TimeProvider® 4100 ePRTC Performance Compliance Report

Introduction

TimeProvider 4100 is a family of precise timing systems with various operation modes that enable a customer to specify a configuration for a use case while leveraging the same hardware.

As part of this delivery strategy, an Enhanced Primary Reference Time Clock (ePRTC) license option has been defined in release 2. This enables a customer to configure the TimeProvider 4100 unit as an ePRTC device connected to a GNSS source and one or two cesium clocks to meet ITU-T G.8272.1 standard performance requirements.

This is the second in the series of performance reports describing the Enhanced Primary Reference Timing Clock (ITU G.8272.1) feature of the TimeProvider 4100 system.

TimeProvider 4100 is architected to support multiple software configurable operation modes on a robust, high-performance, fan-less 1RU hardware platform. The current operation mode configurations supported as of release 2.1.10 are:

- Gateway clock
- Single-domain, high-performance boundary clock
- Multi-domain, high-performance boundary clock
- ePRTC

When configured in the ePRTC operation mode, TimeProvider 4100 is fully compliant with the controlling ITU-T recommendation: timing characteristics of enhanced primary reference time clocks G.8272.1.

TP4100 supports not just one but optionally two autonomous atomic clock references. When configured with dual autonomous atomic clock inputs, TimeProvider 4100 supports both priority reference operation and adaptive timescale ensembling, as described in the first installment.

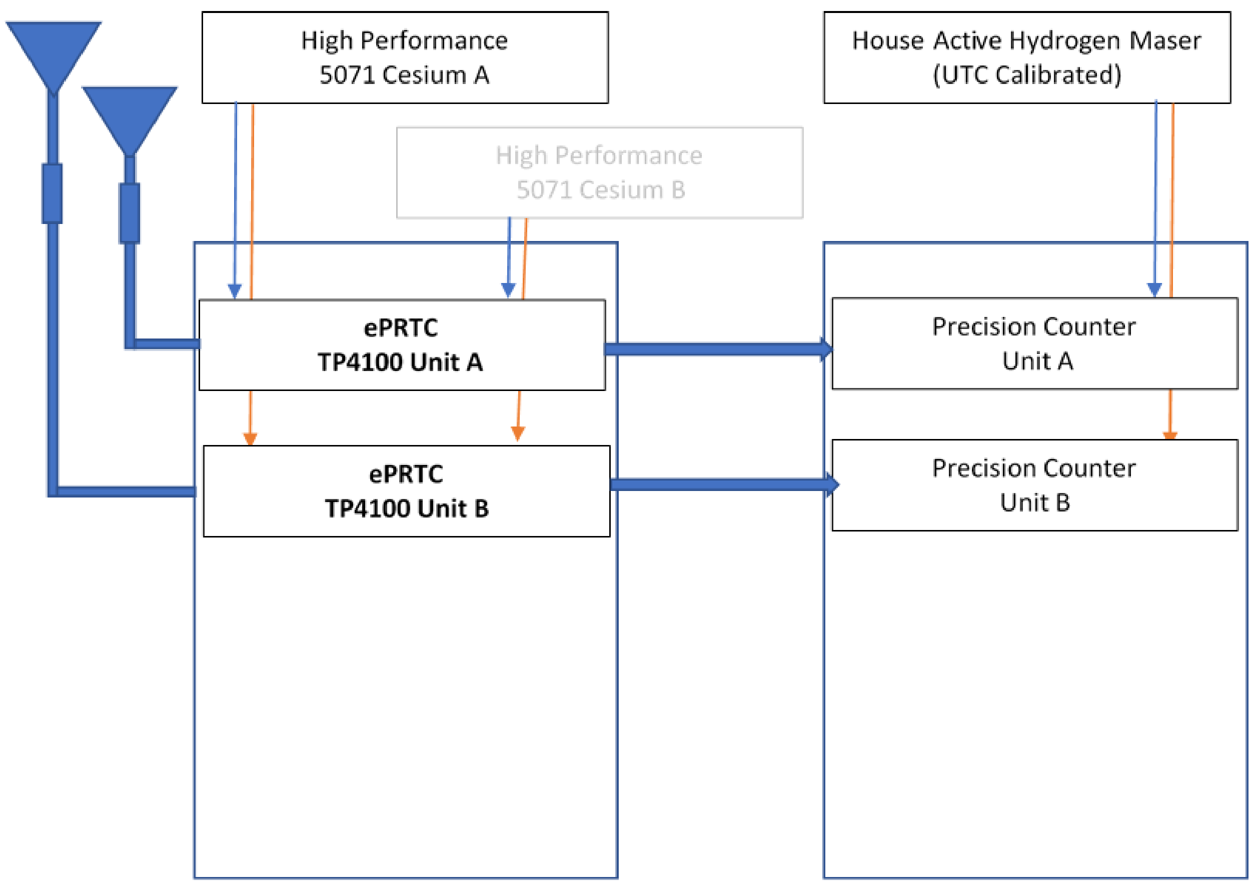
Table of Contents

1. Overview of Time Compliance Testing

The full characterization of time accuracy compliances will be covered in this series of performance reports. In the first report, the time compliance in normal operation was the focus including both single and dual cesium configurations. In this second report, we document a complete compliance certification including all phases of operations from power-up to various holdover outage and recovery conditions.

A test instrumentation like the configuration for the first performance testing is used. For certification testing, we selected our R&D facility in Tuscaloosa, Alabama. This facility provides multiple Universal Time Coordinated (UTC) calibrated hydrogen masers to support the necessary precision and accuracy for proper ePRTC certification. The test configuration is shown below. For the certification we are testing two TimeProvider 4100 systems configured with ePRTC licenses. One unit is configured for single-band GNSS operation and the second unit is configured for multi-band operation (multi-band support is in prototype stage and will be officially available in the upcoming 2.2 release). A single 5071 cesium clock is used as the primary reference source input to both TimeProvider 4100 systems under test.

Figure 1-1. Test Configuration



2. Normal Operation Before Holdover

2.1 Pre-Holdover Normal Learning Stage

2.1.1 First 2 Days of Operation

2.1.1.1 First Day of Operation: May 21

We now have an overnight baseline of the two TimeProvider 4100 ePRTC systems:

- TimeProvider 4100 ePRTC configured to operate as a single-band (L1 only) receiver. (blue graph)
- TimeProvider 4100 ePRTC configured to operate as a multi-band receiver. (red graph)

We are running a long, multi-week performance validation supporting this compliance report. Our Tuscaloosa R&D facility was selected to host this testing as the multiple, high-performance active hydrogen masers and continual traceability monitoring with UTC(NIST) provides the stable and accurate reference necessary to document the pedigree of our ePRTC offering.

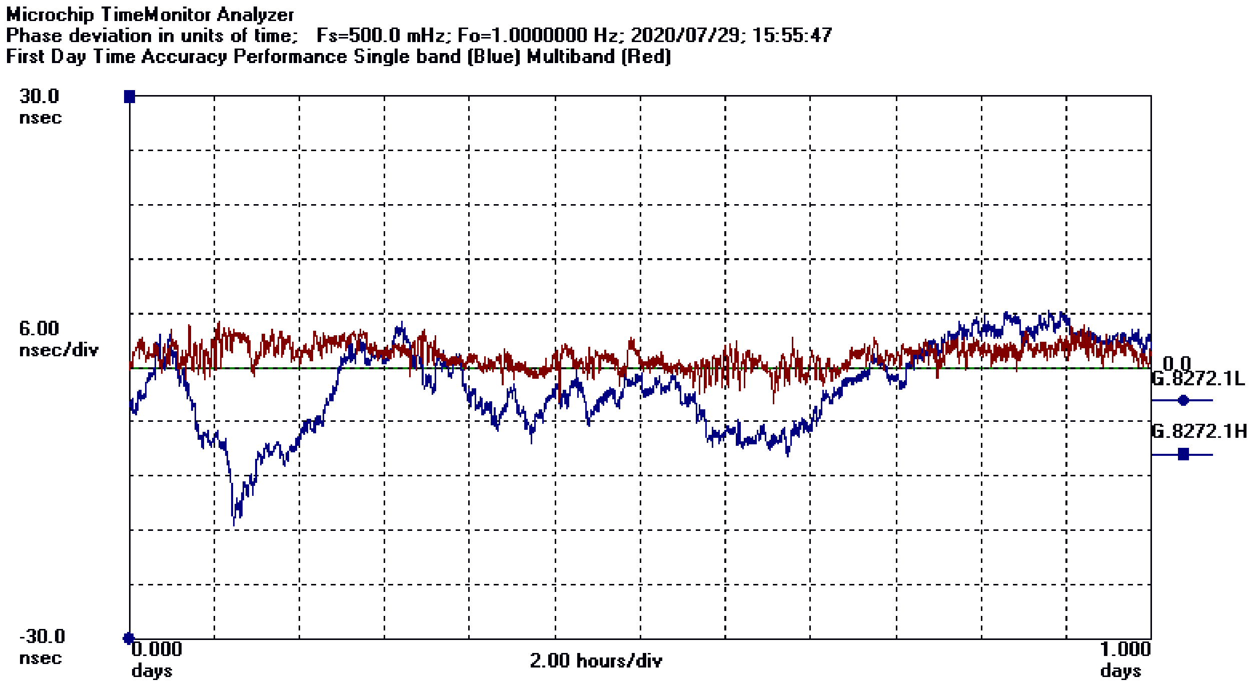
TimeProvider 4100 ePRTC supports a user-visible learning period during the early days of operation. This is indicated to the user by a simple dashboard ePRTC Protection Availability Index. As the system learns the calibration correction needed to maintain the local timescale on UTC, the coupling of the steering data become increasingly loose. In steady state, the de-coupling is such that it is only adjusted based on a full, 24-hour assessment. This provides unparalleled GNSS firewall protection against GNSS errors such as those associated with space weather, local RF jamming and spoofing, multipath, reflections, and other interference.

Since this data is only for the first 24 hours, the Protection Availability Index is still low (15% after the first 21 hours).

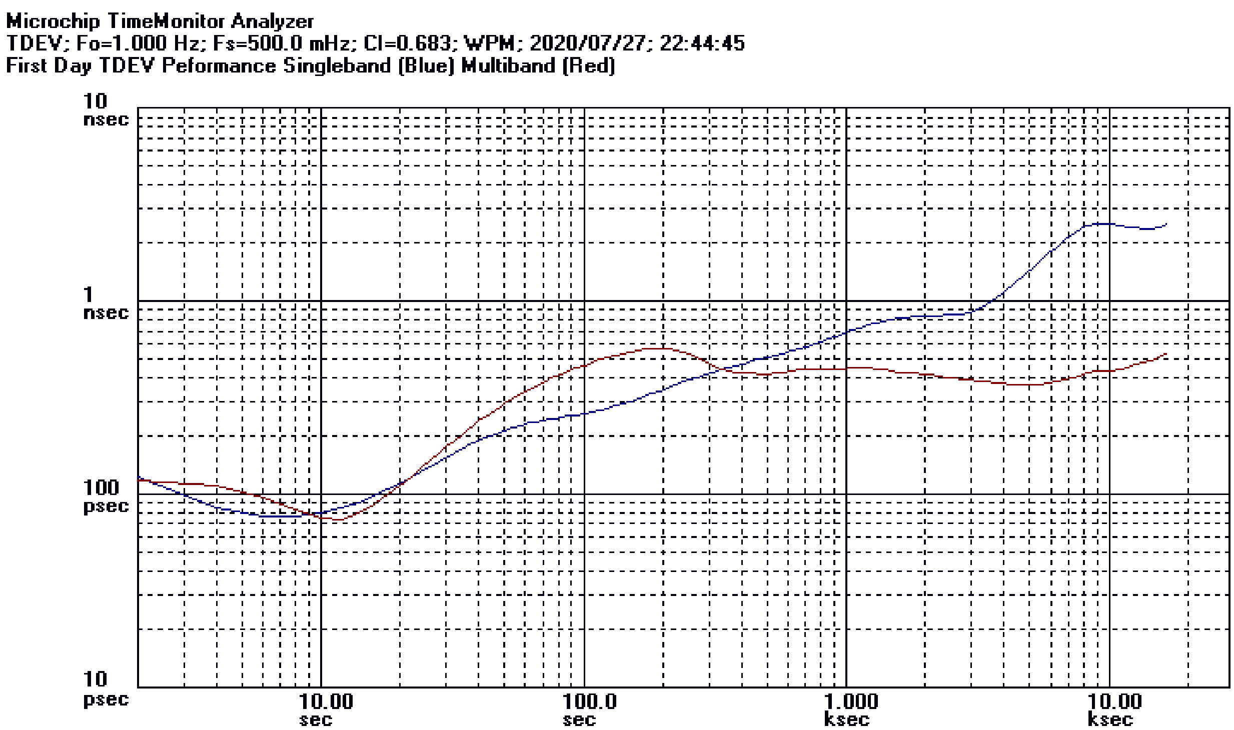
Another start-up effect is the initial 24-hour position survey. We started the single-band unit with auto survey enabled, so it is still learning the position. In contrast, the multi-band unit was started with a manual position as was determined during earlier testing.

The following three graphs show the overnight data.

The first graph shows the PPS time error with respect to the active hydrogen maser for both systems. The time accuracy requirement for an ePRTC is 30 ns. We can see that even during the early learning period we are performing better than this normal operation requirement. Clearly the time error for the single band unit is converging as it is still in dynamic positioning mode.

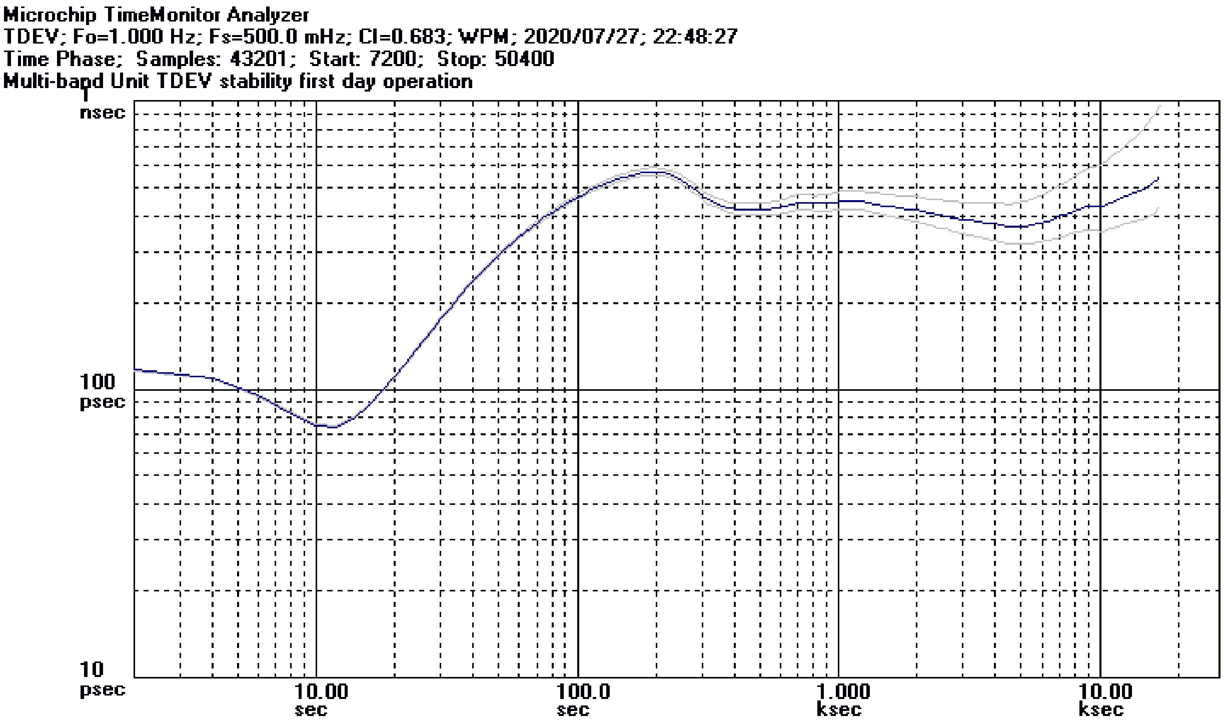


The second graph shows the stability performance. The TDEV performance for the single-band receiver unit (blue graph) is impacted by this same positioning activity and it is too early to consider steady state compliance.



In contrast, consider the TDEV performance of the multi-band system (red graph). It has the benefit of starting in a precisely surveyed-in state and it is operating in multi-band mode including both GPS (L1 and L2) as well as Galileo (E1 and E5b).

The last TDEV graphs show the same multi-band unit TDEV performance with confidence bars. We can see that the performance is nominally at 600 ps, which is well within the 1 ns requirement. The systems are not in normal fully protected mode during the first several days, but we can already see the stability compliance is within steady state margins with a pre-surveyed system.



The ePRTC provides a reference time signal traceable to a recognized time standard (that is, coordinated universal time (UTC)) and a frequency reference. Compared to the primary reference time clock (PRTC) as defined in the except from Scope Rec. ITU-T G.8272.1/Y.1367.1 (11/2016), the ePRTC is subject to more stringent output performance requirements and includes a frequency input directly from an autonomous primary reference clock.

For this long-term testing, both systems are utilizing a 5071 high-performance cesium atomic clock.

