The Loran Data Channel: Progress to Date and Future Plans

Ken Dykstra and Ben Peterson, *Peterson Integrated Geopositioning, LLC*

BIOGRAPHIES

Mr. Ken Dykstra is a software engineer with Peterson Integrated Geopositioning, LLC. He is a 1974 USCG Academy graduate and earned a Masters Degrees in Electrical and Computer Engineering from RPI in 1978. Dr. Ben Peterson is President of Peterson Integrated Geopositioning, LLC. He is a 1969 US Coast Guard (USCG) Academy graduate and earned a Ph.D. in Electrical Engineering from Yale University in 1983. He was the 1997-98 president of the U.S. Institute of Navigation.

ABSTRACT

Since 2005, the Federal Aviation Administration and U. S. Coast Guard have implemented, for evaluation, a Loran Data Channel (LDC) to transmit information that will enhance the Loran system. The LDC is transmitting station identification, time, differential Loran corrections, and almanac information using a ninth pulse position modulation technique. This paper discusses the LDC modulation and coding technique, the LDC message format, the current status, and future plans.

BACKGROUND

In 2004, the Loran Integrity Performance Panel (LORIPP) and Loran Accuracy Performance Panel (LORAPP) determined that an improved version of the LORAN-C system, called Enhanced LORAN, could meet the operational requirements of the Harbor Entrance Approach (HEA) for maritime positioning use, the FAA-derived Required Navigation Performance of 0.3 NM (RNP 0.3) for aviation positioning use, and timing/frequency requirements in the continental United States and could be used as a back-up to a disrupted GPS system. The enhancements recommended in reference [1], to satisfy the Non-Precision Approach (NPA), Harbor Entrance and Approach (HEA), and timing/frequency requirements include a Loran Data Channel (LDC). The LDC would be used to transmit information such as Time/Station Identification messages. This information allows receivers to solve signal source identification and cross chain lane ambiguities necessary for all-in-view, master independent, navigation and to solve for precise absolute Time of Day for timing applications. The LDC will transmit differential corrections for temporal changes in propagation measured at far field monitor sites for use in high accuracy timing and navigation receivers. In reference [1], the LORIPP also concluded that the data channel should transmit early skywave warnings. The U. S. Coast Guard is in the process of evaluating an implementation of the LDC, for use with the current LORAN-C signal. This LDC is currently in the engineering development phase.

LORAN DATA CHANNEL SPECIFICATIONS

There are many encoding techniques that could have been used to send data over the Loran system. However, the requirement that the data channel would not impair a legacy Loran receiver or change the frequency specification of the Loran signal precluded most techniques. In 2000 a Loran Data Channel that employed phase modulation on 6 of the 8 Loran pulses in a group, called Intrapulse Frequency Modulation (IFM), which achieved a data rate of 250 bps was experimented with. The 250 bps requirement was necessary to transmit Wide Area Augmentation System (WAAS) corrections. This method used a set of 16 pulse waveforms with the modulation occurring after the 30 µsec point so as to have minimal effect on legacy receivers. Although this technique worked well, the FAA made a decision in 2002 to focus on the feasibility of Loran for non precision approach, and no further work on the approach was completed. Reference {2] discusses the details of the Loran IFM technique.

The current method under evaluation uses the addition of non-navigation pulses. There are several ways to add additional pulses including interleaving them among the other pulses. The system designers decided to add one pulse after the other eight navigation pulses. This Ninth Pulse modulation scheme was chosen primarily for three reasons. First, adding a ninth pulse has negligible impact on the traditional operational LORAN-C signal. It has no impact on the operation of legacy Loran receivers. The modulation technique of the ninth pulses was selected so that it averages to zero. Second, the additional cross rate interference created by adding a ninth pulse can be managed easier than other modulating techniques. In receivers, the ninth pulse in cross rate would be blanked, while the other eight navigation pulses would be cancelled. The addition of a ninth pulse only adds about 0.5 dB of addition cross rate interference. Third, implementing modulation using a ninth pulse can be easily done with the current Loran Timing and Frequency Equipment and Solid State Transmitters.

