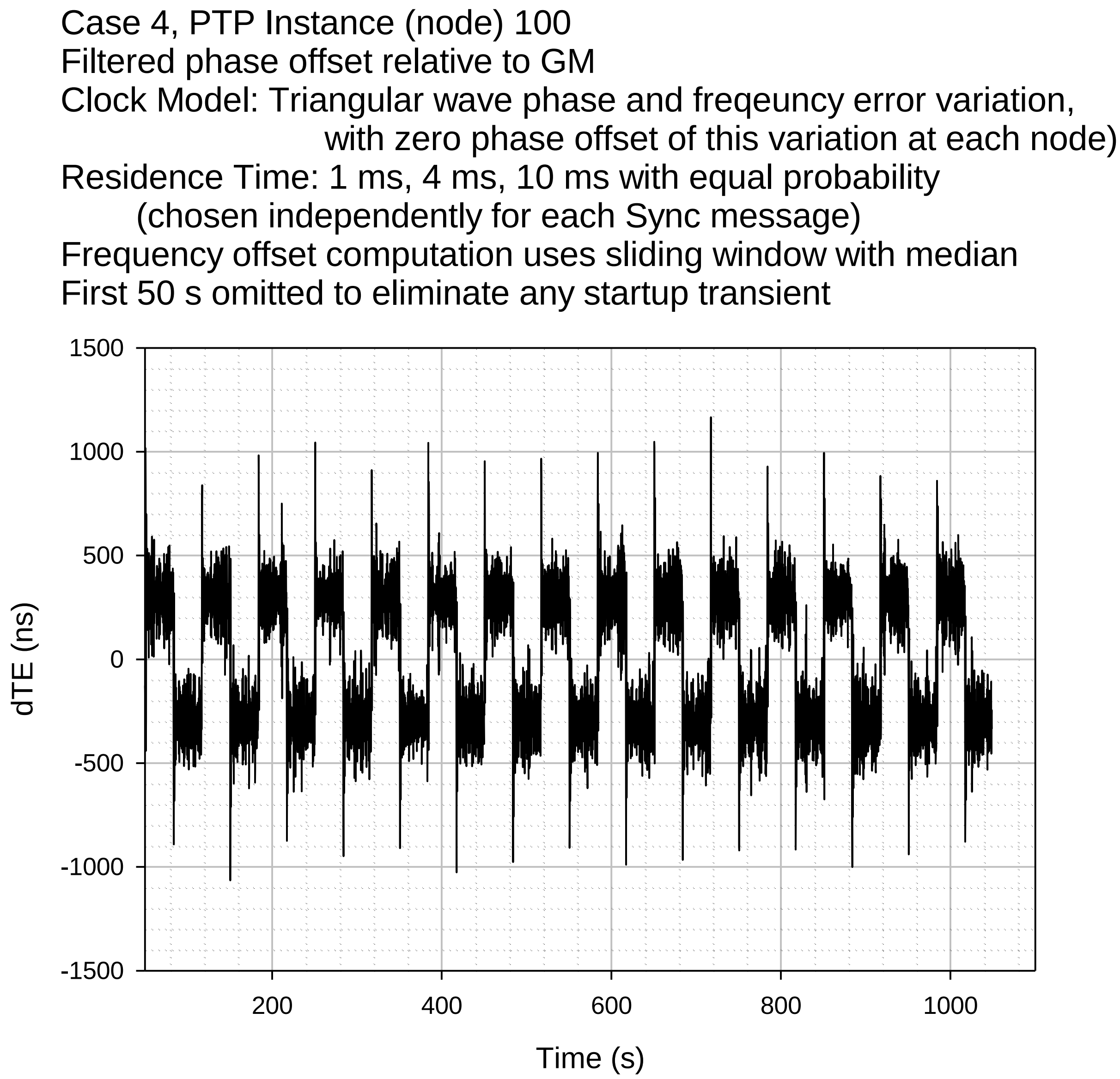


Case 4 - Measured Frequency Offset, Node 50

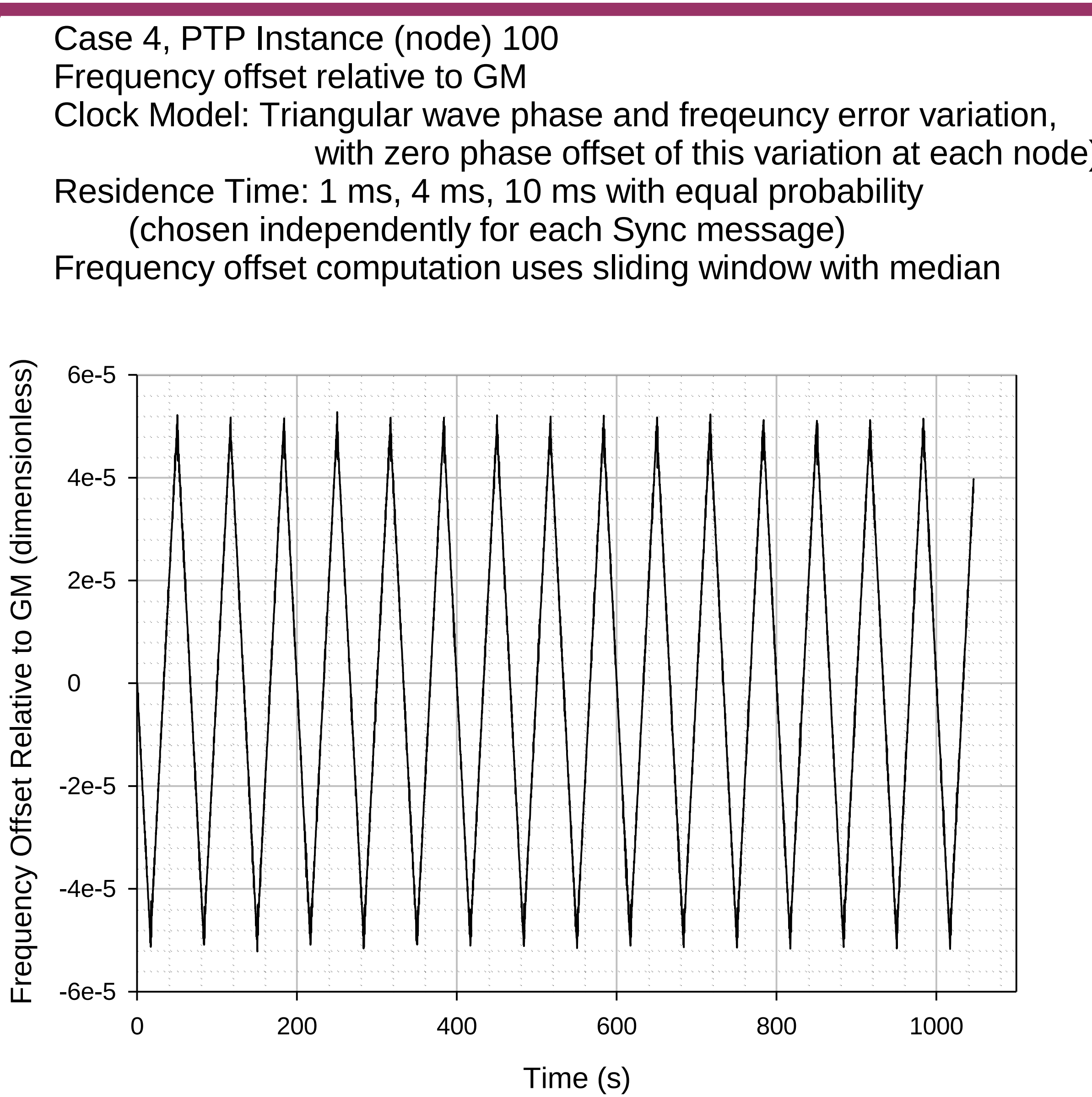
Case 2, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median



Case 4 - dTE, Node 100

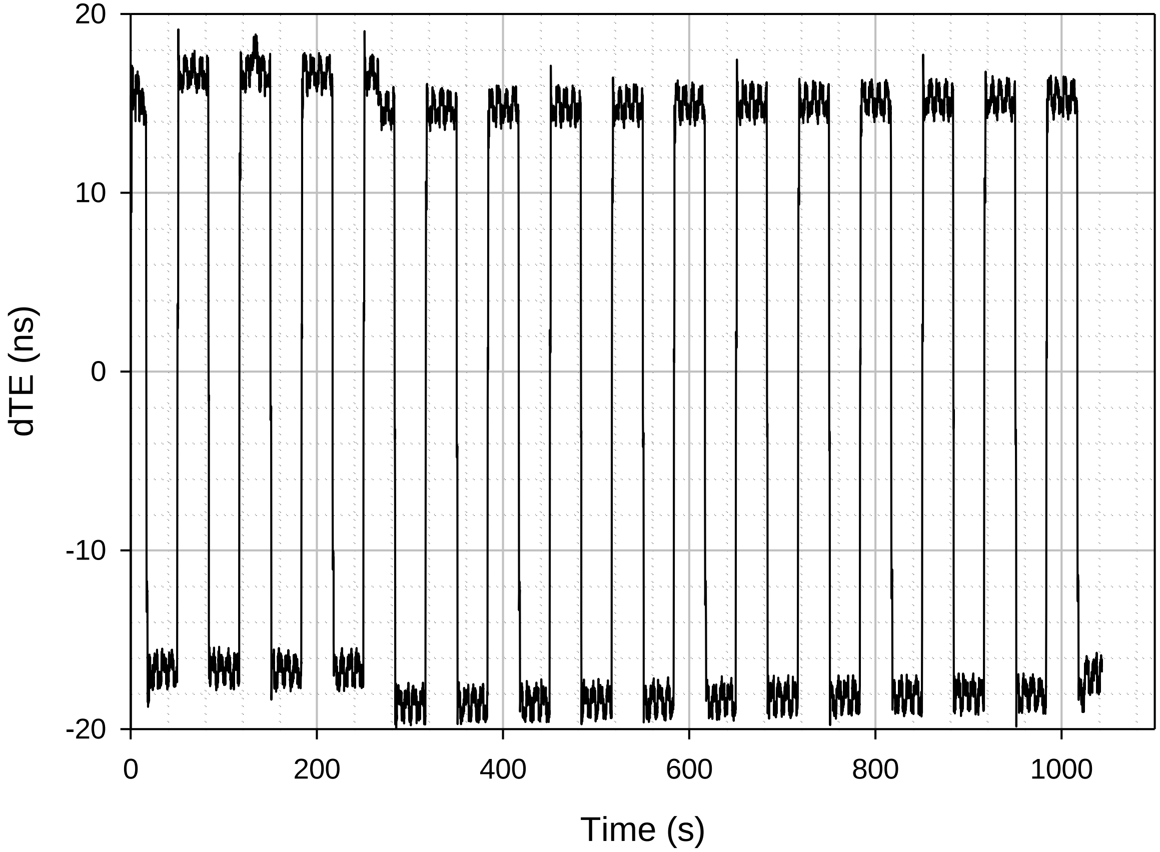


Case 4 – Measured Frequency Offset, Node 100



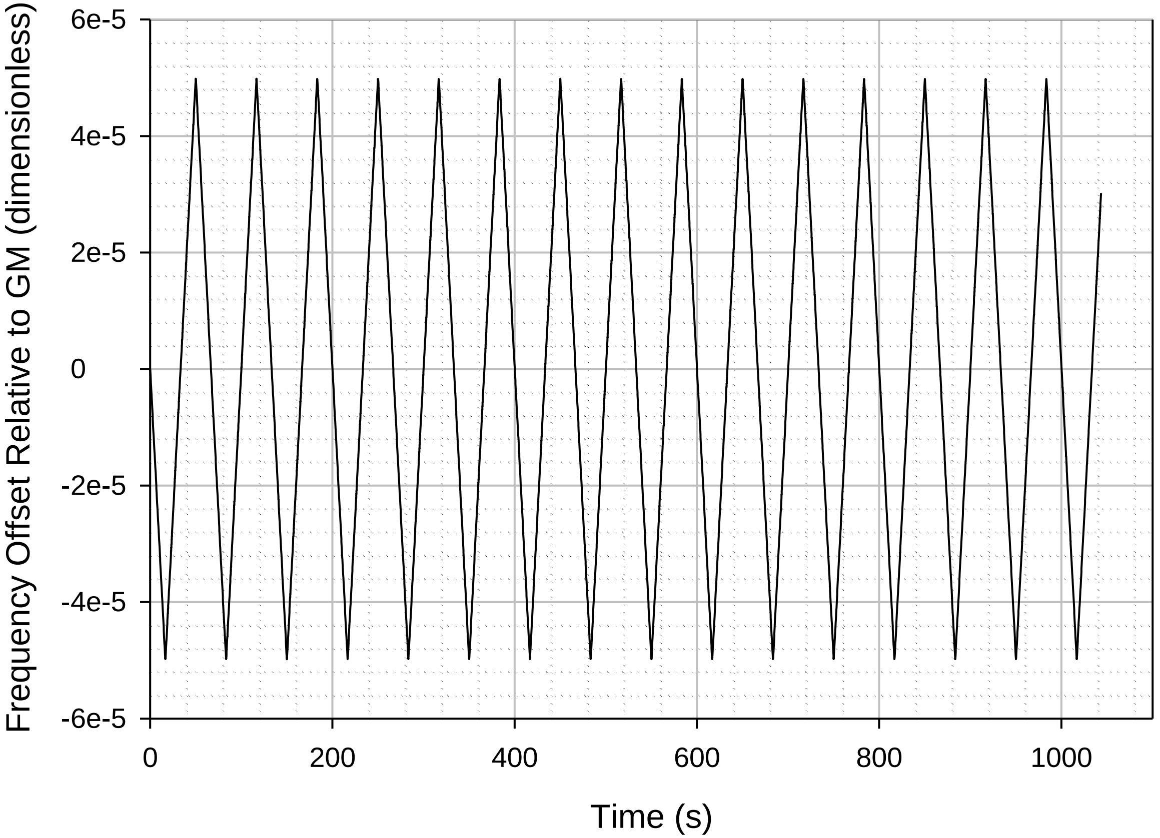
Case 5 - dTE, Node 2

Case 5, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median



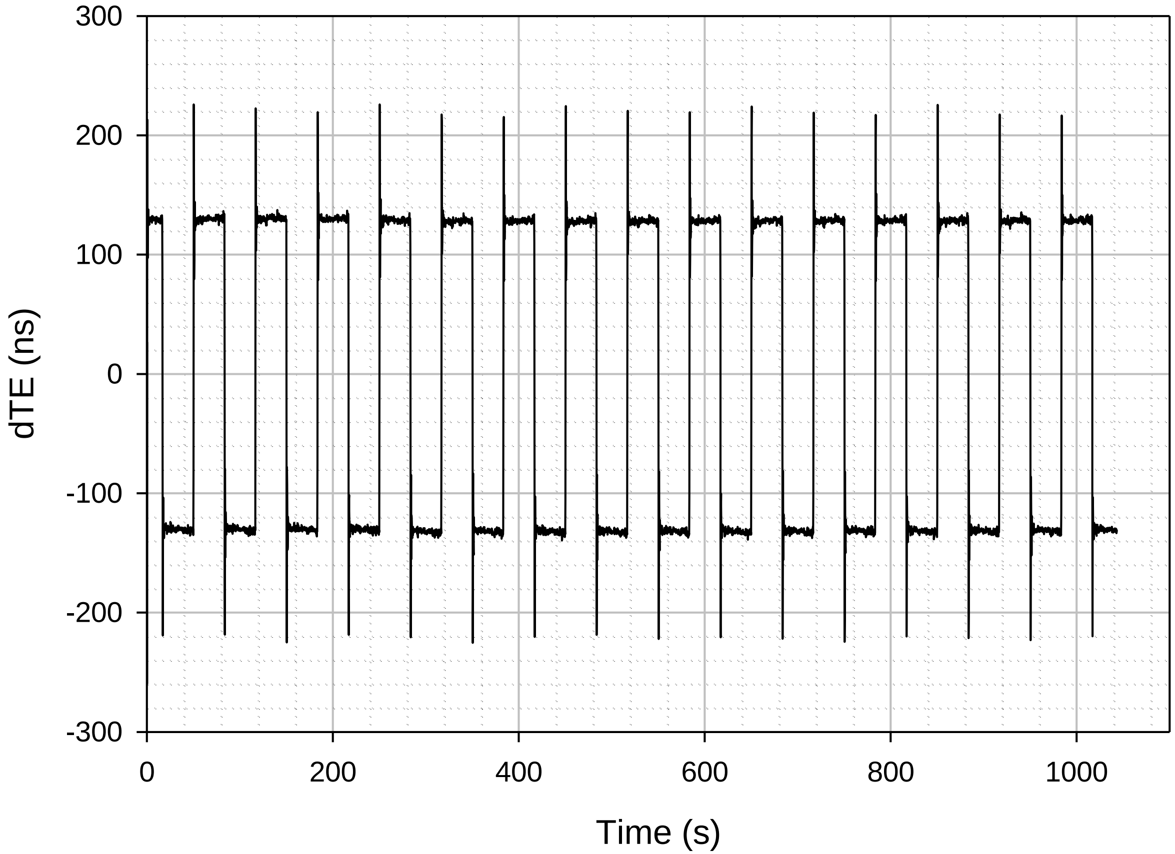
Case 5 - Measured Frequency Offset, Node 2

Case 5, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median



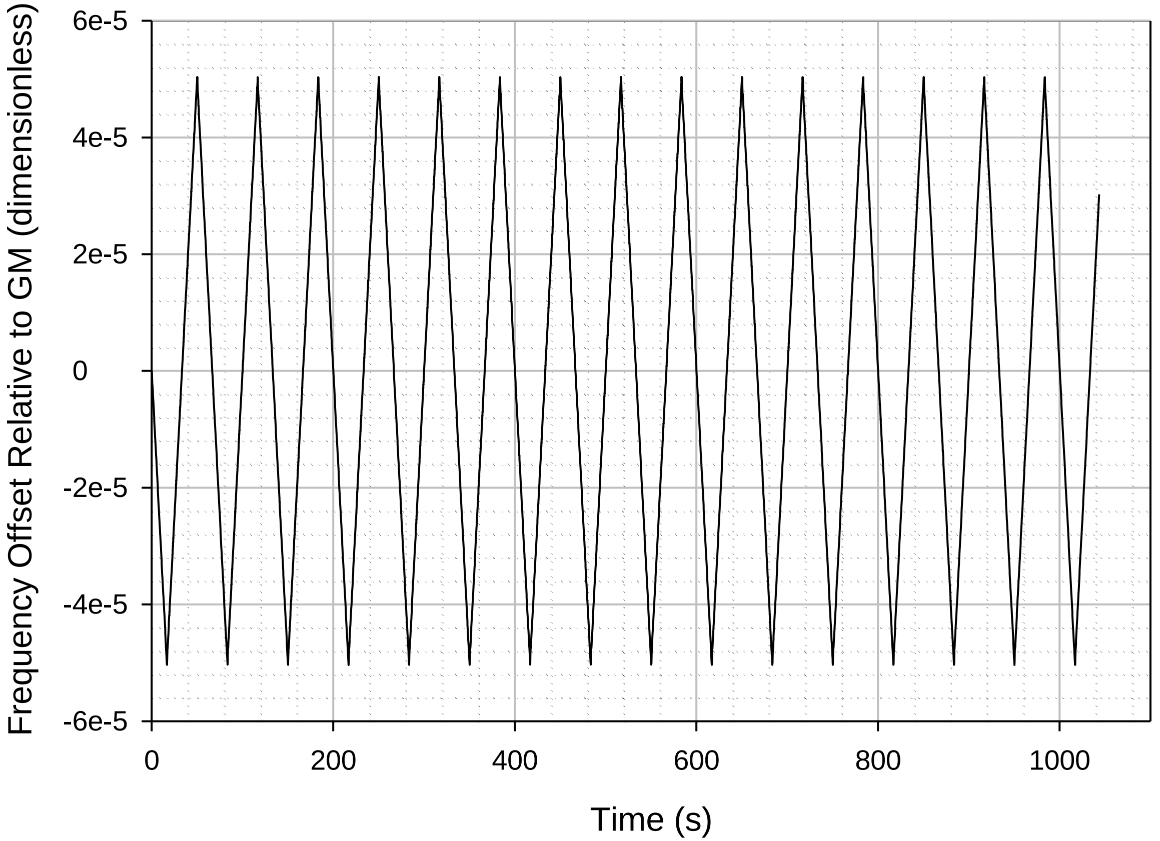
Case 5 – dTE, Node 50

Case 5, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median



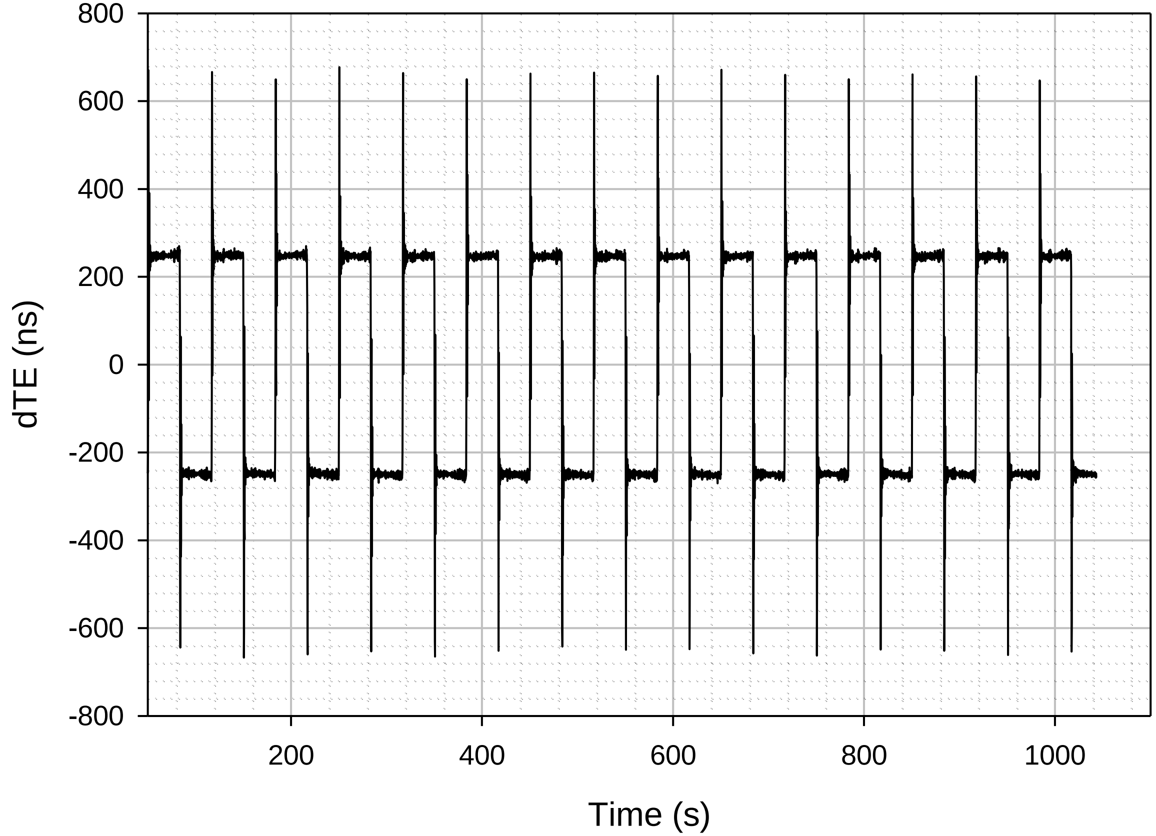
Case 5 – Measured Frequency Offset, Node 50

