ORNL/SPR-2024/3693

Precision Time Protocol Performance Testing Over Optical Transport Network

Amir Osman
Chris Cooper
Joseph Olatt

April 2025

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

ORNL/ SPR-2024/3693

The Center for Alternative Synchronization and Timing (CAST) at Oak Ridge National Laboratory (ORNL)

PRECISION TIME PROTOCOL PERFORMANCE TESTING OVER OPTICAL TRANSPORT NETWORK

Amir Osman
Chris Cooper
Joseph Olatt

April 2025

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

BC	boundary clock
CAST	Center for Alternative Synchronization and Timing
ePRTC	enhanced primary reference time clock
GMC	grand master clock
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
MC	master clock
MTIE	Maximum Time Interval Error
ORNL	Oak Ridge National Laboratory
OTN	Optical Transport Network
PPS	pulse per second
PRTC	primary reference time clock
PTP	Precision Time Protocol
SC	slave clock
WAPA	Western Area Power Administration

ABSTRACT

The US Department of Energy Office of Electricity has partnered with Oak Ridge National Laboratory (ORNL) to find alternative precision timing solutions for the nation's power grid. This effort is in response to the vulnerabilities identified in the Global Navigation Satellite System (GNSS), of which the US Global Positioning System (GPS) platform is a part. Additionally, Executive Order 139055 has highlighted the need for alternative or backup timing solutions. ORNL has established a Timing Lab and has been testing various technologies and timing devices as part of this effort. Precision Time Protocol (PTP), and the off-the-shelf timing devices and network connections that support it, are among the alternatives being tested. This work reports the accuracy of PTP over an Optical Transport Network (OTN) and is part of a series published by the Center for Alternative Synchronization and Timing (CAST).

1. INTRODUCTION

The report provides insight into real-world and baseline performance of PTP over OTNs for electric power distributors, power marketing administrations, and future adopters of PTP [2]. Two OTNs were utilized in this performance testing: (1) an OTN spanning four Western Area Power Administration (WAPA) substations (Loveland, Colorado; Cheyenne, Wyoming; Stegall, Nebraska; and Wayside, Nebraska) and (2) the CAST lab's OTN network at ORNL, where benchmark/baseline measurements were collected.

Two PTP profiles were tested:

- G.8275.1: PTP telecom profile for phase/time synchronization with full timing support from the network [3]
- G.8275.2: PTP telecom profile for phase/time synchronization with partial timing support from the network [4]

The primary objective of the test was to use an enhanced primary reference time clock (ePRTC) system to discipline a boundary clock (BC) or a slave clock (SC), via the PTP protocol over an OTN network, and then measure the time accuracy on the BCs/SCs (and farther downstream, when possible). The ePRTC systems at WAPA and the ORNL lab comprised a grand master clock (GMC) that received a 10 MHz frequency reference from a cesium atomic clock. The GMC is disciplined by 1 pulse per second (PPS) and time of day signals from the GNSS (GPS and Galileo constellations were used). A PTP master clock (MC) on the GMC then propagates time to downstream BCs.

2. PRECISION TIME PROTOCOL OVERVIEW

PTP Version 1 is described in the Institute of Electrical and Electronics Engineers (IEEE) 1588 standard [1]. PTP Version 2 is described in the IEEE 1588-2008 standard [1]. In both standards, a hierarchy begins with MCs that distribute time and ends with SCs that receive time. MCs and SCs are referred to as ordinary clocks because they have a single network interface (meaning they either distribute or receive time, not both). BCs exist in intermediate hierarchy layers and have multiple network interfaces that receive time from above (as a slave to higher clocks) and push time below (as a master to lower clocks). BCs also adjust the received time to correct for the network delay. The GMC is at the root of the entire hierarchy. GMC may be manually configured or elected by all the other BCs and ordinary clocks on that network segment.

In both versions 1 and 2 of PTP, a hierarchy begins with MCs that distribute time and ends with SCs that receive time. MCs and SCs are referred to as ordinary clocks because they have a single network interface (meaning they either distribute or receive time, not both). BCs exist in intermediate hierarchy layers and have multiple network interfaces that receive time from above (as a slave to higher clocks) and push time below (as a master to lower clocks). BCs also adjust the received time to correct for the network delay. The GMC is at the root of the entire hierarchy. A GMC may be elected by all the clocks on that network based on configuration, or it may be manually configured.

Time synchronization using PTP is achieved as shown in Figure 1. In the figure, "Time server" denotes the MC, and "n/w element" denotes a boundary or slave clock.

On the BCs, the following measurements were recorded:

- Comparison of clock time on BCs (disciplined by GMC using PTP), with time received from GNSS. This measurement is the phase offset. It is also referred to as the time error.
- The time taken for the PTP sync message to travel from the GMC to the BC. This measurement is called "master to slave delay."
- The time taken for the PTP Delay_Req message to travel from a BC to the GMC. This measurement is called "slave to master delay.
- The difference between master to slave delay and slave to master delay. This measurement is called "network a10."

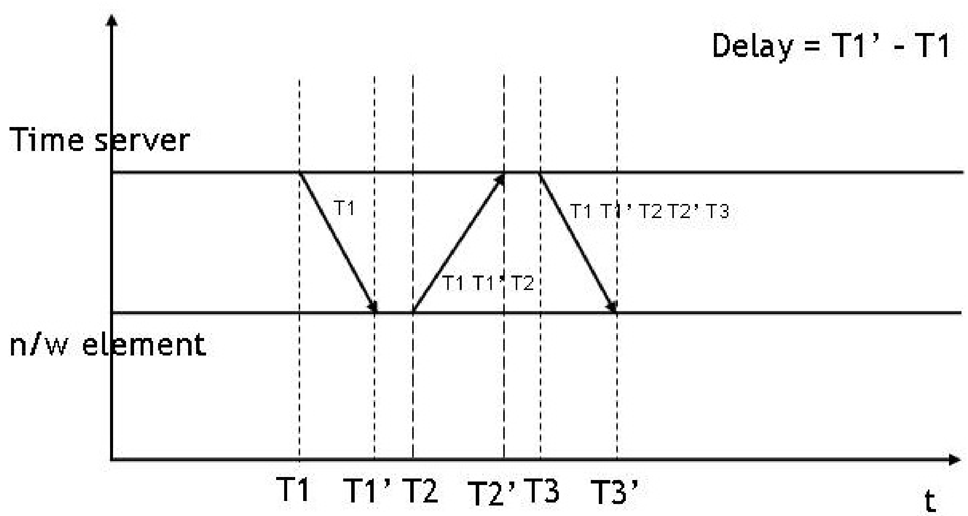


Figure 1. IEEE 1588 synchronization mechanism and delay calculation.

3. OPTICAL TRANSPORT NETWORK OVERVIEW

OTN is a telecommunications industry standard protocol—defined in various International Telecommunication Union (ITU) recommendations such as G.709 [11] and G.798 [12]—that provides an efficient way to transport, switch, and multiplex different services onto high-capacity wavelengths across the optical network. Today, network providers rely on OTN-enabled technology in their optical networks to gain benefits that include increased resiliency, simplified operations, enhanced service-level agreements, extended reach with forward error correction, the ability to efficiently maximize wavelength fill, and guarantee end-to-end service delivery [5].

OTN is commonly called a digital wrapper because it wraps each client/service transparently into a container for transport across optical networks, preserving the client's native structure, timing information, and management information. The enhanced multiplexing capability of OTN allows different traffic types, including IP, Ethernet, storage, digital video, and Synchronous Optical Networking/Synchronous Digital Hierarchy, to be carried over an OTN framing structure—a key reason for the adoption of OTN [5]. A schematic of an OTN is shown in Figure 2.

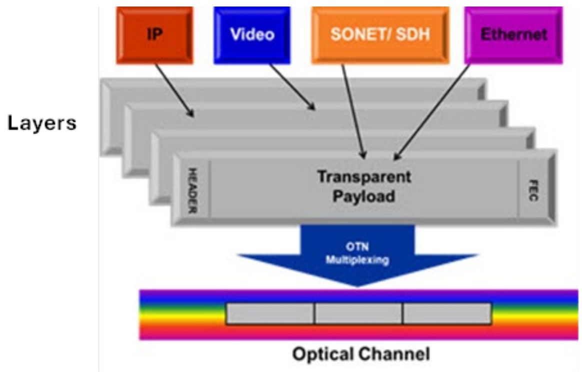


Figure 2. Schematic of an OTN [5].

4. WAPA AND CAST LAB MEASUREMENTS SETUP

The ORNL CAST lab consists of three racks with different clocks (several MCs and BCs). The WAPA setup consists of one MC and one BC at each substation. The following figures illustrate WAPA and ORNL lab architectures in more detail.

The four WAPA substations (Loveland, Colorado; Cheyenne, Wyoming; Stegall, Nebraska; and Wayside, Nebraska) are shown in Figure 3. Figure 4 illustrates the WAPA OTN architecture for the four substations. It shows the distance in kilometers between the stations along with the data transmission speed. Figure 5 shows a WAPA network drawing, detailing how the clocks are connected through router and server. Figure 6 illustrates the CAST lab's OTN setup and shows how the clocks are connected.

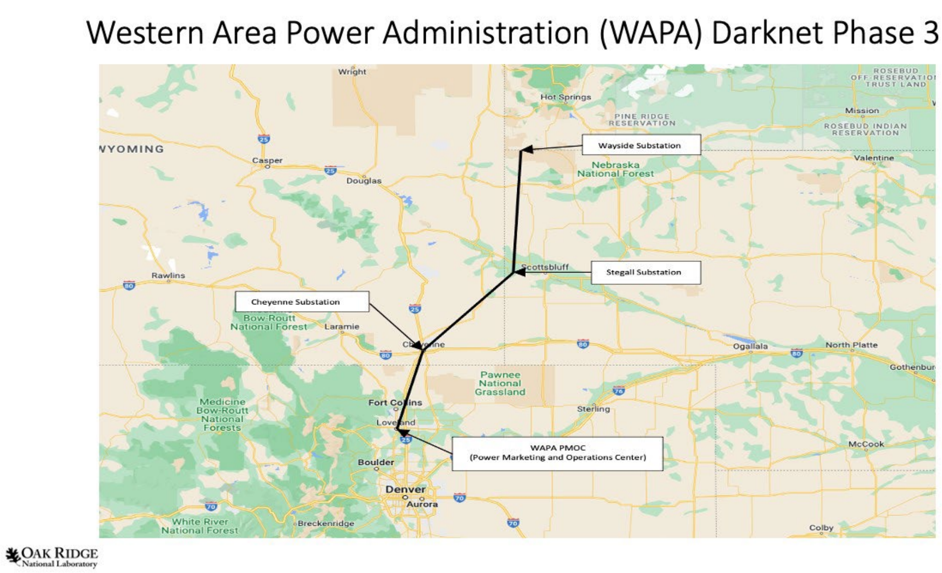


Figure 3. WAPA's four substations.

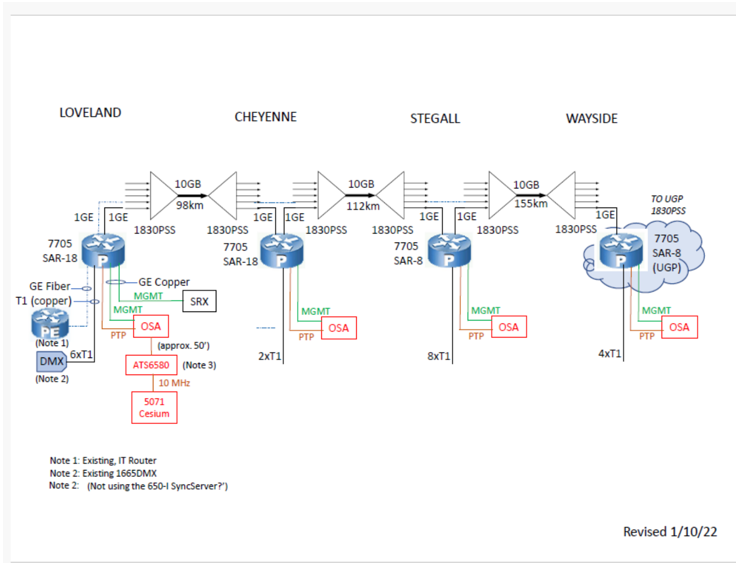


Figure 4. OTN architecture at WAPA.

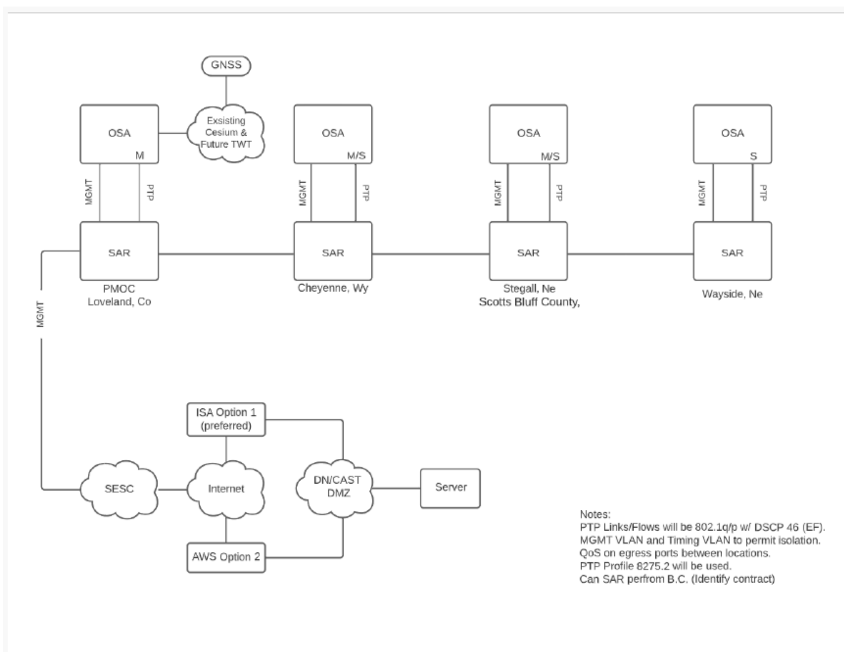


Figure 5. WAPA network drawing.

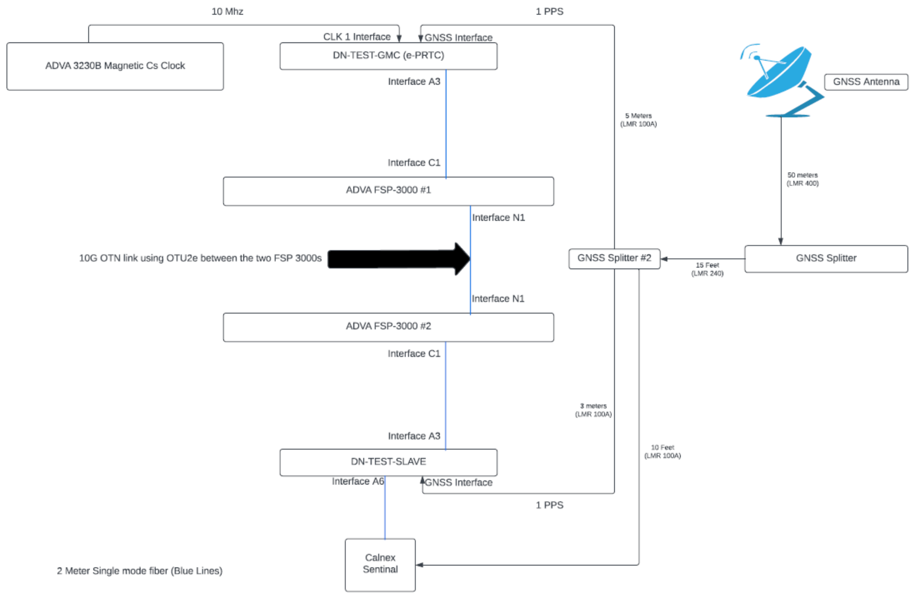


Figure 6. CAST lab OTN.

5. WAPA AND CAST LAB TEST GOAL

5.1 GRAND MASTER CLOCK

The GMC is the pinnacle of timekeeping accuracy and reliability within a PTP network. As the master time source within a PTP network, the PTP GMC provides the reference time to all other devices. It generates precise time signals that synchronize with other network components, optimizing time consistency across the entire network [7].