The specifications for the traditional Loran signal are discussed in reference [3]. Figure 1 shows the pulse pattern for master and three secondary stations. Each vertical line represents a LORAN pulse. Figure 2 shows the ideal Loran pulse. Master station transmits nine pulses and the secondary stations transmit eight pulses. The start of the pulses are spaced 1000 microseconds apart in time, except for the ninth master pulse which is space 2000 microseconds from the eighth pulse. Each group of nine pulses of master (and eight pulses for secondary stations) repeat every group repetition interval (GRI). The GRI is the length of time in microseconds between the start of one transmission of master in a LORAN-C chain to the start of the next. The GRI designator is used to identify the LORAN chain and is the GRI (in usec) of the chain with the last zero omitted. For example, the LORAN chain with a GRI of 99,600 usec is designated 9960. The pulses are also uniquely phase coded. Figure 1 also shows the phase coding, which is repeated every other GRI. Because of the phase coding, the LORAN sequence repeats every phase code interval (PCI) or two GRIs. The first GRI in a PCI is designated GRI A and the second is designated GRI B.

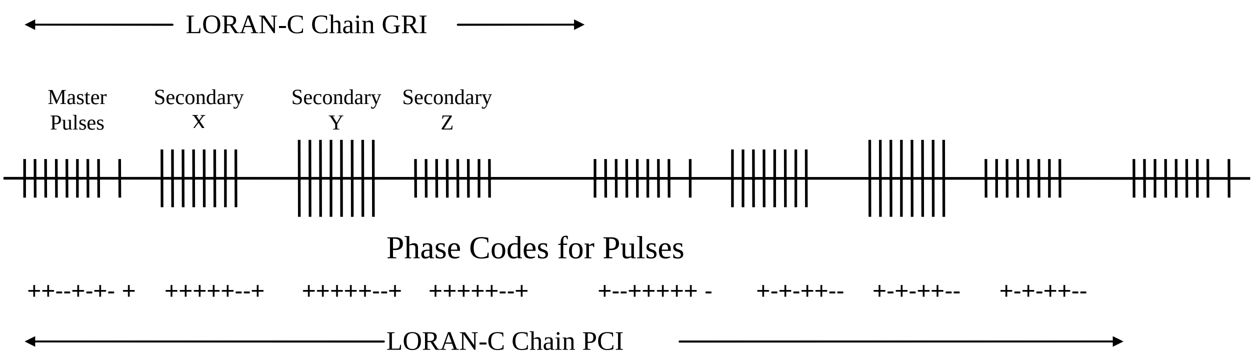

Figure 1. LORAN-C Pulse Architecture

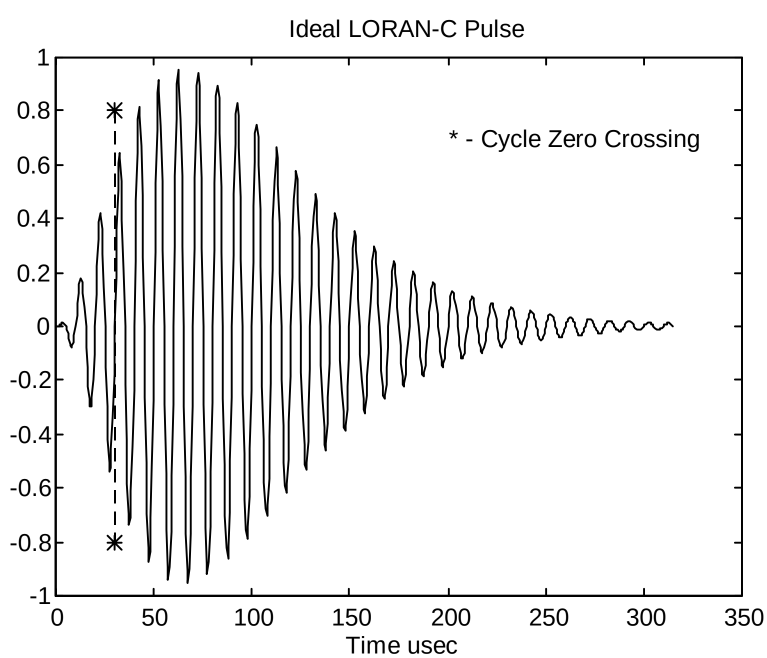

Figure 2. Ideal LORAN-C Pulse.

