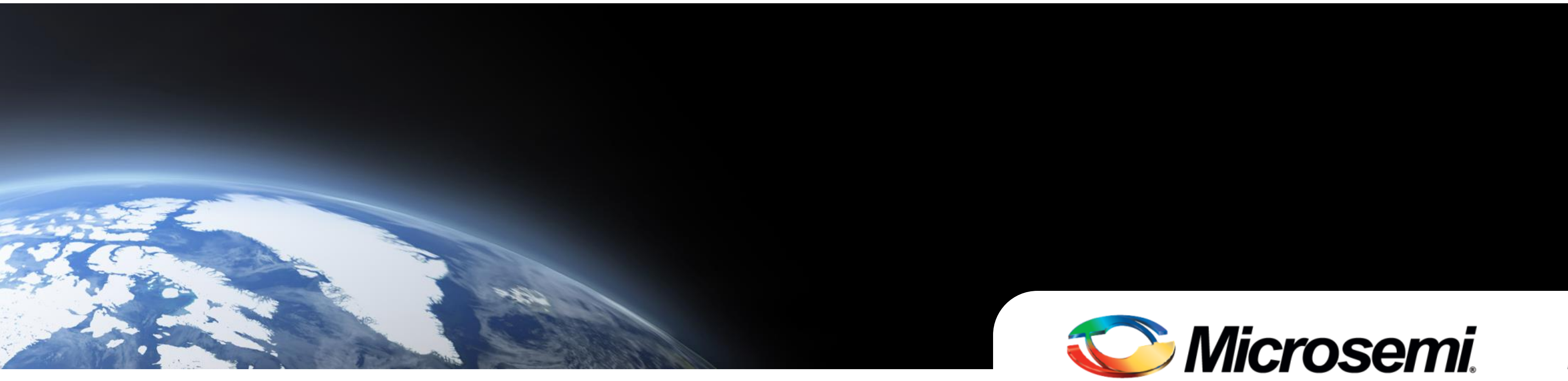
Power Matters.

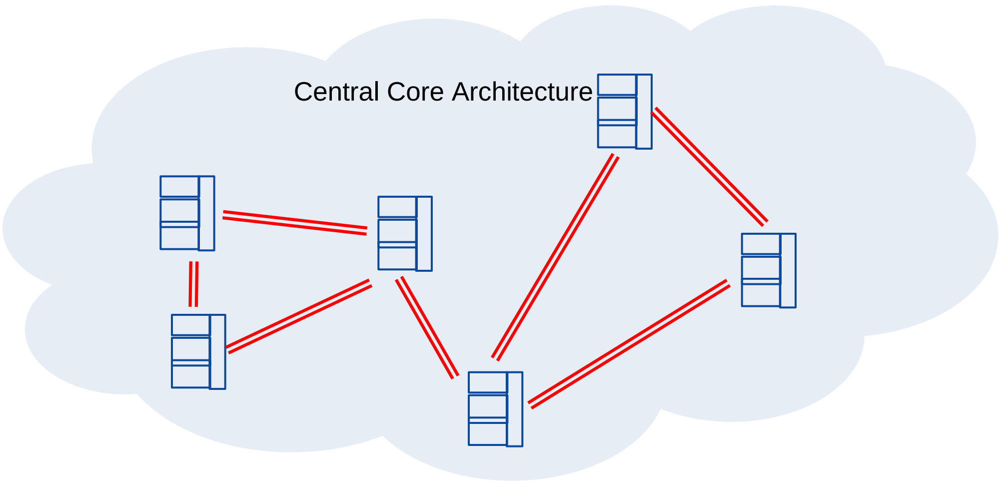


Enhanced PRTC Architecture and Technology

(Coherent Network Primary Reference Time Clocks cnPRTC)

George Zampetti, Chief Scientist FTD

Coherent Network PRTC Overview

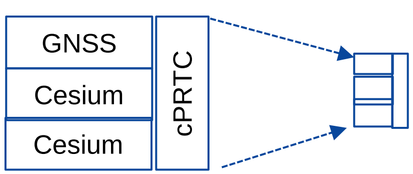


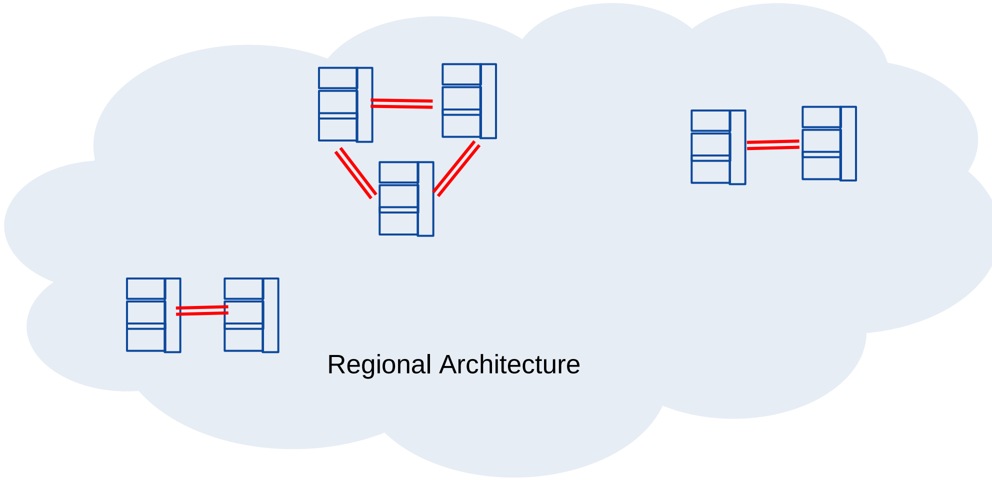
Primary Objectives

- Reliability: Immune from local jamming or outages

- Autonomy: Cesium Ensemble Sustained Timescale (definition of second) GNSS connect non-critical.

