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A Low Frequency Terrestrial Positioning System for Operational Positioning, Navigation, Timing & Data

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ABSTRACT

The USAF Chief of Staff, General Norton Schwartz, recently stated: “It seemed critical to me that the joint force reduce its dependence on GPS.” GPS is inherently vulnerable to interference, disruption, jamming, and spoofing, whether intentional or otherwise. Terrestrial-based, Low Frequency (LF) Position, Navigation, Timing, and Data (PNT&D) systems have required a large footprint, significant infrastructure, expensive equipment, and costly O&M. New LF systems are technologically-advanced and provide a low-cost alternative to lessen the dependence on GPS.

In this paper we present an innovative, small footprint, Terrestrial Positioning System (TPS) based upon eLORAN that is cost-effective, easily transportable, and rapidly-deployable. The system can be used as a standalone site or in conjunction with existing sites, other deployable sites, or other PNT&D technologies. We discuss all aspects of the system and present the design, development, and field test results of a deployment.

We show that our system is significantly smaller and more economical than previous generations. The technology is state-of-the-art, robust, reliable, and affordable, and represents a quantum leap forward in meeting the strict requirements for operational PNT&D. Without a doubt GPS, when available, should remain the first choice. However, alternative PNT&D solutions are invaluable and our system makes land-based LF a more viable solution in GPS challenged and denied environments.

eLORAN: History & Application

eLORAN AND ITS USES

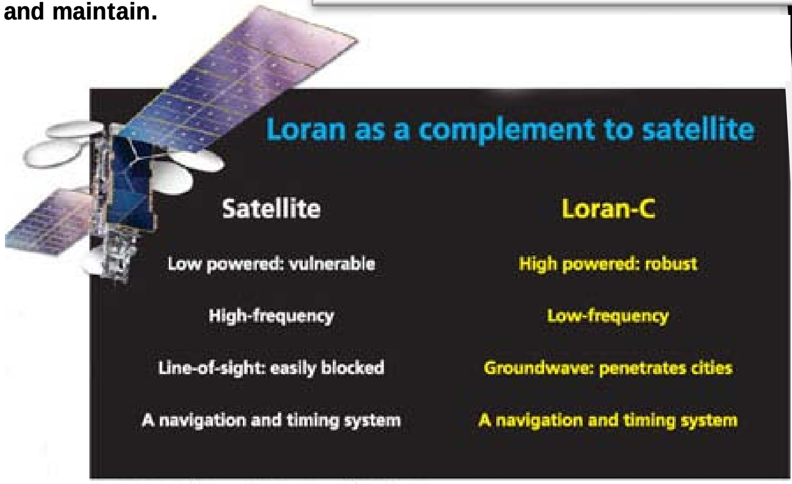
Enhanced LOng RAnge Navigation(eLORAN), or eLORAN, is a modernized, vastly improved version of LORAN-C or “standard” LORAN that was initially developed in the 1940’s. eLORAN is a Low Frequency (LF) system that uses terrestrial-based stations to provide users with accurate, all-weather Position, Navigation, Timing, and Data (PNT&D) services independent of, and complementary to Global Navigation Satellite Systems. Although not as precise as GPS, **tests have indicated that eLORAN meets or exceeds the accuracy, availability, integrity, continuity, and coverage requirements necessary to achieve 8-20 m maritime Harbor Entrance Approach (HEA) and aviation RNP 0.3 nm Non-Precision Approach (NPA) levels of performance.**[1] LORAN is currently operated by 15 countries and existing LORAN stations are capable of providing signal coverage at 72% of the world’s 50 largest ports, concentrated in the north hemisphere.

Despite the findings regarding LORAN’s value as a backup to GPS, the United States Coast Guard (USCG) terminated the United States LORAN-C signal on February 8, 2010. In its continuing efforts to assess the need for a domestic national system to serve as a backup to GPS, we are confident the U.S. Department of Homeland Security will conclude eLORAN, or a similar LF-based system, will be needed. In this case, the results and findings of our work will provide significant benefits in implementing a technologically-advanced, cost-effective system to mitigate the effects of a degradation or loss of GPS service.

