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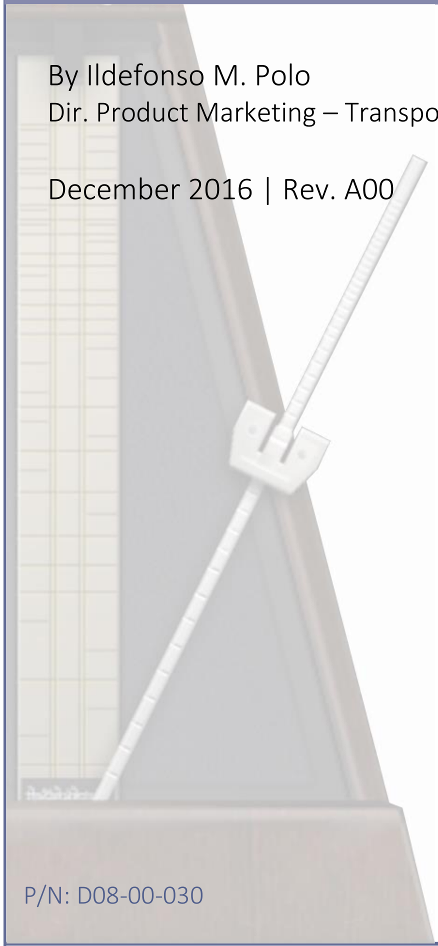
Can Constant Time Error (cTE) be "Measured"?

A Practical Approach to Understanding TE = cTE + dTE



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The data for this article was acquired using VeEX's TX300S and/or RXT-1200 Test Platforms with built-in GNSS, chip-scale Atomic Clock options and Multi-Service Test Modules. TE data is unfiltered and graphs were captured with VeEX Wander Analysis PC Software and/or built-in Clock Wander Analysis function.

The examples presented in this document were not specifically selected, modified or manipulated in any way to make a specific point. They were selected at random.

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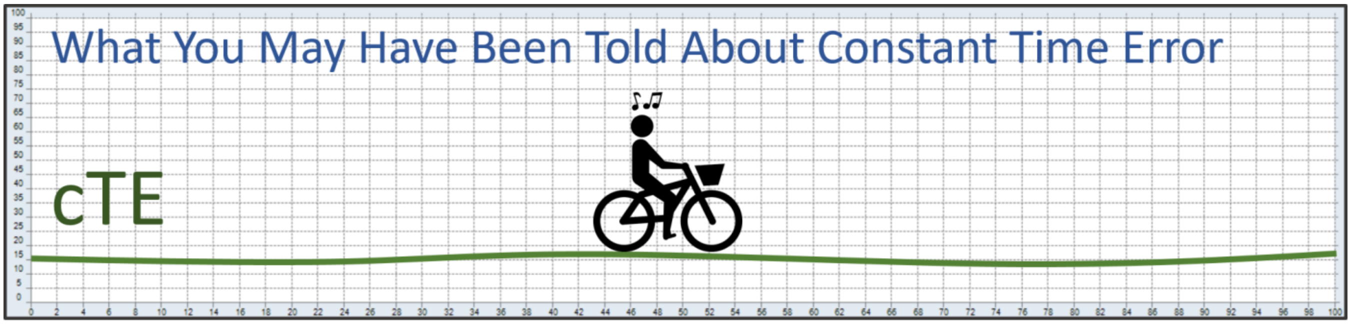
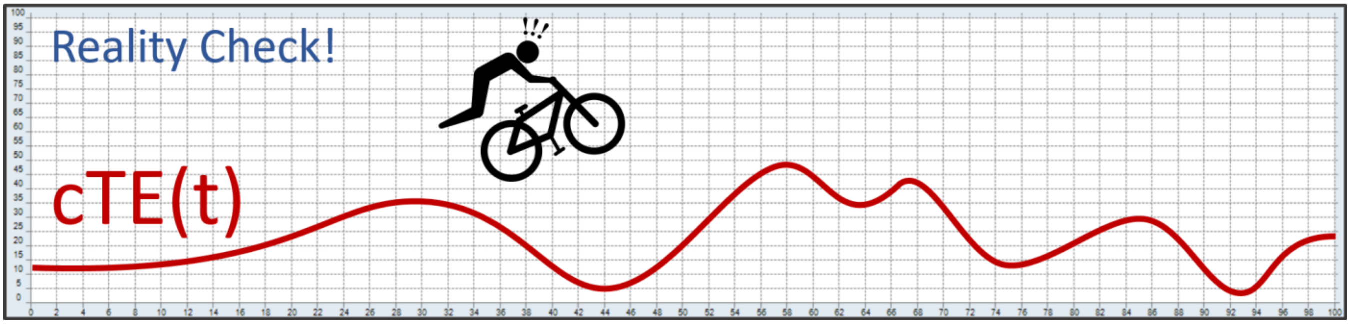
Can Constant Time Error (cTE) be “Measured”?

