Achieving Zero Satellite Dependency with State-of-the-Art Technology

A Leading Provider of Smart, Connected and Secure Embedded Control Solutions

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March 2023

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Why Transition from Satellites to Terrestrial?

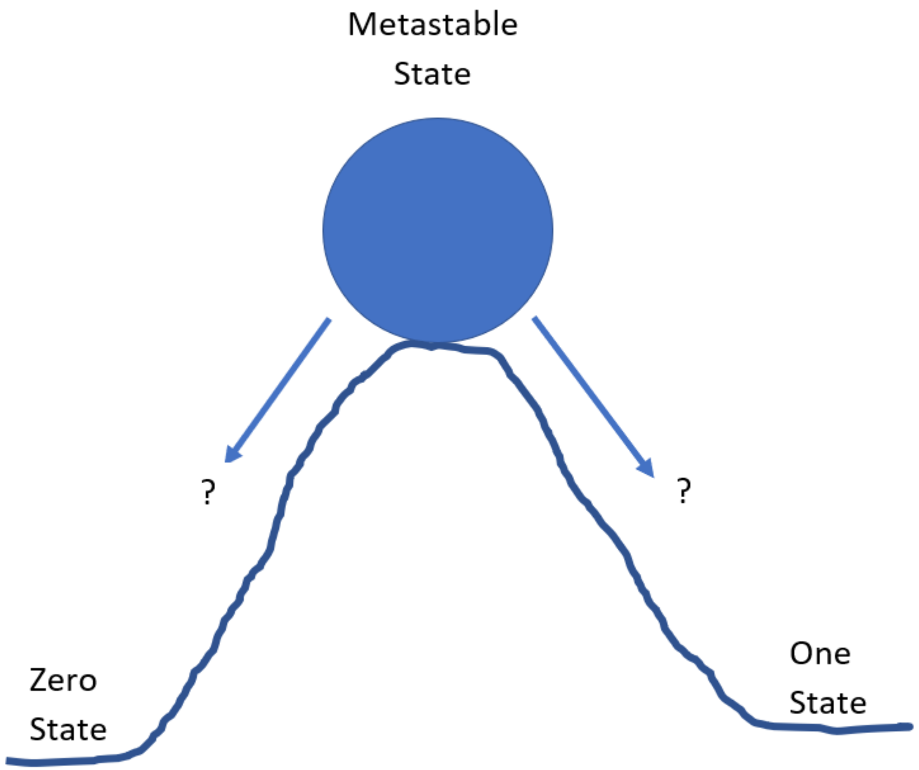
- GNSS especially GPS has a proven track record of providing suitable traceable timing
- Unfortunately, this has led to a worldwide over dependence on satellite-based time service
- Space weather is a fundamental vulnerability out of our control.
- Last mile vulnerabilities include realities of urban canyons as well local jamming and spoofing (Timing systems are generally stationary and local effects are essentially permanent)
- Operational errors have occurred
- Finally, there is the risk of an enemy attack

Example High Accuracy Optical Time Transfer Approaches

- **Optical J.211 Two-Way Protocol:** Based on Optical Extension of Mass Deployed Twisted Pair Two-Way Standard first described in PTTI paper 2008
- **White Rabbit Project:** Open-Source Technology based on PTP and Synchronous Ethernet
- **IEEE 1588 (2019) High Accuracy:** Standardized PTP with Synchronous Ethernet approach. (Extends and generalized the white rabbit project approach)
- **ELSTAB (electronically stabilized fiber optic system):** Based on remote feedback on return optical bi-directional signal
- **ITU Class D Optical Boundary Clocks:** Actively deployed today supporting 5ns per node time distribution
- **Hybrid Time Digital Conversion:** Enhanced approach addressing limitations in alternatives

