On the Uses of High Accuracy eLoran Time, Frequency, and Phase

RIN INC, Manchester, England
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President & CEO
UrsaNav, Inc.
The Problem:
- We need time all the time!
- Focused Example: Telecommunications Industry

The Alternatives

The Solution:
- Co-Primary / Complementary GPS and eLoran

Solution Basics

Wide Area and Local Area Technology

Early Trials

Conclusions and Future Work

Questions, and possibly answers.
“All in all, what is fascinating about the telecommunications ecosystem of 2014 is that mobile is on the leading edge of innovation that crosses virtually every industry and sector, and is a key engine of economic growth for the [U.S.]”

We are Addicted to Speed and Connectivity!

Source: Craig Wigginton, vice chairman and U.S. Telecommunications leader, Deloitte & Touche
The Problem: Pressures

- Ever expanding networks – more nodes (“hops”)
  - Macro, micro, pico, femto

- More complex networks
  - GM, Edge GM, Boundary Clock, Transparent Router, Ordinary Slave Clock, Primary Reference Time Clock
  - Evolving protocols
  - Mix of delivery mediums: copper, optical, wireless

- Increasing demand on networks
  - Voice
  - (Big) data
  - (Streaming) video
  - Cloud
  - Security
  - Spectrum availability and optimization
Mobile payment systems
- Near-Field Communications
- Apple Pay
- CurrentC

Personal & Professional Vertical Market Growth
- Health care
- Education
- Automobile
- Home
- Tourism

- Machine-2-Machine (M2M)

Source: Craig Wigginton, vice chairman and U.S. Telecommunications leader, Deloitte & Touche
<table>
<thead>
<tr>
<th>Application</th>
<th>Frequency Network /Air</th>
<th>Phase</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM, UMTS, WCDMA, LTE - FDD</td>
<td>16 ppb / 50 ppb</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CDMA2000</td>
<td>16 ppb / 50 ppb</td>
<td>± 3 µs to ± 10 µs</td>
<td>--</td>
</tr>
<tr>
<td>LTE - TDD</td>
<td>16 ppb / 50 ppb</td>
<td>± 1.5 µs</td>
<td>&lt; 3 km cell radius</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 5 µs</td>
<td>&gt; 3 km cell radius</td>
</tr>
<tr>
<td>LTE MBMS (LTE-FDD &amp; LTE-TDD)</td>
<td>16 ppb / 50 ppb</td>
<td>± 10 µs</td>
<td>inter-cell time difference</td>
</tr>
<tr>
<td>LTE - Advanced</td>
<td>16 ppb / 50 ppb</td>
<td>± 1.5 µs to ± 5 µs</td>
<td>In discussion by members of the 3GPP</td>
</tr>
</tbody>
</table>
# The Problem: Shrinking Time

## Table 1: LTE and LTE-A Requirements

<table>
<thead>
<tr>
<th>Application</th>
<th>Frequency/Air Interface</th>
<th>Time/Phase</th>
<th>Why You Need to Comply</th>
<th>Impact of Non-compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE (FDD)</td>
<td>16 ppb/50 ppb</td>
<td>N/A</td>
<td>Call initiation</td>
<td>Call interference</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dropped calls</td>
</tr>
<tr>
<td>LTE (TDD)</td>
<td>16 ppb/50 ppb</td>
<td>±1.5 μs</td>
<td>Time slot alignment</td>
<td>Packet loss/collisions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Spectral efficiency</td>
</tr>
<tr>
<td>LTE MBSFN (TDD or FDD)</td>
<td>16 ppb/50 ppb</td>
<td>±500 ns</td>
<td>Proper time alignment of video signal decoding from multiple base transceiver stations</td>
<td>Video broadcast interruption</td>
</tr>
<tr>
<td>LTE-A (TDD or FDD) CoMP/MIMO</td>
<td>16 ppb/50 ppb</td>
<td>±500 ns</td>
<td>Coordination of signals to/from multiple basestations</td>
<td>Poor signal quality at edge of cells</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Location-based services accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower data speeds</td>
</tr>
</tbody>
</table>

Source: electronic design magazine
**Reviewing the Alternatives for Time**

**GPS.**
GPS is the global, gold standard for PNT. When it is available and trustworthy, you should always use it first. GPS is cheap. Making it reliable and resilient is expensive. Multi-frequency (L1, L1M, L2, L2C, L2M, L5) does not make GPS “sole means”. SAASM and M-Code do not help civilian users. No built-in integrity.

**Oscillators.**
Holdover only. Not a co-primary source. Require external reference input (usually GPS). Many OCXO’s are temperature sensitive. Rb is more expensive than OCXO, but less expensive than Cs. Cs is superb, but is expensive, big, and heavy. CSAC?

**IEEE 1588 (PTPv2)**
Grandmaster sources time from GPS or Cs.

**GNSS (GLONASS, CNSS, Galileo).**
Even GNSS experience failures. More satellites result in increased noise floor. Same vulnerabilities as GPS.