PREVIOUS SMALL FOOTPRINT SYSTEMS

The idea of small footprint LORAN systems is not new. There have been several historic efforts to deploy versions of LORAN to support military missions, provide an additional aid for maritime navigation, and for various “tactical” reasons. LORAN-D, the Air Transportable LORAN System (ATLS), the St. Mary’s River LORAN-C Mini-Chain, and Racal Positioning Systems’ Pulse/8 are all such examples. However, technology has significantly improved since the last small footprint LORAN system was phased out of service in the mid 1980s. This inspires a renewed effort to explore LF systems for providing reliable PNT&D services in support of GPS.

Traditional LORAN Stations (LORSTA) have required significant infrastructure, personnel, and support to operate and maintain.



REQUIREMENTS FOR A SMALL FOOTPRINT eLORAN SYSTEM

A small footprint eLORAN system would be capable of providing fixed, en-route, and terminal PNT&D solutions to government and commercial users at a lower cost than installing a fixed system. Some of the basic requirements include:

- **Rapid installation and de-installation (temporary or tactical solution),**
- **Small Size, Weight, and Input Power (SWAIP) requirements,**
- **Significantly lower cost than a fixed system,**
- **Ease of use that supports unmanned operation,**
- **The capability for autonomous operation,**
- **Piece-wise equivalent to a fixed system in signal specification and enhanced transmission formats,**
- **No, or very limited, external cooling,**
- **An easily deployable configuration, and**
- **Equivalent reliability and robustness to a fixed system.**

DID YOU KNOW?

Several countries have identified eLORAN as the best backup for all modes of transportation.[2] **The U.S. Government’s own reports have concluded that eLORAN is the best backup and means to mitigate the impact of a GPS outage because eLORAN is independent, complementary, and seamless across all modes: aviation, maritime, location-based, land-mobile, and precision timing/ frequency.** [3],[4],[5],[6]

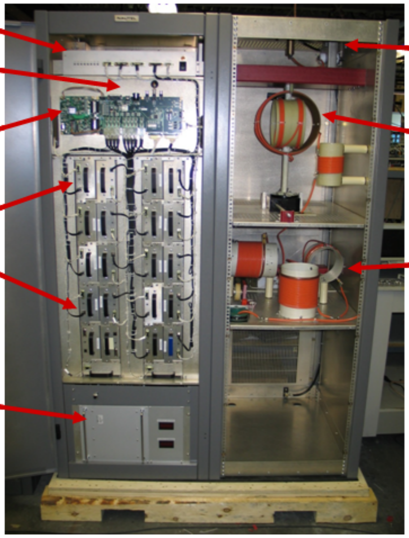
Defining the Small Footprint / Tactical eLORAN System

OVERVIEW OF THE SMALL FOOTPRINT eLORAN SYSTEM

A typical small footprint eLORAN system or eLORAN-in-a-box (ELB) solution consists of the following components or “suite” of systems:

- **Appropriately sized transmitter,**
- **Time Recovery and Signal Generation equipment,**
- **Command, Control, and Communications capability,**
- **Ancillary equipment (i.e., HVAC),**
- **Backup/uninterruptible power,**
- **Transmitting antenna, and**
- **Equipment enclosure, container, or other adequately sized shelter.**

If commercial prime power is not available, then prime generator, or combined power generation would most likely be housed in an appropriately sized separate mini-storage container, such as a QUADCON or TRICON.



Nautel NL Series Proof-of-Concept Transmitter

Nautel NL40 Production eLORAN Transmitter

PROOF OF CONCEPT TRANSMITTER DEVELOPMENT

UrsaNav has worked with Nautel, Inc. to develop LF transmitters that eclipse currently available technology. The challenge was how to transmit low frequencies into physically short antennas while considerably reducing SWAIP. The solution was the Nautel LORAN (NL) Series transmitter which uses a Class D RF amplifier incorporating Nautel’s patent pending pulse power recovery technique. With an overall efficiency typically 70% or better, reflected energy is recycled, thereby reducing input power, cooling, and ventilation requirements and associated costs making it extremely cost effective to own and operate.

