Enhanced Loran-C Data Channel Project

Benjamin B. Peterson *Charles A. Schue, III*
James M. Boyer *James R. Betz*
United States Coast Guard

Abstract

This is the first report of a continuing effort to increase the data carrying capability of the Loran-C Data Channel using combinations of previously developed modulation techniques. This paper discusses the joint effort and status of the evaluation of viable data formats and technology to permit the modulation and demodulation of data messages transmitted using the Loran-C signal. Some limiting factors and constraints that must be overcome in order to use Loran-C as a "high-speed" data channel are also addressed. Four different methods of placing intelligence within the Loran-C signal are discussed:

- *Pulse-Position Modulation (PPM),*
- *Supernumary Interpulse Modulation (SIM),*
- *Intrapulse Frequency Modulation (IFM), and/or*
- *Hybrid combinations of these.*

This paper presents historical efforts and current research into these modulation schemes, including development of a test and transmission site at the U.S. Coast Guard Loran Support Unit. Some simulations conducted at the U.S. Coast Guard Academy, and tests conducted at the LSU are also included. Finally, some future goals are presented.

Introduction

The Fiscal Year 2000 Congressional budget provided funding to the Federal Aviation Administration (FAA) for "further development of the Loran-C navigation system". Subsequently, the FAA has jointly tasked the U.S. Coast Guard Academy (USCGA) and the U. S. Coast Guard Loran Support Unit (LSU), in conjunction with other federal, commercial, and academic participants, in the continued development of Loran-C. The current FAA effort is designed to assess Loran developments in four key task areas:

1) Development of a Loran H-field antenna suitable for aircraft installation,

2) Development of an RTCA DO-194 / FAA TSO-C60b compliant Digital Signal Processing (DSP) Loran receiver,

3) Development of enhanced Loran Communications capability for GPS integrity and potentially for GPS correction data, and

4) Development of a hybrid GPS/Loran receiver architecture.

This paper will concentrate on the third of these four objectives. The LSU and the USCGA, in cooperation with Stanford University, are developing an enhanced Loran-C Communications capability for Global Positioning System (GPS) integrity, and potentially for GPS correction data. Specifically, the following activities are planned:

1) The LSU will acquire a Loran modulator suitable for use with solid-state transmitters,

2) The LSU will prepare the LSU to serve as a test and transmission site,

3) The USCGA will design, assess, and evaluate Loran-C data channel format(s), with an emphasis on receiver design, development, and testing, and

4) Stanford University will design, assess, and evaluate Loran-C data channel format(s).

Stanford University and the Coast Guard Academy are researching and developing several different modulation schemes for simulation and real-world testing. Thus far, efforts are concentrated on further developing techniques that have previously been proposed, or that have actually been demonstrated:

- Pulse-Position Modulation (PPM),
- Supernumary Interpulse Modulation (SIM),
- Intrapulse Frequency Modulation (IFM), and/or
- Hybrid combinations of these.

This is also an essential component of the Loran Recapitalization Project (LRP). The LRP is a multi-year FAA/USCG initiative to "modernize the U.S. Loran-C system to meet present and future radionavigation requirements while leveraging technology and funds to optimize operations, support and training, and reduce total cost of ownership" [1]. As part of LRP Projects FAA31, Tube-Type Transmitter Replacement; FAA34, Loran-C Data Channel (LDC); and FAA35, Timing and Frequency Equipment (TFE) Replacement, LSU is developing functional specifications to procure equipment capable of providing required legacy timing signals. In addition, technology refreshments will include digital modulation capabilities necessary for any approved PPM, IFM, and/or SIM schemes.

Existing or proposed equipment may not be capable of actual transmissions of all of these modulation formats. Stanford University, the USCGA, and the LSU are cooperating to evaluate viable data formats and technology to permit the modulation and demodulation of data messages transmitted via modulation of Loran-C signal pulse(s).

This paper discusses the joint effort and status of the evaluation that may lead to the development of an alternate data link using the Loran-C signal. It also addresses some limiting factors and constraints that must be overcome in order to use Loran-C as a hybrid data channel.

Necessity for Development

The basic GPS service fails to meet the *accuracy* (the difference between the measured position at any given time to the actual or true position), *availability* (the ability of a system to be used for navigation whenever it is needed by the users, and its ability to provide that service throughout a flight operation), and *integrity* (the ability of a system to provide timely warnings to users or to shut itself down when it should not be used for navigation) requirements critical to safety of flight.

In order to meet these requirements, the FAA is developing the Wide Area Augmentation System or WAAS. WAAS is a safety-critical navigation system that will provide a quality of positioning information never before available to the aviation community. It is what the name implies, a geographically expansive augmentation to the basic GPS service. The WAAS improves the accuracy, integrity, and availability of the basic GPS signals. This system will allow GPS to be used as a primary means of navigation for en route travel and non-precision approaches in the U.S., as well as for Category I approaches to selected airports throughout the nation. The wide area of coverage for this system includes the entire United States and some outlying areas such as Canada and Mexico.

The WAAS signal has enough capacity to carry both the differential corrections and the integrity data required to augment GPS. All WAAS messages are 250 bits in length. At a data rate of 250 Bits-per-Second (bps), the duration of a WAAS message is one second. The WAAS uses a robust R=1/2 convolutional error correcting code with the corresponding transmission rate of 500 symbols per second (sps). This convolutional code is attractive, because it is well known and is a standard for satellite communications. Accordingly, decoders are available as integrated circuits. As an alternative, this code can easily be realized in software at the 250 bps data rate required for the WAAS [2].

Recent tests showed that the WAAS signal is better than expected, providing an accuracy within three feet vertically and two feet horizontally. However, the tests also brought out some multi-path signal interference and software glitches. Additionally, we know that there is limited coverage of the geo-stationary satellites for land-based use in urban and mountainous areas, and in northern latitudes, such as Alaska. Recent delays in the WAAS project have the FAA considering delaying Initial Operational Capability (IOC) until December 2001.

Loran-C could provide a land based data channel supplement to Space Based Augmentation Systems (SBAS), like WAAS. The inherent integrity and robustness of the Loran-C signal may obviate the need for some error correction overhead, thereby reducing the data rate required for transmission of WAAS messages using Loran-C to an achievable level. Loran-C also provides a readily available, extremely reliable, strong (+6 to +10 dB SNR) signal over all of the Contiguous United States and Alaska.