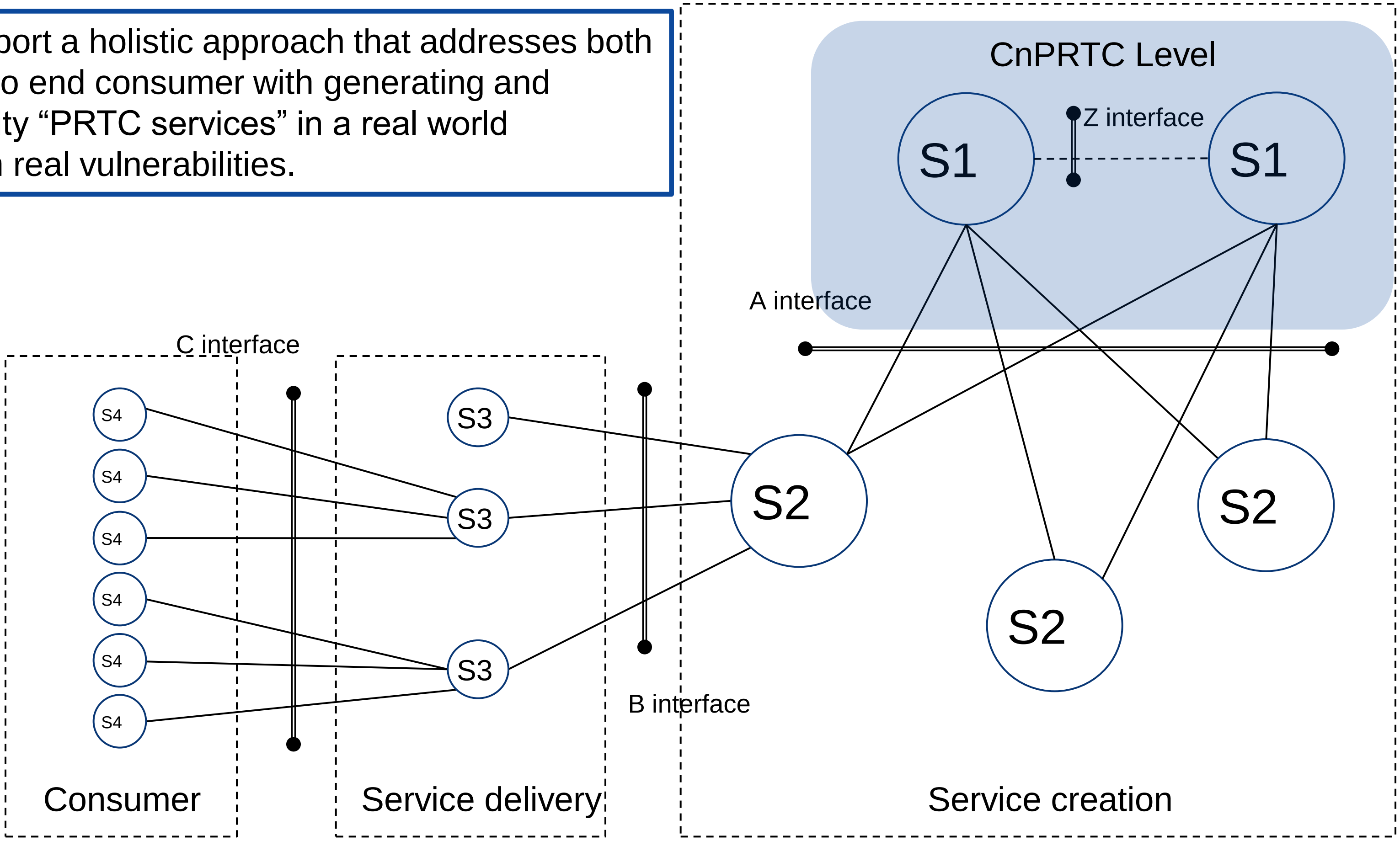
- Coherency: 30ns coordination assures overall PRTC budget





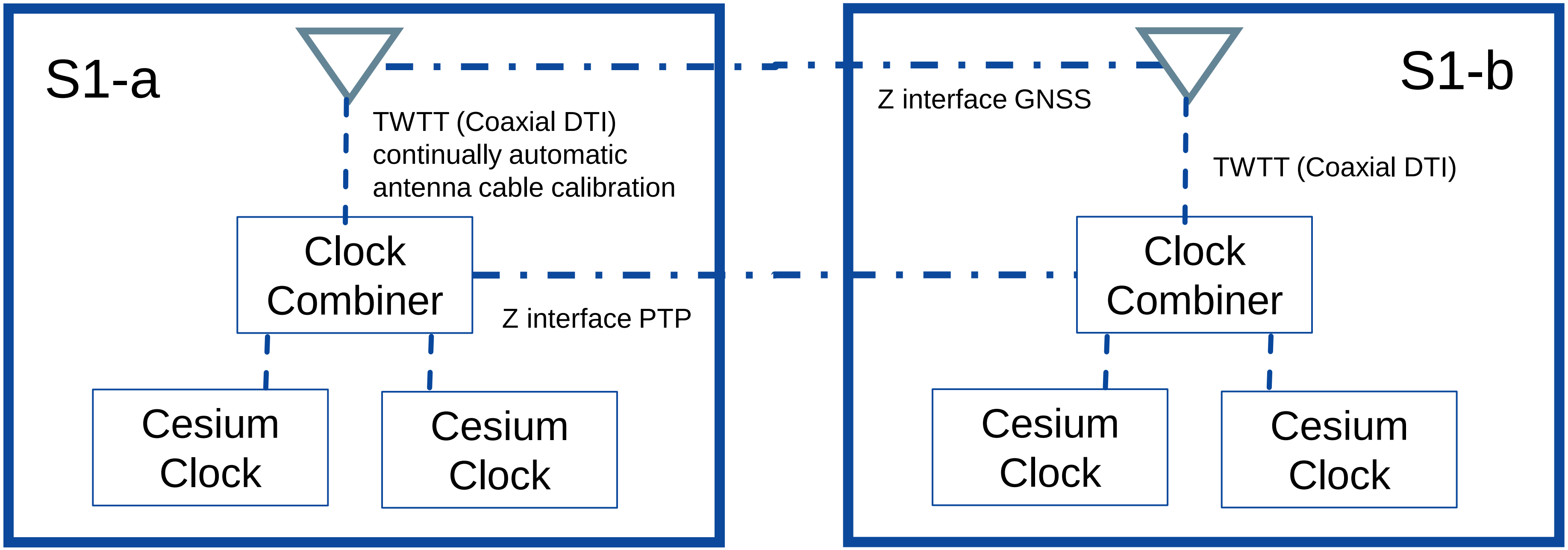
Coherent Time/Frequency Functional Architecture

Architecture support a holistic approach that addresses both service delivery to end consumer with generating and maintaining quality “PRTC services” in a real world environment with real vulnerabilities.



