Power Matters.

Enhanced PRTC Extended Outage Operation

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Overview

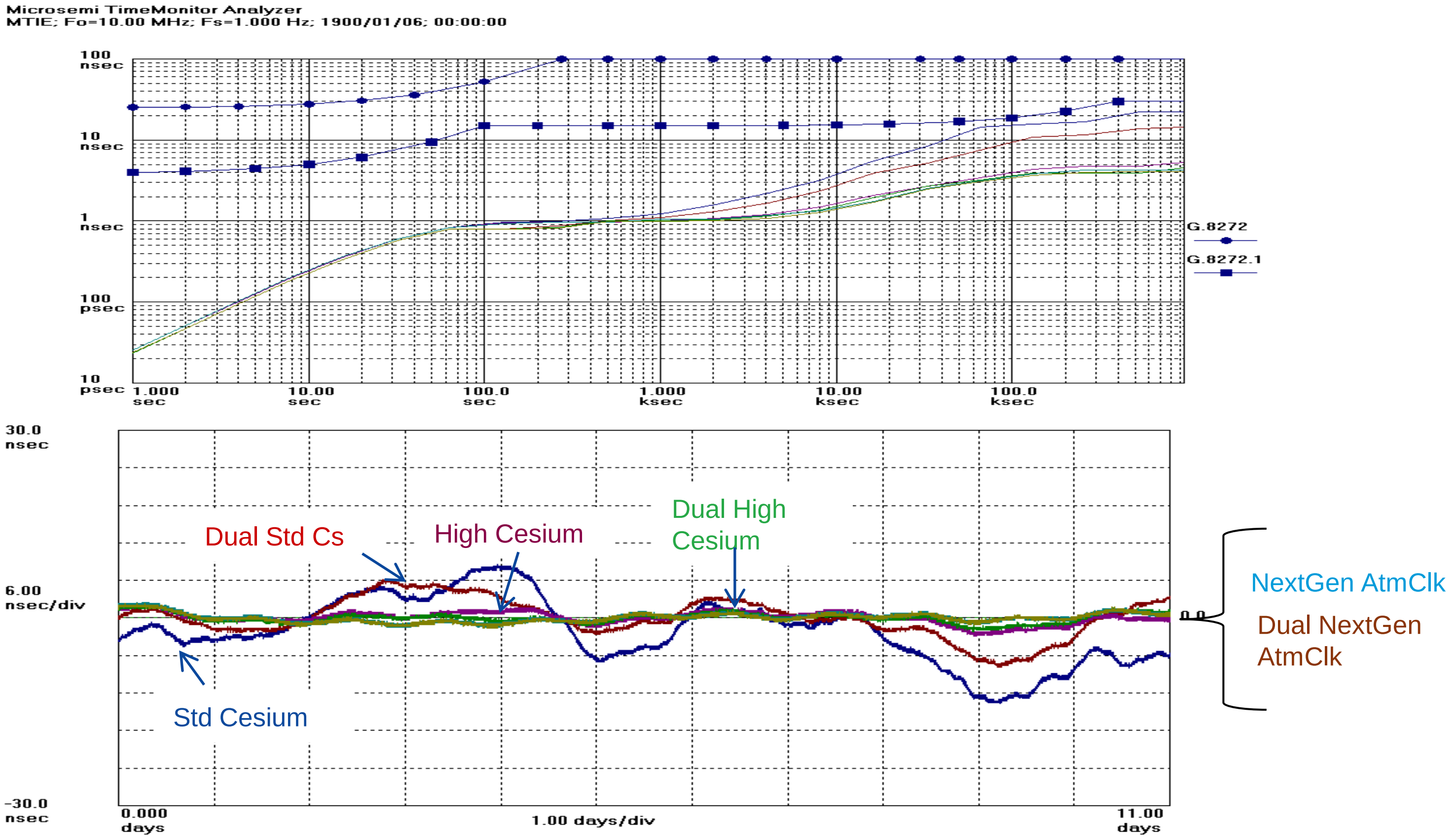
- ITU is defining a new Enhanced level of a Primary Reference Timing Clock in G.8272.1 (ePRTC)

- This ePRTC supports both a higher level of accuracy (30ns) and a higher level of operational reliability to ensure operators can maintain required time service performance in a real world environment subjected to effects such as both intentional and unintentional GNSS jamming and spoofing.

- Central to the ePRTC is the requirement for at least one co-located atomic clock to provide the required operational performance.