5.2 BOUNDARY CLOCKS

BCs act as intermediaries within a PTP network. They receive timing information from upstream clocks (and ultimately the GMC) and distribute it to other network devices, optimizing time synchronization across multiple domains or network segments. BCs play a crucial role in large-scale networks where time precision is essential, and multiple subnetworks must be synchronized [7].

5.3 ENHANCED PRIMARY REFERENCE TIME CLOCK

Key attributes of an ePRTC include the following:

- The ePRTC supports a high level of accuracy—within 30 ns when verified against the applicable primary time standard, such as UTC—and is subject to more stringent output performance requirements compared with current primary reference time clock (PRTC) systems.
- An ePRTC is an autonomous source of time that uses one or two co-located atomic clocks to provide the required performance for both time and frequency, even when connection to GNSS is lost.
- An ePRTC delivers a high level of operational reliability to ensure operators can maintain required time and frequency service performance for long periods regardless of the availability of GNSS.

The core components of an ePRTC system include the following:

- GNSS: provide long-term traceability to UTC
- Atomic clocks (typically cesium or better): provide frequency stability and use as reference
- ePRTC system: combined GNSS and Atomic clock, the combination of both technologies provides an accurate, secure, and robust time and frequency

The objective of the ePRTC solution is to generate time by producing its own independent, autonomous timescale. The timescale provides time, phase, and frequency that are aligned and calibrated to the GNSS signal over a long observation period, and the timescale is maintained autonomously based on the stability of the atomic clock(s). The frequency stability of the atomic clocks serves as a reference for the ePRTC timescale. This feature is the key difference between an ePRTC and a PRTC. In a PRTC, time comes directly from GNSS. The ePRTC is a solution for GNSS vulnerability [7].

5.4 TEST GOAL

The primary objective of the test was to use an ePRTC system to discipline a BC/SC, via the PTP protocol over an OTN network, and then measure the time accuracy on the BCs/SCs (and farther downstream, when possible) because each BC/SC needs to be connected to the GMC to get better time accuracy from the reference GMC. The ePRTC system GMC at WAPA at Loveland, Colorado, and the GMC at the ORNL lab have similar setups: they receive a 10 MHz frequency reference from a cesium atomic clock; are disciplined by 1 PPS and time-of-day signals from the GNSS (GPS and Galileo constellations were used); and a PTP MC configured on the GMC then propagates time to downstream BCs.

Two PTP profiles were tested: G.8275.1 and G.8275.2. The G.8275.1 PTP profile is used when all the network elements (e.g., routers, switches) are PTP-aware—the network elements can take on the role of a BC. This setup reduces the time error as the PTP messages traverse the network element.

G.8275.1 is a Layer 211 profile. The G.8275.2 PTP profile is used in networks where not all network elements are PTP-aware. G.8275.2 is a Layer 312 profile. The tests were run for 1 week for each PTP profile at WAPA and at the ORNL lab.

For these tests, the assumption was that the long distances between WAPA stations would decrease time transfer accuracy because transferring the PTP over long distance will take more time.

6. WAPA AND CAST LAB TIMING AND NETWORK GEAR USED FOR MEASUREMENTS

Table 1 lists the timing and network gear used for measurements at WAPA and the CAST lab.

Table 1. WAPA and CAST lab timing and network gear used for measurements.

Location	Clock system operational mode	Clock model	Router	Switch
Loveland, Colorado	ePRTC	Oscilloquartz OSA 5422 PTP GMC with rubidium oscillator and multiband GNSS receiver	Nokia 7705 Service Aggregation Router (SAR) [8]	Nokia 1830 Photonic Service Switch (PSS)
Loveland, Colorado	ePRTC	Microchip 5071A cesium frequency reference source		
Cheyenne, Wyoming; Stegall and Wayside, Nebraska	Boundary clocks	OSA 5422 boundary clocks with rubidium oscillators and multiband GNSS receivers [9]	Nokia 7705 Service Aggregation Routers (SAR)	Nokia 1830 Photonic Service Switches (PSS
ORNL CAST lab	ePRTC	OSA 5422 PTP grandmaster clock having Rubidium oscillator and multi-band GNSS receiver	OSA Fiber Service Platform (FSP) 3000	
ORNL CAST lab	ePRTC	OSA 3320B Cesium frequency reference source		
ORNL CAST lab	Boundary clocks	OSA 5422 boundary clock having Rubidium oscillator and multi-band GNSS receiver	OSA Fiber Service Platform (FSP) 3000	Calnex Sentinel [10]

7. WAPA AND CAST LAB TEST RESULT

The time on the GMC was compared with the time received from GNSS to detect any large disruptions or anomalies in the GNSS signals. The top of each second was used to generate a 1 PPS signal from both the clock time and the GNSS time. These 1 PPS signals were then compared to calculate the phase offset. The maximum time interval error (MTIE) was also calculated from these measurements.

Table 2 G.8275.1 profile lists the mean and standard deviation for all the measurements recorded for the OTN setup across the four WAPA substations.

Table 2. WAPA G.8275.1 profile results.

WAPA G.8275.1 MTIE result								
	Loveland, Colorado, GMC		Cheyenne, Wyoming, SC/BC		Stegall, Nebraska, SC/BC		Wayside, Nebraska, SC/BC	
	Mean (ns)	Std. dev.	Mean (ns)	Std. dev.	Mean (ns)	Std. dev.	Mean (ns)	Std. dev.
Phase offset	1.07	25.21	−468.38	6.26	6.67	9.86	30.49	9.85
Master to slave delay	n/a	n/a	−2,159.83	6.09	1,540.55	8.71	2,370.82	24.39
Slave to master delay	n/a	n/a	−466.92	6.27	3,054.65	9.90	−13.45	24.51
Network asymmetry	n/a	n/a	−1,692.91	6.26	−1,514.1	8.83	2,384.27	24.38

Figure 7 G.8275.1 profile 1 shows the phase offset between a GNSS 1 PPS signal and a 1 PPS signal generated from the clock time. This clock is the GMC at Loveland, Colorado, substation. This GMC is disciplined by GNSS.

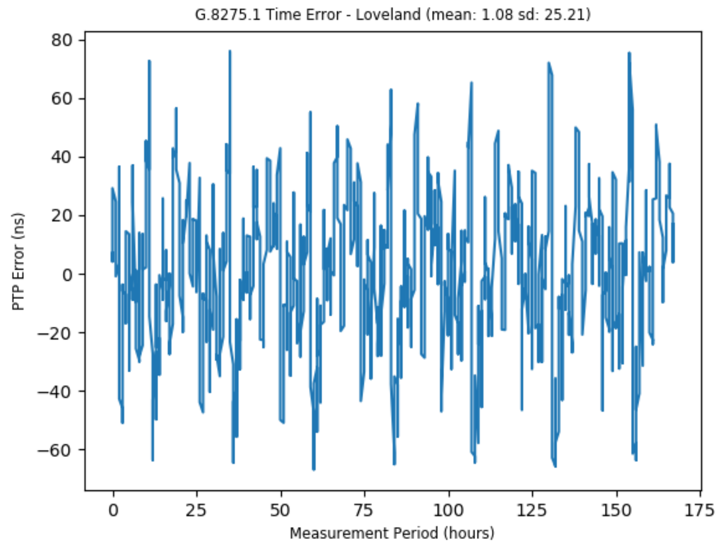


Figure 7. G.8275.1 GMC at Loveland, Colorado: phase offset (GNSS vs. clock time).

Table 3 G.8275.2 profile lists the mean and standard deviation for all the measurements recorded for the OTN setup across the four WAPA substations.

Table 3. WAPA G.8275.2 profile results.

WAPA G.8275.2 MTIE result								
	Loveland, Colorado GMC		**Cheyenne, Wyoming SC/BC**		**Stegall, Nebraska SC/BC**		**Wayside, Nebraska SC/BC**	
	Mean (ns)	**Std. dev.**	**Mean (ns)**	**Std. dev.**	**Mean (ns)**	**Std. dev.**	**Mean (ns)**	**Std. dev.**
Phase offset	1.11	33.62	−29.66	30.66	−17.23	43.54	-27.21	41.97
Master to slave delay	n/a	n/a	638,670.08	29.63	1,391,879.79	43.96	2,360,525.66	75.01
Slave to master delay	n/a	n/a	640,516.12	46.74	1,394,449.89	60.51	2,359,988.12	83.70
Network asymmetry	n/a	n/a	−1,870.21	23.23	−2,579.10	30.35	515.45	30.26

Figure 8 G.8275.2 profile shows the phase offset between a GNSS 1 PPS signal and a 1 PPS signal generated from the clock time. This clock is the GMC at Loveland, Colorado, substation. This GMC is disciplined by GNSS.

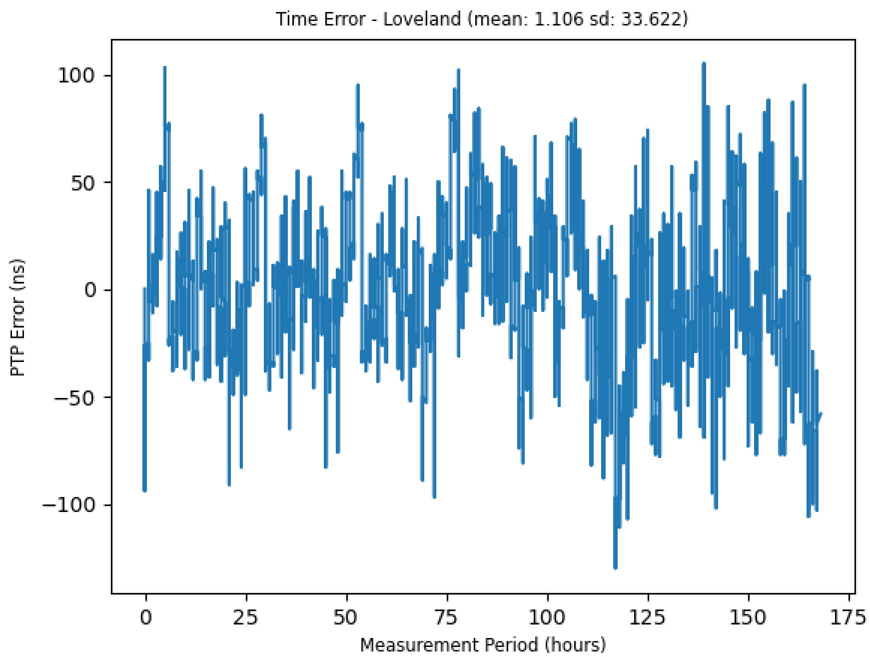


Figure 8. G.8275.2 GMC at Loveland, Colorado: phase offset (GNSS vs. clock time).

Table 4 lists the mean and standard deviation for all the measurements recorded for the OTN setup at the ORNL lab.

Table 4. ORNL G.8275.1 profile results (baseline).

G.8275.1 slave clock at ORNL: phase offset (GNSS vs. clock time)						
	GMC		BC		SC	
	Mean (ns)	Std. dev.	Mean (ns)	Std. dev.	Mean (ns)	Std. dev.
Phase offset	−0.45	5.02	−33.06	4.99	−1.2	11.39
Master to slave delay	n/a	n/a	609.60	4.93	0.53	11.42
Slave to master delay	n/a	n/a	640.90	4.92	−3.27	12.06
Network asymmetry	n/a	n/a	−29.95	4.88	−1.36	2.06

8. VERFICATION AND VALIDATION OF THE RESULT

Because network asymmetry was applied to the phase offset, the result required verification and validation. The WAPA network was dismantled, so the Netropy 10G1 Emulator was used, as shown in Figure 9. For verification and validation, two OSA 5422 were connected to the Netropy 10G1 Emulator, and the same master-to-slave delay and slave-to-master delay as those obtained in the WAPA network were applied. These delays were injected into the OSA 5422 SC, and exactly the same errors as in the OSA syncjack clock probes plots for the phase errors were obtained. Therefore, applying the network asymmetry to remove these delay offsets from the clock phase offset is a reasonable strategy.

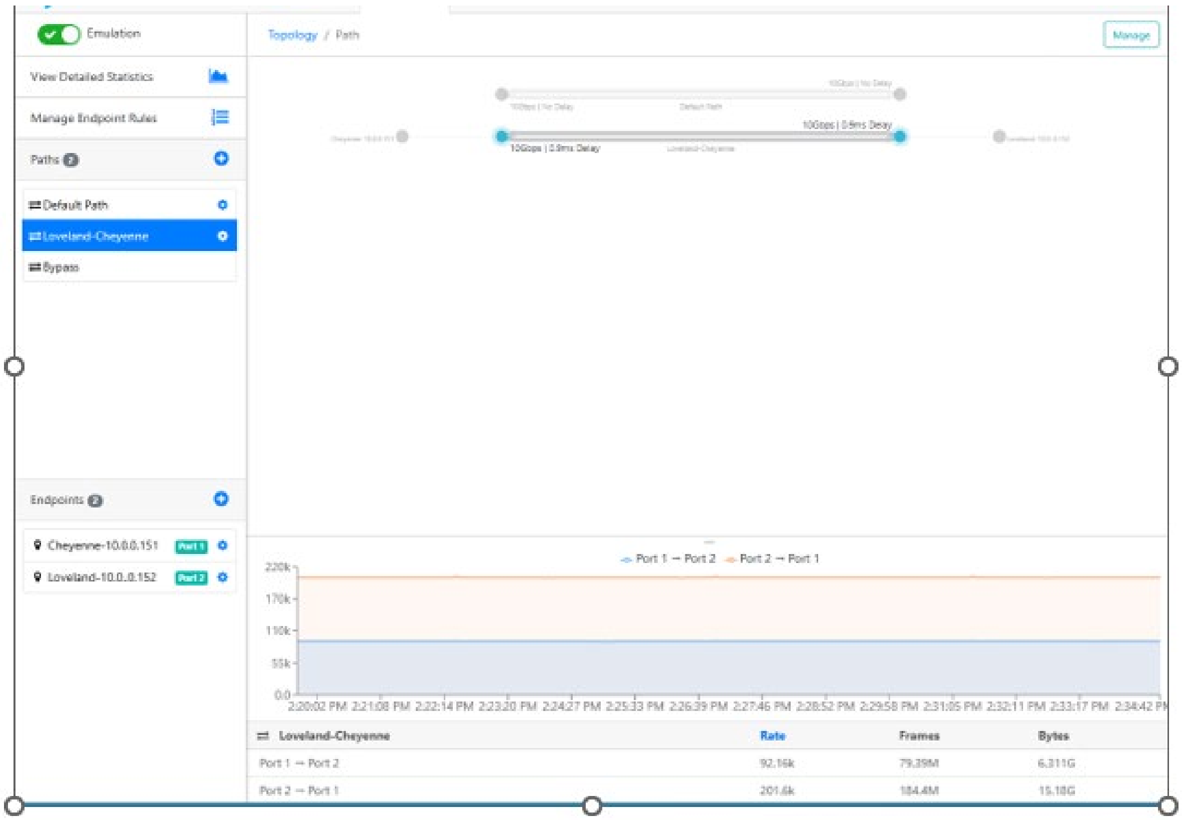


Figure 9. Netropy 10G1 Emulator configuration between Loveland and Cheynne using network delay.

Figure 10 shows clock probes before the Netropy 10G1 Emulator was used. The phase offset increased to 633,807 ns when the emulator was running and dropped to less than 100 ns after the emulator was stopped.