A Practical Approach to Understanding TE=cTE+dTE





Introduction

In early 2016 we started receiving many questions about the usefulness of cTE (constant Time Error) and dTE (dynamic TE), which come from the expression TE = cTE + dTE. Suddenly they seem to have become must-have measurements or parameters around the world. Apparently, they were being promoted as very important requirements to qualify PTP networks, links, nodes, network elements and other timing reference equipment.

Given the opportunity, I always ask people if the fully understand the application or true value added of whatever measurement, parameter or buzzword is in season. As you may imagine, the answers or justifications are not often encouraging. Sometimes we just default to repeat what we hear at seminars, trainings or even sales pitches.

The purpose of this paper is to explore the “true” meaning of cTE and dTE, applied to physical clocks and from a practical point of view. You must understand what they really are, to figure out how much value they can add. In other words, we try will to put TE, cTE and dTE in perspective. All by using actual data and avoiding theoretical simulations or made-up drawings.

Where do cTE and dTE come from?

In general, any physical behavior may be represented as $y(t) = C + K\cdot t + d(t) + n(t)$, in which C is a constant component (e.g. physical phase delay), K·t is a linear behavior (e.g. the effects of constant frequency offset), D represents a non-linear behavior (e.g. effects of frequency drift) and N is random noise (e.g. oscillator stability, PDV, phase noise, etc.). In that sense, absolute Time Error could be expressed as:

$$TE(t) = cTE + (\Delta f/f_{REF})\cdot t + (D_{DUT}-D_{REF})\cdot t^2/2 + dTE_N(t)$$

Ideally, in a fully synchronous system, the clock under test (DUT) is assumed to be fully locked in frequency and phase, and that it is traceable to the same time standard as the measurement reference clock. Based on such assumption, the overall offset and drift components are then considered to be (very close to) zero and conveniently eliminated from the expression. So, we end up with a highly simplified definition: Instantaneous time error is the sum of a <u>c</u>onstant delay plus an unpredictable <u>d</u>ynamic delay.

$$TE(t) = cTE + dTE(t)$$

Although this is just a mere generic definition, not really an equation, many seem to take this "formula" literally.

- **cTE** represents all the static contributions of predictable and constant delay sources, such as the ones induced by antenna cables, electronics, fiber optics, link asymmetry and connection cables. cTE is described as a constant.
- **dTE** represents the dynamic nature of clocks and timing distribution systems, containing the sum of all its unpredictable components. Such as: GNSS timing error, time stamping errors, queues/buffers/memories, PDV, traffic patterns, noise, oscillators' frequency variations and temperature dependencies, among other phase noise sources. dTE(t) is described as the variable part.

ITU-T G.8273.2/Y.1368.2 Appendix III.1 describes them as:

1. *cTE – the mean value of the time error function, measured over a <u>long</u> observation interval;*
2. *dTE – the variation of the time error function;*

*Note that "long" is quite a vague definition to be used in such critical topic as precision timing.

Section 7.1.1 Note 2 of the same specification adds "*For the purpose of testing the limits (for cTE), an estimate of constant time error should be obtained by averaging the time error sequence over 1'000 s*" then 7.1.2 dTE ads "*When temperature effects are included, ...with physical layer frequency support; in this case the maximum observation interval is increased to 10'000 s*"

The following TE(t) graph provides a visual representation of those parameters. cTE is usually portrayed as a flat (constant) line, but in reality it is just the red dot on the right, representing the overall mean value for that window.

