Design and Performance of a Low Frequency Time and Frequency Dissemination Service

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BIOGRAPHIES

Dr. Arthur Helwig is a research scientist at UrsaNav, Inc., an advanced engineering and IT solutions company with principle offices in Virginia. Dr. Helwig is a member of UrsaNav's Low Frequency (LF) Engineering business unit engaged in various R&D project work and product development. Dr. Helwig has over seventeen (17) years of experience in the LF Position, Navigation, Timing, and Data (PNT&D) field, and is one of the co-developers of the Eurofix data channel concept. Eurofix has been deployed at Loran installations worldwide. He has received awards for a number of his scientific papers on radio navigation systems including the Medal of Merit from the International Loran Association. Dr. Helwig received his PhD, with honors, and Master's Degree in Electrical Engineering from the Delft University of Technology.

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Chris Stout is Vice President of LF Engineering for UrsaNav, Inc. As the leader of UrsaNav's LF Engineering business unit, Mr. Stout oversees all LF PNT&D efforts worldwide, including managing all projects and product development. Mr. Stout served on active duty in the US Coast Guard for nine years and was stationed at the Loran Support Unit where he was a member of the team that designed, developed, and implemented the Loran Consolidated Control System. He received his Master's Degree in Electrical Engineering from the University of Michigan and a Bachelor's Degree in Electrical Engineering from the US Coast Guard Academy. He also holds the Project Management Professional (PMP) certification from the Project Management Institute (PMI).

Charles Schue is co-owner and President of UrsaNav, Inc. He champions providing Low Frequency Alternative Positioning, Navigation, Time/Frequency, and Data solutions for "sky-challenged" users. He served in the US Coast Guard, where his expertise included radio navigation systems, and holds Masters Degrees in Electrical Engineering, Engineering Management, and Business Administration. He is a Marine Representative of the ION; a past Chairman and Treasurer of the Washington, DC Section of the ION; and an Associate Fellow of the Royal Institute of Navigation.

ABSTRACT

Synchronization in time and frequency between various geographically separated locations is critically important to a number of industries and applications. Examples include the wired and wireless telecommunication industry, transportation and shipping, banking and financial transactions, utilities and power delivery systems, computer networks, emergency services, and military and homeland security systems. Timing is also a critical component of the U.S. National Position, Navigation, and Timing (PNT) Architecture, the National Airspace System (NAS), and the Intelligent Transportation System (ITS).

The Global Positioning System (GPS) has become the sole means in many instances for obtaining these crucial timing signals. GPS provides the necessary timing performance levels and there are a myriad of low-cost, single-purpose GPS receivers on the market. However, GPS, and in fact any Global Navigation Satellite System (GNSS) or Regional Navigation Satellite System (RNSS), is vulnerable to both intentional and unintentional interference, jamming, and spoofing resulting in a range of service degradation from complete outages to sporadic and unpredictable unavailability to incorrect information.

To maintain accurate timing in a GPS-denied environment using radio signals, we focus on providing high-power, Low Frequency (LF) solutions. Because of its long propagation

range, the ability to measure the arrival time of a pulsed signal with great accuracy, and a well-defined ground wave signal propagation path, an LF solution makes for an attractive terrestrial-based alternative to a low-power, high-frequency, satellite-based signal.

Our paper discusses LF system concepts for providing an alternative precise time and frequency source. A pre-production transmitter has been developed and was installed and tested on-air using an existing LF transmission site. The accuracy of the transmitted signal was measured and evaluated. We outline our plans for setting up an R&D test bed for additional on-air testing and present estimated coverage predictions.

We also discuss the development and production of our first generation LF timing receiver, which has been undergoing testing and evaluation using on-air signals since March 2011. A timing research and development company is providing independent testing and analysis. Available results demonstrate that our receiver performs to Stratum-1 levels and meets the International Telecommunication Union (ITU) requirements for Primary Reference Clocks (PRC) in telecommunication networks. We present test and measurement setup, results, and conclusions based on our work.

INTRODUCTION

The provision of timing signals over a large geographic area, which allows all receivers in that area to operate in a synchronized manner, is a non-trivial effort if it has to be done with a high degree of accuracy. In this context, timing refers to both providing accurate frequency and time references as well as to providing an accurate time-of-day signal.

GPS and other GNSS can provide accurate frequency and Universal Coordinated Time (UTC) to within 50 ns, typically to 20 ns. An increasing number of applications and services rely on accurate timing and may become unavailable if GPS timing is interrupted. Just like any prudent navigator does not rely on a single source for position and navigation information, relying on GPS as the sole means of obtaining precise time for critical systems, without having an alternative system or backup in place, is not prudent or responsible, and can have severe operational and economic impacts.

Besides being able to obtain precise time in the absence of GPS, having an alternative source for precise time to determine when GPS is providing incorrect or misleading data is also important. An alternate, comparable source of precise time helps ensure GPS integrity and signal authentication.