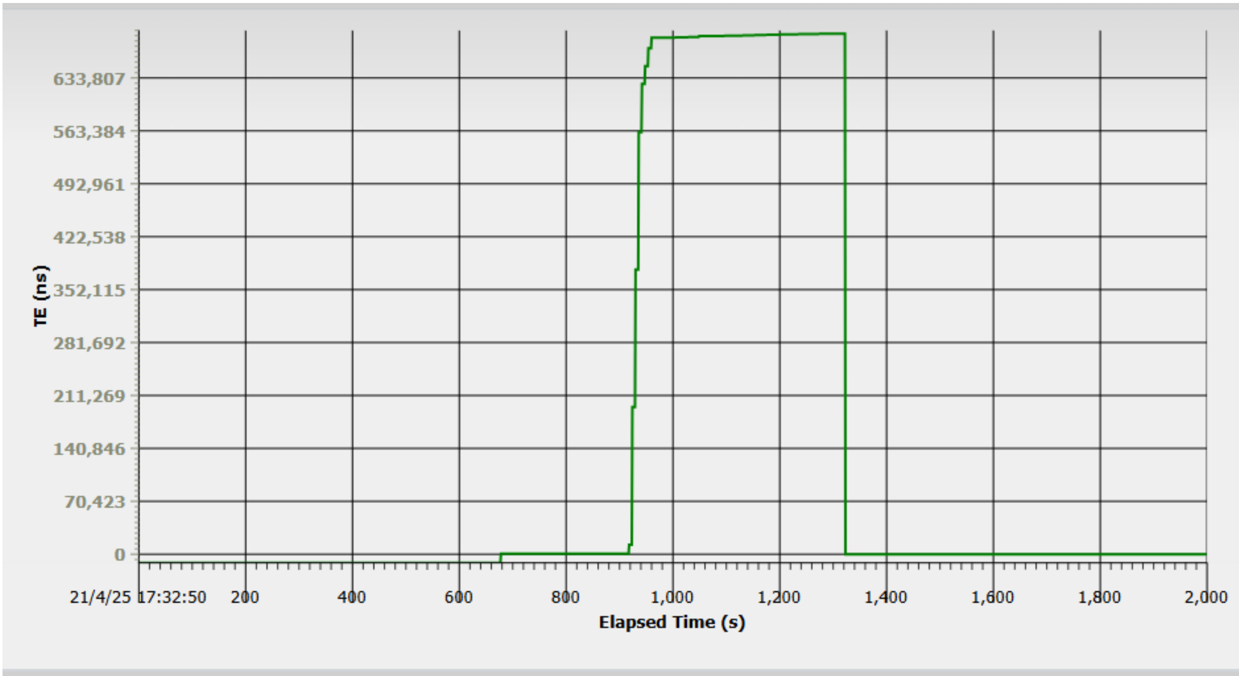


Figure 10. Clock probe phase errors during and after using Netropy 10G1 Emulator.

9. ANALYSIS OF WAPA TEST RESULT

At WAPA, the boundary clocks at the Cheyenne, Stegall, and Wayside substations were disciplined by the ePRTC GMC at Loveland. The testing covered two PTP profiles—G.8275.1 and G.8275.2.

Profile G.8275.1 performed better than the G.8275.2 PTP profile when tested over OTNs, and this we think due to use the Mac's addresses instated of using the IP's. in profile G.8275.1 and G.8275.2 respectively.

The result for the test in the ORNL CAST lab was consistent and acceptable: the average mean error was about 600 ns. The result at WAPA shows different delays for profiles G.8275.1 and G.8275.2. The error was large, most likely due to the large distance between the stations.

As shown in Table 5 (WAPA G.8275.1 profile results), the Cheyenne substation had the worst phase offset, and the Wayside, and Stegall substations had the best phase offsets. This result does not align with the assumption that longer distance from the MC results in worse performance. As shown in Table 3 (WAPA G.8275.2 profile results), the Wayside substation had the best phase offset despite the longer distance. This result was unexpected, and further analysis with more data is needed to investigate the reason for this result. Finally, our hypothesis is consistent with results, but the errors are more independent of distance than expected.

10. CONCLUSION

After applying asymmetry compensation for the phase errors, time-transfer accuracy improved to below 100 ns with the OTN system.

To investigate the OTN network performance, Netropy 10 G1 was used to verify the performance of the PTP over an OTN. Applying a delay to the network using Netropy 10 G1 yielded phase errors in the testing OSA clock identical to the phase errors in the original WAPA network, improving the accuracy to within 100 ns and confirming that applying asymmetry compensation was the correct strategy.

REFERENCES

[1] https://endruntechnologies.com/pdf/PTP-1588.pdf

[2] https://www.itu.int/ITU-T/studygroups/com15/otn/OTNtutorial.pdf

[3] https://www.itu.int/rec/T-REC-G.8275.1/en

[4] https://www.itu.int/rec/T-REC-G.8275.2/en

[5] https://www.ciena.com/insights/what-is/What-is-Optical-Transport-Networking-OTN.html

[6] https://www.federalregister.gov/documents/2020/02/18/2020-03337/strengthening-national-resilience-through-responsibleuse-of-positioning-navigation-and-timing

[7] ePRTC White Paper the Enhanced Primary Reference Time Clock (ePRTC) https://syncworks.com/wp-content/uploads/2023/04/Microsemi_Enhanced_Primary_Reference_Time_Clock_Solution_White_Paper.pdf

[8] https://onestore.nokia.com/asset/174425?_ga=2.99300954.599964947.1697556544-1580635497.1697556544

[9] https://www.adva.com/en/products/open-optical-transport/fsp-3000-open-line-system/network-infrastructure-ols

[10] https://info.calnexsol.com/acton/fs/blocks/showLandingPage/a/28343/p/p-0050/t/page/fm/0

[11] https://www.itu.int/rec/T-REC-G.709/en

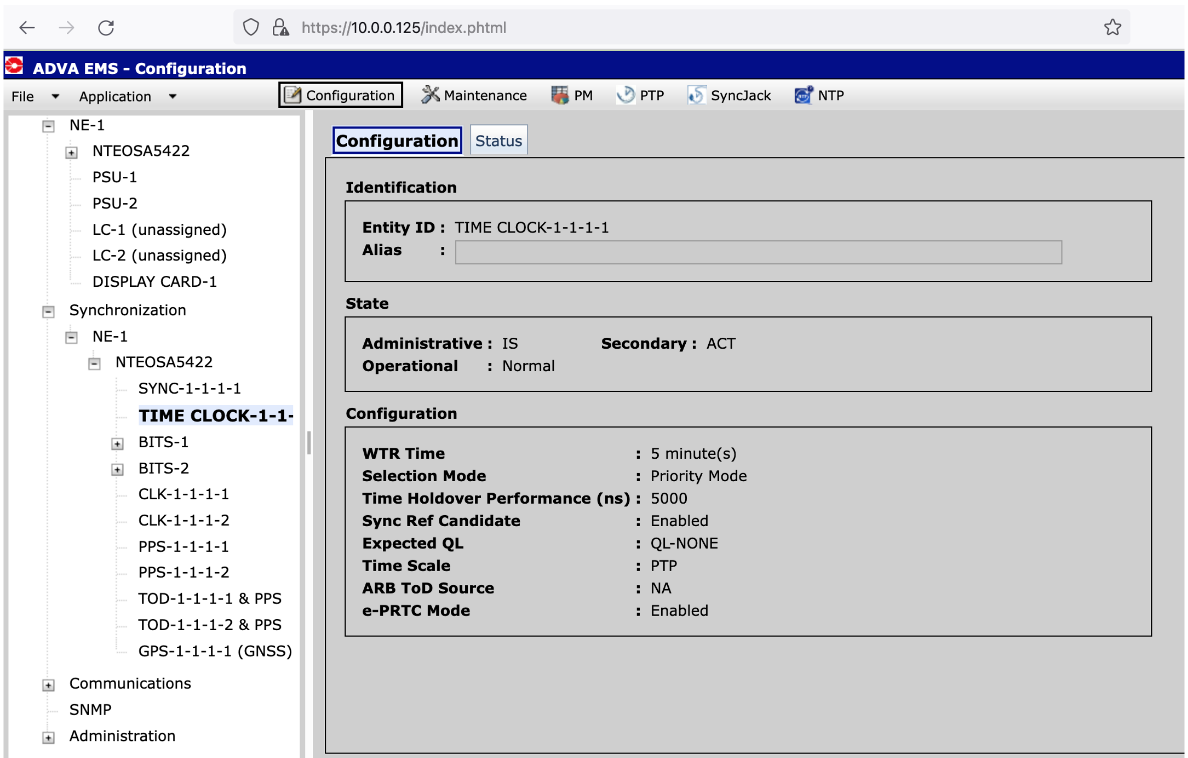
[12] https://www.itu.int/rec/T-REC-G.798/en

APPENDIX A. WAPA AND CAST LAB CLOCKS SETTINGS/CONFIGURATIONS

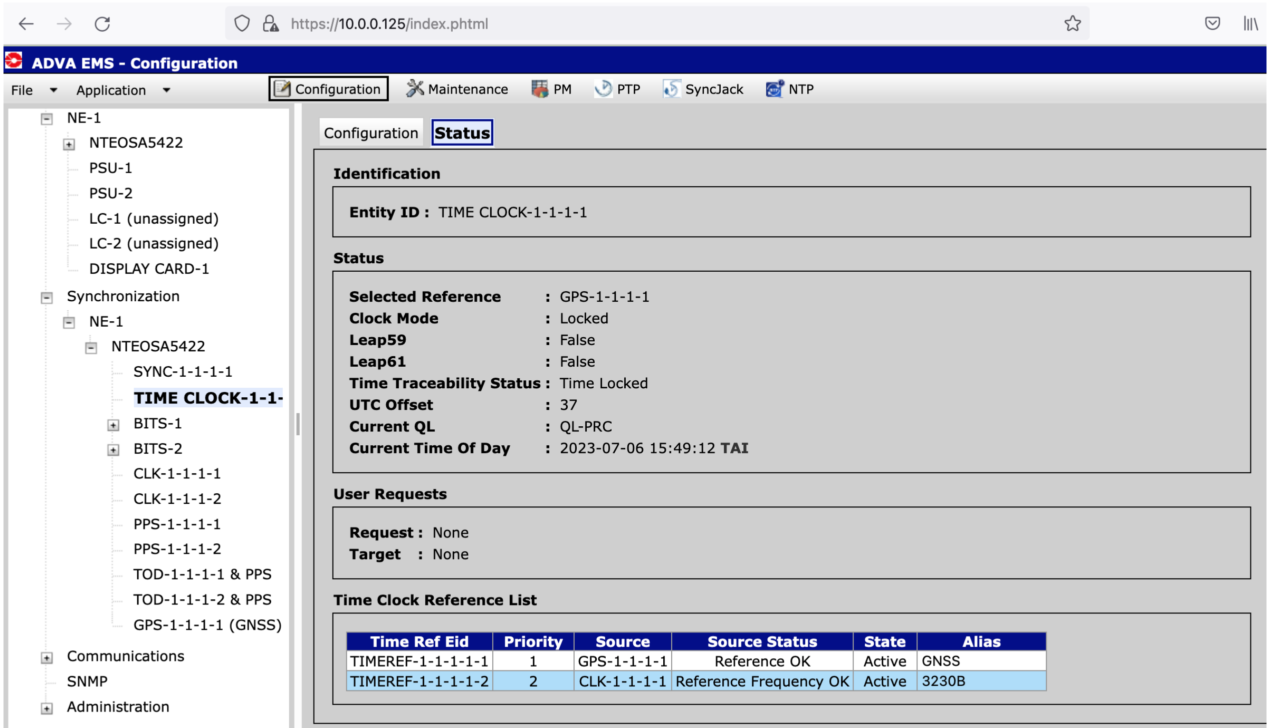
APPENDIX A. WAPA AND CAST LAB CLOCKS SETTINGS/CONFIGURATIONS

WAPA and CAST lab Clocks Settings/Configurations

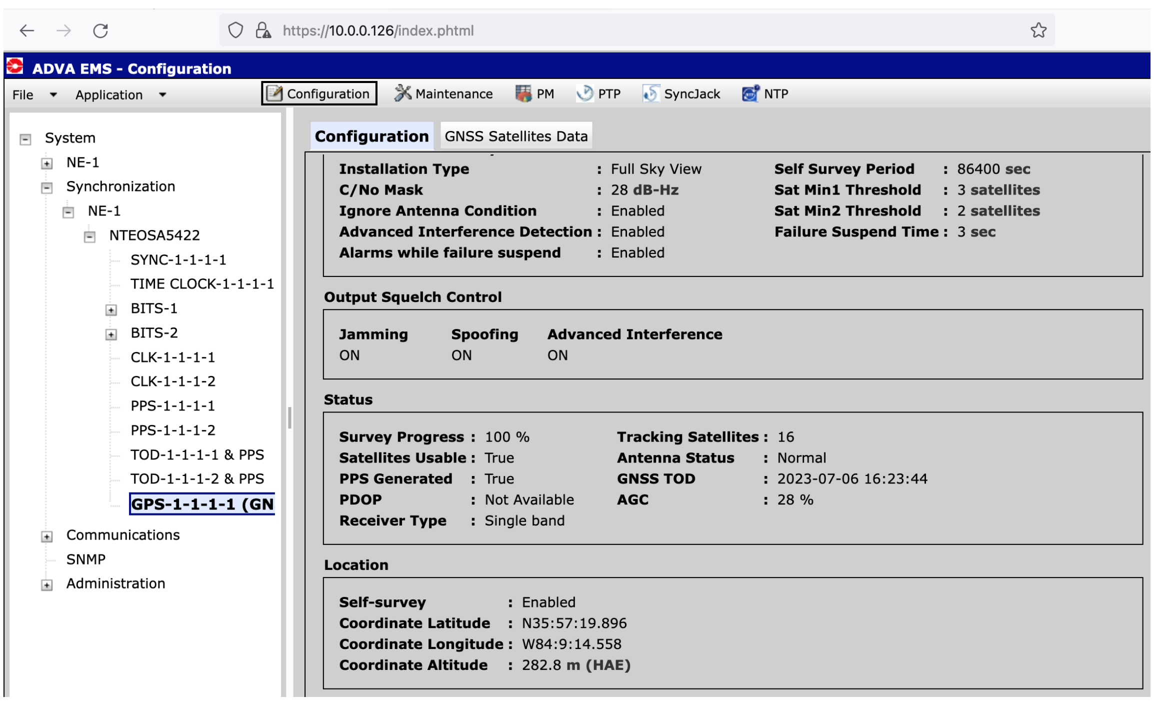
The following figures show various clock settings and configurations used in the Western Area Power Administration (WAPA) and the Center for Alternative Synchronization and Timing (CAST) lab for this test.



Grand master clock (GMC) in enhanced primary reference time clock (ePRTC) mode.



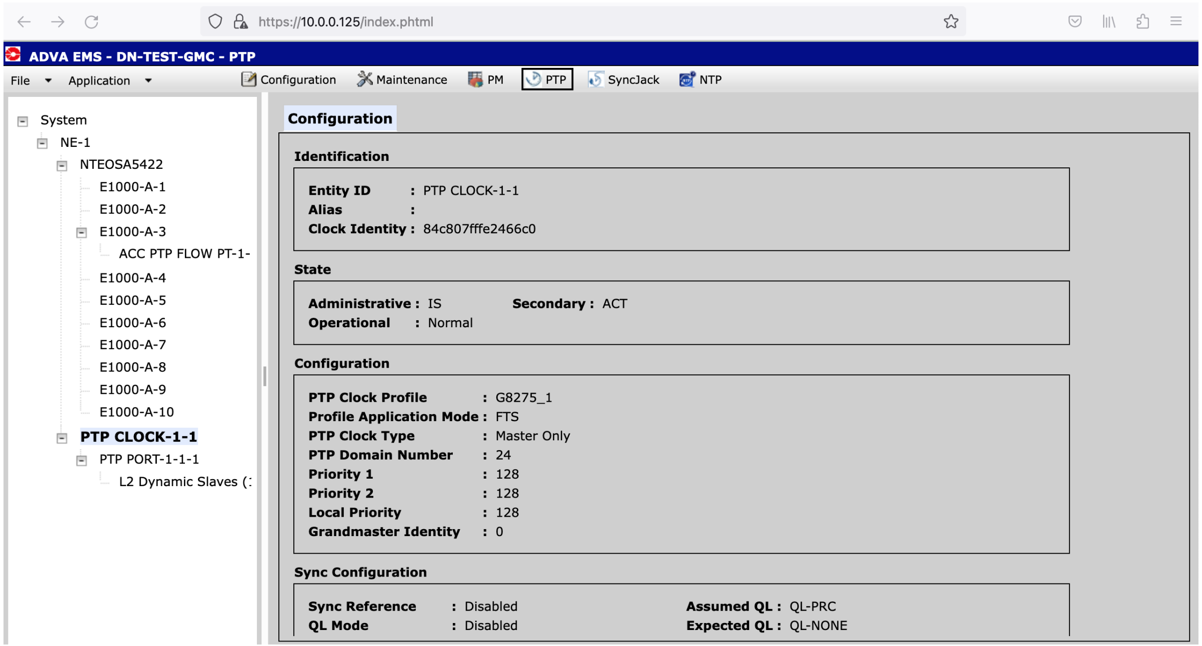
Cesium clock frequency and Global Navigation Satellite System (GNSS) references on GMC.



