LORAN-C Time and Frequency Equipment Capstone

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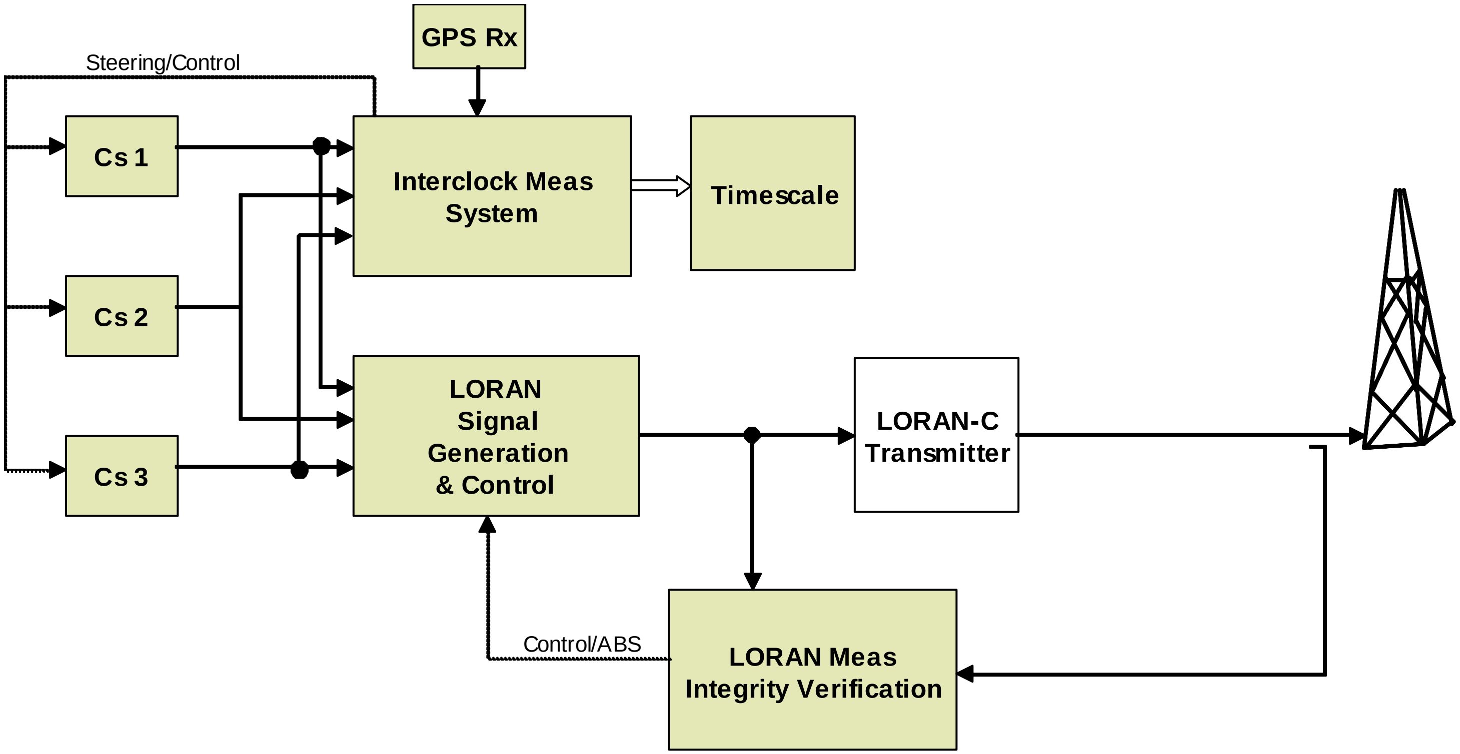
Introduction

- In 1999, the LORAN Support Unit initiated a program to replace the obsolete timing systems at US transmitting LORAN stations with a state-of-the-art system that would not only provide existing timing functionality, but also a platform on which to base future LORAN-C enhancements
  - This suite of hardware, software, and firmware is called the Time and Frequency Equipment
- Since the first delivery, the capability set for TFE has been extended to add functionality
  - Pulse Position Modulation
  - Precise (<1ns) control of signal phase
  - Advanced timescale algorithm for optimal clock and measurement integration
  - Extended (and reconfigurable) Automatic Blink System (ABS)
- By dictating an open, expandable architecture (both physically and functionally), LSU has positioned the US LORAN-C transmitting stations well for the implementation of Enhanced LORAN
  - System allows USCG the flexibility and capabilities required to field the evolving service