There are numerous applications and systems that require accurate and precise time. The US Department of Homeland Security (DHS) has identified fifteen (15) Critical Infrastructure and Key Resource (CIKR) sectors that use GPS for timing. For eleven (11) of the sectors, GPS timing is deemed essential for successful operation. [1] Systems that rely on GPS for timing include:

- *Telecommunications networks*. Landline and mobile telephone systems, paging systems, computer networks, and the internet.
- *Energy and power systems*. Energy plants and substations, nuclear plants, hydro dams, and wind farms which rely on precise time for power grid phase synchronization and flow control.
- *Banking and financial systems*. Stock trading, inter-bank transactions, and ATM transactions.
- *Transportation systems serving maritime, aviation, and land-based operations*. Electronic Chart Display & Information System (ECDIS), Digital Selective Calling (DSC), Automatic Identification System (AIS), Next Generation Air Transportation System (NextGen), positive train control, and the ITS.
- *Emergency services*. E-911, E-112, and the Land Mobile Radio (LMR) network.
- *Military and Defense operations*. C4IT systems, secure communications systems, the defense industrial base.
- *Commerce and manufacturing*. Plant operations, critical manufacturing, shipping, and port operations.

Despite the overwhelming success of GPS as the leading global PNT system, it has vulnerabilities. GPS performance is degraded, or even interrupted, by natural phenomena, such as solar flares, or unintentional or intentional interference. (e.g. jamming or spoofing devices). As shown in Figure 1, jamming devices – sometimes referred to as "Personal Privacy Devices) – and spoofers are easily obtainable, low-cost, and very effective.

Figure 1: Low-cost GPS "Personal Privacy Devices"

In recent years, GPS has had to compete for spectrum with emerging GNSS from other countries whose systems broadcast in the same frequency bands. These systems also contribute to the overall noise level at GPS frequencies. Communications systems are also capable of competing with GPS for spectrum, and communications technologies continue to encroach on satellite navigation spectrum. [2]

Even without these threats, GPS usage has other challenges. In many cases, timing is needed inside buildings or in areas with many sources of local interference. GPS signals can be blocked or become partially unavailable. Installing GPS antennas on the roof of a building to get a clear view of the sky can add to equipment and installation costs.

Alternatives to GPS for precise timing are limited. Other GNSS systems suffer the same sort of vulnerability problems as GPS, and current low frequency time distribution systems such as WWVB, DCF77, and MSF only provide several microseconds to millisecond timing accuracy. Systems that claim GPS "independence" often actually contain a link to GPS signals at some point in their architecture. LF systems, such as the Long Range Navigation (Loran) and Enhanced Loran (eLoran), are the only homogeneous, multi-modal, independent alternative to GPS for providing very wide-area precise time synchronization. [3]

UrsaNav continues to evolve LF technology and, along with its partners Nautel, Inc. and Symmetricom, Inc., has developed proven, robust, and cost-effective solutions for providing alternatives to GPS/GNSS for PNT&D.

LF SOLUTIONS FOR PROVIDING PRECISE TIME

An LF system is a well-suited alternative, complement, and back-up to GPS for providing precise time. It provides the same order of service levels as GPS, with good traceability to UTC. It is interoperable with, and yet independent of, GPS. Our LF solution:

- Is terrestrial-based and provides signals at considerably higher power levels than GPS, improving reception and decreasing the chances of interference.
- Has considerable usable range, with ground wave signal reception possible beyond 1,000 miles, thereby requiring fewer transmitters than other terrestrial-based solutions.
- Has dissimilar failure modes as GPS/GNSS/RNSS.
- Requires only one transmitter/station to provide time, frequency, and data signals over a wide area.
- Uses LF signals that can propagate into areas where GPS signals cannot reach, such as in "urban canyon" environments, indoors, under foliage, i.e. "triple canopy", and to a limited depth under water and ice.
- Uses a pulsed structure that protects against the fading that typically occurs with other LF/MF broadcast systems, such as WWVB, DCF77, and MSF.
- Includes an encryptable and third-party controllable data channel capable of providing in excess of 1,200 bps of information. Uses the 90-110 kHz frequency band, which is protected worldwide for safety-of-life services.
- Includes Loran-C, eLoran, and Chayka signals, as well as alternative waveforms and modulation techniques that can coexist harmoniously with those signals within the 90-110 kHz band.
- Uses 21st century technology that significantly reduces non-recurring and recurring costs.
- Meets stringent timing reference requirements. Transmissions can be synchronized to +/- 10 ns of UTC, with time recovery to within 50 ns (RMS) of UTC. Precise time recovery is ensured through monitoring and data channel correction broadcasts.
- Meets stringent frequency reference requirements, including the Stratum-1 standard (2×10^{-13}).

The government, academia, and industry have extensively studied the dissemination of precise time using LF broadcast transmissions, in particular eLoran. The US Coast Guard (USCG) conducted several tests that showed that eLoran could be used to recover time to less than 10 ns (RMS) over a short baseline and to less than 50 ns (RMS) over a longer baseline. [4] By using new technology and techniques, we expect to be able to replicate and improve upon previous results.