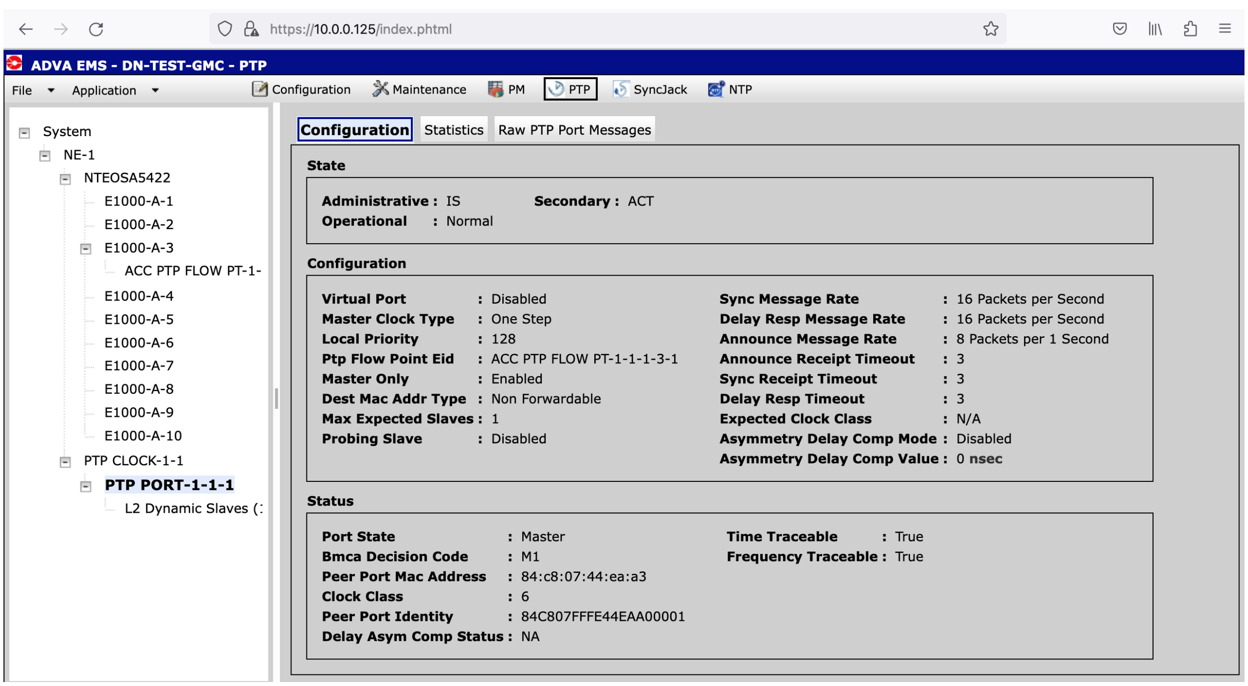
GNSS settings on boundary clock (BC).

WAPA and CAST lab G.8275.1 PTP Clocks Settings/Configurations

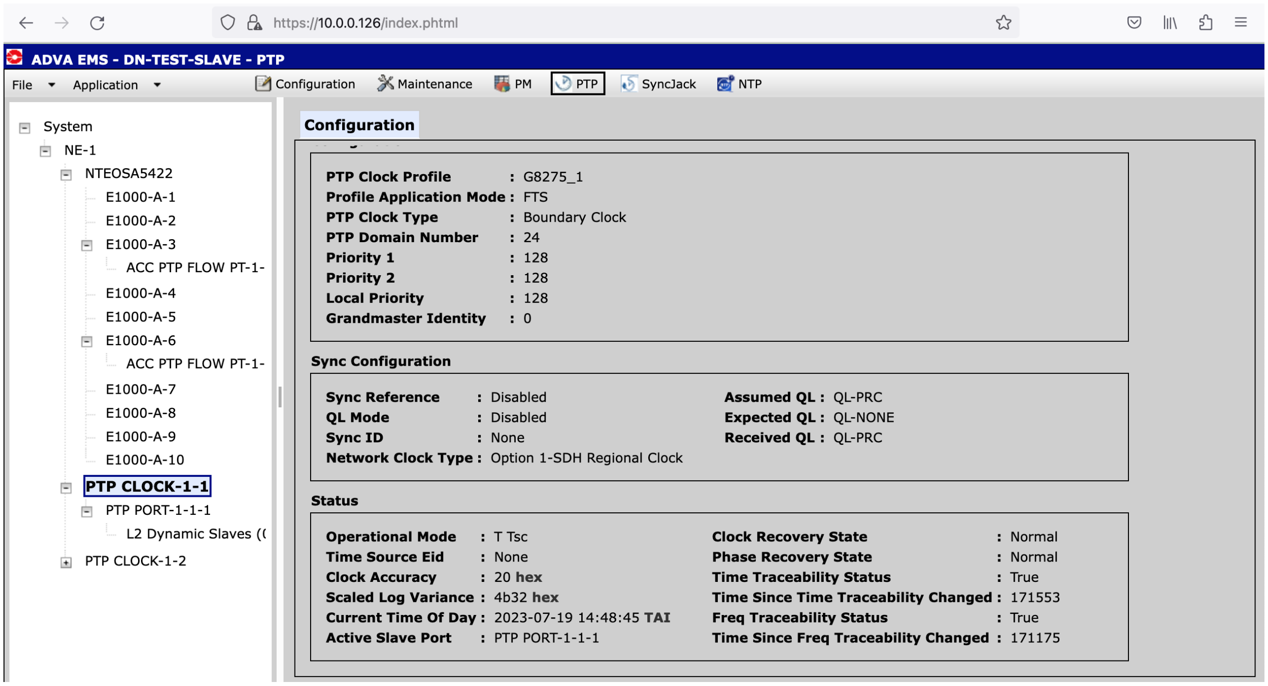
The following figures show G.8275.1 Precision Time Protocol (PTP) profile clock settings and configurations used in WAPA and CAST lab for this test.



G.8275.1 PTP master clock on GMC.

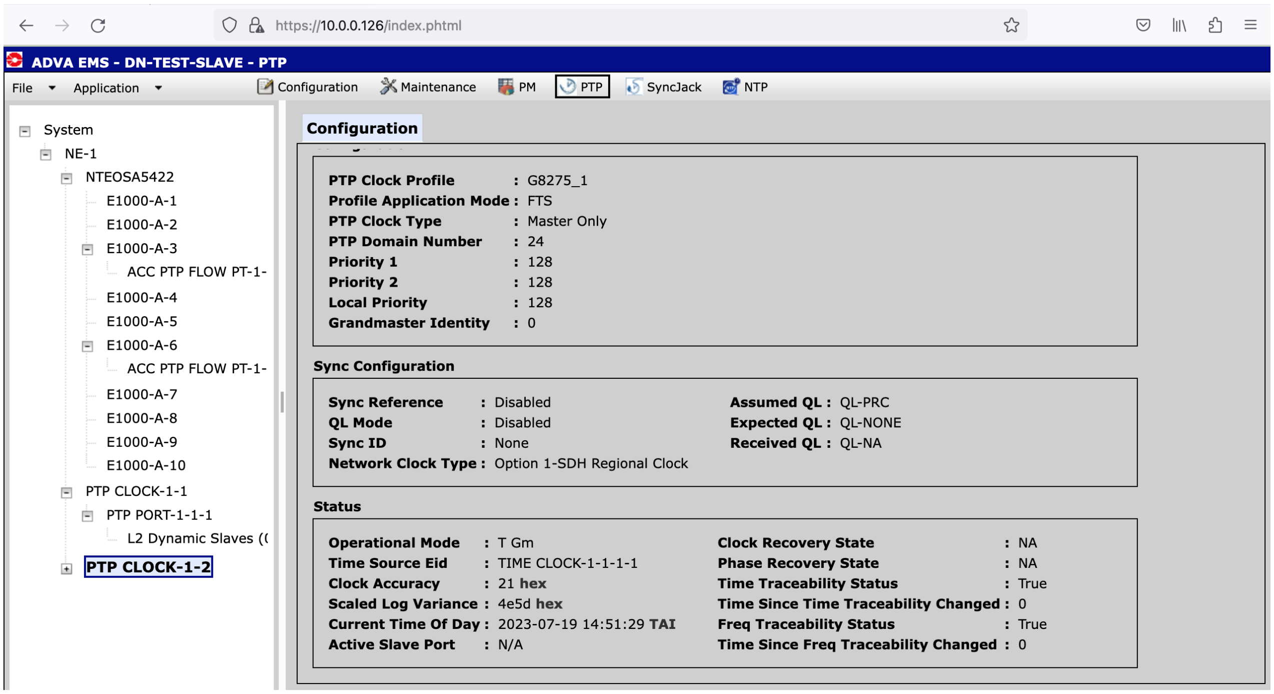


G.8275.1 PTP master clock on GMC.



G.8275.1 PTP slave clock port on BC.

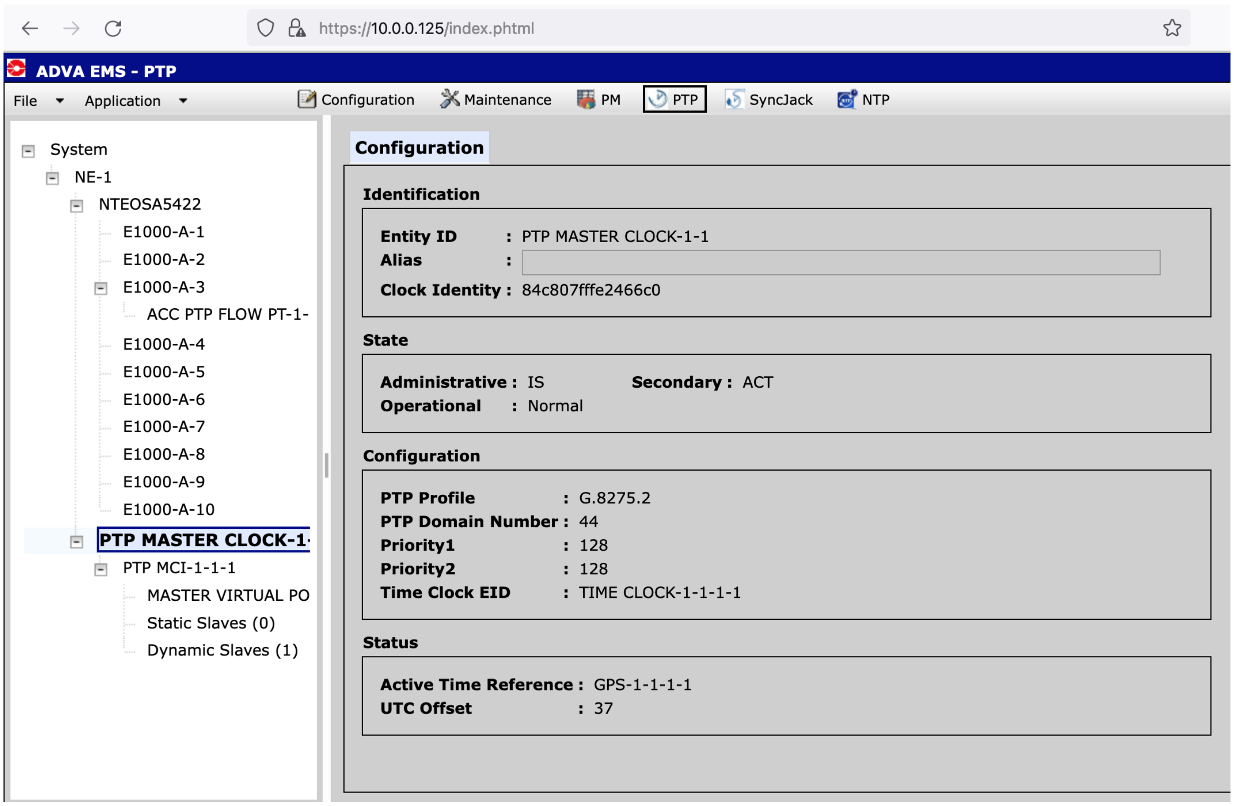
G.8275.1 PTP slave clock port on GMC.



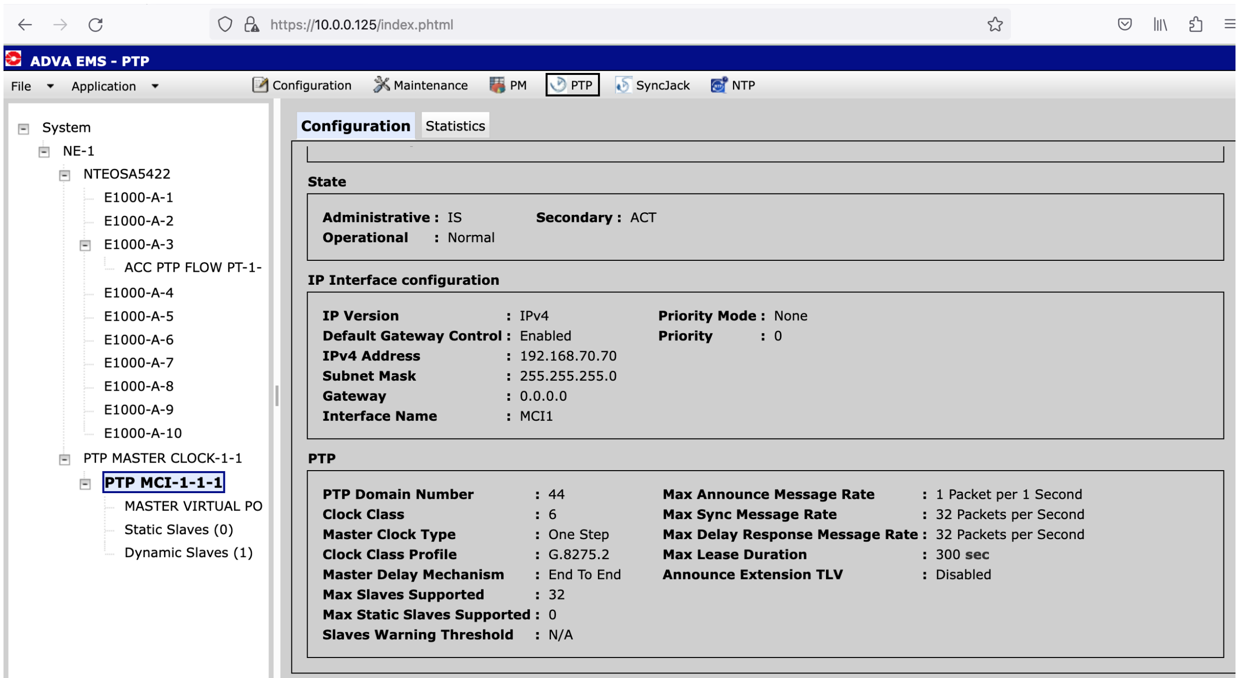
G.8275.1 PTP master clock on BC.

WAPA and CAST lab G.8275.2 PTP Clocks Settings/Configurations

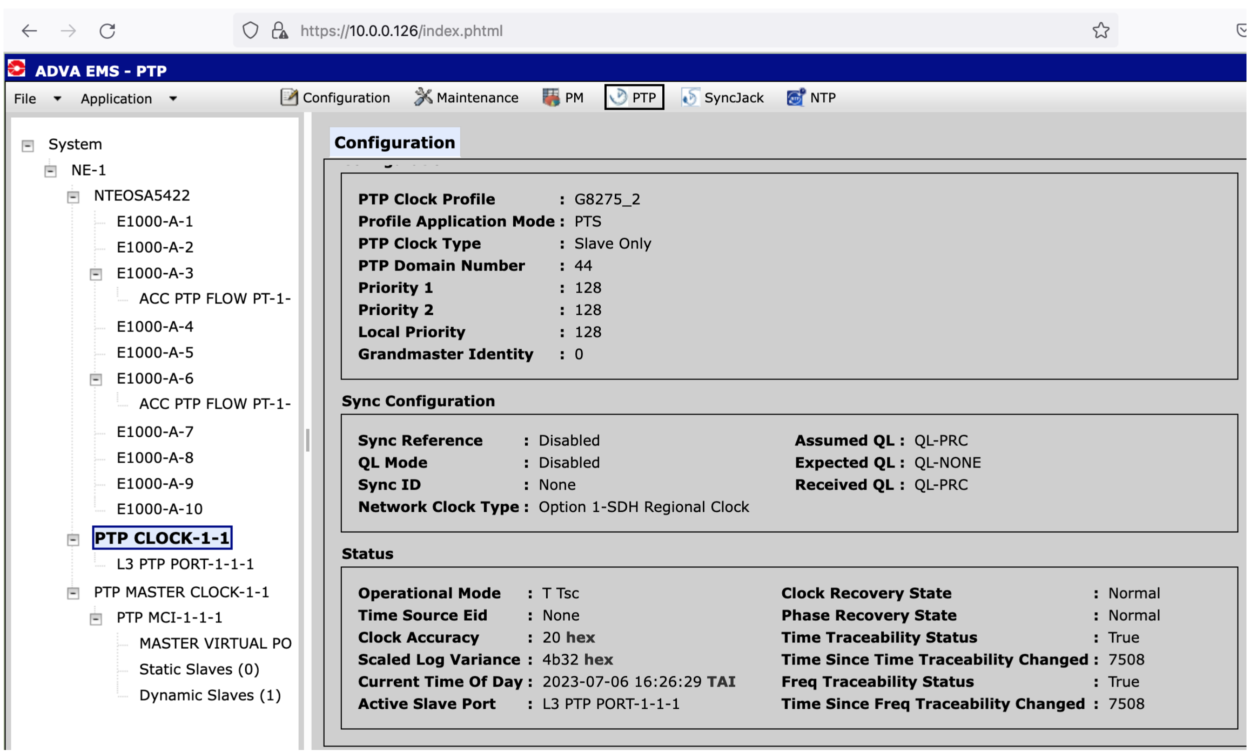
The following figures show G.8275.2 PTP profile clock settings and configurations used in WAPA and CAST lab for this test.