S1: Coherent cnPRTC level– Ensembling timing source, Perpetual Coherent Time Traceability
S2: Hierarchical PRTC level– Redundant Traceable A interfaces from S1 extend service creation from core.
S3: Sync delivery – delivers sync source to clients (PTP and associated path aware standards plus frequency sync e.g. Sync E)
S4: Sync edge/client – consumes the services

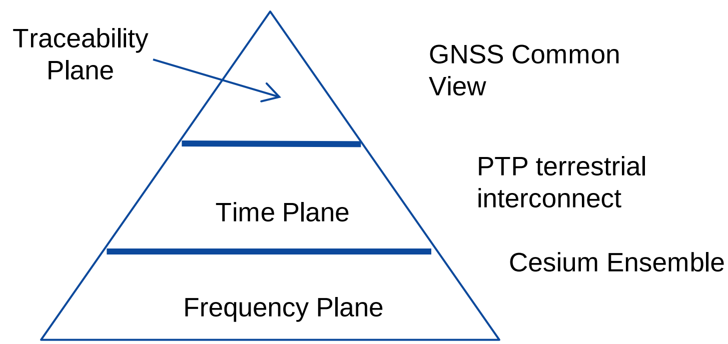
Coherent CnPRTC Service Creation Level



Current Clock Combiner supports patented enhanced clock control ensembling algorithm to generate **robust local timescale** supporting to the PRTCe requirements

Evolution of algorithm is planned to support network coherent operation as precision PTP network interconnect is deployed.

Note: Z interface (between S1 locations) consists of a PTP terrestrial interconnect and a GNSS common-view or all-in-view interconnect



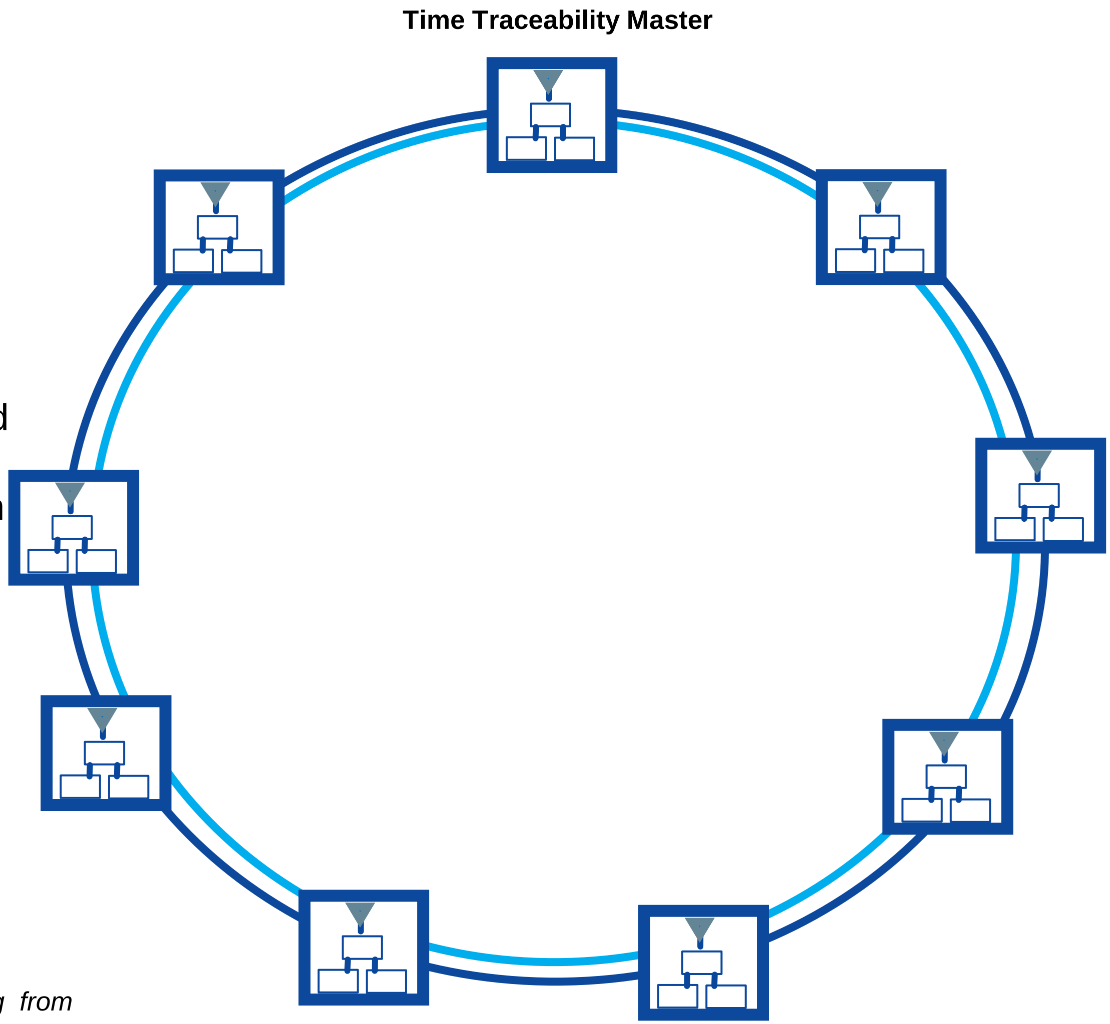
Local Timescale Generation

Coherent CnPRTC Level Dual Ring Topology

Example 9 Node Core CnPRTC Level Network using dual ring interconnect for Z interface.