21ST CENTURY LF TECHNOLOGY

TRANSMITTER TECHNOLOGY

UrsaNav provides industry-leading LF technology from transmission to reception. UrsaNav has worked with Nautel, Inc., a world-class high-power RF engineering company, to develop LF transmitters that eclipse current technology and reduce Size, Weight, and input Power (SWAP) requirements. The solution is the Nautel NL Series transmitter, shown in Figure 2 and Figure 3, which uses state-of-the-art, solid-state signal generation and control technology.

Figure 2: Nautel NL-40 High-Power LF Transmitter (Dimensions = 6 feet tall, 9.5 feet wide, 3.7 feet deep)

Figure 3: NL Series Transmitter Power Amplifier Rack

The building block of the NL Series transmitter is a Class D RF amplifier with Nautel's patented pulse power recovery technique that reuses reflected power from the antenna that is normally dissipated as heat. With an overall efficiency typically above 70%, reflected energy is recycled, thereby reducing input power, cooling, and ventilation requirements, and associated costs. The exceptional efficiency, regardless of antenna height, and low maintenance overhead, makes the innovative NL Series transmitters extremely cost effective to own and operate. For example, we estimate approximately 50% less electrical power consumption compared to legacy LF transmitters, for the same radiated power.

The NL Series transmitter is robust and scalable, as shown in Figure 4, and is able to easily meet a range of user requirements. It is capable of broadcasting all manner of Pulse-Position Modulation (PPM) schemes, including Eurofix and 9th and 10th pulse Loran Data Channel, and schemes using more advanced modulation techniques, such as Intrapulse Frequency Modulation (IFM), Intrapulse Amplitude Modulation (IAM), BPSK-Raised Cosine (BPSK-RC) modulation, and Orthogonal Frequency-Division Multiple Access (OFDMA). [5]

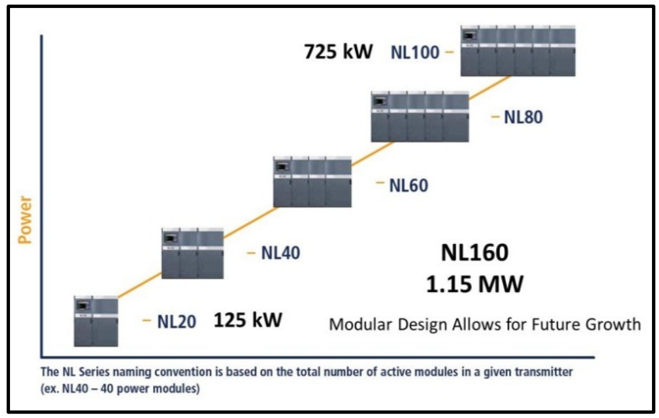

Figure 4: NL Series Transmitter (ERP into a 700-foot TLM Antenna)

The NL Series transmitter provides the industry's tightest tolerances on zero-crossing, pulse-to-pulse timing, pulse shape distortion, and droop. This is extremely important because any deviation from the ideal pulse shape and timing contributes directly to user timing (and positioning) errors. The high-performance power generation, control, and monitoring included in the NL Series transmitter eliminates instabilities within the transmitted signal.

Figure 5 and Figure 6 show the improvement in phase stability, i.e. "jitter," of the NL Series transmitter over legacy LF transmitters during testing of the NL prototype transmitter conducted in March 2011. The NL Series transmitter has a better than eight (8) times improvement in signal phase stability, which equates to over six (6) ns of improvement, or approximately seven (7) feet in position accuracy. The increased phase stability means improved LF receiver signal reception and performance, allowing more cost-effective receiver technology. We expect even better results when the production version of the NL Series transmitter is available later this year.

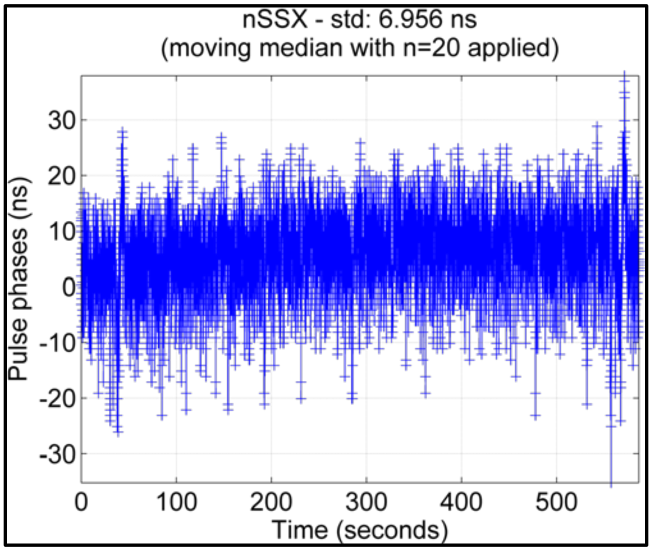

Figure 5: Legacy Loran Transmitter Phase Stability (Measured at 11.5 miles)