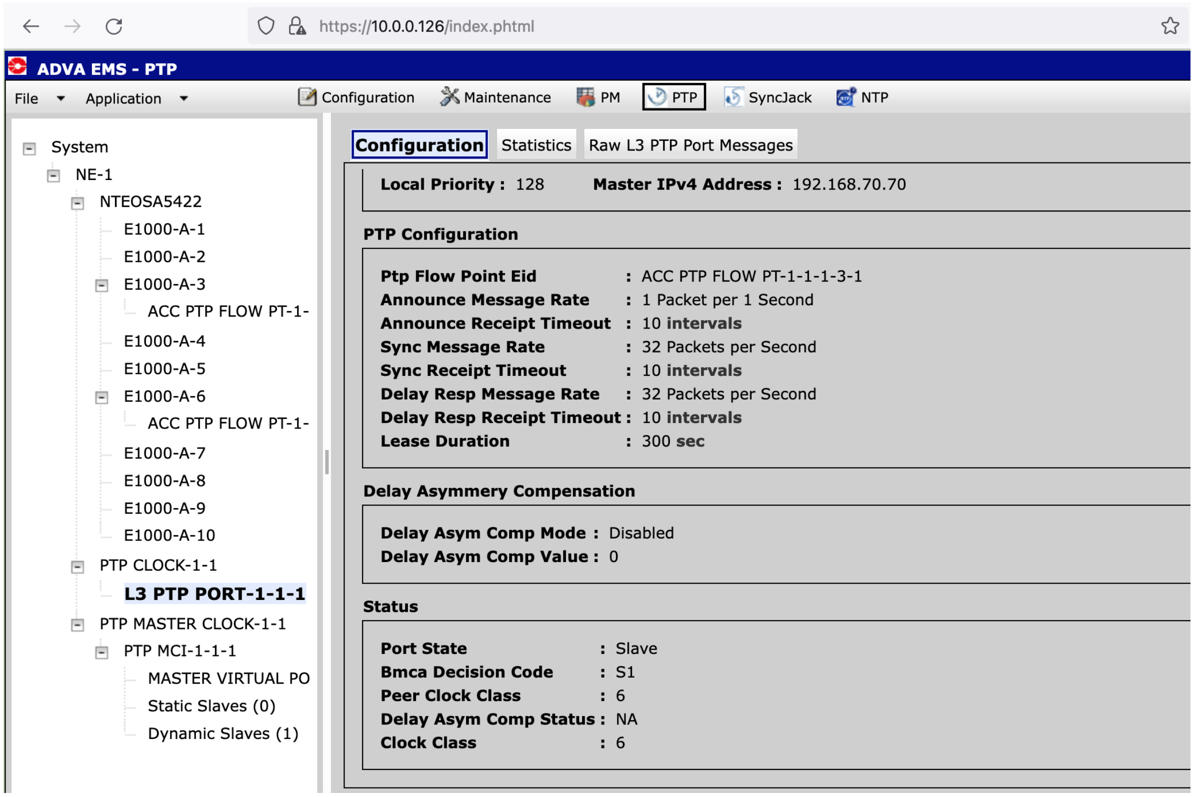
G.8275.2 PTP master clock on GMC.



G.8275.2 PTP master clock port on GMC.



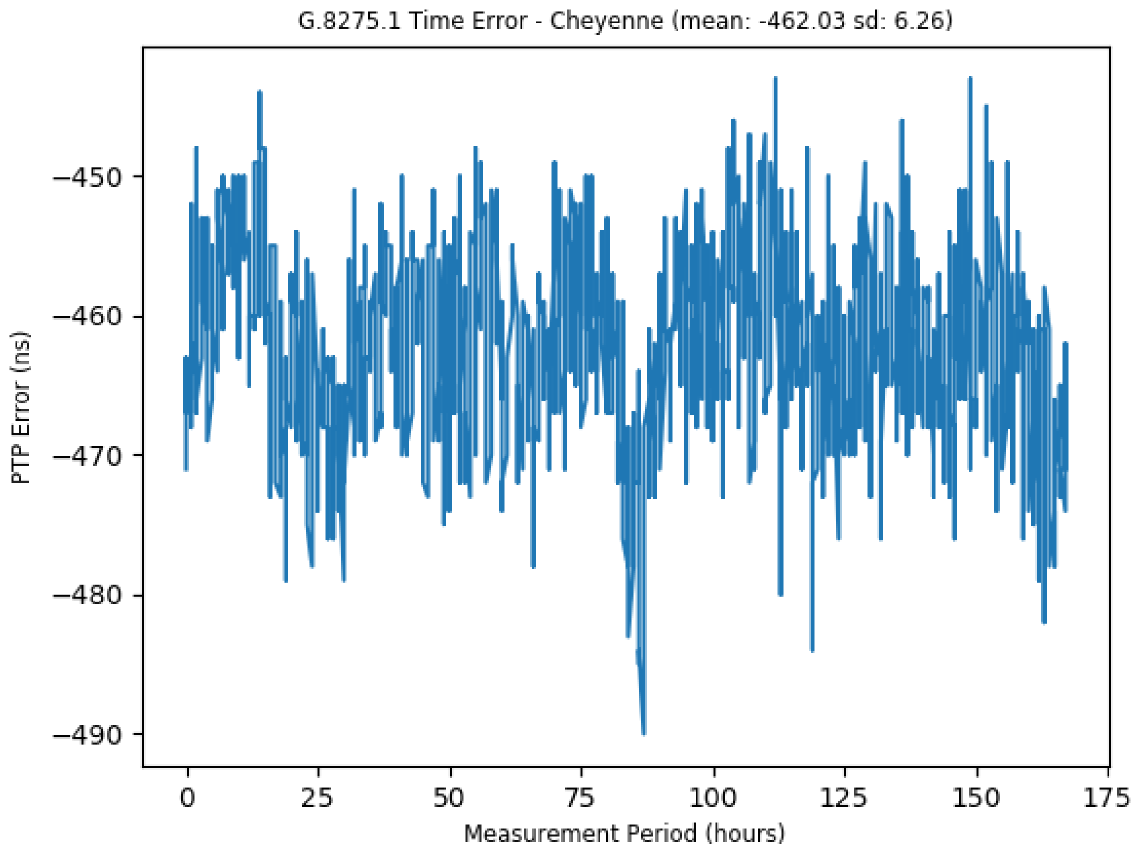
G.8275.2 PTP slave clock on BC.

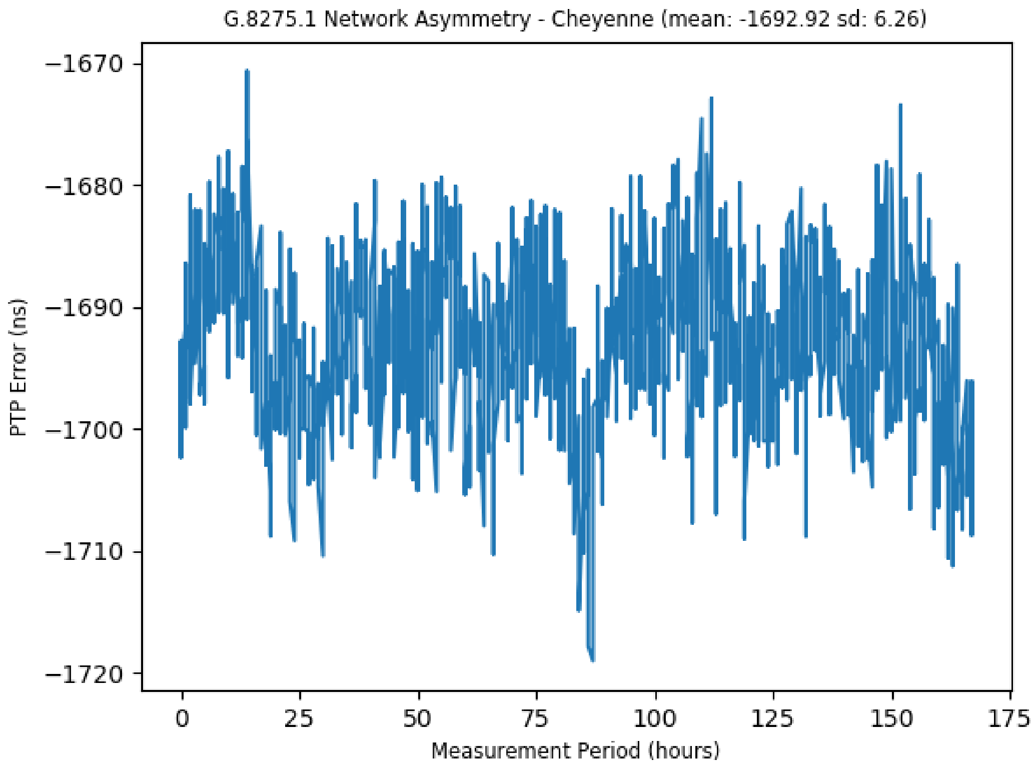


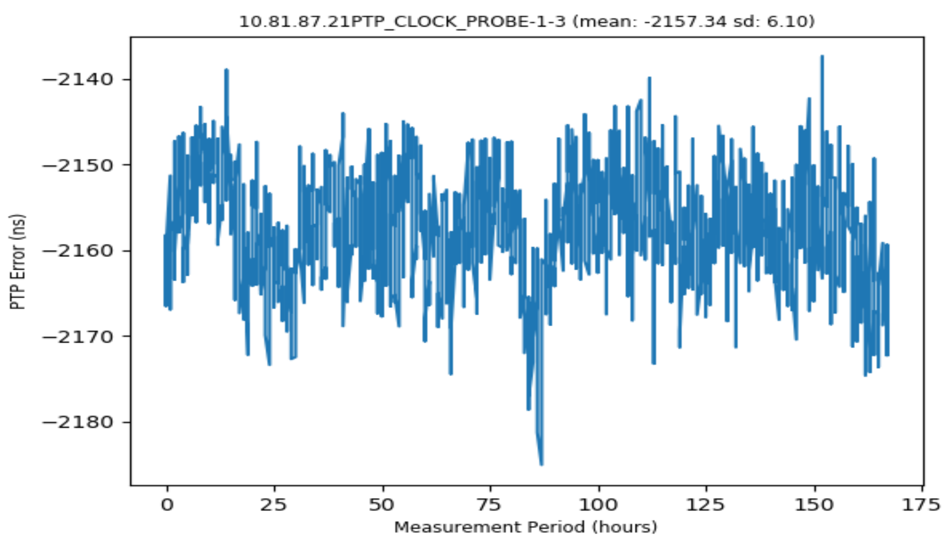
G.8275.2 PTP slave clock port on BC.

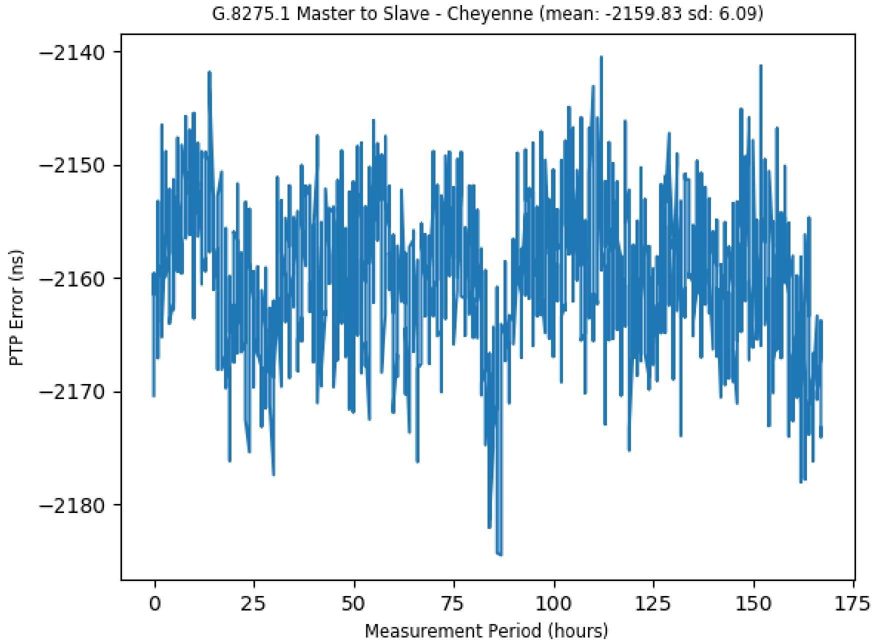
APPENDIX B. WAPA G.8275.1 AND G.8275.2 PROFILES GRAPH RESULTS

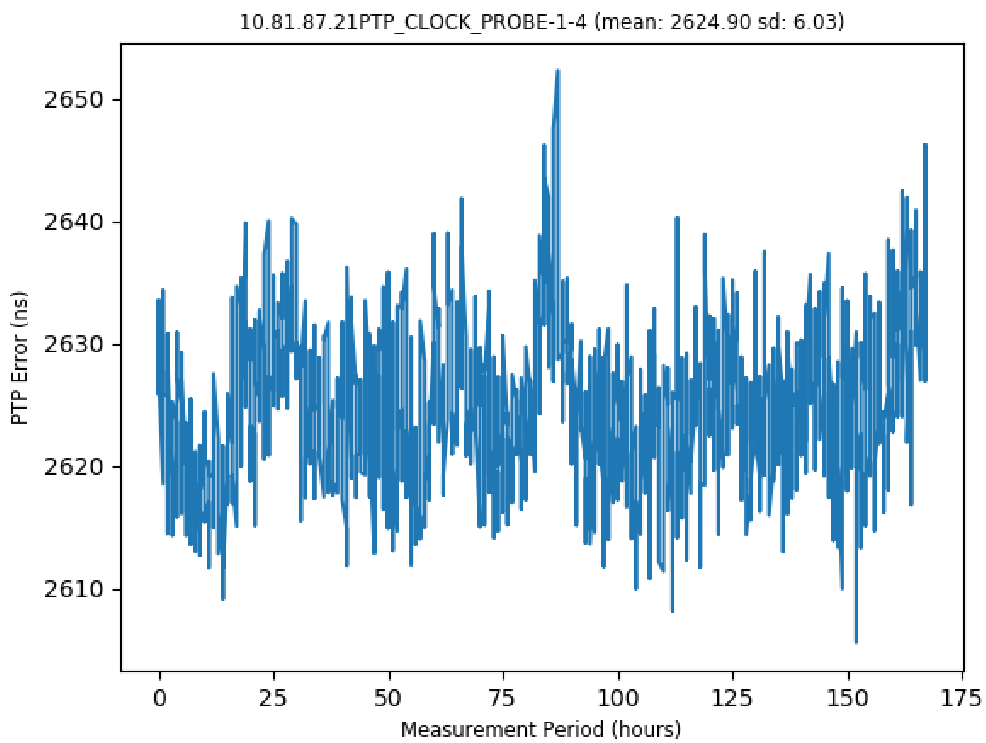
APPENDIX B. WAPA G.8275.1 PROFILE GRAPH RESULTS