Figure 3 shows the pulse pattern for a Loran PCI with station X transmitting the LDC. The modulated ninth pulse is offset a minimum of 1000 microseconds after the 8th navigation pulse. The phase code of the ninth pulse is the same as the eighth pulse: that means the phase of a ninth pulse of a secondary signal is positive in GRI A and negative in GRI B. Currently no decision has been made on where to position the modulated pulses on master signals and only secondaries are transmitting the LDC.

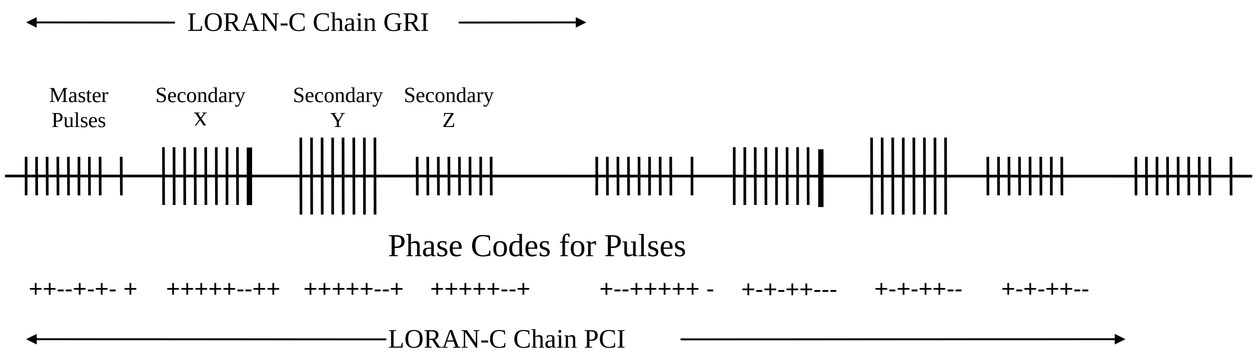

Figure 3. Loran Pulse Architecture with Ninth Pulse Modulation

For pulse position modulation, the LDC uses thirty-two states to specify the pulse delay in time. The data transfer rate is five bits per group repetition interval (GRI). For the slowest GRI, 9990, the data rate is about 50 bps. The zero-symbol offset is 1000 microseconds after the 8th navigation pulse. The remaining 31 symbols are positioned in time a specific number of microseconds later in relationship to the zero symbol. The ideal delays are given by the formula:

$$d_i = 1.25 mod(i,8) + 50.625\, floor(i/8) \text{ usec}$$

The actual delays are the ideal values shifted to coincide with the ticks of a 5MHz clock, a restriction due to the Loran Timing and Frequency equipment. Table 1 lists the symbol i and corresponding time delay d_i with respect to the zero symbol.

i = [0,7]		*i = [8,15]*		*i = [16,23]*		*i = [24,31]*	
Symbol	Delay	**Symbol**	Delay	**Symbol**	Delay	**Symbol**	Delay
0	0.0	**8**	50.6	**16**	101.2	**24**	151.8
1	1.2	**9**	51.8	**17**	102.6	**25**	153.2
2	2.6	**10**	53.2	**18**	103.8	**26**	154.4
3	3.8	**11**	54.4	**19**	105.0	**27**	155.6
4	5.0	**12**	55.6	**20**	106.2	**28**	156.8
5	6.2	**13**	56.8	**21**	107.6	**29**	158.2
6	7.6	**14**	58.2	**22**	108.8	**30**	159.4
7	8.8	**15**	59.4	**23**	110.0	**31**	160.6

Table 1: Symbol Delays from zero-symbol offset (µs)

For the eight state PPM, a phase shift of 1.25 usecs was selected. This divided one cycle into eight evenly spaced divisions. As discussed in reference [2], if the entire Loran pulse is processed, the ability to measure the envelope is 40 times more difficult than the ability to measure the phase of the signal. The envelope shift was selected to have the same minimum Euclidean distance as phase shift. This would require 40 x 1.25 usecs or 50.0 usecs. A separation of 50.625 usecs was selected in the desired Euclidean distance to add slightly more distance. Figure 4 summarizes the symbol space of the 32 PPM symbols.