Case 5, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median



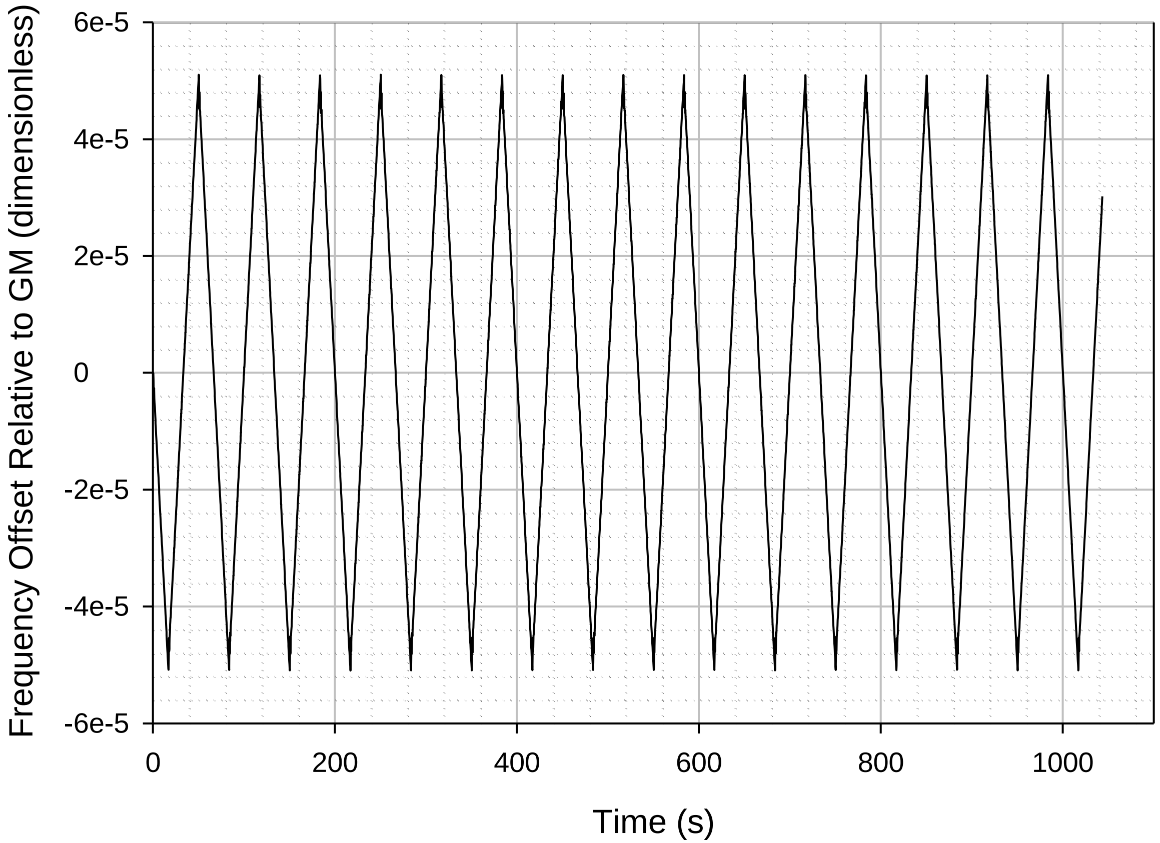
Case 5 - dTE, Node 100

Case 5, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient

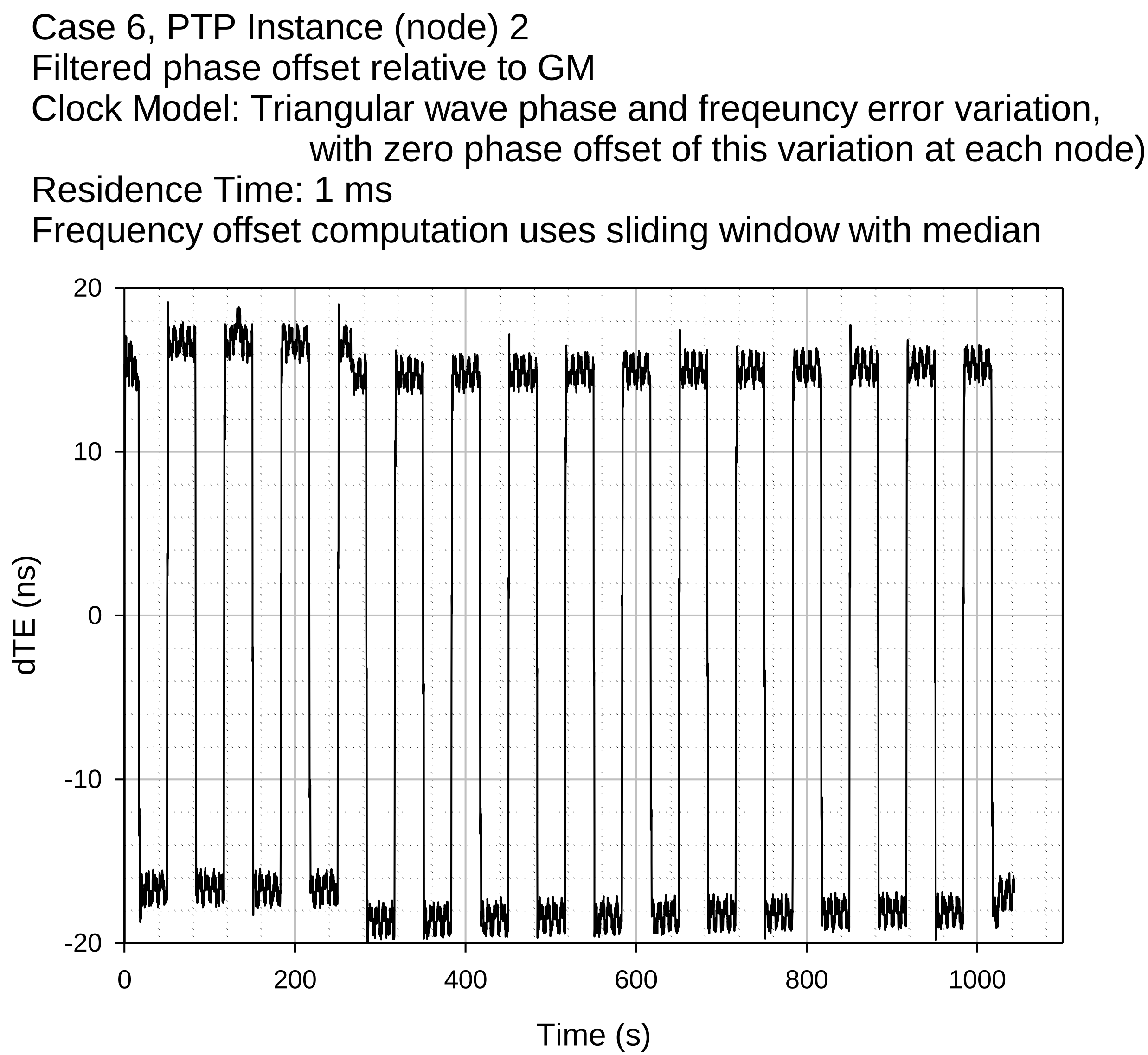


Case 5 - Measured Frequency Offset, Node 100

Case 5, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median

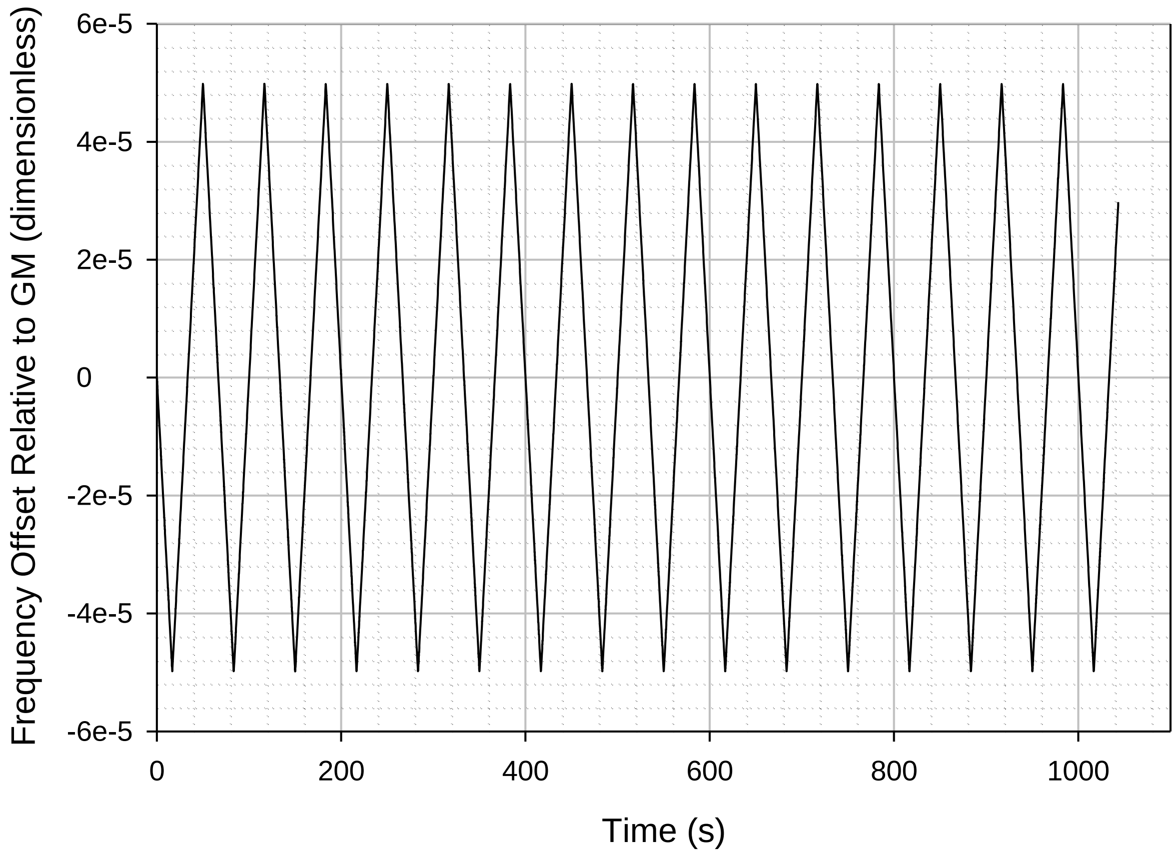


Case 6 - dTE, Node 2



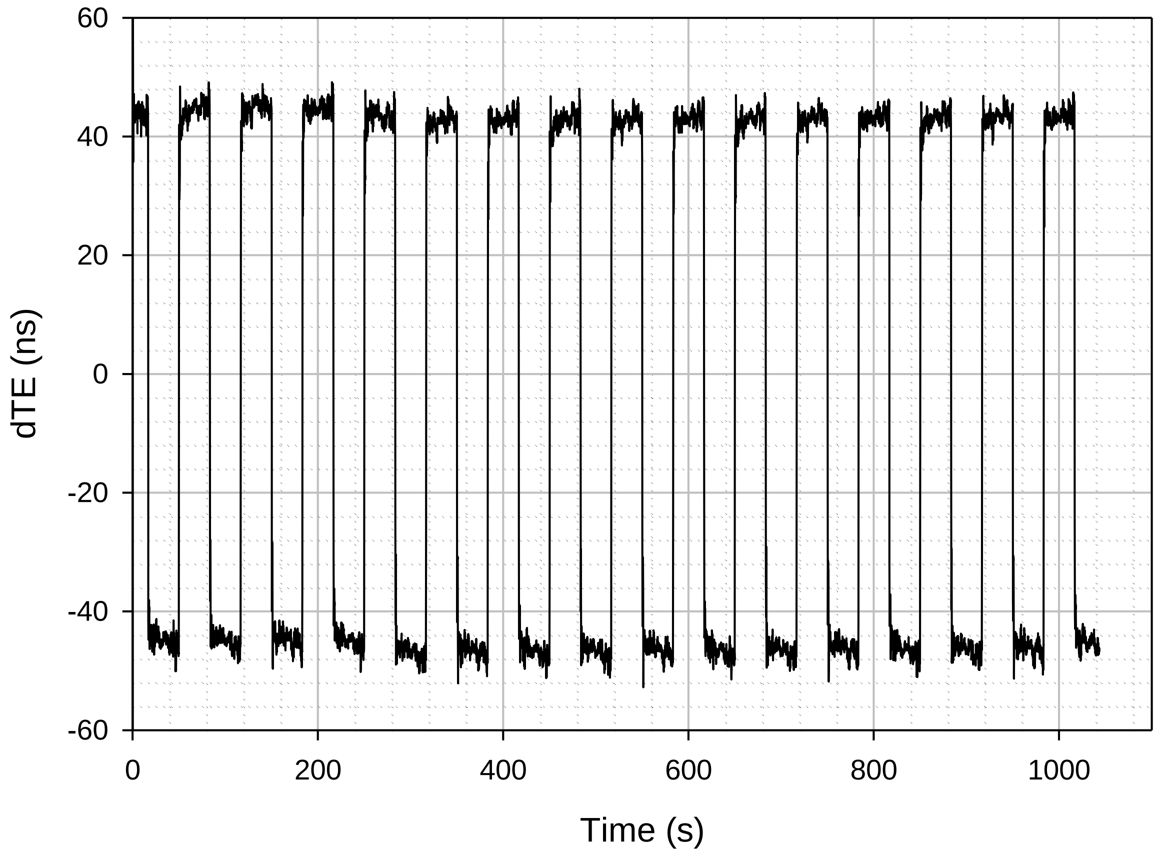
Case 6 – Measured Frequency Offset, Node 2

Case 6, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median



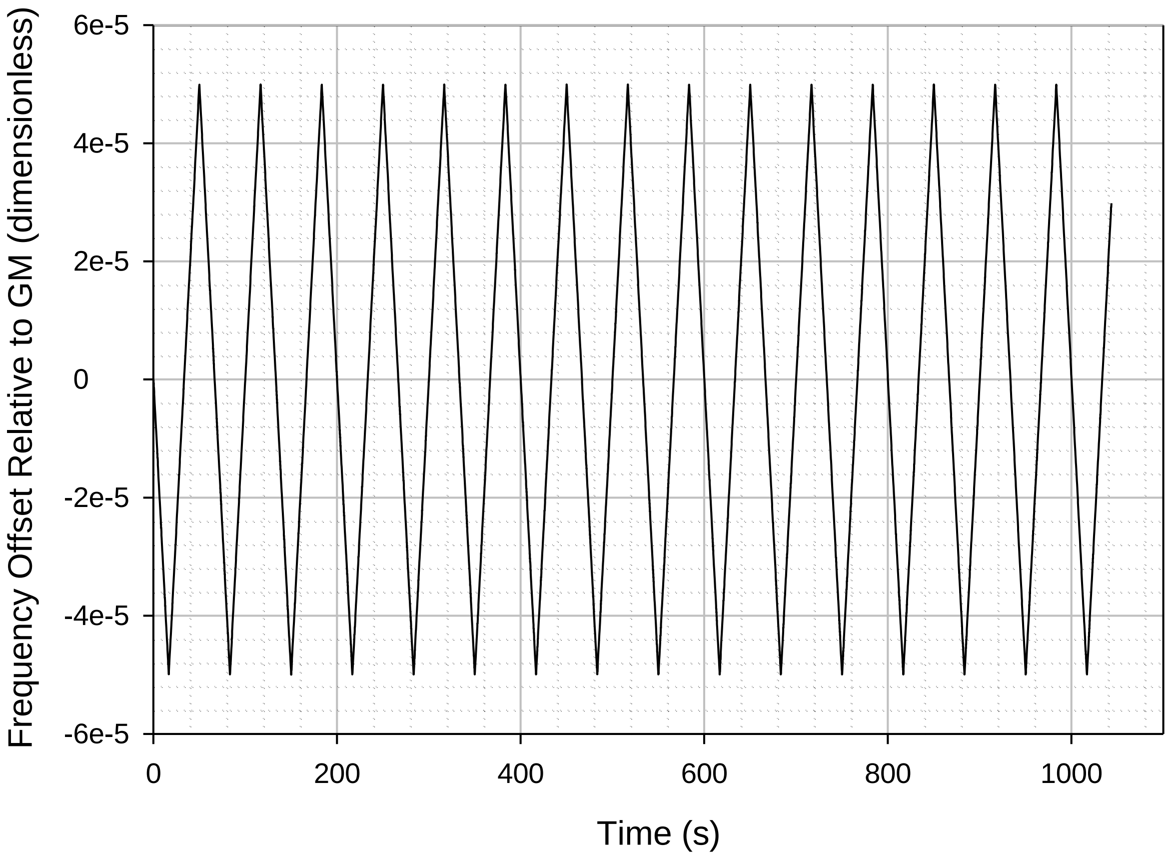
Case 6 - dTE, Node 50

Case 6, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median



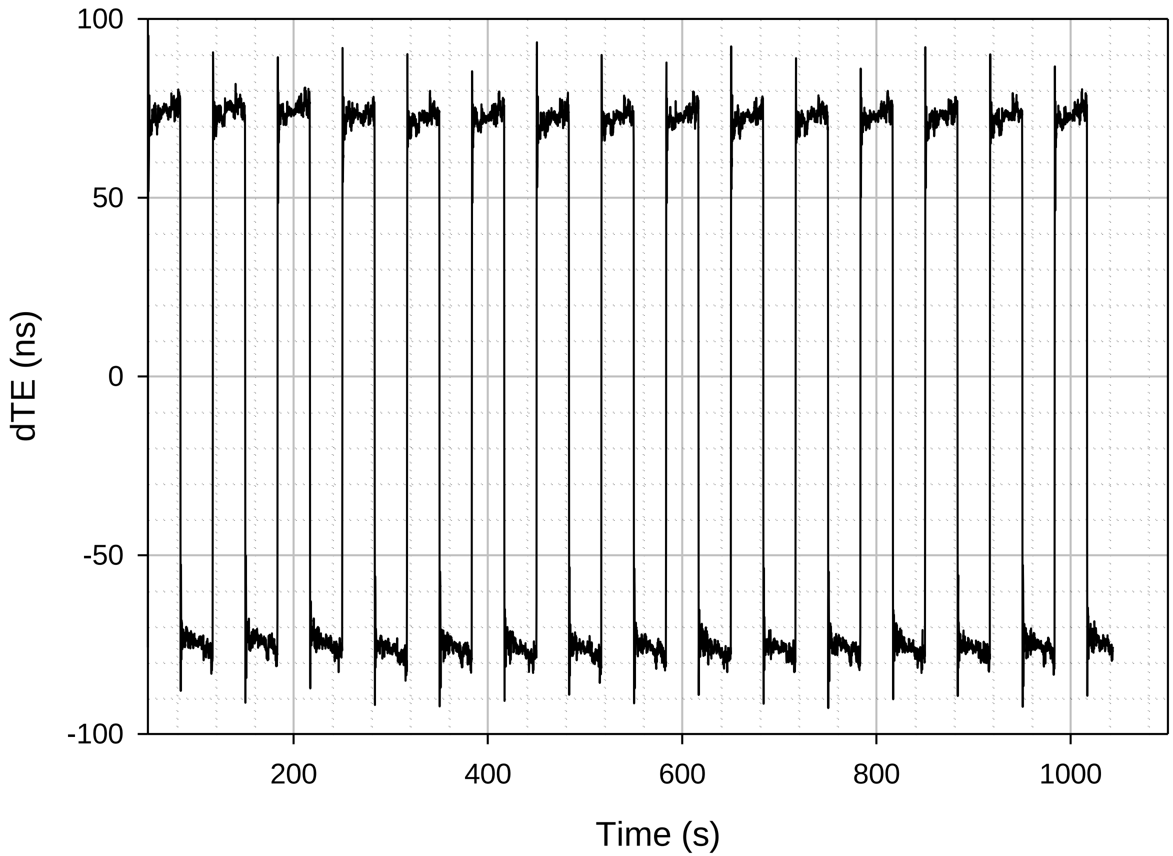
Case 6 – Measured Frequency Offset, Node 50