- Advantages
  - •9 node network requires 18 Z interconnects (compares to 36 interconnects if fully meshed)
  - •Ring Topology simplifies node add or removal
  - •Limit number of Z interconnects in node to practical level
- •Disadvantages
  - Non-Resilient to certain multi-failure scenarios (2 paths to Master)
  - Distance from Time Traceable source is up to "half the ring" (4 nodes). Distance degrades time coherency.

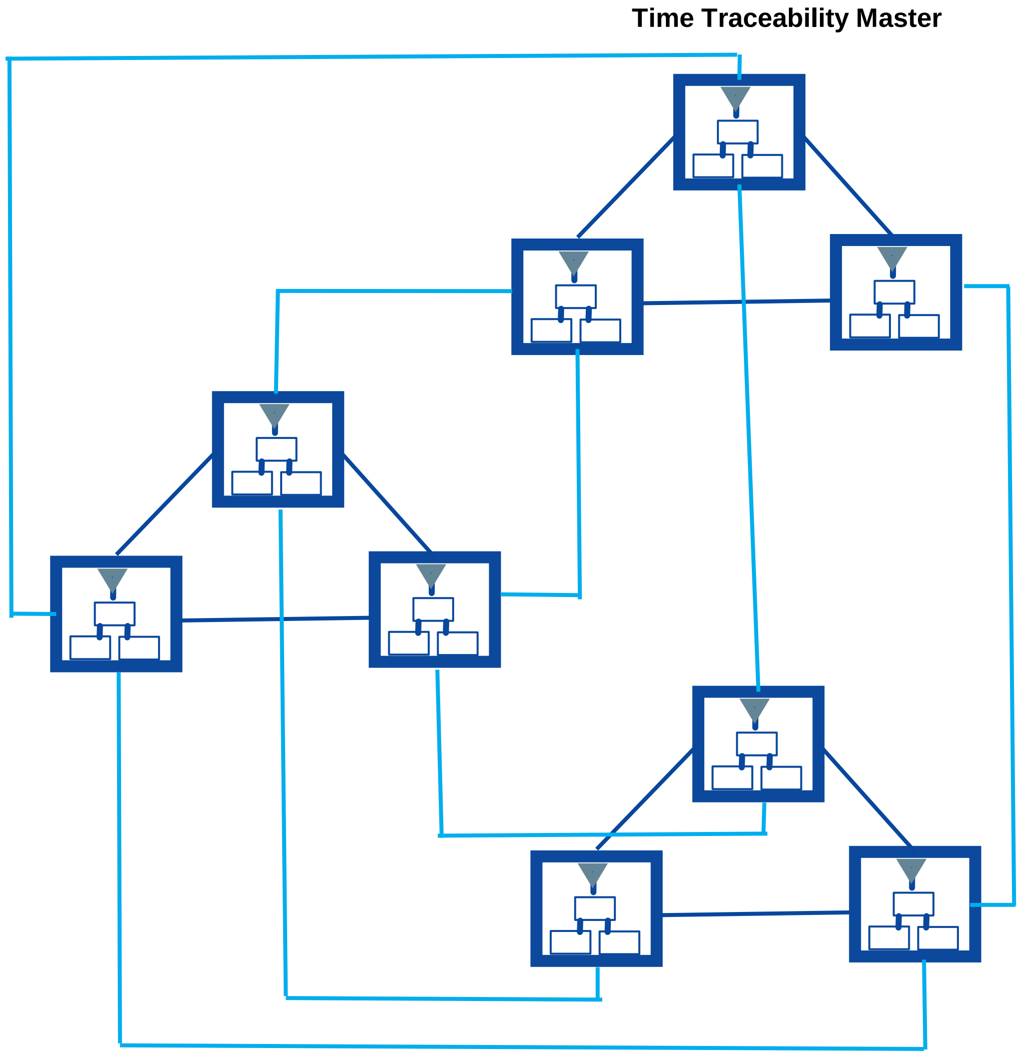
Note: Effective use of Cesium Frequency ensembling from remote nodes limited by distance.



Coherent CnPRTC Level Strongly Interconnect Triangle Topology

Example 9 Node Core CnPRTC Level Network using strong triangle interconnectfor Z interface.

- Advantages
  - •9 node network requires 17 Z interconnects (36 interconnects if fully meshed)
  - •Limit number of Z interconnects in node to practical level
  - •Normal Distance from Time Traceable source only 2 nodes
  - •Highly Resilient (multi-paths to traceable time)
- •Disadvantages
  - •Non-Trivial node add or removal

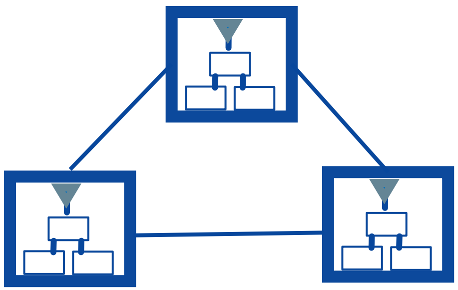


Coherent CnPRTC Topology for Regional Applications (Metro)

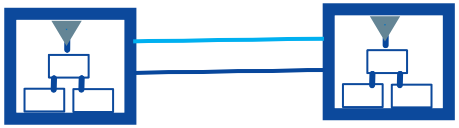
Two Metro Cases Shown

- Three CnPRTC Service Nodes
  - •Allow for “majority vote” within network compared to two node case.
- Basic 2 Node Simple Case
  - •Dependency on GNSS as “third vote”