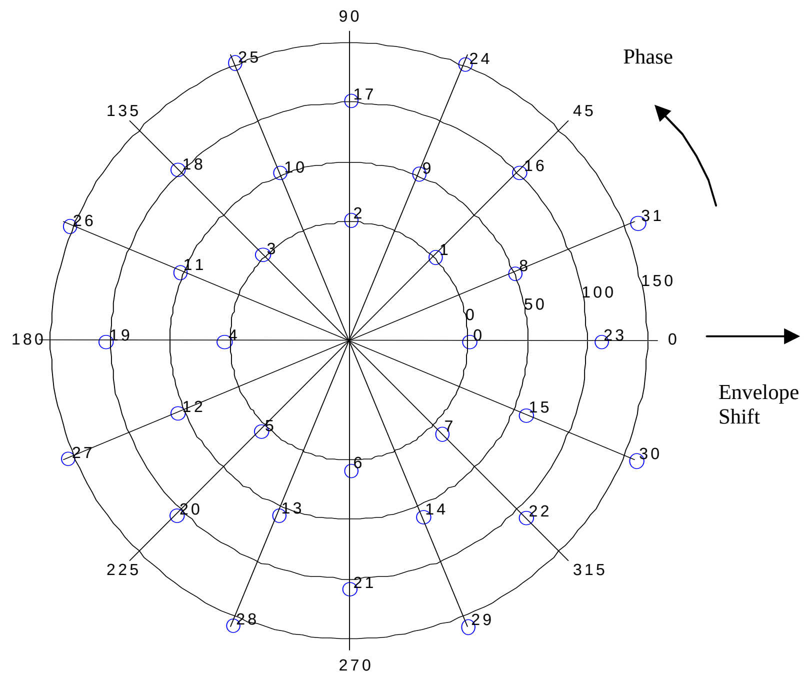

Figure 4. Symbol Space view of 32-state PPM

The LDC message requires some sort of parity and error correction because of noise and cross rate interference. The Reed Solomon Forward Error Correcting (FEC) Code was selected for the error correction. As discussed in reference [2], the Reed Solomon Code is well suited for data channels with burst noise or errors, such as cross rate interference. The LDC uses a RS(31,16) code which uses 5-bit symbols and has 31 code symbols of which 9 are data symbols (45 bits), 15 are parity symbols (75 bits) and 7 are padded with zero. The total message length is 24 symbols or 120 bits. The primitive polynomial used is 29 hexadecimal. The Reed Solomon can correct up to 7 symbol errors with no erasures, 15 erasures (an erasure is a known symbol error), or some combination of errors and erasures where

$$2e + r <= 15$$

where e is the number of error and r is the number of erasures.

Because the Reed Solomon is a cyclic code, if the code is shifted, it will decode but will not be a valid message. For example

T1 = [30 25 14 21 10 16 5 0 10 31 13 4 29 27 26 3 19 9 0 1 12 22 4 17], a valid 24 5-bit symbol message, will decode a time message correctly with 0 errors.

T2 = [25 14 21 10 16 5 0 10 31 13 4 29 27 26 3 19 9 0 1 12 22 4 17 30]; which is T1 shifted one symbol, will decode with 2 errors but is not a valid message.

If T1 is shifted two symbols, it will decode with 4 errors but is not a valid message. If T1 is shifted three symbols, it will decode with 6 errors but is not a valid message. This presents a problem when trying to synchronize to the correct LDC message. To solve the problem, a coset vector is added to the LDC 24 symbol message before transmission. The simple coset vector

coset = [0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23]

is used to add to the 24 symbol LDC message. It is added modulo 32. At the receiver, the coset vector is subtracted, modulo 32, before the Reed Solomon decoder is used. Other coset vectors could be used; however, this vector has been used with good results.

LORAN DATA CHANNEL MESSAGES

The LDC message can send 9 5-bit symbols, or 45 bits of data, per message. Currently, there are three types of messages being used – a phase correction message, an almanac message, and a time message. The types and formats of these messages are still under development. The Coast Guard Navigation Center maintains a web site, www.navcen.uscg.gov, that posts the current status of the LDC project. Reference {4} is a document on the web site that contains the current message formats.