TFE Version 1.0

- The initial delivery of TFE included all functions required to generate, monitor and control a coherent LORAN-C signal set (more than just timing!)
  - Recovery of UTC(USNO) via GPS
  - Timescale computation for 3 atomic standards (local Ensemble) that is steered to UTC(USNO)
  - Automatic Blink System (ABS) control based on out-of-tolerance (OOT) conditions, loss of clock, or extended loss of signal
  - Remote operation via TCP/IP standard protocol
- This set of specifications represented the ability to replace the antiquated timers in the field and enable new logistics for LORAN-C
  - Primary logistics emphasis in the areas of time-of-transmission and remote control
- Crossover technology (from timing industry) where appropriate
  - Direct digital synthesizer for precise control of clocks and signals
  - Timescale of 3 atomic clocks
- Most importantly, the design was a modular chassis with an FPGA engine and expansion capabilities

TFE 1.0: Critical Components



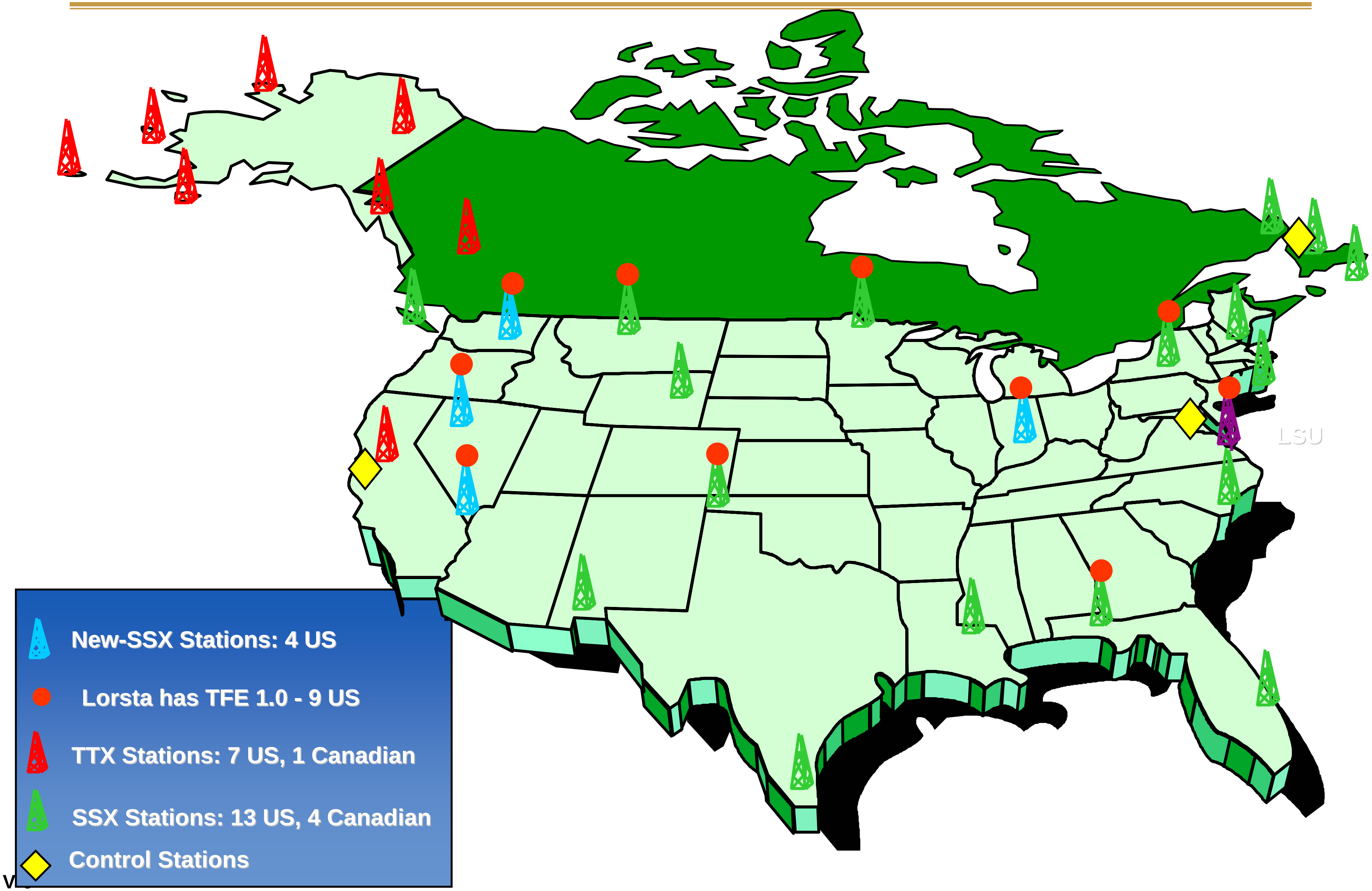
TFE 1.0 Function Set

- TFE 1.0 established the new baseline for timing, signal control, network operation and maintenance for LORAN-C
  - — Signal control, measurements and reporting all tied to the 3 clock timebase at each site (provides best architecture for generating and monitoring system performance)