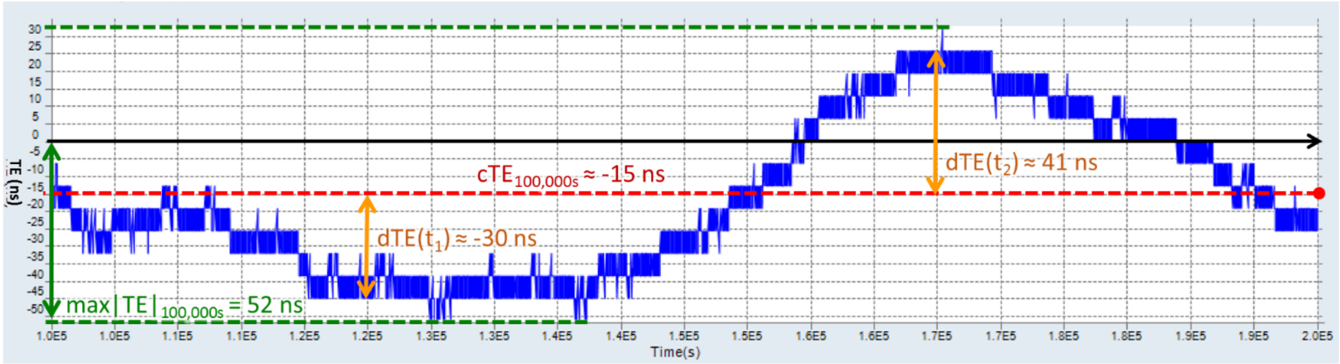


Figure 1. Actual absolute TE graph representing the theoretical concept of cTE and dTE. (Total time: 100,000s)

"Measuring" cTE?

The TE=cTE+dTE "formula" seems to imply that, if you can measure cTE and dTE(t), then you can calculate TE(t). But, in reality, it is the exact opposite. All you can <u>Measure</u> is the instantaneous absolute TE. Once you got enough TE samples, you can <u>Estimate</u> the mean cTE and then you can try to <u>Calculate</u> dTE. That is, you would need a very reliable cTE estimation in order to calculate fairly accurate dTE values.

Since cTE is defined as the mean TE value over a "long" observation interval, a 1000s sliding measurement window seems to be considered appropriate within the telecommunications sector. Good enough to average sufficient TE samples to filter the phase noise out and identify that constant cTE component (in just 16 minutes and 40 seconds).

A "sliding window" means that the T&M system continuously averages the last N samples (1,000s in this case) to calculate the current cTE (e.g. calculated once every second). Here are some real-life examples of that approach.

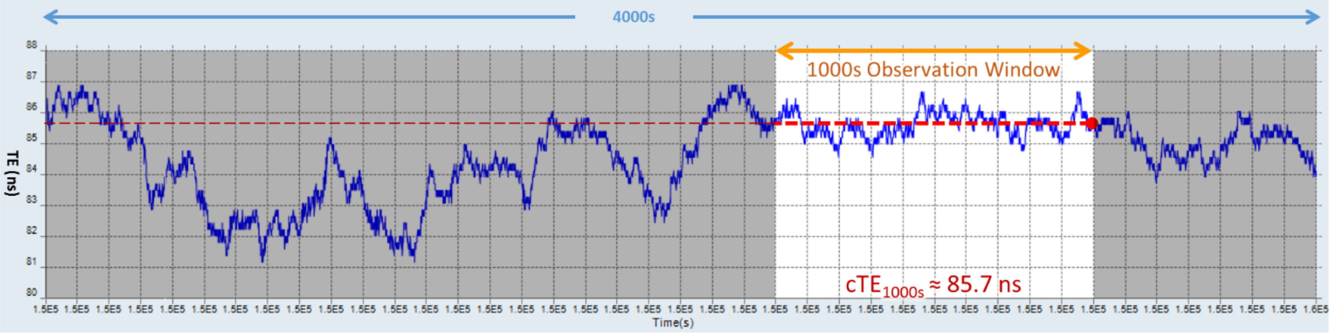


Figure 2. Within this single observation window, one can easily visualize a constant offset or delay. cTE ≈ 85.7 ns