Case 6, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median



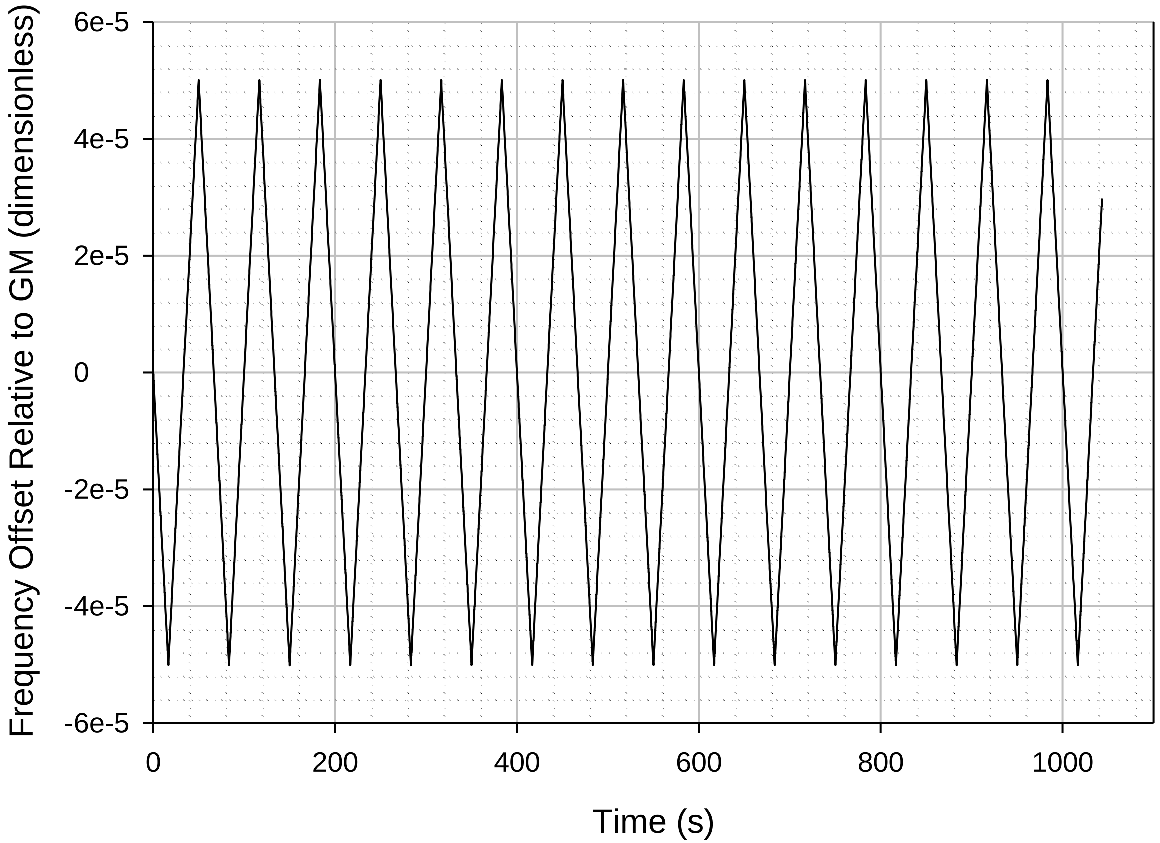
Case 6 - dTE, Node 100

Case 6, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



Case 6 – Measured Frequency Offset, Node 100

Case 6, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with zero phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median

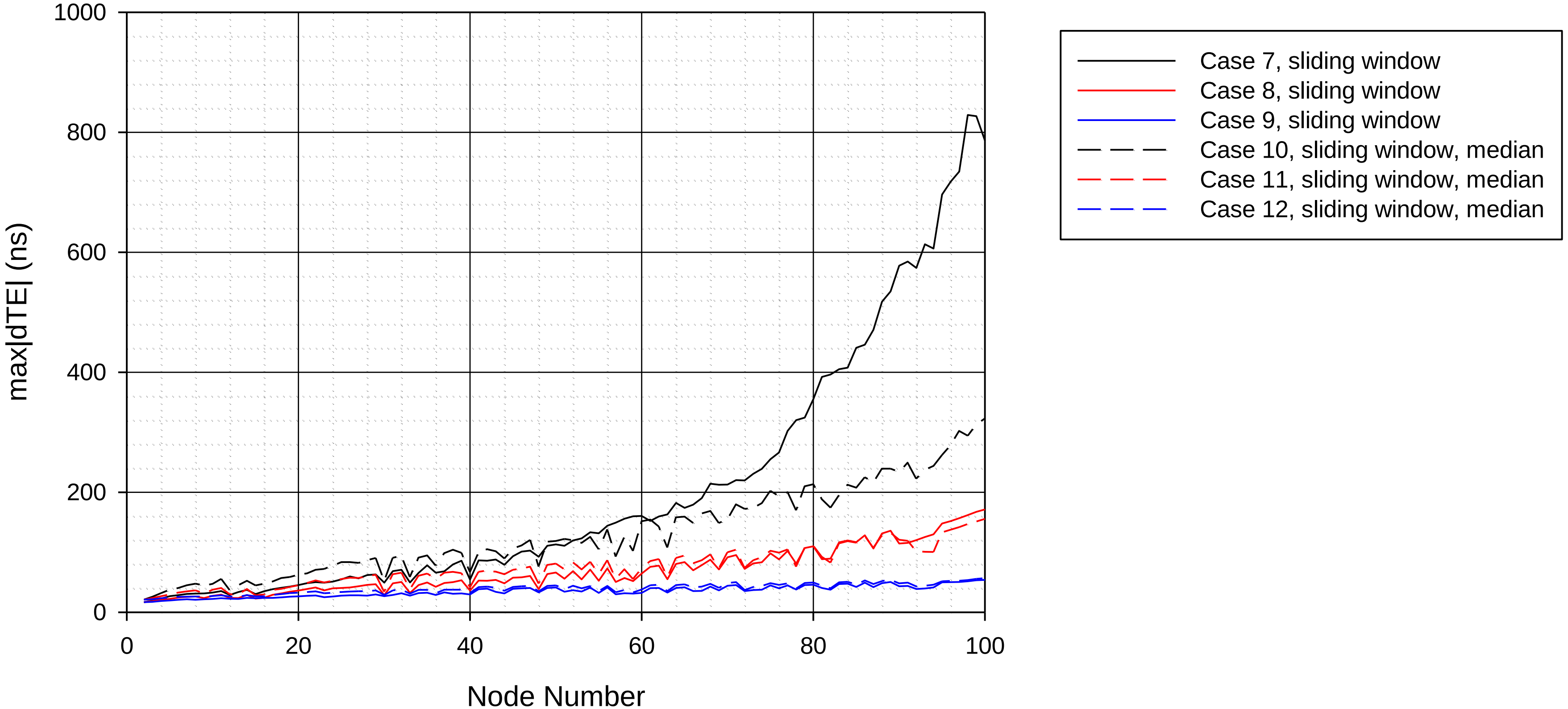


Cases 4 - 6: Discussion

- Results for cases 4 – 6 are qualitatively similar to those for cases 1 – 3
  - This is because cases 4 – 6 differ from cases 1 -3 only in the use of the median to estimate the GM rateRatio
- The node 2 results are essentially the same for all of cases 1 – 6, because these results do not depend on the GM rateRatio
- Max|dTE| results at nodes 50 and 100 for cases 4 – 6 are larger than for corresponding results for cases 1 – 3 (i.e., comparing cases 1 and 4, 2 and 5, and 3 and 6) because the median produces a GM rateRatio estimate whose error is larger

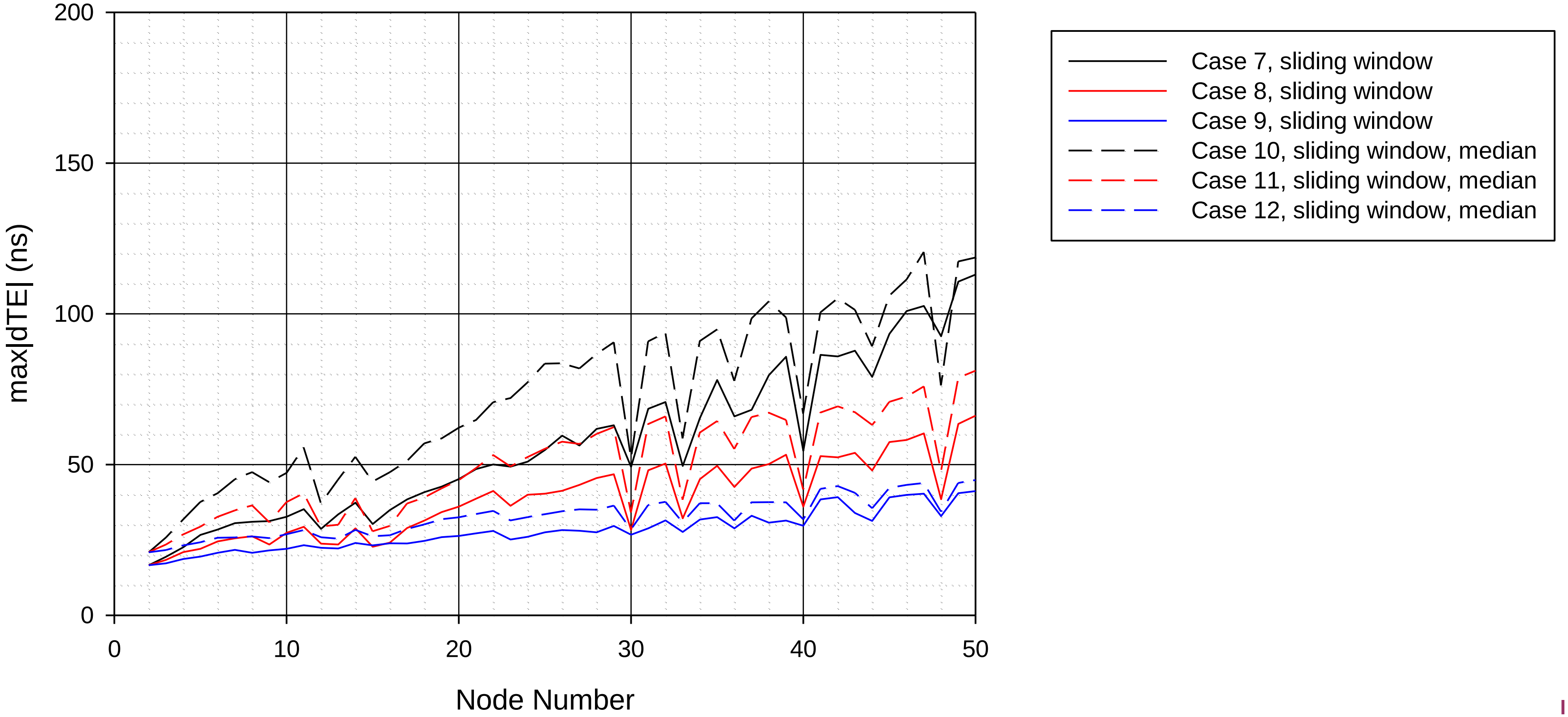
Cases 7 – 12: max|dTE|

Simulation Cases 7 - 12
Single replication of simulation
Clock Model: triangular wave freqeuncy variation
+/- 50 ppm amp, 3 ppm/s max drift rate, out of phase
Cases 7 and 10: 1 ms, 4 ms, 10 ms residence times with equal probability
(chosen independently for each Sync message)
Cases 8 and 11: 4 ms residence time
Cases 9 and 12: 1 ms residence time
Window size is 8 (current plus prev 7 Sync msgs) in all cases,
for computing GM freq offset



Cases 7 - 12: max|dTE|, detail of nodes 1 - 50

Simulation Cases 7 - 12 (detail nodes 1 - 50)
Single replication of simulation
Clock Model: triangular wave freqeuncy variation
+/- 50 ppm amp, 3 ppm/s max drift rate, out of phase
Cases 7 and 10: 1 ms, 4 ms, 10 ms residence times with equal probability
(chosen independ for each Sync message)
Cases 8 and 11: 4 ms residence time
Cases 9 and 12: 1 ms residence time
Window size is 8 (current plus prev 7 Sync msgs) in all cases,
for comput GM freq offset

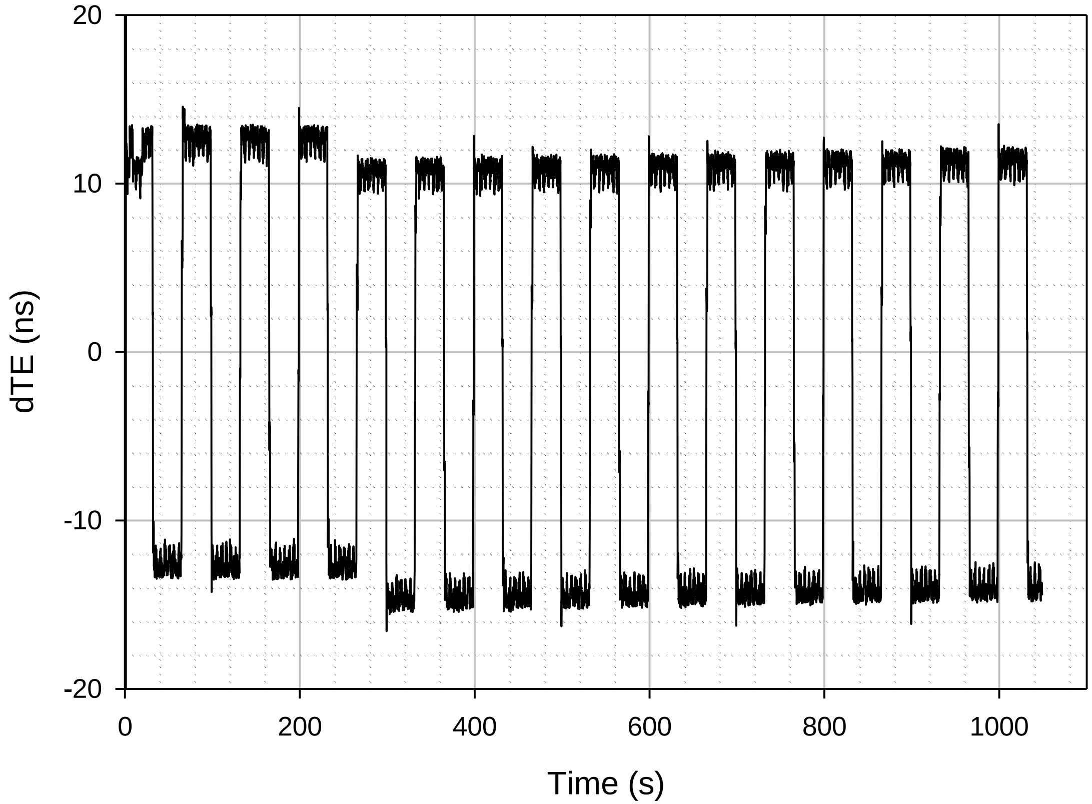


Cases 7 – 12: Discussion of Results – 1

- All the max|dTE| results are less than 1 μs over 100 hops
- In addition, all the max|dTE| results are less than 200 ns at 64 hops
- In general, the results are less than the corresponding results for cases 1 – 6
  - This is because the lining up of the free-running local clock frequency offset triangular waveforms (i.e., relative phases of zero) in cases 1 – 6 is the worst case (the relative phases are chosen randomly at initialization in cases 7 – 12)
  - For residence times of 4 ms (cases 8 and 11) and 1 ms (cases 9 and 12), the results with and without the use of the median for the rateRatio estimate are very similar (for cases 7 and 10, this is not true, and is likely due to the fact that the residence times differ from one message to the next)
- Except for case 7 for 100 hops, there appears to be sufficient margin to meet the max|TE| objective of 1 μs
  - However, these runs are only single replications; results with different (pseudo)-random number generator initialization could be larger (or smaller)
  - To verify that there is sufficient margin, multiple replications should be run, with the random number generator initialized independently for each replication (e.g., using the final random number generator state for the previous replication)
  - Actually, the triangular wave frequencies also should vary from one node and one replication to the next, and should be chosen randomly for each node on initialization

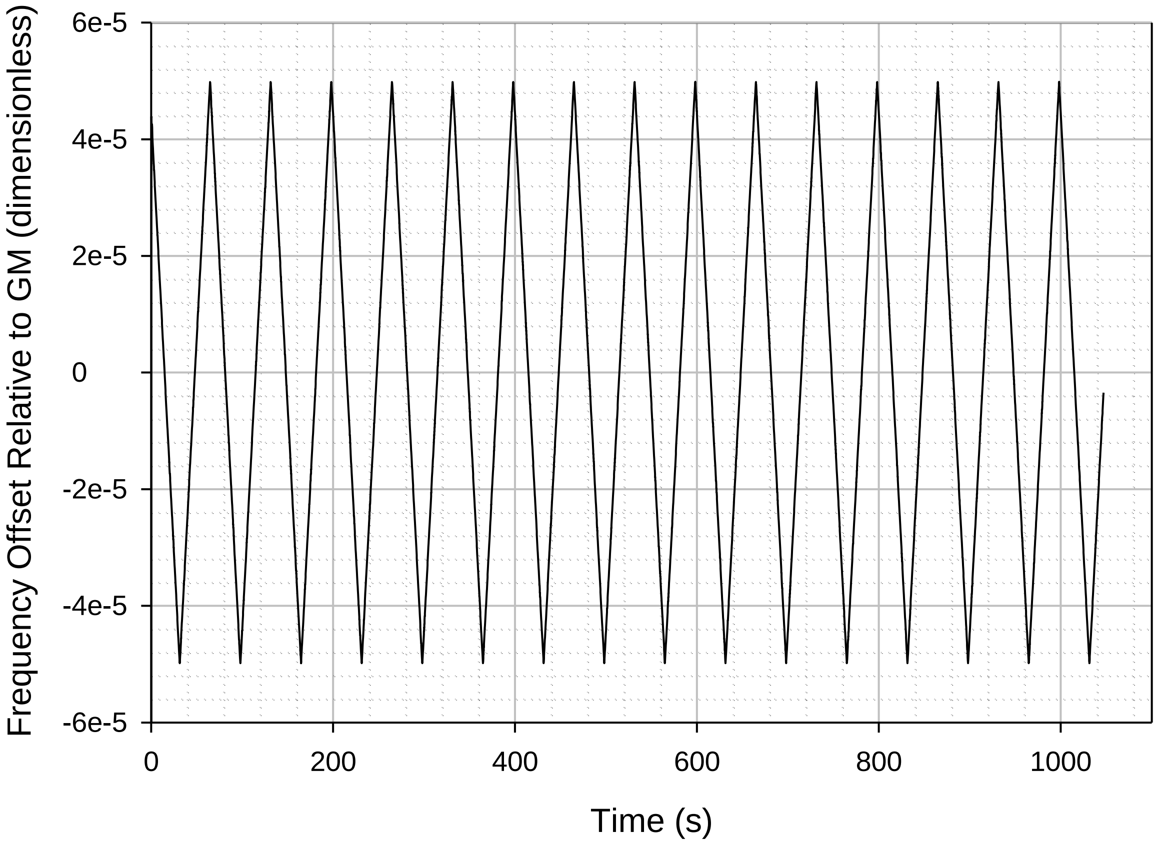
Case 7 - dTE, Node 2

Case 7, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



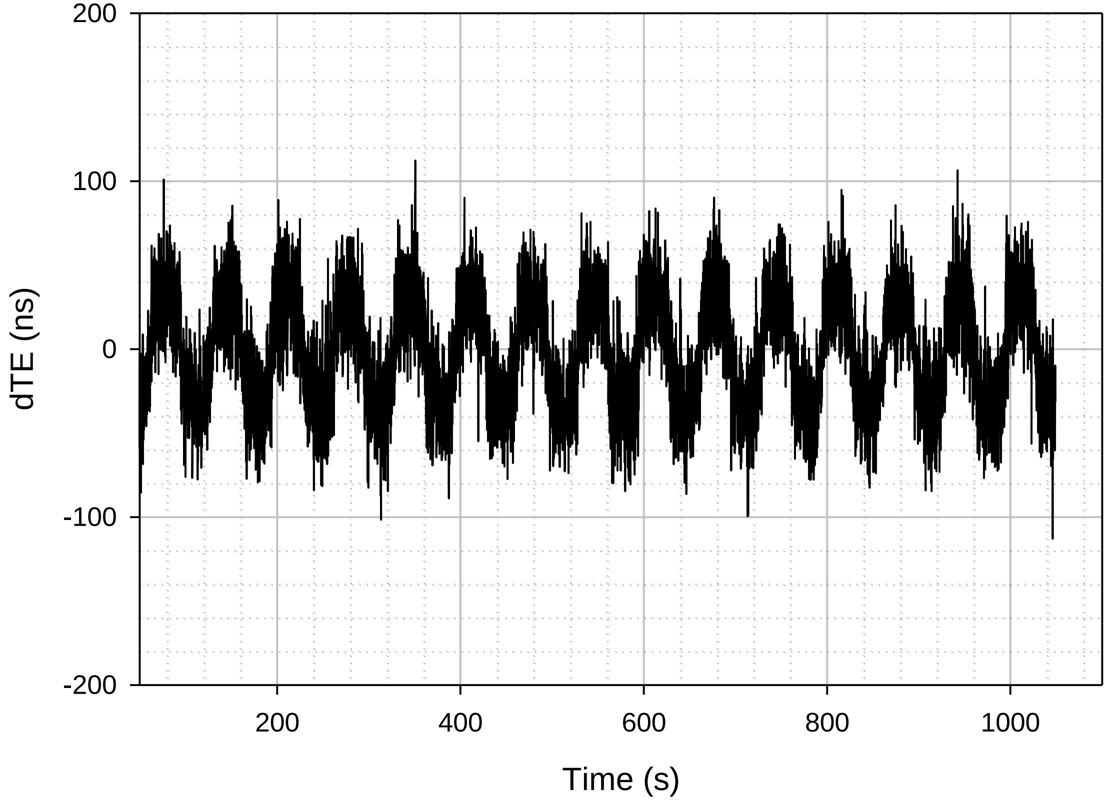
Case 7 - Measured Frequency Offset, Node 2

Case 7, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



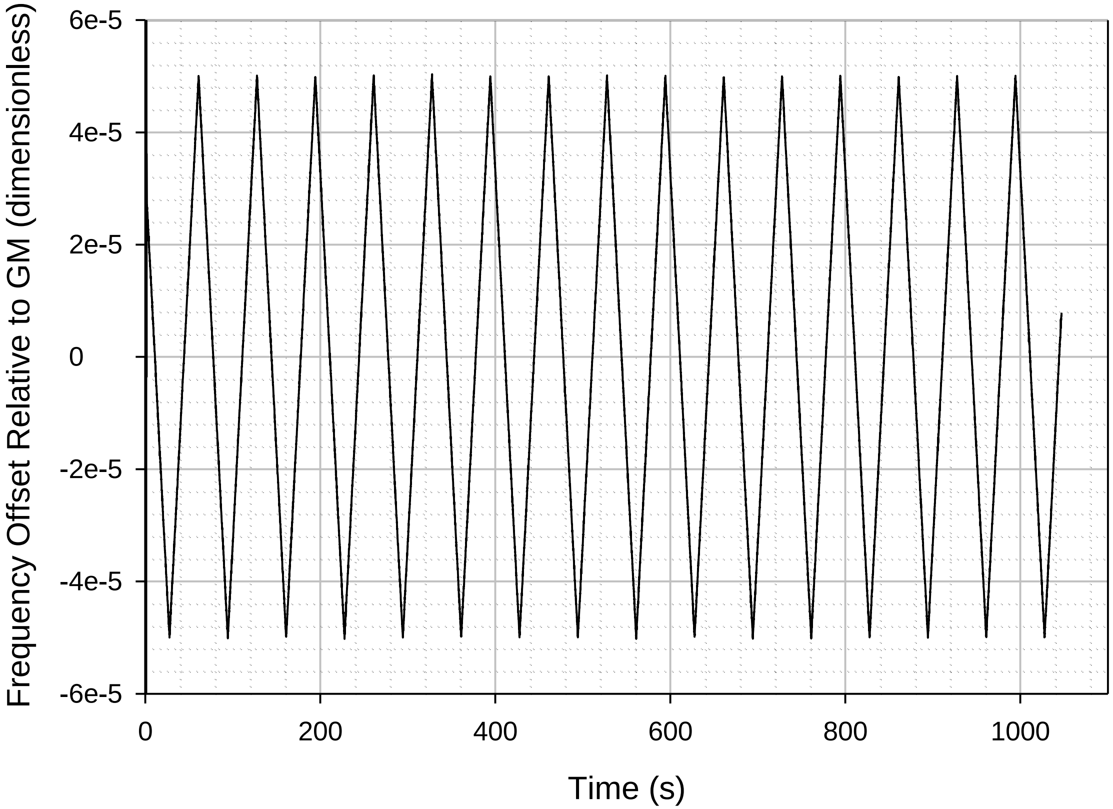
Case 7 - dTE, Node 50

Case 7, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
First 50 s omitted to eliminate any startup transient