Time Traceability Master

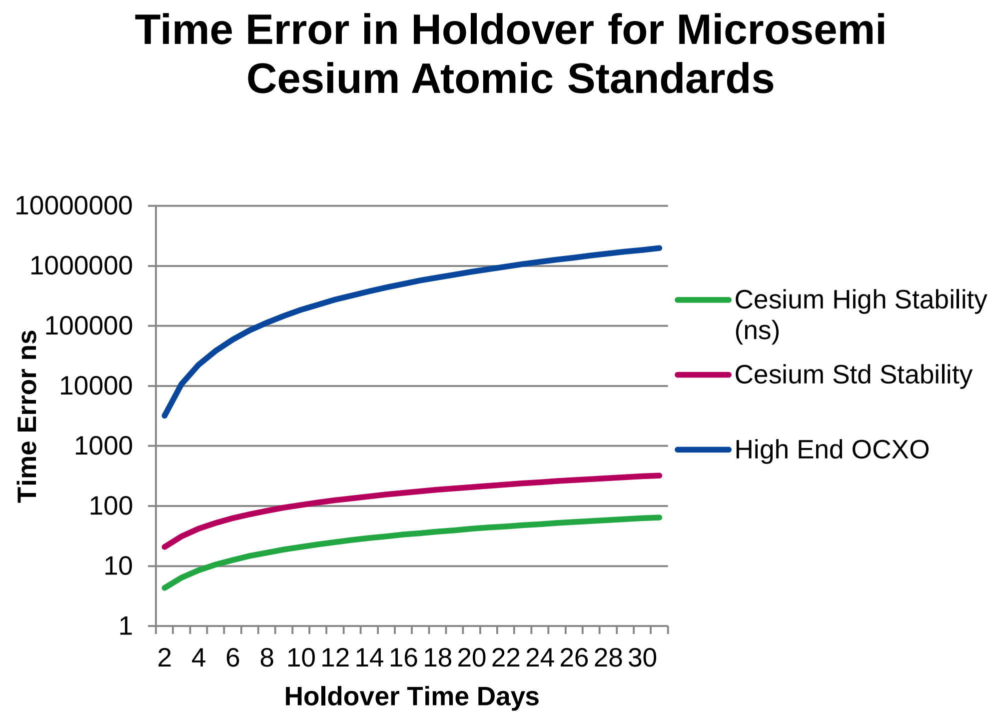


Time Traceability Master



Cesium Standards Provides Robust PRTC Time Performance

- Cesium "Time Keeping" Performance critical to delivering 30ns budget.
- Graph shows timing chasm (3+ orders of magnitude) between high end OCXO systems and Cesium (Primary Atomic Clock)
- With Cesium ensemble performance margin is even better than graph permitting robust time services at 30ns level.



Ionospheric Delay Budget Considerations

- GNSS Time Error highly dependent on delay variations through Ionosphere
- 12 months of delay variation data from study in Bhopal India during solar minimum period (2005)
- All graphs scaled to 50ns.
- Both Strong Diurnal as well as monthly (seasonal) delay variations are introduced by "Ionospheric Weather"

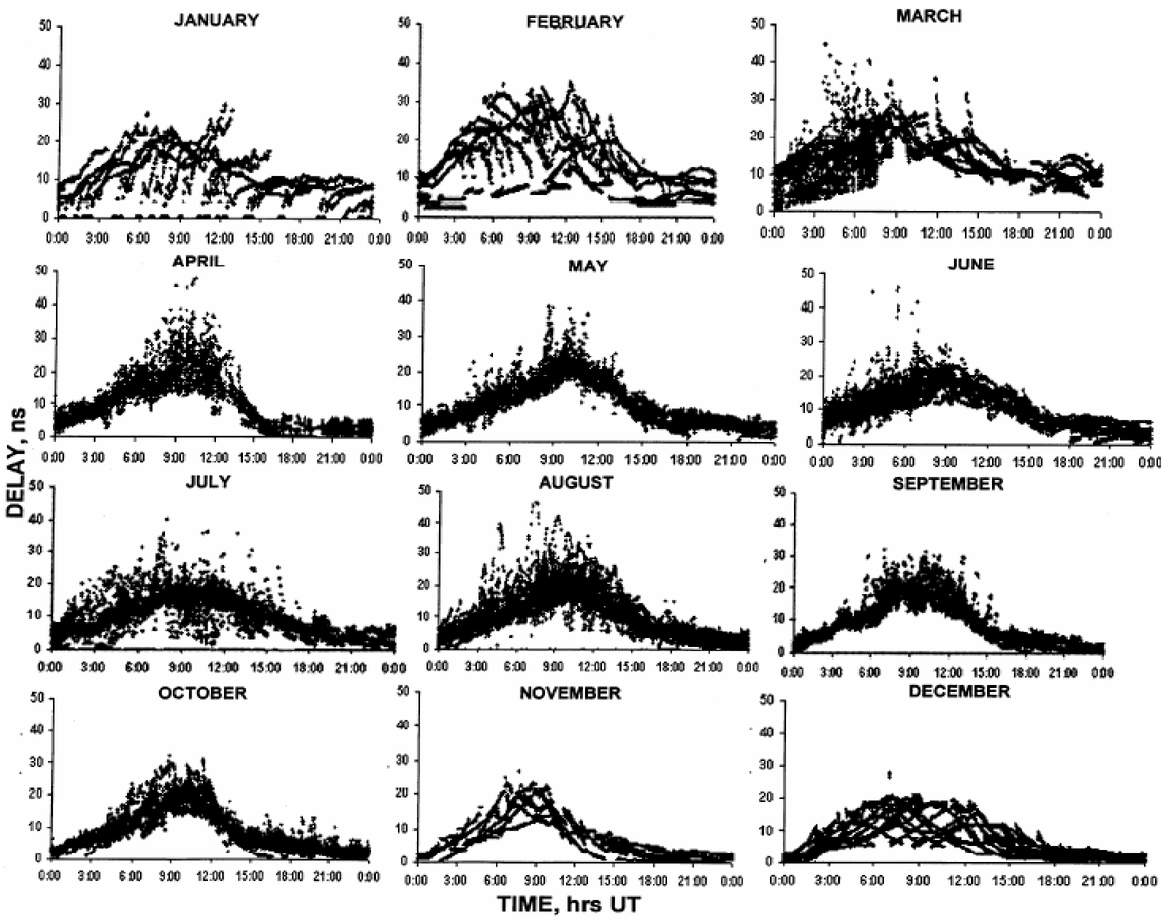


Fig. 1 — Diurnal variation of ionospheric time delay for Bhopal during the year 2005

Bhattacharya S, Purohit P K, Gwai A K, *"Ionospheric time delay variations in the equatorial anomaly region during low solar activity using GPS", Indian J Radio Space Phys., Vol. 38,2009, pp. 266-274*