Timing	Signal Control	Integrity & Availability	Maintenance & Operation
3 Clock Timescale	TOT Control via closed loop around xmitter	Traditional ABS	Remote Control Via IP Sockets
UTC Via GPS	sub-ns Signal Measurements	Redundant HW and SW w/ auto-switch	Built in test and real-time diagnostics
	Phase Adjusts via Freq Change (no steps)		

System is significant as it is the first large-scale timescale application (3 clocks timescale at each station)

TFE 1.0 Installation Status



Timeline for Change: TFE 2.0

- As TFE was developed, tested, and released, Enhanced LORAN began to evolve quickly and the requirement landscape began to change
  - Generation of the FAA report, LORIPP, LORAPP resulted in a technology sprint that pushed TFE forward
- The unprecedented attention that the LORAN architecture and implementation received resulted in the identification of new requirements for TFE
  - Data channel for communicating corrections to the users
  - GPS Independence to establish LORAN-C as a GPS backup
  - Continuing system improvements based on integration testing

TFE 2.0

- Before TFE was even installed at LORSTA George, Timing Solutions was developing a second release (TFE 2.0) to implement new functions and enable new capability
- TFE 2.0 included a few key additions that position Enhanced LORAN well for the future
  - Enhanced timescale that not only enables true GPS independence, but enables the USCG to create a distributed ensemble of 87 cesiums
  - Data communication to the LORAN-C users via Pulse Position Modulation
- TFE design consists of field programmable gate arrays (FPGAs) allowing changes in the digital design by downloading new code to existing hardware
  - Used as a tool to implement new capability into existing hardware baseline
  - Used as a troubleshooting tool for maintenance issues
- As a result of the open architecture, transition to TFE 2.0 is a firmware change only
  - LSU reaping the benefit of a cost effective architecture

TFE 2.0 Additions

- Enhanced Timescale Filter and Two-Way Time Transfer
- Pulse Position Modulation

Enhanced Optimal Timescale Filter

- TFE 1.0 has a 3 clock timescale that provided the standard advantages from a clock ensemble
  - Enhanced stability (by the square root of 3) over the single clock case
  - Enhanced flywheel performance via prediction routine that uses clock characterization history to minimize phase offset during GPS outage
  - Real time diagnostics on clock offset from the ensemble (phase and freq)

- Funding from other DoD programs continued the development of the timescale and added new functionality
  - Real time parameter estimation for adaptive clock weighting
  - Scalability to a network of clocks connected via periodic comms links
  - Inclusion of two-way time transfer data for GPS independence

- The addition of these new features enables two significant upgrade options for the LORAN-C network
  - Two-way time transfer front end for GPS independence
  - Network timescale of all USCG clocks for robust performance

GPS Independence

- Much of the argument for continuing LORAN-C hinges on the system's ability to provide a backup to GPS for navigation and timing users
- Current LORAN-C network has a dependence on GPS
  - System uses GPS to determine UTC and steer the clocks (with a long timescale)
  - Without GPS, clocks will slowly drift away from UTC
    - By grouping the clocks into a timescale, the drift is reduced to the point where specification could be maintained for weeks (loose dependence but still a dependence)
  - System can revert to "internal" mode where a received LORAN-C signal at each transmitting station is used to provide timing reference
    - Results in degraded performance due to noisier timing reference
- While dependence is significantly mitigated by the implementation, the perception of dependence is damaging to our ability to go forward as a true GPS backup

GPS Independence (cont'd)

- Two-way time transfer provides a high fidelity measurement of station timing offset that is truly GPS independent
  - Two-way time transfer has historically been used as a periodic calibration tool for high-end users
    - Sub-nanosecond measurement with custom hardware
  - Traditional two-way implementations are not cost effective and not extensible to network implementation