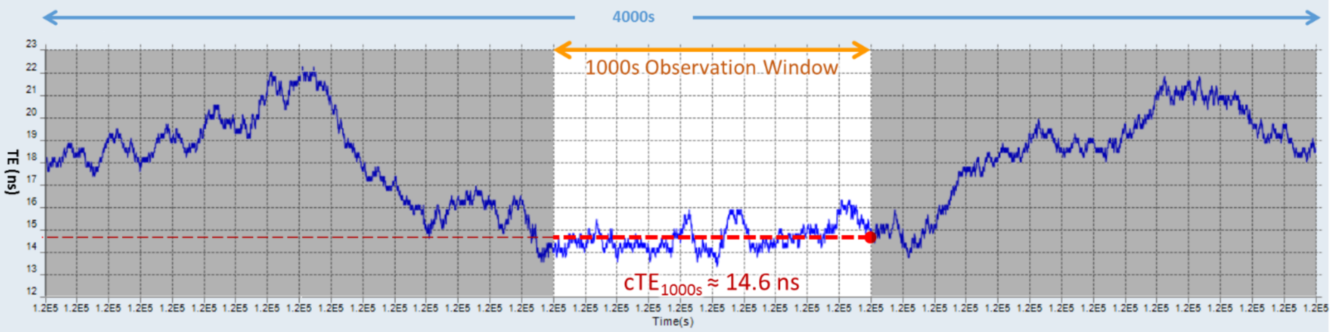


Figure 3. This is another example of a 1,000s observation window, with its mean value. cTE ≈ 14.6 ns

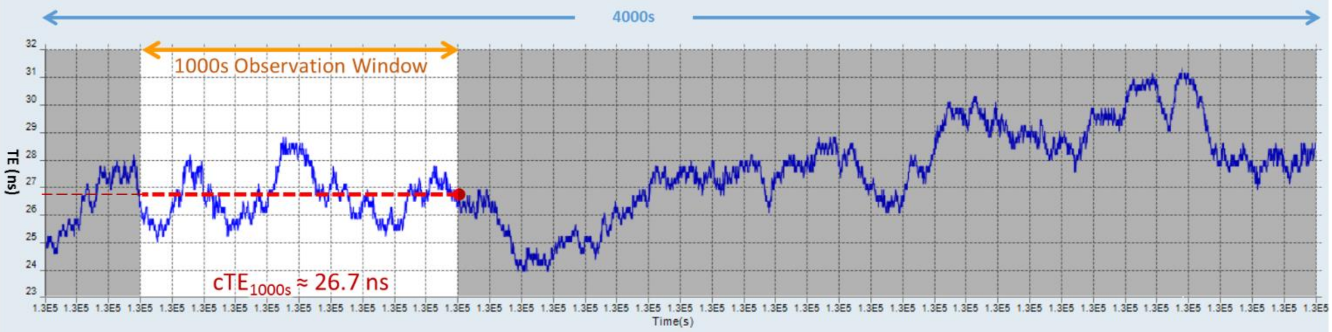


Figure 4. This observation window looks a bit noisier, but one can still visualize its mean value at cTE ≈ 26.7 ns

In certain cases, it is not clear whether there is any constant element within an observation window, nonetheless the algorithm will still output a mean value, based on the last 1,000 seconds being processed. For example, when there is a frequency offset component or frequency drift present in the TE behavior (permanent or temporary).

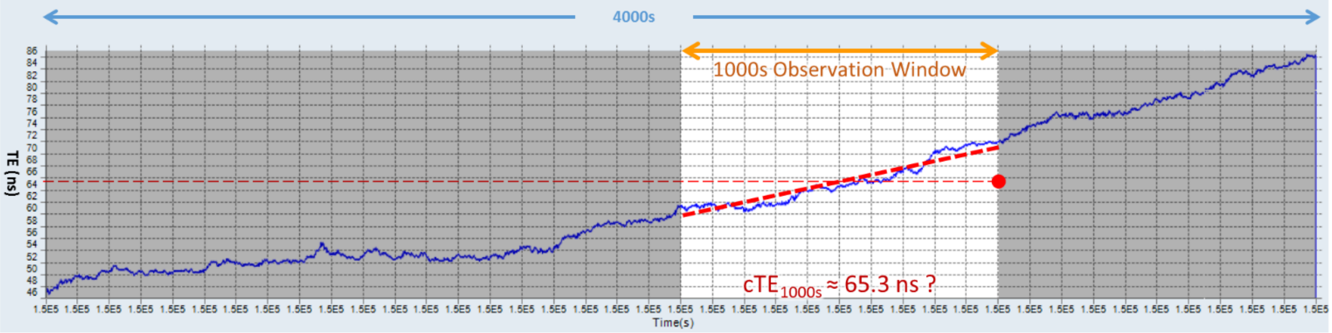


Figure 5. The math calculation still gives a cTE ≈ 65.3 ns result, although there is nothing constant in this window.

But what if I tell you, that all those values came from a single TE(t) measurement? All made within 24 hours and part of one continuous TE measurement, from the same DUT. A GPS-disciplined Oscillator (GPSDO) device under test. The only difference between them are the individual observation windows selected for each example. The following graph shows 24-hour worth of TE data and identifies all the measurement windows described earlier.