In April 2008, we successfully tested a 50 kW Effective Radiated Power (ERP) proof-of-concept transmitter at Nautel’s facility in Halifax, NS. The transmitter was tested at over 600 Pulses-Per-Second (PPS) into a simulated 625-ft TLM antenna on combinations of several LORAN rates. In May 2008, the NL Series transmitter was independently tested by Alion Science & Technology, Inc., in support of the USCG Academy, and Peterson Integrated Geopositioning, at the USCG LORAN Support Unit (LSU) in Wildwood, NJ.

NL SERIES TRANSMITTER

The final production design of the NL Series transmitter was unveiled in October 2009. The NL Series combines 24 hot-swappable RF modules in each power cabinet. The modules are configured as 20 active, two spare, and two damping. The NL Series offers:

- **Redundant power amplifiers,**
- **Redundant exciters,**
- **Multiple parallel/redundant fans,**
- **Redundant low voltage power supplies,**
- **Failsafe manual and remote control,**
- **Redundant switch mode power supplies, and**
- **10% power amplifier overhead.**

The NL Series transmitter is easily scalable using combining techniques that have been proven reliable for over 25 years, and can currently scale to over 1.15 MW ERP. The NL Series features a software configurable pulse shape to meet the requirements of future modulation techniques. The NL Series transmitter is designed to withstand harsh environments anywhere in the world and is ideally suited for unattended, automatic, or remote controlled operation.

DID YOU KNOW?

Independent testing showed the NL Series transmitter has “many advantages for efficient and cost-effective eLORAN operation.” [7]

Timing & Transmission

TIME RECOVERY AND SIGNAL GENERATION

Thanks to the efforts of the LORAN Recapitalization Project, the USCG was able to take advantage of technological advances and make significant improvements to LORAN timing, signal generation, and control. The Timing and Frequency Equipment (TFE) suites used at USCG Loran Station (LORSTAs) can be re-packaged and used in the small footprint eLORAN system. The TFE consists of the following components:

- **Timing source,**
- **Timing front end,**
- **Signal generation, and**
- **Measurement and control.**

Three cesium standards have historically been used at USCG LORSTAs; however, their cost and slightly larger SWAIP could be prohibitive in a small footprint system. A rubidium can provide similar performance in a smaller package at less cost than a cesium.

The timing front end provides an external reference that allows the transmitter to be synchronized within 10 ns RMS of UTC (USNO). Typically an indirectly coupled GPS receiver is used as the timing front end; however, a Two-Way Satellite Time Transfer (TWSTT) front end can provide GPS-independent time synchronization.

Signal generation occurs in a set of FPGAs in the LORAN Integrated Timer and Signals Unit (LITS).

Symmetricon TFE Suite

The LITS unit accepts a 5 MHz signal from the frequency reference and generates transmitter drive and ancillary signals with strict phase relationships based on the stable clock. [8] The signal generator also has the ability to control the pulses (data modulation, blink, cross-rate blanking, phase adjust, etc.) based on commands from the measurement and control components.

The measurement and control component, consisting of a modular chassis with appropriate modules, continually monitors and verifies the LORAN signal to ensure the necessary performance and integrity required of LORAN systems. The measurements are processed to ensure the transmitted pulses have the proper phase relationship to UTC, are consistent within the pulse groups, and maintain acceptable short term frequency stability. Control of the LORAN signal is applied via commands to the LITS.

THE TRANSMITTING ANTENNA

The robustness and efficiency of the NL Series transmitter provides the opportunity to explore antenna configurations that previously may not have been possible. The small footprint eLORAN system could drive historical, existing, or planned antenna configurations, depending upon the required ERP and deploy-ability, including:

- **500-, 625-, 700-, 720-, 850-, or 1350-ft TLM,**
- **Top-Inverted Pyramid (TIP),**
- **Sectionalized Loran Transmitting Antenna (SLT),**
- **290-ft to 306-ft GWEN,**
- **"Antennas of Opportunity" (e.g., re-purposed AM antennas),**
- **300-ft Tilt-up Tower (AN/TSA-17, or equivalent),**
- **300-ft Goodyear or Birdair Type inflatable tower,**
- **Up to 300-ft Andrew Tower Corporation telescoping tower,**
- **290- ft "jack-up", Anthorn, Cumbria "T-type", or**
- **Tri-tethered, aerostat-, airship-, or balloon- supported.**

eLORAN Transmitting Antenna

70-ft Telescopic Mast (Retracted)