2.1.1.2 Second Day Since Power-up: May 22

The first graph shows the time error overlay of both TimeProvider 4100 ePRTC systems:

- TimeProvider 4100 ePRTC configured to operate as a single-band (L1 only) receiver (blue graph)
- TimeProvider 4100 ePRTC configured to operate as a multi-band receiver (red graph)

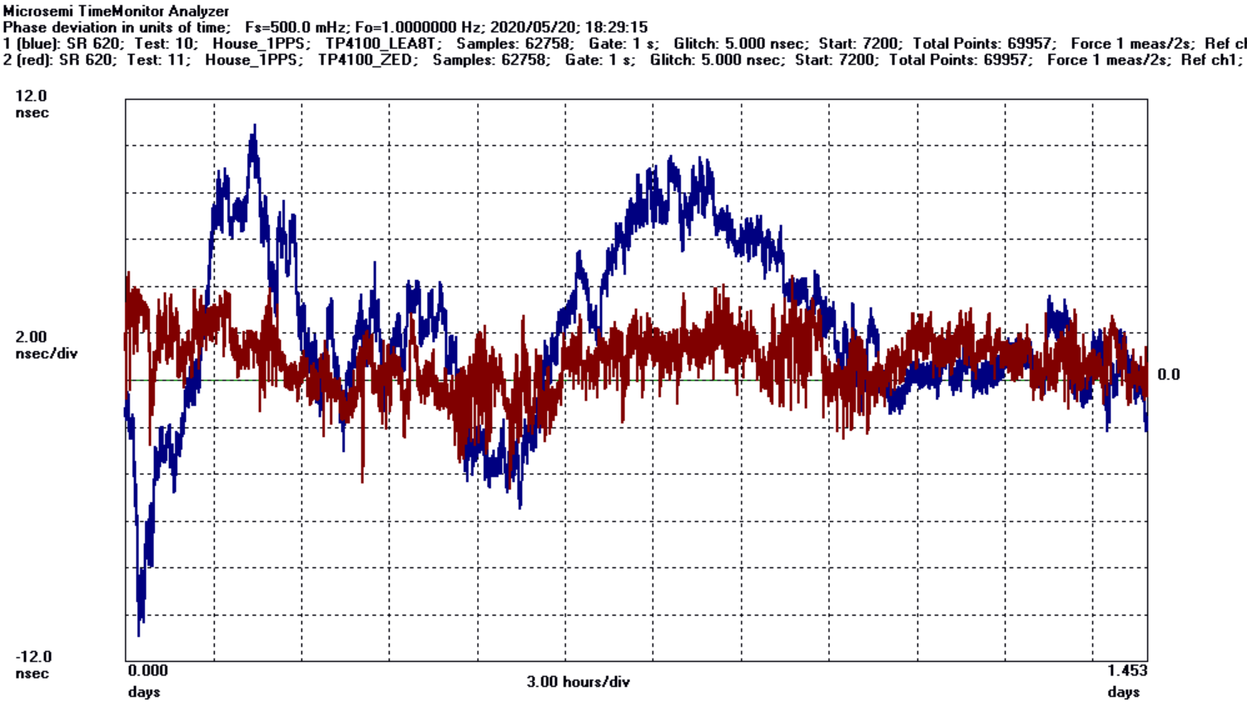
Recall that the blue graph is showing greater dynamics on the first day because we configured automatic 24-hour survey-in. The red (multi-band unit) was set with a precise manual position from the start. The survey-in completed properly after 24 hours and we can see the unit has settled into much better behavior. Again, the ePRTC ITU requirement is to achieve 30 ns accuracy so even with the early dynamics the accuracy is well within specification.

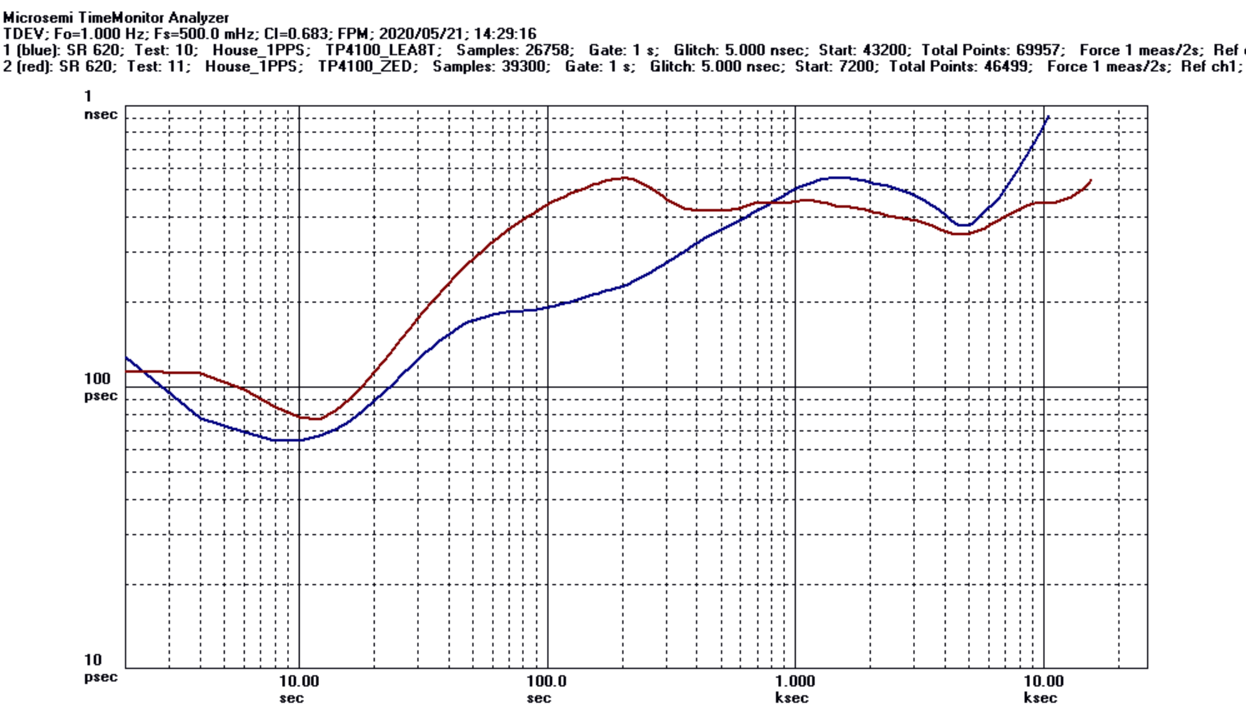
Recall that during the first days of operation the ePRTC algorithm is steadily increasing the GNSS firewall protection. In steady state, we achieve a full day of decoupling between the GNSS measurements and steering estimate adjustments. This is a key value in our ePRTC approach to ensure that we achieve maximum protection from external GNSS real world issues such as jamming, spoofing, multipath, and other local RF environmental issues.

The transition between minimal and maximum protection is happening during the second day of operation. We are now well into the transition (the Protection Availability Index is over 50% and climbing).

During the second day we hand off from the initial GNSS disciplined oscillator operation to the fully protected 24 hours assessment and protected steering. The underlying state estimates need to carefully transition to prevent transients in the control system. Keep in mind this needs to be done in the presence of multiple noise sources. The hand off is operating well within expected limits.

The overlay TDEV stability graph shows the stability performance of both systems. Since the single band unit was in survey-in for the first 24 hours we have skipped the first 24 hours in processing the data. Keep in mind that during this second day the transition puts stress on maintaining stability and the stability will keep improving over the next several days. We are already achieving better than 1ns stability performance for both systems. Of course, from a specification confidence perspective the TDEV stability specification requires a week or more of data once we achieve normal 100% protection, but this early performance is a good indication of the performance.





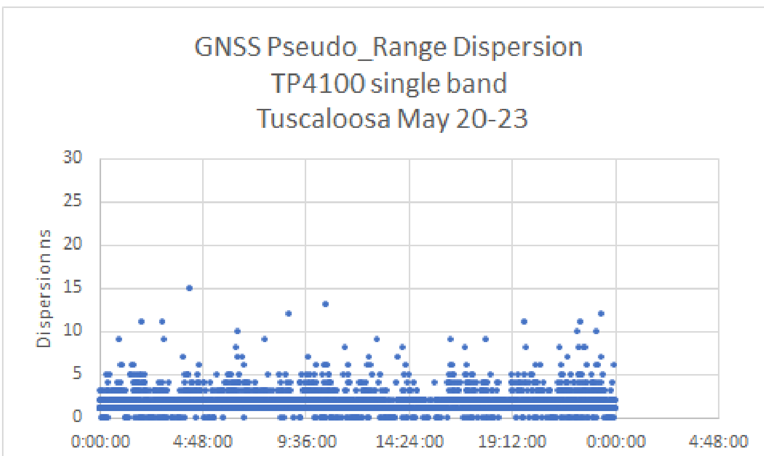
2.2 100% ITU-T ePRTC Compliance: 3-Week Learning Period

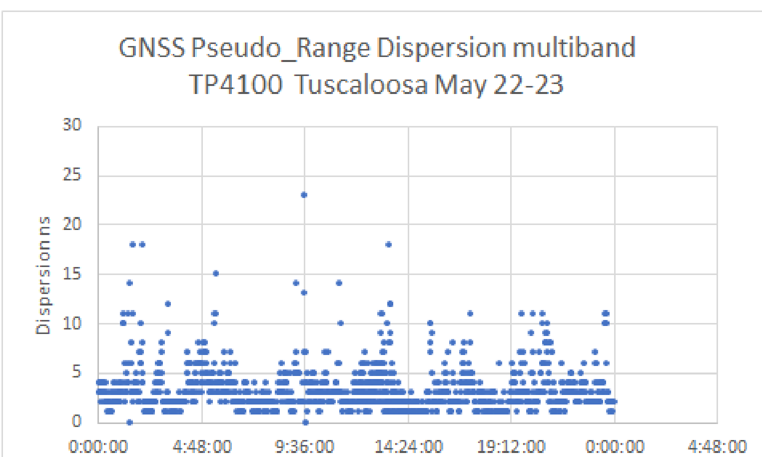
2.2.1 May 25: Day 5

We are now well into the ePRTC validation testing (5 days, 15 hours). We have collected data “under the hood” over the long weekend to ensure the overall integrity of all the subsystems. This data is summarized in the next sections.

2.2.1.1 GNSS Subsystem

We maintain GNSS statistics within the algorithm as timescale steering to maintain UTC traceability is a critical function of the system. The following two graphs show the pseudo-range residual dispersion metrics for both GNSS receivers. The metrics are generated by calculating the root mean squared statistic of the currently contributing satellite pseudo-range residuals to the timing solutions. Since we are in a fixed position operating mode, the pseudo-range errors directly map to clock error. Keep in mind not the same observation windows but generally we see the same levels of dispersion on both units which would be expected as they are in a similar RF roof environment. One of the more critical aspects of timing systems is the fact that they are stationary antenna installations exposed to the same local RF degradations such a reflected RF associated with permanent structures around the antenna location. From a practical perspective, the antenna placement is limited to rooftop of the building where the ePRTC is located. TimeProvider 4100 ePRTC is designed to maximum de-coupling of the effect of GNSS daily degradation with all steering decision based on observing daily filtered estimates of GNSS measurement metrology.

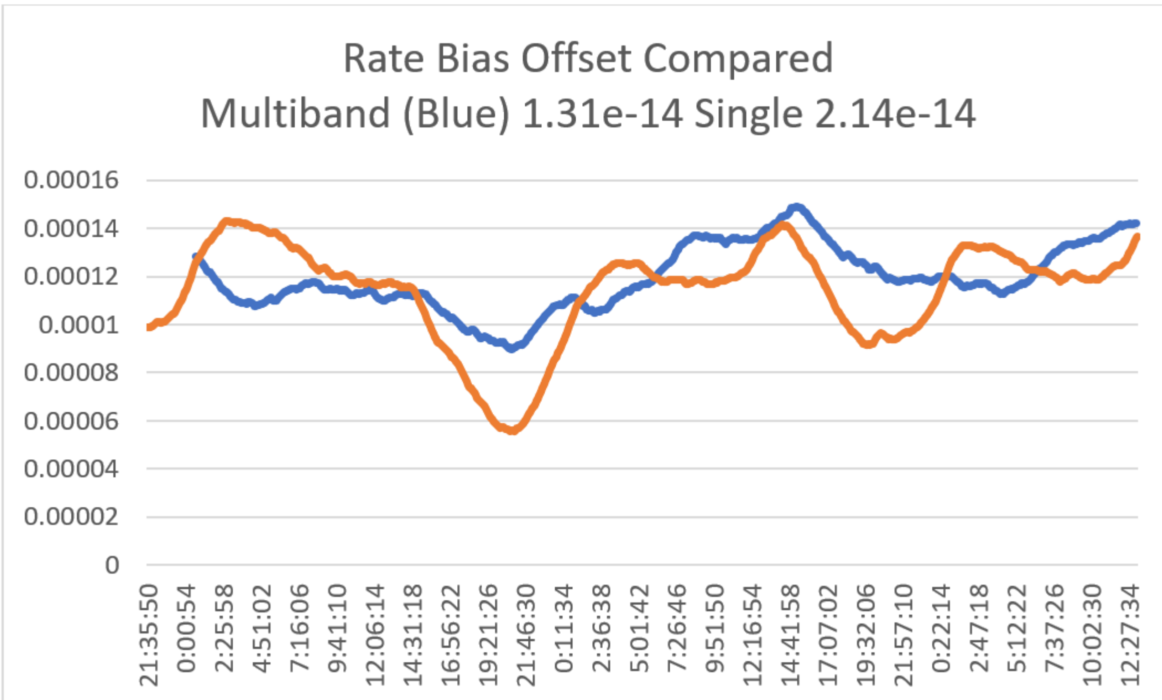




2.2.1.2 Timescale Steering Subsystem

The Timescale Steering Subsystem is responsible for maintaining precise UTC traceability for the ePRTC system. The system has three stages of operation starting with non-protected timescale moving through partially protected timescale and then operating in fully protected timescale. The progression is visible to the user with a simple “Protection Availability Index” which we discussed before. One critical process is the determination of the timescale correction states. The frequency state precision has a strong influence on long term GNSS outages as an ePRTC is required to support 100 ns of accumulated time error over 14 days. To obtain this level of precision in the presence of real-world noise and perturbation effects, the learning process is designed for resilience, and we have a 3-week learning window as part of the overall operation.

The underlying instability of the input frequency estimated can be seen in the comparison overlay graph below. We can see that the frequency offset instability of the single band is (2.14e-14 one sigma) compared to the multi-band (1.31e-14 one sigma). We can see a small but meaningful benefit with the multi-band receiver. The rate bias offset is essentially the steering correction one would get from a very good GNSS disciplined oscillator. We do not use this directly but post-process over the learning period to obtain precision and accuracy necessary to optimize the time error accumulation over the minimally required 14-day outage required interval.



2.2.2 May 26: Day 6

The ePRTC must meet all the requirements for both tracking and holdover as specified in the controlling specification for Enhanced Primary Reference Timing Clocks ITU-T G.8272.1.

There are three principle specifications for normal tracking performance that must be met:

1. Time accuracy: Better than 30 ns with respect to UTC when locked in Normal operating condition. The following excerpt is directly from ITU G8272.1.
   Normal, locked operating conditions mean that:

   – the ePRTC is fully locked to the incoming reference time signal and is not operating in warm-up.

   – there are no failures or facility errors in the reference path, including but not limited to antenna failures.

   – the environmental conditions are within the operating limits specified for the equipment.

   – the equipment is properly commissioned and calibrated for fixed offsets such as antenna cable length, cable amplifiers and receiver delays.

   – the reference time signal (e.g., global navigation satellite system (GNSS) signal) is operating within limits, as determined by the relevant operating authorities.

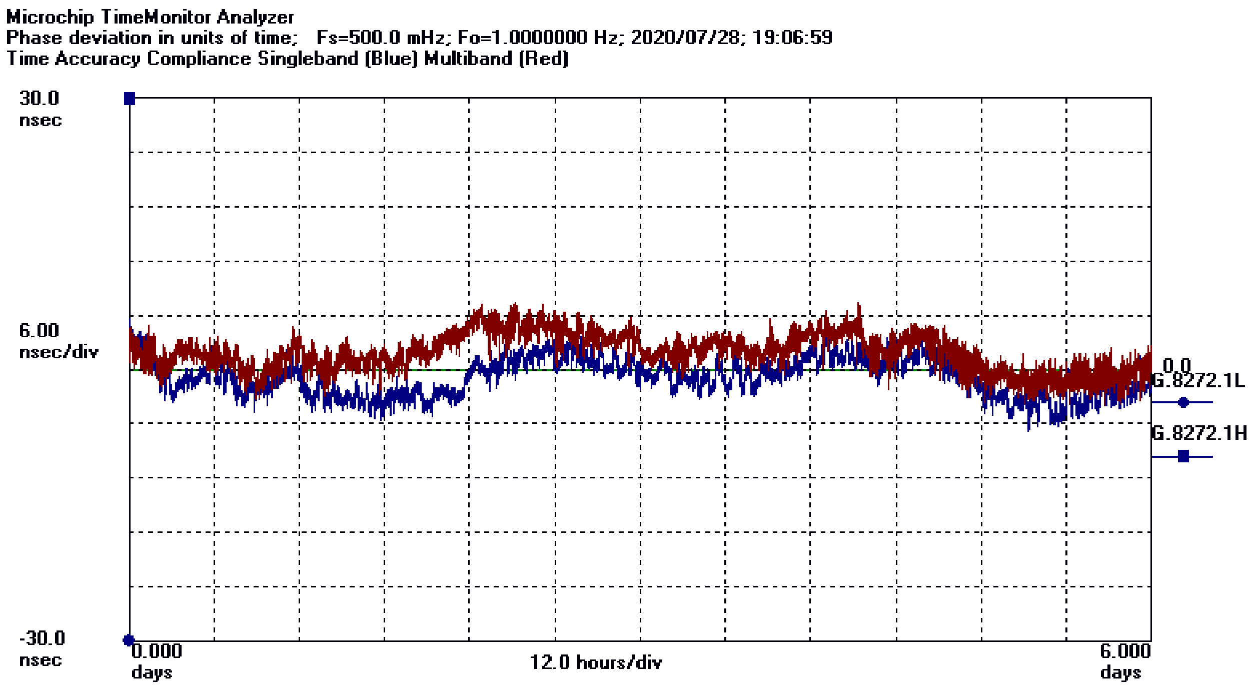
   – if the reference time signal is operated over a radio system such as GNSS, multipath reflections and interference from other local transmissions, such as jamming, must be minimized to an acceptable level.