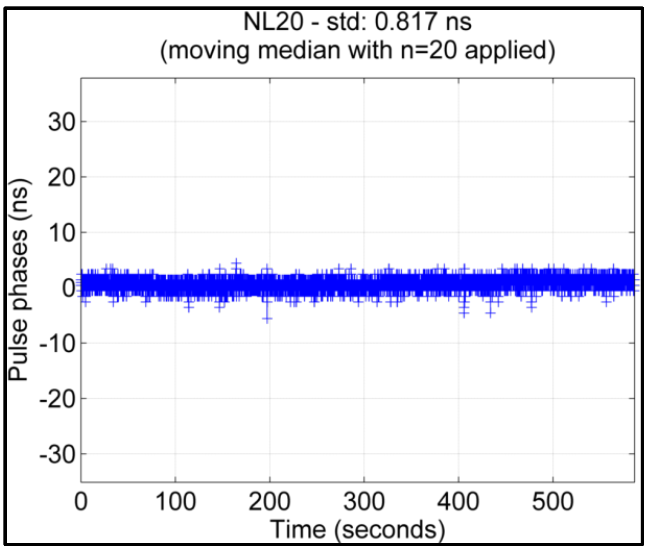

Figure 6: NL Series Transmitter Phase Stability (Measured at 11.5 miles)

TRANSMITTING ANTENNA TECHNOLOGY

Because of the long electrical wavelength of an LF signal, large towers are typically required to efficiently broadcast a useable signal over long distances. Real estate concerns, environmental impacts, and total life-cycle costs of deploying these large towers impact budgetary costs and deployment schedules of any new LF system deployment.

The robustness and efficiency of the NL Series transmitter provides us the opportunity to explore antenna configurations that previously may not have been possible. Figure 7 shows an example of a "Triple-T" (Tactical, Temporary, and Transportable) antenna concept designed to maximize signal area coverage while minimizing large tower structures. The size and configuration of the broadcast antenna varies based on design factors such as available transmitter power, user coverage requirements, equipment costs, horizontal real estate, vertical real estate, and collocated systems, such as differential GPS (dGPS) transmitters.

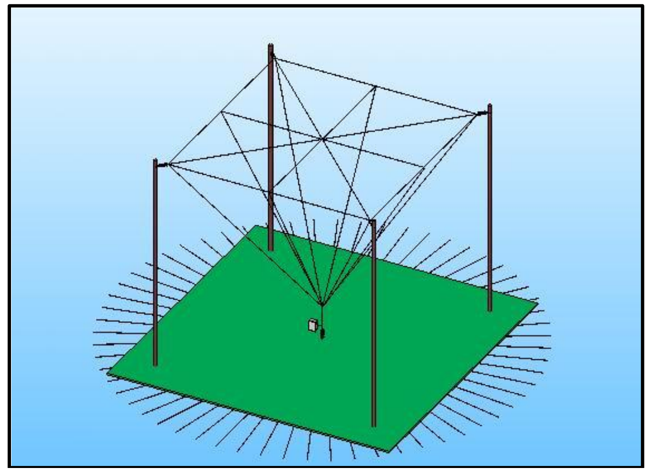

Figure 7: Inverted Cone or TIP Antenna Design (Dimensions 70- x 70- x 70-feet)

Figure 8 shows a balloon-supported antenna option for LF broadcast transmissions. Based on modeling and 20th century prototypes and proofs-of-concept, we estimate that an LF wire antenna supported by a balloon 1,200 feet in the air could achieve a usage range of almost 300 miles.

Figure 8: Aerostat Aloft Supporting an LF Antenna

Our LF solution can also take full advantage of existing broadcast antenna infrastructure, including existing Loran towers, Ground Wave Emergency Network (GWEN) towers, or other available "antennas of opportunity" such as dormant AM broadcast structures.

RECEIVER DEVELOPMENT

We are continually advancing LF receiver technology, and through various acquisitions have combined intellectual property to provide a strong technology foundation for our new products. Figure 9 shows our UN-150 eLoran timing receiver. Independent, third party tests have shown that the performance of UrsaNav's UN-150 eLoran timing receiver exceeds the performance requirements for telecommunications grade PRCs, as specified by the ITU and the European Telecommunications Standards Institute (ETSI). See Figure 10.

Figure 9: UrsaNav UN-150 eLoran Timing Receiver

The UN-150 is also the first and only eLoran receiver to maintain smooth timing through Loran or eLoran station unavailability, shifting reception to an alternate timing source should the primary timing source become unavailable, ensuring continued timing performance meeting the ETSI requirements.