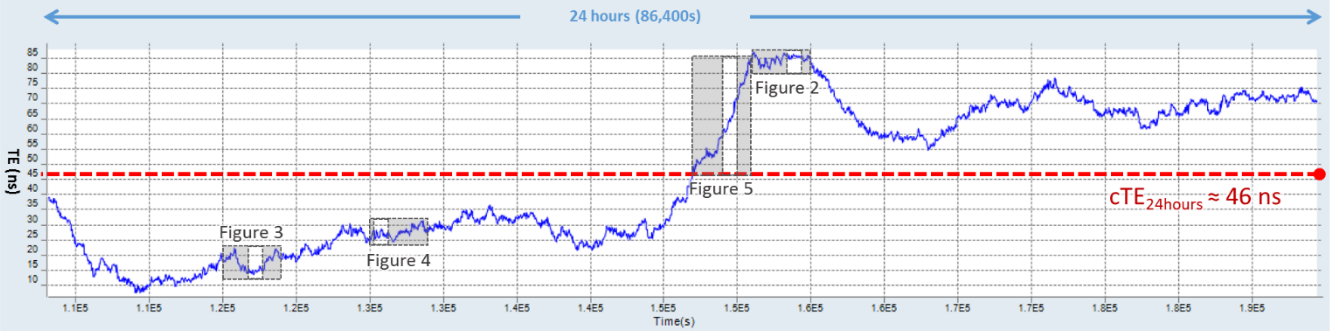


Figure 6. 24-hour view of the TE measurements used to extract all the previous cTE examples.

Having cTE values varying from 14 to 86 ns, would imply that the so-called "Constant" TE may not be that constant after all. At least not for Short observation intervals, such as 1,000s. That is, if you quickly "measure" cTE in the morning, you may get one set of values. If you "measure" it again in the evening, you could get something completely different. So, which value would you use to identify or fix a problem? Note that the dotted red line representing the overall mean value (e.g. 24h) are just presented as a visual reference. Its output is actually a single average value calculated at the end of the observation window (represented by a red dot).

Some may question whether the GPSDO under test may have been going through its disciplining process, which could justify the phase changes and invalidate the results. But, the answer is NO. The GNSS clock was already in steady locked state, doing its job by trying to keep its time aligned, based on the information it continuously received from satellites. You should also keep in mind that the TE measured is actually a combination of the TE_{DUT} and TE_{REF}, which includes phase errors from both. (In the spirit of this discussion, $TE = cTE_{DUT} - cTE_{REF} + dTE_{DUT} - dTE_{REF}$.)

So, where does the idea of a 1,000s observation window come from? Not sure. Although, it may have something to do with the convenience of instant gratification (that urge of getting results quickly). The problem is that those who provide such guidance often fail to explain their reasoning behind it or any of the trade-offs. Sure, you could certainly consider spending one hour measuring TE, most likely get a somewhat constant cTE value, write it down on a report, walk away and move on. But that should not be the point.

Reality Check: When observed at the nanosecond scale, not even PRTCs would give you that ideal flat TE line.

When talking about measuring Wander on precision clocks, with accuracies and stability in the order of parts-per-trillion (10^{-12}), everything happens very slowly. Patience, preparation and dedication are required in order to get valid useful measurements and perhaps good cTE estimates. You need to start by knowing the dynamics of the system under test in order to figure out a reasonable observation window (e.g. PRTC, Grandmaster, PTP link, Boundary clock, Slave clock, GPS clock, etc.).

We are talking about observation times long enough to capture the most complete or typical system cycle possible (or practical). For example:

- If the DUT is a GPSDO or PRTC, then the total observation time could probably be >1 day to capture the day and night ionospheric conditions, as well as hot and cold temperatures, etc.
- If the DUT is a PTP link, then the total observation time may be >1 day to cover high and low traffic, business-oriented packets during the day vs. streaming-oriented packets in the evening, hot and cold temperatures, etc.

For example, here is the same measurement data from the GPSDO DUT in question, showing four days' worth of TE data (still the same test). Longer tests not only provide a better chance of approximating the "true" cTE (one that can be used to "calibrate" or make corrections), it also provides a better idea of the dTE range and MTIE. Most importantly, it provides a better idea of the system's dynamics.