Challenges to Achieving Precise Time Transfer

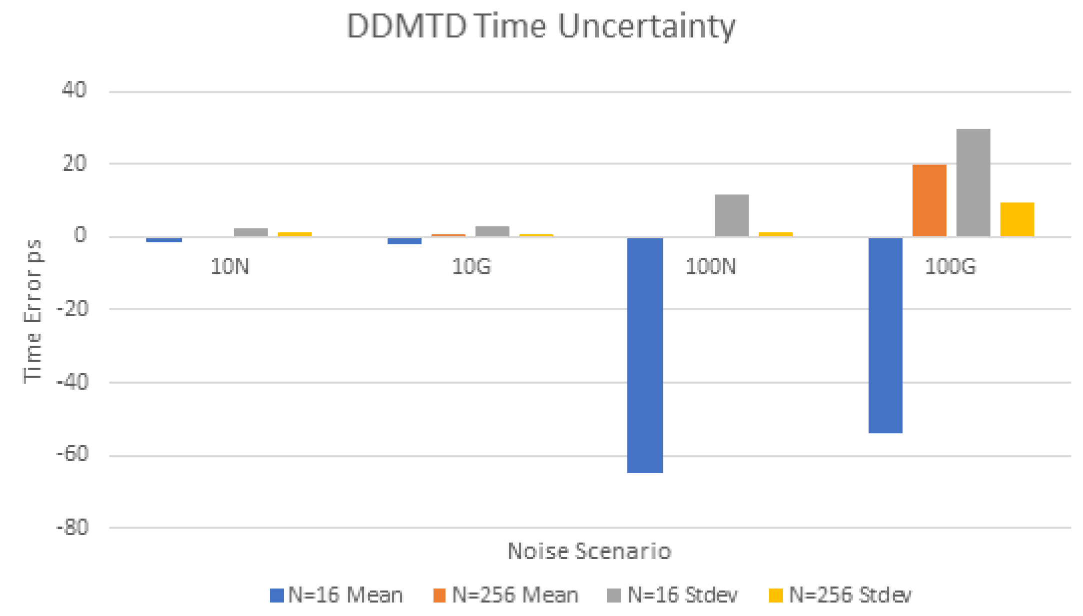
(Example White Rabbit Dual Digital Mixer Time Difference Measurement)



- Determine the exact time incoming carrier edge co-incident with helper frequency
- Event happens at metastable setup and hold violation unpredictable delay to state change decision
- As “ball” inches its way up hill noise will interfere with proper detection
- De-glitching mechanism helps but residual delay uncertainties exist

Challenges to Achieving Precise Time Transfer

(Example White Rabbit Dual Digital Mixer Time Difference Measurement)

