Time Transfer Using a Terrestrial Beacon System

A RESILIENT TIMING SOLUTION

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Agenda

Overview

Need for resilient timing

Terrestrial Beacon system

Two-way-time-transfer over large distances with multiple hops

Field trial results

Conclusions

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Overview

- Timing resiliency is critical for infrastructure
- Challenge: Time transfer over long distances of 50 to 100 Km presents an interesting challenge
  - The topography can change significantly over long distances resulting in varied environmental conditions between source and destination
- The NextNav terrestrial beacon network is designed to deploy “Leader” and “Follower” beacons to maintain relative time synchronization using two-way time transfer techniques (TWTT).
- NextNav demonstrates a functional, stable, and high precision timing system that can transfer time wirelessly over long distances.

SUBTITLE

Resilient Timing

- Timing has become critical for major infrastructure and requires a resilient timing system
  - Most of the timing systems utilize GNSS receivers to derive and provide timing information
- GNSS-based Timing systems are susceptible to the following problems:
  - Low GNSS signal strength creates constraints in antenna placement & cable calibration
  - Jamming: weak GNSS signals are prone to interference
  - Spoofing: various incidents have indicated that GPS system is vulnerable to spoofing which can cause more damage than undesired interference
- TerraPoiNT is a Metropolitan Beacon System (MBS) that provides a superior timing solution capable of overcoming the challenges associated with GNSS-based timing systems.

System Architecture

- Provides full position, navigation and timing capabilities in urban and indoor environments with or without the presence of GPS
- "Mission critical" reliability: support for an encrypted signal and resistant to spoofing/jamming
- Nationwide spectrum owner (920 – 928 MHz) – 95% urbanized POPs
- **Beacons** deployed throughout the coverage area and each beacon has a **steerable local oscillator** as its source of time and frequency
- Beacons share time with each other to maintain **relative synchronization** among themselves
- UTC sync to a small subset of beacons can be provided using:
  - Any absolute alternate timing source (eg., ToF, LEO satellite, TWSTT) and can also be maintained across outages using a local Cesium.
  - Or… holdover from GNSS maintained using local Cesium during GNSS outages
- **Signal is encrypted** to enable user authentication and to provide a level of spoofing protection

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Problem Definition and Proposed Solution

Problem

- **Relative sync requirement:** In order to provide positioning and navigation (PN) services, the terrestrial beacons must maintain accurate and precise time synchronization relative to each other in the presence or absence of GPS or any other time sources.
- **Absolute sync requirement:** Furthermore, in order to provide timing (T) services, all beacons must be synchronized to a universal time source such as NIST.

Solution

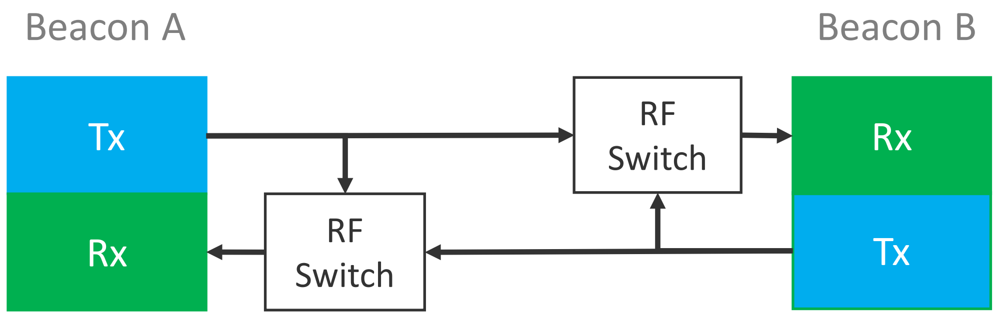
- Terrestrial beacon network is designed to deploy “Leader” and “Follower” beacons to maintain relative time synchronization using **two-way time transfer techniques (TWTT).**
- A “Leader” beacon has access to absolute time source and can provide time to all “Follower” beacons within its network.
- All Follower beacons maintain relative synchronization with Leader beacon enabling their time to be traced to the UTC time

Two Way Time Transfer

- Each beacon can estimate the time-of-arrival (TOA) of the signals from all beacons in its range as well as that of its own signal.