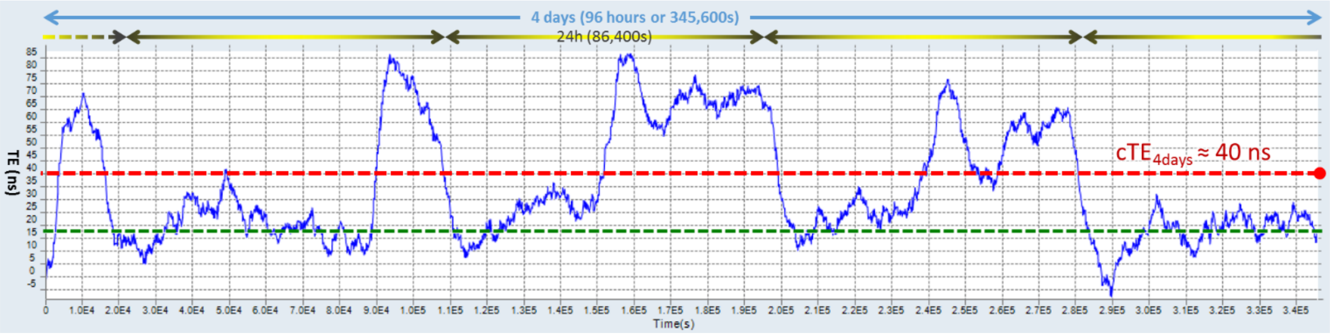


Figure 7. 4-day TE trace from the GPSDO under test, showing daily time offset variations.

Although this system barely passed the G.8272 PRTC mask, this particular example clearly shows the effects of day/night and high/low-temp cycles. This test was performed in late summer with moderately hot days and cooler nights. At 7:00 pm the building's HVAC turns itself off during week days (first and last days) and stays off during weekends (the two days in the middle). Perhaps only human eyes (not formulas) can be aware of the context of each test scenario, filter out impairments and visually identify the true mean error floor. The TE data clearly shows the effects of the environment heating up at noon and cooling down at midnight, by a few degrees. That is actually useful and actionable information. Something that can be used to address the issue and improve the system.

In my opinion, the constant delay of that system should not the 40ns cTE average (calculated over the whole 4-day window). Based on a simple visual analysis, I would consider it to be around 18 ns (green line), which is the mean delay that should remain once the temperature problem is addressed, by moving the DUT to a controlled temperature room (the equipment room) and adjusting its time constant, as suggested by the manufacturer's support team. (Refer to Annex A for more details about its final performance.)

Would four-day monitoring be good recommendation? It all depends. You need to know the application, environment, the dynamics of the system under test and the reason why you need to know cTE or TE in the first place. Once that is all clear, the measurement requirement may become obvious.

For further discussion on cTE usefulness, Figure 8 shows examples of cTE calculated with two different rolling windows and the overall mean value (24h). The one with 1,000s window shows very little difference from the original TE and even the 10,000s window struggles to maintain any constant value for an hour. In any case, the variations seem too high to be useful or to be used for any practical purposes or to be called "constant" at all!

Figure 8. Example of TE(t) and its corresponding rolling cTE(t), calculated with different observation windows.

There should be a good reason why you are being told that you need to know the cTE (as currently defined). Perhaps because you may want to fix it, by inserting an opposite phase offset (calibrate it out), so your system has a better chance of staying within the TE limits during high traffic events, in winter, summer, rainy, snow or sunny days. Based on the actual data and calculations above, the cTE doesn't seem to be doing a good job at it.

What About dTE?

Figure 8 already confirmed that cTE_{1000s} is actually a very variable cTE(t) function, which is remarkably close to the original TE(t), with a just few nanoseconds difference. Now, if we take those cTE calculations for granted and use their values to calculate dTE(t)=TE(t)-cTE(t), we arrive to another surprising result.