- Technology is emerging that makes two-way a reality for a wider range of users
  - Slightly lower performance (< 5 ns) at a much lower cost
    - Both the unit cost and the satellite bandwidth cost (less bandwidth required)

- Technology trend the result of a USAF program to transfer time via communications links to airborne platforms
  - Result of USAF development is that the USCG can field COTS units that can be maintained

Static Two-Way Satellite Time Transfer

- Static two-way time transfer involves making simultaneous time difference measurements between two fixed points on the earth

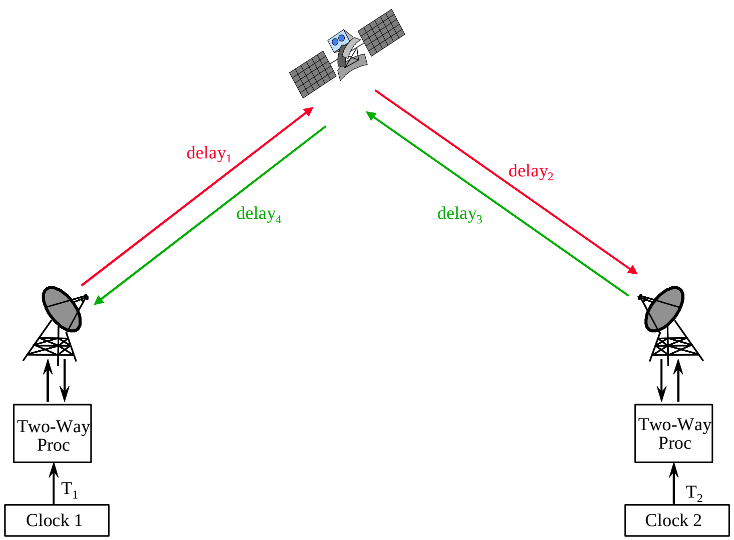
$Meas_1 = T_1 – (T_2 + delay_3 + delay_4 + Sagnac_{12})$

$Meas_2 = T_2 – (T_1 + delay_2 + delay_1 + Sagnac_{21})$

- In the static case, propagation delay to the satellite cancels and two-way equation reduces to:

$T_2 – T_1 = .5*(Meas_2 – Meas_1 + \Delta Sagnac)$

Where ΔSagnac is a time-of-flight measurement effect that is a constant

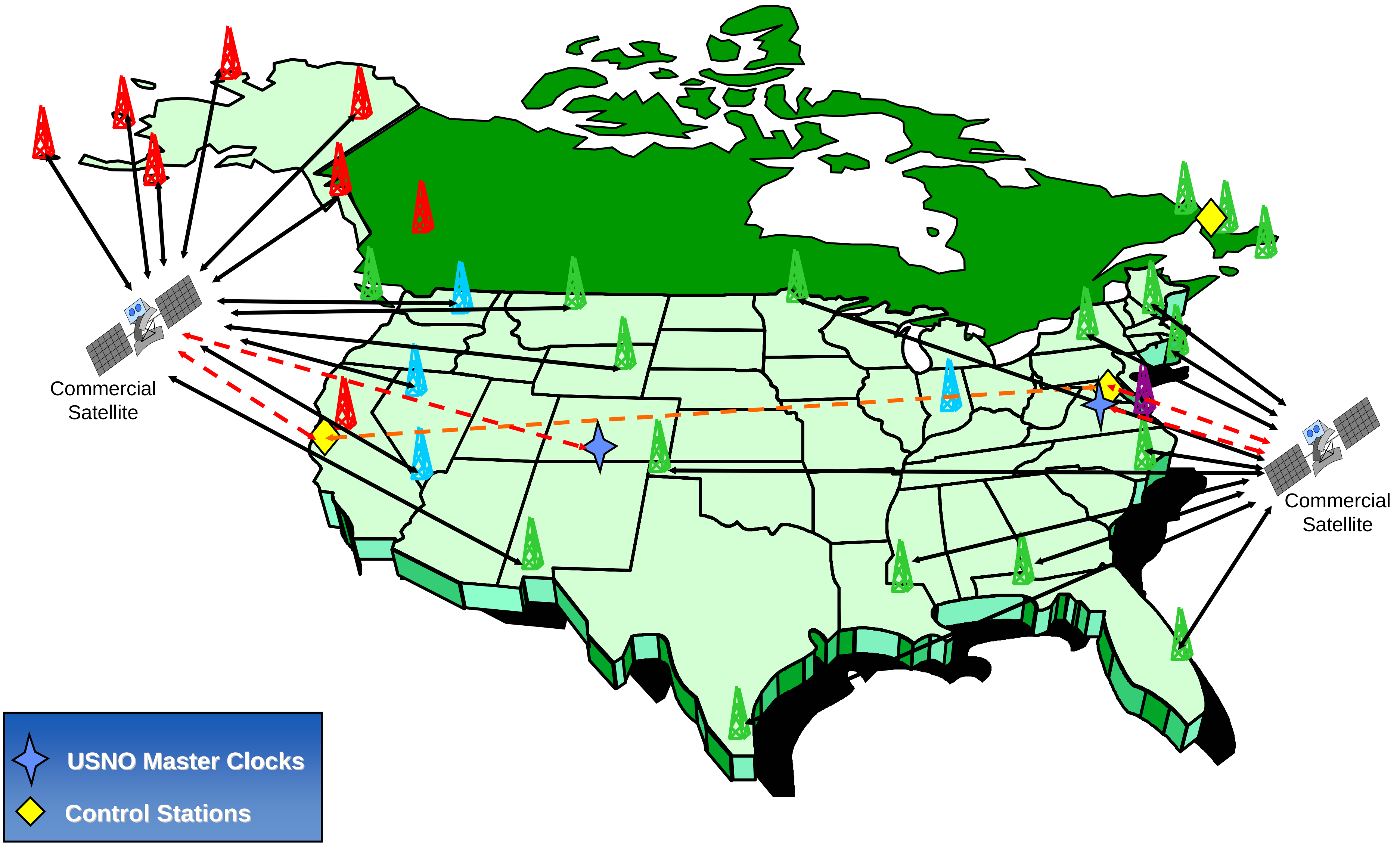


Two-Way Time Transfer provides the best point-to-point time recovery performance

Conceptual Two-Way Implementation

- Two-way time transfer will be implemented as a dual redundant system that mirrors the control system used in LORAN-C
  - Country divides roughly in half with west coast stations performing timing measurement with Petaluma and east coast stations with NAVCEN
- Petaluma and NAVCEN will have directly connectivity with USNO
  - NAVCEN will measure with respect to USNO
  - Petaluma will measure with respect to USNO(AMC)
- Data will be shared between NAVCEN and Petaluma
- Independent network clock ensembles will be computed at NAVCEN and Petaluma for all the LORSTA clocks
  - Each control station will compute the entire LORAN-C clock ensemble and report clock parameters for each clock at each LORSTA
- Robust architecture has no single point of failure and enables advanced timescale operations in the future
  - LORAN-C distributed timescale that would be of interest to other DoD programs

Loran System Ensemble Clock Concept



TFE 2.0 Additions

- Enhanced Timescale Filter and Two-Way Time Transfer
- Pulse Position Modulation

Pulse Position Modulation

- One of the critical features for Enhanced LORAN is to provide differential corrections with the received signal by modulating the position of the transmitted pulses to communicate data

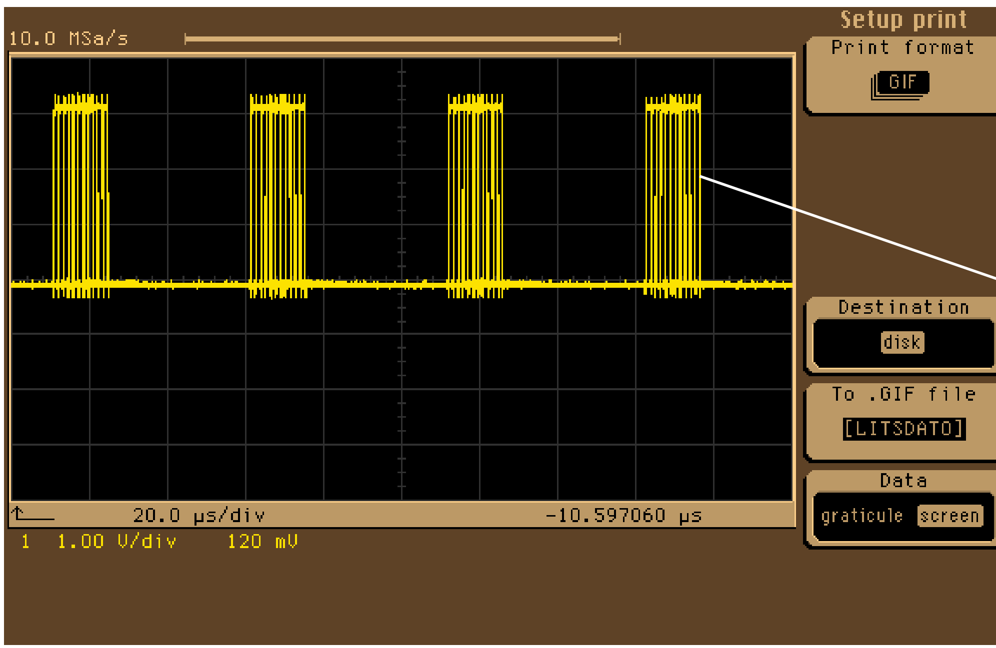
- With the existing TFE clocking scheme, the multi-pulse triggers can be arbitrarily moved with respect to the pulse code interval (PCI) based on data that is received via RS-232 or Ethernet
  - Multi-pulse triggers are pulses that command the transmission of a LORAN-C pulse
  - TFE is the right place to implement any changes to the triggers since they can be precisely controlled with respect to the timescale and measured for verification