Ionospheric Scintillation Fading Considerations

• Ionospheric Scintillation Fading occurs when under solar transient situations multiple delay paths co-exist through ionosphere.
•In example shown the fading was deep 25dB.
•Effect can be mitigated through the use of high sensitivity receivers and well designed processing algorithms

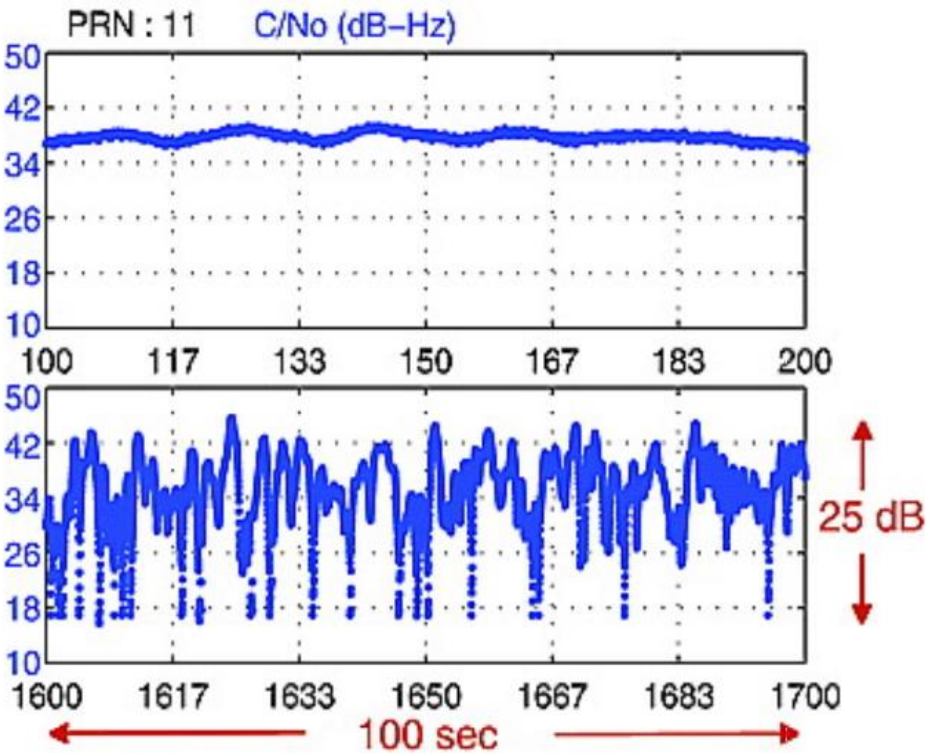


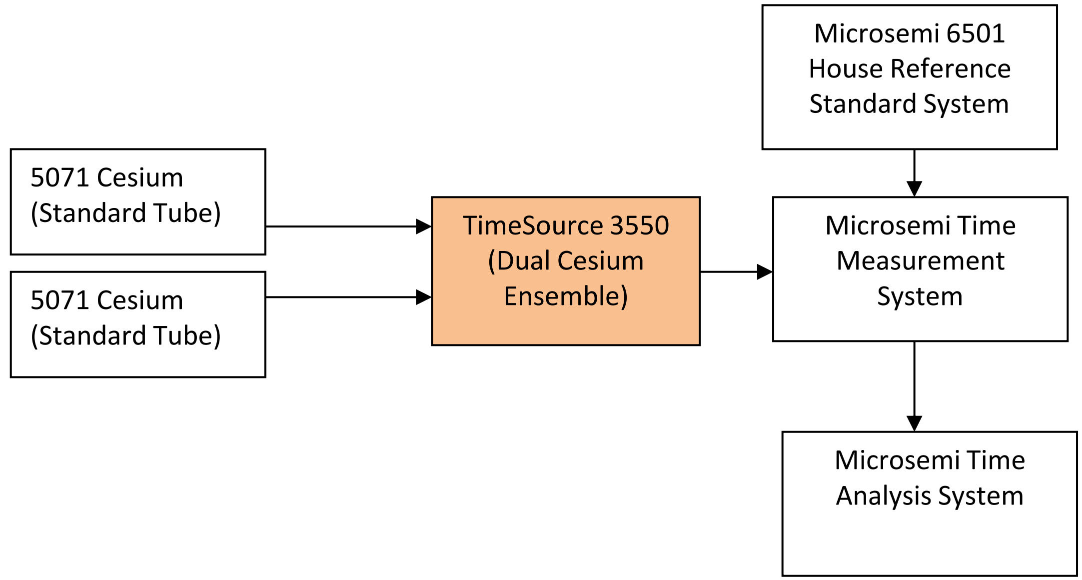
Figure 1.2: Example of deep signal fading due to strong ionospheric scintillation. Top plot shows C/N_0 during a nominal period and the bottom plot shows C/N_0 during a strong scintillation period. Data collected on 18 March 2001 at Ascension Island.

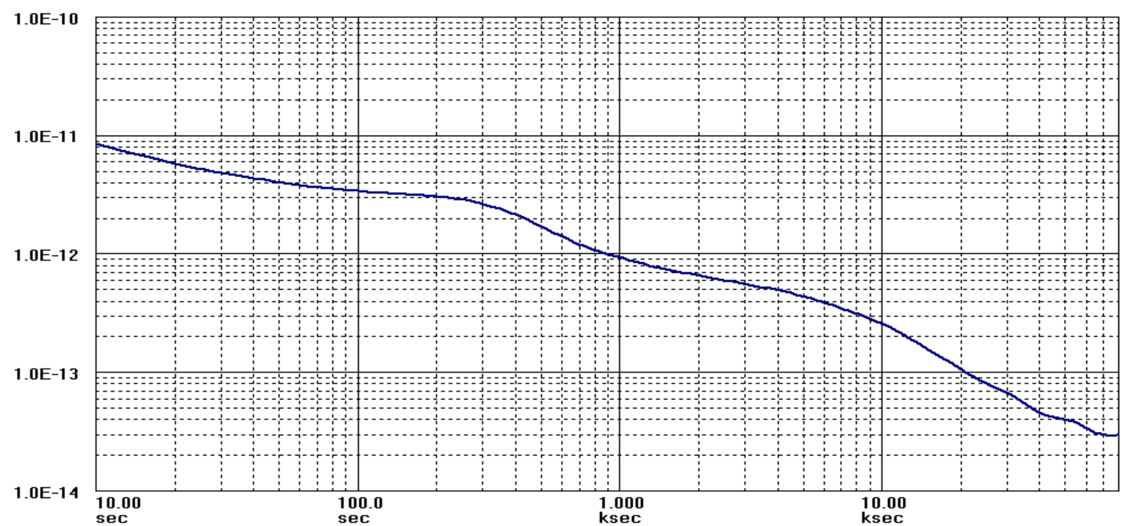
Seo, Jiwon, Per Enge, J. David, Powell, Todd Walter, and Stanford University. Department of Aeronautics & Astronautics. "Overcoming Ionospheric Scintillation for Worldwide GPS Aviation." *Overcoming Ionospheric Scintillation for Worldwide GPS Aviation*. N.p., n.d. Web.