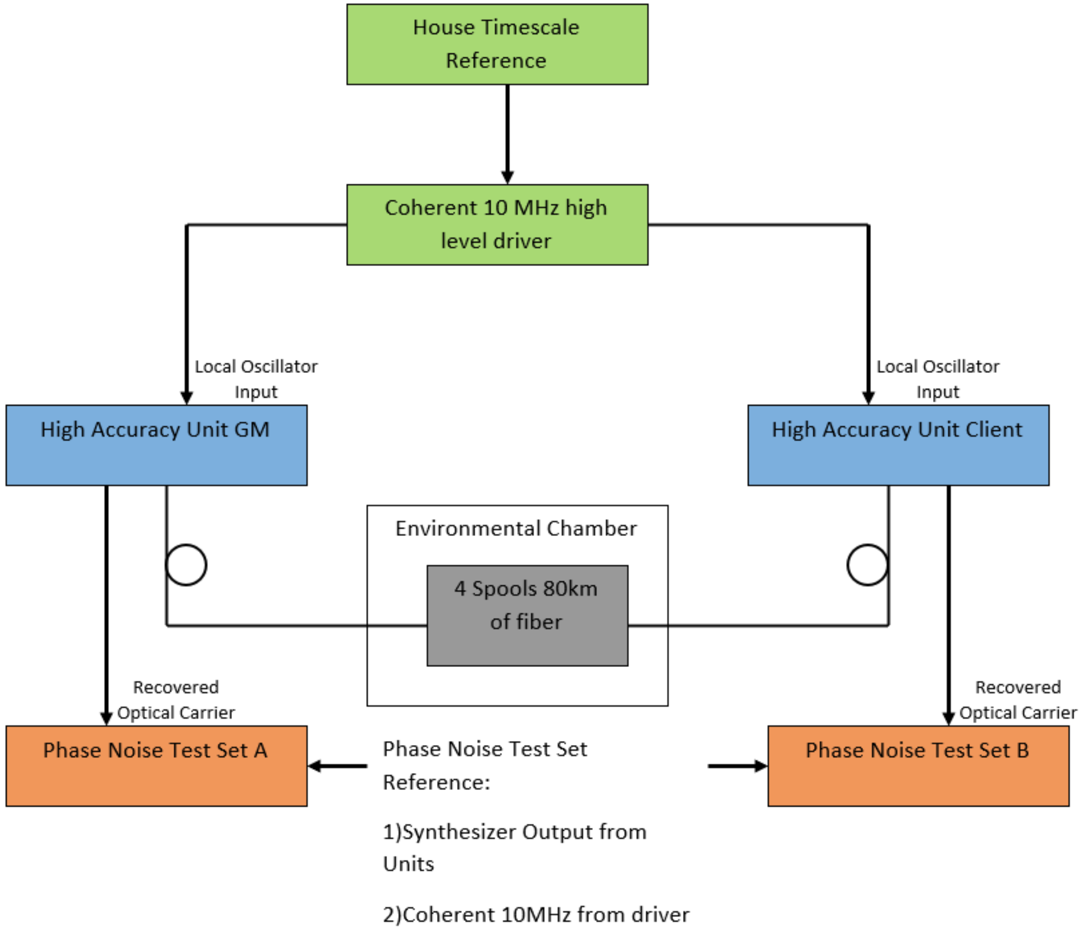


Notes:
1) Two Deglitchers evaluated N is the window size looking for equal number of Ones and Zeros as described in white rabbit project
2)Noise type N: Normal Gaussian G: Gamma alpha = 2.284 Beta = 6.85e-11
3) 10N means 10 ps 1 sigma normal 100G means 100ps 1 sigma gamma noise

- Shown time measurement uncertainty under 4 noise scenarios
- Two 10ps low noise scenarios (10N,10G) reflect original optical interconnect lengths of <20km
- Low noise cases show single digit picosecond performance
- In contrast high noise case show de-glitch delay sensitivities approaching 10x greater than 20km case

Challenges to Achieving Precise Time Transfer

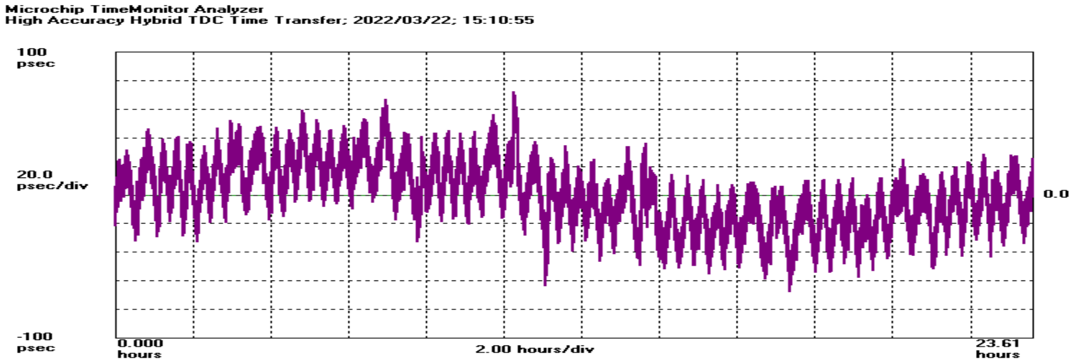
(Sources of Time Error Other Than Measurement)