Time Message

The Time Message format is shown in figure 5. The message contains the message type, the station identification, leap second warning flag, the number of leap seconds, and the time. The leap second warning is set when a new leap second will be added at the end of the current year. Time is transmitted as a 31 bit number representing the message epoch count (number of 24 GRIs) since 1 January 1958. The number of seconds T from 000000Z 01 Jan 1958 to the Time of Transmission (TOT) of the first pulse of the first GRI of this message is given by:

$$T = 24(GRI)(MEC) + ED$$

where GRI, is the group repetition interval in seconds, MEC is the current message epoch count, and ED is the published emission delay of the LORSTA sending this message.

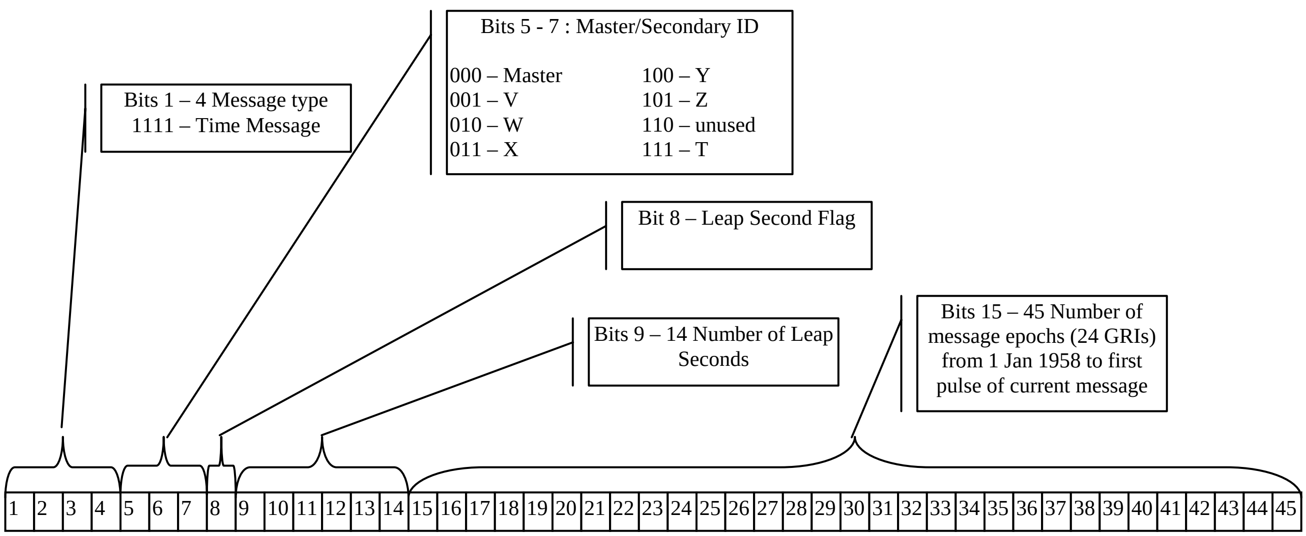

Figure 5. Time Message Format.

Differential Phase Correction Message

The Differential Phase Correction message contains the ASF Phase correction data from a Differential Reference Site. The purpose of this message is to mitigate the temporal component of the ASF. The correction is given relative to a published nominal value determined by calibration. It is expressed as a 2's compliment number (2ns resolution). The total correction used for navigation is the sum of the transmitted correction plus the published nominal value. The published nominal values for the Reference Sites are available at the Coast Guard Navigation Center web site or from the Almanac messages. A phase correction of -1024 (10000000000b) indicates that the signal should not be used. The format of this message is shown in figure 6. The details of these fields are discussed in reference [3]. Each Reference Site may send corrections for up to 12 Loran signals. Therefore, six Phase Correction messages must be sent to transmit the corrections for all 12 Loran signals. Reference Sites may be configured to transmit correction for fewer than 12 Loran signals. They may be configured to transmit 6 corrections, requiring 3 messages, 8 corrections, requiring 4 messages, or 10 corrections, requiring 5 messages.