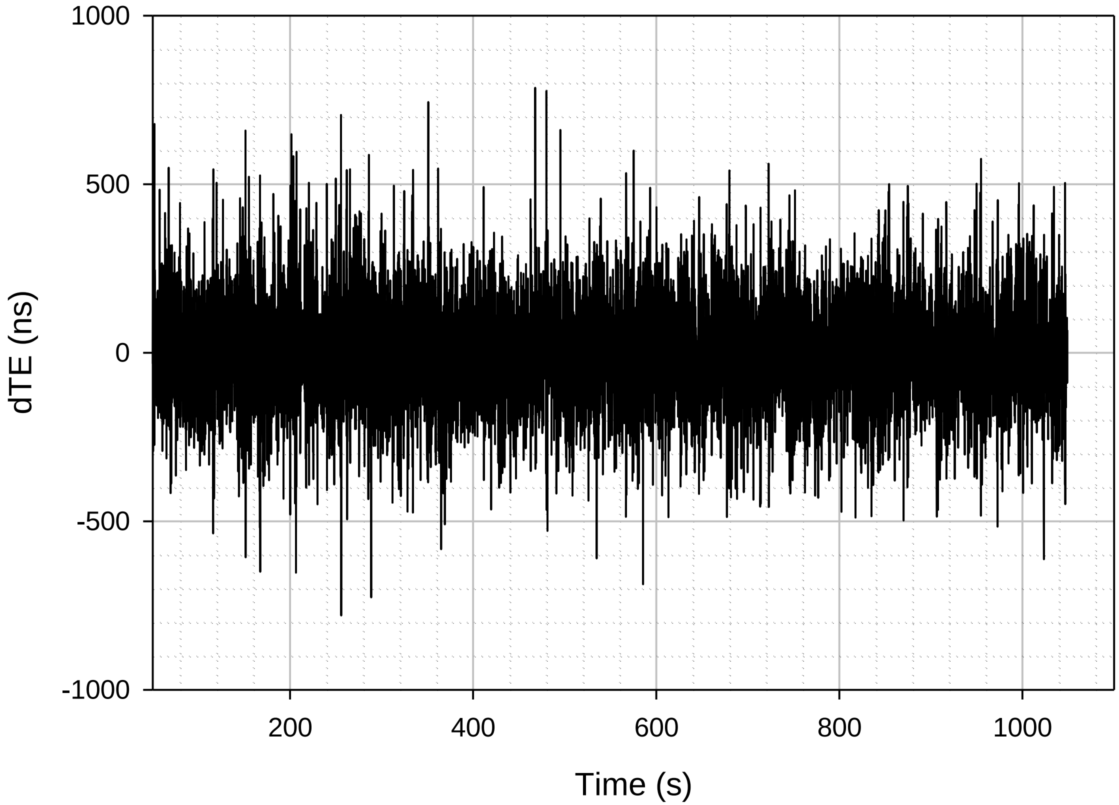
Case 7 – Measured Frequency Offset, Node 50

Case 7, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



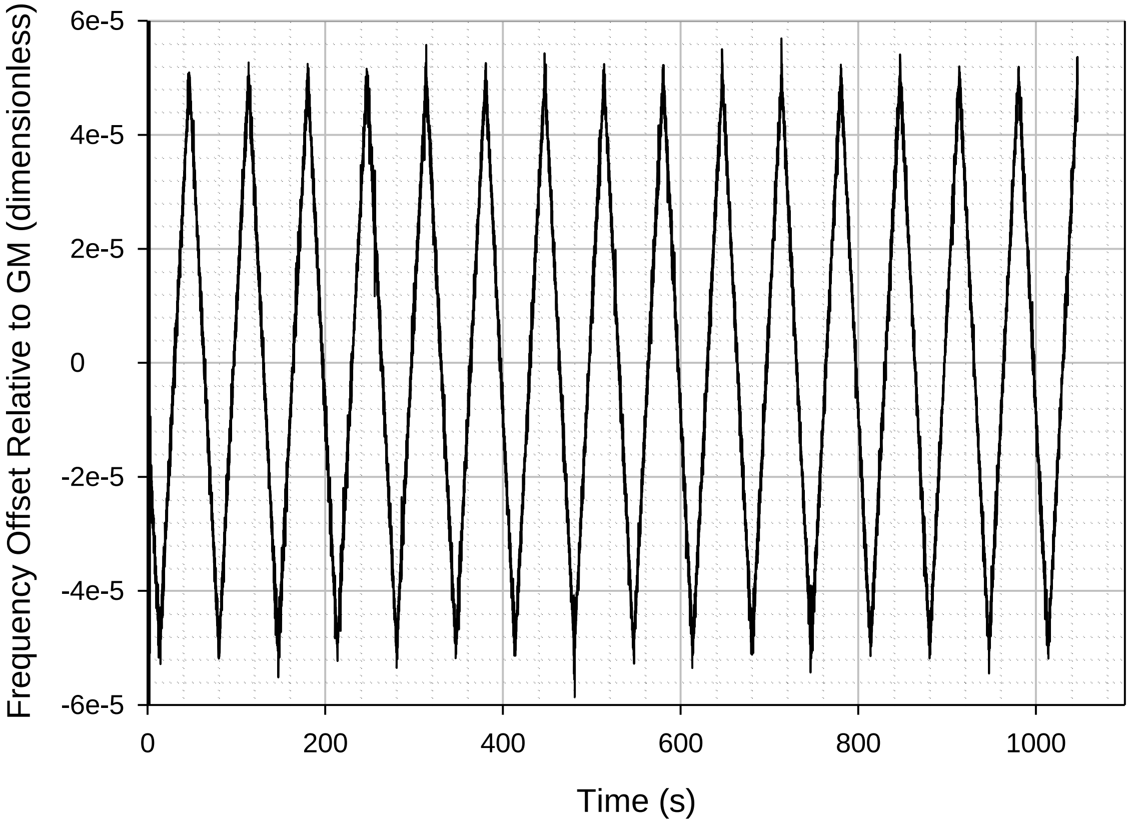
Case 7 - dTE, Node 100

Case 7, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
First 50 s omitted to eliminate any startup transient



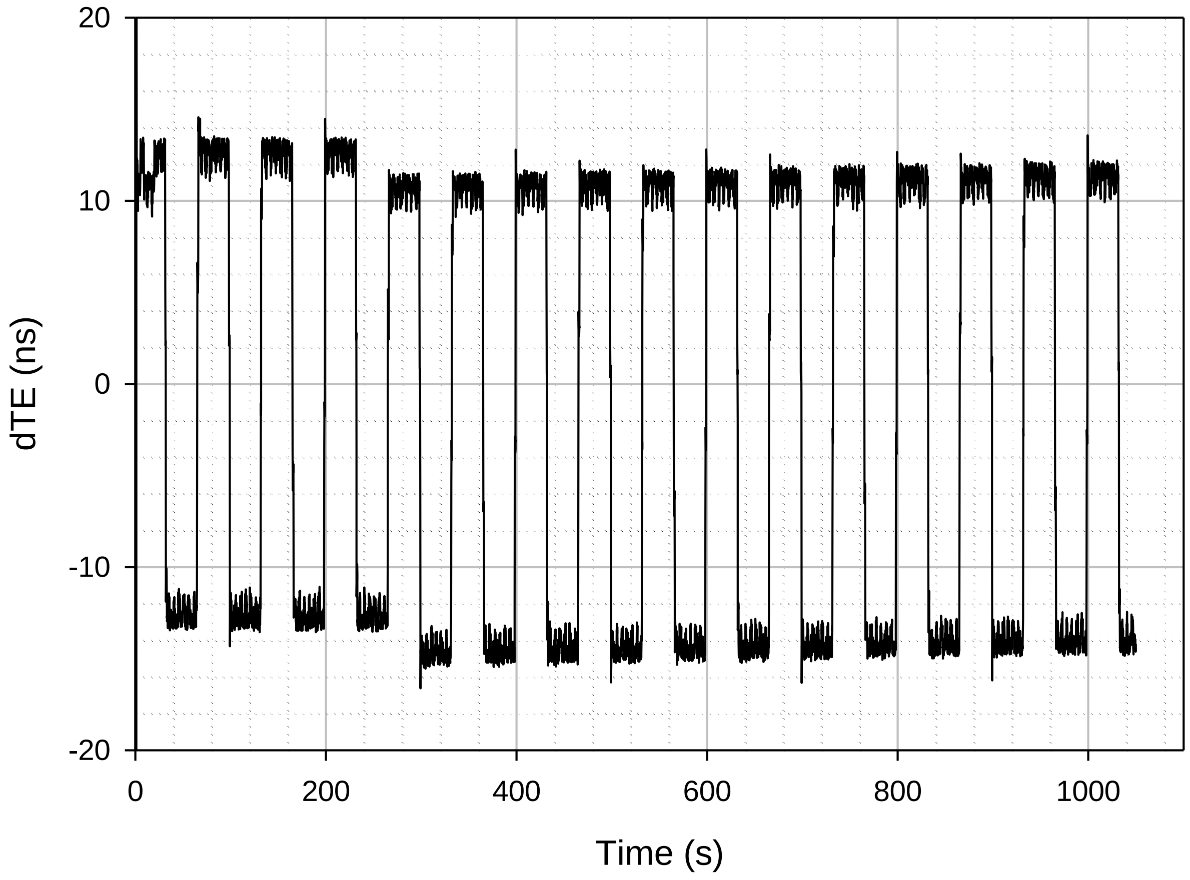
Case 7 - Measured Frequency Offset, Node 100

Case 7, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)



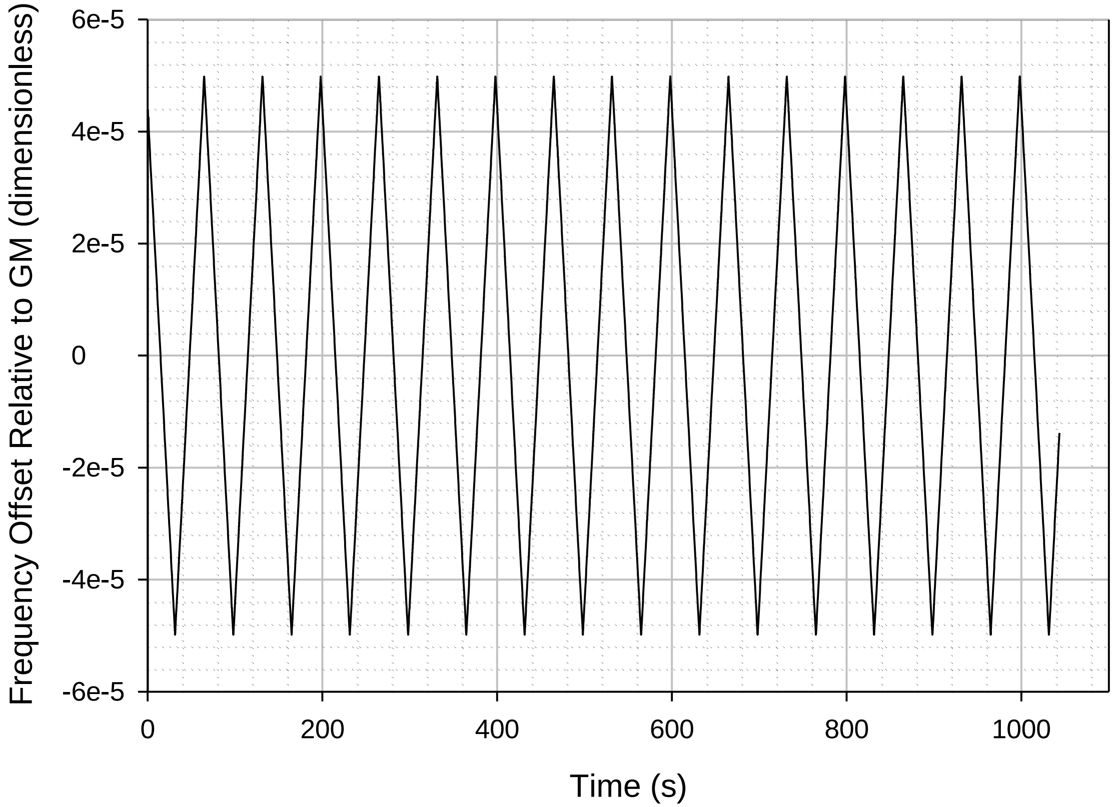
Case 8 - dTE, Node 2

Case 8, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms



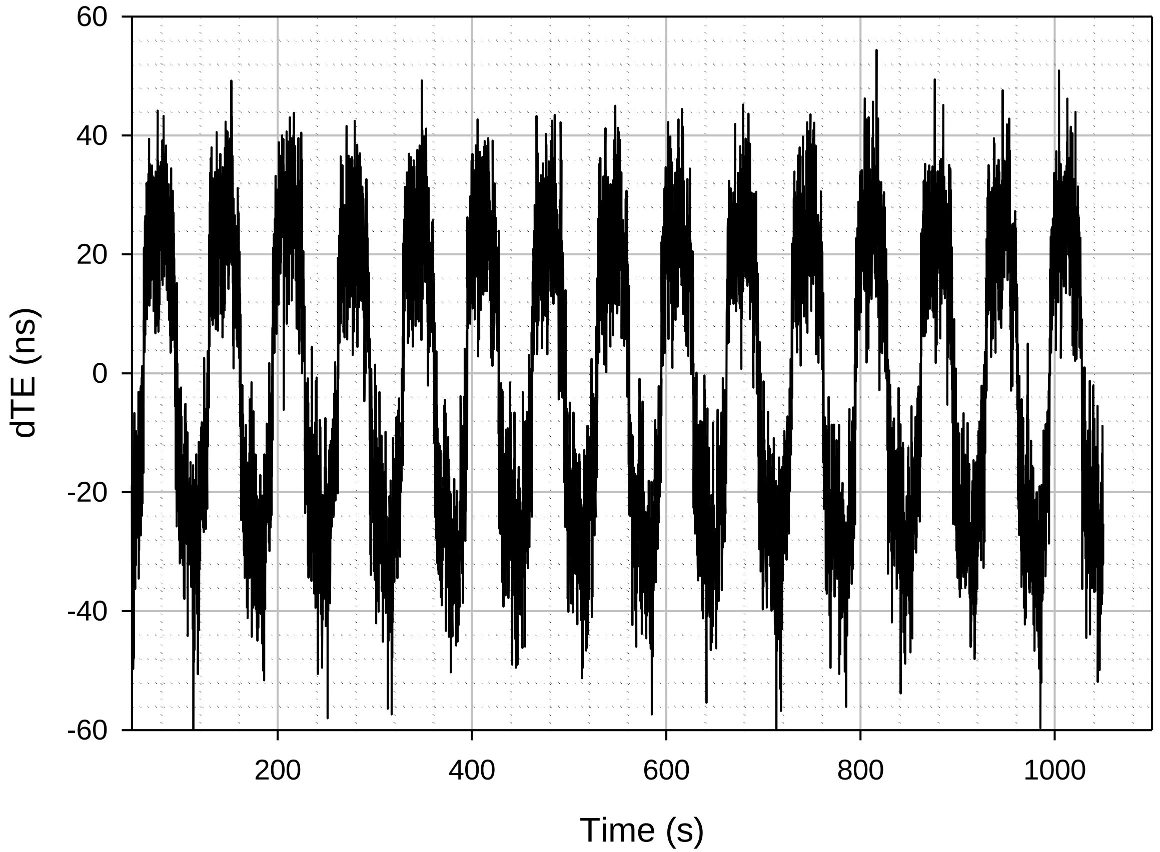
Case 8 – Measured Frequency Offset, Node 2

Case 8, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms



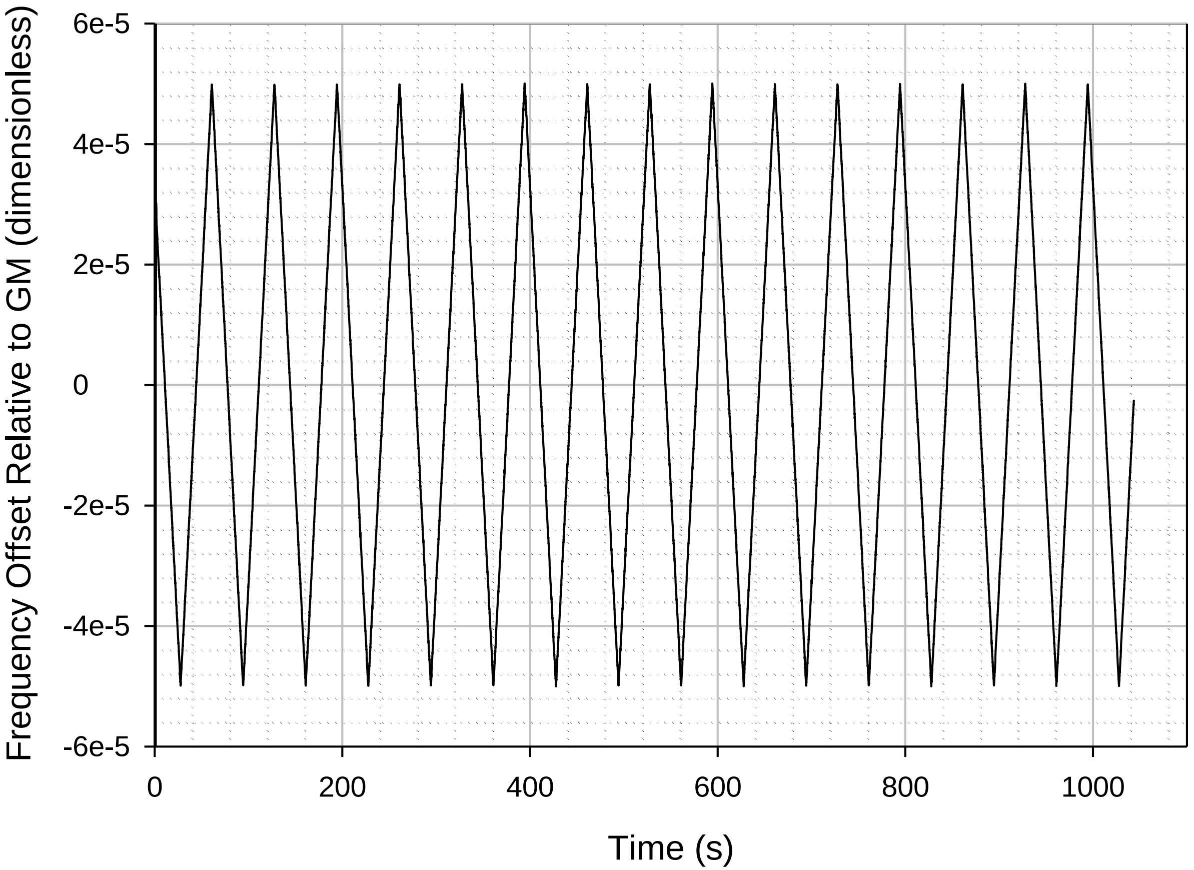
Case 8 - dTE, Node 50

Case 8, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
First 50 s omitted to eliminate any startup transient



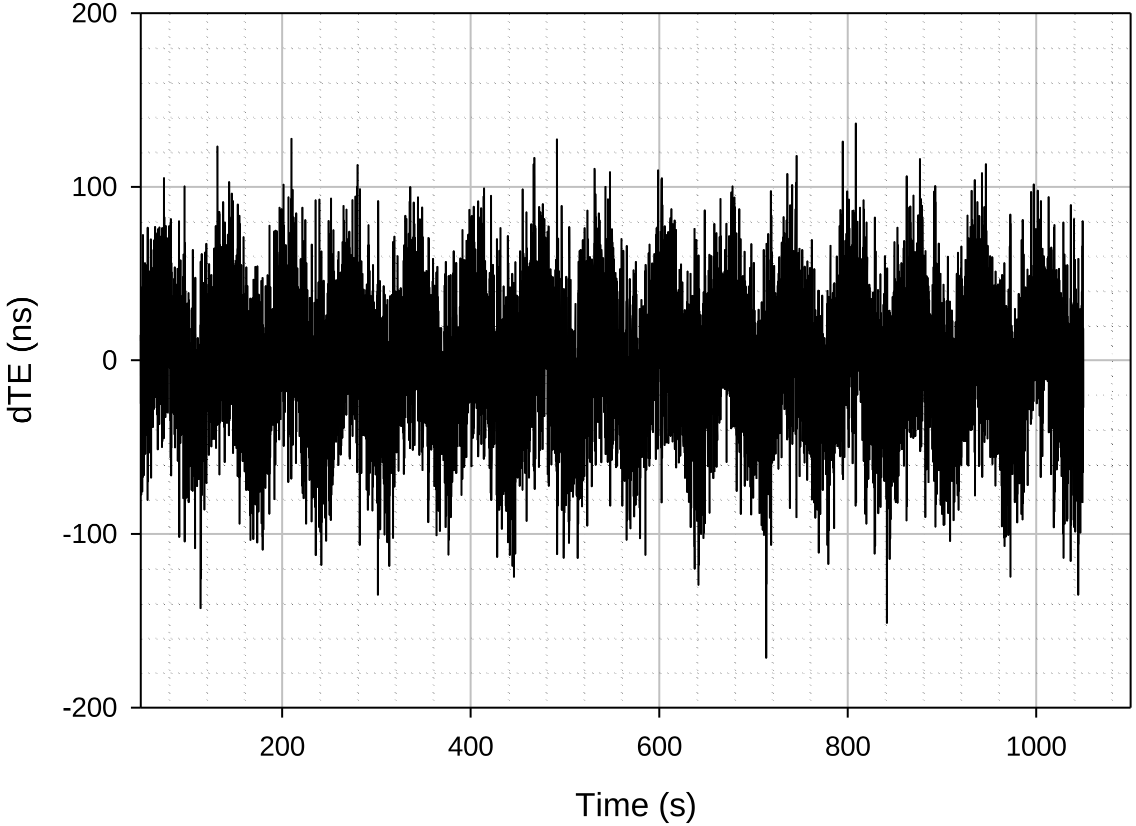
Case 8 – Measured Frequency Offset, Node 50