We are currently developing our next generation LF receiver technology, which is designed with maximum flexibility and robustness to meet a range of user requirements. Figure 11 shows the UN-151, Ursa Mitigator™, an advanced receiver module capable of processing multiple signals in the LF and MF bands. Some highlights include:

- State-of-the-art FPGA/DSP combination for efficient signal processing and expandability.
- Small form factor (approximately credit card size).
- NMEA messaging.
- Complete range of integration capabilities.
- Software configurable.
- Multiple input channels and frequencies.
- H-field and E-field antenna connectivity.
- GPS/GNSS sensor interface with other sensor interfaces available.
- Multiple interfaces including serial, USB, Ethernet, GPIO, and SD/MMC.

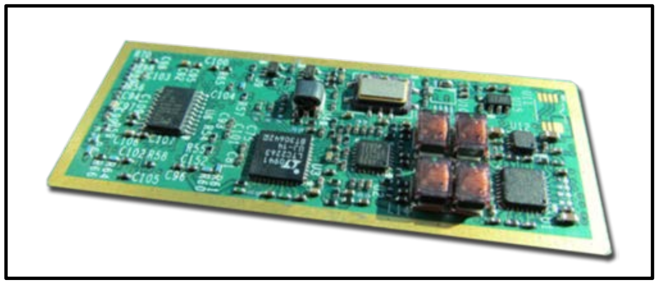

Figure 11: UN-151 Ursa Mitigator™
LF PNT&D OEM Module (Prototype)

The UN-151 is fully capable of receiving Loran-C, eLoran, and Chayka signals, and associated data channel schemes. Its built-in future-proofing allows reception of next generation LF signals that incorporate advanced waveform and modulation techniques.

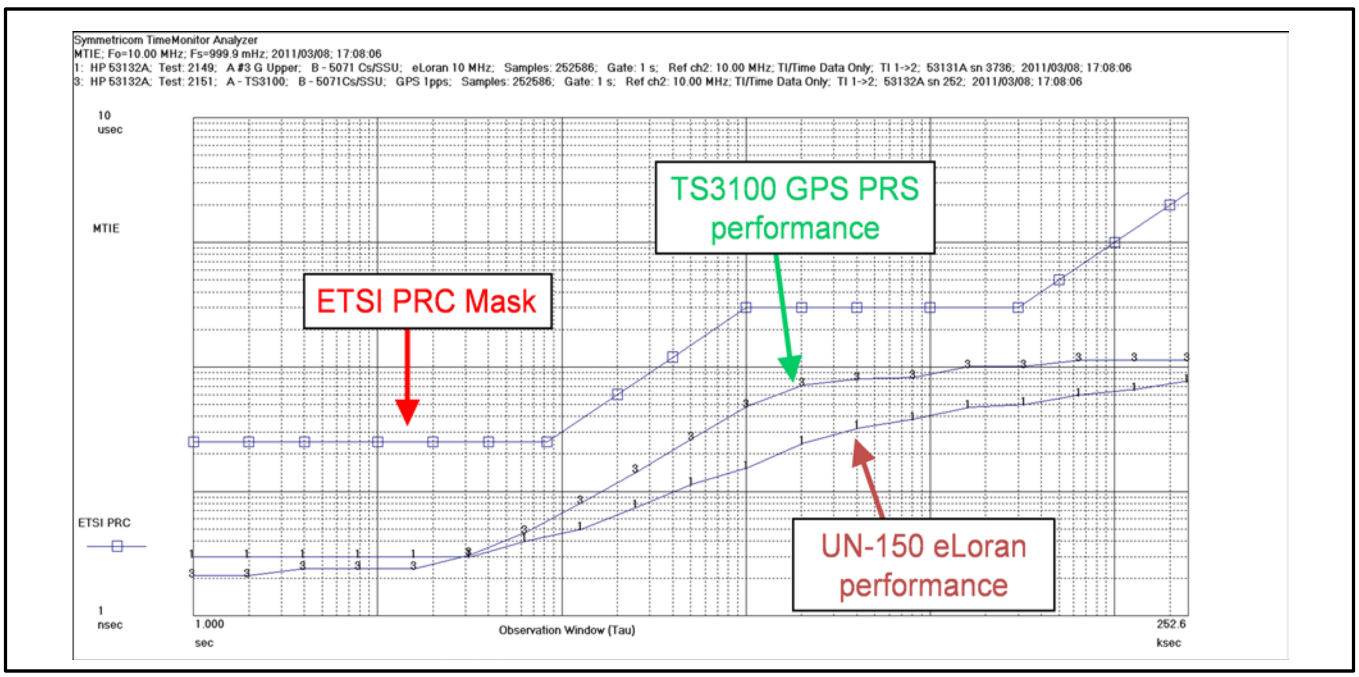

Figure 10: UN-150 eLoran Timing Receiver Performance

LF SYSTEM FIELD TESTING

In October 2009, we conducted initial field testing of our "Small Footprint" LF technology, demonstrating that an LF system could be rapidly and easily deployed and does not require extensive infrastructure, power requirements, or special equipment. [6] Figure 12 and Figure 13 show the transmitting equipment installed in a 26-foot Straight Truck with power provided by a portable generator.