- It then subtracts the TOA of its own signal from those of all the other beacons and sends those time difference (TD) values to a centralized server.

- The centralized server estimates the time-error of each beacon using the TD information it receives from the beacons and provides feedback to the follower beacons enabling them to maintain synchronization to the leader beacon.



- TOA(X,Y) = TOA of Beacon X transmit signal measured by Beacon Y's receiver
- TP(X,Y) = Propagation delay from Beacon X to Beacon Y
- T(X) = transmit time of Beacon X
- RO(X) = time offset of the receiver in Beacon X

- Estimated at Beacon A:

  TOA(B,A) = T(B) + TP(B,A) + RO(A)

  TOA(A,A) = T(A) + RO(A)

- Estimated at Beacon B:

  TOA(A,B) = T(A) + TP(A,B) + RO(B)

  TOA(B,B) = T(B) + RO(B)

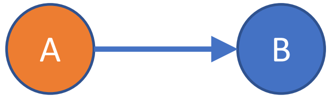
Single-hop TWTT

- TD value computed at Beacon A and sent to the server:

$$TD(A,B) = TOA(B,A) – TOA(A,A) = T(B) – T(A) + TP(B,A)$$

- TD value computed at Beacon B and sent to the server:

$$TD(B,A) = TOA(A,B) – TOA(B,B) = T(A) – T(B) + TP(A,B)$$



- Time error between the two beacons computed at the server:

$$TE(A,B) = (TD(A,B)-TD(B,A))/2 = T(B) – T(A) +(TP(B,A)-TP(A,B))/2$$

- The propagation channel between any pair of beacons is reciprocal in most cases. That means TP(A,B) and TP(B,A) have very similar values and the above time error estimate is unbiased.

Time Transfer Over Long Distances

- Time transfer over long distances of 50 to 100 Km presents an interesting challenge
  - The topography can change significantly over long distances resulting in varied environmental conditions between source and destination

- Time transfer over long distances requires multiple beacons and hops to ensure the beacons can precisely maintain time synchronization

- In the **terrestrial beacon network,** a follower beacon that is not in the radio coverage of any leader beacons can derive timing through intermediate follower beacons resulting in multiple hops from the leader beacon to that follower beacon
  - The mean of the time transfer error between a pair of beacons (one hop) can be positive or negative
  - When time is transferred **across multiple hops, the cumulative mean time error need not grow always**. However, the variance of time error grows as the number of hops increase

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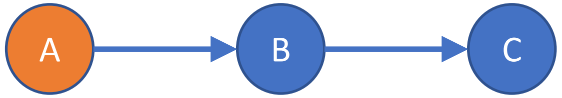
Multi-hop TWTT

- To transfer time to follower beacons that are not in the transmission/reception range of the leader beacon, the other follower beacons in the network are used as intermediate hops in order to transfer time over a path (i.e., chain) of beacons.

- For example, the time error calculations for a two-hop time-transfer path is shown below.