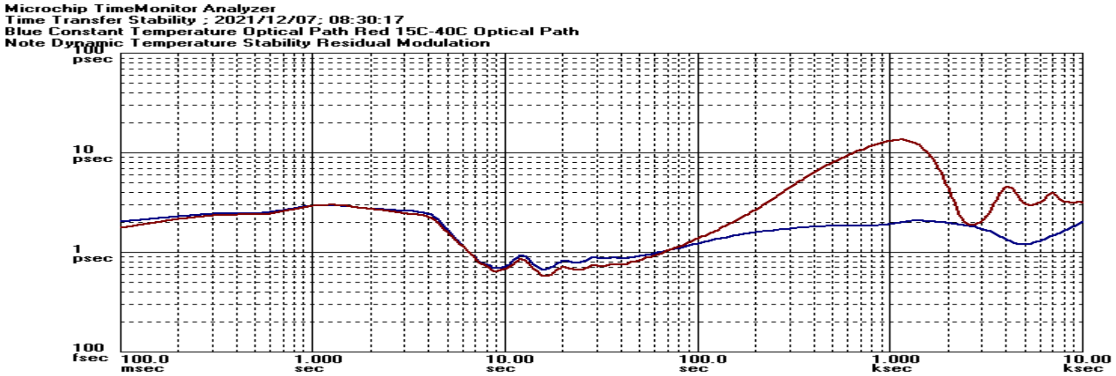


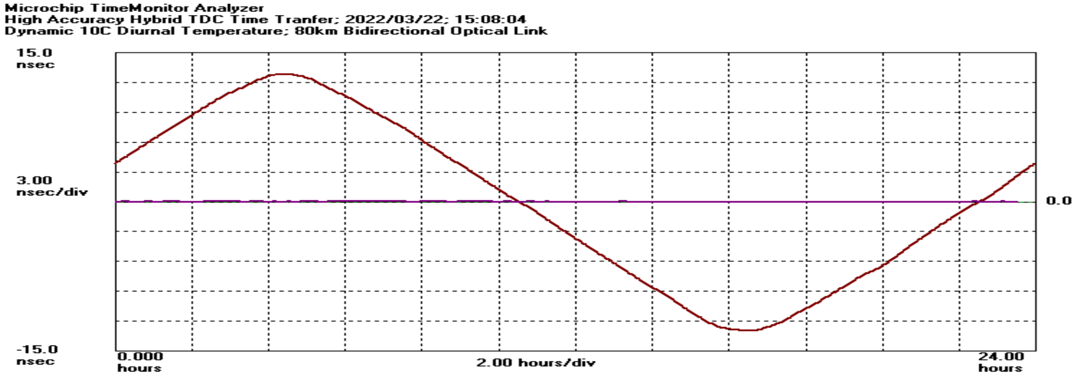
- Experiment set up to investigation time error using bi-directional synchronous ethernet carrier
- Testing of 80km optical path under constant and diurnal temperature conditions
- Sources of time error include both optical path and clock data recovery in FPGA based approach

80km Optical Link Time Error Sources

- First graph show both one-way and two-way time transfer with diurnal temperature
- Over 500x reduction in fiber temperature sensitivity (62fs/km-C)
- In addition, dynamic temperature time error induced 12ps 1 sigma modulation in FPGA cell data recovery
- Note under no temperature stress no modulation (blue graph right)







What is Needed?

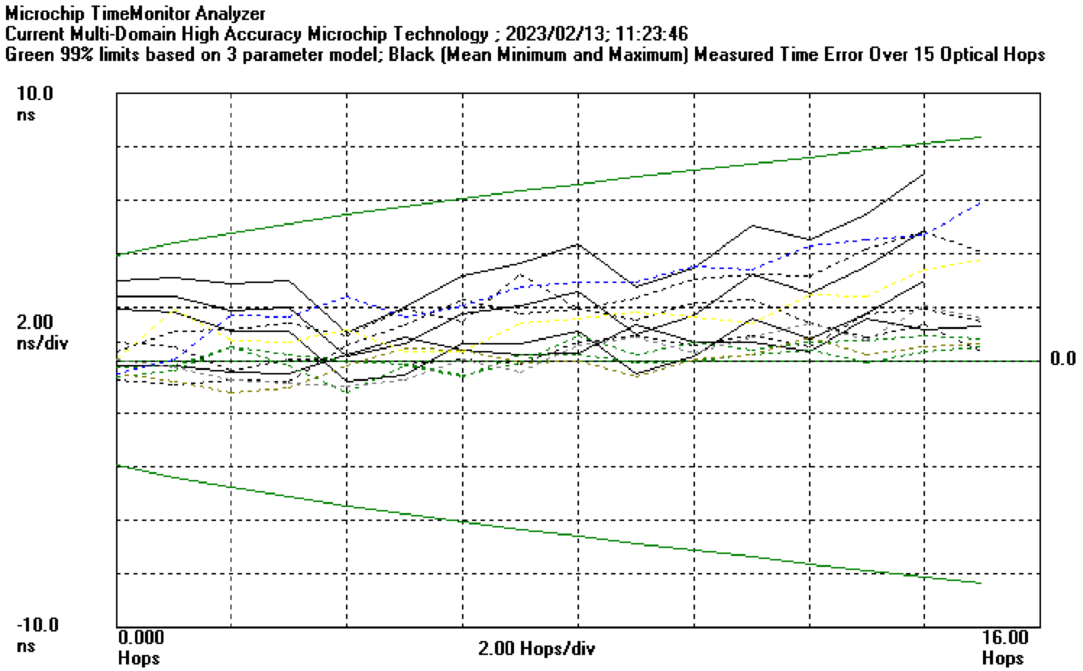
- Method that is agnostic to time transfer technology to characterize terrestrial time transfer
- All methods will have time uncertainty limitations and need a consistent way to both describe and model time transfer paths
- Three parameter model is proposed and used in this presentation

