Low Frequency (LF) Solutions for Alternative Positioning, Navigation, Timing, and Data (APNT&D) and Associated Receiver Technology

Arthur Helwig, Gerard Offermans, Chris Stout, Charles Schue – UrsaNav, Inc
Brian Walker, Tim Hardy, Scott Martin, Kirk Zwicker – Nautel, Inc.

Abstract

Many government and civilian organizations around the world are studying the problem of what to do when Global Navigation Satellite System (GNSS) based services are unavailable to provide Positioning, Navigation, Timing, and Data (PNT&D) information to public and private sector users. There is a general concern about the over-reliance on GNSS which is susceptible to degradation, outages, and unavailability, whether intentional or unintentional, and which operates in many cases without an additional system to provide PNT information for validation and backup. Two recent examples are cited below.

In May 2010, the International Civil Aviation Organization (ICAO) Navigation Systems Panel (NSP) working group developed a flimsy documenting "work being accomplished by the U.S. Federal Aviation Administration (FAA) to assess alternatives for providing PNT services when GNSS is not available due to RFI" [1]. During an FAA APNT public meeting in August 2010, UrsaNav and Nautel recommended the FAA consider a Low-Frequency (LF) Alternative Positioning, Navigation, and Timing (APNT) solution to maintain safety and minimize economic impacts from GNSS interference outages [2].

During the 49th International Association of Marine Aids to Navigation and Lighthouse Authority (IALA) Council Meeting, a side

question was directed to Industrial Members as to what industry is working on or thinking about regarding the ever increasing reliance on GNSS-based navigation systems. There is a growing concern in the marine community that mariners are losing the basic knowledge and skills needed to navigate by other means and becoming too reliant on satellite technologies. It was noted that coastal navigation maintains traditional aids to navigation, such as, buoy, beacons, and racons, but with the planned removal of some Loran stations and other longer range tools, there is a lack of redundant aids for deep sea navigation [3]. The council recommended that "IALA should encourage the development of a global redundant system, or combination of systems, independent and dissimilar to GNSS, to facilitate e-Navigation" [4].

The FAA Working Group Meetings report to ICAO [1] provided three recommendations, none of which included an LF alternative. In this paper we present our research and findings and propose LF solutions that meet the FAA's APNT requirements. Because our proposed LF solutions meet the FAA requirements, they can also meet less stringent requirements from other modes (e.g., time and frequency, maritime, land-based, and mobile). We also include our research on the associated broadcast and reception technology. Our proposed solutions can maintain safety and minimize economic impacts from GNSS interference outages. All of the proposed solutions have a data

capability that can be fine-tuned to a specific need.

Our current efforts expand on several years of work in LF PNT&D systems, including the development of a small footprint LF system that is cost-effective, rapidly-deployable, and easily transportable. Our solutions are technologically-advanced and provide low-cost alternatives that lessen the dependence on GNSS.

1.0 Background

At present, the only LF systems known to offer Positioning, Navigation, Timing and (limited) Data capability are Loran-C and Enhanced Loran, or eLoran. Exhaustive study, analysis, and field trials led by several international authorities, including the FAA, have shown that the eLoran system can meet the accuracy, availability, integrity and continuity requirements for RNP 0.3 and Maritime Harbor and Approach (HEA) described as a minimum system requirement. The spectrum used for the (e)Loran[1] system is globally protected. (e)Loran's signal inherently includes security and integrity, and system provider infrastructures exist in several countries, including the United States.

It is understood that on February 8, 2010, the U.S. began the process of terminating Loran-C radio navigation system broadcasts in North America. This decision was at the same time deleterious and fortuitous. It was deleterious because eLoran, either as currently described in draft documents [5] or as upgraded in one of our proposed options, was a nearly fully deployed system at the time of its termination. It was fortuitous because it allowed the U.S. Coast Guard (USCG) to begin: eliminating high-cost, hard

to support stations at Port Clarence, AK and Attu, AK; hardening other stations and shutting down costly administrative and "hotel spaces"; un-manning all stations; removing older, single-purpose technology; and retaining key, critical equipment (e.g., 5071A cesium standards).

UrsaNav and Nautel are fully committed to continuing to provide (e)Loran solutions worldwide. Meanwhile, the situation in the U.S. has provided us with an opportunity to look deeper into new technical solutions that take full advantage of multi-mode, multi-frequency, broadcast and reception technology to drive the capabilities of LF APNT to a new level. We have determined that a pulse-based positioning system offers a good starting point for studying combined LF APNT and data system concepts.

We interpret LF as including Loran-C and eLoran for current international service providers, LFPhoenix™ (a readily available solution that is primarily based upon the proven science that is eLoran) for North America, and customer-specific variants such as those proposed in this paper. Our LF solutions include a combination of fully developed and proof-of-concept technology that can easily be repurposed for research and development and as solutions to meet world-wide APNT requirements.

We initially proposed LF APNT solutions that reside in the 90-110 kHz spectrum made available in North America when the Loran system signal was vacated. This is the spectrum of choice because it is readily available and is already internationally protected for safety-of-life radio navigation purposes. The FAA report to ICAO provided us with several APNT minimum system requirements and system considerations. We were mindful that this spectrum is still used internationally for Loran-C and eLoran

---

[1] (e)Loran is used in the text when Loran or eLoran are interchangeable.

service. One of our goals includes ensuring that the various LF system concepts considered will operate harmoniously in the global radio navigation ecosystem. Alternative and complimentary frequencies in the VLF/LF/MF spectrum are also considered as we can easily apply our theories to other frequencies outside the Loran spectrum. However, repurposing this existing slice of spectrum is cost effective, meets safety, security, and economic considerations, and is life-cycle smart.

2.0 APNT System Requirements and Considerations

During an August 2010 presentation to the FAA APNT Working Group, we provided initial system concepts for an LF/MF APNT system which included transmission and reception topology which could meet the following minimum system requirements and system considerations [2]. Note that one of the minimum system requirements is a data channel and as a result our presentation focused on APNT with data services. APNT system requirements include:

- Independence from GNSS;
- Co-existence with GNSS;
- Data channel capable of 1,500 bps;
- (e)Loran remaining as possible "modes" of operation;
- Using existing "protected" spectrum, i.e., 90-110 kHz;
- UTC timing to an accuracy of at least 50 ns;
- Inherent system integrity and security;
- Certification for safety-of-life applications; and
- Navigation accuracy, availability, integrity, and continuity are paramount and provision of data should not compromise the reliable delivery of navigation information.

APNT system considerations include:

- The benefits of dual frequency system similar to GPS should be considered, i.e., 100 kHz and 300 kHz or 500 kHz;
- All modulation techniques and signal "tweaks" should be explored;
- Receivers must be "economical";
- Use of existing infrastructures is of benefit;
- System must "pay its way" for its use; and
- Signal must be available to existing installations with as little cabling or other changes as possible.

Figure 1 shows the performance of the basic LF APNT system known as eLoran [5].

Requirement	Accuracy	Availability	Integrity	Continuity
FAA RNP 0.3 (Note 1)	0.16 nm	0.999 – 0.9999	0.9999999	0.999 - 0.9999
	(307 m)		(1 x 10-7)	(over 150 sec)
Maritime Harbor Entrance & Approach (Notes 2, 3)	0.004 – 0.01 nm	0.999 – 0.9999	0.9999999	0.999 - 0.9999
	(8 – 20 m)		(1 x 10-7)	(over 150 sec)

Figure 1: eLoran Performance [5]

Note 1: Accuracy achieved using published signal propagation corrections or ASFs.
Note 2: Accuracy achieved using published ASFs and real-time differential corrections.
Note 3: Able to meet 10 meters IMO accuracy requirement for harbor or coastal operations.

3.0 Navigation Enhancements

We believe that it is equally important to examine new methods which may improve the navigation capabilities of new LF pulse positioning systems. Several enhancements to the pulse positioning system used in (e)Loran were suggested as warranting further investigation. These enhancements include:

- Improved phase codes. Phase codes should average to zero. Current (e)Loran phase codes do not.