Besides supplementing SBAS, other potential uses of the Loran-C data link are possible. It could be used for differential Global Positioning System, (DGPS) corrections, differential Global Navigation Satellite System (DGNSS) corrections, contingency control of the Loran-C system during loss of landline communications, and differential Loran-C corrections.

Of specific concern is the ability to transmit WAAS messages. In the past, the USCG has accomplished data transmissions on Loran-C using Pulse-Dropping techniques, Polyphase Communications (PM) Modulation, Clarinet Pilgrim (CP), and Two-Pulse Communications (TPC). Currently, the EUROFIX (possibly known as Loran Comm or Lorsat) system is correctly transmitting DGPS correction information in Europe. Unfortunately, none of these techniques provide enough bandwidth to transmit the WAAS message format. The fundamental problem is to develop a Loran-C signal data channel with enough bandwidth to satisfy WAAS requirements. If we can meet WAAS bandwidth requirements, other less bandwidth hungry applications are easily satisfied.

Limiting Factors

Most limitations on using Loran-C as a data channel have already been adequately described [3] [4] [5] [6] [7] [8]. Several are listed herein as items for our analysis during the execution of this project:

- Field Strength,
- Atmospheric Noise,
- Skywave affects,
- Continuous Wave Interference,
- Cross-Rate Interference,
- SNR/SIR, and
- Tracking Power Loss.

However, with a resurgence of modulation techniques, other limitations must also be considered:

- Dual-Rating,
- Priority and Alternate Blanking, and
- Transmitter 300 Pulse-Per-Second (PPS) limitations.

Further, the fundamental limitations on modulating the Loran-C signal remain:

- Blinking of the first two pulses must not be impeded,
- Modulation schemes should not introduce insurmountable biases, and
- Navigational power should not be significantly sacrificed for data power [9].

The major obstacle is finding enough data throughput while maintaining the present integrity of the Loran-C system. This becomes extremely difficult using existing equipment and systems. Modifications to legacy signal generation equipment might be more expensive than simply replacing the equipment with modern versions. Hence, the need for the LRP to ensure any new signal modulation requirements are included in the fundamental system design.

LSU as a Test and Transmission Site

The LSU is unique in the world in having representative Master Configuration Baseline Equipment (MCBE) suites for each class of equipment currently operating in the North American Loran-C System. Fully functioning Dual-Rate AN/FPN-44A Tube-Type and Dual-Rate AN/FPN-64A(V) Solid-State Type Loran Transmitting Station mock-ups are installed. Not only is this equipment available for research, development, and project execution, it is capable of real-world operations in one of several test slots. The LSU can operate as a test, or *Tango*, Secondary transmitting station of the 9960 **N**orth **E**ast **U**nited **S**tates (NEUS) chain or the 8970 **G**reat **L**a**k**e**s** (GLKS) chain. We can also operate as a Master station in the 8090 Test chain, and either a Master or a Secondary in the 5030 Test chain. Using either an installed antenna simulator, or fully operational 625-foot Top-Loaded Monopole (TLM) antenna, LSU can perform on-air tests without the risk of affecting navigation or timing users.

Although on-air tests were originally proposed for operational stations at Middletown, CA, and/or in Alaska, those tests will be delayed until system and user impacts are determined through extensive testing at LSU.

Sherman Lo, a Ph.D. candidate at Stanford University, has studied several schemes to encode data onto the Loran-C signal. His preliminary studies indicate that subtle variations, or hybrid combinations, of PPM, SIM, and/or IFM modulation can achieve the data rates necessary for WAAS message transmission using Loran-C [10].

Pulse-Position Modulation (PPM)

History of PPM

Pulse-Position Modulation of the Loran pulses is not a new concept. In the late 1960s, Clarinet Pilgrim (CP) was used to superimpose U. S. Navy Fleet Broadcast on the Loran-C pulse transmissions. Its purpose was to provide a parallel link to improve the reliability of Navy communications in areas covered by Loran-C. The system was designed to provide this capability with minimal effect on the navigational characteristics of the Loran-C system. The Navy Fleet Broadcast data transmitted by the CP system was a radio-teletype stream of binary data. The CP system modulated 3 to 6 pulses depending on the number of groups per second transmitted from each station [3].

In the late 1970s, the Coast Guard developed and deployed Two-Pulse Communications (TPC). TPC was a synchronous communications system that used only two Loran-C pulses to transmit binary information. The seventh and eighth pulses of the Loran-C pulse group were advanced or retarded 1 uS in time from their normal time of transmission. To transmit a TPC message, the Communications Modulator received characters from the teletype (TTY) circuit and placed them into a 192-character memory. The Communications Modulator then encoded characters to be transmitted and provided phase shift commands to the Loran-C Timers to modulate pulses 7 and 8 [11].

A balanced modulation code was used to ensure that the transmission of a TPC message did not cause gross offsets in a Loran-C navigation receiver. A balanced code means that for each Phase Code Interval, each pulse is advanced and retarded once, therefore the net change of position for each pulse is zero [11] [12]. Since serial redundancy was required in TPC, and since only two pulses per Group Repetition Interval (GRI) are available, at least one GRI was required to transmit a message (a bit). In actuality, at least two GRI, a phase code interval (PCI), were used to transmit a bit.

As illustrated in Table 1, a data bit "1" could be transmitted by advancing the time of transmission of the first pulse of GRI A, retarding the time of transmission of the second pulse of GRI A, retarding the time of transmission of the first pulse of GRI B, and advancing the time of transmission of the second pulse of GRI B. To transmit a data bit "0", the sequence would be complemented; i.e., retard-advance-advance-retard. In all cases, the phase shifts were identical (+/- 1 uS). With this coding, any navigation receiver that averaged all of the pulses of a PCI would see a net phase shift of zero, regardless of what the transmitted message was.

		1 PCI			
		GRI A		GRI B	
Data Bit	Modulated Amount +/-	First Pulse	Second Pulse	First Pulse	Second Pulse
1	1.0 uSec	Adv	Retard	Retard	Adv
0	1.0 uSec	Retard	Adv	Adv	Retard
Sync	2.4 uSec	Adv	Adv	Retard	Retard

Table 1. Balanced Code Transmission Format for TPC.