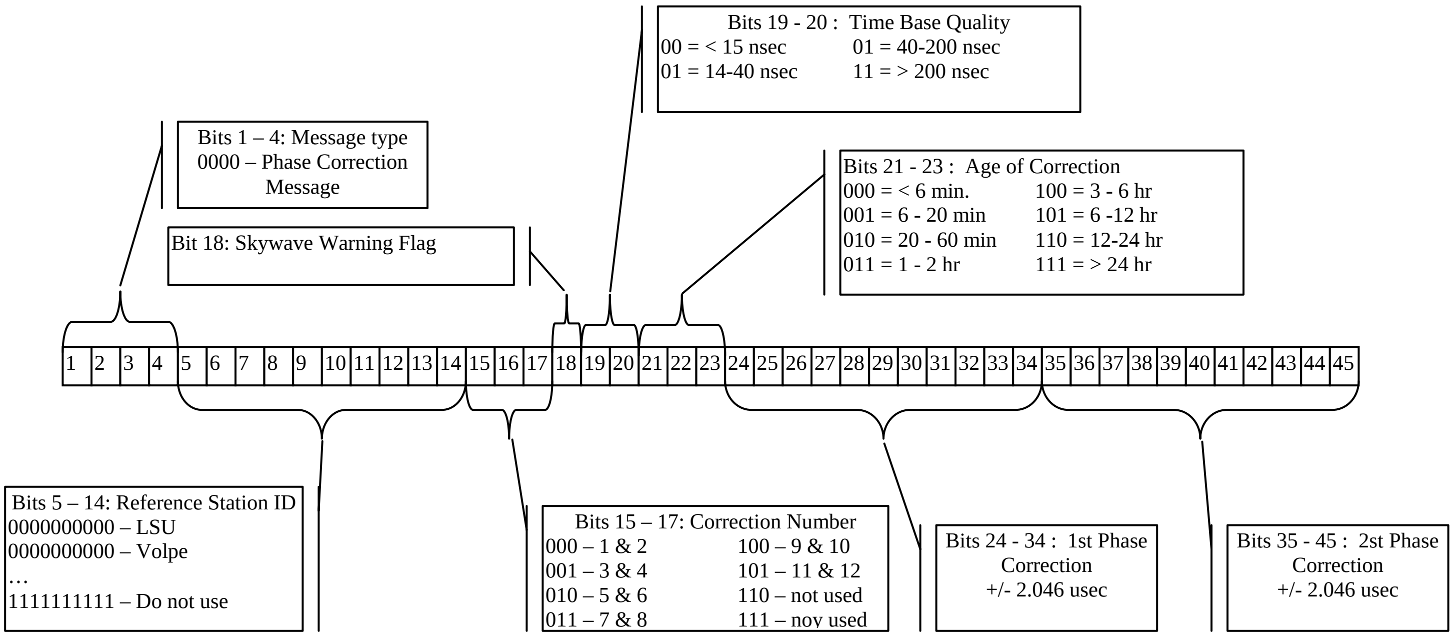

Figure 6. Differential Phase Correction Format.

Almanac Message

The Almanac message contains system-wide almanac data that is useful in high-integrity receiver systems. It is used to pass updated system information to the end user. Because of the large amount of data required in the almanac, this message is divided into sub-types according to the information content. The details of this message type are discussed in reference [4].

Sub-type 0: Reference Station List: This message is used to communicate which reference station corrections are being sent from which LORSTA, and to indicate the status of the LDC broadcast from other Loran stations.

Sub-type 1: Reference Station Latitude: This message contains the latitude of a reference station.

Sub-type 2: Reference Station Longitude: This message contains the longitude of a reference station.

Sub-types 3-6: Reference Station Correction List: These messages contain the signal ID codes for the corrections from a particular reference station. Sub-type 3 contains the codes for signals (1-3), sub-type 4 contains the codes for signals (4-6), sub-type 5 contains the codes for signals (7-9), and sub-type 6 contains the codes for signals (10-12). The signal ID code is the GRI and mater/secondary identification.

Sub-types 7-10: Reference Station Nominal List: These messages contain the nominal ASF values that a particular differential reference site associates with the corrections it calculates. Sub-type 7 contains the nominal values for signals (1-3), sub-type 8 contains the nominal values for signals (4-6), sub-type 9 contains the nominal values for signals (7-9), and sub-type 10 contains the nominal values for signals (10-12). The nominal ASF values are in microseconds.

Message Sequence

When the LDC is fully implemented, many messages of each type will be transmitted. A station may transmit up to 12 corrections from up to 10 monitor sites; this would require 30 phase correction messages (2 corrections per message). The almanac that must be transmitted to describe the LDC configuration may contain several hundred messages. In order to transmit time messages as often as possible, the following message sequencing was adopted for the LDC.