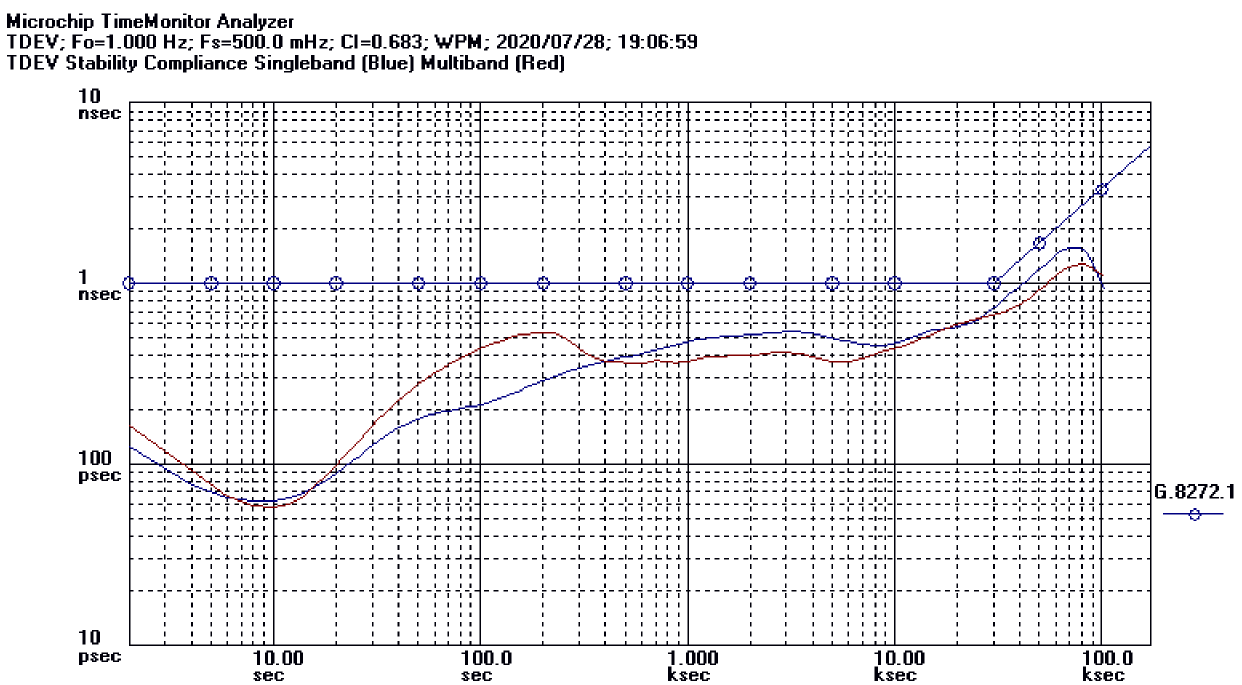
   – there are no extreme propagation anomalies, such as severe thunderstorms or solar flares.

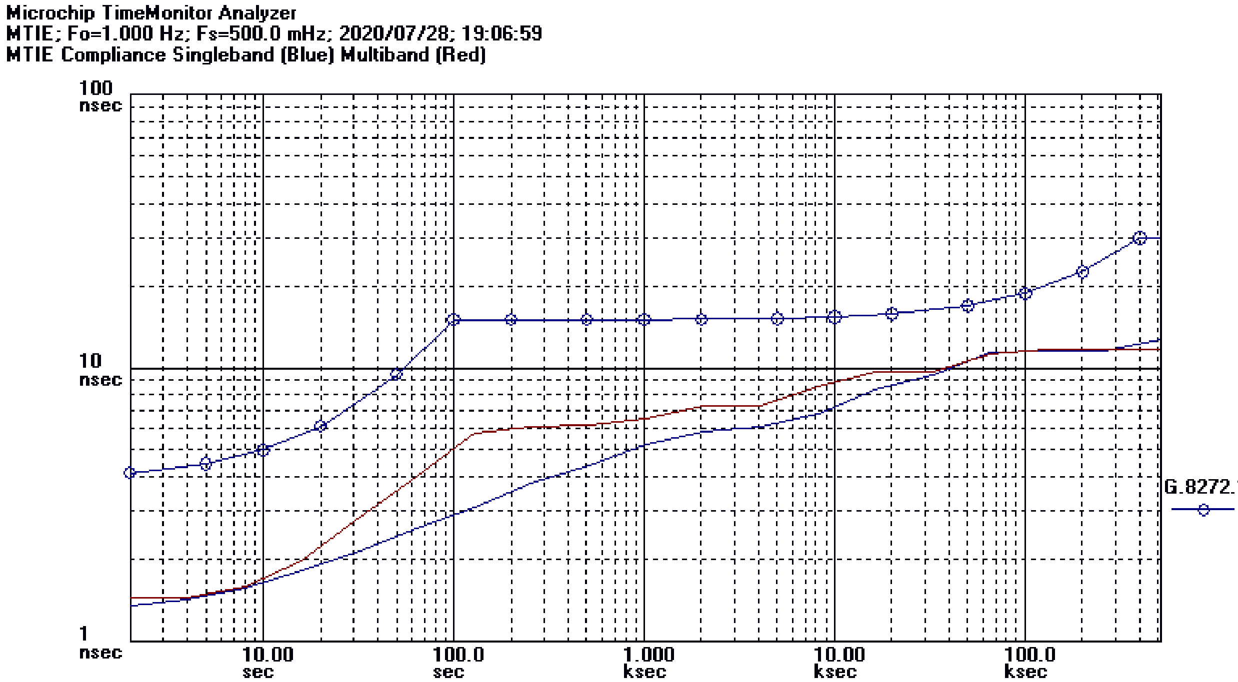
2. TDEV stability better than specified mask. This stability specification is challenging to test properly. Here are some issues related to compliance testing:
   2.1. Stability of the reference PPS: One of the reasons we perform certification testing in our Tuscaloosa R&D facility is that our hydrogen masers support over an order of magnitude of stability measurement margin. In contrast, the cesium-based Timescale system house references are at the same stability level as the ePRTC which limits effective compliance testing.
   2.2. Contribution of input GNSS signal: Issues such as space weather, multi-path, reflections, and RF jamming and even spoofing can impact compliance verification. We test with real world live GNSS signals and do not consider certification with ideal GNSS simulation a robust test methodology.
   2.3. Thermal environment: The dynamic temperature variation in even a benign indoor environment can have measurable effects. We support TDEV performance not just at constant temperature but under real world dynamic limits (5 °C diurnal temperature range during TDEV compliance testing).
   2.4. Learning convergence: The timescale undergoes a modestly higher steering control during the first weeks of operation. A properly designed ePRTC ensures this does not exceed the TDEV requirements.
   2.5. Confidence interval: TDEV is statistical and what is observed is an estimate of the true TDEV noise. In fact, we observed confidence interval error bars as well in processing the data. For a longer observation window confidence decrease. In general, there is a need for a data set that is 10 to 20 times the longest window of interest (which in practice means weeks of testing).
3. MTIE performance within the mask. MTIE compliance is not as challenging to test. MTIE compliance margins are good. The caution with all MTIE testing is that it is essentially a peak detector and one instrumentation transient (for example, a trigger glitch in the external counter and not the system) can impact an entire test. This is effectively addressed with very careful test set-up and sometimes multiple measurements in parallel.

The compliance graphs were generated with the removal of the first day of operation. As you may recall, the L1 single band unit was operating in an early survey-in mode and we are looking at normal operational compliance. Since we are measuring with respect to the house Maser the raw PPS data has a known relationship with UTC(NIST). For compliance with respect to UTC(NIST) this calibration correction is applied to the counter data to show compliance to UTC.

With all the above background, the compliance performance day 2 through day 7 is presented below. The ePRTC TimeProvider 4100 systems are fully compliant with the standard. Keep in mind the overall TDEV curves margin will improve over the next few weeks as the system learning converges to steady state.


Microchip TimeMonitor Analyzer
Phase deviation in units of time; Fs=500.0 mHz; Fo=1.0000000 Hz; 2020/07/28; 19:06:59
Time Accuracy Compliance Singleband (Blue) Multiband (Red)
30.0 nsec
6.00 nsec/div
-30.0 nsec
0.000 days
12.0 hours/div
6.000 days
0.0
G.8272.1L
G.8272.1H


Microchip TimeMonitor Analyzer
TDEV; Fo=1.000 Hz; Fs=500.0 mHz; CI=0.683; WPM; 2020/07/28; 19:06:59
TDEV Stability Compliance Singleband (Blue) Multiband (Red)
10 nsec
1 nsec
100 psec
10 psec
10.00 sec
100.0 sec
1.000 ksec
10.00 ksec
100.0 ksec
G.8272.1

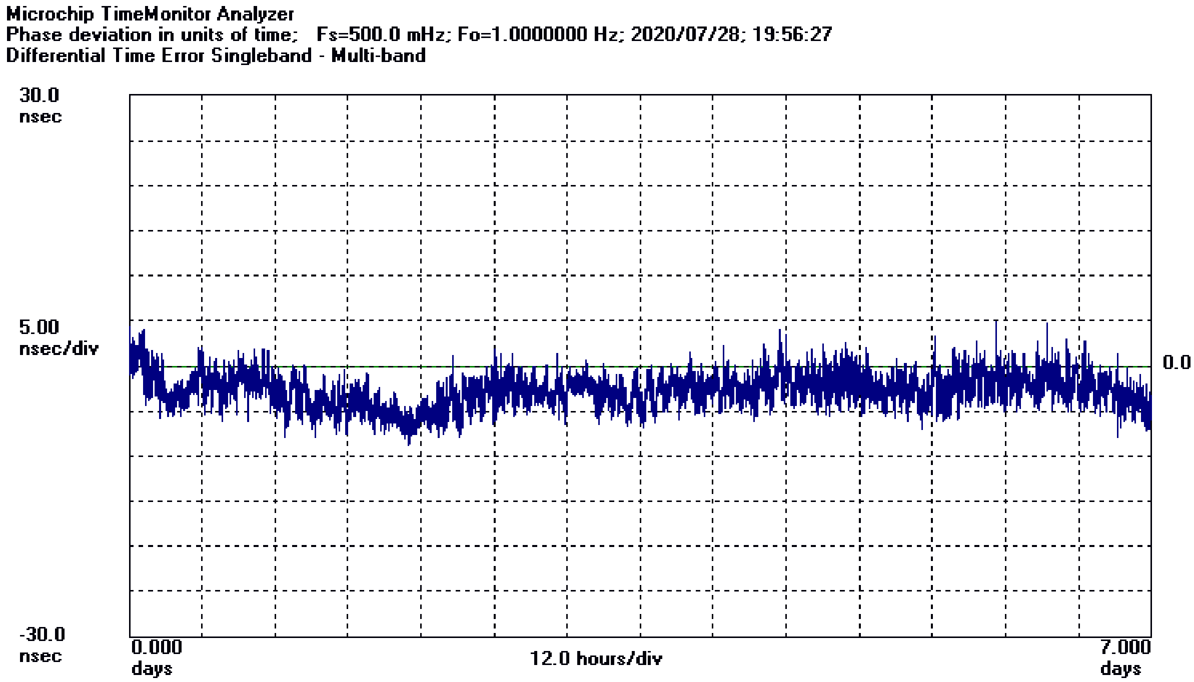


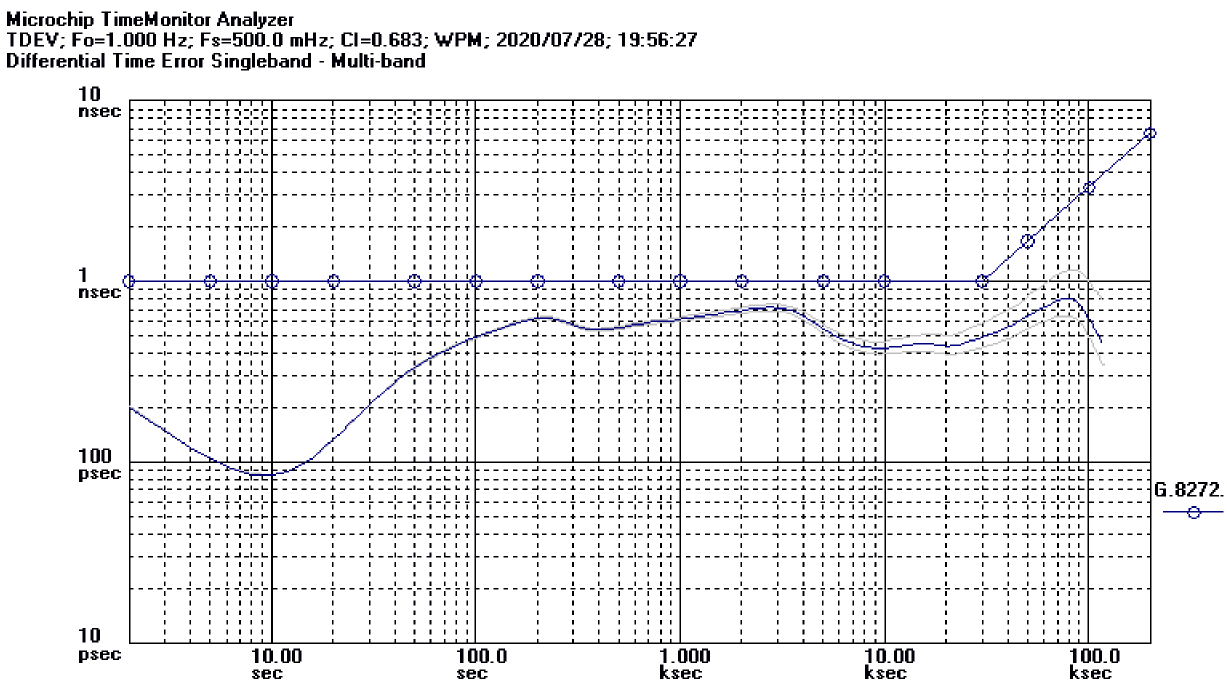
2.2.3 May 28: Day 8

2.2.3.1 Differential ePRTC Performance

In practice, it is the relative difference in time between a pair of ePRTC systems that is important. There is strong correlation (common mode behavior) between well designed ePRTC systems that are in proximity. The differential time error over the 7 days of observation is shown below with both the time error graph and the TDEV stability graph.

One observation is that the shorter-term time error noise is the primary residual error. This is really the intrinsic noise of the current TimeProvider 4100 clock system. We observe a peak instability of 700 ps between the two systems. Assume equal contribution from both then we can estimate the intrinsic noise of each ePRTC system at 500 ps (one sigma).





2.2.4 June 3: Day 13

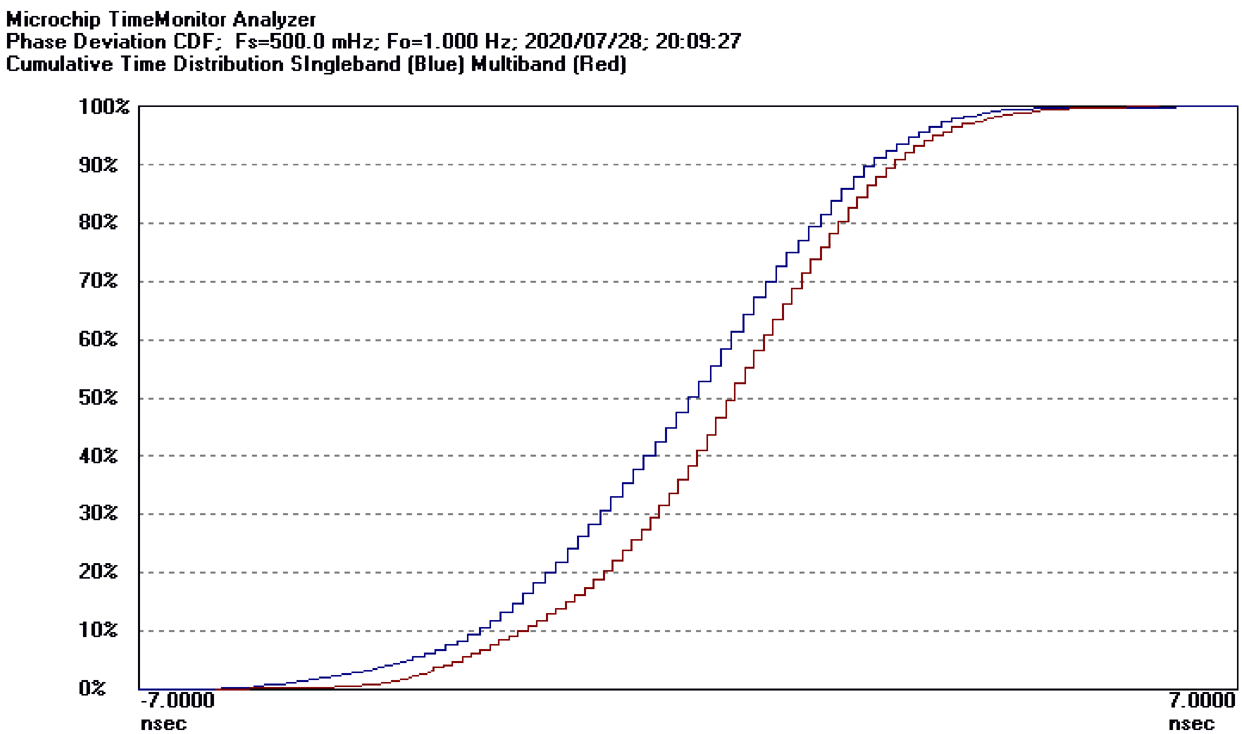
2.2.4.1 Time Accuracy and Cumulative Distributions

One of our capabilities with the Microchip Time Analyzer Tool Kit is the ability to observe signals as distributions. It is useful to look at our PPS time error data from the perspective of a cumulative time error distribution. The overlay plot for the two ePRTC TimeProvider 4100 units operating in Tuscaloosa through last night is shown below. Ideally, we want no dispersion in the time error. The ideal case would look like a step jump from 0 to 100% at zero-time error. The dispersion of the real-world time error essential smears this ideal step out. One key metric is the magnitude of the time error that is maintained with high probability. For example, a 2-sigma bound means the 95% of the operating time the accuracy of the output would be within the stated bound. The 95% bound for both ePRTC TimeProvider 4100 systems under test is better than 5 ns:

- L1 single-band TimeProvider 4100: 4.76 ns
- Multi-band TimeProvider 4100: 4.53 ns

Although the multi-band unit is marginally better than the standard unit, this is not a significant difference. We should be careful not to incorrectly conclude that the multi-band does not have measurable value. Several things are at work here:

- The primary benefit of multi-band is space weather protection. We are in a relatively quiet period of space weather so an “umbrella is not of particular value if it’s not raining”.
- The diurnal delay variations during a quiet period are mitigated by our de-coupled timescale steering algorithm as we are leveraging our local atomic clock. This is equally effective for both receivers when there is no space weather and we would expect similar results.