- The initial USCG Loran Data Channel (LDC) approach involves adding a pulse whose position is modified based on a data stream that is constructed from a set of data messages
  - Additional pulse is 10th for masters and 9th for secondaries
  - Data messages include absolute timing information as well as differential corrections

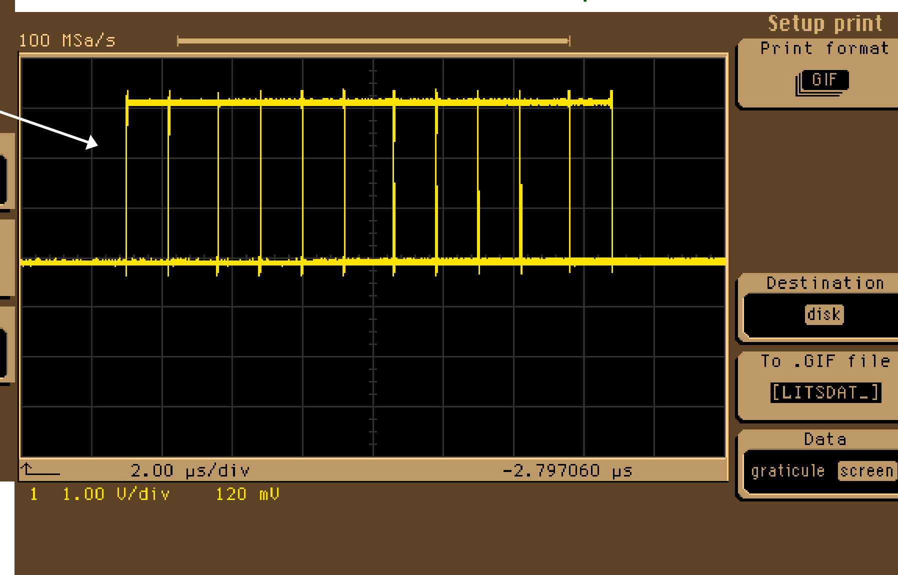
LORAN Data Channel Implementation

- USCG scheme for LORAN-C PPM implementation includes 4 groups of 8 states for 32 states per pulse
  - Pulse groups separated by ~50 microseconds
  - Pulses inside each group separated by ~1.2 microseconds