TE(A,B) = (TD(A,B)-TD(B,A))/2 = T(B) – T(A) +(TP(B,A)-TP(A,B))/2

TE(B,C) = (TD(B,C)-TD(C,B))/2 = T(C) – T(B) +(TP(C,B)-TP(B,C))/2

➡ TE(A,C) = TE(A,B) + TE(B,C) = T(C) – T(A) + (TP(B,A)-TP(A,B))/2 + ((TP(C,B)-TP(B,C))/2

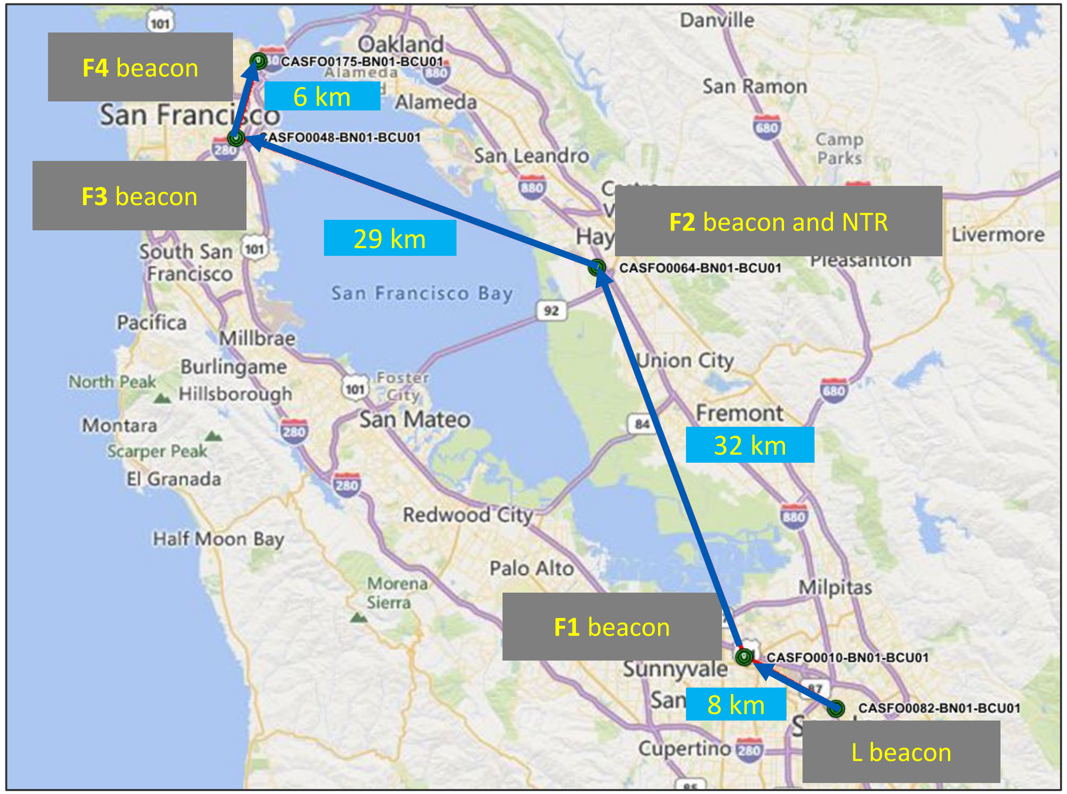
Time Transfer Demonstration

- **A network of 5 beacons**
  - One leader beacon (L) and four follower beacons (F1 to F4)
  - Total of 75km with just 5 beacons

- **NextNav Timing Receiver (NTR)**
  - Provides HW based PPS + 10MHz + time of day (TOD) message including residual time corrections
  - Automatically selects the best beacon signal for extracting timing & can be located anywhere in network
  - Located at the site - Beacon F2
  - Configured to track Beacon F4 as its “preferred” source of time
  - Time is transferred from the network to NTR using One-Way-Time-Transfer

- To measure the beacon timing performance in this demonstration, an absolute time source (GPS) is used at each beacon as truth time

Beacons and Timing Receiver Locations



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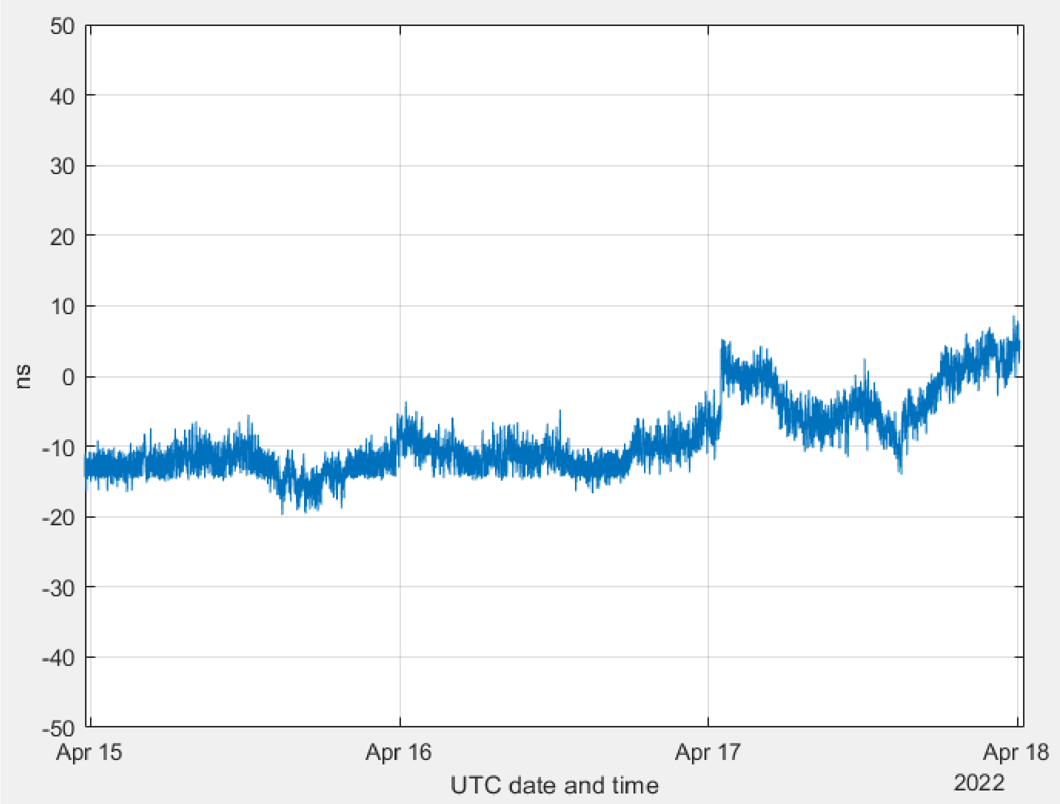
Leader Synchronization Performance