In the 1990s, a team at the Delft University of Technology (TUDelft) added several new ideas to PPM studies. For example, they proposed using three-level modulation (trits) instead of using two-level modulation (bits). Their subsequent application of three-level modulation (1 uS advance, prompt, or 1 uS delay) increased the raw data rate by an approximate factor of ${}^2\log 3 = 1.58$. Reference [9] shows that three-level modulation gives a total of 141 different balanced combinations of the possible $3^6 = 729$ total modulation combinations. This application, called Eurofix, is an integrated navigation system, which combines Differential GNSS and Loran-C. Here the Loran-C navigation system is used to transmit differential corrections and integrity information for GNSS by modulating the last six Loran-C pulses. The Eurofix system has already demonstrated its capabilities of providing high quality DGPS corrections in Europe as well as in the United States [9] [13]. There are many detailed articles that have been published on the concepts and performance specifications of Eurofix [9] [13] [14].

Eurofix has had a phenomenal positive impact on the radio navigation community, and has kept the possibility of using Loran-C as a data channel alive since it was first proposed by Dr. Durk van Willigen in 1989 [15].

1994 Tests at LSU

As part of a cooperative effort between the USCG, Volpe National Transportation Systems Center (VNTSC), and Megapulse, Inc., the first on-air tests of the Eurofix concept was demonstrated using the U.S. Coast Guard’s Master Configuration Baseline Solid-State Transmitter at Wildwood, NJ in September 1994. The results of these tests have been reported earlier [16].

1998 Tests at LSU

Through a joint USCG, TUDelft, and Megapulse, Inc, effort, a Eurofix demonstration was conducted at the LSU in Wildwood, NJ in March and April of 1998 using LSU's Master Configuration Baseline Solid-State Transmitter. Many of the results of these tests have been reported earlier [14][17]. The objectives for the tests were to:

1) evaluate the effect of Eurofix modulation on the LORAN-C signal,

2) evaluate the characteristics of the Eurofix datalink, and

3) validate the navigation accuracy performance of Eurofix.

Reference [17] focused mainly on the first and reference [14] focused on the last two of these three objectives.

In the tests conducted in 1998, a Eurofix receiver at the USCGA, in New London, CT, processed approximately 6% erasures on the Wildwood signal [14]. In contrast to the Sylt signal, where 23.7% of the 6731 groups are all or partially blanked by the 7499 priority rate, the Wildwood transmitter was operating as a single rate transmitter with no blanking. Virtually all of the errors and erasures were because of cross rate interference, primarily from Nantucket on 5930. Datalink performance was very good. The evaluation demonstrated the robustness of the Reed-Solomon forward error correction code as well as the overall Eurofix technology. Position accuracy was very impressive considering the limited bandwidth available in the Loran-C signal [17].

Five-Level Modulation

A new pulse position modulation scheme that is worth examination takes Eurofix's trit method to another level. Instead of using two-level (bits), or three-level (trits), we are considering five-level (P-bits) modulation. The application of five-level modulation (for example: 2 uS advance, 1 uS advance, prompt, 1 uS delay, or 2 uS delay) increases the raw data rate by an approximate factor of ${}^2\log 5 = 2.32$. These phase-shift patterns were selected for test purposes only. The actual amount of phase shift required for P-bit modulation that minimizes transmitter and receiver affects has not been determined.

As mentioned previously, the modulation should be balanced to prevent undesired tracking biases. This equates to an equal number of advances and delays per GRI. Using the same procedure for calculating modulation schemes and balanced number of combinations as shown in reference [9], the five-level modulation scheme produces 1,751 balanced patterns of a possible $5^6 = 15,625$ modulation patterns.

Five-Level Proof of Concept

A Virtual Instruments Pulse Modulation Engine, with Graphical User Interface (GUI), was developed at the LSU that drives an arbitrary waveform generator to perform proof-of-concept testing on the TTX MCBE system located at LSU. The Modulation Engine creates transmitter drive waveforms (TDWs) that are input directly into the AN/FPN-44A transmitter. TDWs are waveforms that are synchronized to the 100 kHz sine wave output of the timer unit. These waveforms are similar to the waveforms that are actually sent to the transmitter to create the standard Loran-C T^2 pulses. Figure 1 shows the pulse created from the software-generated TDWs. The reason for the distorted shape of the pulse is that the TTX was being operated in low power mode to ensure that nothing internal to the TTX was damaged by this testing process.

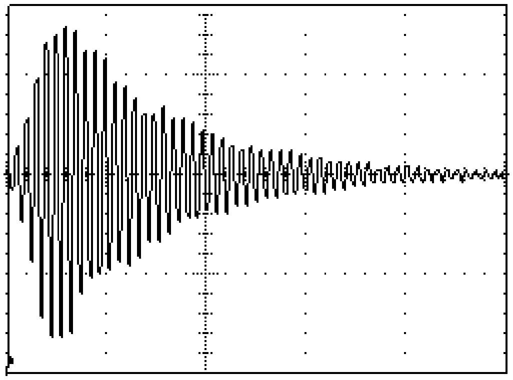

Figure 1: Single Pulse from Software Created TDWs in TTX.

This first version of the software has the capability to position modulate all 20 of the possible pulses that it can create. Later versions will include other modulation schemes, discussed later. After creating a waveform at the standard 8090-M rate, various pulses were then position modulated through all five positions (advance and delay 2 uS, advance and delay 1 uS, and 0 uS for a prompt.). Oscilloscope pictures of the third pulse can be seen in Figure 2. As can be seen, the pulse is advanced 2 uS, followed by a prompt, and finally a 2 uS delay. The pulse can also be advanced and delayed 1 uS, confirming that P-bit modulation is achievable.

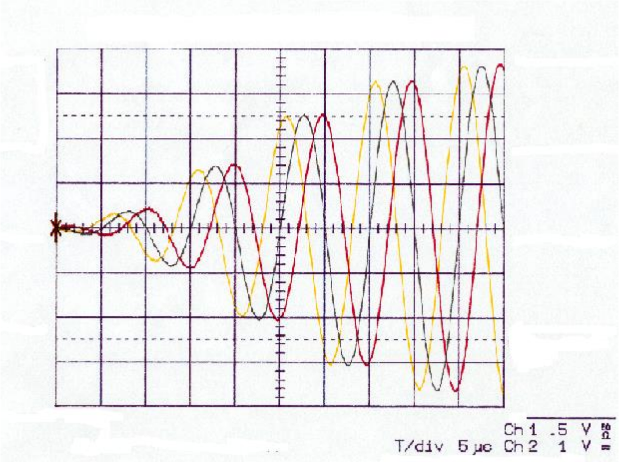

Figure 2: Oscilloscope Image of +/-2 uS Shift and Prompt.