- This presentation looks at the real world operational performance capabilities including both normal operating conditions, as well as GNSS outages, equipment outages, GNSS firewall capabilities and antenna system delay calibration requirements.

ePRTC Steady State Normal Performance



Dual Std Cs

High Cesium

Dual High Cesium

Std Cesium

NextGen AtmClk

Dual NextGen AtmClk

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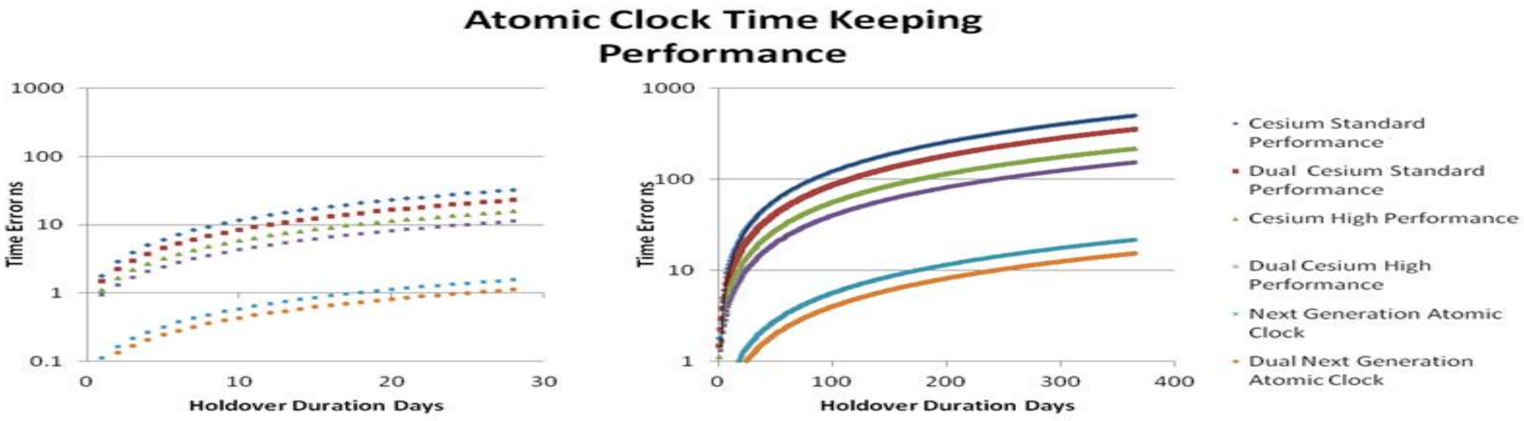
Local Atomic Clocks Provides Robust ePRTC Time Performance



- A least one local atomic clock is required for an ePRTC
- The graph above shows that atomic clocks can support the proposed ePRTC holdover requirement:

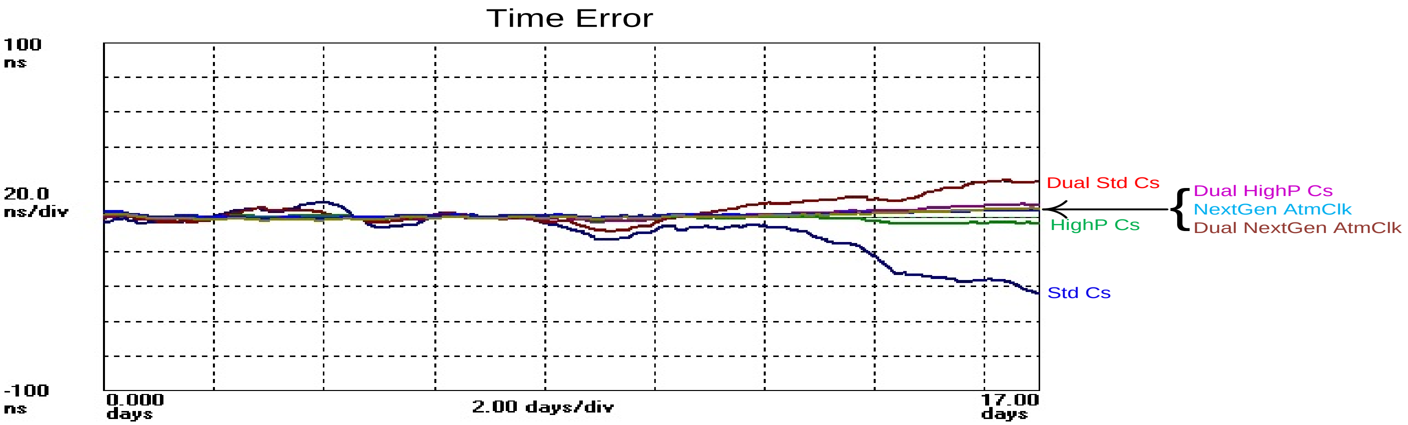
from the start of phase/time holdover, after 30 days of normal operation, the time output of the ePRTC should be accurate, when verified against the applicable primary time standard (e.g. UTC), to a value increasing linearly from 30 ns to 100 ns over a 14 day period.