- Pseudo-Random Noise (PRN) based phase codes. PRN-based phase codes will allow unique identification of a station in a group and will reduce cross-correlation of signals from other stations.
- Remove Master 9th pulse. In (e)Loran there is no need for a master 9th pulse. Integrity warnings (blink) will be communicated in a different way. Removing the 9th pulse will reduce cross-rate and free up time for data communication.
- Improve pulse shape. The current (e)Loran pulse shape can be improved, especially at the tail end of the pulse. This may result in a slight increase of "spill" outside the 90-110 kHz frequency band (current requirement is 1% overspill outside the band is allowed) which would need to be investigated and discussed with regulatory agencies. A shorter pulse will reduce cross-rate overlap time, and reduce transmitted power (in the part of the pulse which is not used for navigation). A shorter pulse will make shorter pulse spacing possible (more pulses in a given period of time).
- Reduce cross-rate effects. The inclusion of more stations in a group with the same GRI will lead to reduced cross-rate. All stations are to be single rated. It was decided that further investigation is warranted into the possibility to put all stations in an area into one GRI with still a sufficiently high number of pulses per second from each station for positioning and time. Additional review and investigation will be conducted into the potential benefits of a PRN type phase code which allows cross-rate to be dealt with effectively. **Appendix A** provides some additional thoughts and investigation into reducing cross-rate effects within a defined country or region by using a single and relatively long GRI.

4.0 Data Transmission Enhancements

One area where current LF systems could be improved upon is in the amount of data throughput. While current (e)Loran standards allow for some data transmission, (e)Loran stations typically transmit less than 100 Bits Per Second (BPS). There are several major issues with attempting to transmit data on the navigation pulses:

- The pulse cannot be significantly lengthened without changing the spacing between pulses, negatively affecting navigation and potentially leaving the data throughput only marginally increased;
- The relatively short duration of the pulses mean that it is difficult to use the bandwidth effectively, resulting in a mostly idle channel to avoid interference at the receiver; and
- The data rate is tied to the repetition rate, and there is a limit to how many pulses could be added to increase capacity.

Instead, a proposed method would allocate a time slice for navigation and a time slice for communications. Initially, the division being considered is 370 ms of navigation followed by 130 ms of communications, although this could be changed depending on the amount of data transmission required. This time division scheme would be used by all stations so that the communications would not interfere with navigation accuracy. Removing the restriction that the communications must be done through pulses brings up some interesting possibilities. More conventional digital communications methods can now be used to obtain much higher data rates. **Appendix B** contains a thorough analysis of data transmission in an APNT system.

5.0 Introduction of LF APNT&D System Concepts

We considered several LF system concepts and decided that three LF APNT system concepts merited consideration for further investigation and study. The study group believes that all three LF APNT system concepts have the potential to meet the minimum system requirements and system considerations. In each case, the APNT system proposed includes some sort of data channel capability, so we excluded the cumbersome "APNT&D" format. The three LF APNT system concepts are:

- LF APNT Mode 1: LF pulse positioning system for navigation and timing at 100 kHz with a limited data channel of less than 100 BPS. A separate but complimentary data channel is provided at an available VLF/LF/MF frequency with a bandwidth of 20 kHz.

- LF APNT Mode 2: LF pulse positioning system for navigation and timing at 100 kHz with an expanded data channel of 1,500 BPS.

- LF APNT Mode 3: LF pulse positioning system for navigation and timing at 100 kHz with an expanded data channel. An additional complimentary pulsed positioning system for navigation and timing with an expanded data channel is provided at an available VLF/LF/MF frequency, e.g., 300 kHz or 500 kHz. Note that we have selected 300 kHz or 500 kHz simply as reference frequencies upon which to build our conceptual system. We are not advocating their use without further study and appropriate international approvals (i.e., ITU, IMO, RTCA, RTCM, IALA, etc.).

5.1. LF APNT Mode 1 System Overview

The LF APNT Mode 1 system has the following characteristics:

- LF pulse positioning system providing positioning, navigation, and timing in the 90-110 kHz protected spectrum.
- Limited (<100 BPS) or no data channel at 90-110 kHz.
- The proposed system concept is similar to eLoran. International authorities including the FAA have shown that the eLoran system can meet the accuracy, availability, integrity, and continuity requirements for RNP 0.3 and Maritime Harbor Entrance and Approach (HEA) described as a minimum system requirement. The spectrum used for the (e)Loran system is globally protected and (e)Loran has inherent security and integrity, and system infrastructures exist in several countries including the U.S. The infrastructure of prime importance is the availability of large transmitting antennas.
- The need to offer legacy Loran-C system capability for legacy Loran-C is not required in the U.S. and as a result some further improvements can be considered to the eLoran system concept to make better use of the available resources, e.g., frequency, bandwidth, and infrastructure.
- Data channel with 20 kHz bandwidth provided somewhere in the VLF/LF/MF frequency bands to meet data channel requirements of 1,500 BPS. This allows optimal use of the available frequency bandwidth for communication purposes.
- PNT transmitters and data transmitters could be co-located and potentially di-plexed on same transmission antenna.
- The potential exists to use, re-purpose, or add additional capability to existing infrastructures (i.e., Loran-C, NDB, LF/MF

DGPS Radio Beacons, MF Telegraph/ Navtex).

- The LF PNT and VLF/LF/MF data channel could be received on the same receiving antenna and receiver.

5.2. LF APNT Mode 2 System Overview

The LF APNT Mode 2 system has the following characteristics:

- LF Pulse positioning system providing Positioning, Navigation, and Timing in the 90-110 kHz protected spectrum.
- Expanded data channel at 90-110 kHz providing a target data capacity of 1,500 BPS.
- The separation of Positioning, Navigation, and Timing from the data in time with the use of the same frequency should allow for optimization of the PNT signal and data channel signal separately.
- The system concept proposes preliminarily that 10-30% of the time is used for data transmission and 70-90% for navigation/timing. It is understood that the allowable time available for PNT and data will depend on the system's capability to first meet the system requirements for PNT accuracy, availability, integrity, and continuity while attempting to achieve a data channel capacity of near 1,500 BPS. The percentage of time allocated to PNT and data are parameters which will require further investigation.
- The system concept minimizes the effect of guard time intervals.
- Orthogonal Frequency Division Multiplexing (OFDM) modulation will be considered as a potential for the modulation scheme necessary to attain a target of 1,500 BPS for data capacity.
- The transmitted navigation pulses have a strict relationship to UTC and can be used together with the broadcast data to provide frequency stability and UTC time determination.

Appendix C contains some additional investigation and insight into the LF APNT Mode 2 system concept.

5.3. LF APNT Mode 3 System Overview

The LF APNT Mode 3 system has the following characteristics:

- Long range LF pulse positioning system providing Position, Navigation, and Timing in the 90-110 kHz protected spectrum which also contains an expanded data channel with a goal of 1,500 BPS.
- Shorter range pulse positioning system (100-200 km) providing Position, Navigation, and Timing somewhere in the VLF/LF/MF frequency bands which also contains a data channel with greater capacity than that provided at 100 kHz.
- The dual-frequency system may provide additional information regarding the transmission path between transmitter and user, and therefore lead to further increases in accuracy.
- The shorter range system could benefit from less skywave effects and therefore have a higher pulse rate. (Faster rise time can only be achieved in a wider bandwidth, which may not be viable moving forward).
- Transmission systems could be co-located and potentially diplexed on the same transmission antenna.
- The potential exists to use, re-purpose, or add additional capability to existing infrastructures (Loran-C, NDB, LF/MF DGPS Radio Beacons, MF Telegraph/ Navtex).
- We expect that both systems would be received on the same receiving antenna and receiver. However, this would require additional study.

6

6.0 Additional LF APNT System Benefits

6.1. Repurposed Infrastructure

In North America, any of our proposed LF system concepts can be spring-boarded to quicker operation by using some of the infrastructure that was made available when the U.S. and Canadian Loran-C systems were terminated. The key infrastructure assets include the tall transmitting antennae, the input electrical power, and the telecommunications lines. The 625- and 700-foot transmitting towers are easily adapted for use across the LF band, are in good repair, and are already annotated on Sectional Aeronautical Charts.

The other infrastructure assets, including installed electronic and electrical equipment, are not necessary. Our proposed solutions can easily fit inside commercial-grade, ISO-standard, or militarized CONEX boxes, can be situated next to existing transmitting towers, and can be installed in about a day (not including any requisite civil engineering work). Our transmitters are extremely efficient (73% as compared to traditional/legacy transmitters operating at ≤ 44% efficiency), so prime power, backup power (e.g., generators, UPS, etc.), and HVAC requirements are significantly smaller than in previous generations. We are not proposing that all of the existing (e)Loran sites be repurposed; only that the transmitting towers and electrical/communications infrastructure be maintained in the interim as possibilities for future use.