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**HOLDOVER PERFORMANCE**

<table>
<thead>
<tr>
<th>Oscillator</th>
<th>Phase ±1.5 μsec</th>
<th>Phase 5 μsec</th>
<th>Phase 10 μsec</th>
<th>Freq 16 ppb</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCXO</td>
<td>1 hour</td>
<td>4 hours</td>
<td>12 hours</td>
<td>1 month</td>
</tr>
<tr>
<td>Rubidium</td>
<td>24 hours</td>
<td>3 days</td>
<td>5 days</td>
<td>5 years</td>
</tr>
</tbody>
</table>

Holdover values are approximate and assume operation at constant temperature, no initial frequency or phase offset, and that the units have been powered on for 2 weeks and locked to GNSS for three consecutive days.
Key characteristics

- **High power** (~ 150 kW to >1 MW)
- **Low frequency** (100 kHz)
- **Pulse shaped signals** allow groundwave - skywave separation
- **Data channel** to provide UTC information, differential corrections, and integrity information
- **Long range** (>1,000 miles) coverage
- **No common failure modes** with GNSS
- **Provides the same information as GNSS** (time/phase, frequency, position, heading)
Each transmitting site synchronized to UTC using “ensembling” of technologies and methods
  - Three Primary Reference Standards
  - “Sky-Aided”
    - GNSS input(s), when available; not directly coupled
    - TWSTT input from UTC source; not directly coupled
  - “Sky-Free”
    - Two-Way Low-Frequency Time Transfer (TWLFT)
- Differential corrections for improved accuracy
  - Differential Loran (dLoran)
- All-in-View signals
- No “chains” or “grid warping”.
- Data Messaging Service (relatively low rate – one way)
  - Additional integrity
  - Other differential corrections (e.g., dGPS)
  - Other secure communications
## The definition of complementary: GPS & eLoran

<table>
<thead>
<tr>
<th>Parameter</th>
<th>eLoran</th>
<th>GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>100 kHz</td>
<td>1.2-1.5 GHz</td>
</tr>
<tr>
<td>Propagation</td>
<td>Groundwave</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>Propagation Error</td>
<td>Conductivity, tropo variations</td>
<td>Iono delay variations*</td>
</tr>
<tr>
<td>Penetration</td>
<td>Walls, ground, 6' seawater</td>
<td>Very little penetration</td>
</tr>
<tr>
<td>Modulation</td>
<td>TD + CD</td>
<td>Spread spectrum CD</td>
</tr>
<tr>
<td>Rx Signal Strength</td>
<td>Relatively high</td>
<td>Very low</td>
</tr>
<tr>
<td>Timing Basis</td>
<td>Three Cs</td>
<td>Up to four Cs or Rb</td>
</tr>
<tr>
<td>Tx Location</td>
<td>Ground - stationary</td>
<td>Space - moving</td>
</tr>
<tr>
<td>Data Channel</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

* Propagation errors are affected at different times and places by components of solar storms.
* GPS propagation variations are not correlated with Loran-C or eLoran propagation errors.

**eLoran:** Interoperable, “integratable” with GNSS / INS / SAG / Augmentations / etc.

Seamless PNT for users.

Provides much, much better than 250 ns timing accuracy over long distances, without the use of differential corrections.

With differential corrections, provides better than 50 ns timing accuracy.

**eLoran and GPS:** Stratum-1 frequency sources.

Provide UTC aligned 1 PPS, Time of Day, 10 MHz receiver output.
The Foundation for eLoran Already Exists

Norway
Denmark
UK
Germany
France
Wide Area Timing from the Transmitting Site

“Sky-Aided”
Remote Time Scale:
TWSTT
GNSS

“Sky-Free”
Remote Time Scale:
TWLFTT

Local Time Scale:
Triple (disciplined) 5071A Primary Reference Standards

“Sky-Aided”
Remote Time Scale:
TWSTT
GNSS

“Sky-Free”
Remote Time Scale:
TWLFTT

Local Time Scale:
Triple (disciplined) 5071A Primary Reference Standards
- User is equipped with a receiver that has a stored Additional Secondary Factor (ASF) chart / map
- Corrections for the area of operation calculated at a fixed site
- Correction info sent to transmitter for broadcast via data channel
- Corrections can be applied by receiver and are monitored for integrity
Locally Improved Timing via dLoran: Technology

- **Display**
- **Triple Rack-Mount 1u UN-154 differential eLoran RSIMs**
  - Configurable as Reference Station (RS) or Integrity Monitor (IM) or Hot Standby (RS or IM)
  - Contains eLoran Receiver, Kontron CPU, and SSD
  - E-field antennas for each of the three UN-154s
- **Server with three years of storage capability**
- **KVM**
- **UPS**

dLoran Reference Station System
- GLAs have installed Differential eLoran Reference Stations at seven harbors along the UK East Coast
- RSIMs generate corrections for eLoran maritime **navigation** to enable 10-meter positioning accuracy to mariners
- Initial Operating Capability announced in 2014
GLAs system performance model of predicted versus actual accuracy.