DESIGNING THE ANTENNA

In 2009, we contracted Nautel to design and develop a suitable antenna for field testing of the small footprint eLORAN system. To help reduce costs and expedite a short-duration field test, we chose the following design conditions for the transmitting antenna:

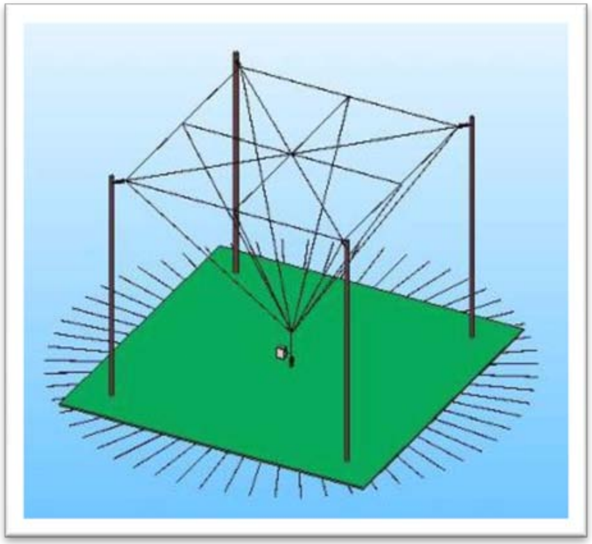
- **Operating range of 25 nautical miles,**
- **Field Strength of 55 dBμv/m at ground level (assuming ground conductivity of 1 mS/m),**
- **Transportable using common carriage, such as moving vans, trailers, small cargo aircraft, etc.,**
- **Erectable within 4-6 hours without the use of heavy or special equipment,**
- **Able to withstand a variety of environmental conditions worldwide, and**
- **Minimum physical size and footprint.**

Because the wavelength of the transmitted signal is three kilometers, historical LORAN systems have generally used large antennae. Typical fixed LORAN stations with large antennae operate at power levels from 250 kW and higher. We determined that a peak radiated power of only 40 W would produce a field strength of 55 dBμv/m at 25 nm. Nautel engineers proposed the following structures commonly used in the low and medium frequency bands:

- **75-ft fiberglass whip with 6 X 70-ft Top Loading TLEs and sixty 60-ft ground radials,**
- **"Tee" antenna 60-ft high by 150-ft long with twenty 90-ft and eighteen 135-ft ground radials, and**
- **Two inverted cone or TIP designs: 60-ft cube and 70-ft cube with thirty-six 60-ft and thirty-six 70-ft ground radials, respectively.**

Nautel engineers evaluated the antenna designs using the GNEC-4 antenna analysis software and compared the peak antenna voltages. To avoid the onset of corona, the input voltage needed to be below 50 kV. The 70-ft inverted cone design was the only antenna to have a peak voltage (46 kV) below this limiting factor and was chosen as the prototype antenna design for the small footprint eLORAN system.

With a Q value of approximately 480, the 70-ft inverted cone antenna requires an input voltage of approximately 1,800 V (2,500 V peak) to produce the necessary 10 W radiated power (40 W peak). We determined the 50 kW proof-of-concept transmitter, capable of 3,000 V output, could meet this requirement. Because of the high Q, a separate Antenna Tuning Unit (ATU) positioned at the apex of the antenna is necessary.



Inverted Cone or TIP Antenna Design

CONSTRUCTING THE ANTENNA

Four lightweight masts that could be easily erected were required to support the wires of the antenna and to meet the requirements for transportability and erect-ability. We selected 70-ft telescopic masts made from aluminum alloy that are pneumatically extended in seven sections using a 12 VDC air compressor. Each mast is triply guyed at three heights using pre-stretched polyester ropes connected to the mast using D-rings and connected to ground anchors. We selected stainless steel wires and lightweight insulators as a compromise between weight and maximum workable voltage. Each mast is designed to sustain 50 mph winds when properly guyed. Additional telescoping mast heights are available for implementing various types of inverted pyramid antenna configurations.