- Leader beacon was provided with an absolute time source synchronized to UTC
  - This source can be any of absolute sources like GPS, Time-over-fiber, LEO-based
  - The time information is used to discipline the leader beacon's oscillator
- The leader's time was compared with GPS time to determine the timing accuracy.
- Results show that the leader beacon can maintain sync with UTC to within 20ns across multiple days.
- The high frequency noise in this plot is mainly due to the jitter in the GPS receiver's clock and not the beacon clock itself.

Leader beacon time error relative to GPS time

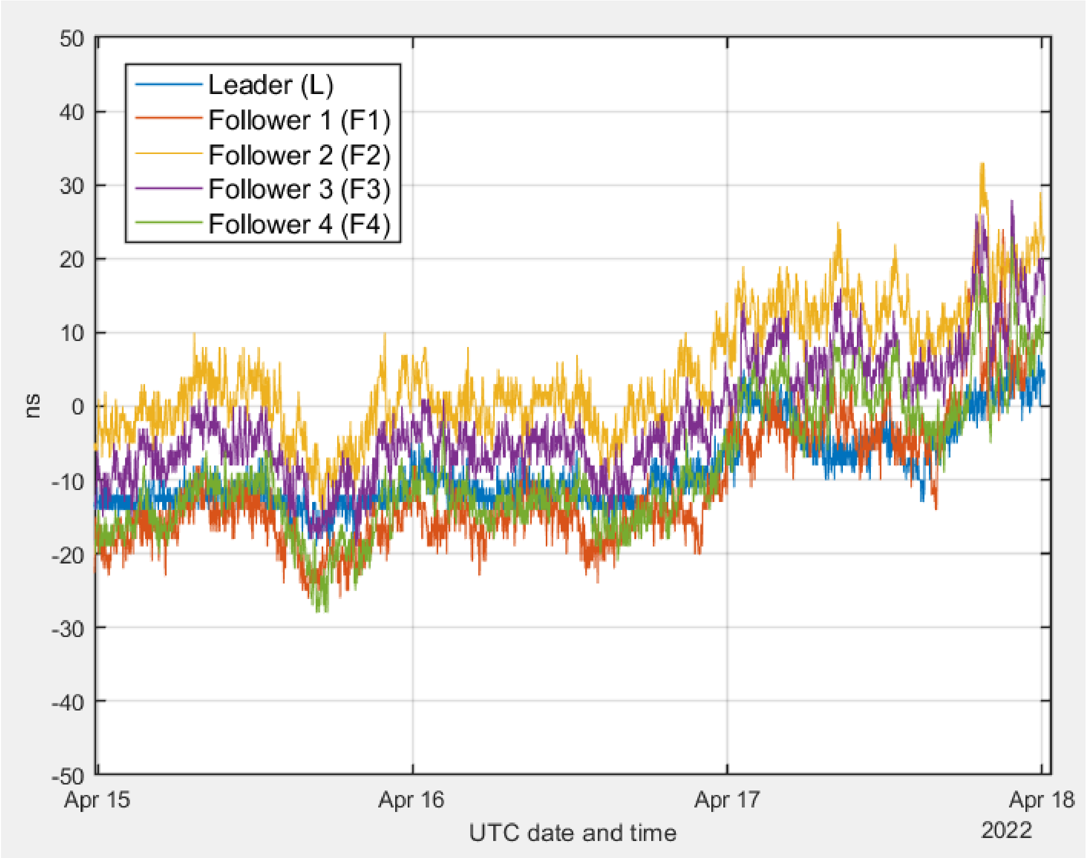


Network Synchronization Performance

Absolute sync performance

- Follower beacons maintain relative synchronization with the leader beacon enabling them to have time synchronized to UTC