The next step will be to test the P-bits concept on the Solid-State Transmitter (SSX). To do this, the Modulation Engine will need to be altered to match the required timing input signals for the SSX.

Supernumary Interpulse Modulation (SIM)

History of SIM

Supernumary Loran is the process of interleaving additional Loran pulses in between the current Loran-C pulse group. In the late 1960s and early 1970s, this concept was put into practice as Loran-D. Loran-D was a lower power, shorter range, tactical version of Loran-C that modified the Loran-C pulse pattern by interleaving an additional 8 pulses after each pulse of the current Loran-C pulse pattern. The interleaved additional pulses were coded in a pattern to which the normal Loran-C receiver was non-responsive. Thus conventional Loran-C receivers designed to receive only the 8-pulse Loran-C pattern operated on the imbedded Loran-C portion of the Loran-D signal [18].

At the same time that the U.S. Air Force was developing Loran-D, Motorola developed the Multi-User Tactical Navigation Systems (MUTNS), also known as Loran-F, for the U.S. Army. Loran-F was a continuously pulsed pseudorandom coded low frequency navigation system used for drone control. Loran-D came out ahead during system evaluations, and no further work was done on MUTNS/Loran-F.

In standard Loran-C, the pulses of a Loran group are spaced 1000 uS apart for all Secondaries. The Master's pulse spacing is the same for the first 8 pulses. Having an additional 9th pulse located 2000 uS after the 8th pulse identifies the Master station. The most obvious spacing to interleave additional pulses between the standard Loran-C pulses is to use the previous Loran-D format. In Loran-D the spacing was 500 uS apart. The original Loran-D pulses peaked at 80 uS, with the standard sampling point located at 60 uS. Later, Loran-D pulses were transmitted identically to Loran-C.

Hybridized Loran-C/D

Let us presume that the standard Loran pulses are identified as P1 through P9 for a Master pulse group, and P1 through P8 for a Secondary. If we combine some of the techniques we have used in the past (TPC, CP, Loran-D), then maybe we can increase the data rate accordingly. CP and TPC were the parents of Eurofix. TUDelft took a look at previous work, added a few twists that made it better, and then went on to prove that Loran could be used as a "high-speed" and robust data channel.

CP, TPC, and Eurofix are all limited BW modulation schemes because only a limited number of pulses are modulated. Even adding the superb idea of using trits vice bits, as is used in Eurofix, does not yield enough raw throughput. Adding layers of CRC and Forward Error Correction reduces the bit rate again, although this is certainly necessary if you want bullet-proof DGPS corrections in the harsh European RF environment.

CP, TPC, and Eurofix modulation techniques may have presumed limitations on the number of pulses transmitted that might not be necessary with newer equipment. What if we interleave "extra" pulses between the existing Loran pulses, similar to Loran-D? Then the inter-pulse identification could start with D1 ("D" for Data) between P1 and P2, D2 between P2 and P3, and so on through D8 following P8. We would probably not want to introduce a pulse in the D1 or D2 slot as it might interfere with our built-in integrity (blink), if not from the receiver perspective, certainly from the operator's eyeball on an oscilloscope. We probably do not want to introduce a new pulse at the D8 position for similar reasons (possibly conflicts with identifying Master). However, these restrictions are only speculatory at this point, as the true measure of usefulness is whether or not a receiver is confused, not an operator’s interpretation of an oscilloscope!

If we want an even number of pulses as well as a balanced set of pulses, and still remain within our PPS limitations, then we probably max out at 10 pulses (modulating P3-P8 and D3-D6). Adding four Data Pulses (D3-D6) and modulating them along with six Navigation Pulses (P3-P8), for a total of 10 modulated pulses, would give us 8953 possible balanced combinations. Adding two Data Pulses (P3-P8 and D3-D4), for a total of 8 modulated pulses, yields 1107 possible balanced combinations. Eurofix provides 141 possible combinations. A realistic upper limit is to modulate a full set of available Navigation Pulses (P3-P8) and Data Pulses (D1-D8), a total of 14 modulated pulses. Modulating 14 pulses using the P-bit method produces an amazing 5^{14}=6,103,515,625 possible combinations producing a great number of balanced combinations. Whether these 14 pulses would be modulated at a trit, P-bit, or other level has not yet been determined. At this point, we will restrict ourselves to raw contributions of data, since we are not certain what are the best methods for CRC, and Forward Error Correction, as well as the affects on power level, spectrum, and other limiting factors.

We are also not sure what size data "word" we want to use. Eurofix makes a 7-bit word out of the six modulated pulses. For example, should we use a straight 8-bit word generated from the 8 modulated pulses? Do we use ten modulated pulses to generate an 8-bit word plus 2-bits for error correction? No attempt at optimization has been made at this juncture.

Since our legacy transmitters are limited by a maximum 300 PPS constraint, we must consider that transmitting Loran-D (16 pulse Loran spaced at 500 uS intervals) would probably only be practical in single rate modes. Otherwise, the 300 PPS constraint would be exceeded and transmitters would either not work properly or fail altogether. However, if we only add a few interleaved pulses vice an additional eight, we might be able to increase the data rate and remain within the operational capacity of the transmitter. Calculations on PPS for priority and alternate blanking for Eurofix (6 Pulses Modulated), CP+2 (2 Pulses Interleaved; 8 Pulses Modulated), and CP+4 (4 Pulses Interleaved; 10 Pulses Modulated) were performed for all 12 North American Loran rates. We exceed 300 PPS in the CP+4 mode on some stations, so the "optimum" might be the CP+2 mode. One worst case scenario would be the U.S. LORSTA at Shoal Cove, AK. This LORSTA transmits in the 7960-Y and 5990-X slots. Shoal Cove would be required to transmit 453 PPS (16 pulses in 7960, and 16 pulses in 5990), presuming an alternate blanking scheme is used. If hybrid Loran-D (SIM plus PPM) were adopted for the National Air Space, a new upper limit of approximately 500 PPS might be required for transmitting equipment.

SIM Proof of Concept

For the very simple proof-of-concept test, we altered our TTX MCBE to allow transmission of SIM pulses on the 8090-M and 9960-T rates. Since this dual-rate combination exceeds 360 PPS when alternate blanking is used, we opted to begin our testing using only the 8090-M slot.