The various components of the antenna are packaged in 12 wooden crates with a total volume of 260 cubic feet and a total weight of 2,300 lbs. This does not include a "support crate" containing spare components, tools, and analyzing equipment.

Antenna Crate Loading on a Towable Trailer

FIELD TESTING THE eLORAN SYSTEM

EQUIPMENT ENCLOSURE/TRANSPORTATION

NL Series transmitters are typically at least one-half the size of competing solid state high power LORAN transmitters. The NL Series transmitter, along with the necessary TFE and backup power equipment, can be constructed entirely within the confines of an ISO standard 20-ft container, or equivalent space. The NL Series transmitter has a depth of 3.5-ft and a height of 6.0-ft, with the width ranging from 5.5-ft to 25.0-ft for the NL20 and NL160, respectively.

To keep testing costs low, we chose to rent a moving truck that approximated the interior dimensions of a CONEX box. The 26-ft Ryder truck provided more than adequate space for loading all the components of the small footprint eLORAN system, including installation and support equipment. The truck included a rear hydraulic lift gate and ramp and a side door. We positioned the truck close enough to the antenna to use a flexible, low-profile antenna feed line and still avoid obstructing any of the guys.

POWER AND ANCILLARY EQUIPMENT

We calculated the power requirements of our eLORAN system, including the portable A/C unit, and determined that a 220 V, 20 kW generator was the easiest size to rent at our test location. Although it far exceeded our requirements – especially given the colder weather precluded the need for A/C – it was available locally at a good price, and delivery was included.

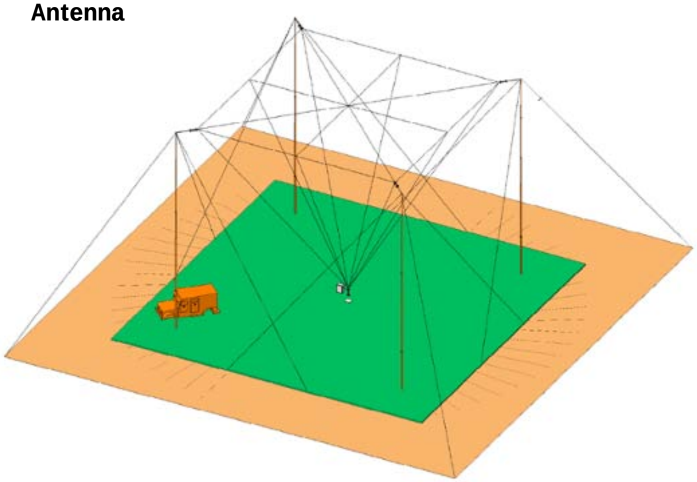
SITE LOCATION

The inverted cone antenna masts require an 80-ft square area, but we needed a 160-ft square area to accommodate the outermost guy points. We surveyed several locations but decided on a test site approximately 450-ft long by 240-ft wide providing ample room for setting up the eLORAN system and not posing any challenges to anchoring the guys. A circular concrete pad to the north of the test location served as an equipment staging and storage area. Although this area required anchoring the guys in sandy soil, it provided a relatively level test location free from obstructions.

NL Series Transmitter CONEX Box Mock-up

Test Site Location for the Small Footprint eLORAN System

Transmitter Truck Positioning for Connecting to the Inverted Cone Antenna



Transmitter Truck and Diesel Generator

FIELD TESTING THE eLORAN SYSTEM

SETTING UP THE ANTENNA

The prototype inverted cone antenna was designed to be erected in 4-6 hours without any heavy or special equipment and with adequate personnel for simultaneously erecting all four masts. This was our first time erecting the antenna in the field and even with the learning curve, limited number of personnel, and poor weather, we were able to fully construct the antenna and begin testing in slightly less than two workdays. No specially trained personnel (e.g., tower riggers) were necessary to successfully construct the antenna.