- The time errors of all beacons are measured relative to GPS time.
- Results show that beacons can maintain absolute time synchronization within +/- 30ns of the UTC
- Again, the high frequency noise in these plots is mainly due to the jitter in the GPS receiver clocks and not the beacon clocks themselves.

Network time error relative to GPS time



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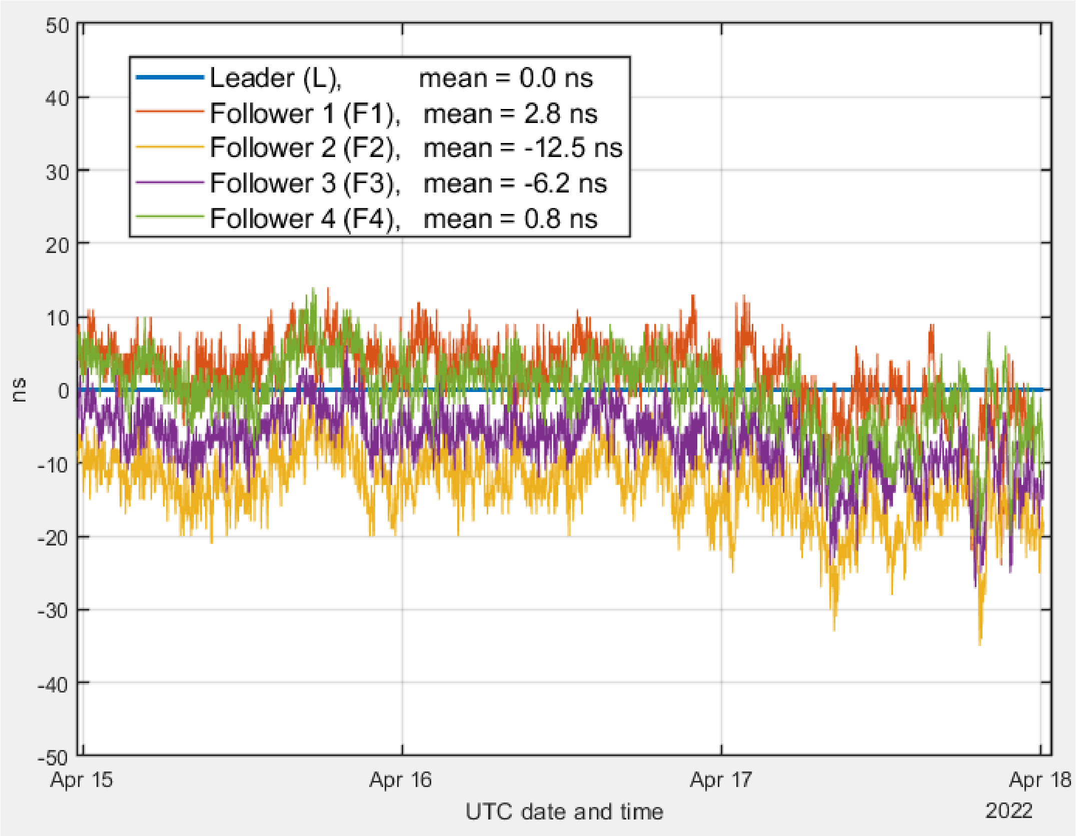
Network Synchronization Performance

Relative sync performance

- This figure shows the time error of the follower beacons relative to the leader beacon.
- The magnitude of the average relative error ranges between 0.8 ns (Follower 4) and 12.5 ns (Follower 2)
- The non-zero mean values are mainly due to residual calibration errors and not multipath fading