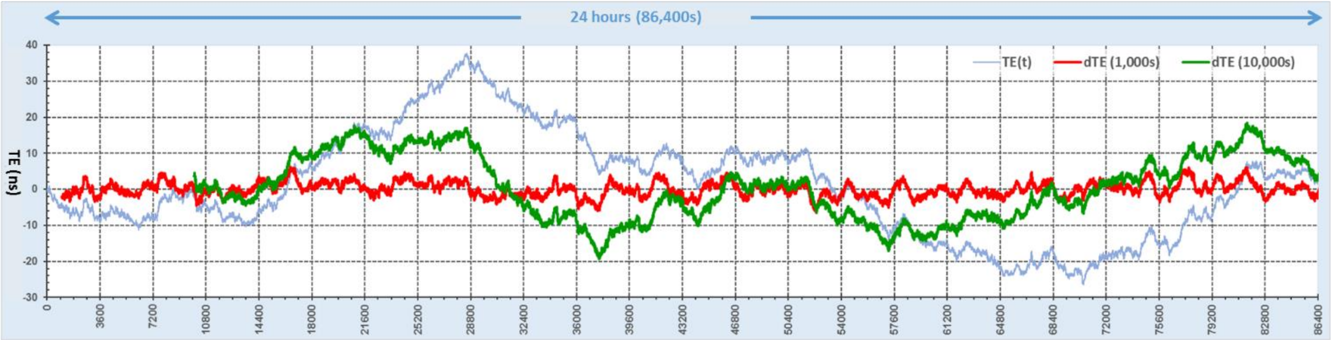


Figure 9. dTE(t)=TE-cTE calculated from the data in Figure 8. Dynamic dTE_{1000s} (red) looks surprisingly constant.

dTE seems to be behaving more like a constant. Although it is not what we were originally told, dTE_{1000s} just seems to be doing a very good job at isolating the high frequency noise (high pass filter).

What if dTE is used (irresponsibly) and the red ±5ns dTE_{1000s} graph alone is presented to you? At first glance it may look like the clock under test is much more stable than it actually is (the actual TE data tells us that it is 6 ±32 ns). So, if TE already tells the full and true story of the DUT, why would we need cTE or dTE?

Conclusion

We need to fully understand what cTE really is and what to expect from it, in order to know when to use it and how it could help us improve our network and timing sources. Always keep in mind that cTE may not be a constant and that it can't be measured directly. Keep in mind that this article focuses on physical timing signals and does not address potential applicability of dTE and cTE at the logical level (protocol/packet time stamping and latency).

Are the cTE concept and values useful? Not sure. But it certainly has some limitations that you need to be aware of. It may be only be somewhat accurate in determining the required delay compensation for extremely stable systems and under lab environments.

Get to know the system's dynamics in order to identify the proper observation window. Then weight that against your practical requirements. For example, do you really have 24, 48 or 96 hours to test a link? If not, then embrace your reality, adapt your process to it and acknowledge any trade-offs.

Some may still argue that cTE is needed in order to know the constant Delay (or Time Offset) of a system. But, the true system delay may be closer to the minimum delay measured (e.g. caused by cables, fiber and bare electronics delays) and it is always positive. For example, in the packet network that would be the true lucky packets' latency times, since information can travel faster or arrive earlier.

When measuring or verifying Precision Timing devices or systems, I (personally) prefer to stick to the good-old TIE, TE, MTIE and sometimes TDEV, because they provide the whole picture, full of actionable information. Something that can be used to fix or improve the settings and hence the synchronization quality of the system. For example, from TIE or TE data we can easily identify and calculate frequency offset, with great accuracy. Then that information can be used to remove it by calibrating (adjusting) the oscillator. That can't be said for many other acronyms people usually hear at conferences and then start repeating around, for no apparent reasons.

Keep in mind that, as we zoom in into the nanosecond scale, used for Precision Timing, nothing is steady or constant anymore. Also, timing references available to mortals like us, have time error of their own and they will be embedded in your measurement results. When working outside of controlled labs, you have to embrace those facts and account for the uncertainties.

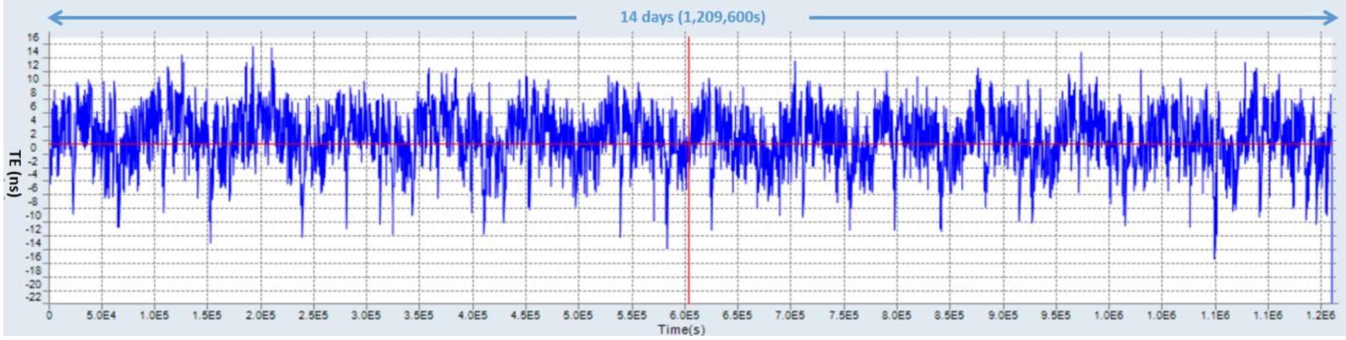
Perhaps this paper does not provide any specific answers, but we certainly hope it has raised a few questions and pointed you in the right direction, so you can investigate, evaluate and question the usefulness of the cTE and dTE concepts and take them for what they really are.