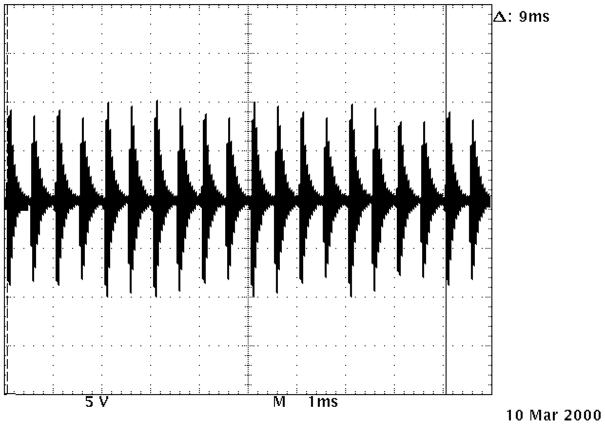

Figure 3: 20 Pulse Group Demonstrating Software Flexibility.

Data Pulses were interleaved one at a time in between all of the standard Navigation Pulses until slots D1 through D7 were filled. Then slots D8, D8a (the position 500 uS after D8), D8b (the position 1000 uS after D8), and D9 were filled until 20 pulses were being transmitted into the antenna simulator (configured as a 625-foot TLM). Standard 8090-M generates 111 PPS, while a 20-pulse group generates 247 PPS. Nominal AN/FPN-44A TTX plate current for 8090-M is 1.6 amps; plate current when all 20 pulses were applied increased to 4.8 amps. The upper limit for plate current on an AN/FPN-44A is approximately 6.0 amps. Figure 3 shows the output to the antenna simulator for a maximum of 20 pulses, which demonstrates the flexibility of the testing software. Figure 4 is an expanded view of the 500 uS pulse spacing used with SIM.

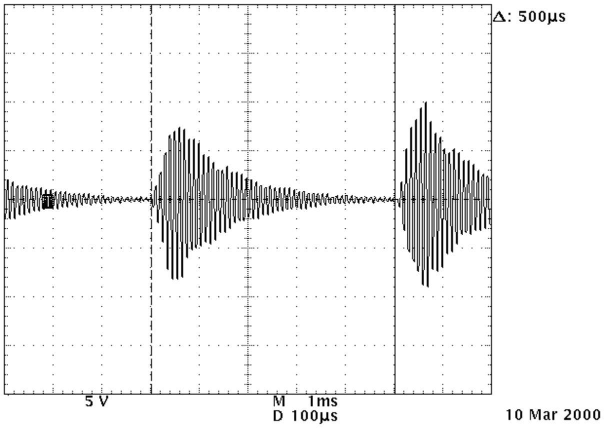

Figure 4: Expanded View of 500 uS Spacing.

The same testing is planned for the AN/FPN-64A(V) SSX, except here the issue of tailbiters needs to be addressed before additional pulses can be inserted. In the top portion of each coupling cabinet of the SSX are from one to eight tailbiters. The tailbiters ensure dissipation of the last remnant of antenna energy, so that the tail current is down at least 60 dB from its peak value by 500 uS. Part of the tailbiter circuit is a Hold-ON Power Supply. This circuit is used to create a resonant discharge through the tailbiters by keeping them turned ON for an additional 300 uS beyond the initial 500 uS ON period for a total ON time of 800 uS. Any extra energy introduced during the time that the tailbiters are damping the tail could cause them to fail. An undamped pulse is shown in Figure 5.

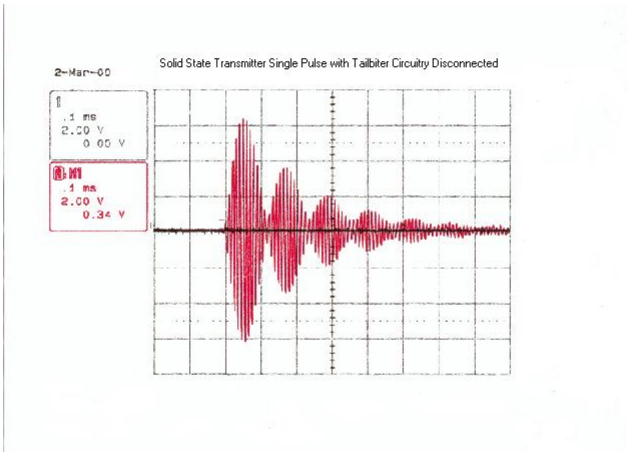

Figure 5: SSX Pulse with Tailbiter Circuit Disengaged.

We will also have to modify the SSX Pulse Amplitude and Timing Controller (PATCO) slightly to reduce the size of the 970 uS "no-way" window that surrounds each individual transmitted pulse. This circuit effectively protects the Half-Cycle Generator (HCG) if a failure of the hardware, software, or blanking schemes occurs. Once we devise a method for interleaving pulses in this type equipment, we will perform SIM testing.

Intrapulse Frequency Modulation (IFM)

History of IFM

Intrapulse Frequency Modulation is the concept involving the gradual change in the frequency of the Loran-C signal within the pulse itself. This begins at a lower limit of 90 kHz and ends at an upper limit of 110 kHz. The reason for the lower and upper limit of 90 and 110 kHz, respectively, is to ensure that 99% of the radiated power is contained within the allocated frequency band of 90-110 kHz. This avoids interference with other users of the frequency spectrum and ensures adequate (relatively long) range [19]. IFM induces a different phase and signal pattern to the pulse. A gradual change in frequency will result in a phase shift of up to 90 degrees in 100 uS. Multiple symbols may be transmitted on each pulse. Two possible combinations are a three symbol system with a -90, 0, 90 degree change, or a five symbol system with a -90, -45, 0, 45, 90 degree change. The choice of starting time and the duration for the frequency shift is arbitrary, as is the phase difference for each level. IFM is especially interesting because it does not require balancing schemes; all the realizable combinations of frequency change can be used for data [10].

At least two predecessors to IFM are known to have existed for Loran. The DECCAjection technique required the transmission of energy in the pulse ringdown that is out of phase with energy in the leading edge. This technique produced notches in the spectrum at the various DECCA frequencies and still allowed power spectrums radiated to be within ITU requirements. Further, the navigation pulse rise was undisturbed [5].

Additionally, the U.S. Coast Guard conducted Polyphase Modulation (PM) testing at Wildwood, NJ in April and August 1974. PM was a technique whereby the tail of a pulse was transmitted in a state selected from a number of phase relations relative to the navigation sampling point. A schedule, or “truth” table, was used to relate bits of information to the communications state of tail phase. The number of phase relations used was a function of the number which could be radiated with acceptable control and the number which could be identified by a communications receiver under conditions of noise, interference, and sky wave contamination. Simulations were performed, and tests were run on AN/FPN-39 and AN/FPN-44 TTX systems [20].