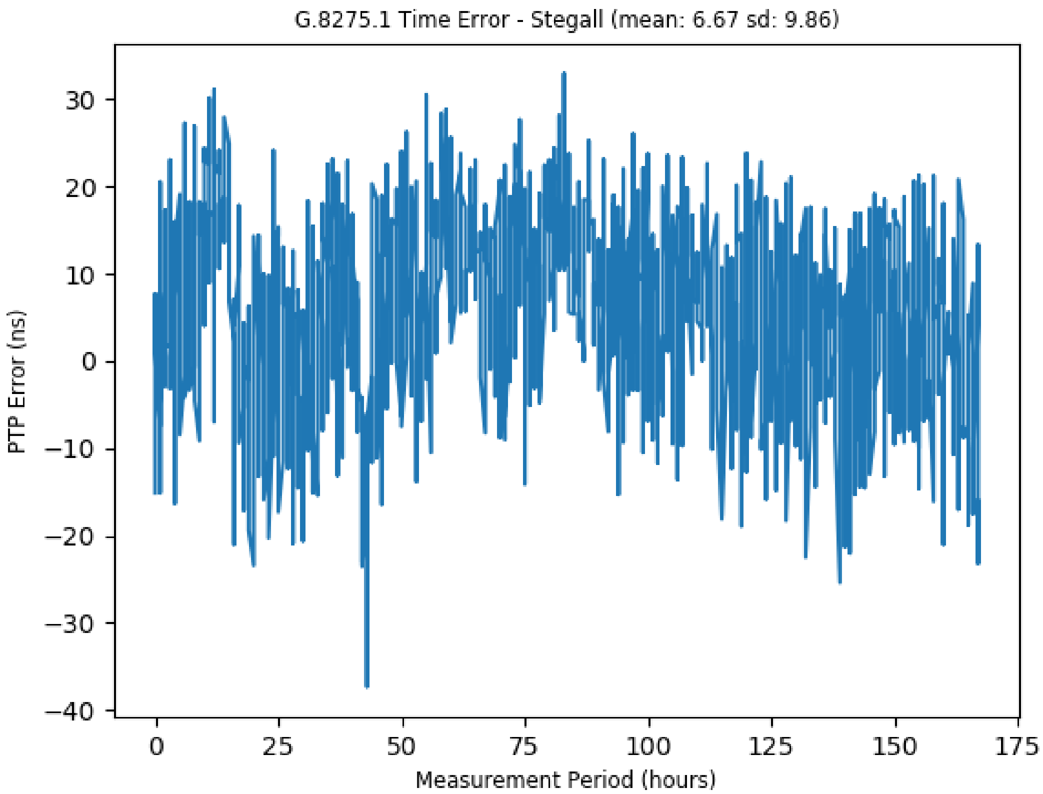


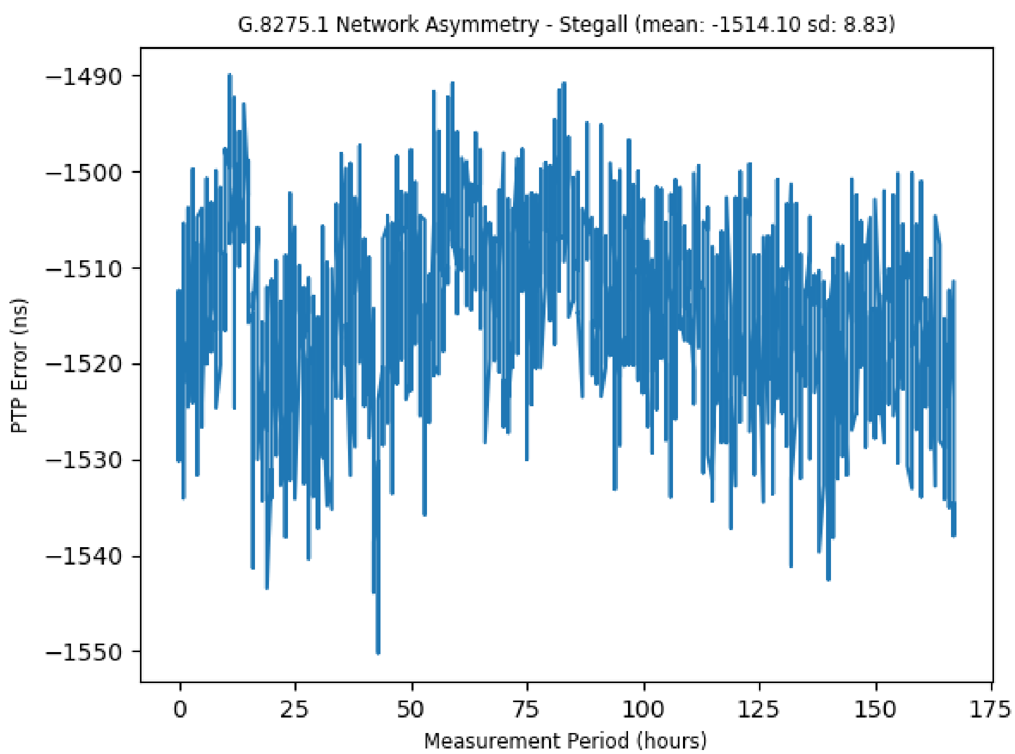

G.8275.1 Network Asymmetry - Cheyenne (mean: -1692.92 sd: 6.26)
−1670
−1680
−1690
−1700
−1710
−1720
PTP Error (ns)
0
25
50
75
100
125
150
175
Measurement Period (hours)

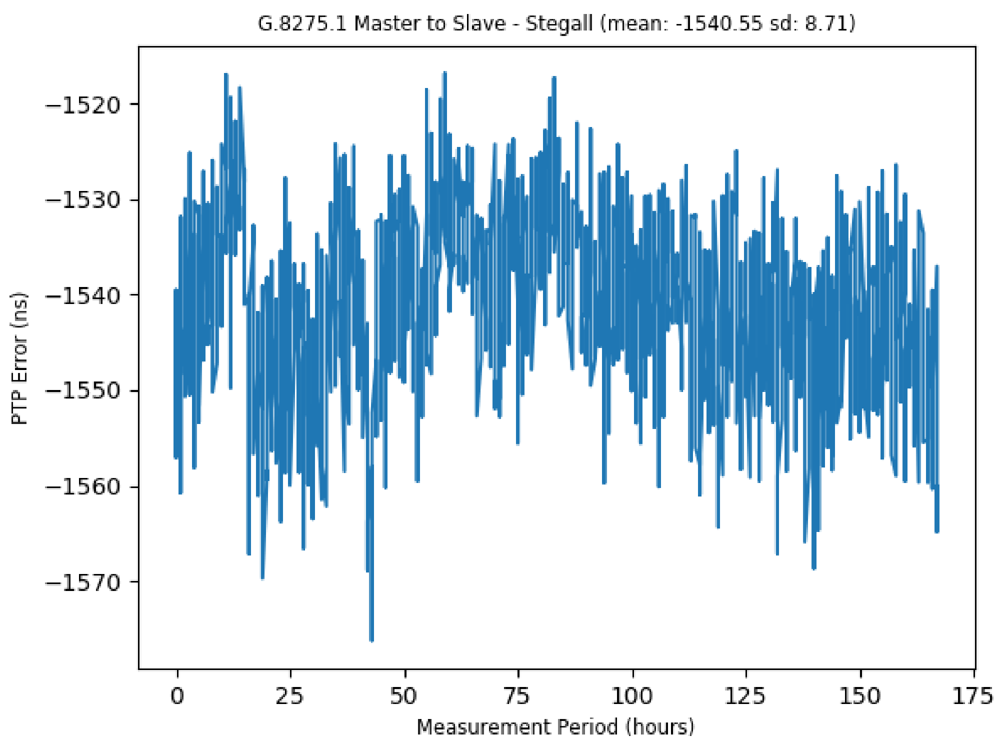

10.81.87.21PTP_CLOCK_PROBE-1-3 (mean: -2157.34 sd: 6.10)
−2140
−2150
−2160
−2170
−2180
PTP Error (ns)
0
25
50
75
100
125
150
175
Measurement Period (hours)


G.8275.1 Master to Slave - Cheyenne (mean: -2159.83 sd: 6.09)
PTP Error (ns)
−2140
−2150
−2160
−2170
−2180
0
25
50
75
100
125
150
175
Measurement Period (hours)

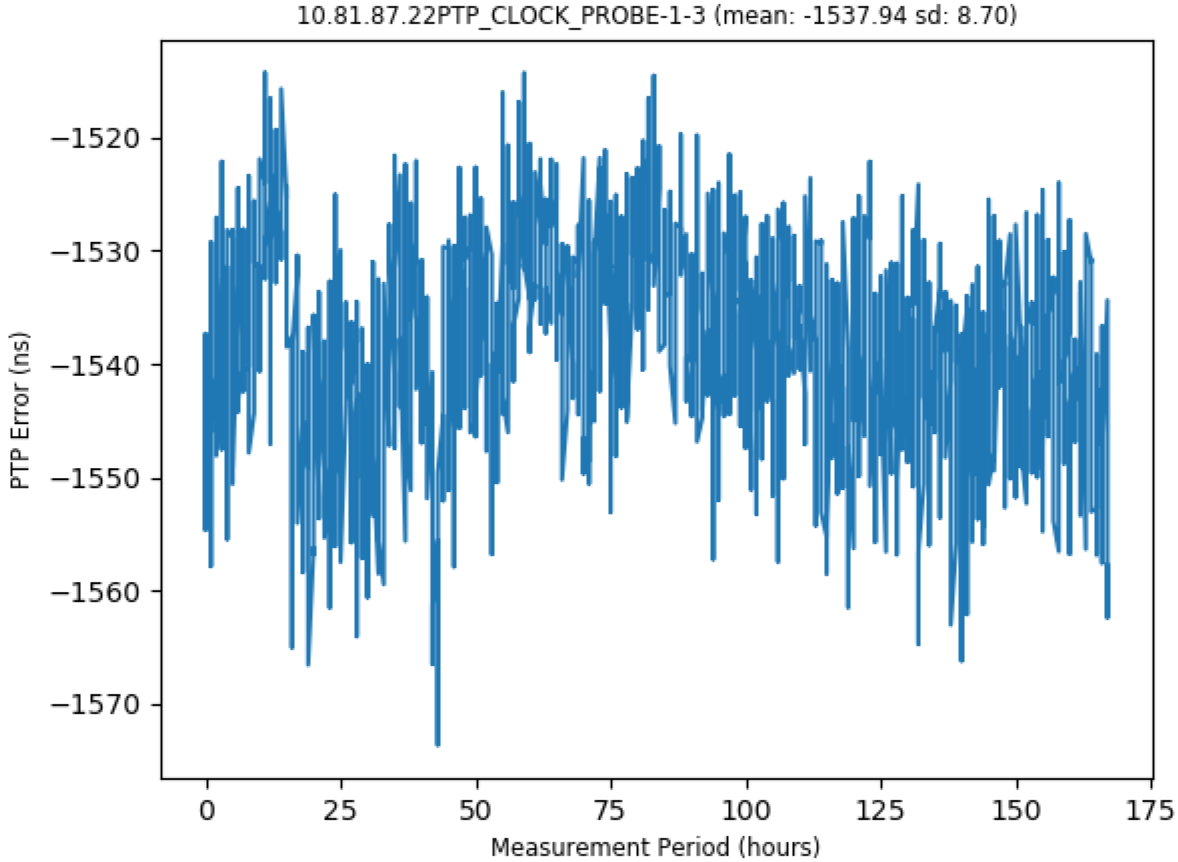

10.81.87.21PTP_CLOCK_PROBE-1-4 (mean: 2624.90 sd: 6.03)
PTP Error (ns)
2650
2640
2630
2620
2610
0
25
50
75
100
125
150
175
Measurement Period (hours)

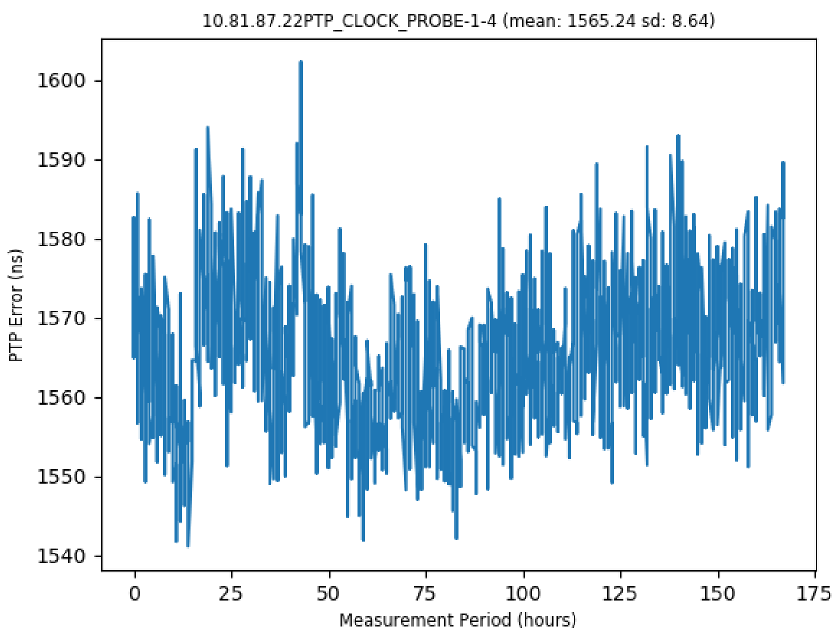

G.8275.1 Time Error - Stegall (mean: 6.67 sd: 9.86)
PTP Error (ns)
Measurement Period (hours)
30
20
10
0
−10
−20
−30
−40
0
25
50
75
100
125
150
175

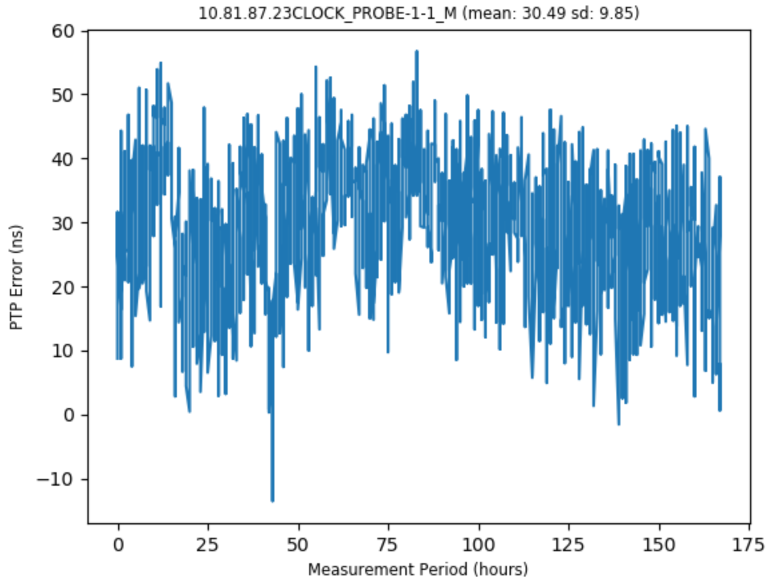

G.8275.1 Network Asymmetry - Stegall (mean: -1514.10 sd: 8.83)
PTP Error (ns)
Measurement Period (hours)
−1490
−1500
−1510
−1520
−1530
−1540
−1550
0
25
50
75
100
125
150
175