- Proposed next generation Atomic Clocks such a cold-ion based can extend performance by an order of magnitude

Some Observations

- The performance of a dual configuration shows the anticipated ensembling performance improvement.
- The quantum step improvement with the next generation atomic clock technology is apparent.
- Relative to the +/- 30ns ePRTC normal time performance requirement the clock timekeeping performance shows acceptable margin to achieve the minimal 3 day holdover while maintaining 30ns specification.
- Relative to the +/- 100ns ePRTC extended holdover time performance requirement the clock timekeeping performance shows acceptable margin to achieve the minimal 14 day holdover while maintaining 100ns specification.

ePRTC Holdover Performance



- This slide shows the holdover performance for a complete ePRTC system including the effects of the local atomic clocks as well as GNSS errors (such as ionosphere) and measurement noise

- ePRTC including all sources of error meets proposed Holdover Requirement *“from the start of phase/time holdover, after 30 days of normal operation, the time output of the ePRTC should be accurate, when verified against the applicable primary time standard (e.g. UTC), to a value increasing linearly from 30 ns to 100 ns over a 14 day period.”*

Strength in Numbers

- Although an ePRTC requires one local atomic clock there are significant operational advantages in having a dual configuration.

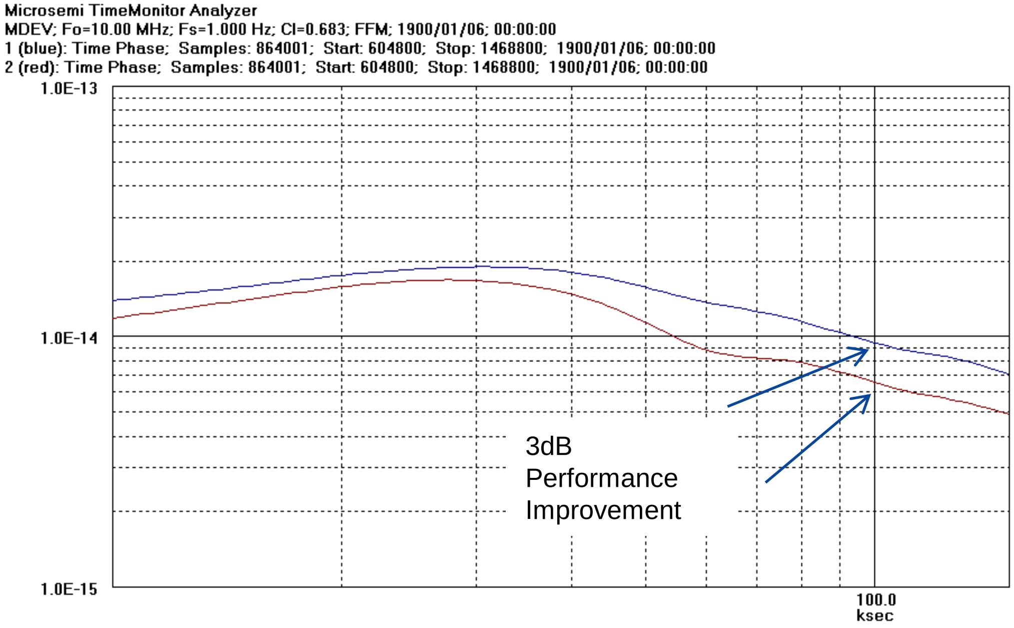
- One advantage is the capability to use both atomic clocks simultaneously to generate a local ensemble time scale to improve performance margin.

- A second advantage is the ability to maintain ePRTC performance when a single atomic clock requires maintenance.

Enhanced Performance Margin with Dual Configuration

- Blue Graph shows ePRTC operational performance stability with a single high stability Cesium while the Red Graph shows operational performance with Dual Cesium clocks.

- Anticipated 3dB improvement in stability performance observed. Stability Improvement at 100K seconds:
  20 log(9.48e-15/6.54e-15) = 3.22 dB.