The application of existing infrastructure not only applies in the U.S., but also world-wide. The flexibility of the Nautel NL series multi-mode LF transmitter allows for a variety of existing and new antenna configurations and given the reduced Size, Weight and Input Power (SWAIP) of the transmitter, large infrastructure is not required. LF stations (e.g., Loran-C, eLoran, and LFPhoenix™) are capable of operating on generator power and require no pre-existing infrastructure, although pre-existing power and communications infrastructure would be ideal.

6.2. Wide Area or Localized Stratum-1 Timing Sources

Our proposed LF options could be used to coherentize a network of users who require GNSS independence or are operating in an area where GNSS reception is marginal. Any option provides frequency syntonization at the Stratum-1 level and time synchronization (to UTC) at the sub-50 ns level.

6.3. Costs of Deploying LF options

For each LF option, the transmission site costs are relatively equivalent. A representative LF solution using our small footprint solution loaded into a repurposed 700-foot Top Loaded Monopole (e)Loran antenna, and providing 425 kW of Effective Radiated Power, would be significantly less expensive than traditional/legacy systems. A typical small footprint site would include an appropriately sized CONEX/ISO enclosure, and all required timing, control, monitoring, and transmission equipment for the site. Depending upon the requirements, civil engineering work, Two-Way Satellite Time Transfer (TWSTT) technology, installation services, electrical infrastructure, telecommunications infrastructure, prime or backup power, UPS, or associated items might also be necessary. Our representative system is easily scalable upward and downward, including an appropriately sized small footprint transmitting antenna.

6.4. Avionics Considerations

For use in aeronautical applications, the avionics equipage issues for each LF option are also relatively equivalent. In each case, the proposed technology must be integrated into the cockpit. Irrespective of the technology used, future cockpits must be equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) technology. Including the requisite LF technology as a sensor input of any ADS-B equipage is only incrementally more complex or costly. The critical issue is accessing appropriate antennae on the exterior of the airframe without having to pierce the body. In this case, one solution we recommend is multi-purposing the ADF cable as a broadband pipe for both the ADF and our LF receiver antenna.

6.5. LF/MF Transmission System Expertise – Nautel, Inc.

Nautel has more than forty (40) years of experience in the design, manufacture, and support of highly reliable and state of the art LF/MF Navigation, MF Telegraph/Navtex and MF broadcast transmission systems. Nautel's Multidisciplinary Research & Development team of over thirty (30) technical staff possess the design skills and complete system experience enabling them to design LF/MF systems which exceed customer expectations.

Since designing and manufacturing the first solid state radio beacon, Nautel has supplied more than 3,800 LF/MF navigation and communication systems worldwide which are typically installed in remote locations and in environments that range from arctic to desert to tropical jungle. Field data indicates that Nautel Navigation transmitters have an MTBF of 3,000,000 hours. In addition Nautel has designed and manufactured more than 2,700 MF Broadcast transmitters worldwide and is considered a world leader in this field.

In 2008 Nautel's design team developed innovative and patent-pending technology as part of a proof-of-concept transmitter designed to demonstrate alternative solid-state transmitter solutions are available for use in (e)Loran systems. The proof-of-concept transmitter was successfully operated on the air at the USCG Loran Support Unit, Wildwood, NJ in May 2008. Nautel has subsequently presented several papers on this leading edge LF technology and on alternative LF antenna system designs. In October 2009, Nautel was presented with the "International Loran Association's John M. Beukers Award for Technical Innovation" as a result of their development of an "innovative new Loran-C and eLoran transmitter."

Nautel's experience in the design, manufacture, installation and support of these LF/MF systems provides a solid foundation for the design, manufacture, and supply of LF/MF PNT&D transmission systems which meet or exceed current international requirements and objectives.

6.6. LF Receiver and System Integration Expertise – UrsaNav, Inc.

UrsaNav has almost four decades of experience and extensive expertise in designing, developing, implementing, and supporting Loran, eLoran, LFPhoenix™, and associated LF systems. UrsaNav, along with its partners Nautel and Symmetricom, are committed to providing industry-leading, end-to-end solutions for the LF ecosystem including:

- Special purpose, tactical, and temporary transmitting antennae;

- Operations into available "antennae of opportunity" such as AM broadcast, DGPS, and GWEN antennae;
- State-of-the-art, high-efficiency, multi-mode transmitters;
- Precision timing and frequency solutions (including TWSTT);
- Data channel solutions (Loran Data Channel (LDC), 9th pulse, 10th pulse, Eurofix, CDMA, TDMA, OFDM, DSSS, etc.);
- User-grade, timing-grade, monitor-grade, reference-grade, differential, or scientific-grade receivers;
- Associated command, control, and communications solutions;
- Equipment and system monitoring solutions;
- Containers and housings; and
- Installation, documentation, certification, training, and follow-on support.

UrsaNav recently purchased the complete technology assets of a globally known and well-respected PNT receiver company: Locus, Incorporated (Locus, Inc.). UrsaNav also purchased the Intellectual Property (IP) of another eLoran receiver manufacturer, CrossRate Technology, LLC. UrsaNav is building upon proven receiver technology to develop the next generation of Loran-C, eLoran, LFPhoenix™, and LF receivers.

7.0 Conclusions

This paper, along with its appendices, demonstrates that our proposed LF system concepts provide a valuable APNT solution, and can meet the APNT analysis objectives. [1] Our LF options:

- Meet minimum requirements for Maritime Harbor Entrance and Approach (HEA);
- Meet the minimum system requirements for aviation Performance Based Navigation (PBN) RNAV and RNP for enroute, terminal, and non-precision approach operations equivalent to RNP 0.3;
- Are independent of, but can co-exist with, GNSS;
- Include data channel capabilities of at least 1,500 BPS;
- Ensure Loran-C and eLoran remain as "modes" of operation ("do no harm" internationally);
- Use existing "protected" spectrum at 90-110 kHz;
- Provide UTC timing to an accuracy of at least 50 ns;
- Provide integrity and security (advanced security such as geo-encryption are available);
- Are inherently Safety-of-Life because of their "DNA";
- Ensure navigation accuracy, availability, integrity, and continuity are paramount and provision of data does not compromise the reliable delivery of navigation information;
- Provide multi-modal APNT&D service (aviation, maritime, land mobile, location-based, time & frequency);
- Provide a common non-GNSS time reference;
- Avoid recapitalization costs in the U.S., estimated at $1.0B for some APNT options under consideration, and leverage existing infrastructure world-wide; [Note that a complete LF APNT solution that covers the National Airspace System (NAS) of the United States is estimated to cost between $85M and $100M, or one-tenth that of some options.]
- Potential exists to use, re-purpose, or add additional capability to existing infrastructures (Loran-C, NDB, LF/MF DGPS Radio Beacons, MF Telegraph/ Navtex) minimizing deployment costs.

Our LF options can co-exist within the international LF ecosystem (Loran-C and

eLoran), bridge GNSS capability gaps, provide users services that are interchangeable with GNSS, and contribute to the detection and mitigation components of the United States DHS' *Interference Detection and Mitigation (IDM)* and the United Kingdom's *GNSS Availability, Accuracy, Reliability and Integrity Assessment for Timing and Navigation (GAARDIAN)* programs.

We have already developed a high-efficiency, small footprint, LF system and have deployed it at Cape May, NJ for operational testing [6]. Our LF solutions include a combination of fully developed and proof-of-concept technology that can easily be repurposed for research and development and as solutions to meet world-wide APNT requirements.

We are also building upon proven receiver technology to develop the next generation of Loran-C, eLoran, LFPhoenix™, and future LF PNT&D receivers that meet user requirements for cost, performance, and small form factor.

8.0 Recommendations

Government-, academic-, and industry-sponsored evaluations consistently conclude that LF solutions, specifically eLoran, provide the best alternative PNT source when GNSS is not available. LF solutions are technically feasible, truly multi-modal, cost effective alternatives and complements to GNSS and its augmentations. LF solutions are completely interoperable with and independent of GNSS, with different propagation and failure mechanisms, plus significantly superior robustness to radio frequency interference and jamming. LF solutions provide a seamless backup, and their use will deter threats to national and economic security.

We recommend that LF options receive the highest consideration as alternative solutions for the international PNT community.