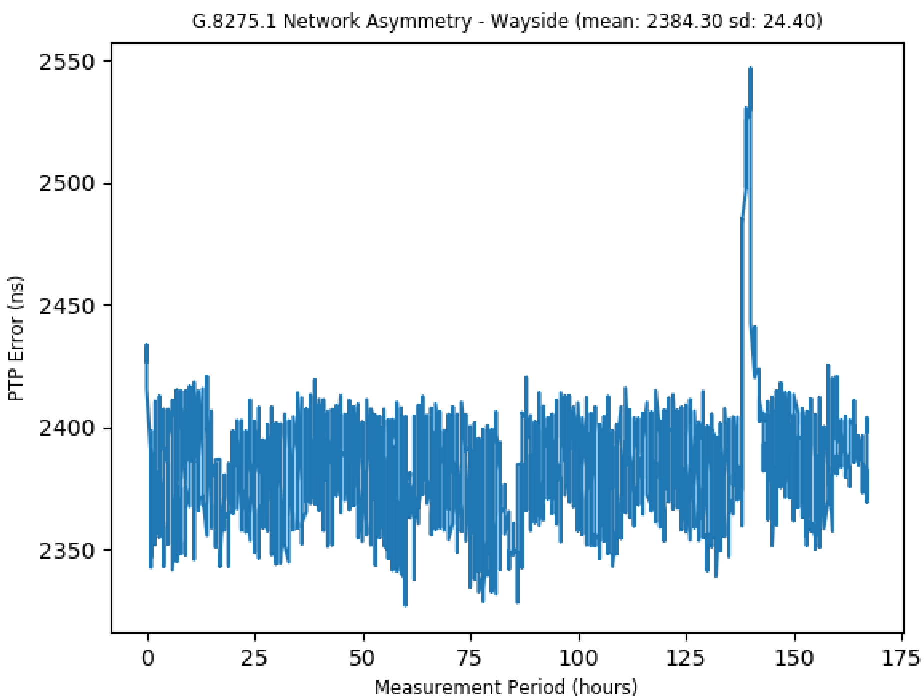


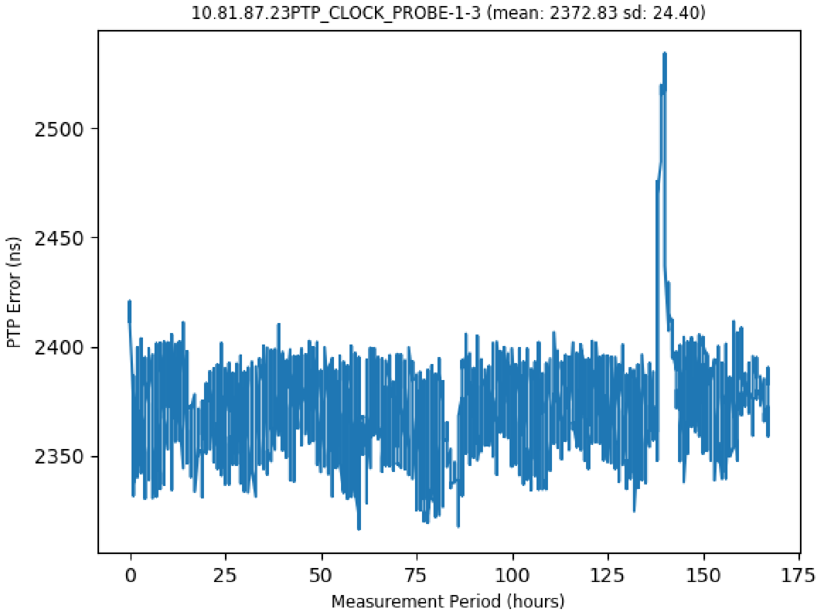
G.8275.1 Master to Slave - Stegall (mean: -1540.55 sd: 8.71)
PTP Error (ns)
−1520
−1530
−1540
−1550
−1560
−1570
0
25
50
75
100
125
150
175
Measurement Period (hours)

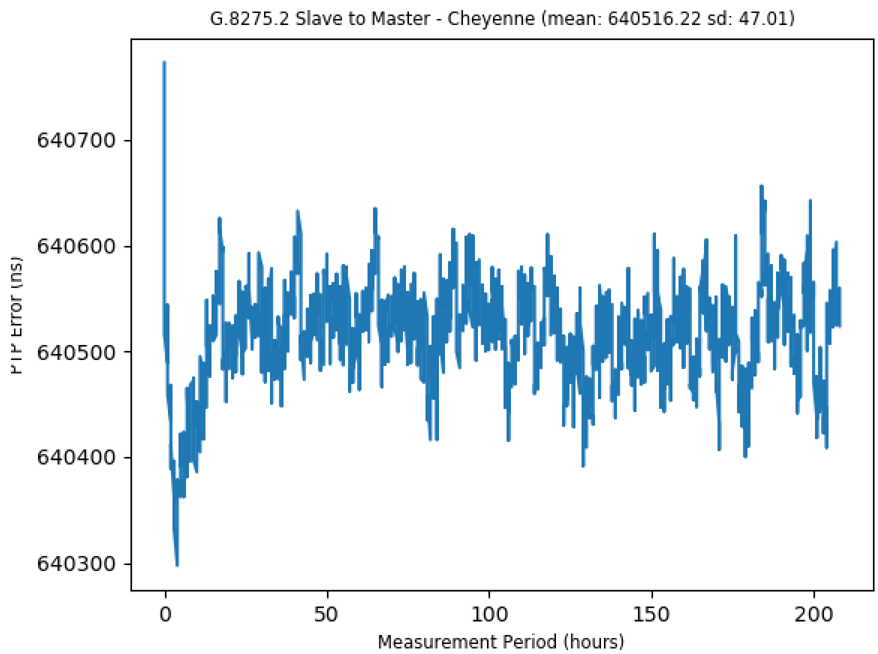

10.81.87.22PTP_CLOCK_PROBE-1-3 (mean: -1537.94 sd: 8.70)
PTP Error (ns)
−1520
−1530
−1540
−1550
−1560
−1570
0
25
50
75
100
125
150
175
Measurement Period (hours)

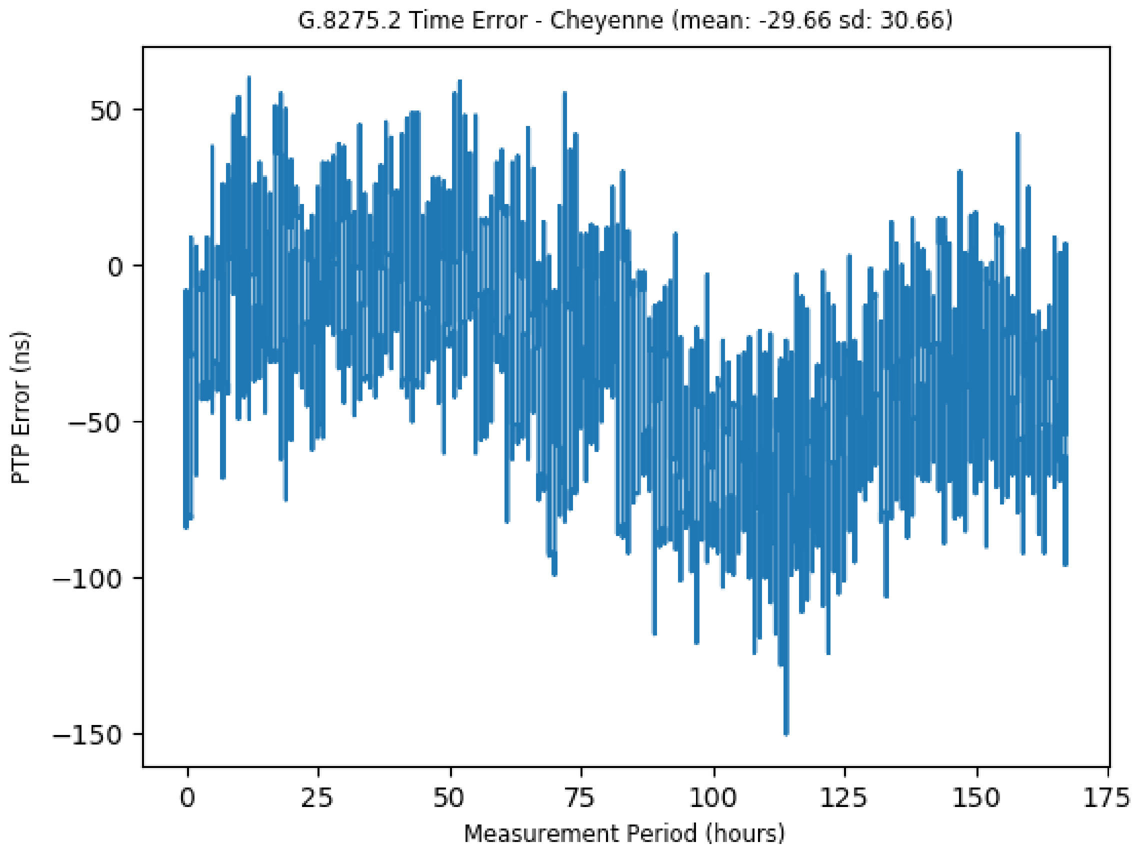

10.81.87.22PTP_CLOCK_PROBE-1-4 (mean: 1565.24 sd: 8.64)
PTP Error (ns)
1600
1590
1580
1570
1560
1550
1540
0
25
50
75
100
125
150
175
Measurement Period (hours)

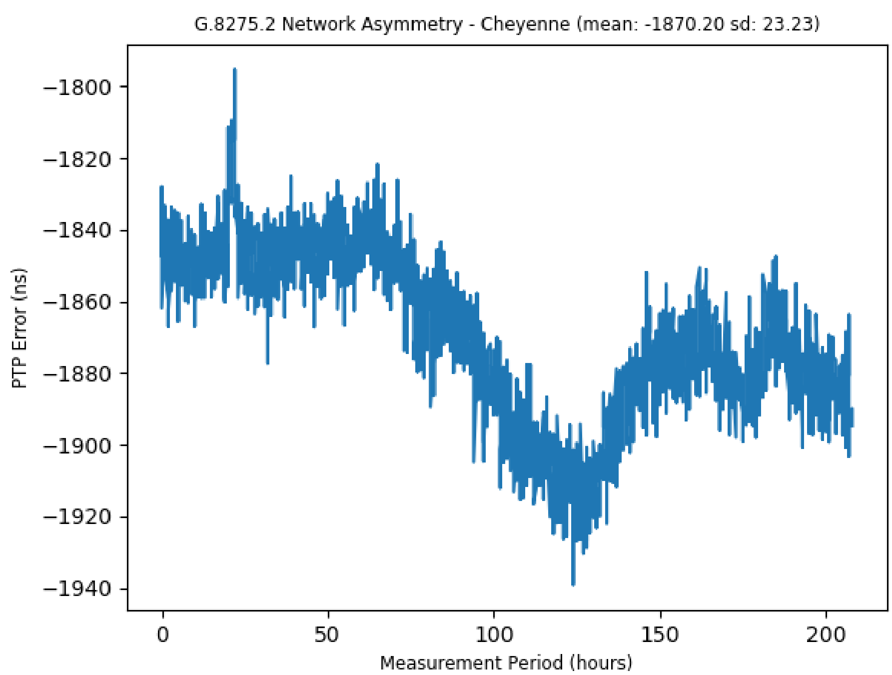

10.81.87.23CLOCK_PROBE-1-1_M (mean: 30.49 sd: 9.85)
PTP Error (ns)
Measurement Period (hours)
60
50
40
30
20
10
0
−10
0
25
50
75
100
125
150
175

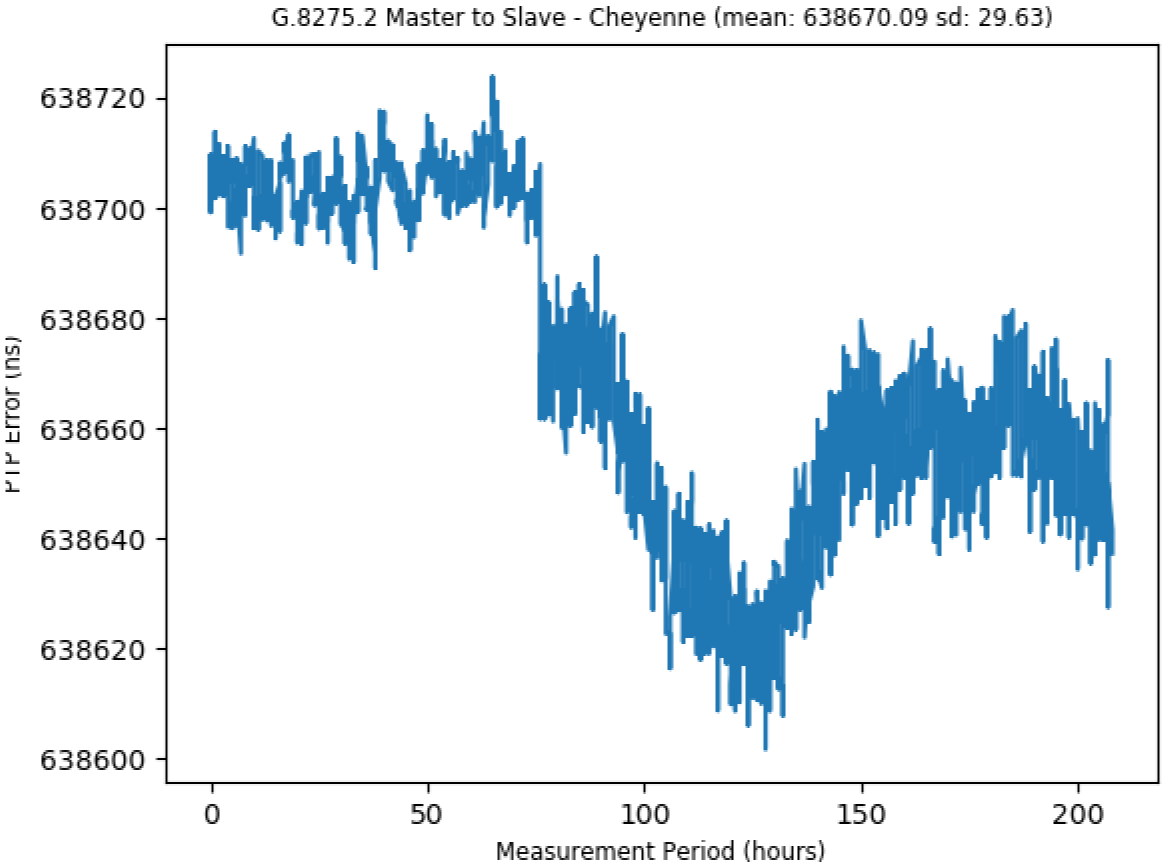

G.8275.1 Network Asymmetry - Wayside (mean: 2384.30 sd: 24.40)
PTP Error (ns)
Measurement Period (hours)
2550
2500
2450
2400
2350
0
25
50
75
100
125
150
175

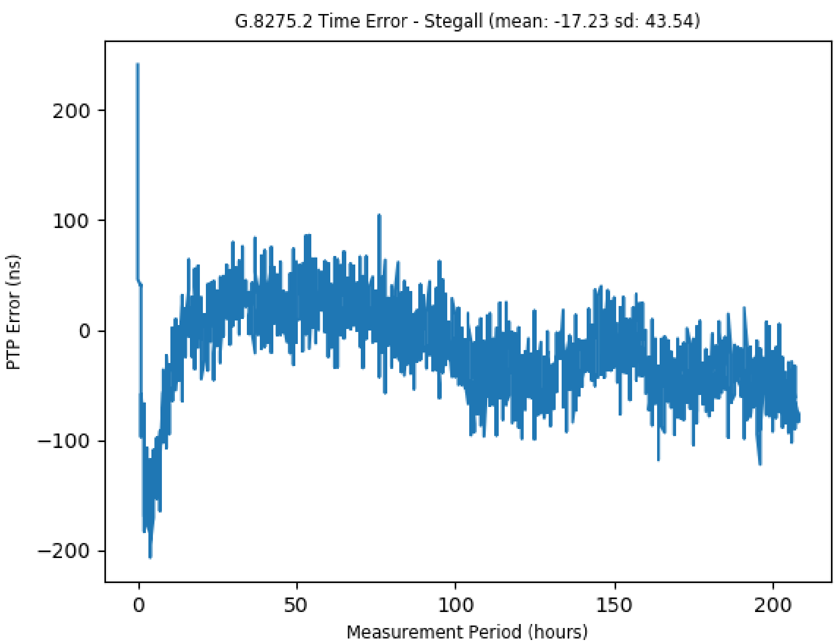

10.81.87.23PTP_CLOCK_PROBE-1-3 (mean: 2372.83 sd: 24.40)
PTP Error (ns)
2500
2450
2400
2350
0
25
50
75
100
125
150
175
Measurement Period (hours)