Figure 12: Straight Truck and Generator

Figure 13: View inside Straight Truck

Figure 14 shows the inverted cone, or inverted pyramid, antenna, as modeled in Figure 6, which was designed to be transportable using common carriage, erectable in 4-6 hours without the use of heavy or special equipment, minimum size and footprint, and with an operating range of 30 miles.

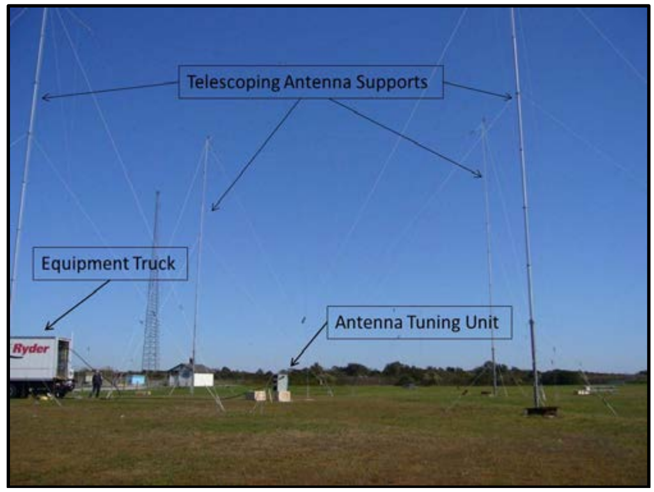

Figure 14: Small Footprint eLoran System

With an Effective Radiated Power (ERP) of only 10 watts (40 watts peak-to-peak), our testing demonstrated that we could not only receive a signal of at least +55 dbµv/m at 30 miles (assuming a ground conductivity of 1 mS/m), but that our signal could be received at much greater distances. As shown in Figure 15, the Loran Monitor Station in Sandy Hook, NJ, located 132 miles from the transmitter, received the signal with a +6 db SNR. Figure 16 shows the "real world" implications of receiving an LF timing signal at this distance. Locations benefiting from LF coverage out to 132 miles from our test site include: New York Harbor; Philadelphia, PA; Delaware Bay; Baltimore, MD; Chesapeake Bay; and the Washington DC metropolitan area.

Figure 15: eLoran Signal Reception at Sandy Hook, NJ

Figure 16: LF Signal Coverage out to 132 miles

LF R&D TEST BED

In January 2012, the USCG announced its intent to enter into a Cooperative Research and Development Agreement (CRADA) with UrsaNav to research, evaluate, and document at least one alternative to GPS as a means of providing precise time, namely a wireless technical approach. [7]

The CRADA will allow us to continue testing our advanced LF technology and use US government facilities and frequency authorizations to demonstrate to what distance and to what accuracy LF signals can be used for obtaining precise time. We anticipate beginning live, on-air testing from the former Loran site in Wildwood, NJ starting in March 2012. It should be noted that the USCG has no intent to acquire, operate, or provide wireless time technology or services. The DHS is investigating precise time transfer using fiber optic networks and has asked the USCG to investigate wireless time transfer technologies as part of a national wide-area time service solution.

As previously mentioned, the concept of using LF technology, specifically eLoran, to transfer precise time has been exhaustively researched, studied, and tested. Given our evolutionary technology, we expect our testing will show greatly improved results. The flexibility of the NL Series transmitter allows us to experiment with a variety of advanced signal structures and waveform techniques without having to compromise between what is needed and what is possible.

Figure 17 shows some sample waveforms that were previously broadcast during our first on-air trials.

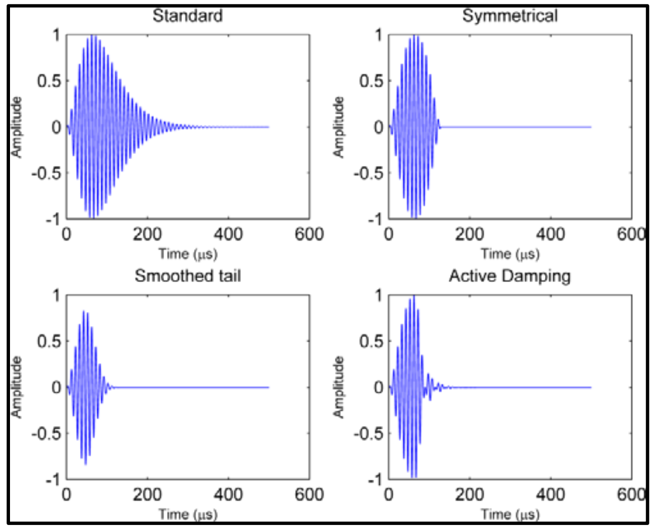

Figure 17: Sample Waveform Alternatives

Legacy LF transmitters have typically been limited to 300 Pulses-Per-Second (PPS). However, the NL Series transmitter has been successfully tested at 700 PPS, thereby allowing more signal energy to be transmitted. Alternate waveforms allow full and efficient use of the available spectrum, and shorter pulses allow for higher speed data communications without degrading timing performance. Improved coding schemes can eliminate crossrate interference, as well as provide other improvements.