Annex A. Resulting GPSDO Performance Improvements

Figure 7 showed the fairly good, but not good enough, performance of a GPS-disciplined oscillator (PRTC) and this section has been added to close the loop on this test case, as it was used as a real-life practical example.

Although it barely passed the PRTC mask, a simple visual inspection of the original TE graph showed that something was not quite right and that there was room for improvement. The first hint was the cyclical nature of the TE variations, which the time-line identifies as a daily cycle. That in turn leads to suspects like day/night variations and temperature changes. This shows that the original TE(t) measurement is a very powerful tool on its own.

After contacting the manufacturer’s customer support team, they suggested adjusting the time constant (TC) and not using the default settings that came programmed in the brand new Rb GPSDO being used as a PRTC. An 18 ns phase adjustment was also applied, based on the assumption (educated guess) explained earlier. The 14-day TE results below show the resulting improvements. It has come down to TE ≈ 1 ±15 ns, from its original 38 ±48 ns.



Its G.8272 PRTC mask validation, over a 14-day test, has also improved significantly.


Wander Analysis(2.0.8.18235)

Primary : C:\...\20161017-GPSDO-900s-50ns_10MHz-14daysPRC\mtie
Secondary :

Start Time: 10/18/2016 3:58:29 PM
End Time: 11/1/2016 3:58:29 PM
Total: 1209600 s
Sampling: 1/s

Primary MTIE ☑
Primary TDEV ☑
Mask G.8272 - Primary Reference Time Clock (PRTC) in Locked Mode

PASS

Further stability improvements are also expected when the system is moved into a more controlled environment.

This goes to show that the absolute TE data provides actionable information, which can be used to troubleshoot, fix and improve the system under test. In my opinion, TE is a far more practical value for field applications.

Abbreviations & Acronyms

1PPS	One Pulse Per Second (its rising edges indicate a beginning of new standard seconds)
cTE	Constant Time Error
dTE	Dynamic Time Error
DUT	Device (or System) Under Test
GNSS	Global Navigation Satellite Systems (often refers to the receivers used to extract standard timing)
GPS	Global Positioning System (the most prevalent GNSS)
GPSDO	GPS Disciplined Oscillator or GPS Clock
HVAC	Heating, Ventilating and Air Conditioning system
ITU-T	International Telecommunication Union - Telecommunication standardization sector
MTIE	Maximum Time Interval Error (maximum peak-to-peak TE or TIE)
NE	Network Element/Equipment
NEM	Network Equipment Manufacturer
PDV	Packet Delay Variation
ppb	Parts per billion (1.0E-9 or $1\text{x}10^{-9}$)
ppm	Parts per billion (1.0E-6 or $1\text{x}10^{-6}$)
ppt	Parts per trillion (1.0E-12 or $1\text{x}10^{-12}$)
PRC	Primary Reference Clock (Frequency only)
PRTC	Primary Reference Time Clock (with 1PPS timing and ToD output)
PTP	Precision Timing Protocol (IEEE 1588v2)
REF	Reference Clock (often a traceable PRTC)
T&M	Test and Measurement (industry or equipment)
TDEV	Time Deviation
TE	Time Error
TIE	Time Interval Error

Notes

About VeEX Inc.

Founded in 2006 by test and measurement industry veterans and strategically headquartered in the heart of Silicon Valley, VeEX Inc. provides innovative Test and Measurement solutions for next generation networks, services and communication equipment.

With a blend of advanced technologies and vast technical expertise, VeEX's products diligently address all stages of network design, verification, deployment, maintenance, field service turn-up, troubleshooting and integrate legacy and modern service verification features across DSL, Fiber Optics, WDM, CATV/DOCSIS, Mobile backhaul and fronthaul/DAS (CPRI/OBSAI), next generation Core & Transport Network, Fibre Channel SAN, Carrier & Metro Ethernet technologies and Synchronization.

The VeEX team brings simplicity to verifying tomorrow's networks.

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