References

1. Eldredge, Leo; Enge, Per; et al, "Alternative Positioning, Navigation & Timing (PNT) Study", International Civil Aviation Organisation Navigation Systems Panel (NSP) Working Group Meetings, Montreal, Canada, May 11-27, 2010.

2. Schue, C. A.; Stout, C. R.; Zwicker, K., "LF Phoenix™ - Next Generation Low Frequency APNT", presentation at the FAA APNT Public Meeting, Stanford, CA, USA, August 10-12, 2010.

3. Side Question Directed to Industrial Members during the 49th IALA Council Meeting, Marseilles, France, June 22 - 24, 2010.

4. 49th IALA Council Meeting Draft Conclusions and Recommendations, IALA Bulletin 2010/2.

5. International Loran Association, "Enhanced Loran (eLoran) Definition Document", Version 1.0, October 16, 2007.

6. Schue, C. A.; Stout, C. R., "Designing, Developing, and Deploying a Small Footprint eLoran System", Institute of Navigation International Technical Meeting, San Diego, CA, USA, January 2010.

Appendix A: Preliminary Proposed System Structure for Transmission of Low Frequency (LF) Pulses

Cross-rate is a phenomenon in a pulsed Time Division Multiple Access (TDMA) system where pulsed transmissions interfere with each other at the receiver due to transmitters broadcasting at different repetition intervals. Because of cross-rate, the amount of usable pulses from a distant transmitter may be reduced by 40% or more, due to transmissions from other transmitters operating at a similar or closer range.

Initial studies have shown that by a re-arrangement of the broadcast scheme, cross-rate from the three transmitters nearest to the user from any transmitters within at least d=10,000 km distance to the user can be eliminated. Parameter d should be chosen sufficiently large so that any distortion caused by transmitters operating at a distance larger than d is safe to be simply ignored by a receiver.

The re-arrangement involves moving every transmitter into the same repetition interval (GRI), whereby every transmitter is placed in one out of n possible timeslots. All transmitters sharing a timeslot will broadcast at exactly the same moment in time. Transmitters at sufficient distance from each other can share a timeslot. Given enough distance differential, a user operating near a transmitter operating in timeslot t can easily distinguish that transmitter from more remote transmitters operating in the same timeslot, since the transmissions from the nearest transmitter will be received before any others. The arrangement is such that the stations closest to any user location never share a timeslot, so that their signals never overlap when they are received by the user. For the Continental U.S., it was found that using n=6 timeslots seems sufficient to provide the described properties based on the existing Loran transmitter locations.

The length of a single timeslot should be sufficiently long so that the signals from all stations sharing that timeslot within distance d are be received by the user before the next timeslot begins. For d=10,000 km, this means that a single timeslot should be approximately 33 milliseconds long. The repetition interval (GRI) would then be n times the length of a single timeslot.

The signal to be transmitted in each timeslot, including the number of pulses and possible data content, is yet to be determined. Identification of each transmission will likely be done by including a station ID into the data broadcast. The guarantee that the signals from the transmitters that will yield the best positioning accuracy can be achieved free of cross-rate interference should give an improvement in positioning accuracy and availability over existing LF positioning methodology. The proposed transmission scheme can be extended to include more sites when lower-power transmissions are used.

Figure A1 shows an example division of twenty-one existing transmitter sites into six timeslots. Every transmitter site is color coded in red, blue, green, cyan, magenta, or black. Transmitters sharing a color transmit at exactly the same moment. Cross-rate that does occur will only distort signals that are not necessary for accurate positioning at that location. With d=10,000 km and n=6, the effective GRI length would be 200 ms.
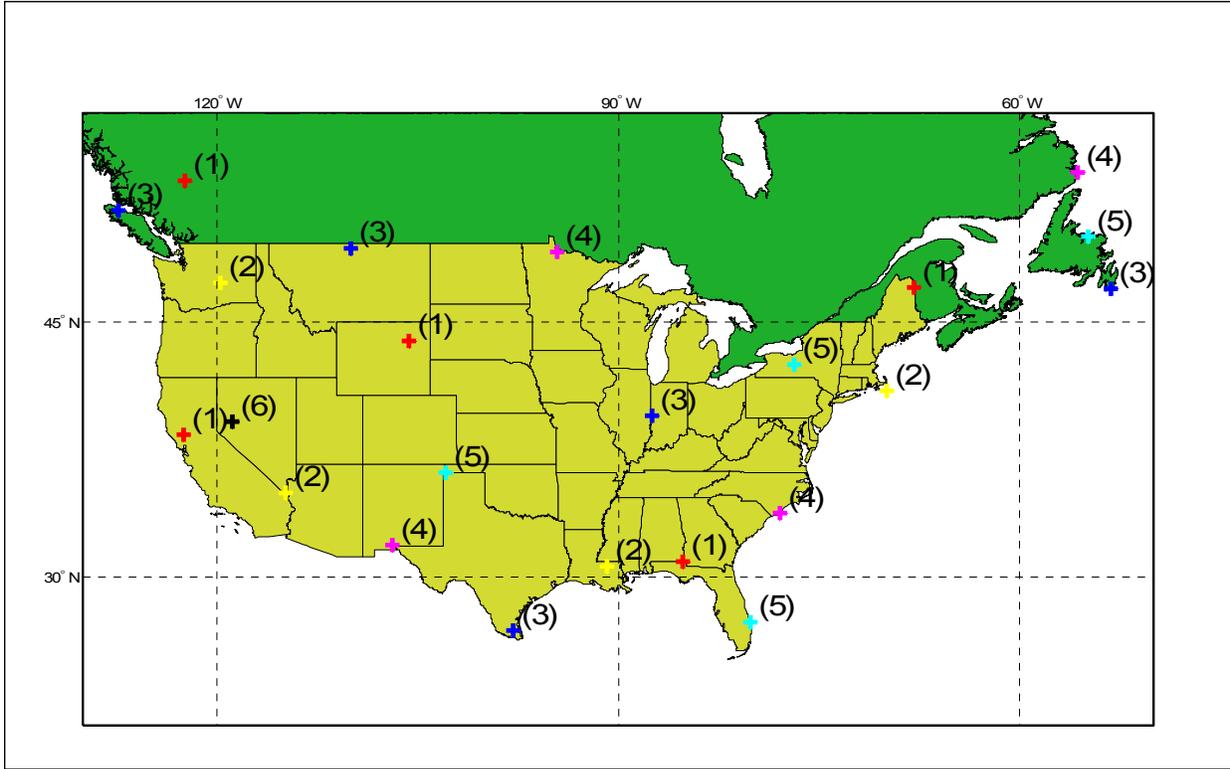
**Figure A1: Example division of 21 existing transmitter sites into six slots**

Appendix B: Preliminary Investigation into Data Formats for Low Frequency (LF) Positioning, Navigation, Timing, and Data (PNT&D)

Because all of the stations in an Alternative PNT (APNT) system are transmitting their communications at the same time, in the same channel, the scheme used must deal with allowing multiple access. There are several possibilities that immediately present themselves:

1. Code Division Multiple Access (CDMA). In a CDMA scheme, each transmitter is assigned a unique pseudorandom sequence, or code that is used to frequency spread the transmitted signal. This type of scheme is used in several communication systems where a large number of narrowband users must share a wider frequency channel such as with cellular telephones. It is also used for GPS satellites since it allows for precise timing information to be extracted. Unfortunately, many of the benefits of CDMA would be difficult or impossible to realize at LF. There is not a large amount of bandwidth available and the number of transmitters is fairly small compared to a typical CDMA system so the frequency spreading is not very large. This translates into small gains in the noise floor and in terms of eliminating interference. In addition, the large geographical distances involved with LF navigation make it impractical to synchronize the signals as seen by the receiver, resulting in the system having a large amount of self-interference.

2. Frequency Division Multiple Access (FDMA). In this type of system, the channel is typically subdivided into several narrower bandwidth channels with the transmitters operating independently. For an LF system that is also transmitting navigation pulses, this will result in much higher transmitter peak voltage requirements for those sites that have channels further away from the center frequency. Practically, this would mean that the channels would be very narrow, resulting in low data capacity.

3. Time Division Multiple Access (TDMA). The pulsed system is already effectively operating in this mode. The main disadvantage of this type of system is a result of the large areas covered by LF navigation. In order to minimize the interference between transmitters, large guard intervals will be necessary otherwise the propagation delay of further transmitters would result in interfering signals at the receiver.