As part of our next series of on-air tests, we will be transmitting eLoran signals at over 40 kW ERP from a 625-foot Top Loaded Monopole (TLM) antenna shown in Figure 18. Figure 19 shows the predicted signal strength coverage.

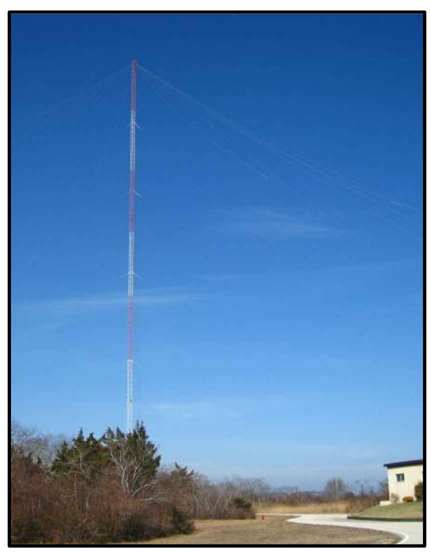

Figure 18: 625-foot TLM Antenna in Wildwood, NJ

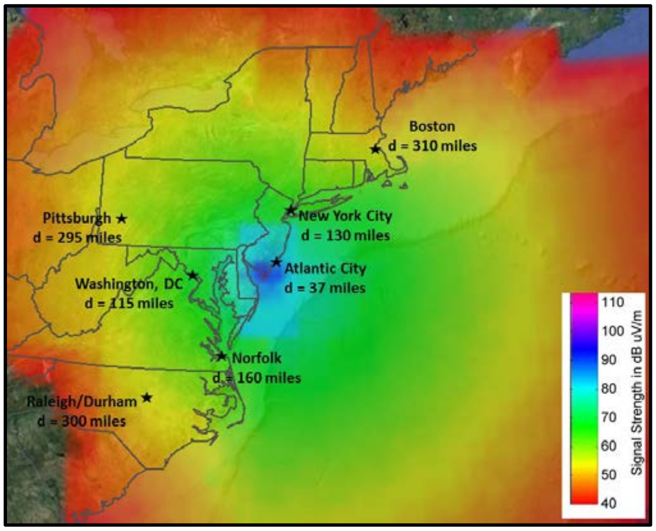

Figure 19: Predicted Signal Strength Coverage for Initial LF Testing from Wildwood, NJ

Based on eLoran experience and previous results, +55 dbμv/m is a good starting point for determining at what distances we expect to be able to receive the signal, demodulate the data message, and obtain precise time. With our modern transmitter and receiver technology, we expect to receive the signal at lower signal strengths and higher SNRs in the coverage area.

Figure 20 shows the predicted signal strength coverage for the testing of advanced signal waveforms and modulation techniques.

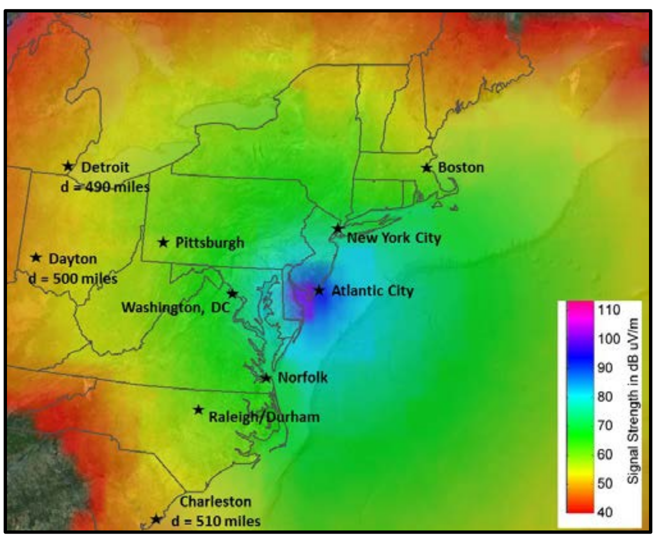

Figure 20: Predicted Signal Coverage for Advanced LF Testing from Wildwood, NJ

The wide area covered by the LF signal encompasses many major metropolitan areas and cities, and includes various critical infrastructure and systems that rely on precise time, including telecommunications hubs, financial institutions, power generation and distribution facilities, major ports, and major airports.

Figure 21 shows the predicted signal strength coverage for the testing of advanced waveform and modulation techniques from Las Cruces, NM.