Baseline Performance Dual Cesium Timescale Ensemble

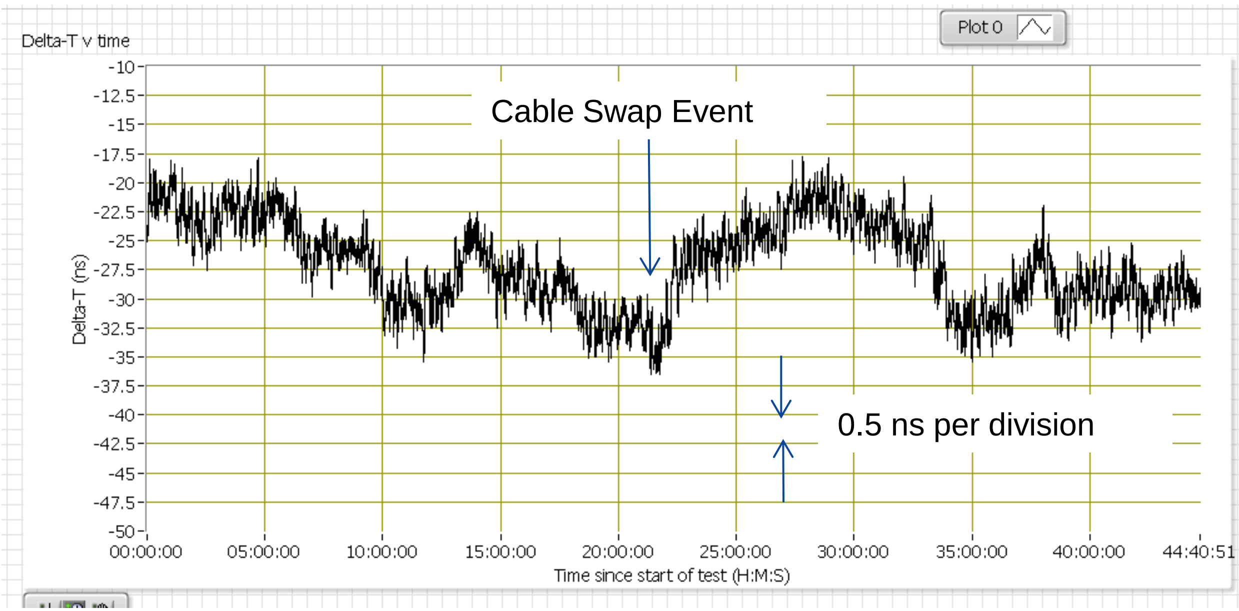
- Test Configuration is as shown.
- The Clock Combiner algorithm is operational in the TimeSource 3550 system
- The internal laser driven Rubidium is disciplined based on the combined performance of both external Cesium clocks.

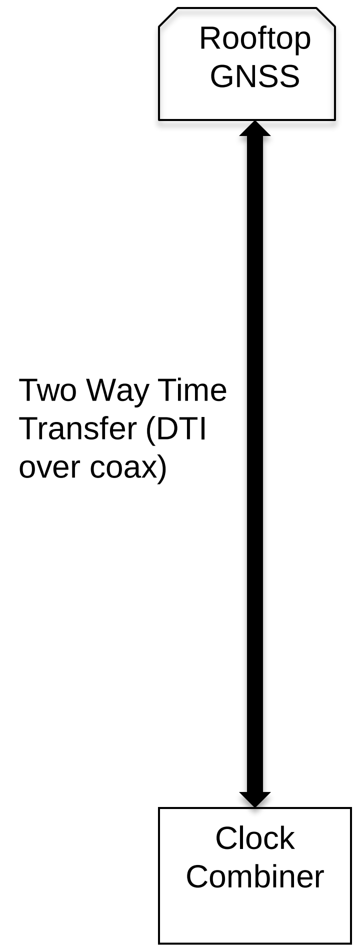
The testing interval result shown over a 4.5 day test. The test result shows a stability noise floor at the 3e-14 level consistent with an ensemble of two standard performance 5071 cesium standards.