4. Orthogonal Frequency Division Multiple Access (OFDMA). With OFDM, the channel is subdivided into a large number of carriers originating from a single transmitter. This allows for longer symbol times, spreading the effect of impulsive noise and better frequency utilization. The difference in OFDMA is that different sets of carriers are used by each transmitter, allowing for the same channel to be shared by several transmitters without interference. Because the power from each transmitter is approximately centered on the same frequency as the navigation pulses, the requirements for all sites are similar and the existing Antennae Tuning Unit (ATU) and antenna could be used without modification. The main disadvantage with an OFDM signal is that it can contain very large peaks relative to the average power in the signal.

Due to the advantages offered by OFDMA, this signal scheme is proposed for the communications portion of the LF APNT signal. It will allow all transmitters to occupy the

channel simultaneously, without making it overly difficult by having any of them off frequency from 100 kHz. The chosen scheme is both time and bandwidth efficient, and the signal has been designed to take advantage of the additional power possible from 95-105 kHz, with lower power carriers occupying the remainder of the bandwidth. The signal contains 99.9% of the power within the bandwidth from 90-110 kHz, easily meeting the current restrictions on out of band power. A power spectral density plot of the signal is shown in *Figure B1*.
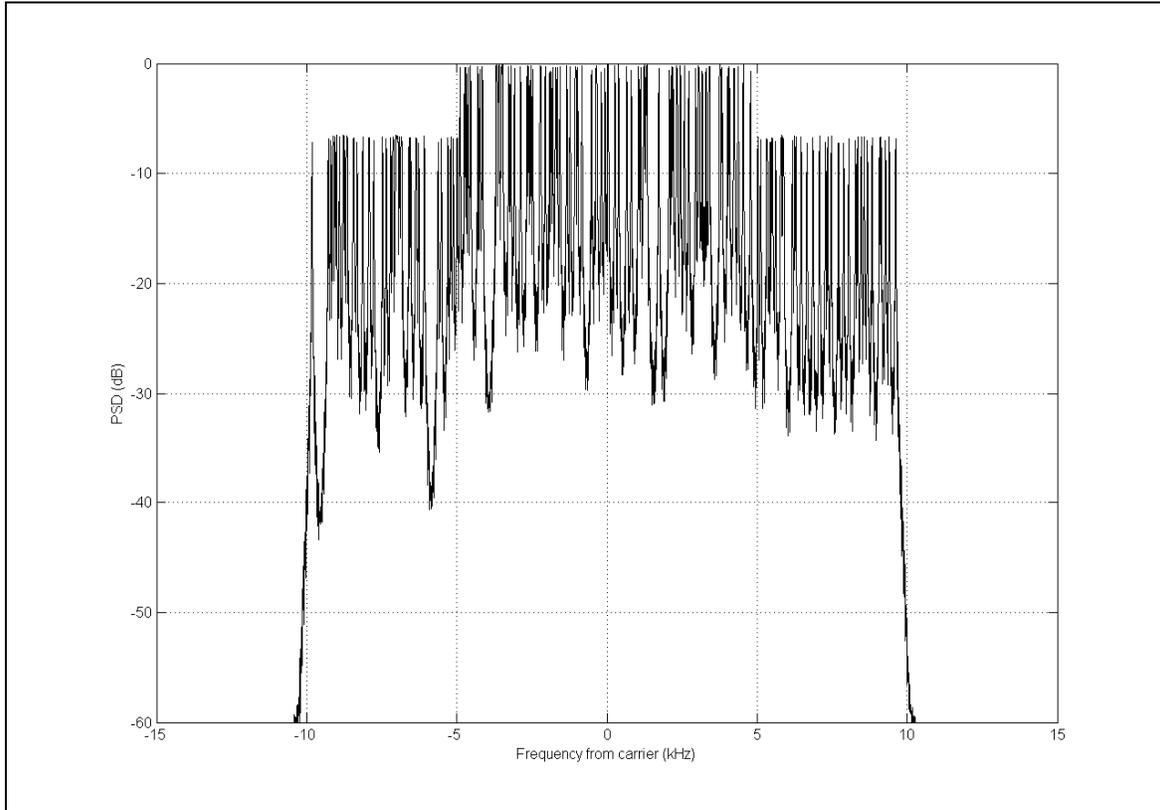
**Figure B1: Power spectral density of the proposed signal using a
10 Hz resolution bandwidth**

The initial parameters chosen for the OFDMA are shown in *Table 1*. With a 24.4 Hz carrier spacing, there are 4025 total carriers in the 20 kHz channel. To support the multiple access technique, these are divided into five sets to be assigned to the transmitters, giving 805 carriers per transmitter. There are five pilot carriers modulated with BPSK, at one bit per carrier in each symbol. Correspondingly, the QPSK carriers have four possible states, giving two bits per carrier and the 16 QAM carriers have 16 possible states, giving four bits per carrier. With five pilots, 78 QPSK carriers, and 78 16 QAM carriers, the total data per symbol is given as 473 bits. With a 26% time slice allocated for data, and a 43.52 ms symbol time, the system would transmit six symbols per second, giving a raw bit rate of 2,838 BPS. For reliable reception, 30-40% of the bits would likely be allocated for forward error correction, such as with a 2/3 rate convolution encoder, so the remaining capacity should be in excess of the target of 1,500 BPS.

Raw bit rate	473 bits/symbol per transmitter
Symbol duration	43.52 ms
Symbol rate	23 Hz
Modulation	QPSK/16 QAM on data carriers
	BPSK on pilots
Number of carriers	805 total, 161 per transmitter
	5 BPSK pilot carriers
	78 16 QAM carriers
	78 QPSK carriers
Carrier spacing	24.4 Hz

Table 1: OFDMA signal parameters

There are several considerations when designing a communications signal. The carrier spacing and the symbol duration are very closely related. The carrier spacing must be large enough to easily handle the Doppler shifts that could be possible with a mobile user. Because of the low carrier frequency, even a user traveling at Mach 5 would only experience a 0.55 Hz offset, which is still only a small fraction of a frequency bin; the receiver would have no issue receiving the signal. Conversely, the symbol time should be long enough that the effects of impulsive noise are spread out, but short enough to keep the throughput delay reasonable. The values chosen meet both criteria.

One of the most difficult parameters to choose is the modulation type for the signal. The factors that determine it are the transmission environment, since that will determine the received signal to noise ratio, and the desired bit error rate of the system. With this transmitted signal, the raw bit error rate should be below 0.1% at the receiver, so with coding it could easily be brought to the 0.0001% range or lower, depending on the system requirements. From there, any remaining errors could easily be detected by using proper techniques, such as an appropriate length Cyclic Redundancy Check (CRC). The received SNR in the channel versus bit error rate is shown in *Figure B2*.
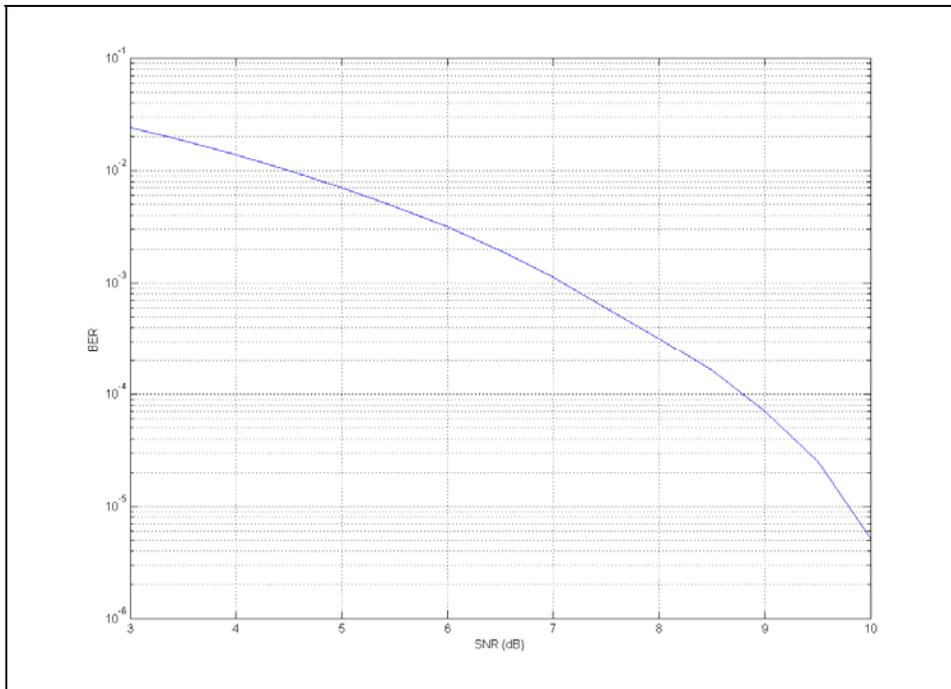
Figure B2: Uncoded bit error rate vs. received SNR for the proposed signal

The system has initially been configured for five different sets of carriers; allowing five transmitters to operate without any interference, but that number would need to be determined based on a frequency planning and reuse strategy. A bare minimum number would be three, since at least that many transmitters are required for navigation, but it should be higher to handle unwanted signals from adjacent Loran channels. A consequence of allowing more transmitters to operate simultaneously is that it would lower the throughput from each individual transmitter, although potentially the receiver could receive the multiple transmissions simultaneously.