All 32 states for PPM pulse



Zoom View of one set of 8 pulses

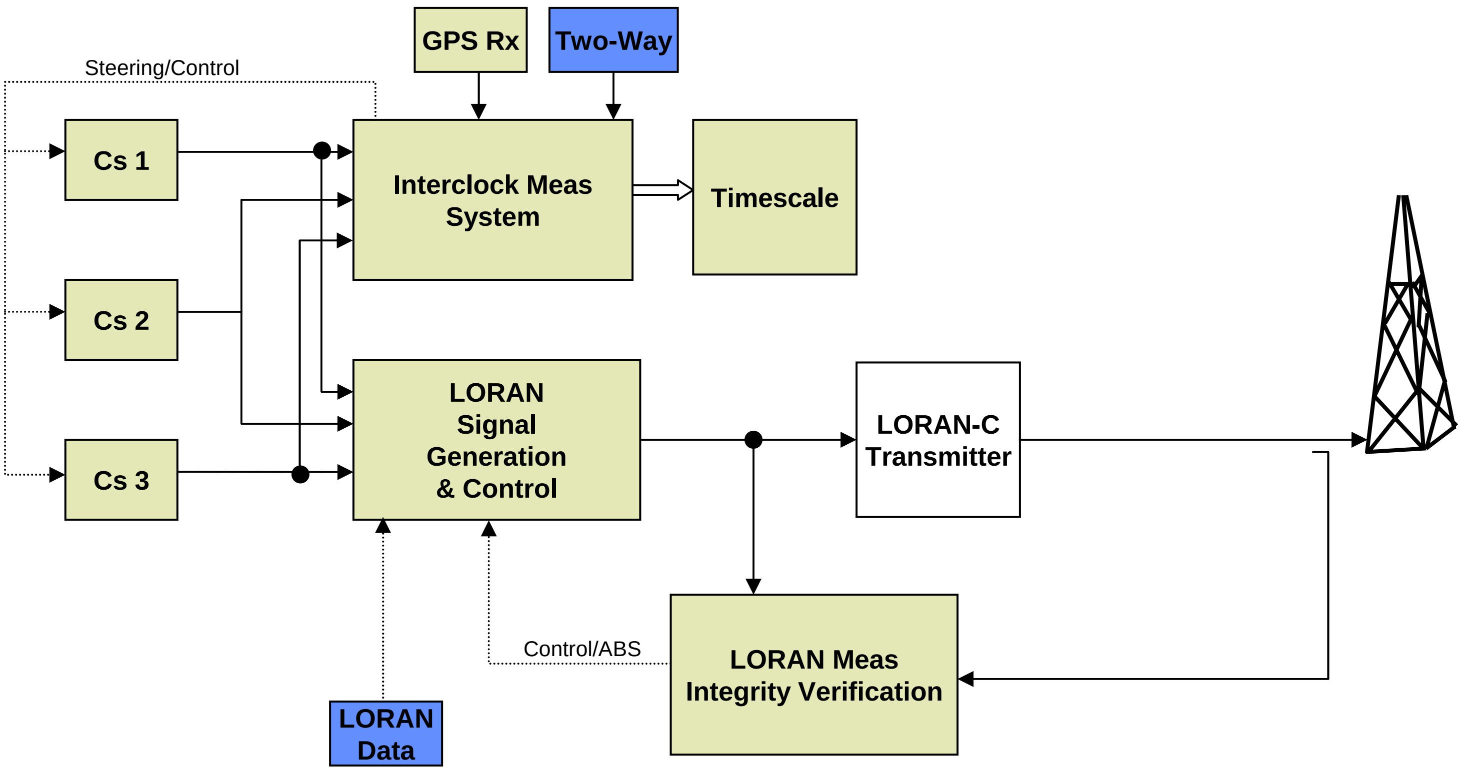


TFE 2.0 Function Set Additions

Timing	Signal Control	Integrity & Availability	Maintenance & Operation	Data
3 Clock Timescale	TOT Control via closed loop around xmitter	Traditional ABS	Remote Control Via IP Sockets	Data Channel via PPM
UTC Via GPS	sub-ns Signal Measurements	Redundant HW and SW w/ auto-switch	Built in test and real-time diagnostics	
Timescale Extensions for GPS Independence	Phase Adjusts via Freq Change (no steps)	Extended ABS		

- GPS independence and data capability are significant upgrades to the LORAN capability set
- ABS extensions are the result of LSUs continuous improvement process