2.2.5 June 6: Day 16

2.2.5.1 Holdover Gas Gauge

TimeProvider 4100 advanced holdover prediction algorithms generate statistically sound estimates of not only the optimal clock estimation states but also the expected accumulated time error during holdover operation. The concept is straightforward. Just like a gas gauge will tell you how much gas is left in the tank or perhaps convert it into how many miles (or kilometers) you have until empty, TimeProvider 4100 provides the same information relating to the time error during holdover. In holdover, we are essentially allowing our precisely calibrated local oscillator to operate with the best prediction of how the time error will accumulate. After this prediction is applied, there will still be residual time error that will accumulate the longer the outage period is. There are several methods utilized to support this holdover gas gauge feature:

- In Gateway Clock mode and High Accuracy mode, the key use case is what happens if we lose all external references and are forced to operate on our local oscillator (inside TimeProvider 4100) in prediction mode. The method to estimate the internal oscillator (with prediction) timekeeping capability is based on the Time Uncertainty (TUNC) approach discussed shortly.
- In ePRTC mode, the key use case is what happens if we lose the time reference (GNSS) but we still have external atomic clock references. In this case, the internal local oscillator never operates in prediction mode as

we are still actively generating a local timescale with the external atomic clock inputs. The gas gauge prediction is now based in a timescale modeling approach which is well matched to this mode of operation.

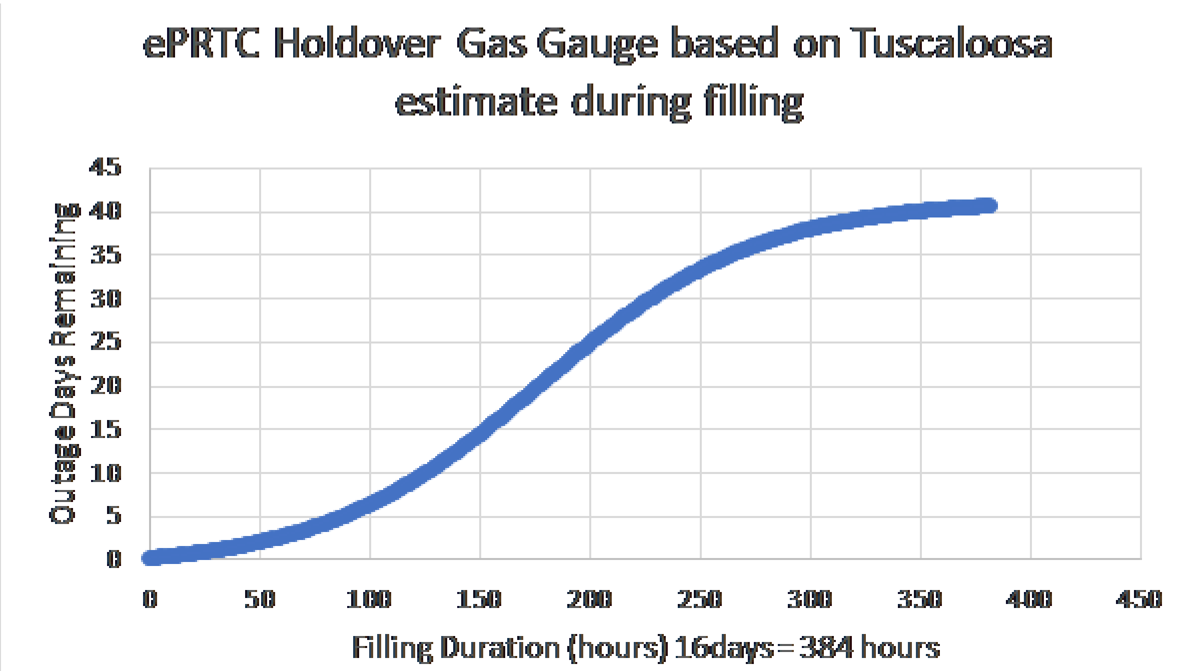
What is important for the user is that they have a holdover gas gauge (and a time to empty reading) so they can proactively address the situation.

2.2.5.2 ePRTC Holdover Gas Gauge Reading in Tuscaloosa

In the ePRTC use case, we have at least one co-located cesium atomic clock to support continual local timescale generation during the local time reference (GNSS) outage. In ePRTC mode, the system seamlessly switches to a timescale modeling approach to estimate the holdover gas gauge. Since the timescale is based on cesium atomic clocks with an established pedigree of predictable timing performance, this modelling approach is very effective.

Even though we are not quite done with the three-week learning period, we took a snapshot of the “Holdover Gas Gauge” in Tuscaloosa. Since both systems share a common cesium atomic clock, they both have similar holdover gas gauge levels so for simplicity we are showing a single graph that represents both systems.

During the learning period, the holdover gas gauge is operating in a filling mode. As we learn the holdover prediction, the length of time we can support 100 ns holdover (as required in ITU-T G.8272.1) increases. We are now at day 16, which is 384 hours and the filling graph shows the holdover gas level at 40 days. Now the requirement for ePRTC holdover is a minimum of 14 days, so we can see that the operational performance of the TimeProvider 4100 is far exceeding the minimum with a predicted 40-day holdover capacity.



2.2.6 June 8: Day 18

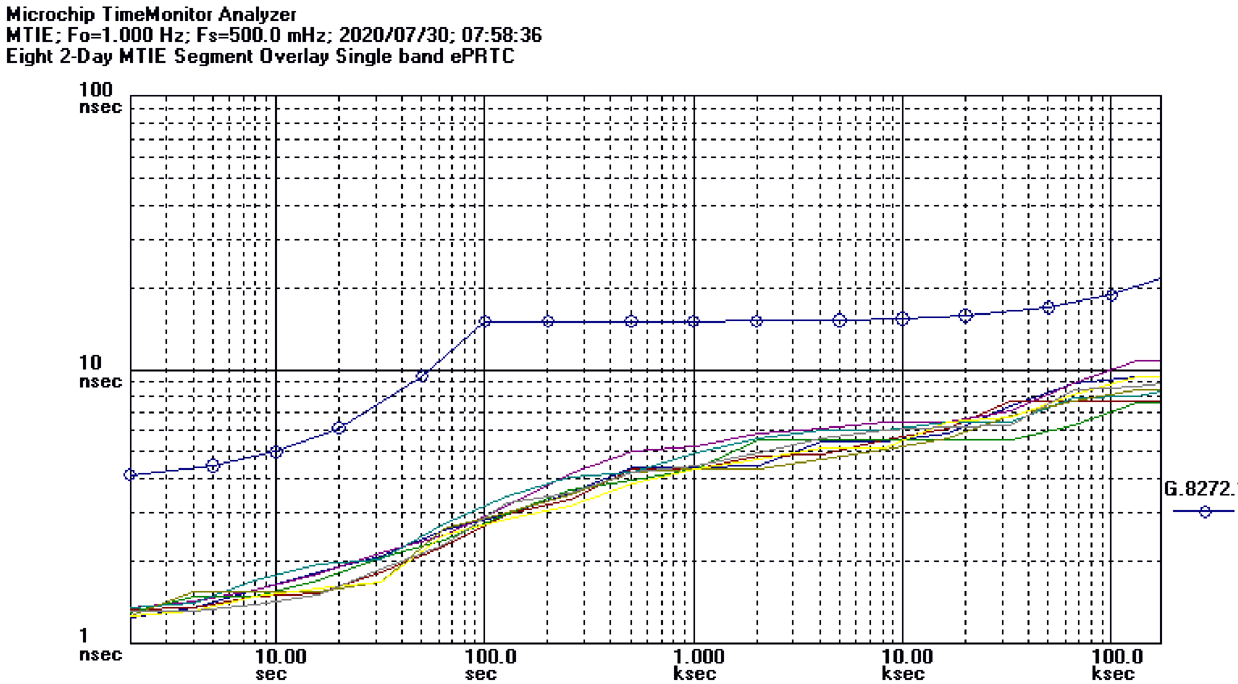
2.2.6.1 Deeper Look at MTIE

Maximum Time Interval Error (MTIE) is a well-established metric used in timing standards for many decades. Historically, the real attraction with the metric is that it directly relates to the appropriate sizing of buffers in communication networks to accommodate time variations in signals. Clearly, the utility of the metric has stood the test of time as we are still defining compliance with MTIE.

Unfortunately, the metric’s simplicity in construction introduces some potential for issues in proper compliance testing.

To see how this can come about, consider the MTIE overlay graph shown below. To show eight different graphs, we have simply extracted from the complete time error dataset and created eight “two-day” tests. We can see the MTIE compliance test results for all these eight in the graph. We do observe a significant variation in the test results. Since MTIE is a peak detection metric, proper test instrumentation is not designed into the metric itself. The lack of strong statistical control presents challenges in its use:

- Compliance by repetition. Basically, the variability in the test results for a collection of a single system or single test time window samples drives a need for testing involving multiple test windows and units to properly assess the performance of a device under test.
- Test instrumentation vulnerability. MTIE measurement is vulnerable to transient events in the testing system itself. For example, a thermal event or external noise transient can introduce incorrect MTIE measurement results. We typically instrument multiple tests in parallel to rule out instrumentation related issues.

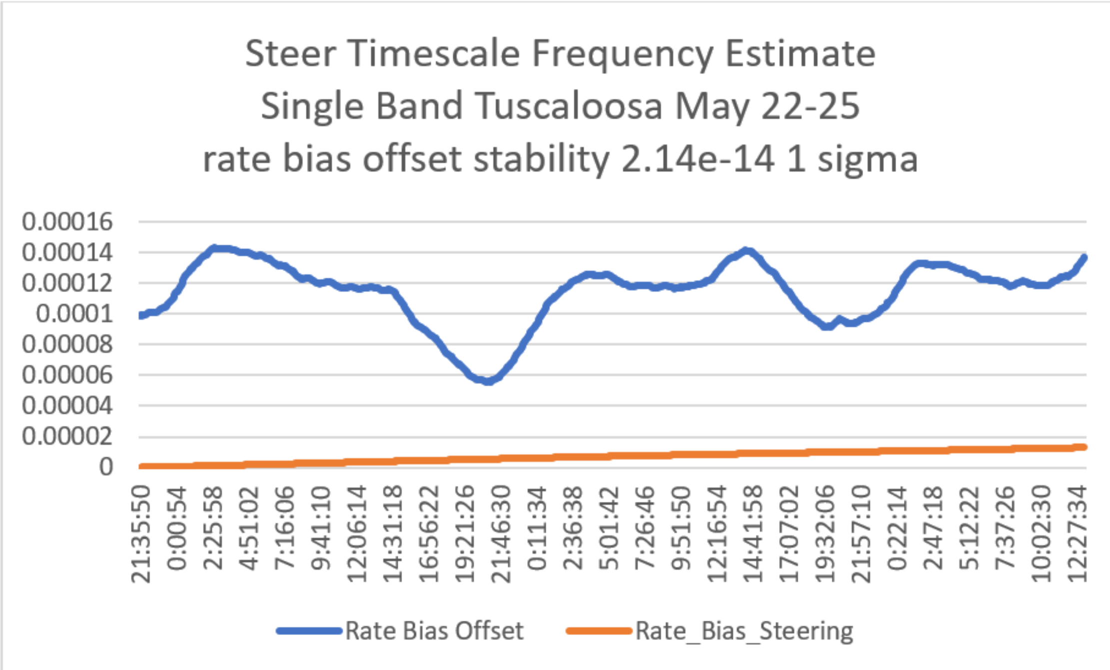


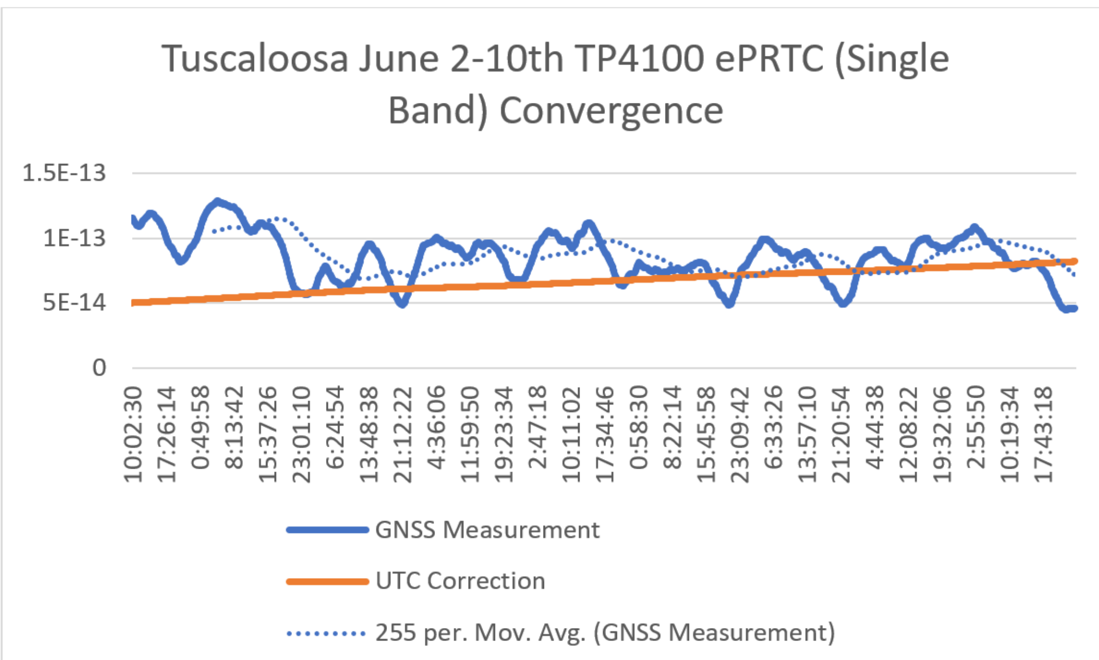
2.2.7 June 11: Day 21

Well we have come to the end of the 3-week learning period and it would seem to be a good time to ask the question: “Did we learn anything?”.

2.2.7.1 Learning the UTC Frequency Calibration

We touched on the timescale steering subsystem and the learning period back on May 25. The graph below shows the state of the Rate Bias Steering Estimate during the first week of operation. We can see that the estimate is in the process of converging as we see a clear gap between the GNSS rate bias offset measurement process and the estimator. Contrast this with the current state of the estimator (second graph). We can visually see that over the last week the gap is closed, and we have converged to steady state.





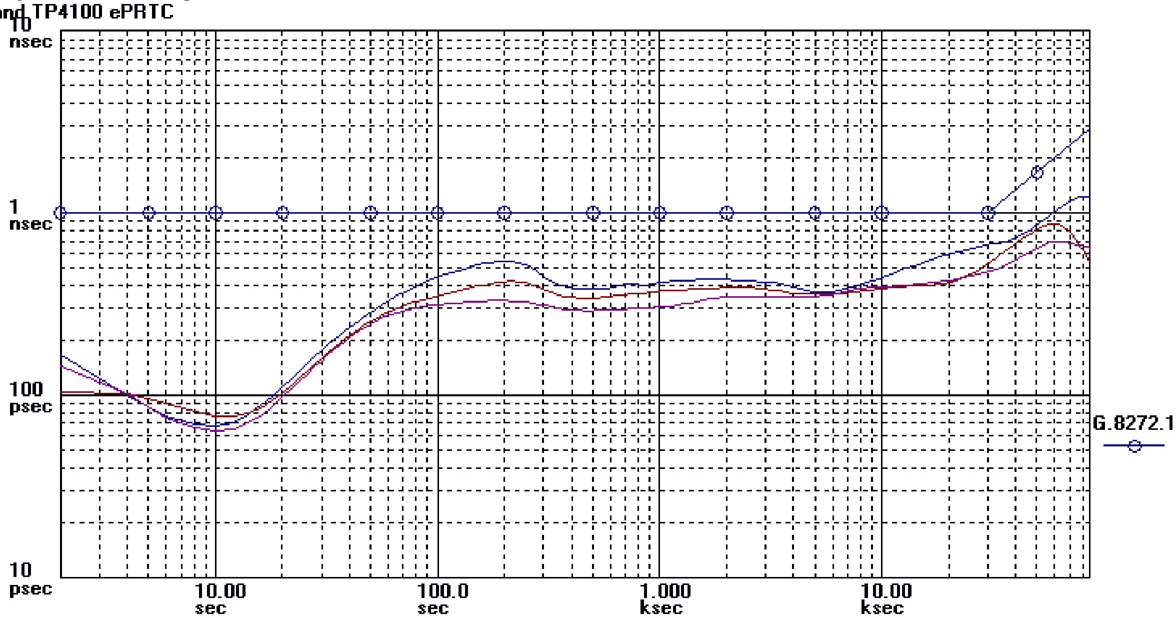
2.2.7.2 Learning UTC Calibration Improves Stability

The TDEV overlay graph below shows the stability of the multi-band unit for each of the three weeks during the learning period:

1. Blue: Week 1
2. Red: Week 2
3. Magenta: Week 3

We are using the multi-band-based unit to observe the stability improvement as the contribution of the GNSS steering process to instability is less over the longer Tau's, giving us a window into the improvement in the local timescale itself. We can visually see a small but measurable improvement each week in the stability of the timescale. Multiple second-order mechanisms are at work here and it is beyond the scope of this report, but we certainly can see the timescale noise improve as we learn.