IFM Proof of Concept (MATLAB Simulations)

Simulations were conducted for this modulation concept. The change was made after the Standard Zero Crossing (SZC) to reduce the coding scheme effects on the navigation function of Loran-C. Figure 6 shows a single pulse configuration of both an unmodulated Loran-C pulse and an Intrapulse Frequency Modulated pulse.

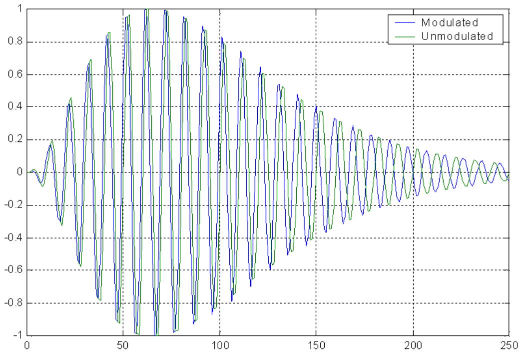

Figure 6: Single Pulse Configuration for Modulated and Unmodulated Pulses.

Figure 7 shows the SNR in 30 kHz NEBW versus Error Rate for a 5 kHz change from 70 uS to 170 uS. Figure 8 shows the same data for a 5 kHz change from 50 uS to 150 uS. It can be seen that lower error rate for the same SNR is obtained by starting the IFM process earlier in time on the pulse.

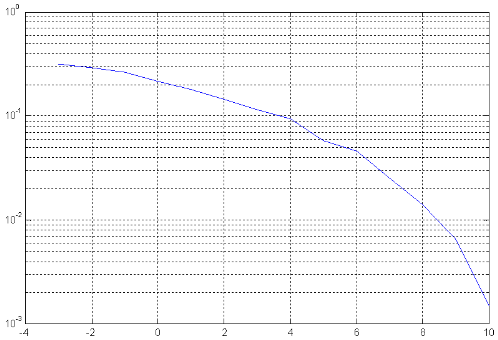

Figure 7: SNR vs Error Rate for 5 kHz change from 70 - 170 uS.

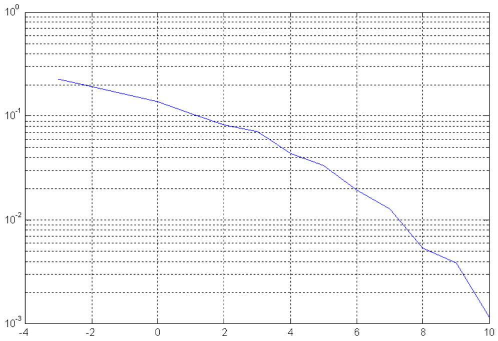

Figure 8: Error Rate vs SNR for 5 kHz change from 50 - 150 uS.

As mentioned previously, maintaining 99% of the total Loran-C signal power between 90 and 110 kHz is needed to avoid interference with other users of the frequency spectrum. Figure 9 shows the power in the 90-110 kHz band for both the unmodulated Loran-C signal and the IFM signal. Note the radiated power is well within the required frequency limits.

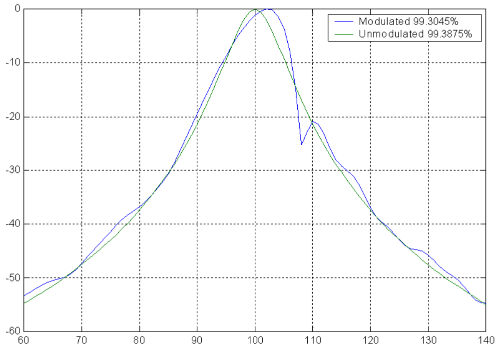

Figure 9: Power in 90-110 kHz Band.

Another type of IFM was simulated that changes frequency, but then goes back to 100 kHz at a phase of +/- 120 degrees relative to an unmodulated pulse. Figure 10 shows a picture of the modulated (+) and modulated (-) pulses relative to the standard unmodulated pulse.

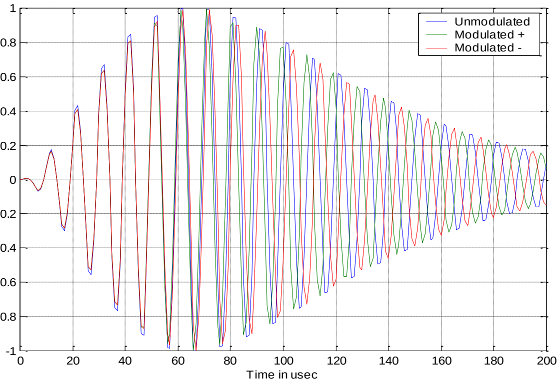

Figure 10: Modulation of +/- & Prompt back to 100 kHz.

The frequency and phase plots of this scheme are shown in Figure 11 for various rates of changing phase. As can be seen in Figure 12 a much lower bit error rate is obtained than from either PPM or the first version of IFM.

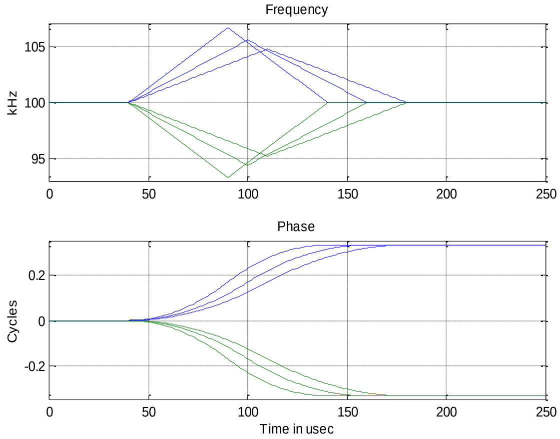

Figure 11: Freq. & Phase for Various Rates of Phase Change.

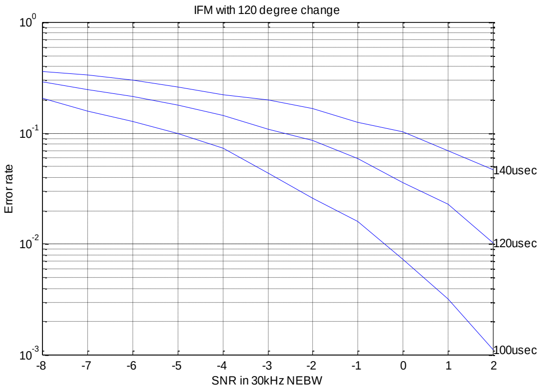

Figure 12: Error Rate vs SNR for 120 degree change.