3dB Performance Improvement

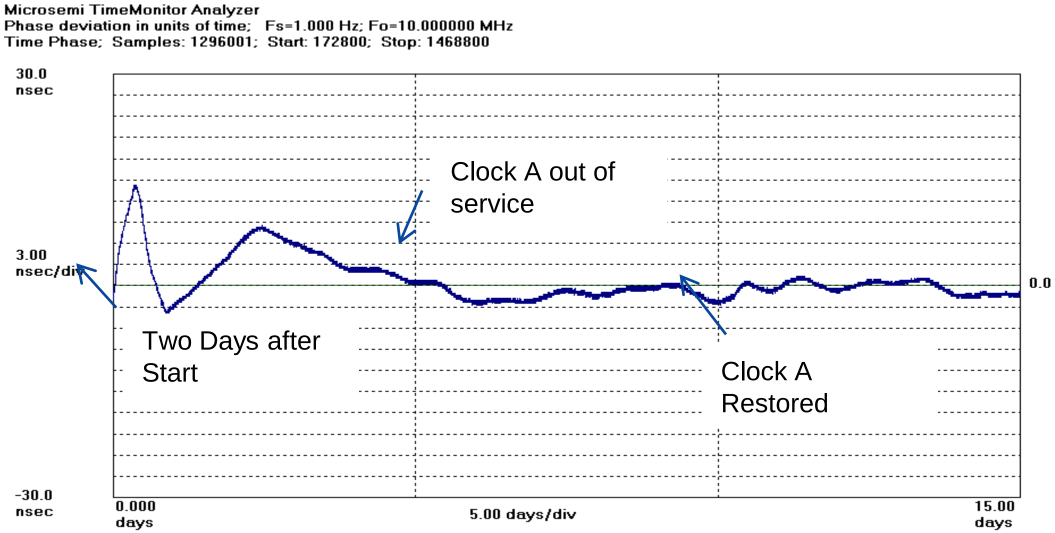
Maintaining ePRTC Normal Performance During Atomic Clock Maintenance

- The graphs shows the PPS performance of an ePRTC before, during and after a 5-day maintenance outage on Cesium A

- The system was tested with our simulation test capability that supports playback emulation of all key components (GNSS input, Atomic Clocks, Thermal Environment …

- A well-designed ePRTC system learns the clock model of each Atomic Clock to provide a hitless event when a clock is taken out of service

- When a clock is restored to service a well designed ePRTC learns the performance of the new clock before automatically bringing it on line.



Clock A out of service

Two Days after Start

Clock A Restored

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”
- Other unintentional or intentional sources of spoofing will map to delay variation error as well