Microchip TimeMonitor Analyzer
TDEV; Fo=1.000 Hz; Fs=500.0 mHz; CI=0.683; WPM; 2020/07/28; 07:45:30
TDEV Improvement week by week
Multiband TP4100 ePRTC



3. 14-Day Holdover and Recovery

3.1 14-Day Holdover Outage Stage

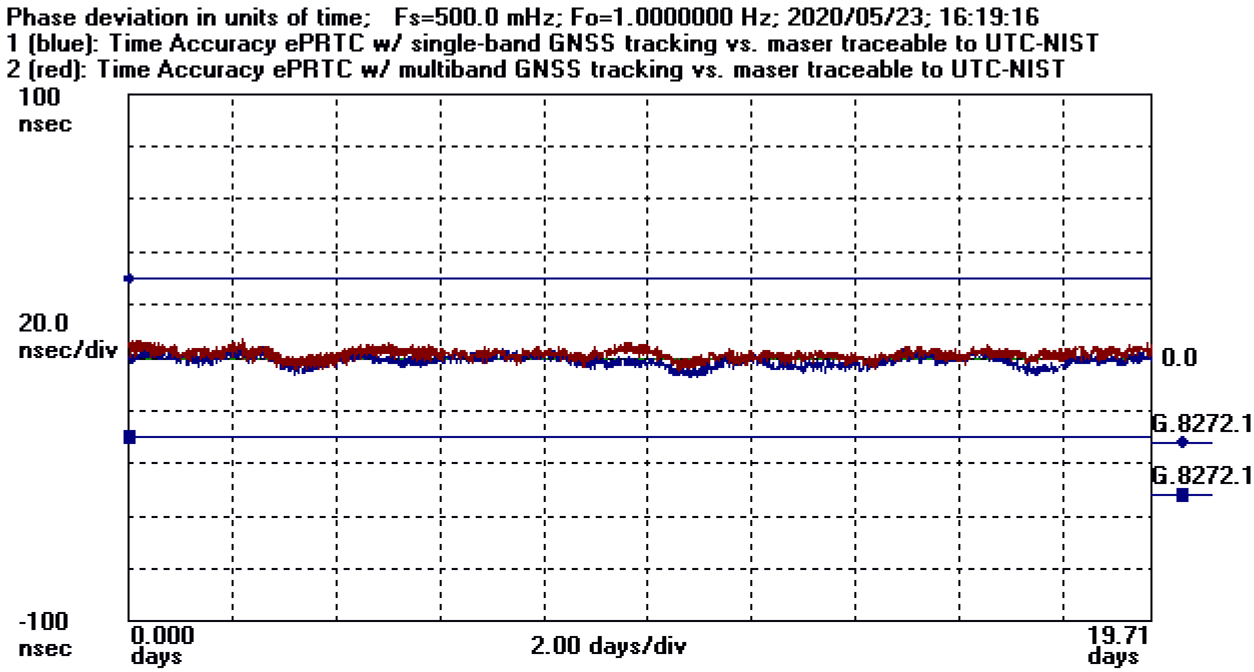
3.1.1 June 12: Start of Holdover

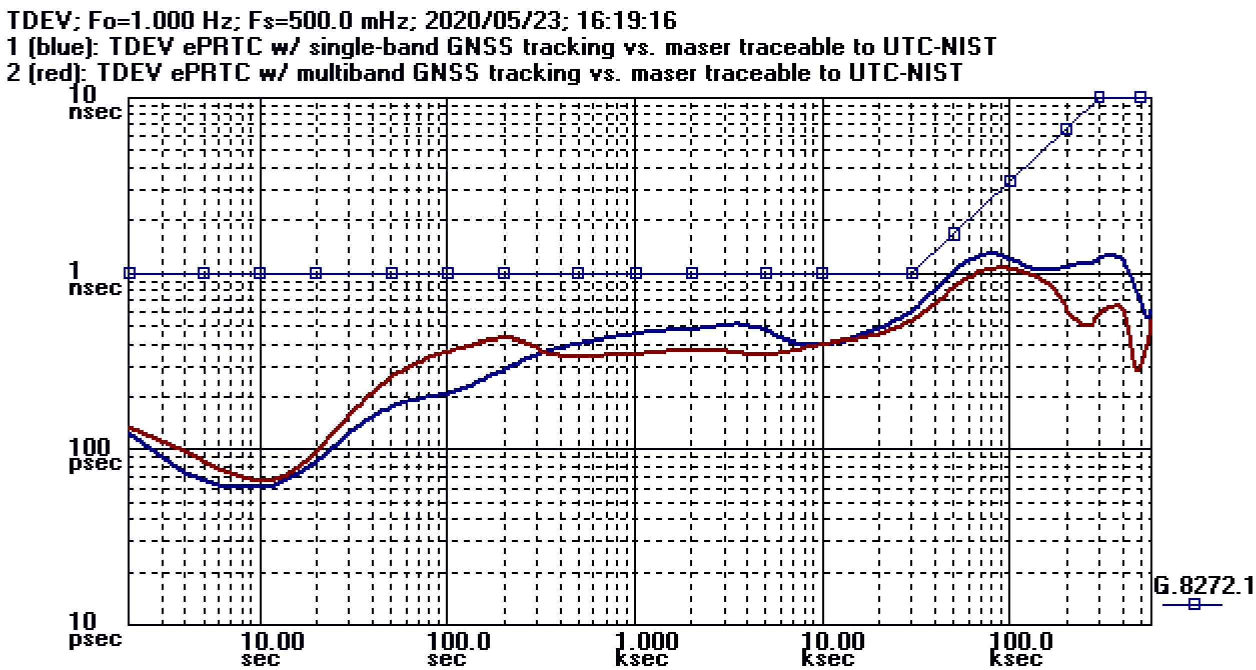
We have completed the normal operational testing phase in the Tuscaloosa ePRTC certification testing.

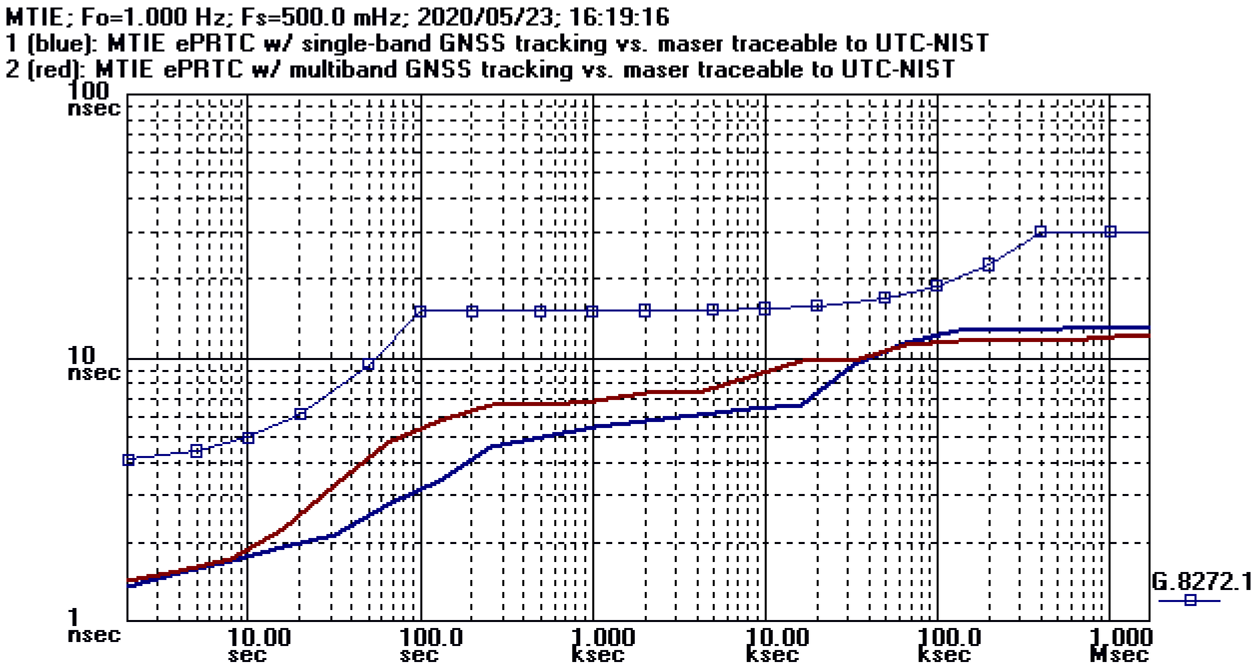
We will pull the GNSS antennas on both systems and start the holdover testing stage later today. We can now evaluate the full tracking performance testing stage for compliance.

3.1.1.1 ITU ePRTC Compliance Graphs (Completion of 21 Days Normal Operation)

The full, 21-day normal operation stage is complete and both TimeProvider 4100 ePRTC systems demonstrate consistent and fully compliant ITU-T G.8272.1 ePRTC operation.


Phase deviation in units of time; Fs=500.0 mHz; Fo=1.0000000 Hz; 2020/05/23; 16:19:16
1 (blue): Time Accuracy ePRTC w/ single-band GNSS tracking vs. maser traceable to UTC-NIST
2 (red): Time Accuracy ePRTC w/ multiband GNSS tracking vs. maser traceable to UTC-NIST
100 nsec
20.0 nsec/div
-100 nsec
0.0
G.8272.1
G.8272.1
0.000 days
2.00 days/div
19.71 days


TDEV; Fo=1.000 Hz; Fs=500.0 mHz; 2020/05/23; 16:19:16
1 (blue): TDEV ePRTC w/ single-band GNSS tracking vs. maser traceable to UTC-NIST
2 (red): TDEV ePRTC w/ multiband GNSS tracking vs. maser traceable to UTC-NIST
10 nsec
1 nsec
100 psec
10 psec
G.8272.1
10.00 sec
100.0 sec
1.000 ksec
10.00 ksec
100.0 ksec



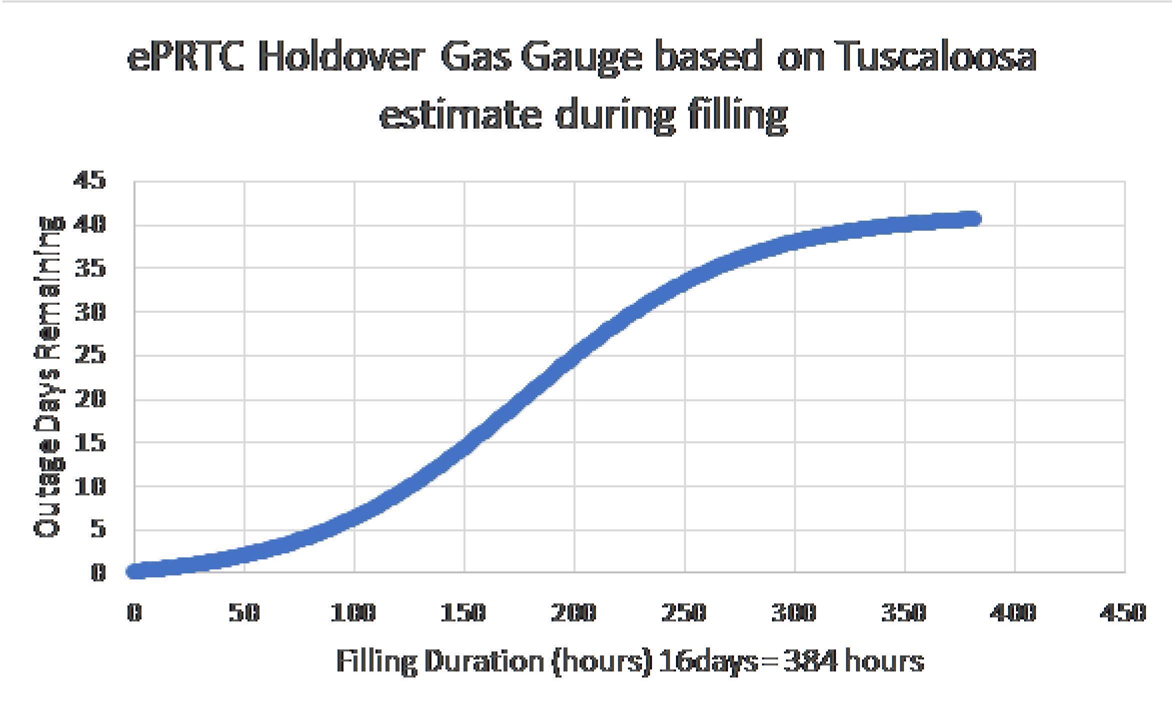
3.1.2 June 15: Day 3 of Holdover

Before we look at the holdover results, we may recall that we have a “Holdover Gas Gauge” that puts us on record predicting the future. Just before we pulled the antenna, we checked the gauge.

3.1.2.1 Checking the Holdover Gas Gauge

The following graph is a reprint of snapshot of the filling graph just before we pulled the GNSS antenna. We can see that with the current estimate of timescale prediction noise the holdover gas tank estimate is 40 days. Since we have two TimeProvider 4100 ePRTC units operating in holdover we will perform two different holdover evaluations:

- The single-band TimeProvider 4100 ePRTC will operate in holdover for the 14-day outage period specified in the standard. At the end of the 14-day outage, the GNSS antenna will re-connect and both holdover recovery and post-holdover normal tracking will be evaluated.
- The multi-band TimeProvider 4100 ePRTC will operated in an extended holdover period (beyond 14 days) to verify the 40-day holdover gas gauge prediction. Holdover recovery will be deferred until the time error exceeds 100 ns.

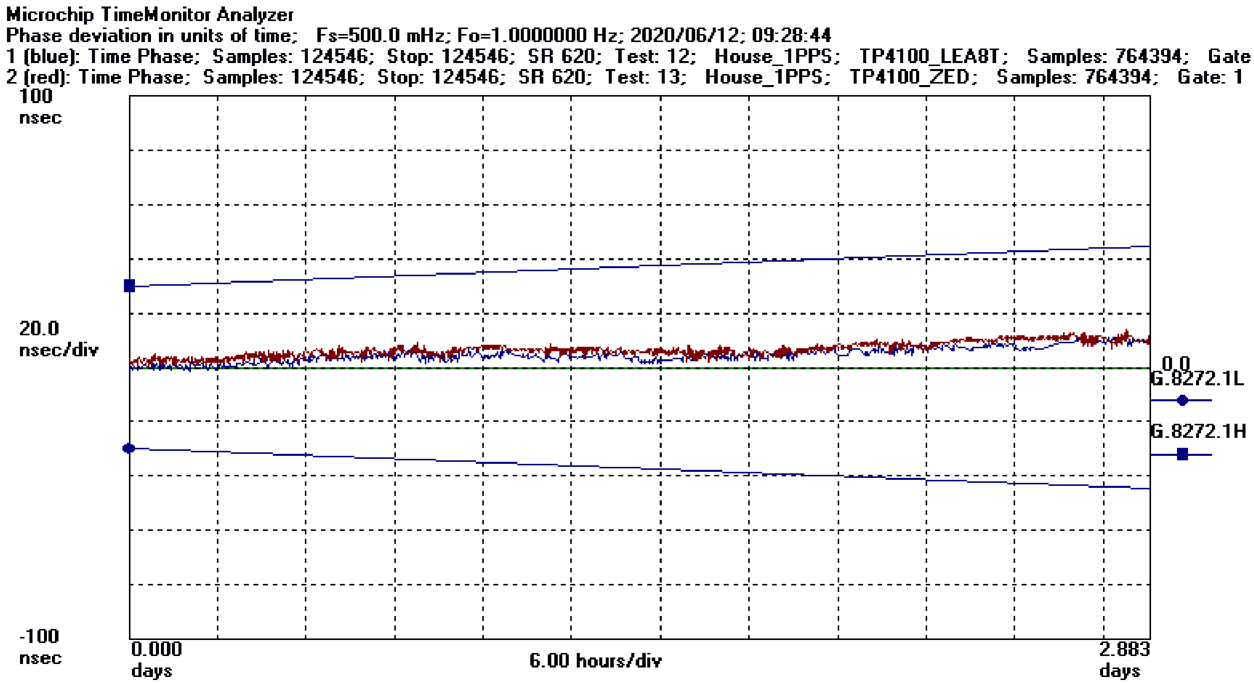


3.1.2.2 ITU ePRTC Holdover Compliance

We need to hold 100 ns over 14 days and we have predicted 100 ns over 40 days. We have been in holdover 2.75 days, which is nominally 20% of the way to 14 days. The graph below shows the time error accumulation of both TimeProvider 4100 ePRTC units over the weekend. The graph is displayed with a range of ±100 ns. The 100 ns range set the maximum time error we are allowed beyond 14 days of outage as specified by ITU.

Several observations. The overall time error accumulation is consistent for both units. Given that both units shared the same cesium we would expect similar holdover results. The time error accumulation rate per day is a useful metric. We can see that the early estimate is limited by both the noise as well as evidence of small but measurable thermal effects.

We will apply more rigorous analysis as we get further into the holdover stage but as a visual estimate, we are seeing between 5–10 ns over the 2.75-day holdover period. Splitting the difference, we are seeing about 2.72 ns per day of time error accumulation. If we extrapolate with this rough estimate, we should exceed 100 ns in about 37 days. Again, it is too early to have much confidence, but we are generally on the correct track.



3.1.3 June 18: Day 6 pf Holdover

Before we take another look at how the ePRTC systems are performing in holdover as we complete our sixth day without GNSS traceability, we should touch on the topic of patternicity.