Case 8, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms

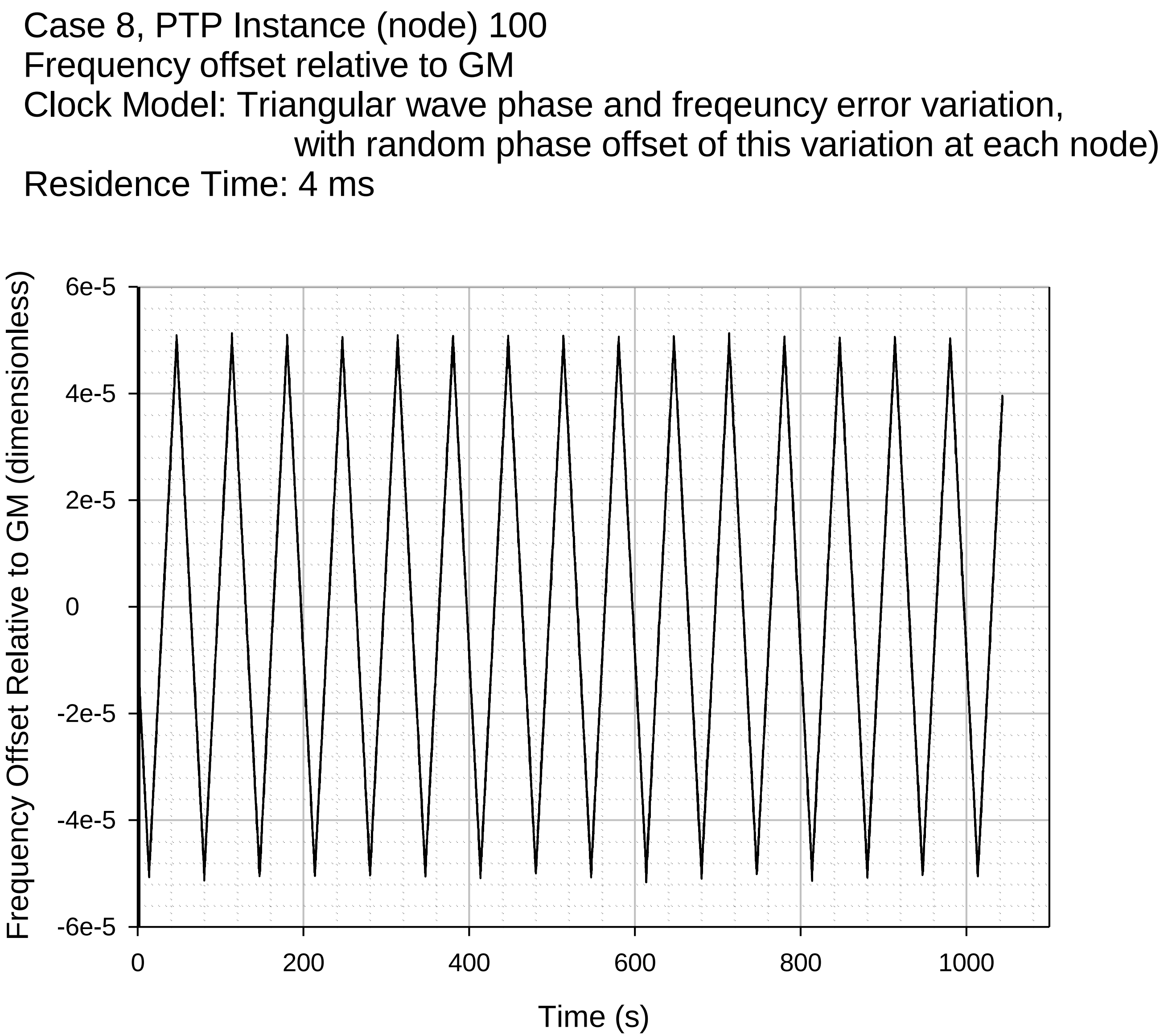


Case 8 - dTE, Node 100

Case 8, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
First 50 s omitted to eliminate any startup transient

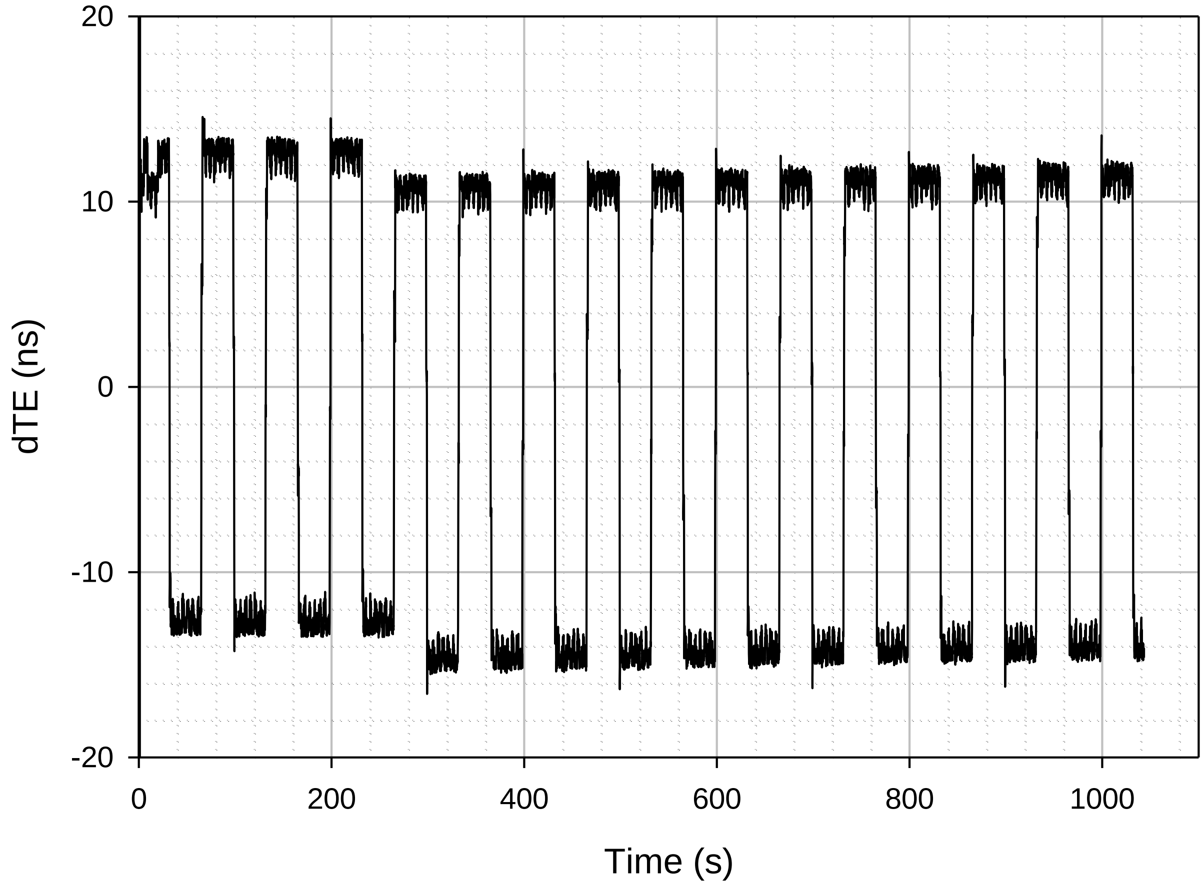


Case 8 - Measured Frequency Offset, Node 100

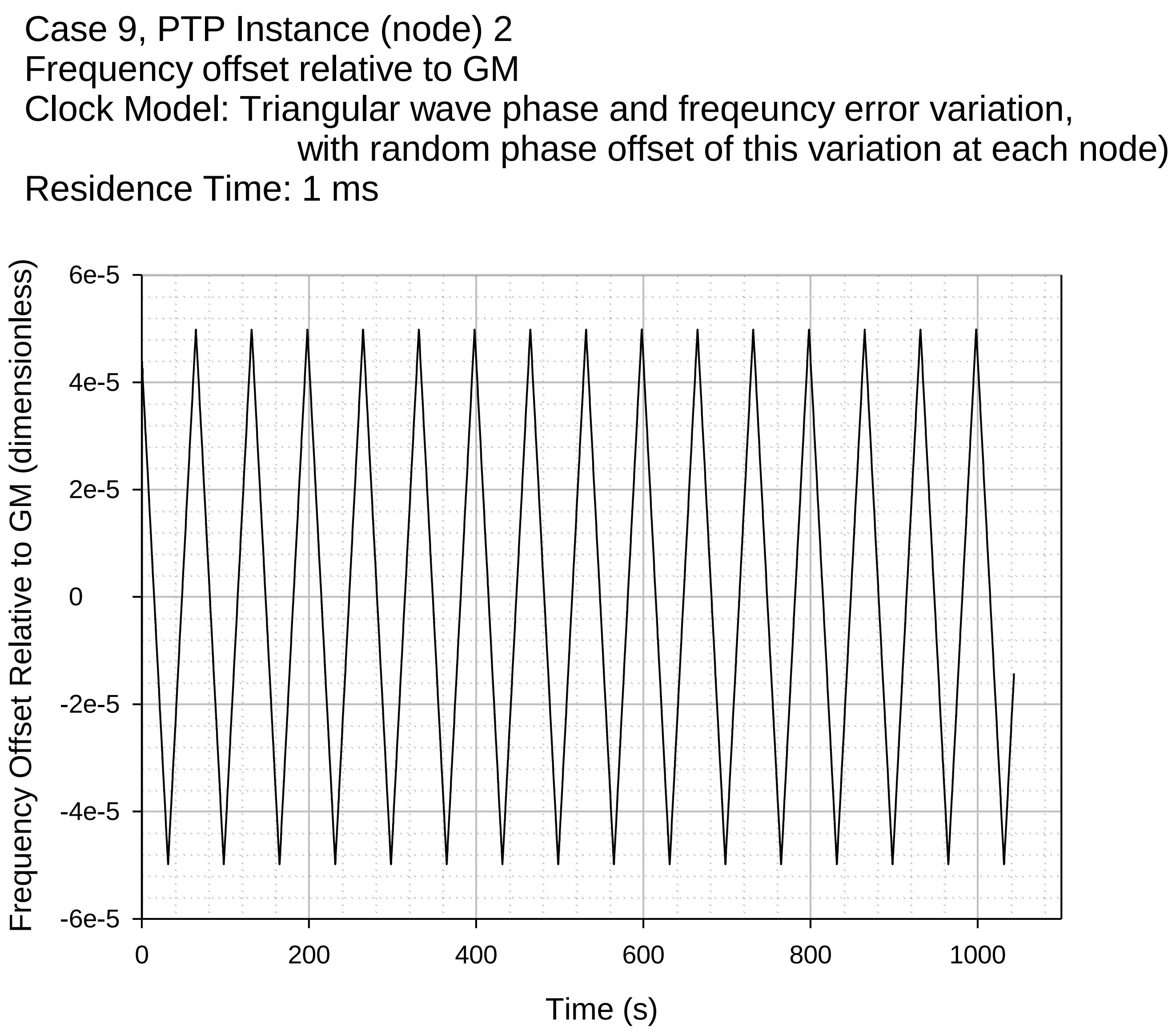


Case 9 - dTE, Node 2

Case 9, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms

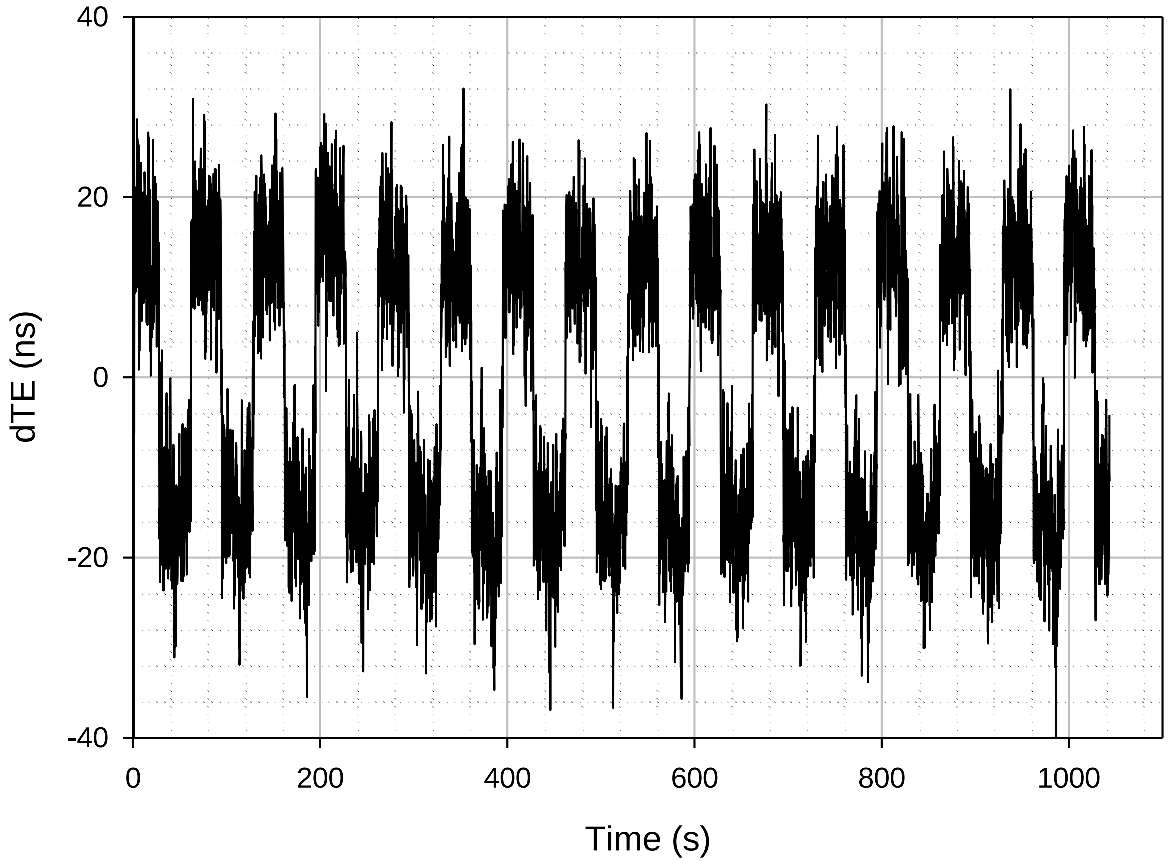


Case 9 - Measured Frequency Offset, Node 2



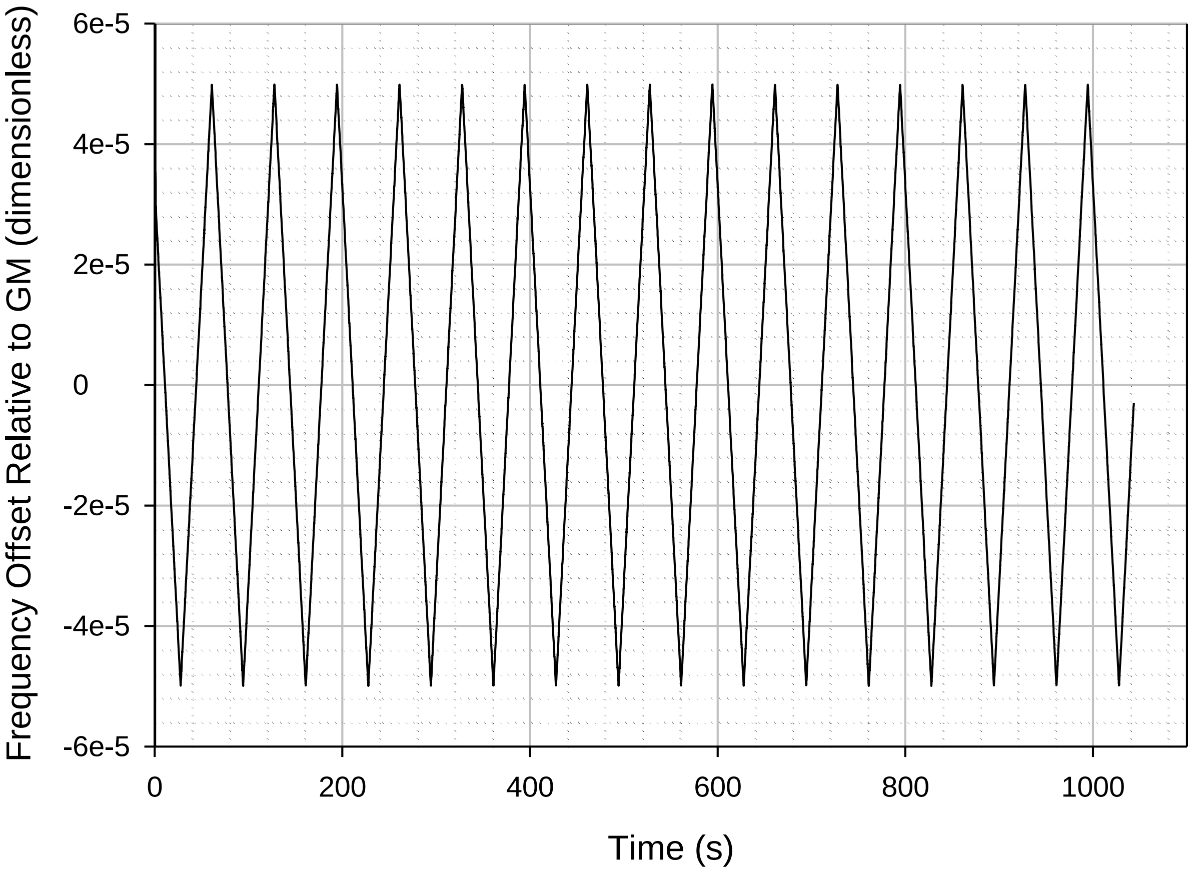
Case 9 - dTE, Node 50

Case 9, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms



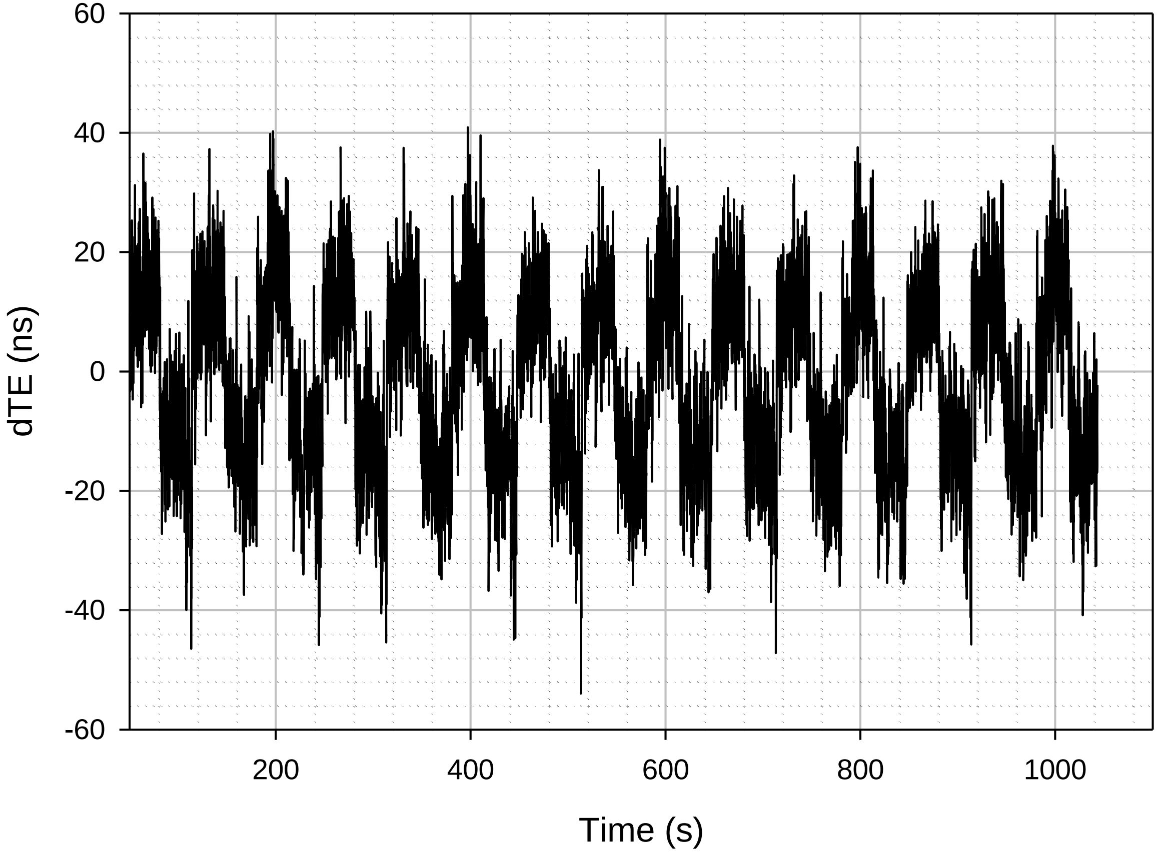
Case 9 – Measured Frequency Offset, Node 50