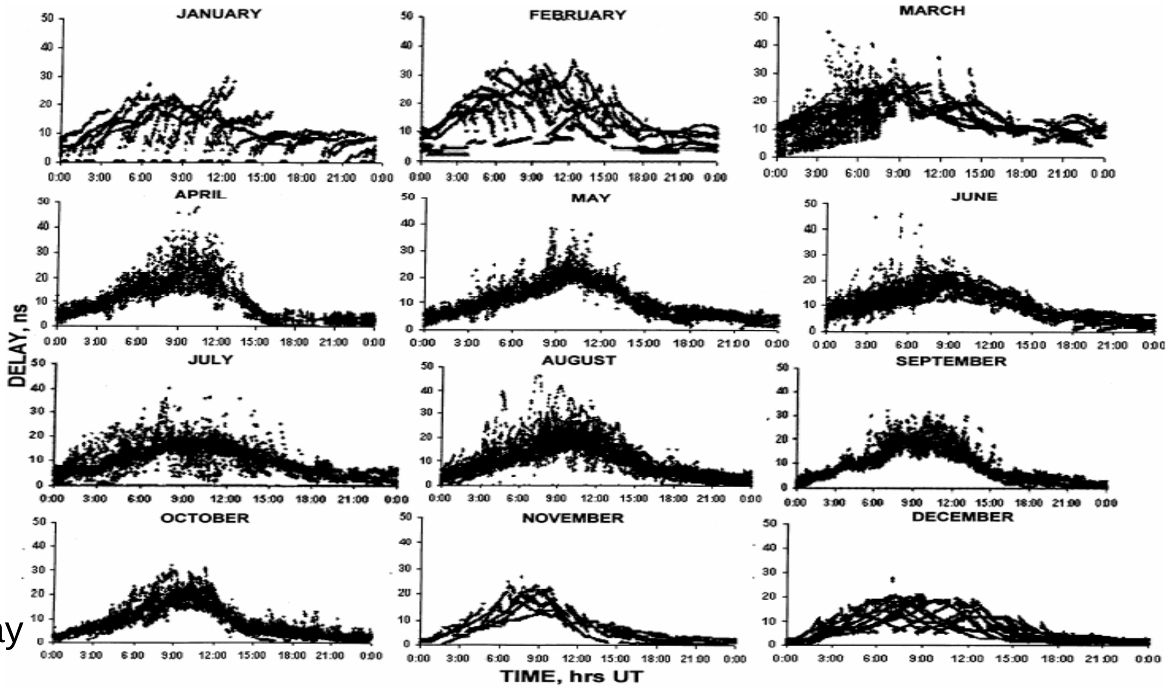


Fig. 1 — Diurnal variation of ionospheric time delay for Bhopal during the year 2005

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

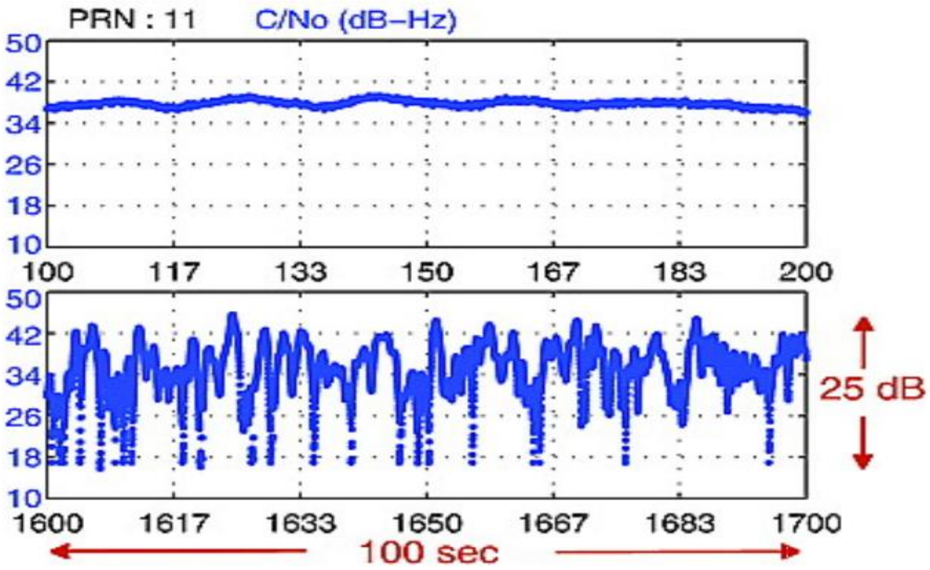


Figure 1.2: Example of deep signal fading due to strong ionospheric scintillation. Top plot shows C/N_0 during a nominal period and the bottom plot shows C/N_0 during a strong scintillation period. Data collected on 18 March 2001 at Ascension Island.

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.

ePRTC Diurnal Filtering

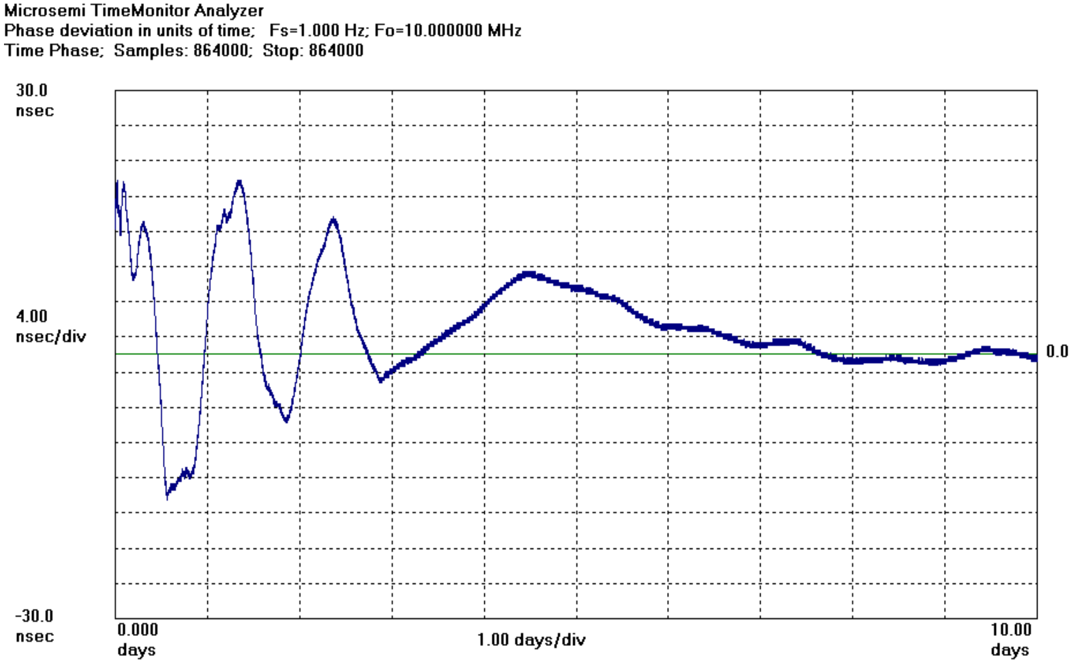
- The graph shows the PPS timing performance on an ePRTC system from startup.