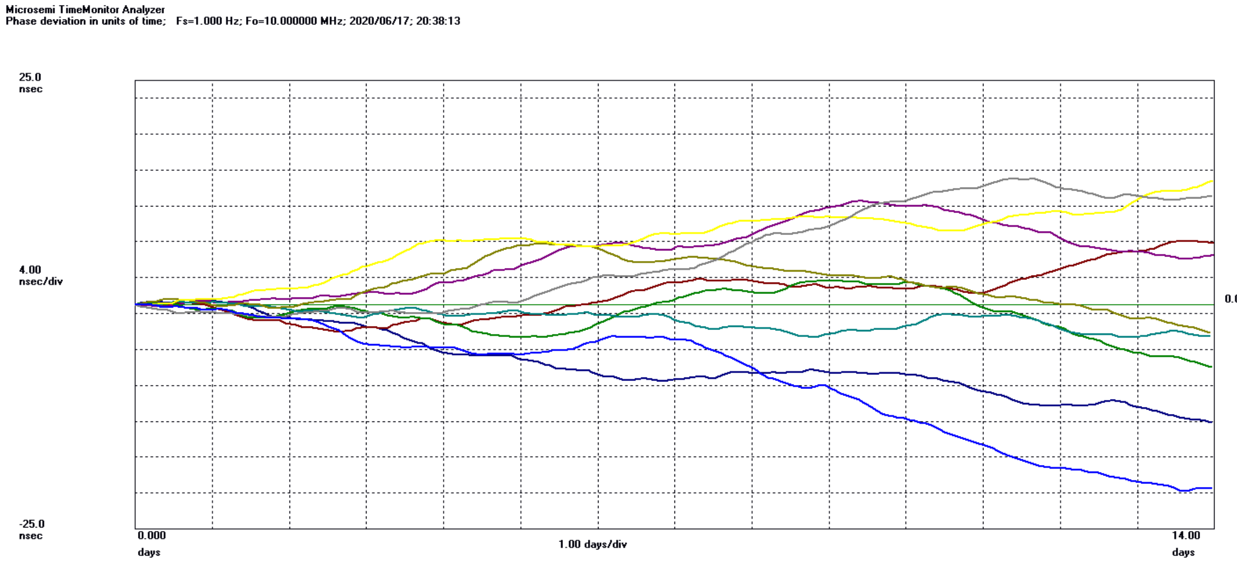
3.1.3.1 Seeing Patterns in Noise

Why do people see faces in nature, interpret window stains as human figures, hear voices in random sounds generated by electronic devices or find conspiracies in the daily news? “Patternicity: Finding Meaningful Patterns in Meaningless Noise” in *Scientific American* (November 25, 2008).

The measure of a good prediction algorithm is what is left after you remove the prediction. In the case of timescale prediction, the residual error process in holdover should be the flicker noise floor of the atomic clocks supporting the timescale. In this test we are looking at one sample of all the possible flicker noise process samples that would meet the exceptional noise floor specification of our cesium atomic clock.

The overlay graph below shows nine 14-day time error processes all based on the same 1e-14 flicker noise floor Monte Carlo but with random starting seed values.

Now, if we look at the results as a population ensemble of all possible outcomes, we can see that certain structures like the envelope of increasing dispersion in time error could be statistically meaningful. However, we may also find that patterns that we are sure we see in the data really have no deterministic meaning. For example, the blue curve that is the lowest time error values we see. If this was the only example of a holdover test, then one might see what appears to be a frequency shift in the middle of the pattern. A properly designed holdover algorithm is underpinned by statistically sound architecture and verification.

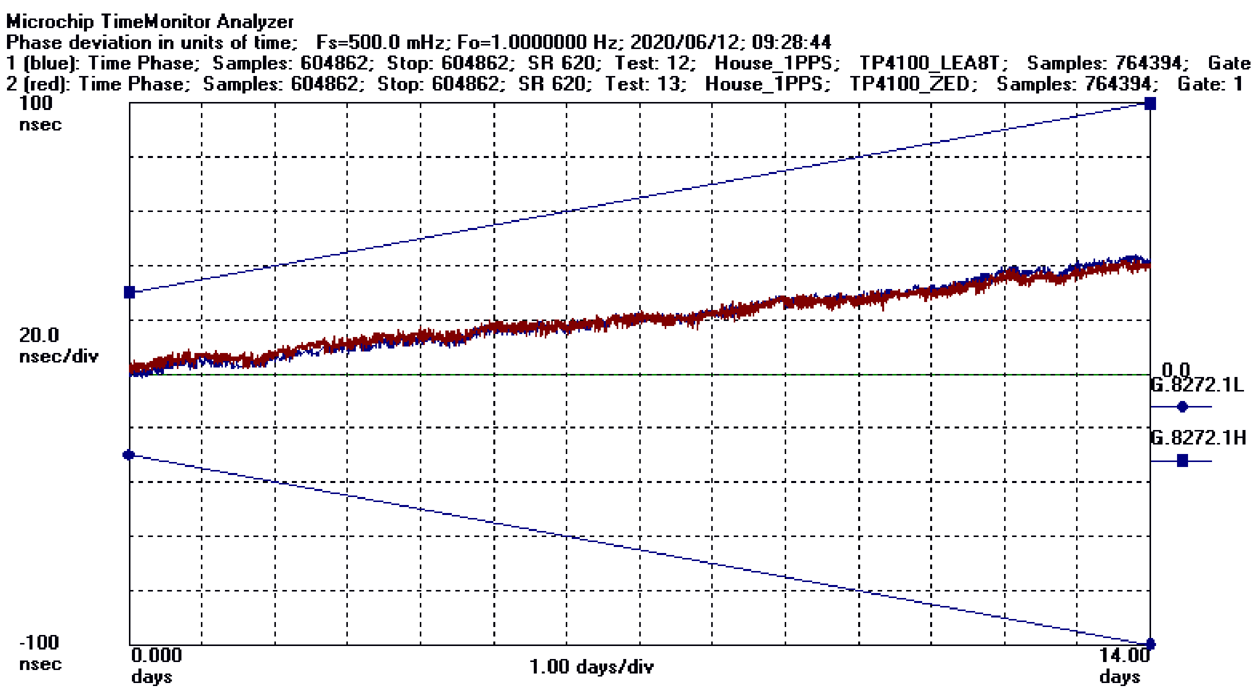


3.1.4 June 26: Day 14 of Holdover

Fourteen days of GNSS outage are completed and as discussed below the holdover performance exceeds the ITU requirements with excellent margins. As we discussed at the start of the holdover stage of this evaluation, we will reconnect the single-band ePRTC TimeProvider 4100 system to GNSS today but will allow the multi-band system to continue in extended holdover to fully characterize the performance capabilities of our ePRTC systems.

3.1.4.1 ITU ePRTC Holdover Compliance (Day 14 of Holdover)

The 14-day outage test results are shown below. The time error is well within the 100 ns requirement (42 ns) and both units exhibit consistent operational results. In fact, both units are maintaining performance with the normal operating ranging (better than 30 ns) for the first ten days of holdover.

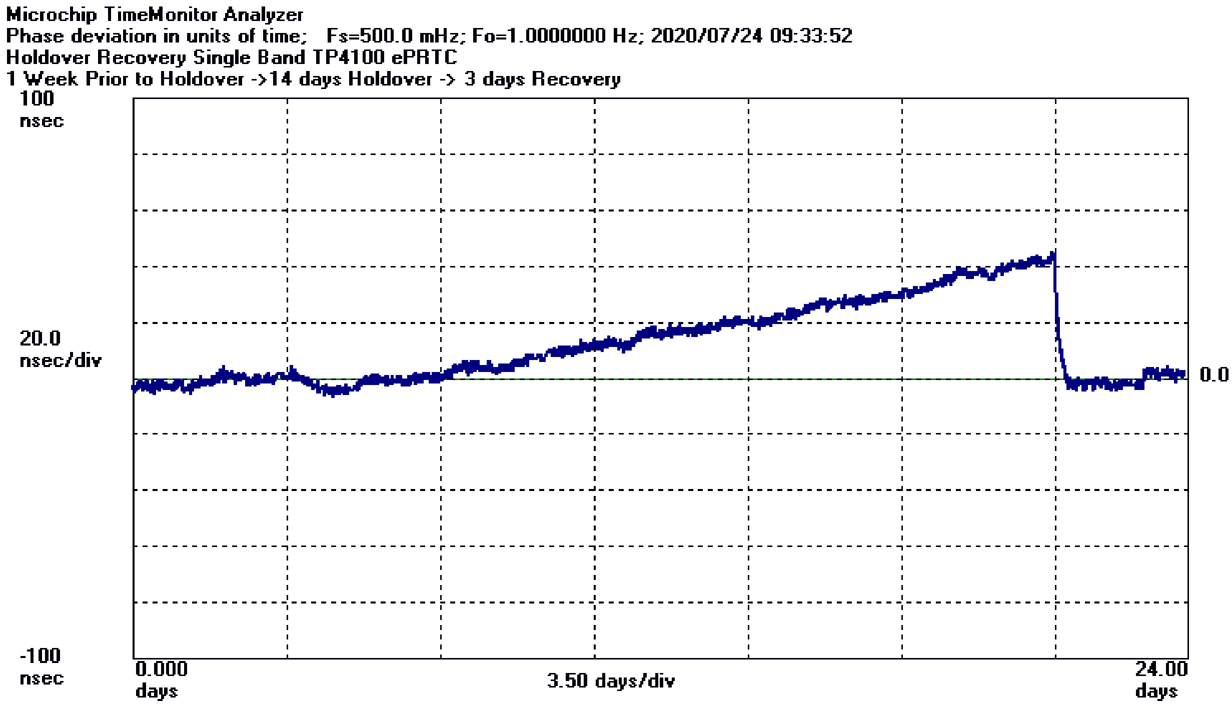


3.2 Holdover Recovery Stage

3.2.1 June 29: Day 3 Holdover Recovery, Day 17 Extended Holdover

We have just completed the holdover stage for the single-band TimeProvider 4100. On that same afternoon we performed the simple step of plugging the GNSS antenna back into the single band unit.

We have selected a time window including the week before holdover with the holdover and holdover recovery to see the overall picture (see graph below). We can see the normal tracking performance for 7 days before we pulled the antenna followed by the 14-day outage period where we accumulated timing error well within the 100 ns ITU allowance. Finally, we can see that we successfully re-converge and re-established normal 100% timescale protection operation over the weekend.

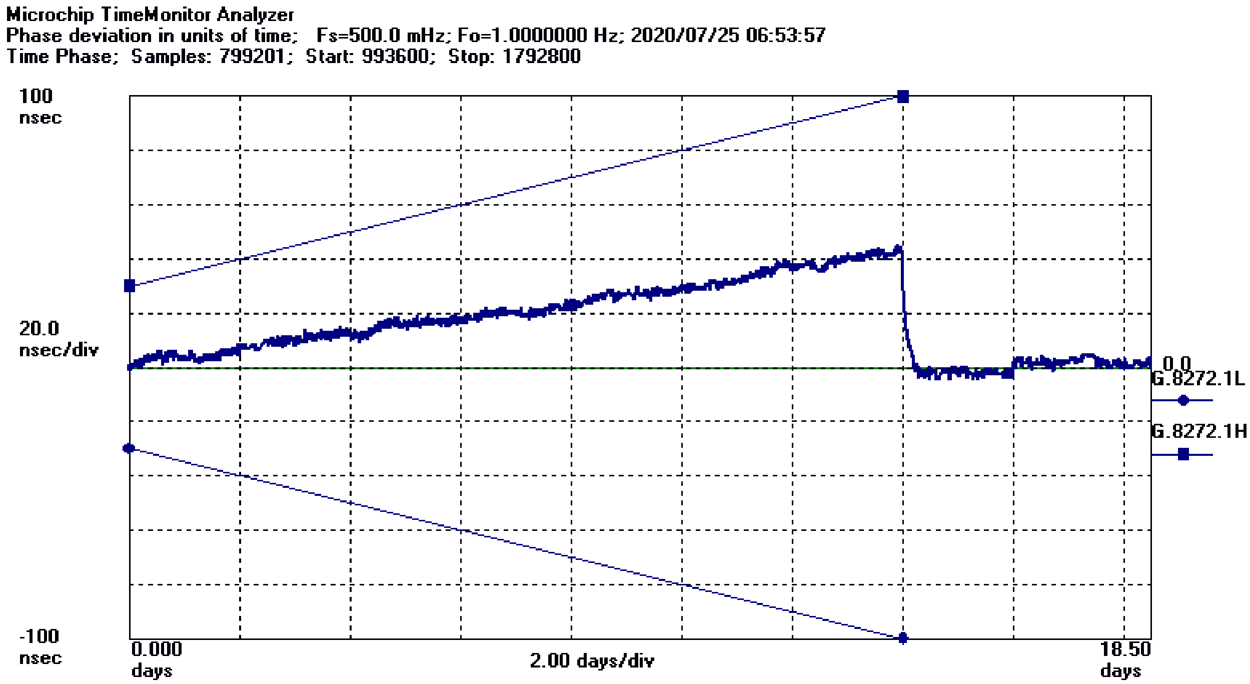


3.2.2 July 1: Day 5 Holdover Recovery, Day 19 Extended Holdover

3.2.2.1 Single Band ePRTC Holdover Recovery Performance (Day 5 Holdover Recovery)

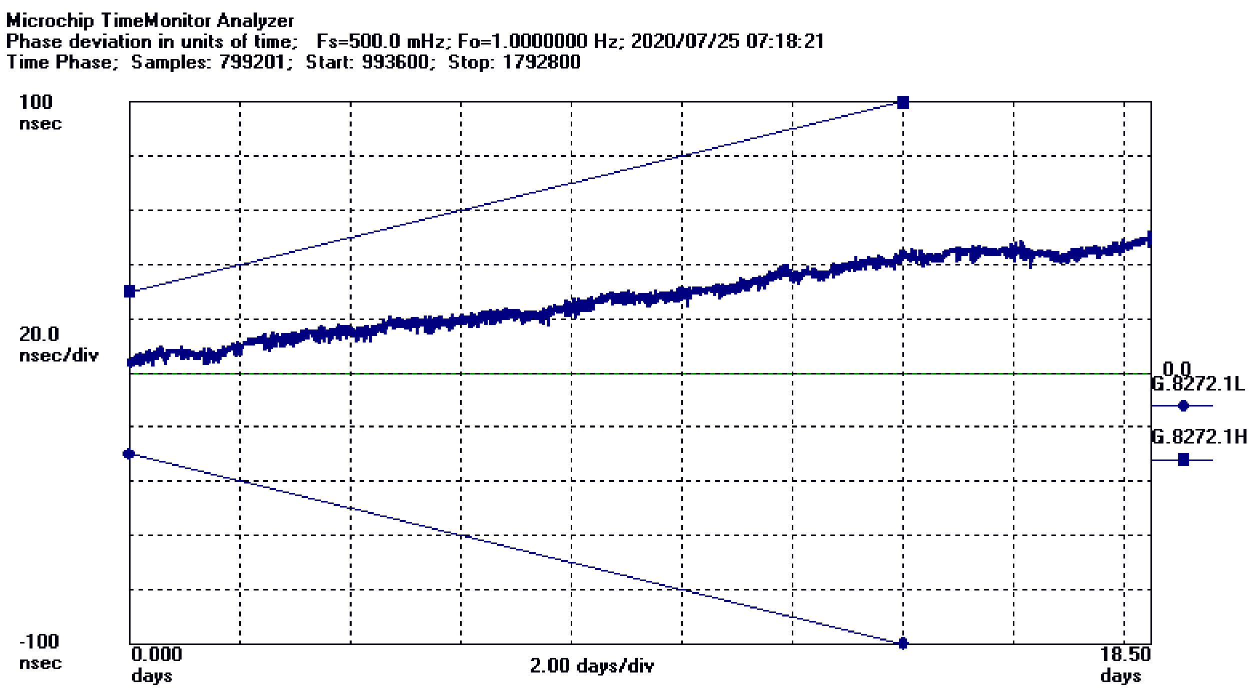
The graph below shows the time error of the single-band L1 unit during the holdover and recovery. We can see that we are now approaching 5 days of recovery. During the early recovery transient, the timescale protection availability drops below 100% and it takes several days to re-establish steady state operation.

The time error process is in steady state and we are in another waiting process until July 6 to capture a statistically significant window of steady state operation post recovery. The Summary section of this report includes all the data through July 6.



3.2.2.2 Multi-band Extended Holdover Performance: Day 19 Extended Holdover

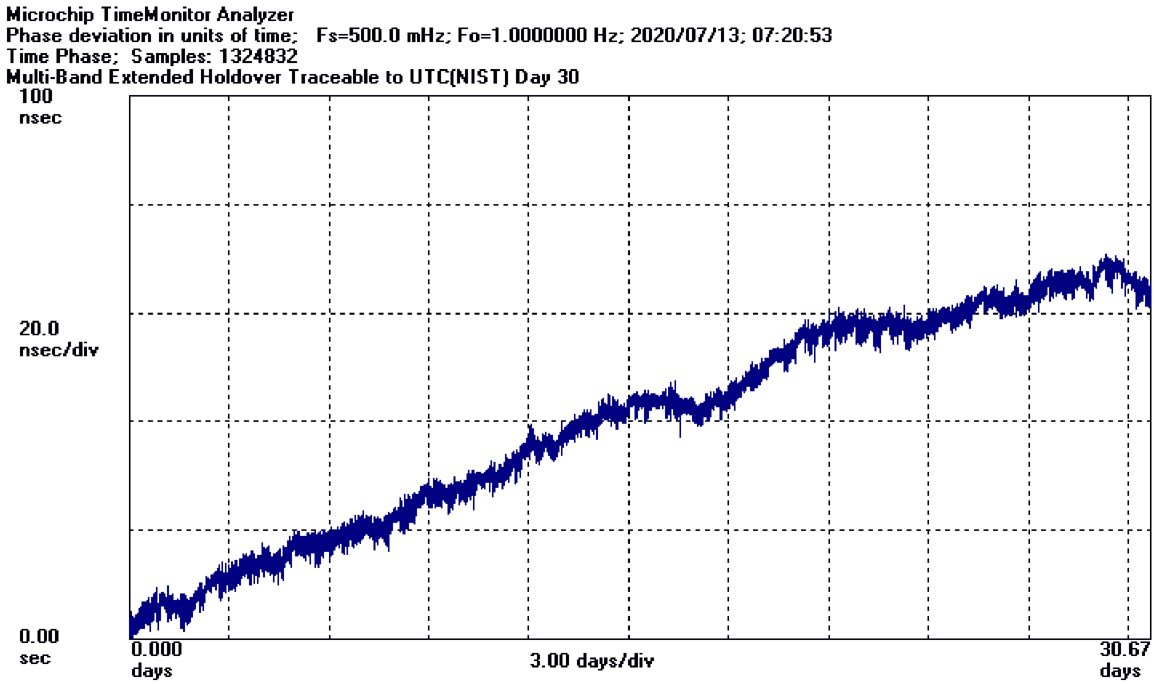
We have not reconnected the GNSS antenna to the multi-band TimeProvider 4100 to investigated how well our prediction model operates in conjunction with the stability of the 5071 high accuracy cesium in real life. Now the multi-band GNSS receiver has not been playing an active role since we pulled the antenna 18.5 days ago. However, the prediction model estimates for the clock state are influenced by the GNSS noise so that a better GNSS set of measurements will yield a better prediction. The graph below shows the time error performance during the 19-day holdover outage period. The clock model for a cesium atomic clock constrains the drift state to be zero so the initial frequency estimate initial plays a significant role. However, as the flicker noise frequency process plays out, we are starting to see the noise process starting to play a bigger role. Since flicker noise FM generates a linear increase in time prediction error, our approach of linearizing the time error prediction is warranted.