Case 9, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms



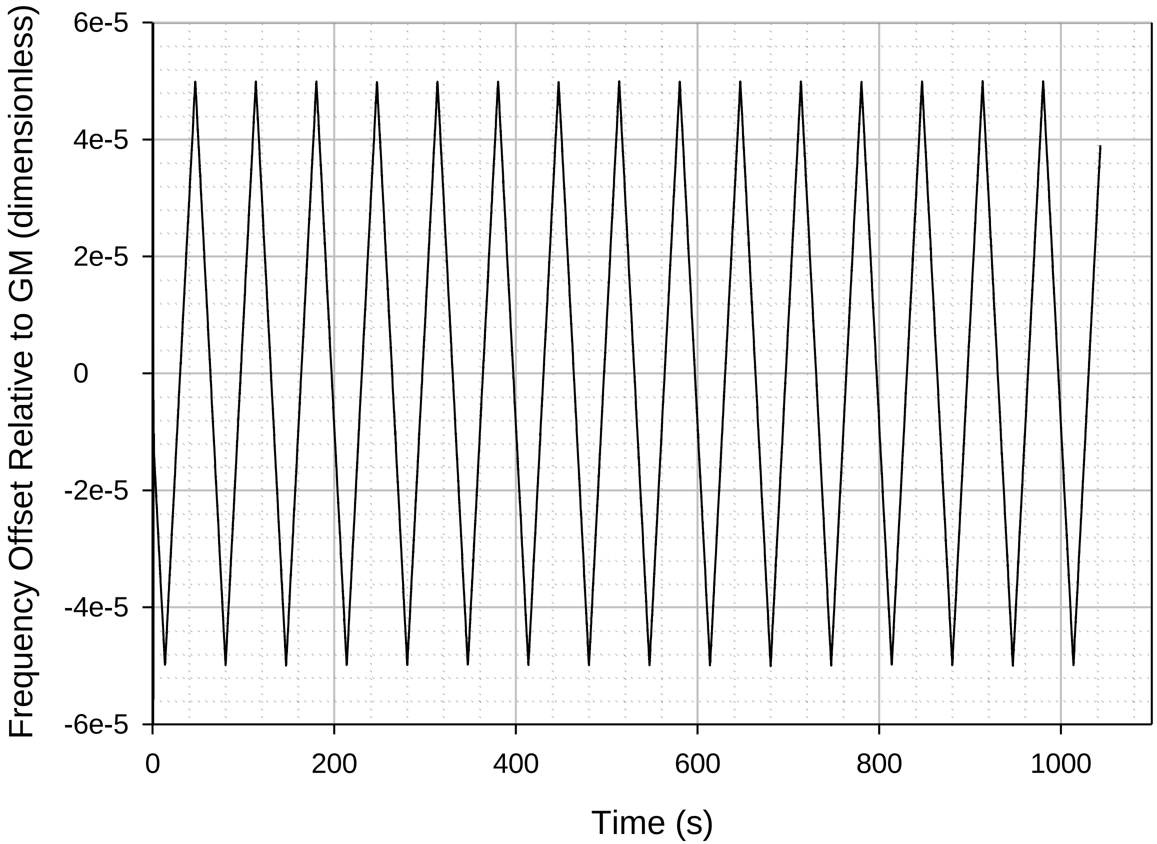
Case 9 – dTE, Node 100

Case 9, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms
First 50 s omitted to eliminate any startup transient



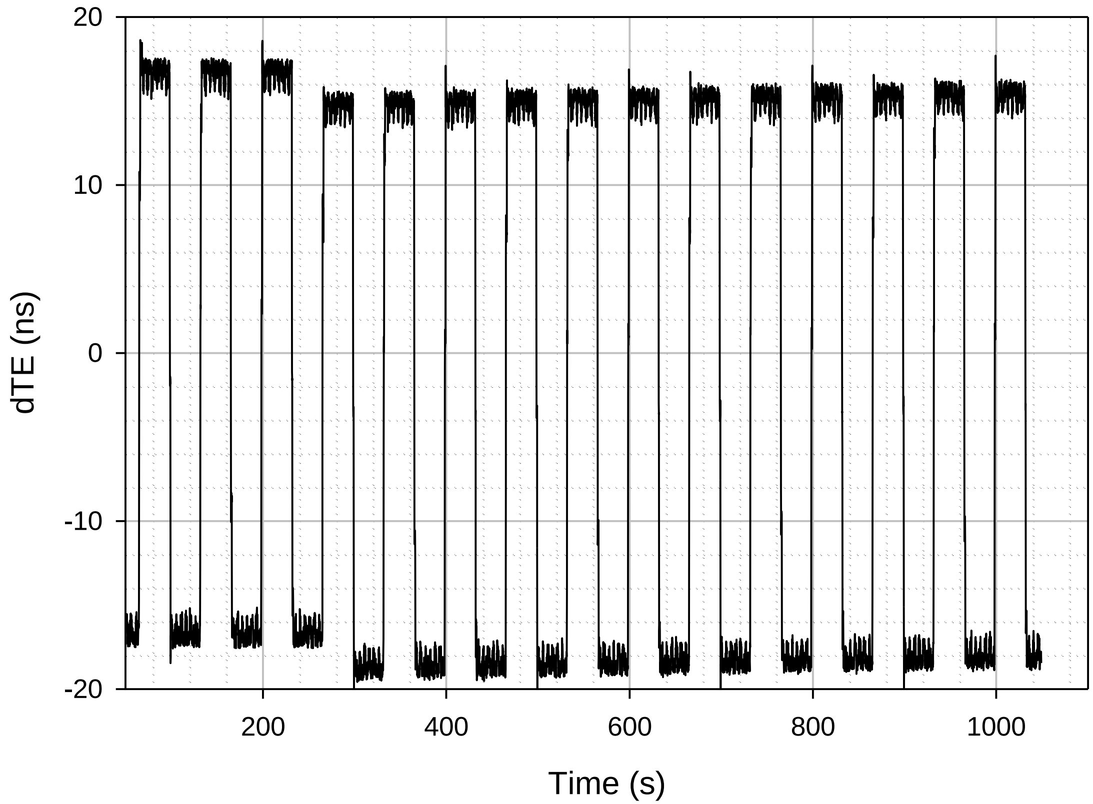
Case 9 – Measured Frequency Offset, Node 100

Case 9, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms



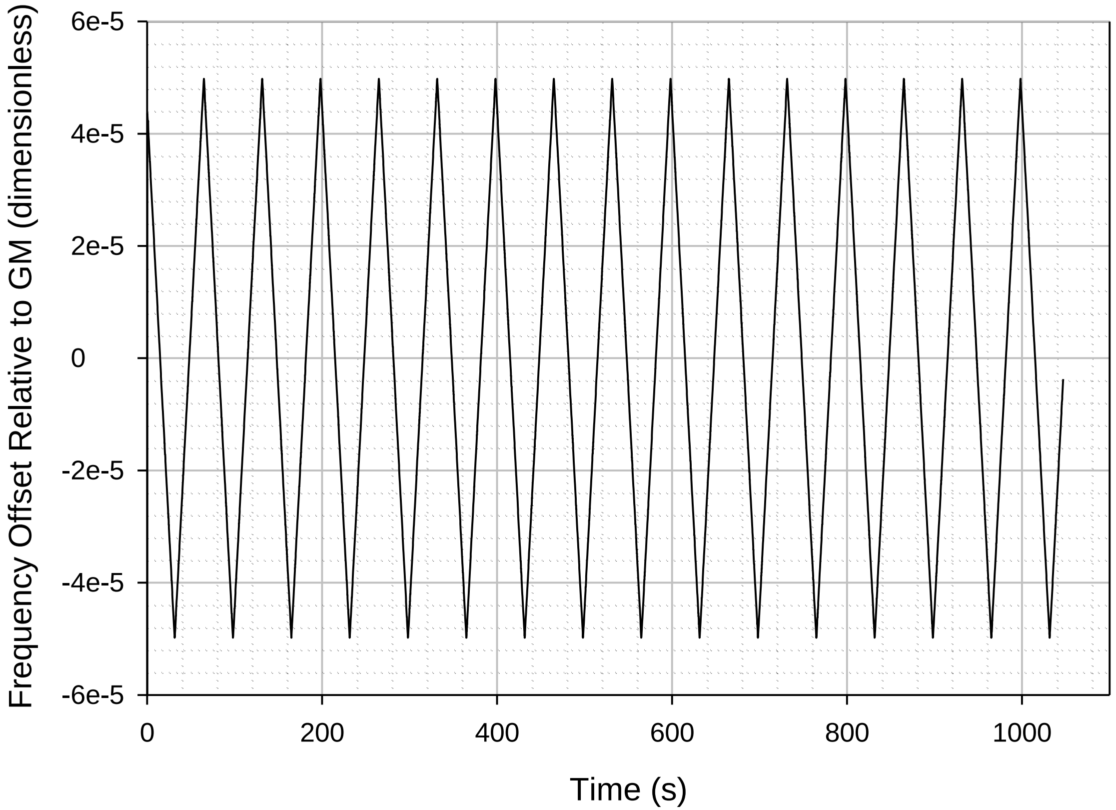
Case 10 – dTE, Node 2

Case 10, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



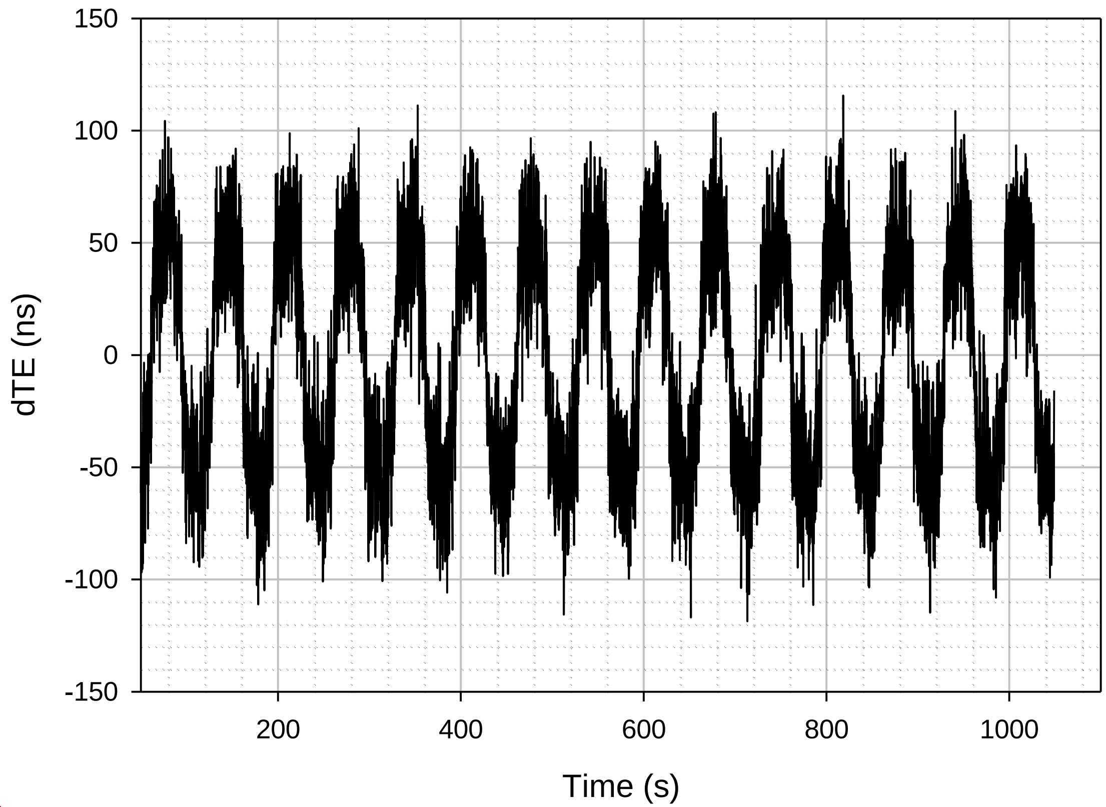
Case 10 – Measured Frequency Offset, Node 2

Case 10, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median



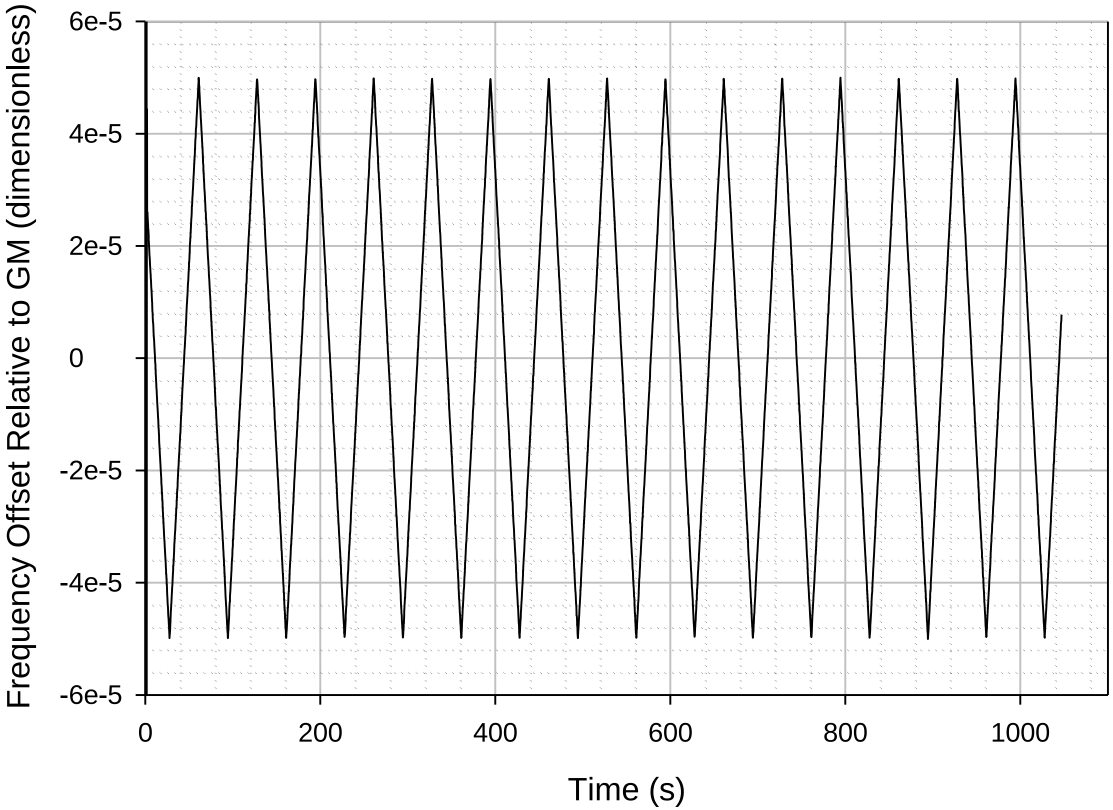
Case 10 – dTE, Node 50

Case 10, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



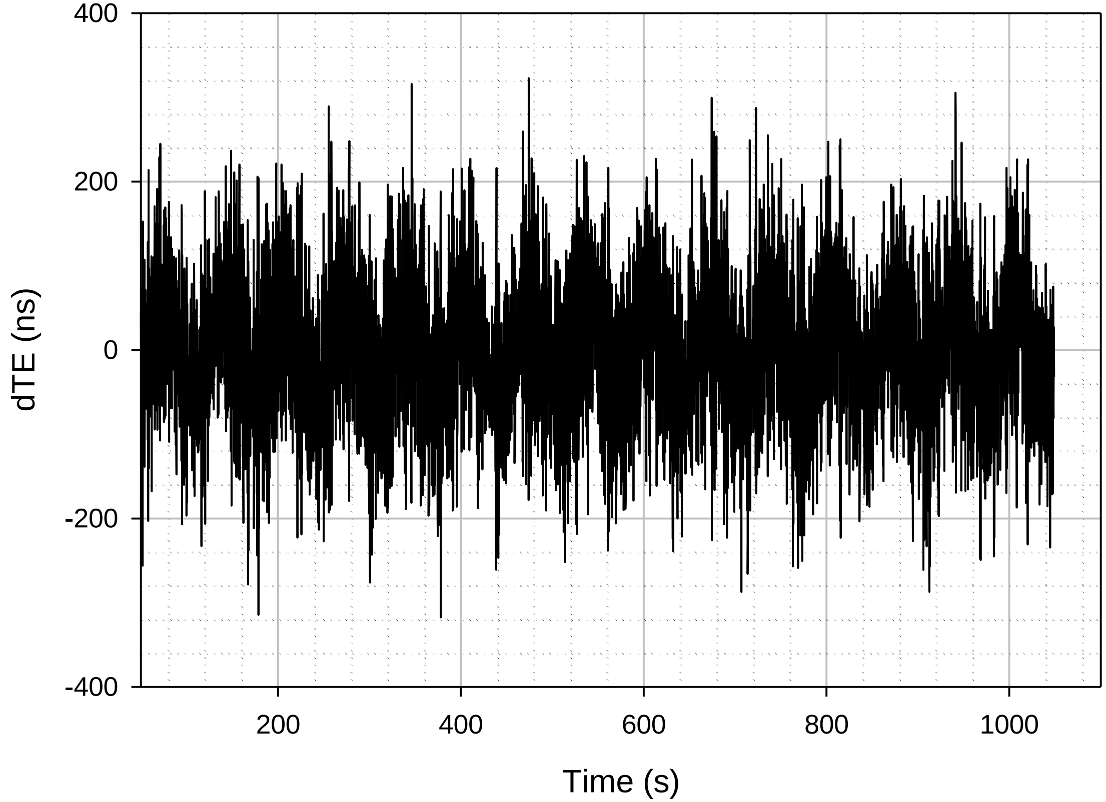
Case 10 – Measured Frequency Offset, Node 50

Case 10, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median



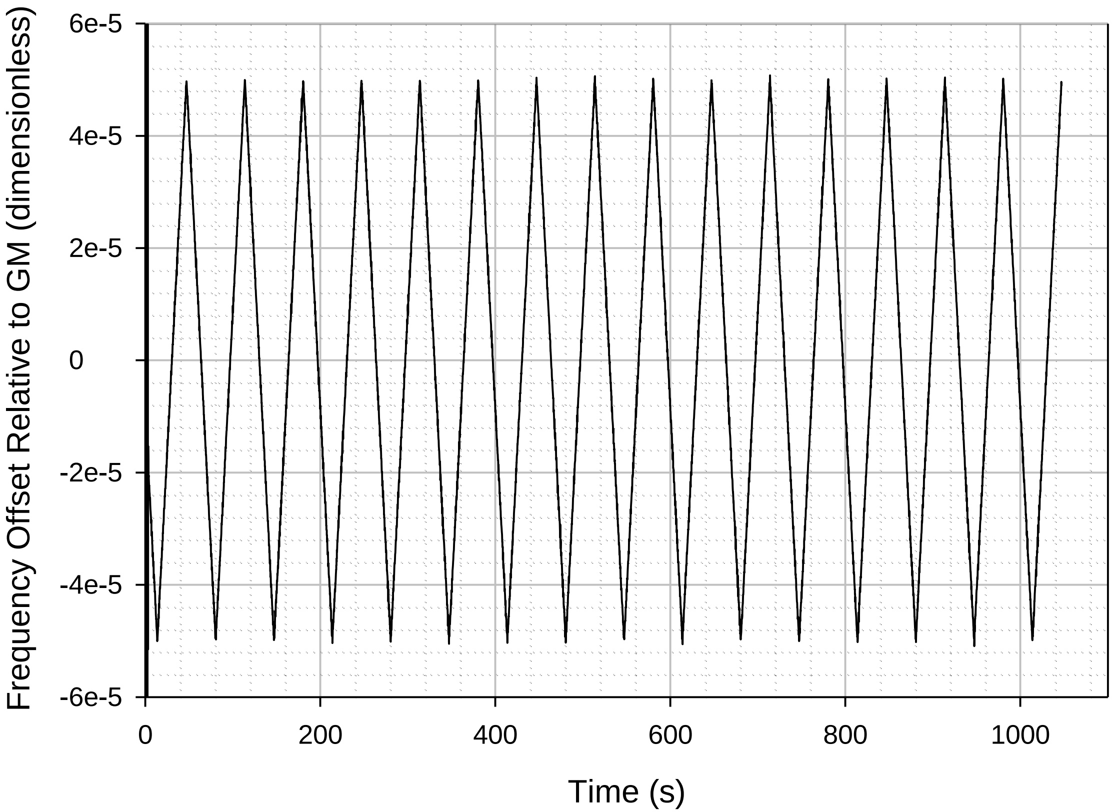
Case 10 – dTE, Node 100

Case 10, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



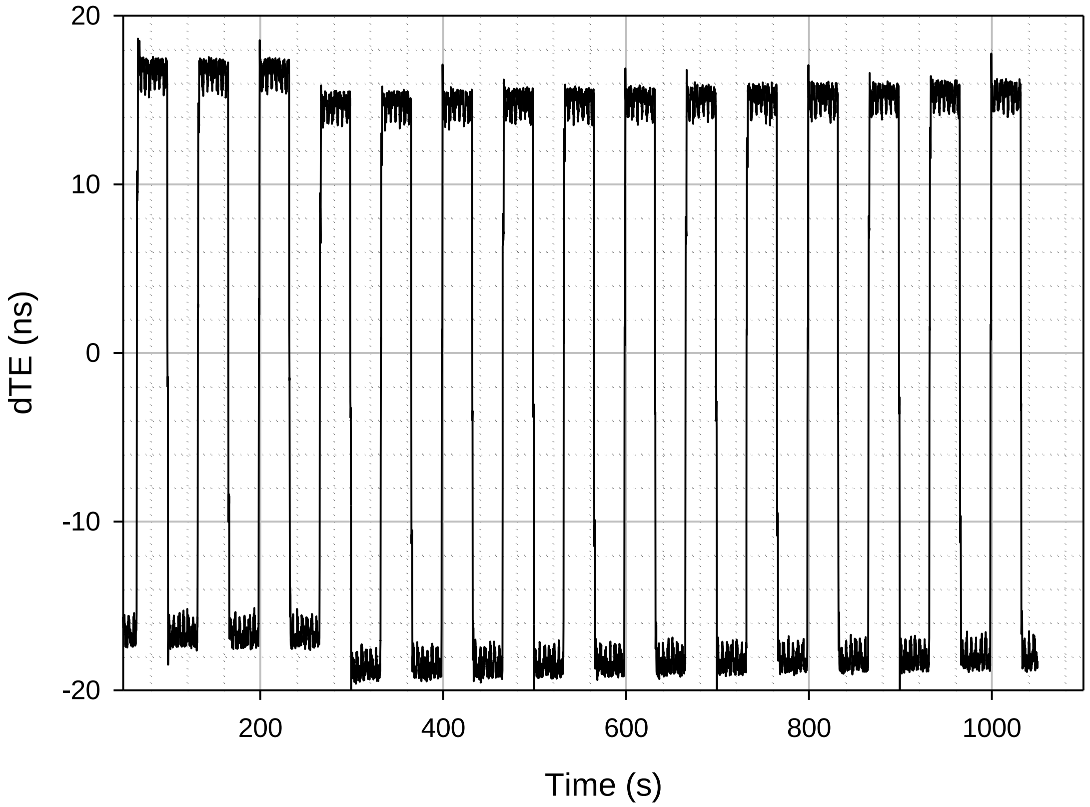
Case 10 – Measured Frequency Offset, Node 100