TWTT Continual Automatic Antenna Cable Delay Calibration

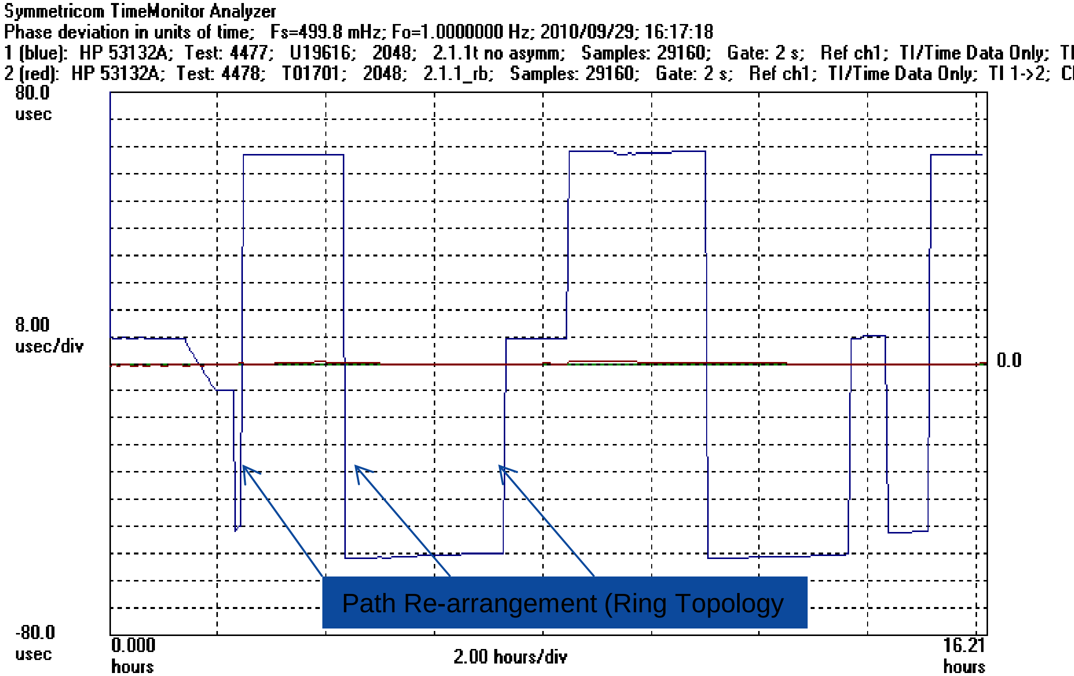




Cable Delay Bias Mitigation Test Results (200ft and 700ft cable swap)

Z interface combined strength of PTP and GNSS

- **Asymmetry Correction Algorithm supplies external correction factor defined in 1588 standard.**
- **Algorithm learns asymmetries to prevent in-accurate time output**
- **Addressed both PTP and GNSS potential vulnerabilities**



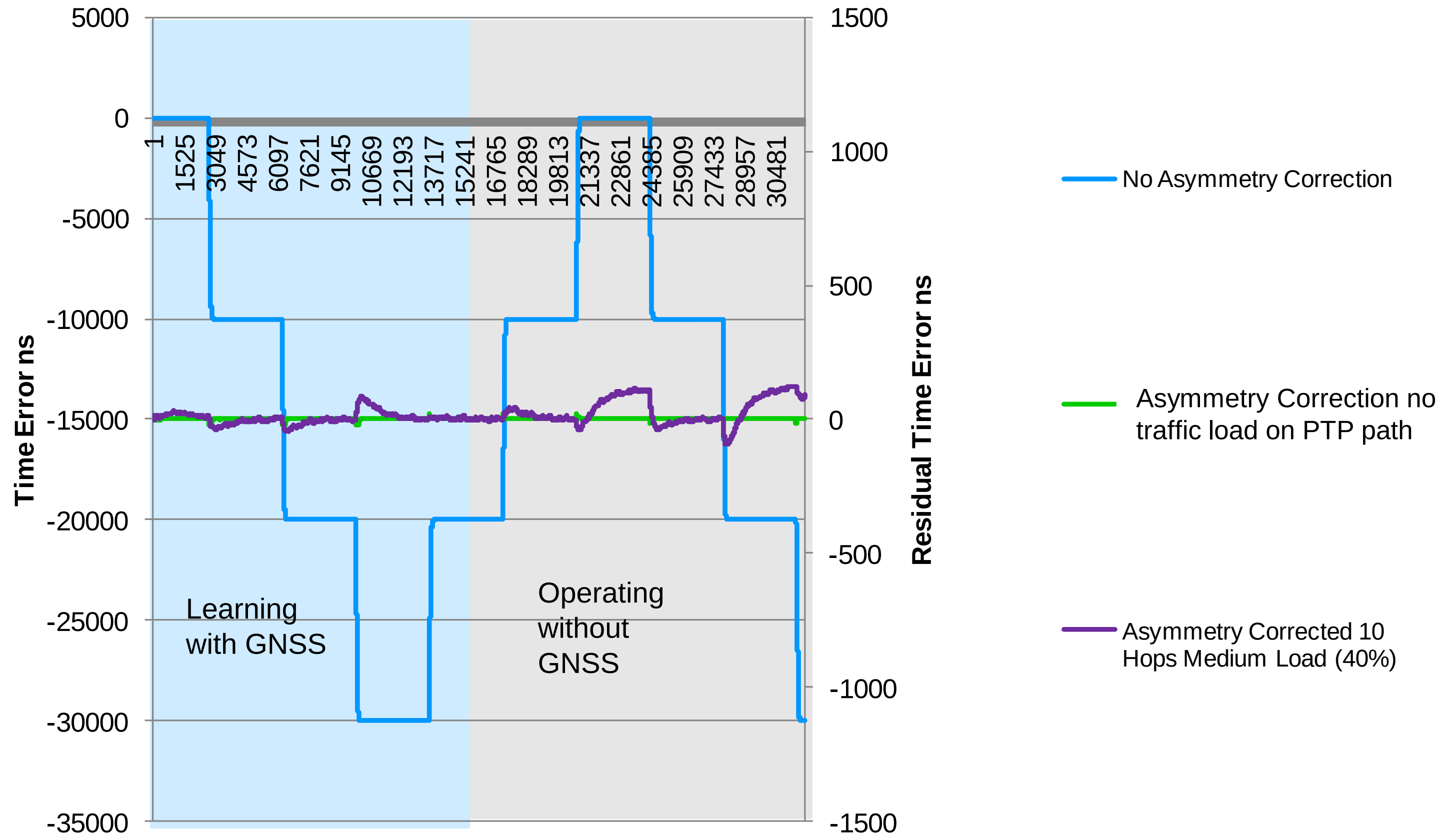
Path Signature			Asymmetry Bias (ns)
Round Trip Delay	Observed Bias	Secondary Path Parameters	
Path Signature A			AAA.A
Path Signature B			BBB.B
Path Signature C			CCC.C

Performance on Customer Network test environment:

BLUE: PPS Performance without Asymmetry correction.

RED: PPS Performance with Asymmetry correction.

Automatic Path Delay Compensation Learning Behavior



Summary

- CnPRTC addresses operating a phase/time service in a real-world environment with vulnerabilities such as GNSS jamming.
- CnPRTC complements local PRTC distribution.
- CnPRTC leverages the strengths of both GNSS and PTP

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