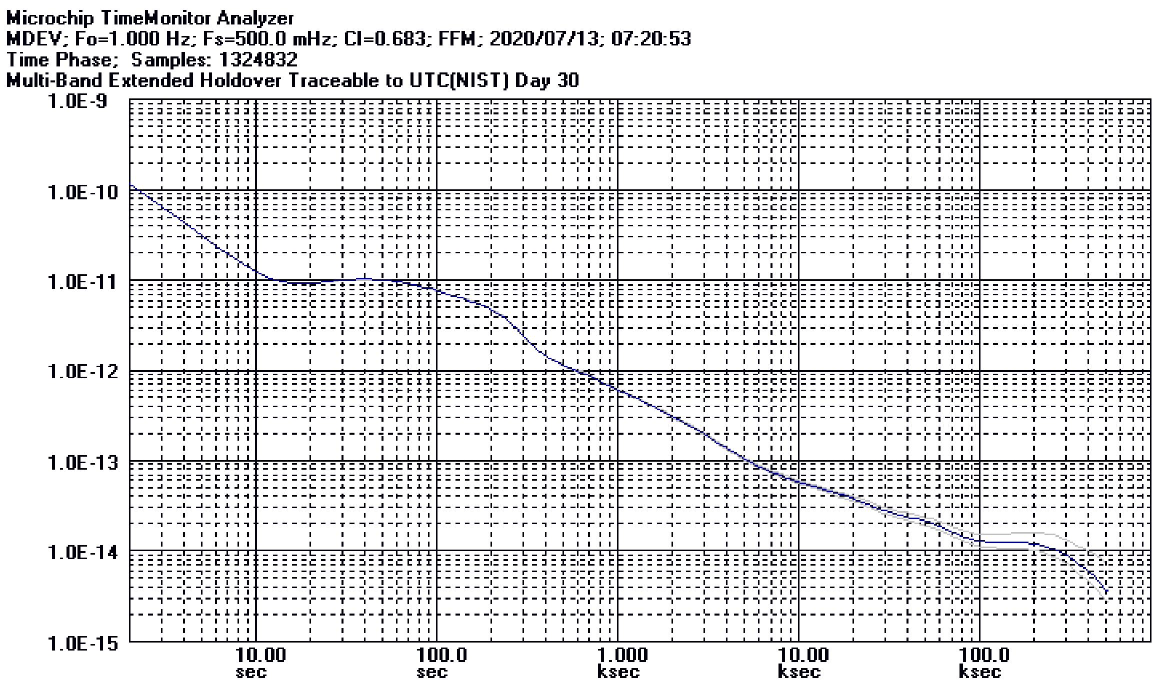


4. Extended Holdover Testing

4.1 July 13: Day 30 of Extended Holdover

Even though one main deliverable of the certification evaluation of the ePRTC is completed, we are continuing the long-term performance testing to investigate the extended holdover capabilities of TimeProvider 4100 ePRTC. It has been a month without reference. We can see that the time error accumulation is well behaved with no obvious longer-term degradation beyond the 1e-14 flicker noise floor expected behavior. We can see our 1-sigma confidence for the flicker noise floor is now 8e-15 (MDEV graph below). We are well on our way to surpass the 40-day, 100 ns initial projection.

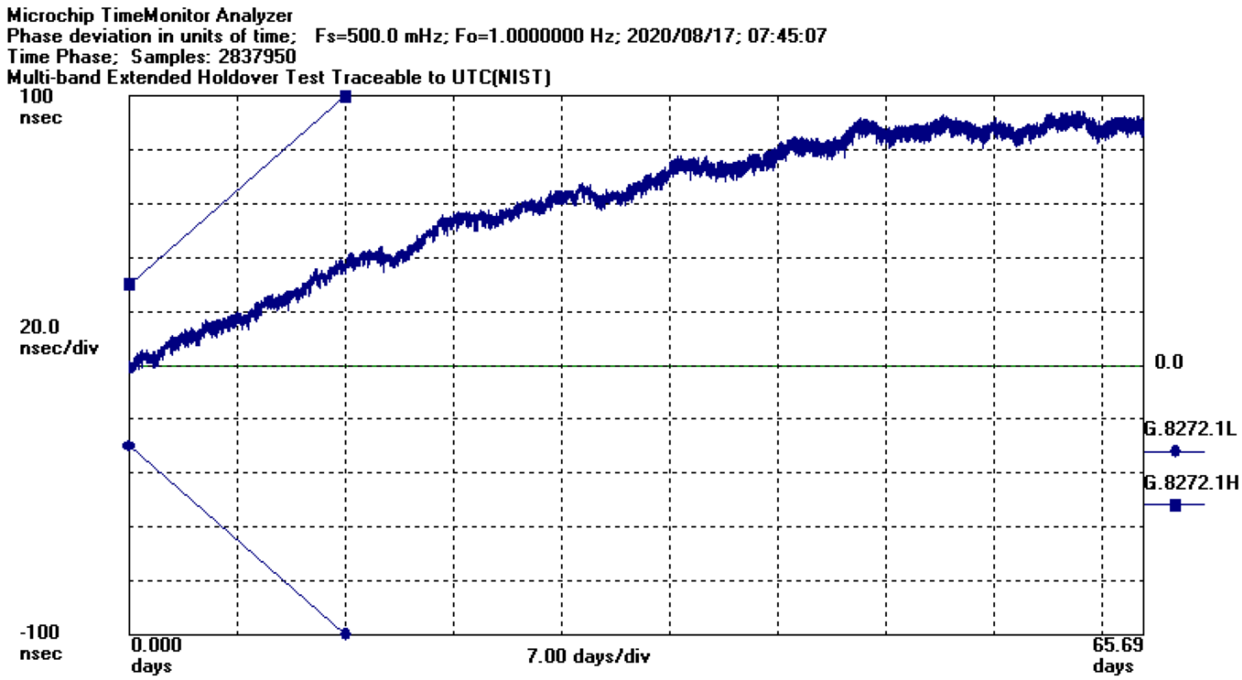




4.2 August 17: Day 65 of Extended Holdover

It was over 65 days ago when we predicted that we would support 100 ns operation for 40 days. We are beyond the 40-day holdover mark (65 days) and the Holdover Gas Gauge estimate of at 40 days of Holdover before exceeded 100 ns can now be evaluated. The actual accumulation of time error is 78 ns at day 40 of holdover. Recall the holdover gas gauge has been designed to provide a 1-sigma estimate of the number of days in the tank. This implies that there is a 2/3 probability that the holdover time will be equal or greater than the days estimated. We can see that this holdover sample falls in the “greater than 40 days” category, which is what we would expect typically. We are on pace to reach over 70 days before exceeding 100 ns. To put this in perspective, consider the holdover capabilities of alternative oscillator choices. A good OCXO would support 100 ns for a few hours while a good rubidium can support

100 ns for a day. The step up to a co-located cesium clock ensures unprecedented protection from GNSS vulnerabilities as we can operate for not hours, not a day, but over a month without exceeded 100 ns PRTC time compliance.



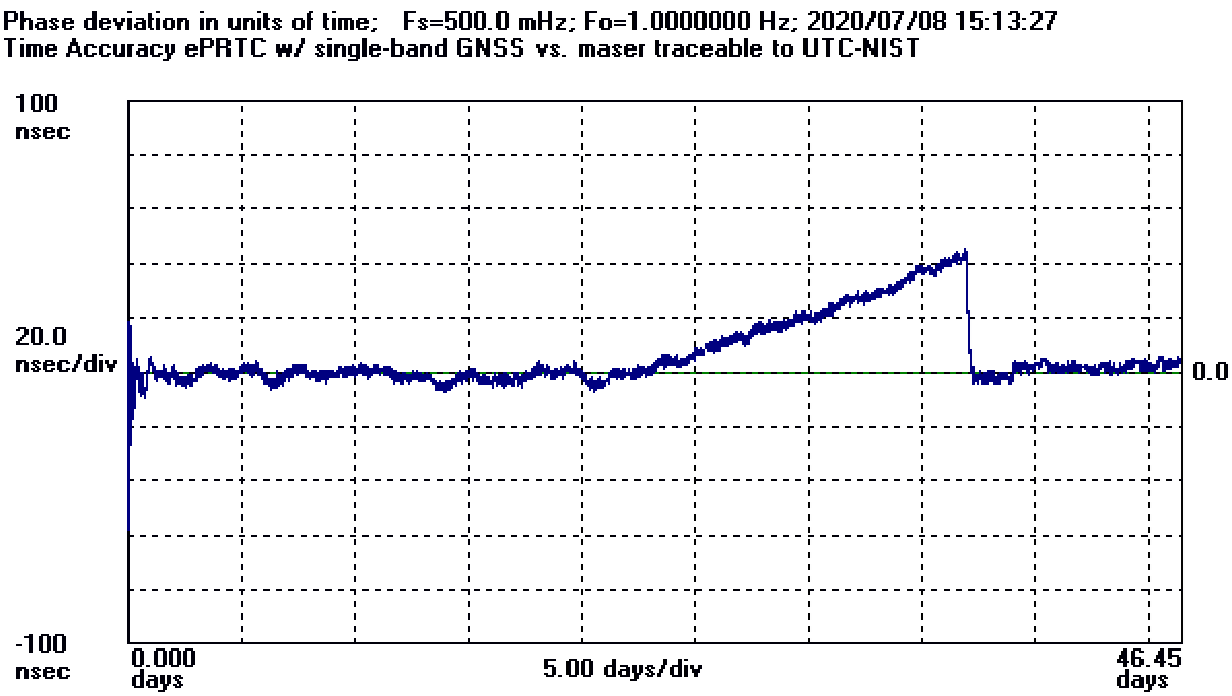
5. Performance Compliance Summary

The results confirm the overall excellent performance, summarized as follows.

5.1 Overall, 46-Day Time Performance

Before showing the ITU ePRTC compliance for all three phases of the testing (Pre-Holdover Normal Tracking, Holdover, and Post-Holdover Normal Operation), it is good to get an overall view of the entire 46-day, long-term performance evaluation.

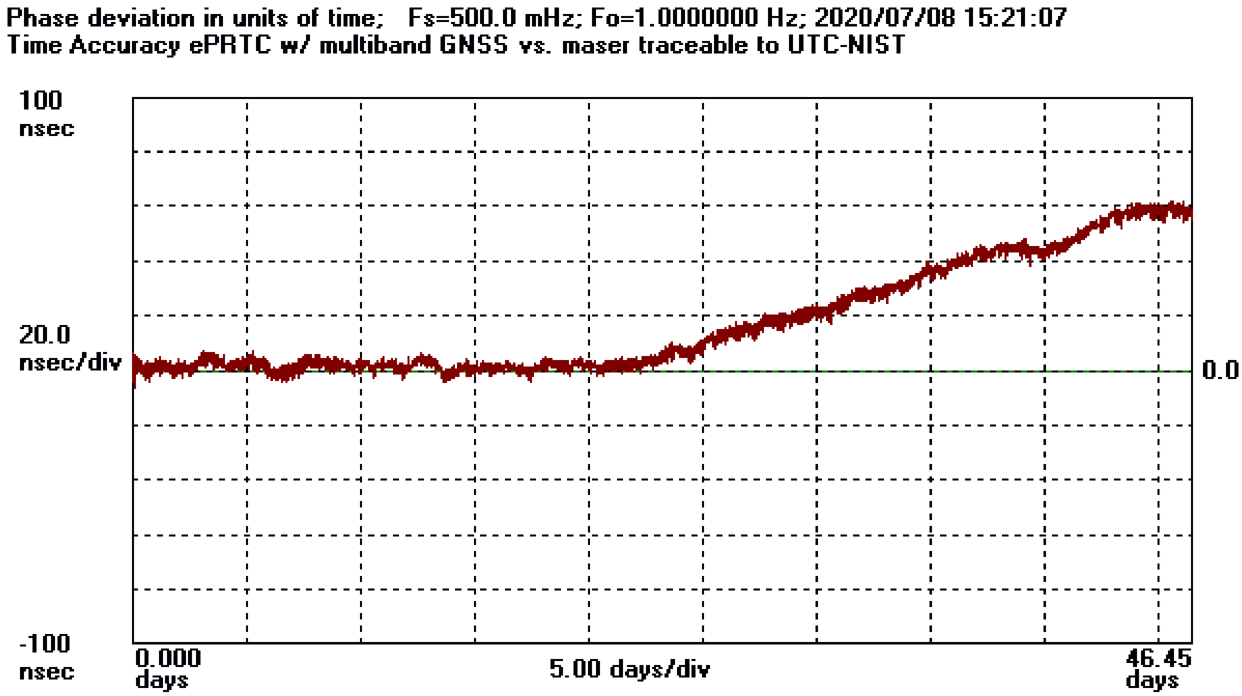
The graph below shows the single-band TimeProvider 4100. We can make several observations. We can see some early small settling behavior during the first three days as we progress from operating in disciplined oscillator mode to fully timescale protection mode with the GNSS steering de-coupled so that a full day of GNSS measurements is observed before making small steering adjustments.



We then operate for 21 days in normal tracking operation while we learn the optimal holdover state estimated to achieve maximum holdover protection.

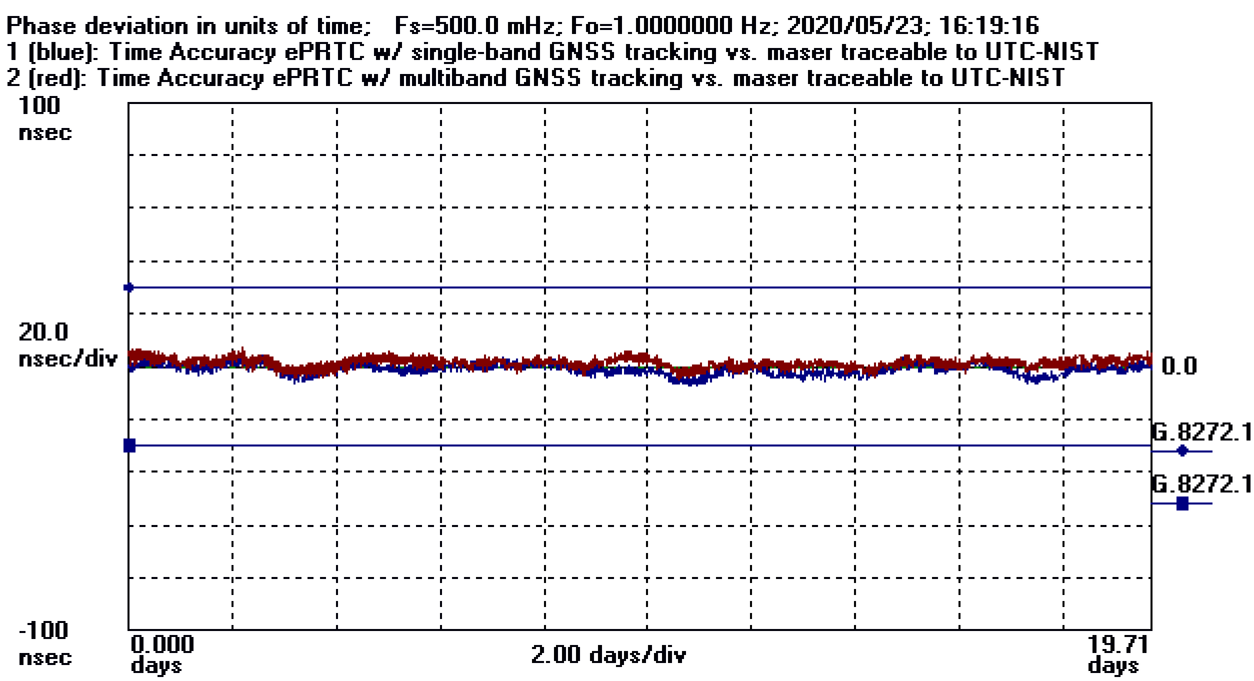
For the L1-only system, we maintain a continuous outage of GNSS for two weeks and then reconnect the GNSS antenna. We maintain time error performance well within the 100 ns ITU requirement during the holdover. Finally, we can see the recovery from holdover and return to normal fully protected operation.

The second graph shows the performance of the multi-band, GNSS-based TimeProvider 4100. For this system, we continued the holdover period to confirm the Holdover Gas Gauge which showed that we have over 40 days of GNSS outage protection before we would exceed 100 ns. We are on pace to maintain sub-100 ns holdover over 50 days.