Equalization:

One of the properties of the typical Loran channel is that it includes sky wave propagation of the signal. This additional signal path requires that the navigation portion of the system be pulsed in order to avoid interference, since it relies on measuring the propagation delay from the transmission site to the receiver. For data communications, the signal itself is important, rather than the delay, so the sky wave signal can be used to enhance the received signal strength. Due to variations in the antenna and the channel, particularly at night when the sky wave component is strongest, the received data signal will require equalization in order to be received properly. This can be accomplished in two ways.

The navigation pulses are very well defined, and have frequency components over the entire communications bandwidth. They can effectively be used as a training signal to measure the channel, allowing for an equalizer to be developed in the time domain. This equalizer can then correct for variations in frequency and group delay across the channel created by the various signal paths.

Once an approximate equalizer has been determined using the navigational pulses, pilot carriers in the signals from each transmitter can be used to detect minor variations in the frequency response and group delay in the channel. Both equalizers would need to be determined for each transmitter being received.

Signal Strength:

Initial investigations have shown that the proposed signal could be transmitted with a similar peak power to the navigation pulse coming from the same transmitter. This signal is unlike the traditional navigation pulse, and would require a transmitter capable of handling a more general signal. One similarity to the navigation pulses is that the transmitter must still be capable of sourcing and sinking current from the antenna in order to produce the desired waveform. For the purposes of considering the feasibility of transmission using a real antenna, a system Q of sixty will be used, assuming an antenna Q of fifty-five and a transmitter filter Q of five. The frequency response of this antenna is shown in *Figure B3*.
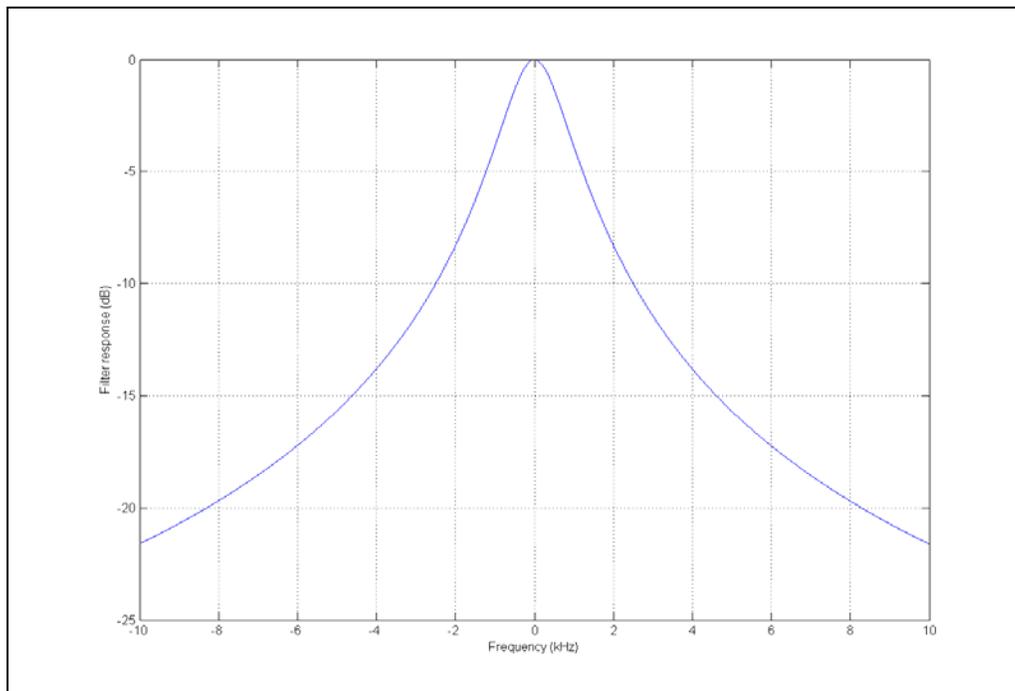

**Figure B3: Frequency response of a transmitter filter
and antenna with a combined Q of 60**

Due to this frequency response, a certain amount of transmitter overhead would be required for the navigation pulses. With a Q of sixty, the required voltage from the transmitter would be more than five times that actually applied to the radiation resistance. The driving waveform is shown at baseband in *Figure B4* along with the desired pulse for reference.
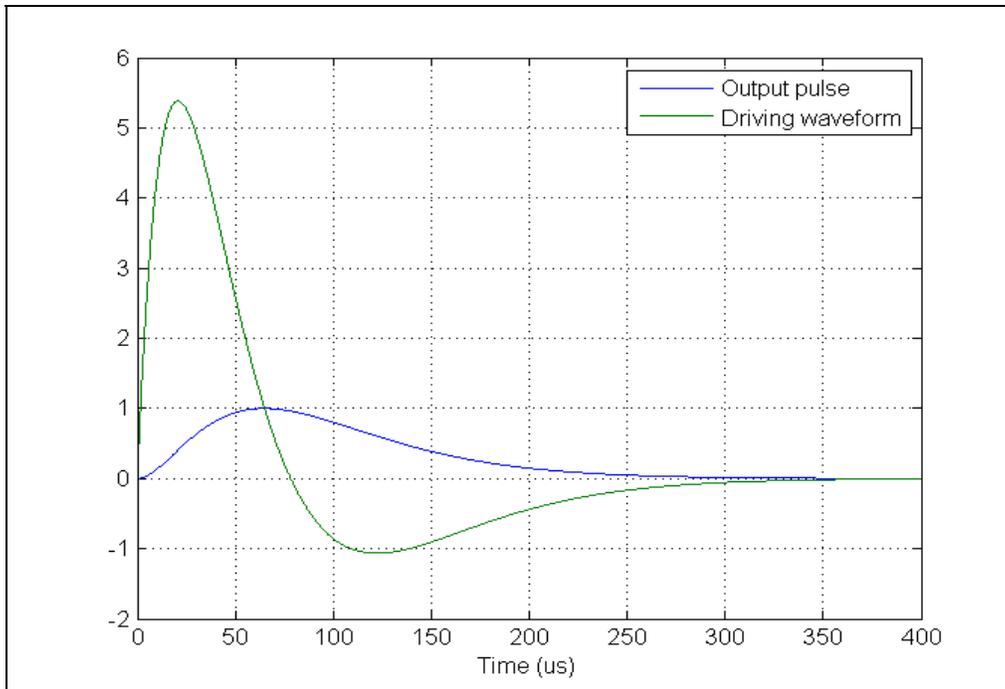
Figure B4: Desired Loran pulse along with the driving waveform required to achieve it into an antenna system with a Q of 60