Assuming the three states (+, prompt, -), to meet the 99% specification with 99.4% in a standard pulse, 98.8% would have to be in the 90-110 kHz range for a modulated pulse. Looking at the radiated power in Figure 13, we note that the change of 120 degrees of phase must not happen faster than 120 uS for the modulated signal to maintain 99% of its power in the required frequency band.

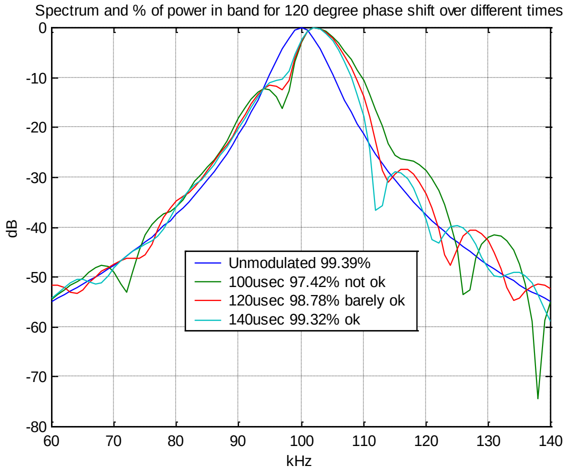

Figure 13: Power in 90-110 kHz Band. (Note: falls below required 99%).

What SNR Do We Design To?

Figures 14 and 15 show contours of the predicted SNR's for the strongest and the next strongest Loran-C station in North America. The noise figures used are the 95% values as described in reference [12]. If a single station with 99.9% availability is good enough, then the minimum SNR is about +5dB to provide coverage throughout the U.S. [12]. If redundant coverage is required, then the minimum SNR is -4dB. Based on the simulations above, to meet the data rate requirement in this level of SNR will require extensive error correction. A more realistic approach might be to analyze the probability (averaged over both space and time) that the SNR of the next strongest station is +5dB or better in the event the primary station is off air. For example, if this is 90% or more, we could have 99.99% availability at +5dB SNR.

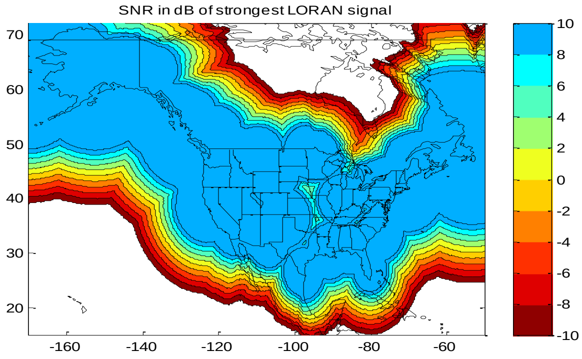

Figure 14: SNR of Strongest Loran Signal.

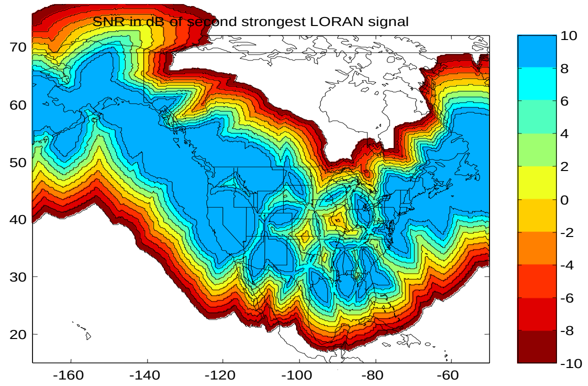

Figure 15: SNR of Second Strongest Loran Signal.

Hybrid Combinations

The obvious next step in our progression is to combine various PPM, SIM, and/or IFM techniques to achieve the maximum data rates while keeping signal generation and receiver impacts to a minimum. Lo has already performed a preliminary analysis of possible hybrid combinations that would significantly increase the data rate of the Loran-C Data Channel [10]. Fortunately, advanced DSP technology, coupled with extremely fast processing power, might allow us to mitigate many of the consequences of hybrid combinations of PPM, SIM, and/or IFM.

Diplexing?

Although concurrent research is being conducted at the LSU, this paper does not include any discussion of diplexing Loran-C and DGPS signals to operate simultaneously into one antenna. Further, work on Intergroup Modulation (IGM) via out-of-band diplexing or in-band modulation is not covered in this paper.

Future Plans

Most of the testing completed to date has been performed on the AN/FPN-44A TTX equipment located at LSU in Wildwood, NJ. A Modulation Engine was created to perform both SIM and PPM testing. The next steps in the proof-of-concept method will be to alter the Modulation Engine to drive the SSX equipment at LSU. This allows us to complete PPM and SIM testing on legacy equipment. The next near-term goal is to generate P-bit PPM of 14 pulses on the 5030, and then 9960 test rates at the LSU.

All work done so far in the concept of IFM has been performed using MATLAB simulation tools. Additional MATLAB/SIMULINK simulations are planned for IFM, and hybrid combinations of PPM, SIM, and IFM. As a result of our simulations, we will determine whether it is reasonable and cost-effective to modify our AN/FPN-44A and AN/FPN-64A(V) MCBE to permit IFM testing into our antenna simulator and/or TLM.

A thorough analysis of the entire transmitted signal will need to be conducted. The effects on ECD, cycle compensation, droop, jitter, spectrum, etc., all require examination.

Versions of PPM, SIM, and IFM have all been studied previously. CP, TPC, and Eurofix have verified the PPM technology. Loran-D transmissions at 12 worldwide locations have verified the SIM technology. We now need to validate the IFM technology, as well as interactions between combinations of PPM, SIM, and IFM.

As in other tests, and to the best extent possible, we plan to research the affects of the various modulation techniques on existing, and proposed, timing and transmission equipment, Primary Chain Monitor Set (PCMS) site equipment, and user receivers.

Conclusions

Eurofix has proven that Loran technology provides an excellent medium for relatively high-speed communications. However, additional modulation techniques are necessary to meet the data rate requirements for WAAS type messages. This cooperative research effort has begun exploring various methods of modulation to increase the throughput of the Loran data channel. All of these methods were discussed herein. Many of these concepts are still in their infancy period of testing and substantially further analysis is needed before these concepts can be implemented in a practical fashion.