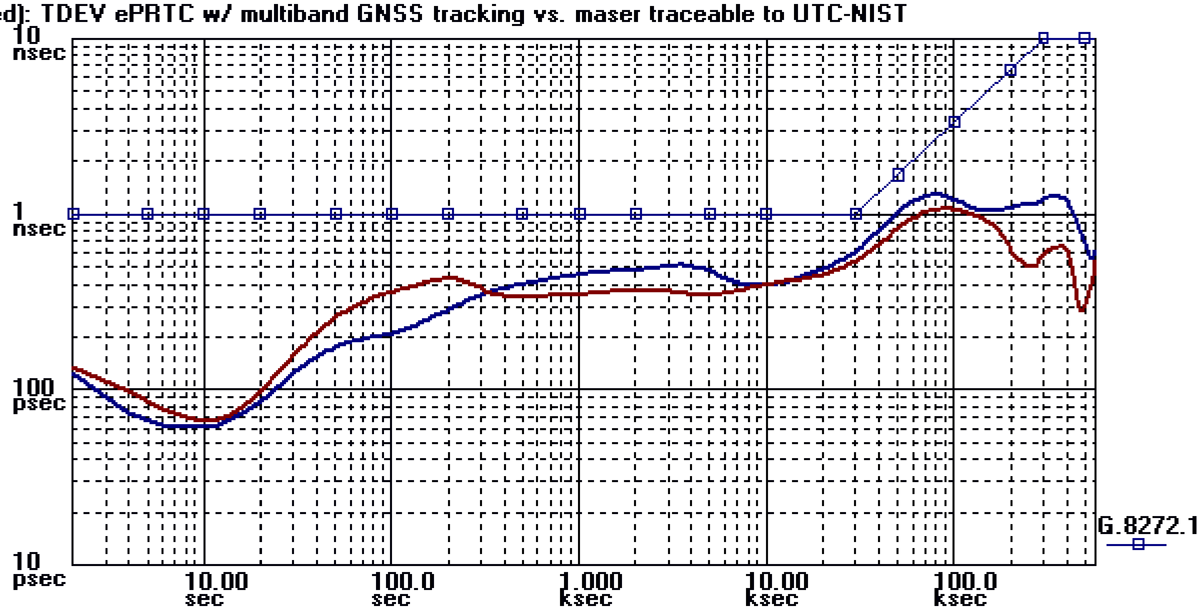
5.2 Pre-Holdover, 21-Day Normal Operation ITU Compliance

An ePRTC system will spend most of the time operating in normal mode. Keep in mind that in normal mode a properly designed ePRTC is leveraging the atomic timescale to provide constant protection against GNSS vulnerabilities that are not limited to just outage events, but real-world degradations associated with being a stationary timing receiver in an RF-vulnerable local environment. This leveraging of the atomic clocks during normal tracking ensures consistent reliable day-to-day operation, as we see in the test results. Note that the test window is 19.71 days as we started the normal testing when we achieved 100% protection availability at the very start of testing.



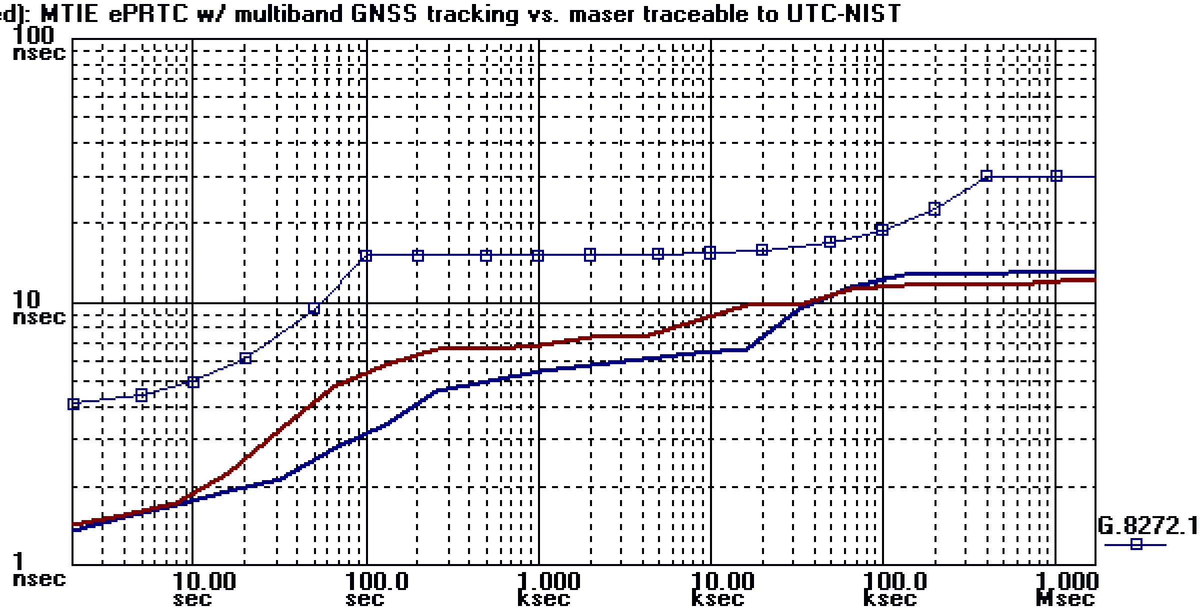
The next graph shows the TDEV compliance results. What is interesting is that the multi-band TimeProvider 4100 ePRTC (red) is showing a small but significant roll off in the TDEV curve at the longest TAUs as compared to the single band unit. It is likely that the longer-term performance of the multi-band is benefiting from both the direct, dual-band ionospheric correction as well as the increase in GNSS satellite sources (from all three bands).

TDEV; Fo=1.000 Hz; Fs=500.0 mHz; 2020/05/23; 16:19:16
1 (blue): TDEV ePRTC w/ single-band GNSS tracking vs. maser traceable to UTC-NIST
2 (red): TDEV ePRTC w/ multiband GNSS tracking vs. maser traceable to UTC-NIST



The MTIE compliance is shown in the graph below. MTIE as discussed is a well-established metric to bound the dynamic peak-to-peak time error variations as a function of observation time. It works well as a pass-fail compliance metric rather than as a characterization of underlying processes. We can see that both ePRTC systems-maintained compliance throughout the test window.

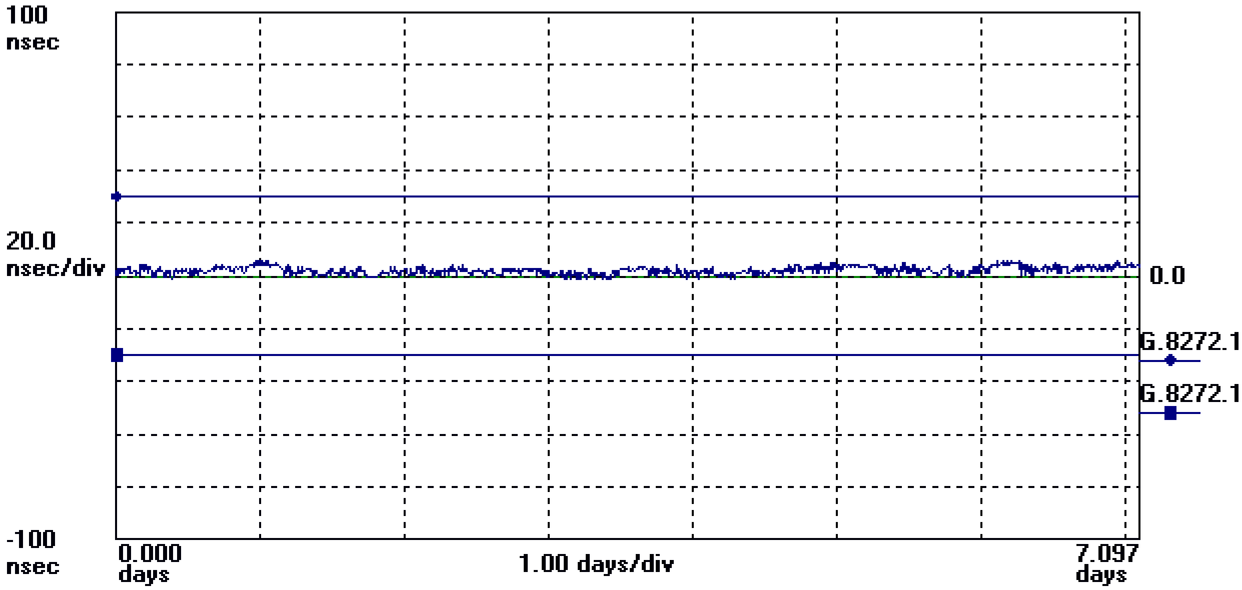
MTIE; Fo=1.000 Hz; Fs=500.0 mHz; 2020/05/23; 16:19:16
1 (blue): MTIE ePRTC w/ single-band GNSS tracking vs. maser traceable to UTC-NIST
2 (red): MTIE ePRTC w/ multiband GNSS tracking vs. maser traceable to UTC-NIST



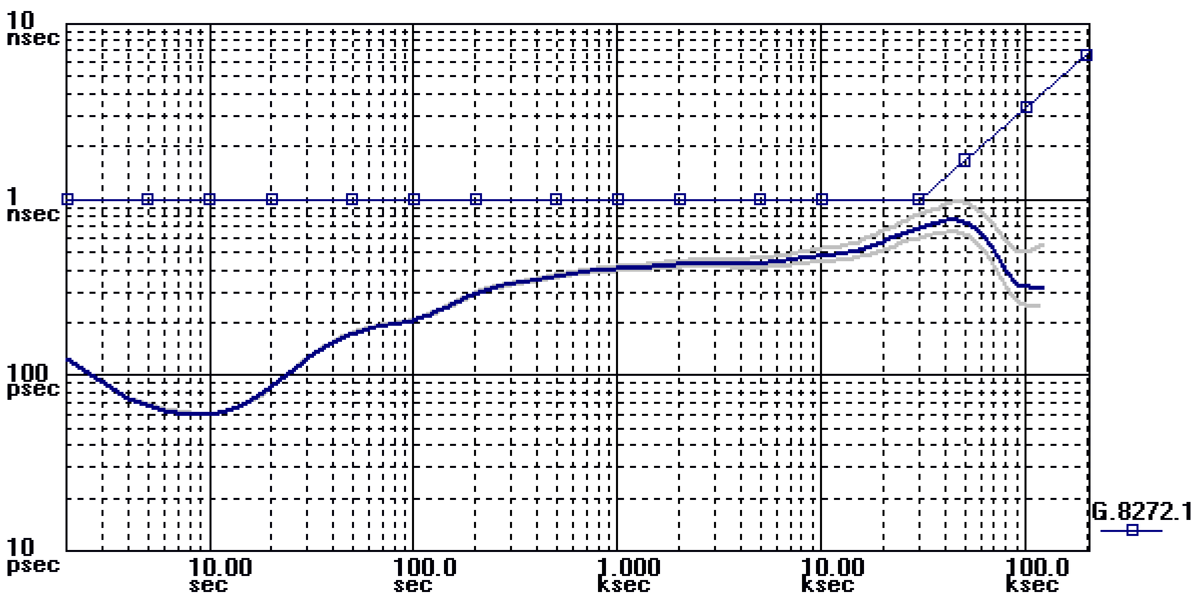
5.3 Post-Holdover, Last 7 Days of Normal Operation ITU Compliance

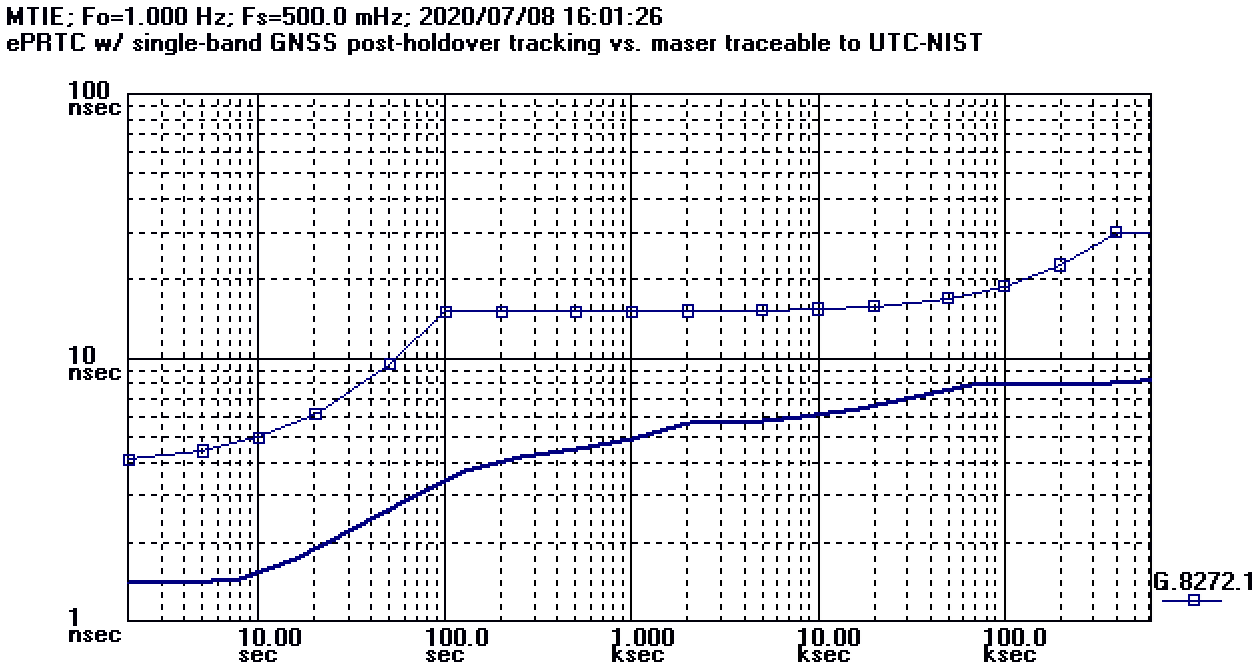
This portion of data is from the last week of operation to verify that TimeProvider 4100 ePRTC has returned to proper normal operation after the 14-day holdover and 2-day recovery. We can see that the compliance margins are modestly better than during the 21-day learning period after power-up. This is related to reduction in the intensity of the steering process correction which added a small but measurable noise to the earlier results. This steady state observation from day 39–46 is a better representation of the expected steady state performance of TimeProvider 4100 ePRTC.

Phase deviation in units of time; Fs=500.0 mHz; Fo=1.0000000 Hz; 2020/07/08 16:01:26
Time Accuracy ePRTC w/ single-band GNSS post-holdover tracking vs. maser traceable to UTC-NIST



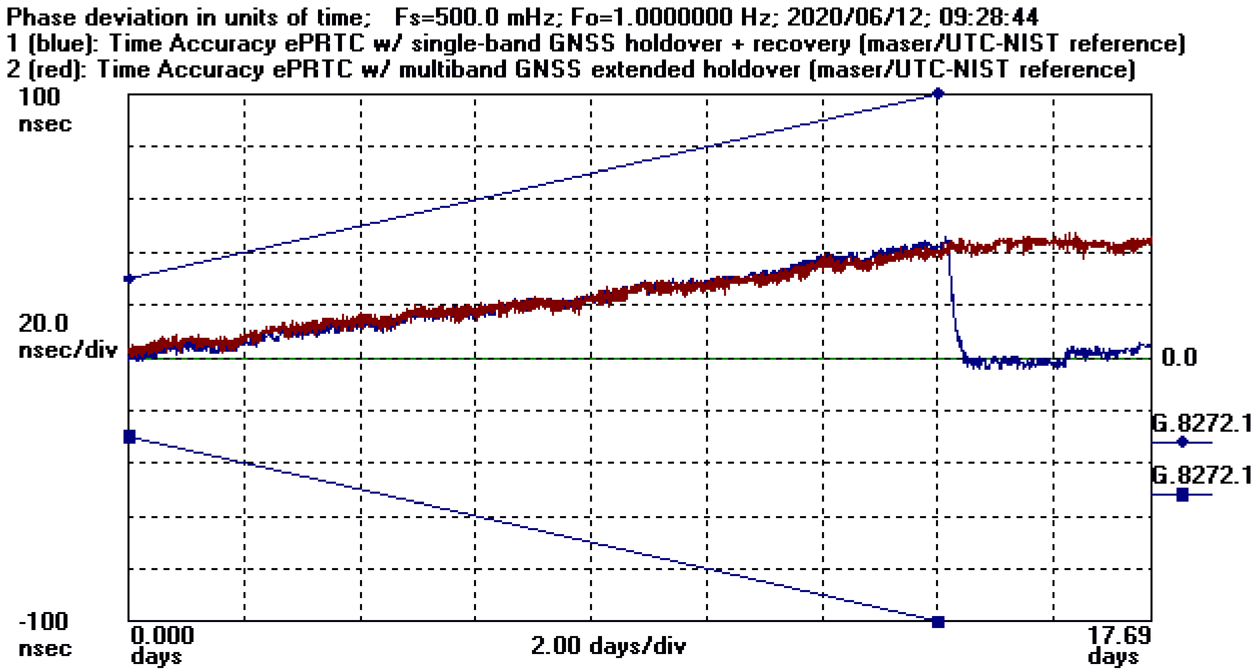
TDEV; Fo=1.000 Hz; Fs=500.0 mHz; CI=0.683; WPM; 2020/07/08 16:01:26
ePRTC w/ single-band GNSS post-holdover tracking vs. maser traceable to UTC-NIST





5.4 Holdover, 14-Day GNSS Outage Operation ITU Compliance

A critical performance requirement for an ePRTC system is the capability to maintain 100 ns (ITU PRTC level) timing performance not just for hours (OCXO) or even a day (MAC rubidium) but for a minimum of 14 days. This outstanding holdover protection is supported by the required autonomous cesium atomic clock (also known as primary reference clock) in concert with optimal holdover clock model prediction. The 14-day outage test results are shown below. The time error is well within the 100 ns requirement (42 ns) and both units exhibit consistent operational results. In fact, both units are maintaining performance with the normal operating ranging (better than 30 ns) for the first ten days of holdover. For a complete perspective we show the timing performance after day 14. The single band system (blue) was reconnected to GNSS and shows the expected recovery to normal operation. The multi-band system (red) was not connected and continues into extended holdover as discussed in the extended holdover section.


Phase deviation in units of time; Fs=500.0 mHz; Fo=1.0000000 Hz; 2020/06/12; 09:28:44
1 (blue): Time Accuracy ePRTC w/ single-band GNSS holdover + recovery (maser/UTC-NIST reference)
2 (red): Time Accuracy ePRTC w/ multiband GNSS extended holdover (maser/UTC-NIST reference)
100 nsec
20.0 nsec/div
-100 nsec
0.0
G.8272.1
G.8272.1
0.000 days
2.00 days/div
17.69 days

6. Revision History

Revision	Date	Section	Description
A	08/2020		Initial Revision

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