The same demonstration can be made with the proposed communication signal. One of the disadvantages of OFDM is its relatively high peak to average power. Typically the signal peaks would be limited at a reasonable ratio where the limiting would have little effect on the quality of the signal. For this analysis the signal will be limited to 10 dB peaks, which should be a rare event in any case. The Complementary Cumulative Distribution Function (CCDF) of a signal is used to determine the probability of exceeding a given power level relative to the average. It shows the probability of clipping the signal and can help determine the necessary transmitter overhead. The signal CCDF can be seen in *Figure B5*, and shows that the probability of limiting the signal is approximately $5e^{-5}$. This will correspond to the signal being limited approximately once every 3.8 seconds, for a bandwidth of 20 kHz at six symbols per second.
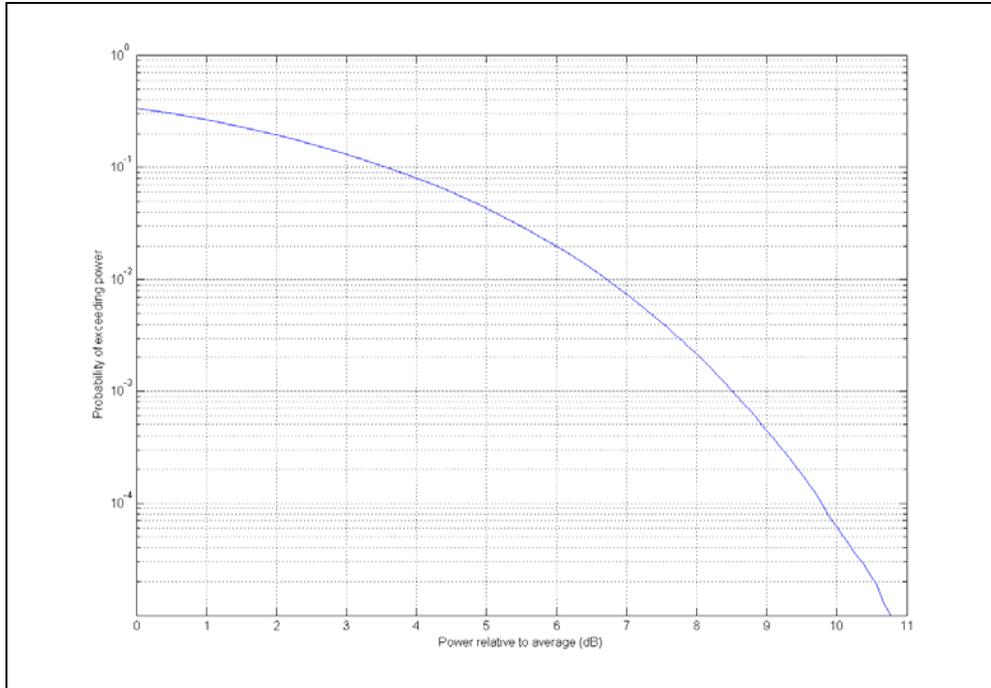
Figure B5: Signal CCDF, showing the probability of exceeding various power levels relative to the average

Based on this signal, a transmitter capable of outputting a certain peak navigation pulse power would be able to output 9.7 dB lower continuous OFDM power. The amount of overhead required for the navigation pulse and for the OFDM is very similar. If more power were required, it would be possible to more aggressively limit the peaks, at the expense of minor degradation of the signal at the receiver.

Synchronization:

With an OFDM signal, the receiver needs to be able to properly synchronize in order to decode the signal. This can be challenging particularly at the edges of the service area. Normally, this would be handled by having pilot carriers and using tracking algorithms to determine the symbol start time and frequency offset. An additional benefit of the navigation pulses also being present in this system is that the timing can be determined accurately and with relative ease. The carrier frequency can also be extracted from the pulses, allowing for any frequency offset to be identified and compensated. Several pilot carriers have still been included, although they are modulated with Binary Phase Shift Keying (BPSK). This allows them to be used to track any fine changes in the delay, and will improve the received bit error rate.

Appendix C: Preliminary Analysis of the Time Slice Allocations for Low Frequency (LF) Alternative Positioning, Navigation, and Timing (APNT) Mode 2

While positioning/timing pulses require a strict relationship between their broadcast time and system time or UTC, data communication does not require this strict relation. In short, for positioning we know what we will receive but the time of reception is unknown (this leads to the ranging information). For data communication we only know what sort of modulation we expect to receive, but the receiver does not know the data beforehand (which would make a data broadcast system useless otherwise). The information lays in the unknown modulation symbols which need to be detected and the uncertainty of the received signal shape make data signals more difficult for navigation.

The proposed LF APNT system separates Positioning, Navigation, and Timing (PNT) from Data (PNT&D) in time but uses the same frequency. This allows for optimization of the signal shapes for PNT and data separately. The time slices division available for PNT and data will depend on the requirements for PNT accuracy and data bandwidth (BPS). Preliminary, these time slices have been assigned 10/30% for data communication and 90/70% for PNT, but remain a parameter in the design.

The data communication time slice is shared among all data broadcast sites. The OFDM modulation technique ensures that the transmitters do not interfere with each other. All stations broadcast at the same time in the data time slice. It is assumed that the closest data broadcast station provides all vital information for the application and although reliable reception of more than one data stream is very well feasible it may not be required for minimum operation capabilities.

The PNT time slice is organized in a Time Division Multiple Access (TDMA) fashion. The PNT signals will most probably be pulsed signals on a 100 kHz carrier wave to be able to distinguish between groundwave and skywave reception. The TDMA is organized in such a way as to minimize or even eliminate cross-rate (reception of signals from more than one station at the same time). It needs to be verified if a TDMA scheme can be designed with a larger number of geographically separated transmitters (e.g., 600-1000 km apart) with no cross-rate from nearby stations (e.g., as close as 2,000-3,000 km) or no cross-rate at all.

Figure C1 depicts the time sequence of the LF PNT&D system. At the start of the data communication time slice, all data broadcast transmitters broadcast their data messages using their designated OFDM subcarriers. After the DCTS, a guard time with no transmission from any transmitter follows. This guard time is necessary to make sure that all data signals have propagated to the user or sufficiently decayed before any user receiver in the service area starts to receive the navigation pulses of PNT1. Subsequent guard times are necessary between any two consecutive transmissions from two transmitters in the group in order to make sure the signals will not overlap at any user receiver in the service area.
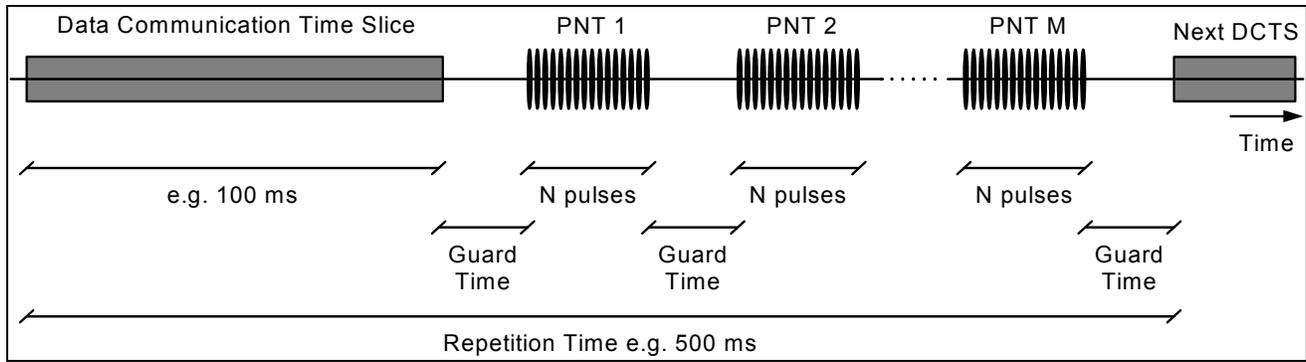
**Figure C1: Time sequence of a possible LF PNT&D system**

Each transmission from a PNT transmitter consists of N pulses. The optimal number for N is subject for further study. A larger N allows for more optimal PRN type phase codes and provides more navigation signal power, while reducing the total guard time necessary. The repetition time is determined by the total number of M transmitters in the same repetition group, by the duration of each group of N pulses and by the cumulative guard times needed to cause no overlap between station signals. A larger repetition time allows more PNT transmitters in the same group but increases the receiver update time for each transmitter. It is anticipated that the PNT receiver will at a minimum provide updated measurements once per second.