Acknowledgements

Mr. Mitch Narins and Mr. Bill McPartland, of the Federal Aviation Administration, are sponsoring this work. Mr. Ron Davis and Mr. Jim Nagle, of Booz-Allen Hamilton, are providing project coordination expertise. Dr. Per Enge and Mr. Sherman Lo, of Stanford University, are our research associates.

We would like to express our sincerest appreciation for the virtual instrumentation programming skills of Mr. Ed Campbell. Additionally, we appreciated the equipment operating assistance of Petty Officer’s Jeff Coombs, “K” Kanta, and Rob Wills.

About the Authors

Captain Benjamin Peterson is Head of the Engineering Department at the U. S. Coast Guard Academy, located in New London, CT. He is a 1969 Academy graduate and earned a Ph.D. in Electrical Engineering from Yale University in 1984. He was the 1997-98 president of the U.S. Institute of Navigation.

Lieutenant Commander Charles Schue is the Commanding Officer of the U. S. Coast Guard's Loran Support Unit, located in Wildwood, New Jersey. He holds a Master of Science Degree in Electrical Engineering from the Naval Postgraduate School and a Master of Science Degree in Engineering Management from Western New England College.

Lieutenant Jay Boyer is Chief of the Transmitters Engineering Branch at the Loran Support Unit. He holds a Master of Science Degree in Electrical Engineering from the University of Rhode Island.

Lieutenant Jim Betz is Assistant Chief of the Command, Control, Communications, Computers, and Information (C4I) Branch at the Loran Support Unit. He holds an Associates Degree in Electrical Engineering Technology from the Pennsylvania State University.

For further information, please contact:

CAPT Ben Peterson
Department of Engineering
USCG Academy
27 Mohegan Ave.
New London, CT 06320-8101
860-444-8541, FAX 444-8546
BPeterson@exmail.uscga.edu
www.cga.edu/acd/eng & www.cga.edu/cas/default.html

or,

LCDR Chuck Schue
Commanding Officer
USCG LSU
12001 Pacific Avenue
Wildwood, NJ 08260-3232
609-523-7248, FAX 523-7307
CSchue@lsu.uscg.mil
www.uscg.mil/hq/lsu/webpage/lsu.htm

References:

1. Commanding Officer, LSU, “Loran Recapitalization Project Joint Requirements Planning Session Report,” March 1, 2000.

2. Bradford W. Parkinson, James J. Spilker, Jr., Penina Axelrad, & Per Enge, “Global Positioning System: Theory and Applications,” Volume 164, American Institute of Astronautics and Aeronautics, 1996.

3. Walter N. Dean, “Clarinet Pilgrim System,” Proceedings of the 2nd Annual Symposium of the Wild Goose Loran-C Association, Washington, DC, 1973.

4. A.W.S. Helwig, G.W.A. Offermans & D. van Willigen, "Implementation and Testing of Eurofix in Standard Loran-C Receiver Technology,” Proceedings of the 25th Annual Technical Symposium of the International Loran Association, San Diego, CA, November 1996.

5. Walter N. Dean, “Loran-C for Emergency Communications,” Proceedings of the 3rd Technical Symposium of the Wild Goose Loran-C Association, Great Gorge, NJ, October 2-4, 1974.

6. Carl S. Mathews, “Loran-C Spectrum: Navigation and Communications,” Proceedings of the 3rd Technical Symposium of the Wild Goose Loran-C Association, Great Gorge, NJ, October 2-4, 1974.

7. Randall V. Gressang, Gerald G. Iverson, & Ronald A. McClellan, “A Case History of Reducing Loran Chain Cross Rate Interference by Using a Balanced Phase Code,” Proceedings of the Sixth Annual Convention of the Wild Goose Association, Seattle, WA, October 12-14, 1977.

8. Robert L. Frank, “Successive-Cycle Phase-Distortion Effect on Loran C/D Accuracy,” Proceedings of the Sixth Annual Convention of the Wild Goose Association, Seattle, WA, October 12-14, 1977.

9. G.W.A. Offermans, A.W.S. Helwig, & D. van Willigen, "The Eurofix Datalink concept: Reliable Data Transmission Using Loran-C," Proceedings of the 25th Annual Technical Symposium of the International Loran Association, San Diego, CA, November 1996.

10. Per Enge & Sherman Lo, "Data Transmission Using LORAN-C," unpublished research paper, November 1999.

11. Technical Manual for the Loran-C Two-Pulse Communications Equipment, CG 7610-01-GE9-4001, USCG, July 1981.

12. Specification of the Transmitted LORAN-C Signal, COMDTINST M16562.4A, Commandant, USCG, May 1994.

13. B.B. Peterson, A.W.S. Helwig, & G.W.A. Offermans, "Improvements in Error Rate in Eurofix Communications Data Link via Cross Rate canceling and Antenna Beam Steering," Presented at the Institute of Navigation Annual meeting, Cambridge, MA, June 1999.

14. A.W.S. Helwig, G.W.A. Offermans & D. van Willigen, "Eurofix - Description and results of US-based field trials done in a US-European co-operation," Proceedings of the 27th Annual Technical Symposium of the International Loran Association, Danvers, MA, October, 1998.

15. D. van Willigen, "Eurofix: Differential Hybridized Integrated Navigation," Proceedings of the 18th Annual Technical Symposium of the Wild Goose Association, Hyannis, MA, November 1, 1989.

16. W. F. Roland, C. M. Sweet, & J. H. Andersen, "Loran Augmented GPS/Eurofix Preliminary Demonstration," Proceedings of the 23rd Annual Technical Symposium of the Wild Goose Association, Newport, RI, November 1-3, 1994.

17. S. J. Bartlett & C. A. Schue, III, "Eurofix Concept Evaluation," Proceedings of the 27th Annual Technical Symposium of the International Loran Association, Danvers, MA, October, 1998.

18. R. L. Frank, "Current Developments in Loran-D," Navigation, Vol. 21, No. 3, pp 235-241, Fall 1974.

19. Loran-C Users Handbook, COMDTPUB P16562.6, November 1992.

20. Commanding Officer, EECEN, "Project WO709-A4, Phase Modulation Evaluation (series)," February 1974 – February 1976.

-Note- The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard or the U.S. Department of Transportation.