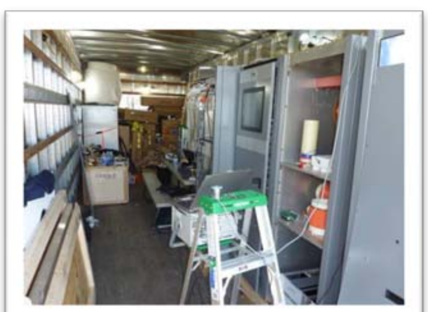
We first off-loaded the antenna crates and positioned them in the test area. Although our team could have physically carried each of the crates into position, we used a pickup truck to expedite the process. After determining the center point for the inverted cone antenna base insulator plate, we used a pre-fabricated length of rope with markings to determine the mast and guy anchor points. The antenna is designed to use galvanized steel anchor spikes; however, given the poor soil conditions, wetness of the ground, and strong winds, we buried an anchor plate for the outermost guys since they would carry the most strain.

We next positioned and extended the four antenna masts. One person controlled the electric compressor, another person climbed to the top of the base and tightened the section collars as the mast was extended, and three people manned the guys. We next laid the 36 ground radials consisting of solid bare copper wire spaced evenly apart.

Extending the Transmitting Antenna Mast

The antenna wires/radiating elements and top insulators were arranged on the ground in an inverted cone shape before being raised in the air. The antenna was raised using a nylon halyard at each mast until the top insulators were approximately eight feet from the tip of the mast providing a balance between the strain on the mast and the sag in the antenna wires with the objective to raise the wires as high as possible with as little sag as possible. We continuously monitored the strain and made adjustments to the guys to keep the masts straight.

We next attached the apex of the antenna to the base insulator and connected the ATU. As previously discussed, since the antenna had such a high Q (≈480), an additional tuning unit was needed in addition to the tuning unit built into the NL transmitter. A motor was installed so the ATU tuning components could be operated from inside the transmitter truck.



NL Series Transmitter Positioning in the Transmitter Truck

Completed Small Footprint eLORAN System

SETTING UP THE TRANSMITTER EQUIPMENT

We used the Nautel 50 kW proof-of-concept transmitter to drive the prototype inverted cone antenna. The 50 kW transmitter supplies the required 2,500 V of input power producing 40 W of radiated power from the antenna to meet our 25 nm operating range requirement. The transmitter ships in a single crate containing the amplifier and control rack, and the filter and antenna tuning/coupling rack. The TFE rack and the antenna simulator are crated separately. There was plenty of space for the operational equipment, spares, test materials, storage, and even a "picnic" work table in the 26-foot transmitter truck.

To minimize costs, and since redundancy and backup was not a high-priority during the field test, we used one-half Symmetricom TFE consisting of: 1) 5071A Cesium Beam Oscillator with standard tube, 2) LITS unit, and 3) 2000 Series chassis, modules, and software. We used 60 feet of Heliax cable to connect the transmitter to the antenna. We used the antenna simulator to test the transmitter prior to connecting it to the antenna to ensure all components worked properly following transport.

RESULTS & BEYOND

PERFORMANCE AND TEST RESULTS

We worked with the USCG Navigation Center and the USCG LORAN Support Unit to obtain the necessary approvals to conduct on-air testing. We conducted our testing from October 20-22, 2009. We operated the transmitter single-rated on the 8090M, 5030W, and 9960T rates, and dual-rated on 8090M and 5030W. We broadcasted 9th pulse data, i.e., the LORAN Data Channel (LDC), on 5030W and 9960T.

We used a LORAN monitor receiver to monitor the transmitted signal and set up the equipment in parking lot areas at two test sites. Several additional locations at much greater distances were also able to track our signals including:

- **80 nm: Vehicle crossing the Francis Scott Key Bridge in Baltimore, MD,**
- **115 nm: LORAN Monitor Station (LORMONSTA) Sandy Hook, NJ; SNR = +6 db,**
- **243 nm: LORSTA Seneca, NY; SNR = +1 db,**
- **263 nm: LORSTA Nantucket, MA; SNR = -2 db, and**
- **328 nm: LORSTA Carolina Beach, NC; SNR = +1 db.**

Because some of the receivers used during the test required a master-secondary pair for normal operations, we configured the NL Series transmitter to operate dual rated on 5030M and 5030W (approximately 338 PPS), providing the opportunity to test the NL Series transmitter over long periods at high duty cycles. 300 PPS has been the typical limit for previously designed and in-service transmitters. The current version NL Series transmitter comfortably operates at up to 700 PPS, ensuring flexibility to meet the needs of future requirements.