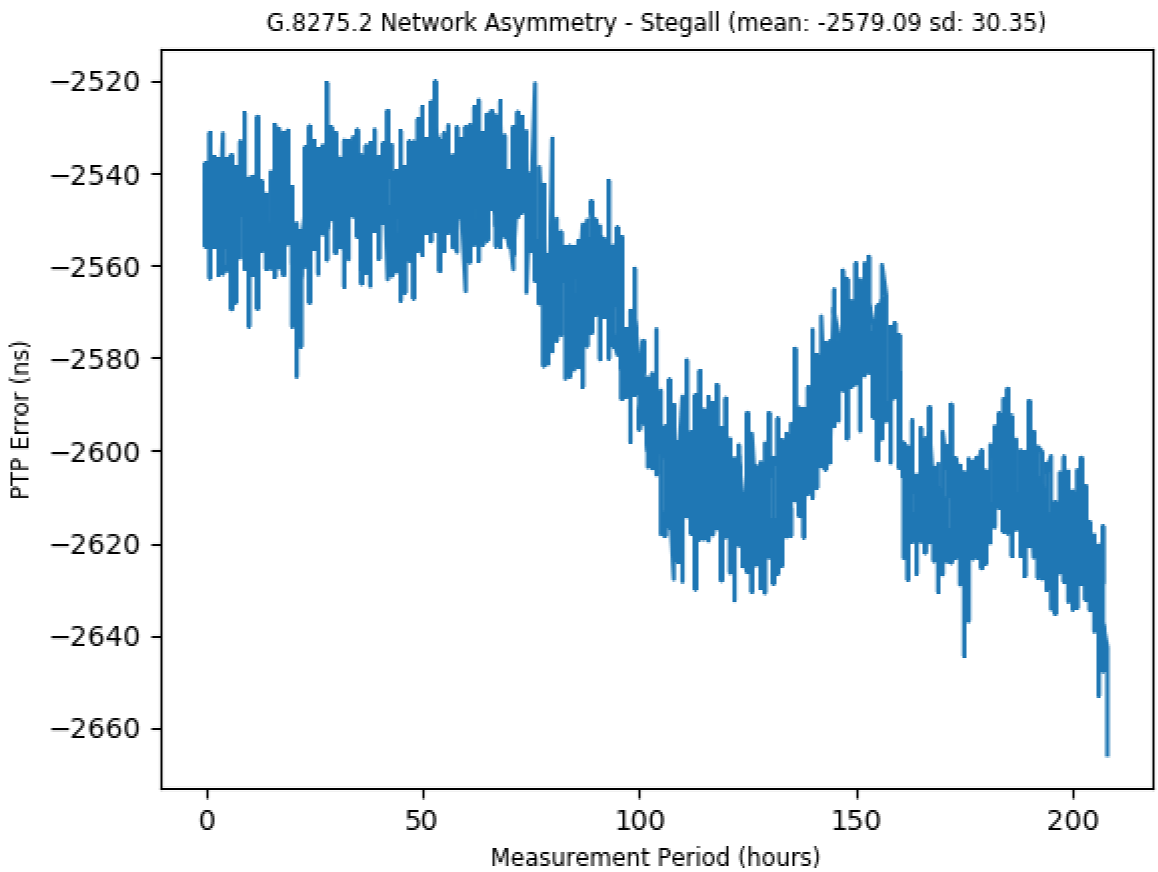

G.8275.2 Slave to Master - Cheyenne (mean: 640516.22 sd: 47.01)
640700
640600
640500
640400
640300
0
50
100
150
200
Measurement Period (hours)

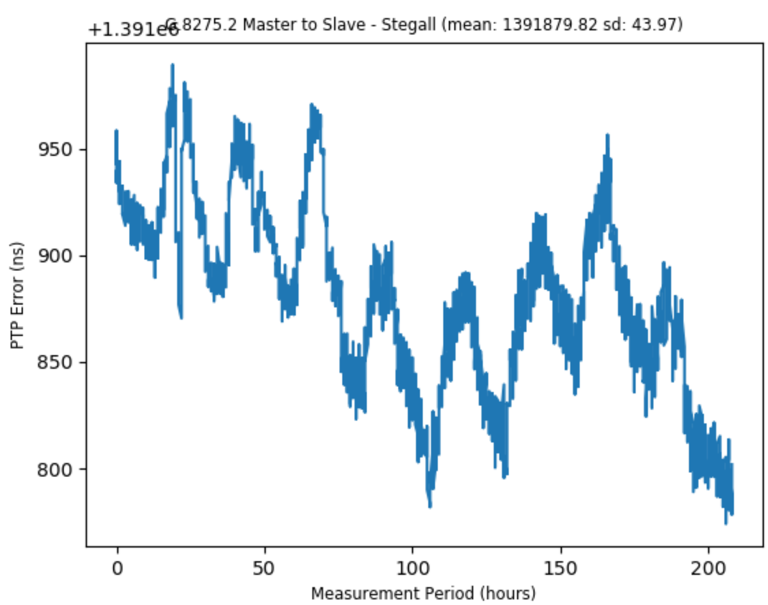

G.8275.2 Time Error - Cheyenne (mean: -29.66 sd: 30.66)
PTP Error (ns)
50
0
−50
−100
−150
0
25
50
75
100
125
150
175
Measurement Period (hours)

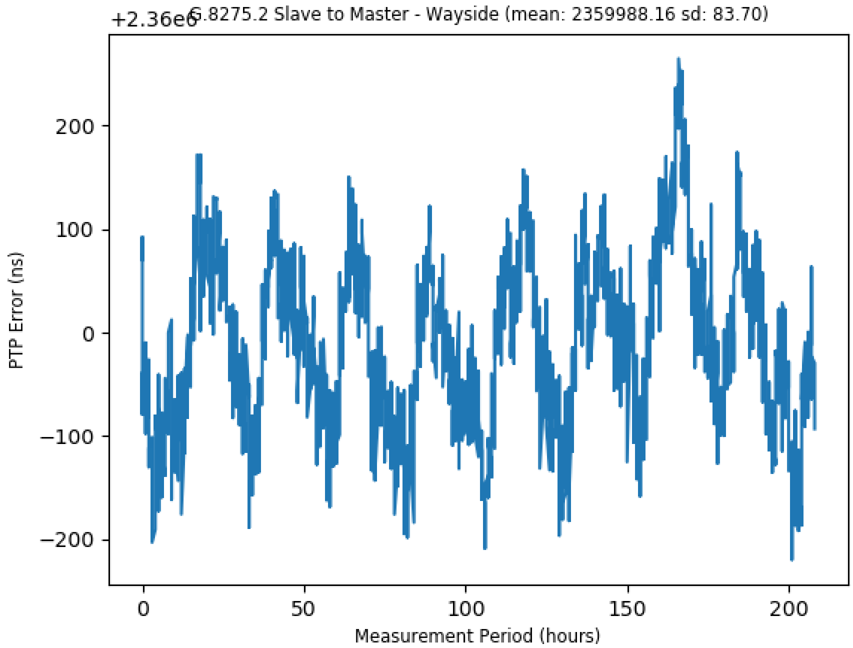

G.8275.2 Network Asymmetry - Cheyenne (mean: -1870.20 sd: 23.23)
PTP Error (ns)
−1800
−1820
−1840
−1860
−1880
−1900
−1920
−1940
0
50
100
150
200
Measurement Period (hours)

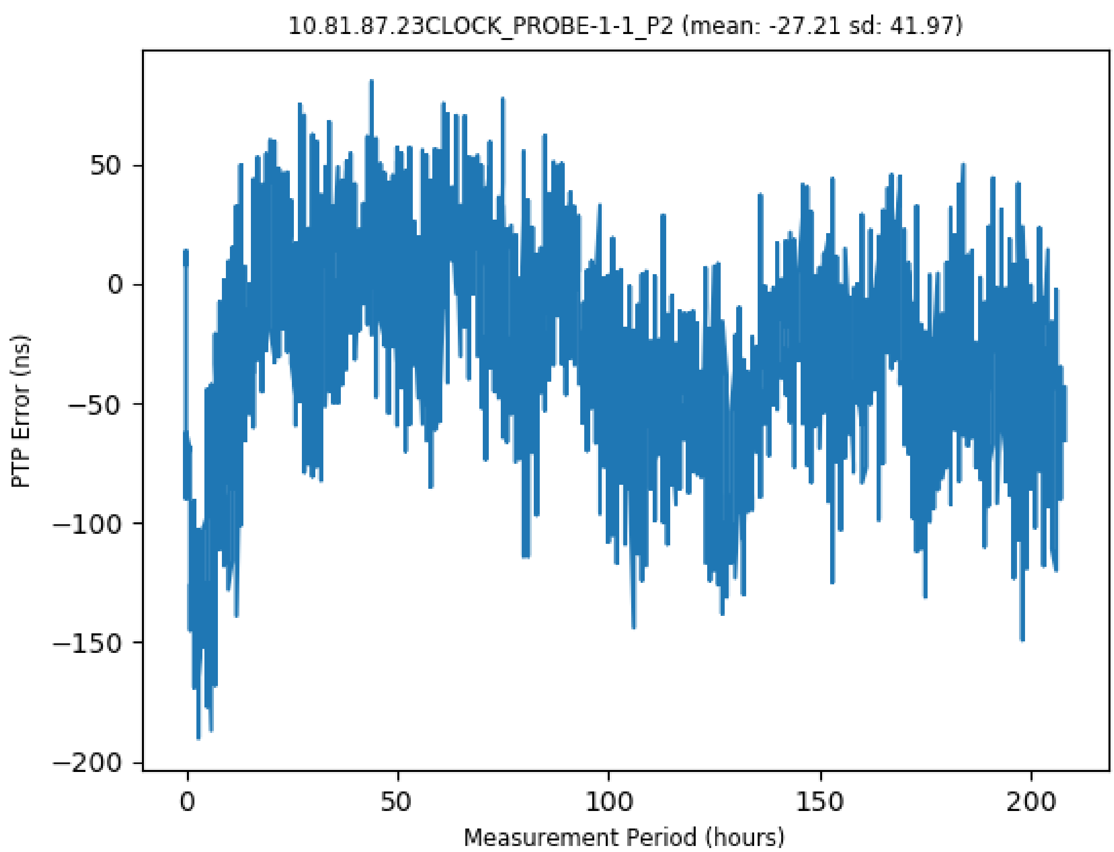

G.8275.2 Master to Slave - Cheyenne (mean: 638670.09 sd: 29.63)
PTP Error (ns)
638720
638700
638680
638660
638640
638620
638600
0
50
100
150
200
Measurement Period (hours)

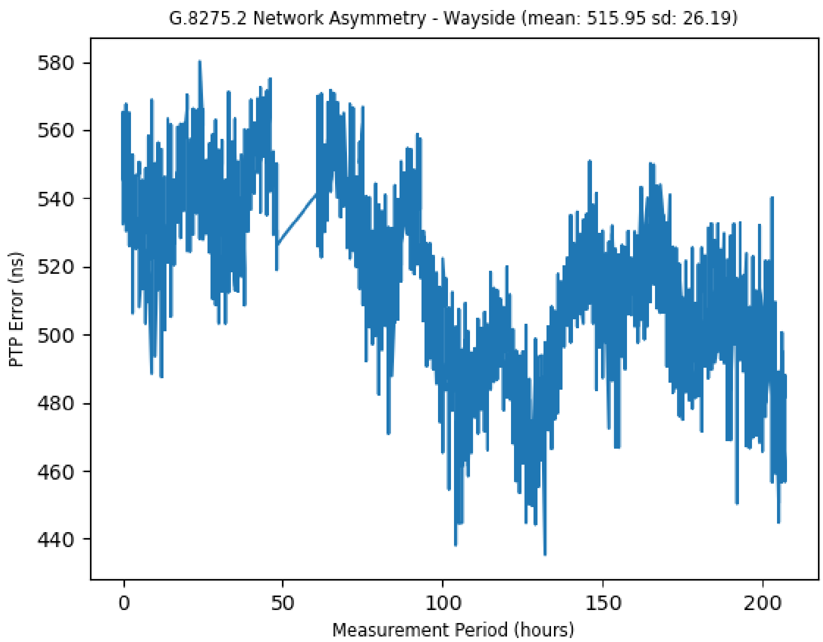

G.8275.2 Time Error - Stegall (mean: -17.23 sd: 43.54)
PTP Error (ns)
200
100
0
−100
−200
0
50
100
150
200
Measurement Period (hours)

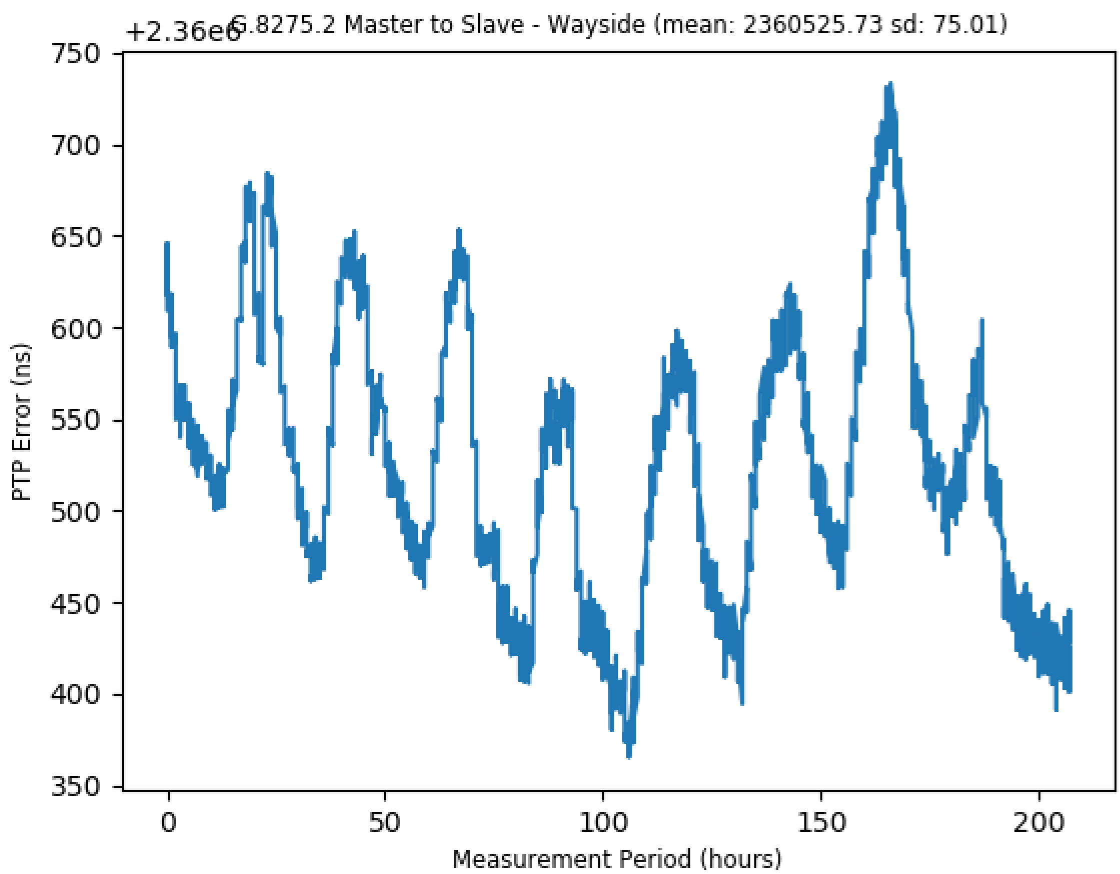

G.8275.2 Network Asymmetry - Stegall (mean: -2579.09 sd: 30.35)
PTP Error (ns)
−2520
−2540
−2560
−2580
−2600
−2620
−2640
−2660
0
50
100
150
200
Measurement Period (hours)


G.8275.2 Master to Slave - Stegall (mean: 1391879.82 sd: 43.97)
+1.391e6
PTP Error (ns)
950
900
850
800
0
50
100
150
200
Measurement Period (hours)


+2.36e6
G.8275.2 Slave to Master - Wayside (mean: 2359988.16 sd: 83.70)
PTP Error (ns)
200
100
0
−100
−200
0
50
100
150
200
Measurement Period (hours)


10.81.87.23CLOCK_PROBE-1-1_P2 (mean: -27.21 sd: 41.97)
PTP Error (ns)
50
0
−50
−100
−150
−200
0
50
100
150
200
Measurement Period (hours)


G.8275.2 Network Asymmetry - Wayside (mean: 515.95 sd: 26.19)
PTP Error (ns)
580
560
540
520
500
480
460
440
0
50
100
150
200
Measurement Period (hours)


G.8275.2 Master to Slave - Wayside (mean: 2360525.73 sd: 75.01)
+2.36e6
PTP Error (ns)
750
700
650
600
550
500
450
400
350
0
50
100
150
200
Measurement Period (hours)