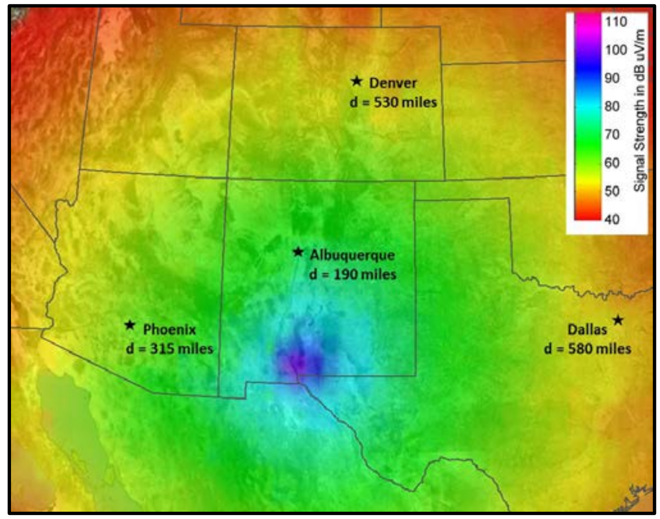

Figure 21: Predicted Signal Strength Coverage for Advanced LF Testing from Las Cruces, NM

The Federal Aviation Administration (FAA) has previously indicated that the Southwest portion of the United States contains many areas where GPS testing results in a degradation and/or loss of the GPS signal. See Figure 22. An LF signal would allow users to continue to receive precise time during these GPS tests.

Figure 22: Areas Impacted by US Department of Defense Testing [8]

CONCLUSIONS

There is no doubt that GPS, when available, should remain the first choice for obtaining precise time. However, government-, academic-, and industry-sponsored evaluations consistently conclude that LF solutions provide the best alternative for timing, as well as positioning and navigation, when GPS/GNSS is not available. LF solutions are technically feasible, truly multi-modal, cost effective alternatives that complement and co-exist with GPS and its augmentations. LF solutions are completely interoperable with and independent of GPS, with different propagation and failure mechanisms, plus significantly superior robustness to radio frequency interference, jamming, and spoofing. LF solutions provide a seamless backup, and their use will deter threats to national and economic security.

Because the United States has abandoned the LF spectrum between 90-110 kHz, there is an opportunity to demonstrate using LF technology to provide a precise timing and frequency source as an alternative and backup to GPS. Through our CRADA-enabled testing, we expect to validate our predicted wide-area timing coverage.

Using our 21st century technology, we expect to demonstrate:

- Significant radiated power gains over legacy LF allowing greater signal coverage (in excess of 1,000 miles) and improved reception.
- Improved signal stability and signal quality resulting in a more usable signal in the coverage area.
- Transmissions accurate to +/- 10 ns of UTC.
- Time recovery to within 50 ns RMS (UTC).
- Complete GPS-independence using Two-Way Satellite Time Transfer (TWSTT)
- “Sky-free” independence using Two-Way Low-Frequency Time Transfer (TWLFTT).
- Signal encryption methods.
- A twelve-fold or better improvement in data throughput over existing solutions (>1,200 bps).

We have partnered with industry leaders in the fields of high-power RF technology (Nautel, Inc.) and precise time and frequency technology (Symmetricom, Inc.) to provide a complete LF solution from transmission to reception. We can provide a range of fully-developed and proof-of-concept technology, built upon proven technology and performance. We will demonstrate in our future testing that our next generation LF PNT&D solutions are suitable alternates to GPS for precise time, and can co-exist in the worldwide timing and LF ecosystem.

ACKNOWLEDGEMENTS

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REFERENCES

1. Caverly, James, “GPS Critical Infrastructure Usage/Loss Impacts/Backups/Mitigation,” Available at HTTP: http://www.swpc.noaa.gov/sww/SWW_2011_Presentations/Wed_830/GPS-PNTTimingStudy-SpaceWeather4-27.pptx, April 2011.

2. Last, David; Basker, Sally, “Expert Advice: Give Us This Day Our Daily Bread,” GPS World, January 2012.

3. Lombardi, Michael; Celano, Tom; Powers, Ed, “The Potential Role of Enhanced LORAN-C in the National Timing Infrastructure,” Proceedings of the 2005 International Loran Association (ILA) and Technical Symposium, October 2005.

4. Celano, Tom; Biggs, Casey; Peterson, Benjamin; Shmihluk, Kevin, “Modernized Loran-C Timing Test Bed Status and Results,” Proceedings of the 37th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2005.

5. Helwig, Arthur; Offermans, Gerard; Schue, Charles; Walker, Brian; Hardy, Tim; Zwicker, Kirk, “Low Frequency (LF) Solutions for Alternative Positioning, Navigation, Timing, and Data (APNT&D) and Associated Receiver Technology,” Proceedings of the ION International Technical Meeting (ITM), January 2011.

6. Stout, Chris; Schue, Charles, “Designing, Developing, and Deploying a Small Footprint Low Frequency System for Positioning, Navigation, Timing, and Data Services,” Proceedings of the IEEE/ION PLANS 2010 Symposium, May 2010.

7. US Coast Guard, “Cooperative Research and Development Agreement: Technology to Provide Wireless Precise Tim; Alternatives to Global Positioning Systems,” Docket No. USCG-2011-1167, Federal Register Vol. 77, No. 7, January 2012.

8. Narins, Mitch, “Alternative Positioning, Navigation, and Timing Initiative: Assumptions and Requirements,” FAA APNT Public Meeting, August 2010.