Test Site Locations and Measurements

Based on our results and raw test data, the small footprint eLORAN system was able to broadcast a signal that could be used for PNT purposes out to at least 25 nm. We were also able to successfully receive and demodulate the LDC data. We anticipate that modulating additional pulses would have increased the distance at which we were able to receive and demodulate the LDC data.

Areas benefiting from LF coverage out to 115 nm from our test site. This small footprint system, if moved NW about 25 miles, could provide critical backup timing service to four of the largest metropolitan area on the eastern seaboard: New York, Philadelphia, Baltimore, and Washington, DC.

POTENTIAL USES AND SCENERIOS

There are many potential uses for a small footprint eLORAN or LF-based Terrestrial Positioning System (TPS) as a means to augment and backup GPS, provide PNT&D services where GPS is degraded or unavailable, or provide PNT&D services to users who require GPS independence. Potential uses include:

- **Military operations subject to GPS unavailability, e.g., triple canopy, jamming scenarios, and mountainous terrain, and**
- **Critical infrastructure protection for ports, harbors, airports, key assets, etc.,**
- **High-profile events such as the Olympic Games,**
- **Interference-enabled crime fighting, e.g., car theft, border crossing, tracking felons, and toll "cheating,"**
- **Wide-area or localized timing source providing +/- 30 ns to UTC (Stratum 1).**

As we demonstrated in our testing, it takes minimal time, effort, and cost to set-up a small footprint LF system. Increasing the signal coverage area is a straightforward task and would provide an additional means of obtaining PNT&D services independent of GPS.

LF SOLUTIONS FOR PNT&D SERVICE

CONCLUSIONS

The results outlined in this paper have demonstrated how state-of-the-art technology can be applied to implementing a **small footprint, rapidly deployable, easily transportable, and cost-effective** LF-based Theater Positioning System (TPS). In a short time, we took this idea from conceptual design to proof-of-concept prototyping of various components to successful field-testing of a complete small footprint eLORAN system.

Although the focus of these efforts has been eLORAN, the technology could be applied to other LF systems being considered for various PNT&D solutions, particularly in those instances where GPS is degraded or unavailable. A small footprint LF system would be capable of supporting **multiple missions** (e.g., eLORAN, emergency/data communications, subsurface/submarine broadcast), **multiple modes** (e.g., aviation, maritime, land mobile, location-based time & frequency), and **multiple signal formats** (e.g., Pulse Position Modulation, Supernumary Interpulse Modulation, and Intrapulse Frequency or Amplitude Modulation). Because we have proven the technology works, our efforts are spawning research, such as investigating alternative waveforms (Binary Phase Shift Keying and Raised Cosine), that may result in applying our techniques to improving LF service. [9]

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- **Mr. Kirk Montgomery of Symmetricom, Inc.**
- **Dr. Ben Peterson of Peterson Integrated Geopositioning, LLC.**

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UrsaNav
Follow the Stars!

Beyond *the Box*, Behind *the Bear.*

UrsaNav is a founding member of the Enhanced Loran Industry Working Group (eLIWG).

We are the exclusive worldwide distributor of Nautel and Symmetricom LORAN and eLORAN products.

In October 2009, UrsaNav, Inc. and business partner Nautel, Inc. received the John M. Beukers Award for Technical Innovation at the 38th International Loran Association Conference in Portland, ME. UrsaNav was cited for their participation with Nautel in the development of an innovative new LORAN-C and eLORAN transmitter.

ADDITIONAL READING

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What’s the Buzz?

The latest news includes our recent ranking in *Inc.* magazine’s 28th annual Inc. 500|5000, an exclusive ranking of the nation’s fastest-growing private companies. UrsaNav was ranked as the 8th fastest growing company in the Engineering division and the 807th fastest growing company overall. We were also named one of the “Top 25 Best Places to Work in Hampton Roads” by *Inside Business* magazine for three consecutive years, including the #1 Best Place to Work for 2009 in the Mid-Sized business category. Also in 2009, the Hampton Roads Chamber of Commerce listed us as one of the “Top Ten Businesses to Watch”.

You can rely on the UrsaNav team.