Case 10, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms, 4 ms, 10 ms with equal probability
(chosen independently for each Sync message)
Frequency offset computation uses sliding window with median



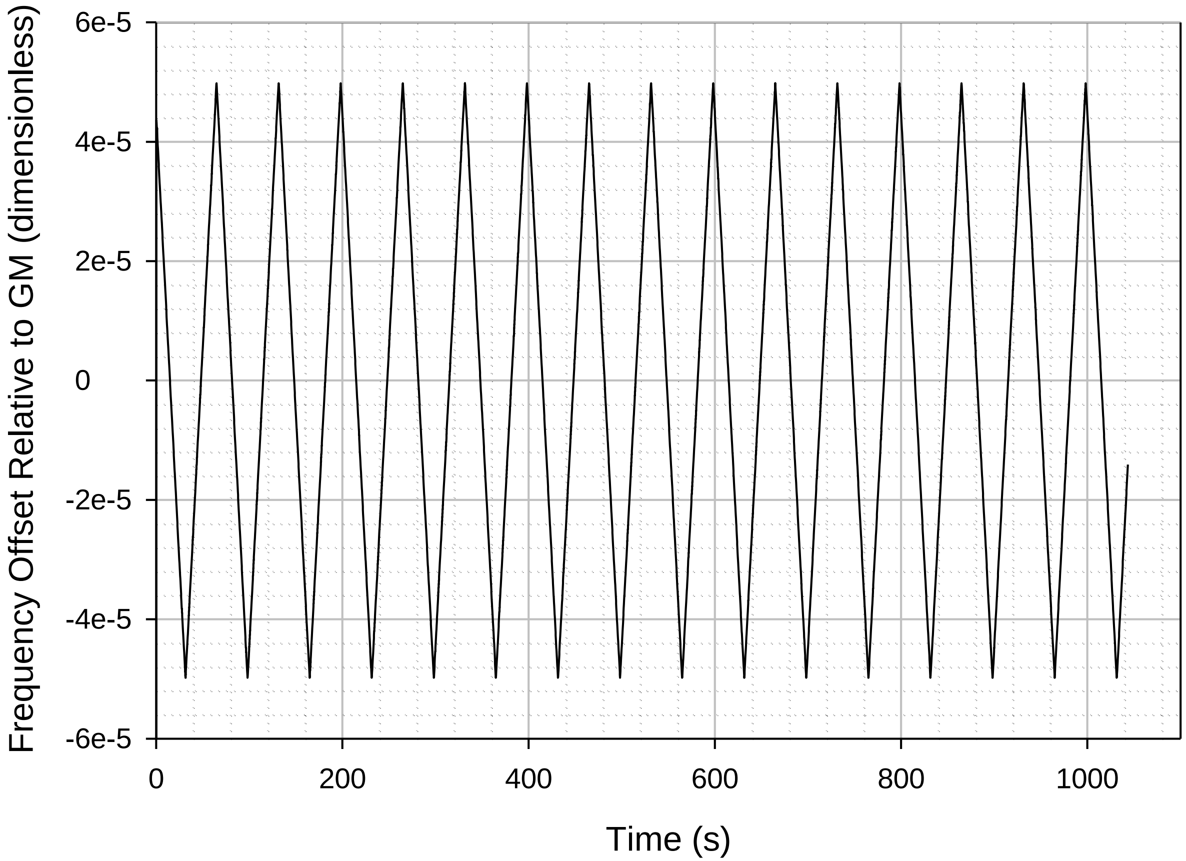
Case 11 – dTE, Node 2

Case 11, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



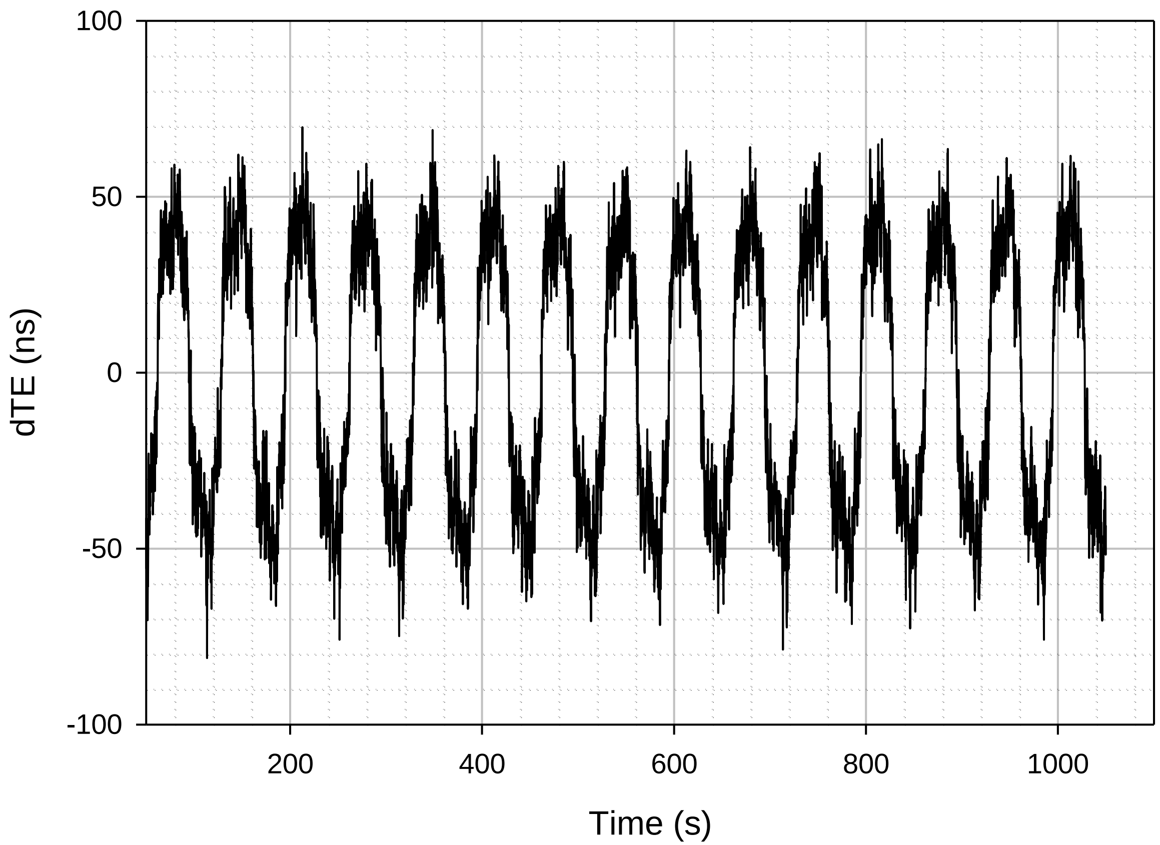
Case 11 – Measured Frequency Offset, Node 2

Case 11, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median



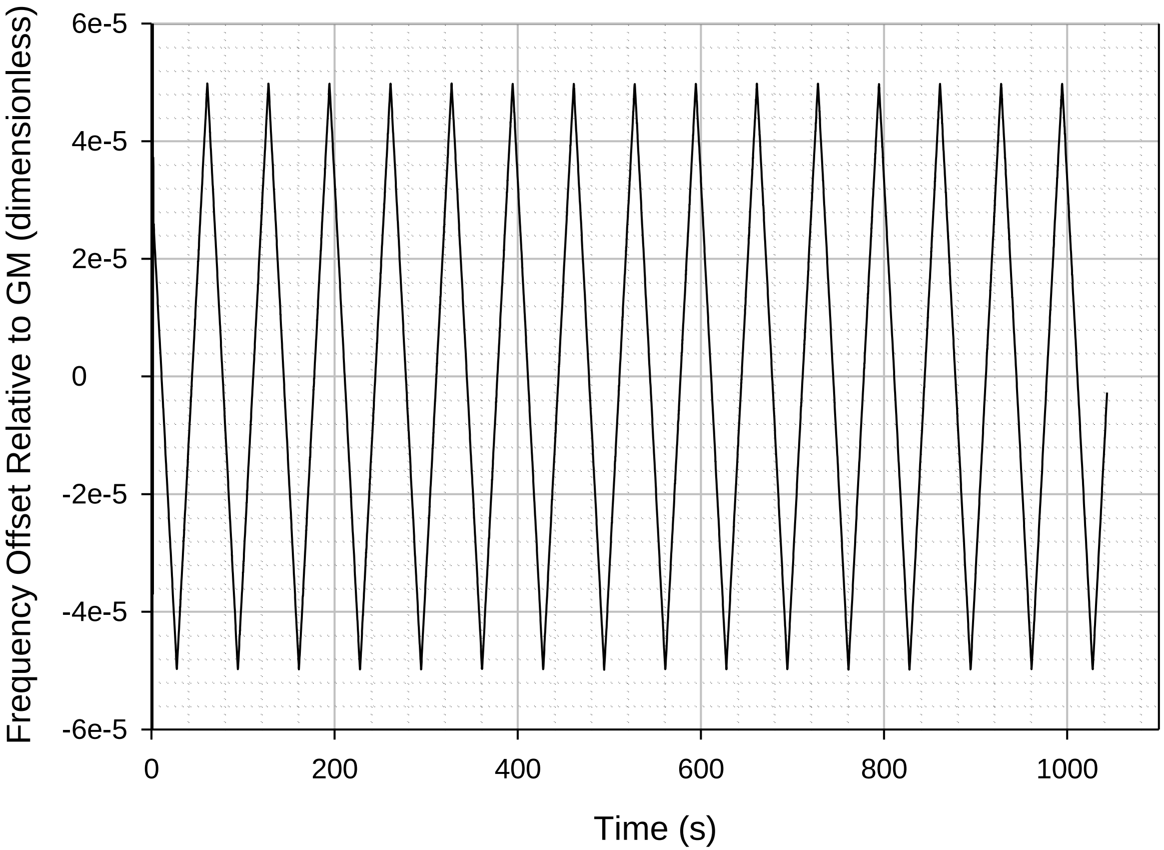
Case 11 – dTE, Node 50

Case 11, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



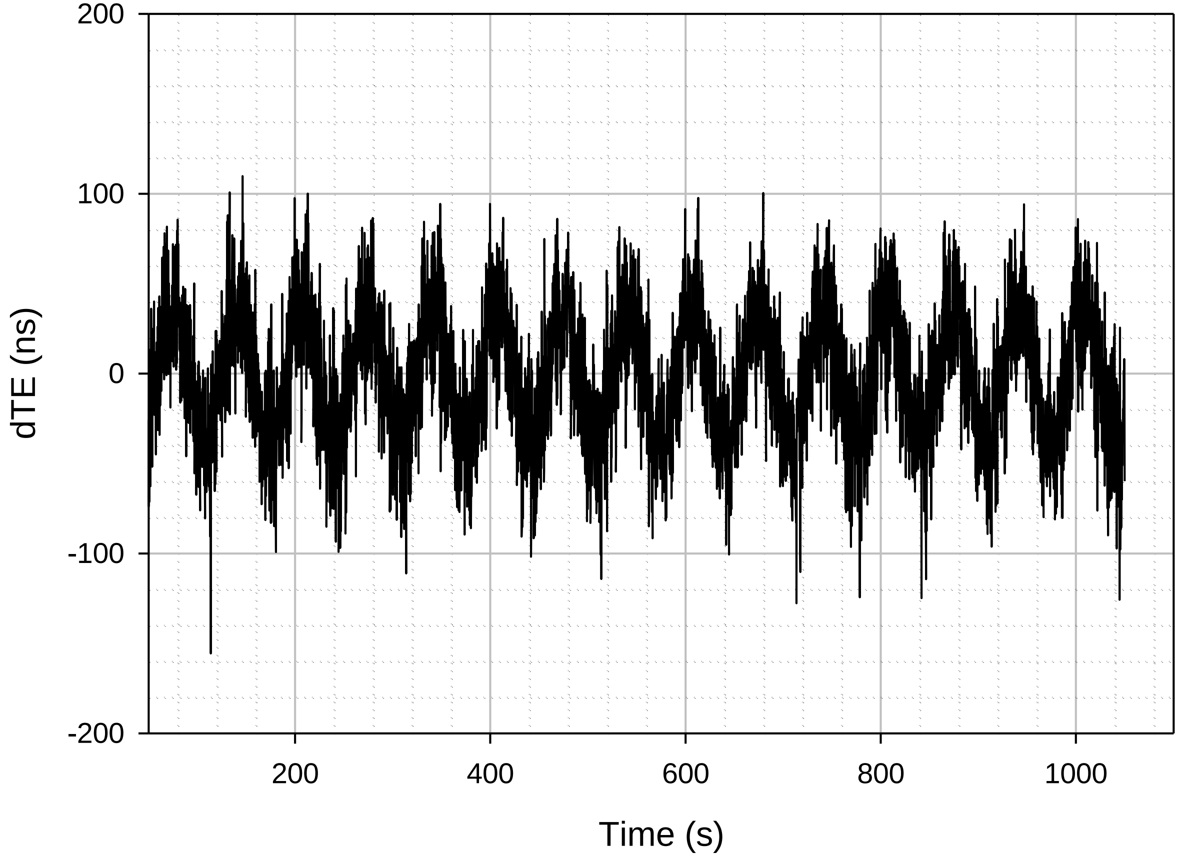
Case 11 – Measured Frequency Offset, Node 50

Case 11, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median



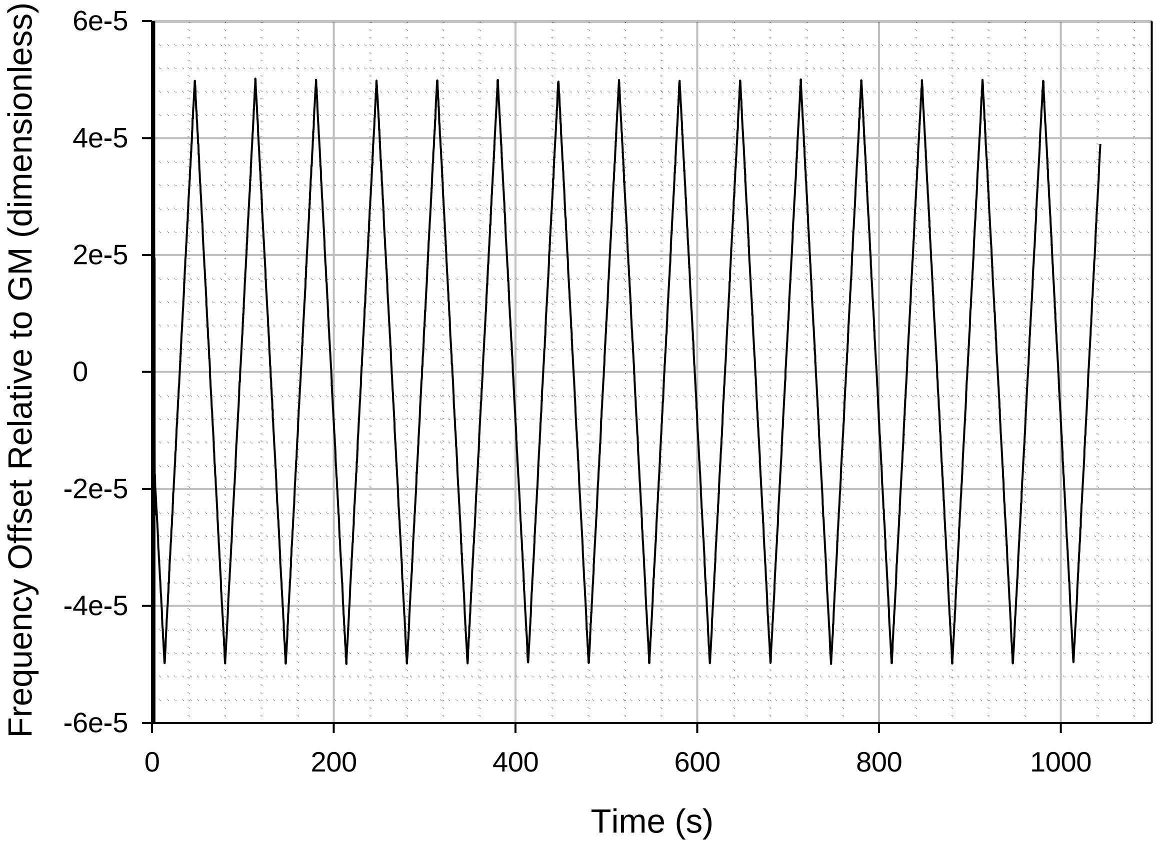
Case 11 – dTE, Node 100

Case 11, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



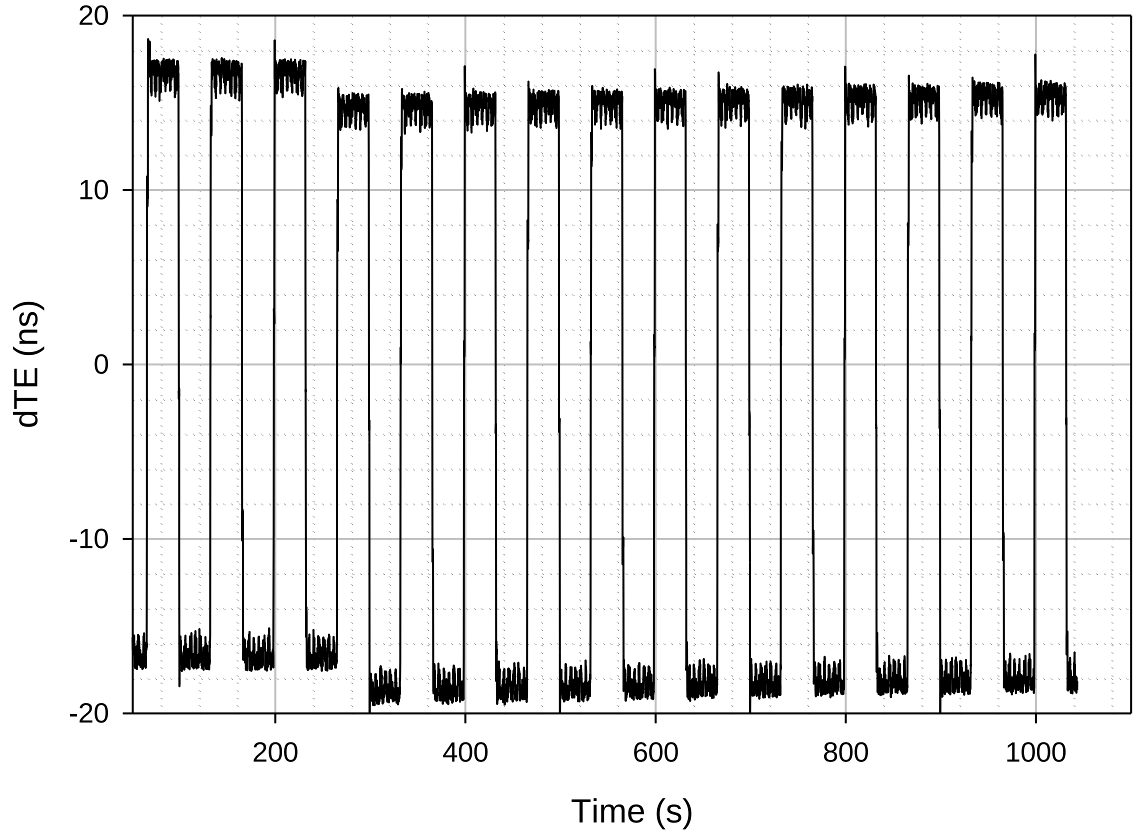
Case 11 – Measured Frequency Offset, Node 100

Case 11, PTP Instance (node) 100
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 4 ms
Frequency offset computation uses sliding window with median



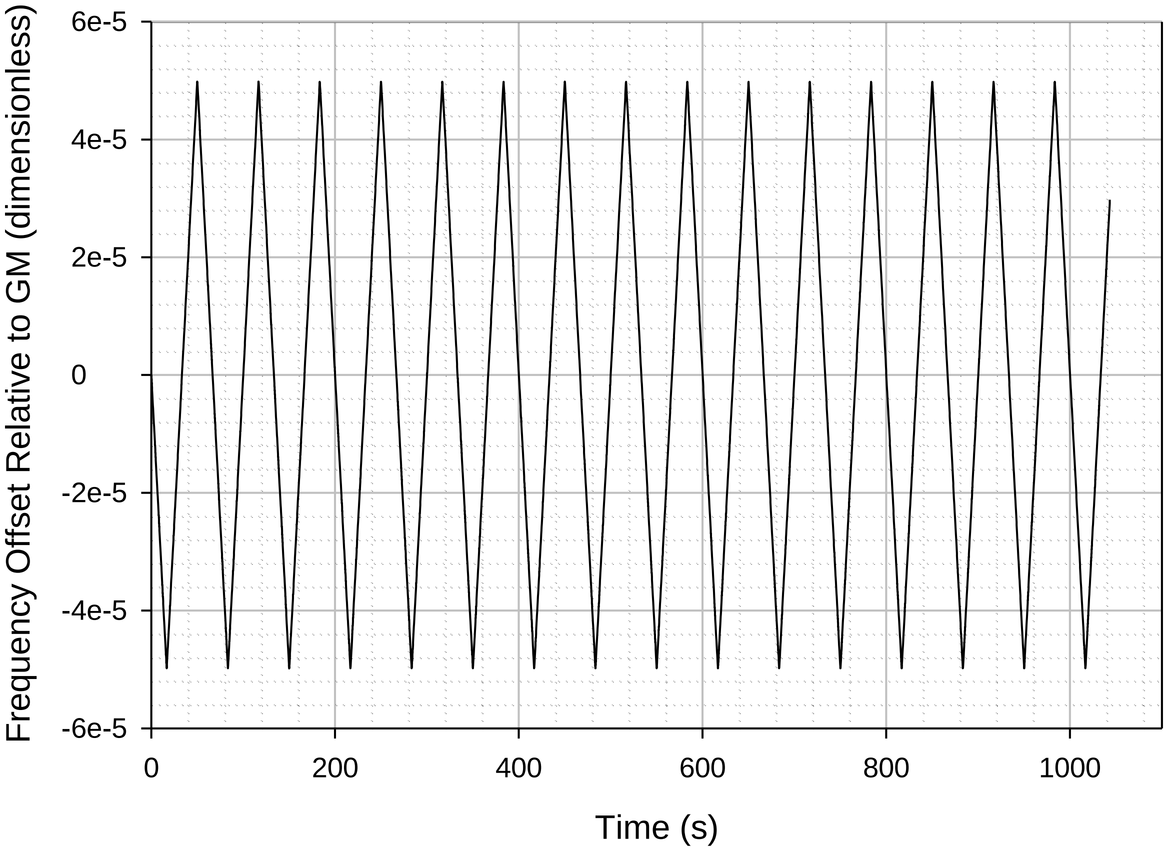
Case 12 – dTE, Node 2

Case 12, PTP Instance (node) 2
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