Measured data can be compared to predicted. Data shown analyzed for a one week period (5 sec TOA integration, 600 sec dLoran correction integration, dLoran update rate of 120 sec).
GLAs system performance model of predicted versus actual accuracy.

Measured data can be compared to predicted. Data shown analyzed for a one week period (5 sec TOA integration, 600 sec dLoran correction integration, dLoran update rate of 120 sec).
- UN-155 Resilient PNT Receiver
  - GPS/DGPS/eLoran
  - Dual band (100/300 kHz) E-Field antenna
  - Custom user interface
- USB ports to access stored data
- Includes a UN-152 eLoran Timing receiver
  - Receiver oscillator disciplined by signals from Lessay Loran transmitter

- Reference Station eLoran antenna
- Zero-baseline Monitor eLoran antenna
- GPS antenna to provide independent source of UTC
  (Both Reference Station and Zero-baseline Monitor use the same GPS as a UTC reference)

Initial Rover data collection started to assess the spatial decorrelation of ASFs and Differential Corrections
Initial Rover Receiver Results

- No ASF map used; only corrections from Reference Station applied
- Short duration (20 minutes) measurements
- Measured offsets within expected range of ASF change
- Receiver oscillator disciplined by signals from Lessay Loran transmitter

<table>
<thead>
<tr>
<th>Location</th>
<th>Measured Offset (Std)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bertem</td>
<td>-7 ns (14.4 ns)</td>
</tr>
<tr>
<td>Location 1 (25 km)</td>
<td>118 ns (  8.5 ns)</td>
</tr>
<tr>
<td>Location 2 (50 km)</td>
<td>-57 ns (  8.5 ns)</td>
</tr>
<tr>
<td>Location 3 (75 km)</td>
<td>270 ns (  6.7 ns)</td>
</tr>
</tbody>
</table>
Zero Baseline Data

1PPS Difference between eLoran (UN-152) and GPS (NovAtel)

Zero-baseline before application of differential corrections

- Raw Data as measured by reference station
- Mean value of the data set is: -314.7 ns
- Standard deviation is: 20.2 ns
Zero-baseline after application of differential corrections

- Corrections based on 10-minute observation intervals, sent over the LDC every two (2) minutes
- Mean value of the data set is: -7.3 ns
- Standard deviation is: 14.4 ns
Zero-baseline performance with differential corrections applied from 29 Jan 17:00
Recent Activity and Results

Performance of Rover in Linden (10 km from Reference) before and after differential corrections applied, from 29 Jan 17 PM
Former, still operating, Northern European Loran System (NELS) stations shown.

New eLoran station at Anthorn, UK shown.

Former, dismantled, Southern European Loran System (SELS) transmitting sites in Spain, Italy, and Turkey shown only for illustrative purposes.

Very conservative 500 mile radius circles.

Each overlap adds redundancy and resiliency.
- We implemented a very basic Differential eLoran service for Timing, Frequency, or Phase applications.

- We applied rudimentary Differential Corrections that removed diurnal variation.

- Because ASF maps are not available in Belgium yet, we used a one-time calibration to approximate ASF data at our Reference Station Site.
  - Differential Corrections are applicable over larger distances, but application of an ASF map (or one-time calibration) is needed to eliminate the offsets caused by different nominal ASFs at different locations (i.e., Reference and Rover sites).

- Even with an experimental version dLoran trial, we were able to show the considerable timing accuracy available to Critical Infrastructure / Key Resource sectors, such as the telecommunications ecosystem.
Future Work

- Develop an ASF survey at selected trial locations within a 100 mile radius of our Reference Station (i.e., 10, 25, 50, 75, and 100 miles).
- Find the midpoint ASFs for these selected trial locations.
- Perform more comparisons between E-Field and H-field antennas to determine which is best for timing, phase, and frequency.
- Incorporate additional terms into our model, such as dew point, to improve the ability to manage weather effects.
- Perform measurements around dLoran Reference Station Sites in the UK.
- Once we have been granted another Cooperative Research and Development Agreement (CRADA) with the U.S. Government, Department of Homeland Security, restart trials in the CONUS.
Acknowledgements

- Thanx and acknowledgement to Martin Bransby, Dr. Paul Williams, and Chris Hargreaves of the General Lighthouse Authorities of the United Kingdom and Ireland (GLA) for their inputs to this presentation.

- Thanx to the GLAs for allowing UrsaNav to trial differential UTC corrections from the transmitter at Anthorn, Cumbria, UK.

- Thanx also to the UrsaNav team of Dr. Gerard Offermans (Belgium); and Steve Bartlett, Andrei Grebnev, and Erik Johannessen (USA).

Thank-you for your attention.

Questions, and possibly answers?