Three Parameter Time Transfer Model

1) **Static Time Bias:** limit of the maximum static calibration time error per hop
2) **Mean Time Bias Noise:** limit of residual average calibration time error per hop
3) **Accumulating Time Error:** model as a random walk phase per hop and addresses noise accumulation in path

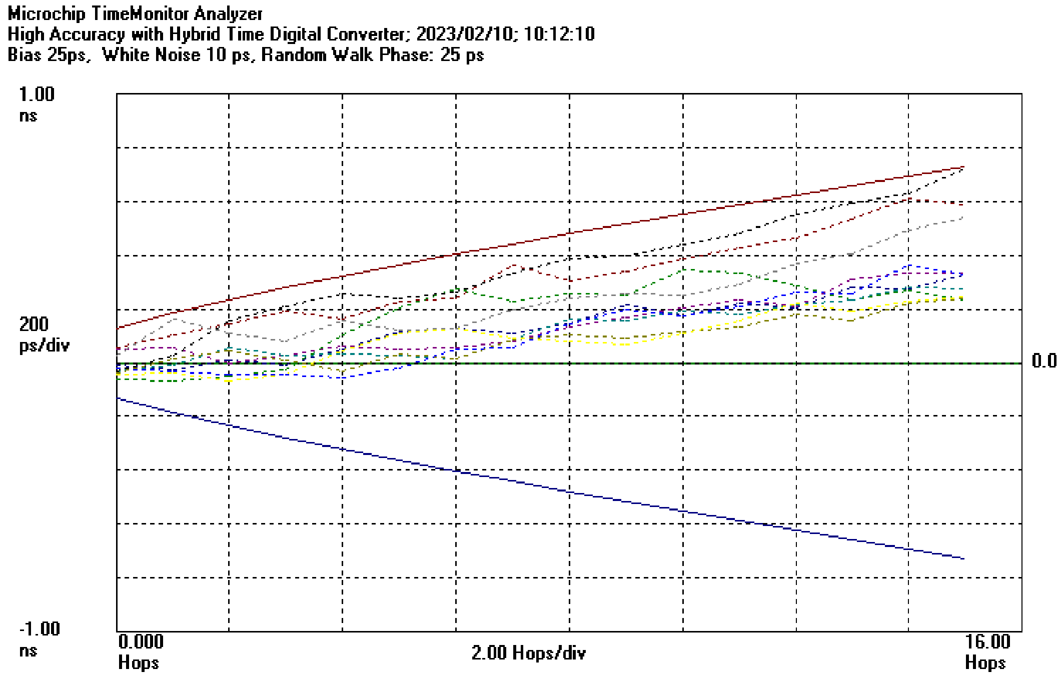
Three Parameter Time Error Model: Current Use Case

- A chain of 15 Microchip multi-domain boundary clocks configured in Lab
- All 15 clocks PPS outputs are observed concurrently with an overnight run
- The limits (green) show the 99% predicted by the 3-parameter model for this system
- The mean, minimum and maximum (black) show the actual measured performance
- The dashed data shows Monte-Carlo results from a simulation based on the model
- The model is agnostic to the underlying technology and provide a consistent statistically sound means to characterize clock chains



Three Parameter Time Error Model: Next Generation

- Next generation high accuracy will utilize two-way observation of carrier frequency as define in that latest IEEE high accuracy PTP standard
- The carrier observation can be implemented in a variety of manners
- State-of-the-art synthesizer chips support high accuracy functionality that enhancing current DDMTD mechanism
- The graph shows the next generation performance based on the Three Parameter modelling



Conclusions

- There is a growing consensus that the future of time and frequency is both terrestrial and optical
- Three Parameter Model for path of optical time transfer works well and is needed
- Current high accuracy (without carrier assist) supports 10ns over path
- Carrier enhanced methods can achieve a 10x improvement
- Properly designed high accuracy optical networks will outperform satellites with enhancement in accuracy, resiliency and security