TFE 2.0: Critical Components



Synergies

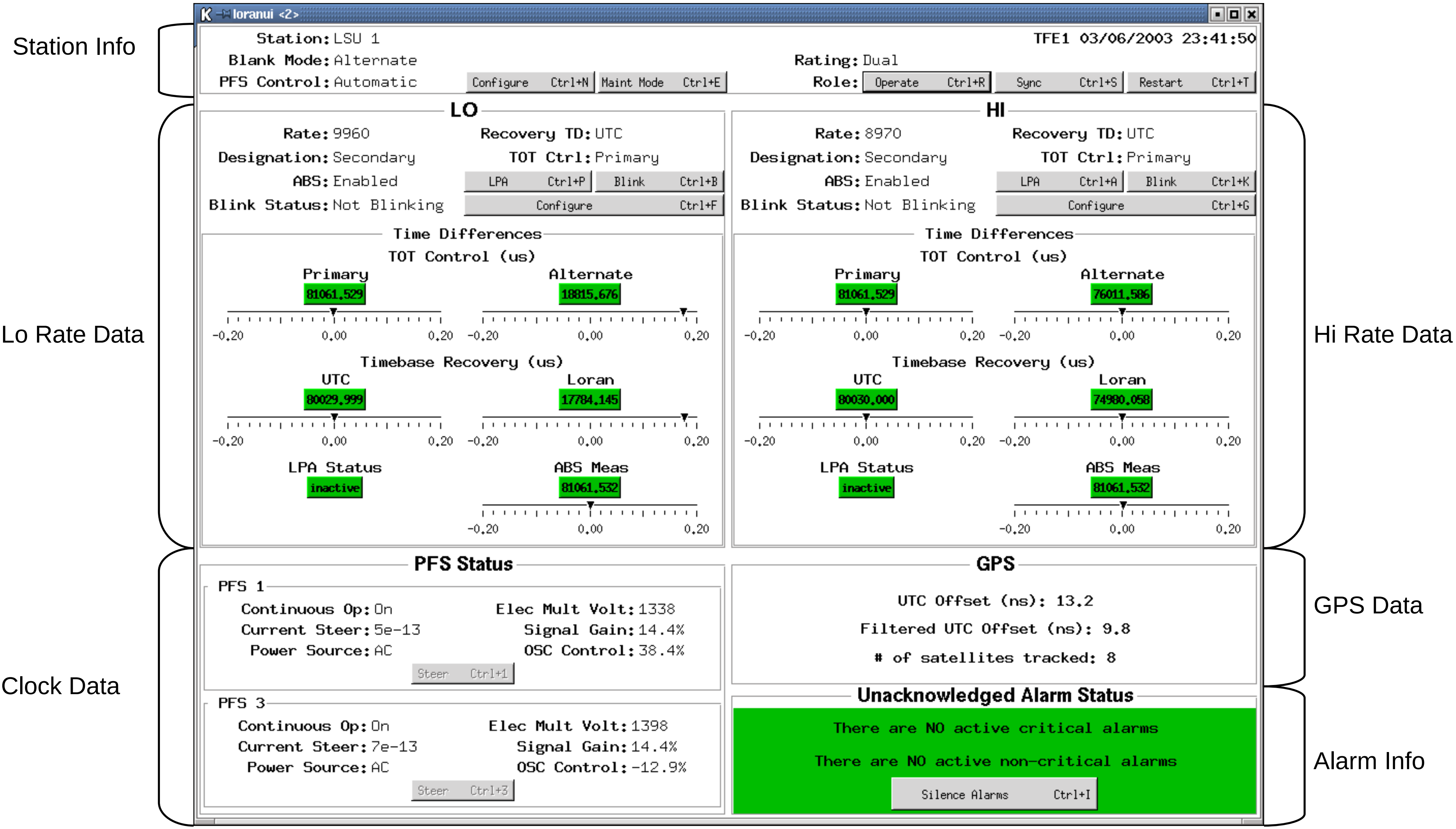
- Timing Solutions working with a group of US government agencies with a common interest in precision time
  - USAF, Intel Community, USCG, US Navy, NASA
- The overlap of program goals has enabled considerable value to each participant in the joint program
- USCG benefiting directly from the association
  - USCG inherits enhanced timescale from Navy and USAF work
  - USCG inherits COTS two-way time transfer modem from USAF work
- USCG also providing value to other participants
  - USCG has a network of geographically dispersed sites with atomic clocks that is of interest to other programs for advanced timing tests
- Many of the additions (current and future) to TFE are a result of this collaboration

Conclusions

- TFE 1.0 is fielded and operational at 50% of CONUS stations
  - Systems in 24/7 operation with no issues to date
- Evolution in TFE functionality continues via enhancements added in TFE 2.0 and beyond
  - Pulse Position Modulation
  - Timescale filter that supports two-way time transfer data
  - Enhanced LORAN foundation that can be modified via firmware to implement new parameters and techniques
- TFE 2.0 has been released to LSU for testing
  - Because of the significant additions, the release will require months of testing
- Coordination and teaming arrangements with other US Government organizations adding significant value to the program
  - USCG has forged new relationships with USAF, DoD Test Ranges and other programs that have raised visibility of USCG programs and created opportunities to expand LORAN-C user group

TIMING SOLUTIONS

TFE 2.0 GUI



GPS Holdover Example (Rb)

- By modeling the clock performance, the phase error that accumulates during holdover is significantly reduced
- Example below shows a Rubidium that accumulates 25 ns of phase error during a 24 hour GPS outage
  - — Rubidium with 1e-12 at 1 day would accumulate 90 ns of error
  - — For cesium, the errors are an order of magnitude smaller
    - » Native cesium is 8 ns and we would expect ~2ns