- The system was tested with our simulation test capability that supports playback emulation of all key components (GNSS input, Atomic Clocks, Thermal Environment …

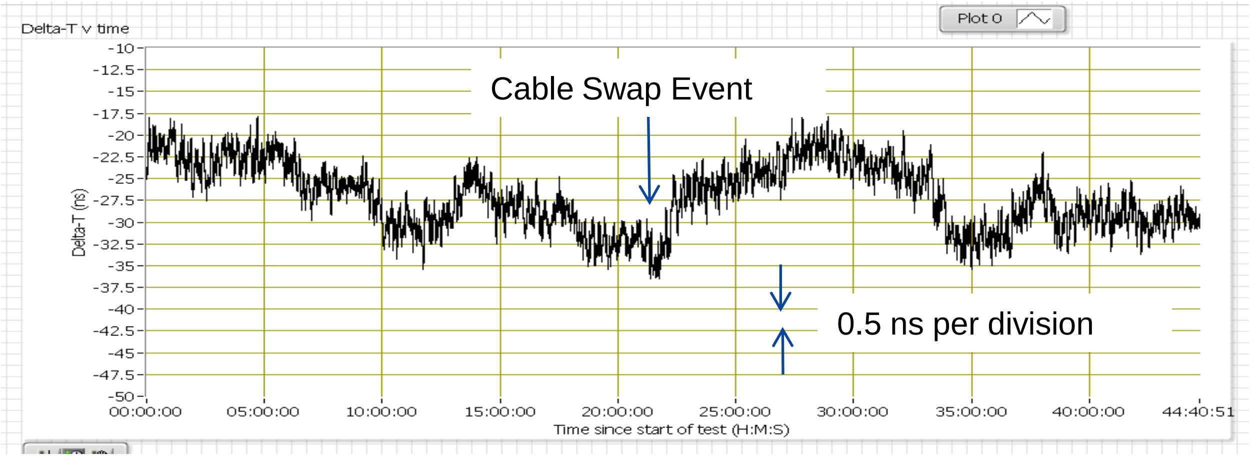
- The GNSS input in this case was based on a model that captures the diurnal ionosphere delay effect.

- The ePRTC system learns the diurnal effect and mitigates as can be seen in the graph.

- The Diurnal Filtering supports ultra-high resistance to jamming and spoofing on GNSS as the clock is effectively "steered once per day" only of the GNSS Daily Performance is normal.

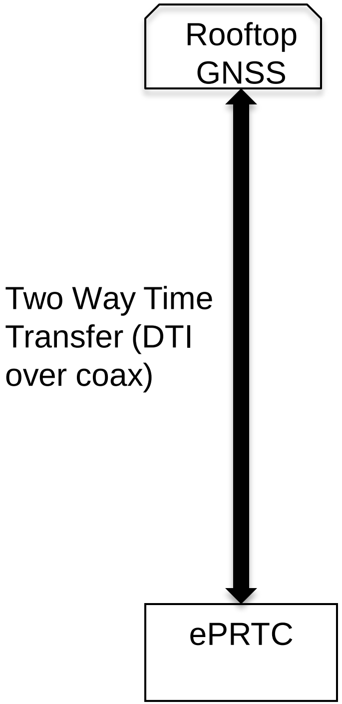


TWTT Continual Automatic Antenna Cable Delay Calibration



Cable Swap Event

0.5 ns per division



Rooftop GNSS

Two Way Time Transfer (DTI over coax)

ePRTC

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

Summary

- Delivering Reliable Timing Services in a real world environment requires the sensible use of EPRTC based clocks in a given operational domain.

- A well-designed EPRTC system based on at least one co-located Atomic Clock can meet all requirements in a real operational network.