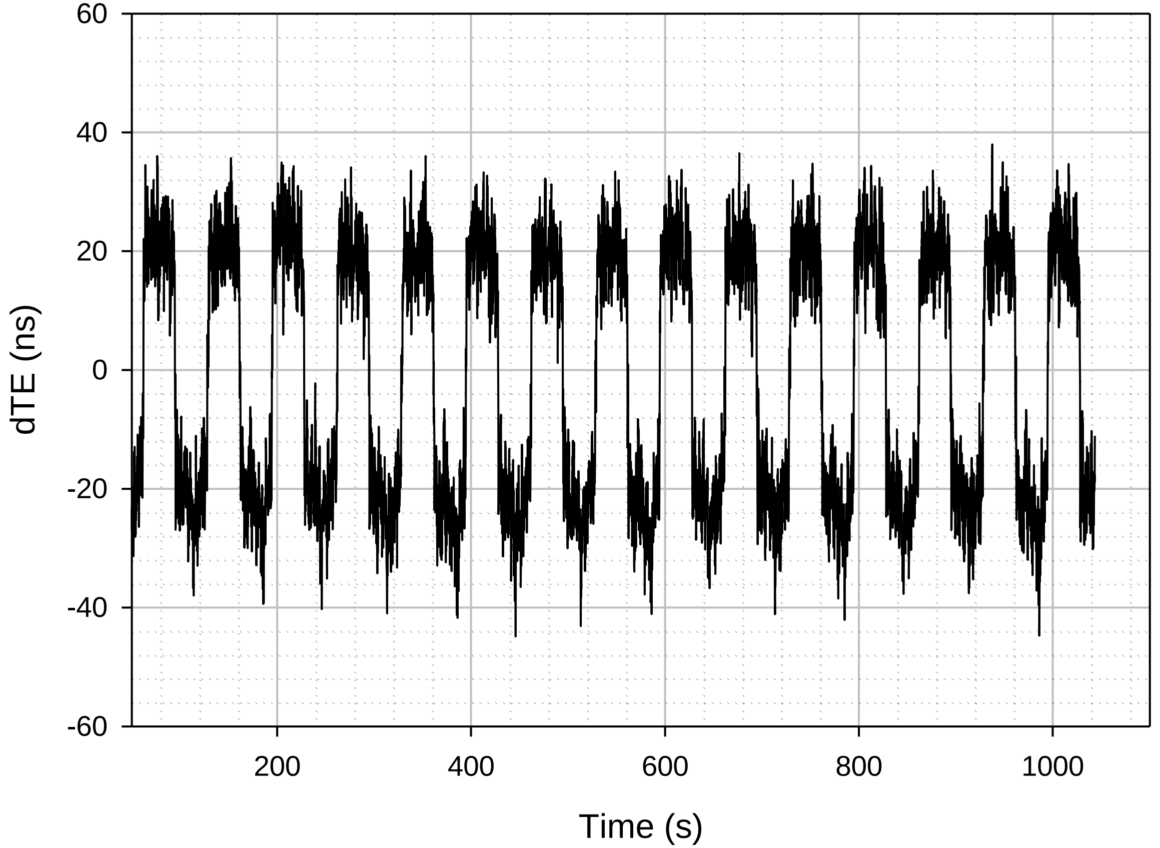
Case 12 – Measured Frequency Offset, Node 2

Case 12, PTP Instance (node) 2
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median



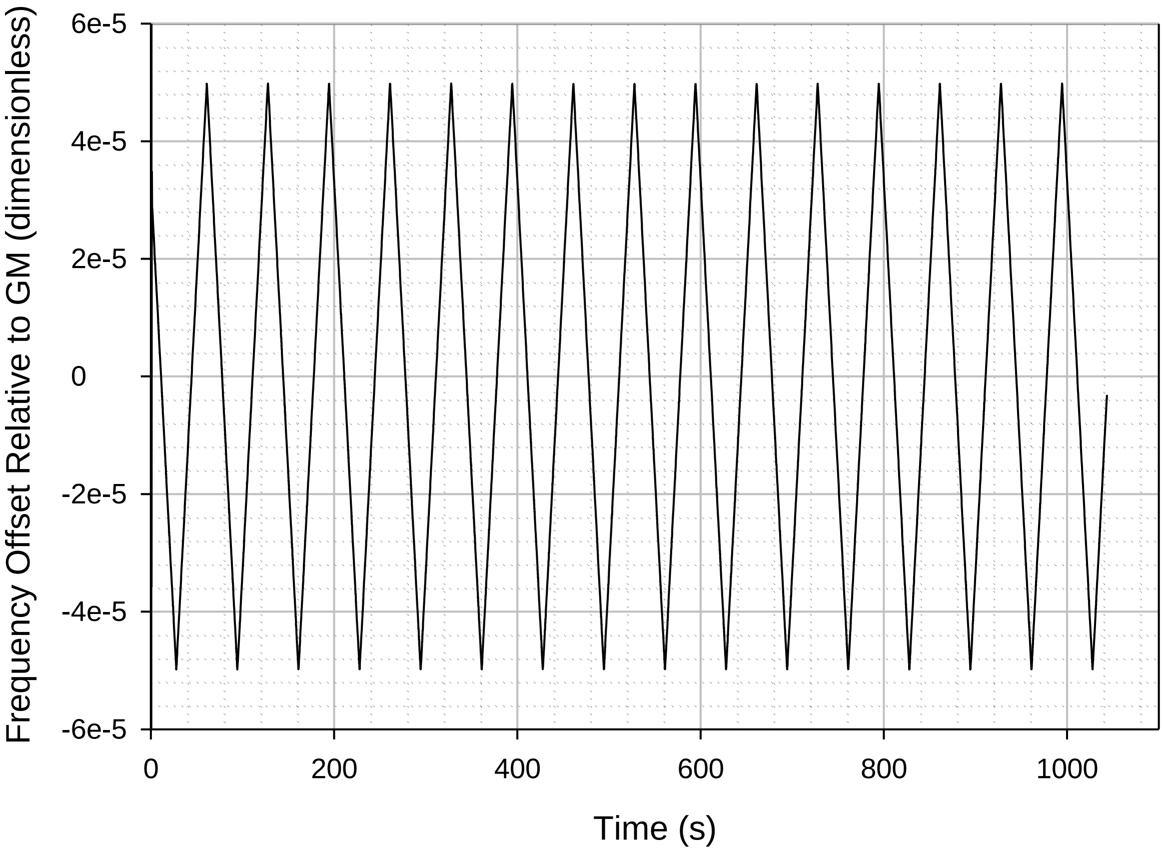
Case 12 – dTE, Node 50

Case 12, PTP Instance (node) 50
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



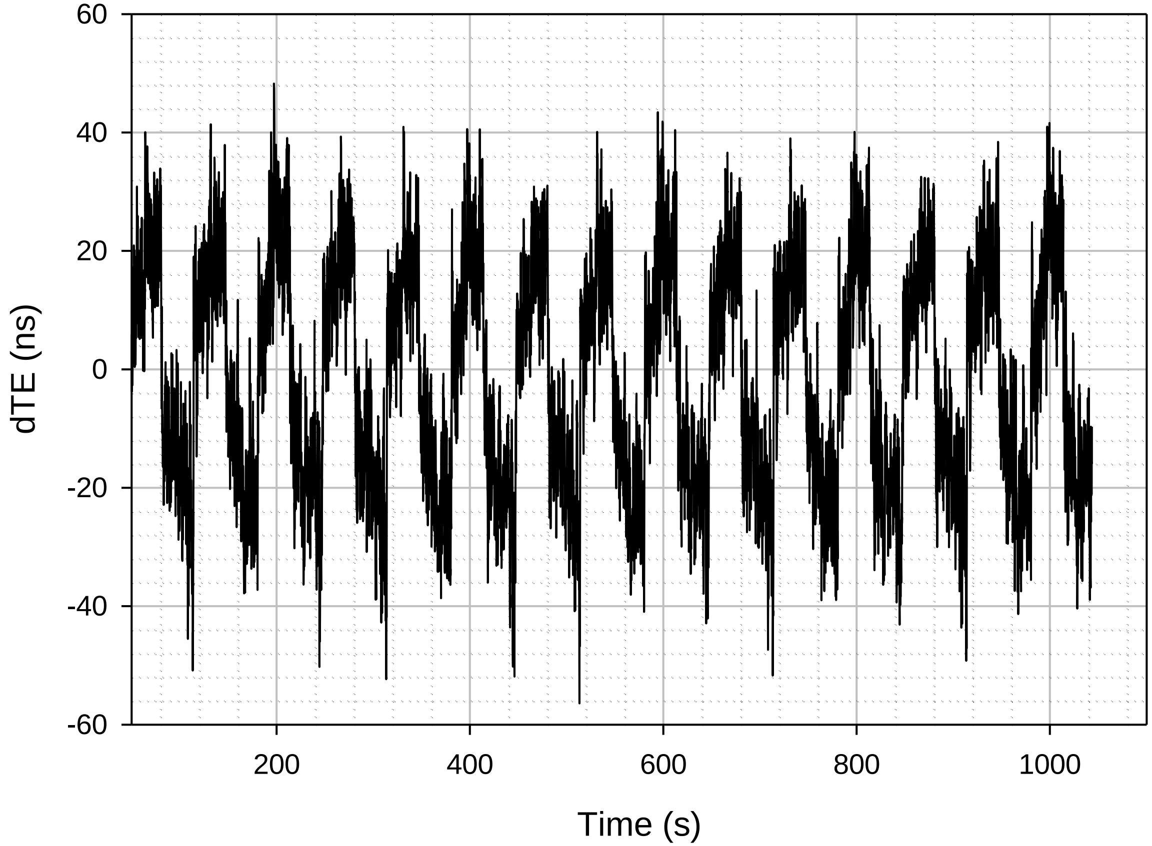
Case 12 – Measured Frequency Offset, Node 50

Case 12, PTP Instance (node) 50
Frequency offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median

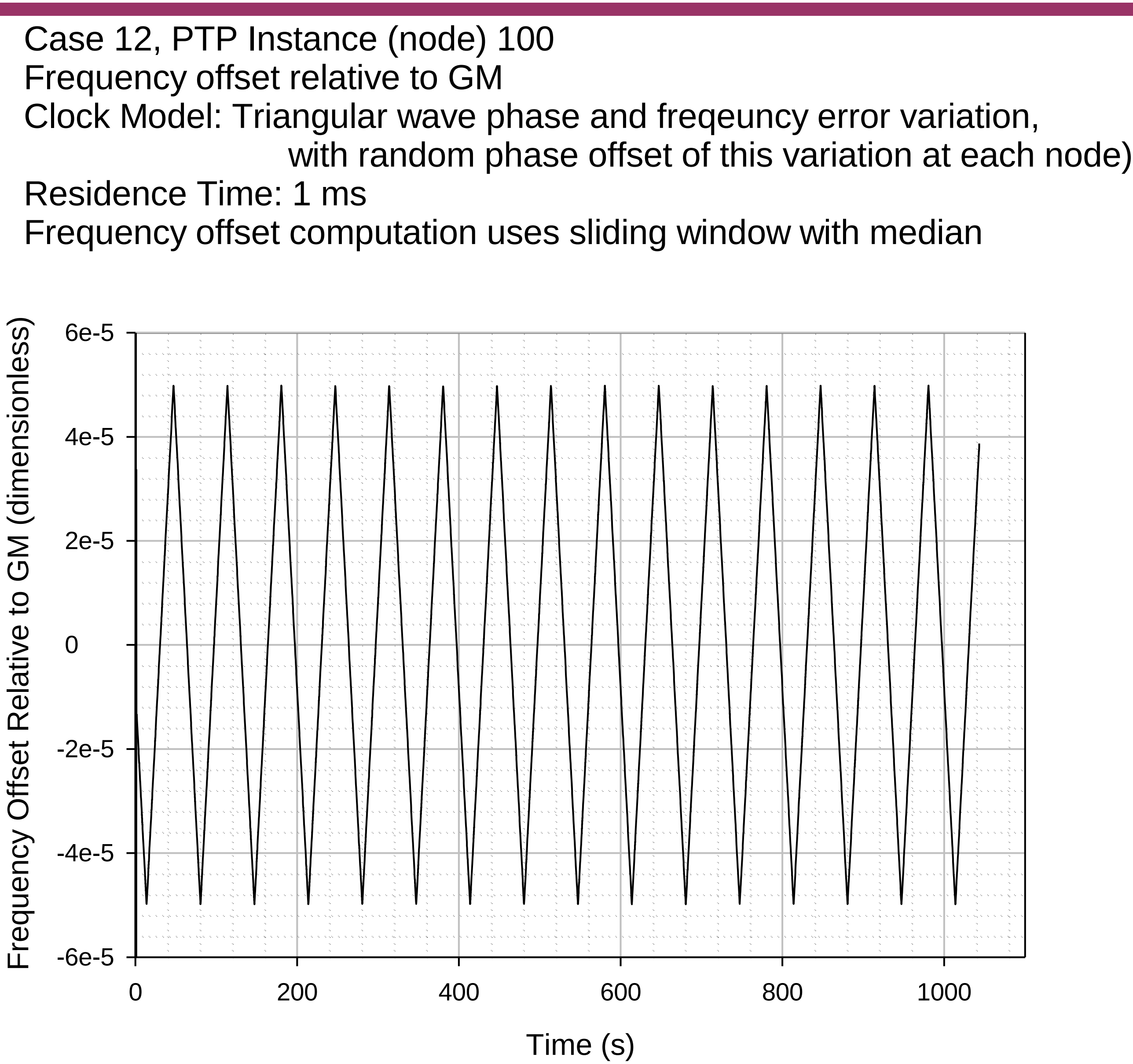


Case 12 – dTE, Node 100

Case 12, PTP Instance (node) 100
Filtered phase offset relative to GM
Clock Model: Triangular wave phase and freqeuncy error variation,
with random phase offset of this variation at each node)
Residence Time: 1 ms
Frequency offset computation uses sliding window with median
First 50 s omitted to eliminate any startup transient



Case 12 – Measured Frequency Offset, Node 100



Cases 7 – 12: Discussion

- ❑Consistent with the max|dTE| results in previous slides, results for cases 7 – 12 less dTE accumulation than for corresponding results for cases 1 – 6
- ❑Results for node 2 are approximately the same in all the cases (1 – 12) because node 2 results do not depend on residence time
  - There are small differences due to the different phase offset for the triangular wave at node 2 in cases 7 – 12 (compared to the corresponding cases 1 – 6, where the triangular wave phase offset is zero)
- ❑The square-wave characteristic of dTE is not maintained at later nodes in cases 7 – 12, compared to the corresponding cases 1 – 6, due to the random phase of the triangular wave local clock frequency variation

Conclusion and Discussion of Next Steps - 1

- With the current assumptions, it appears possible to meet the 1 μs objective for max|TE| over 100 hops (and therefore over 64 hops) if the residence time does not exceed 1 ms
- If the residence time is 4 ms (or less), it appears possible (with the current assumptions) to meet the 1 μs objective for max|TE| over 64 hops
  - For 100 hops, it appears there is sufficient margin to meet the objective if the median is not used in the GM rateRatio measurement
    - If the median is used, there might not be sufficient margin (further analysis is needed of the gain peaking inherent in the rateRatio measurement, as described below)
- If the residence time is allowed to take on the values 1 ms, 4 ms, and 10 ms, each independently (for each Sync message) with probability of 1/3, there is not sufficient margin to meet the 1 μs objective for max|TE| over either 64 hops or 100 hops

Conclusion and Discussion of Next Steps - 2

- The results clearly show the effect of gain peaking inherent in the estimation of rateRatio using successive Sync messages
  - The effect is less pronounced using a sliding window, as in the current presentation (compared to the jumping window used in [1]); however, the effect is still present
- As indicated in [1], an initial analysis of the effect of gain peaking in the use of successive Sync messages was presented in [8] and [9] (and also discussed in [7] and [10])
- While [7], [8], [9], and [10] are available in docs2007, they were prepared and presented over 13 years ago
  - The analysis contained in [8] and [9] is detailed; however, it should be reviewed for its exact applicability to the current scenario (i.e., regarding the exact assumptions)
  - This specifically relates to the computation of a numerical value for gain peaking and equivalent damping ratio in terms of the various parameters
  - Since the author of the current presentation was the author of [8] and [9], updated versions of [8] and [9] can be prepared if there is interest
  - This might be particularly relevant if it is desired to use the current parameters/assumptions, but with a residence time larger than 1 ms

Conclusion and Discussion of Next Steps - 3

- [1] also mentioned another improvement to the method of using successive Sync messages that was discussed in 802.1 during the February – May 2007 timeframe
  - This method was referred to as the “split syntonization method” (see [7] – [12])
  - In this method, the residence time is divided into two parts:
    a) The residence time as measured by the free-running local clock
    b) The correction to the residence time due to the measured rateRatio of the local clock relative to the GM
  - Component (a) above is accumulated in the correctionField (along with the gPTP link delay
  - Component (b) is accumulated separately (e.g., in a TLV)
  - rateRatio relative to the GM is computed using correctedMasterTime values that include component (a) but not component (b)
  - Synchronized time is computed using correctedMasterTime values that include components (a) and (b)
  - By not including component (b) in the rateRatio computation, the effect of errors in rateRatio at one node are not propagated downstream
  - Initial analysis of this scheme (see [8] and [9]) indicated that the growth in time error as a function of node number would be linear rather than exponential
  - However, this must be confirmed; this work was not pursued in 2007 because 802.1 decided to use the current method, i.e., accumulating neighborRateRatio

Conclusion and Discussion of Next Steps - 4

- An additional point regarding the use of successive Sync messages to measure GM rateRatio, rather than accumulate neighborRateRatio, is that the use of this method requires an amendment to IEEE Std 802.1AS-2020
  - This is because IEEE Std 802.1AS-2020 currently requires that the accumulated neighborRateRatio be used
  - This is true even if the Pdelay mechanism is turned off by setting the mean interval between Pdelay_Req messages to a very large value; in this case neighborRateRatio is initialized to 1.0 and, in the worst case, accumulated rateRatio is 1.0
  - Such an amendment would not necessarily need to be complicated, e.g., it could simply allow a TSN profile to optionally use successive Sync messages instead of accumulated neighborRateRatio, but leave more detailed specifications to the profile (this is just an example of one approach to this problem; it is not being advocated here)
    - However, the amendment would be needed
    - Note that no amendment is needed for IEEE Std 1588-2019, as 1588-2019 does not require any particular method for measuring GM rateRatio (in fact, it does not require that it be measured at all)

Conclusion and Discussion of Next Steps - 5

- Another point, which was noticed while performing the simulations, is that when the residence time is allowed to vary from one message and node to the next, as in cases 1, 4, 7, and 10, a Sync message that corresponds to earlier Sync information from the GM can be received at a downstream node later than a Sync message that corresponds to later information
  - Neither IEEE Std 1588-2019 nor IEEE Std 802.1AS-2020 address this possibility (or even mention it)
  - Indeed, if 1588-2019 were to mention this at all, it would be only in the context of transmission of a Sync message from one BC to another BC over some number of TCs; this is because a Sync message transmitted by a BC is considered to be a new message, i.e., it is not a retransmission of any previously received Sync message by that BC
  - Since 802.1AS-2020 considers the PTP Relay Instances to be BCs, the same applies
  - This initially appeared relevant because, when using successive Sync messages (separated by some number of Sync messages) to measure GM rateRatio, the question arose as to what if the two successive Sync messages corresponded to information transmitted by the GM in reverse time order from their order of reception
    - However, this appears to not be an issue, because what matters at the BC receiving the Sync messages are the correctedMasterTimes corresponding to those Sync messages, and these will be in the same order of reception assuming they do not have very large errors
    - Also, the likelihood of the order of reception being inverted is smaller for larger window size
    - In any case, this is mentioned here mainly for information

Conclusion and Discussion of Next Steps - 6

- In addition to the above points, it is also possible to refine or change one or more of the various assumptions
- However, it does seem that if it is desired to use successive Sync messages to estimate GM rateRatio, the analysis of [8] and [9] should be used (and updated if necessary), so that gain peaking and equivalent damping ratio for the method (use of successive Sync messages, with a sliding window) can be computed explicitly
- Among other uses for this, it may be desired to express the requirements of this approach in terms of maximum equivalent gain peaking (since the actual algorithm for GM rateRatio measurement is likely not to be specified in detail but would be left to implementation)
- It is proposed that the IEC/IEEE 60802 group discuss the above points and next steps

Thank you

References - 1

[1] Geoffrey M. Garner, *New Simulation Results for Time Error Performance for Transport over an IEC/IEEE 60802 Network*, Revision 1, IEEE 802.1 presentation, May 2020.

[2] Geoffrey M. Garner, *Initial Simulation Results for Time Error Accumulation in an IEC/IEEE 60802 Network*, IEEE 802.1 presentation, March 2020.

[3] Geoffrey M. Garner, *Discussion of Assumptions Needed for 60802 Network Simulations*, IEEE 802.1 presentation, January 2020.

[4] Geoffrey M. Garner, *Comparison of 802.1AS Annex B and 60802 Clock Stability*, IEEE 802.1 presentation, January 2020.

[5] Guenter Steindl, *IEC/IEEE 60802 Synchronization requirements and solution examples*, IEEE 802.1 presentation, available at http://www.ieee802.org/1/files/public/docs2020/60802-Steindl-SynchronizationModels-0620-v1.pdf.

References - 1

[6] Geoffrey M. Garner, *Simulation Results for Time Error Accumulation in a Cluster HRM of T-BCs Timed by PRTC-B (G.Supp65)*, Correspondence Document for ITU-T Q13/15, April/May 2020 Correspondence, CD13-08.

[7] Chuck Harrison, *Cascaded Gain Phenomena in IEEE 1588v2 Transparent Clock Chains an Initial Study*, IEEE 802.1 contribution, March 3, 2007.

[8] Geoffrey M. Garner, *Effect of a Frequency Perturbation in a Chain of Syntonized Transparent Clocks*, IEEE 802.1 presentation, March 10, 2007

[9] Geoffrey M. Garner, Effect of a Frequency Perturbation in a Chain of Syntonized Transparent Clocks, contribution (white paper) to IEEE 1588 and IEEE 802.1, March 10, 2007.

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