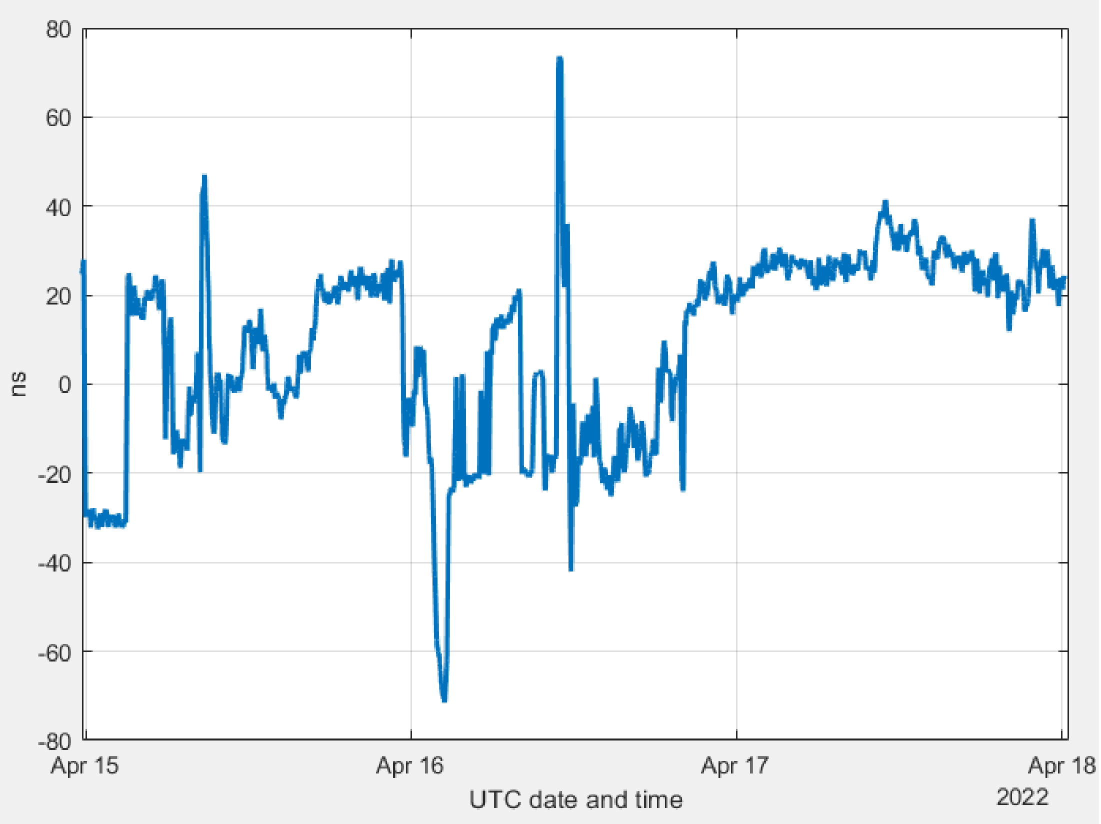
Network time error relative to leader time



Timing Receiver Synchronization Performance

- NTR's sync performance was measured by comparing its output PPS phase against the PPS phase of the GPS receiver onboard Beacon F2 using a TIC.
  - NTR was configured to have Beacon F4 (the last beacon in the TWTT chain) as its "preferred" source of time.
  - However, it was allowed to switch to other beacons depending on some quality measure of the derived time
- The results show that the **NTR can maintain time within +/- 40ns, 95% of the time**.
  - This indicates that the terrestrial beacon system can provide accurate and precise time over large distances without the need for an absolute time source at each beacon.
- The large jumps in the NTR time error are a result of the switching between beacons and the fact that different beacons are seen with different multipath excess delays (time transfer to NTR is one-way and multipath delay cannot be removed)

NTR time error relative to GPS time



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Conclusions

- Demonstration showed time synchronization of a wide area network through wireless time transfer techniques over long distances using a functional, stable, and high precision Terrestrial GPS-free timing system in a real-world environment.

- Showed that terrestrial beacon timing distribution network can be easily scaled over a large geographical area using a small number of beacons without significant loss in performance