Figure C2 and *Figure C3* show the time domain and frequency domain response of three different pulse shapes. In red is the standard Loran pulse shape, in blue is a symmetrical pulse with the leading edge of a standard Loran pulse as leading and trailing edge. In green is a raised cosine shaped pulse. All pulses have the same maximum amplitude at the top at 65 µs.
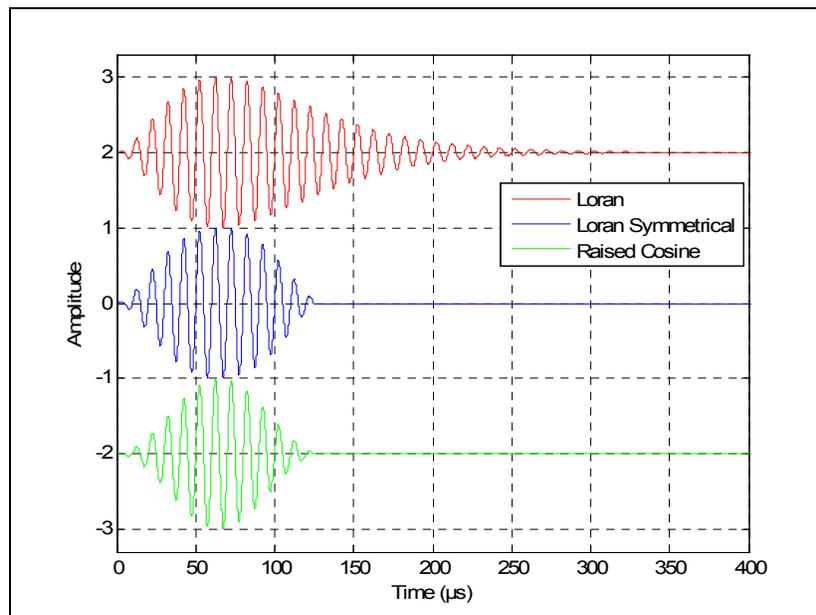
Figure C2: Time domain response

From the time domain figure, it can be concluded that the Loran symmetrical and raised cosine pulses are significantly shorter, which reduces cross-rate. Further, the power spectrum shows a lower total of radiated power as compared to the standard Loran pulse with a slightly increased spill over outside of the assigned frequency band of 90-110 kHz. The symmetrical Loran pulse remains better within the 90-110 kHz frequency band than the raised cosine pulse. Based on these results a symmetrical Loran pulse is favored over the other two.
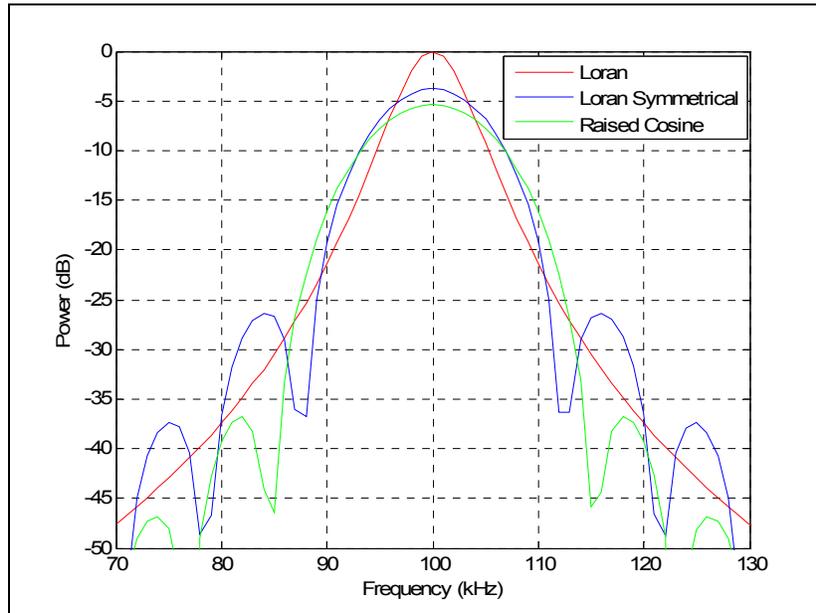

Figure C3: Frequency domain response

Shorter transmitted pulses will also reduce cross-rate duration and power from remote stations, be it through groundwave or skywave propagation. An additional benefit in the use of a shorter pulse is the reduction of intrapulse spacing of one ms to 500 ms or lower. Typical Skywave conditions in which the receiver should still be able to perform within the minimum system requirements are as follows [Draft RTCM SC127 MPS for eLoran receivers]:

The receiver shall acquire and track, in the presence of skywave interference with delays from 37.5 µs and greater. The acquisition and tracking must occur with skywave signals having signal levels (SGR) of up to 12 dB to 26 dB relative to the desired signal for skywave delays of 37.5 and 60 µs, respectively. For skywaves with values of delay between 37.5 and 60 µs, the maximum relative skywave level is linearly interpolated from the values at 37.5 and 60 µs. For delays greater than 60 µs, 26 dB is specified. This tracking shall be achieved without any change in the overall performance from the case where no skywave exists.

Figure C4 shows a simulated, received, composite pulse consisting of a groundwave with a 12dB stronger skywave starting 37.5 µs after the groundwave. *Figure C5* illustrates a simulated, received, composite pulse consisting of a groundwave with a 26 dB stronger skywave starting 60 µs after the groundwave. In *Figure C5*, the standard Loran pulse shape shows significant residual skywave components well above 350 µs of the start of the

groundwave, whereas the skywave for the shorter pulse shapes is down to zero before 200 μs after the start of the groundwave. Even with some room for margin the intrapulse spacing for a shortened pulse might be reduced to 300 μs (to be verified). Any longer delay skywaves need to be cancelled through a proper choice of PRN-like phase codes.
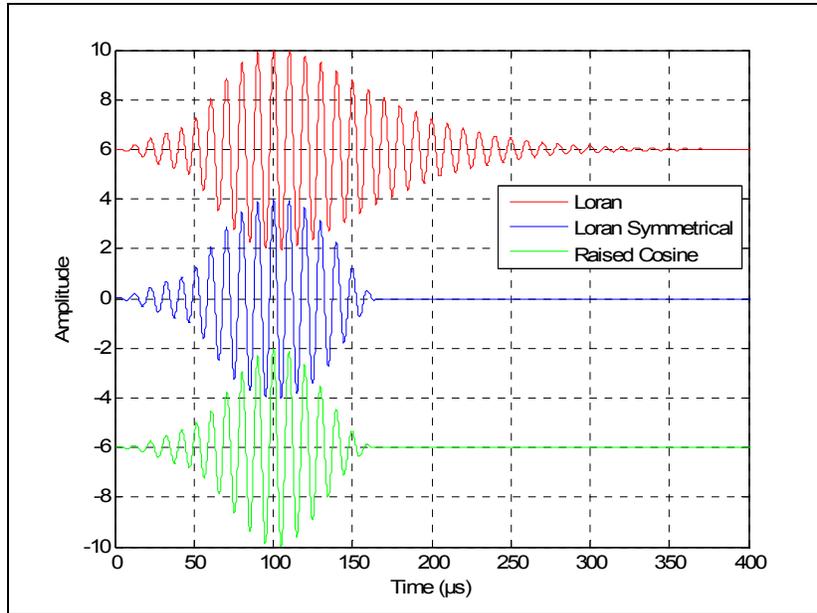
Figure C4: Simulated, received, and composite pulses with 12 dB stronger skywave
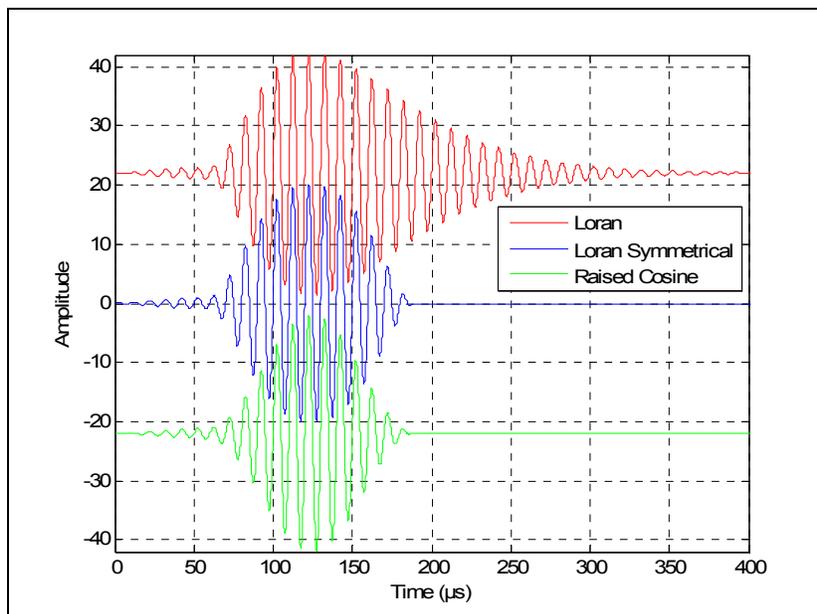
Figure C5: Simulated, received, and composite pulses with 26 dB stronger skywave