An LDC transmitting station will transmit one time message, followed by one almanac message. After these two message types, the station will transmit the phase corrections from two reference stations (a maximum of 12 phase correction messages). After the phase correction messages, a new time message will be sent, followed by the next almanac message. Then the phase corrections from the next two reference stations will be sent. The LDC transmitting station will cycle through all the almanac messages and phase correction messages for the reference stations. A new time message will be available, worst case, every 14 messages.

The number of phase correction from a reference station may be less than 12 (6, 8, or 10). In that case the time messages will occur more often than every 14^{th} message.

LORAN DATA CHANNEL CURRENT STATUS

In October 2005, the Coast Guard began transmitting the LDC messages from selected Loran Stations for testing and development. Since October 2005, the Jupiter Florida Loran station has been transmitting time messages. In October and November 2005, the Las Cruces New Mexico Loran station was transmitting time messages to support testing during JAMFEST at White Sands Missile Range; now is continues to transmit the time messages. In December 2005, the Seneca New York Loran station began transmitting time messages and differential corrections from the monitor at USNO. Currently it is transmitting time messages and phase corrections from five monitor sites. In October 2006, the Gillette Wyoming Loran station started transmitting time messages. In cooperation with Stanford University, the Middletown California Loran station began transmitting time messages and a test authentication message in October 2006. A test of the leap second transition on January 1, 2006 was conducted and successful in both modulator and user receiver.

FUTURE PLANS

In the spring of 2007, the Loran Sations at Dana, IN, George, WA, and Grangeville, LA, will begin LDC transmissions. When this expansion is complete, there will LDC coverage over the entire CONUS.

Stanford University is currently working on a geo-encyption application. In a geo-encrption system, a location and time dependent authentication is required. Stanford is researching whether Loran can be used in a geo-location system. Loran would provide the location and a message type could be assigned to provide a time dependent encryption. Stanford is researching various authentication methods.

Future plans also include a method to issue an early skywave warnings. In reference [1] the LORIPP concluded that the data channel should also transmit the early skywave warnings. Reference [5] recommends that these warnings are necessary when solar activity results in anomalously low ionospheric layers and causes the leading edge of the skywave to interfere with the normal tracking point on the Loran pulse. This interference, if either in phase or 180 degrees out of phase with the ground wave, causes shifts in the measurement of the time of arrival of the Loran envelope which may cause a receiver to select the wrong zero crossing. If the phase of the interference is at +/-90 degrees relative to the ground wave, the effect changes the phase at the tracking point and thus the measured time of arrival (TOA). Because the delay between groundwave and skywave is dependent on range to transmitter, the effects vary considerably by receiver location. Since the delay decreases and the skywave to groundwave amplitude ratio increases with range the effects are more pronounced at longer ranges. The consensus of the LORIPP was that a receiver could reasonably be designed such that no adverse effects would occur within 800 kilometers (km) of a transmitter.

In the current Loran system, the envelope tracking point relative to the phase tracking point or Envelope to Cycle Difference (ECD) and the Time Difference (TD) between the TOA of Master and Secondary are measured at a single far field location (called a System Area Monitor or SAM) for a particular Master/Secondary pair or baseline. If the ECD at this location varies by more than 1.5 microseconds from its nominal value (CSECD) or if the measured TD location varies by more than 0.1 usec from its nominal value (CSTD), the operator will “blink” the baseline by blanking the first two pulses in the group of eight 75% of the time. For small changes in TDs it is an operator judgment call whether the shift is due to early skywave or due to the normal diurnal and seasonal shifts in phase velocity and whether to blink the baseline or to adjust the time of transmission (TOT) of the secondary. This blink denies all receivers the use of the baseline independent of whether or not the signal at their location has been negatively affected. If the shift in TD is due to early skywave, adjusting the TOT of the secondary will adversely affect users distant from the SAM. In addition, users at a distance from the SAM may be adversely affected by early skywaves, but the effects not be observed at the SAM and no warning issued. The use of an early skywave warning message vice blinking due to anomalous ionospheric activity is an attempt to address these issues. When a warning is issued the LDC will transmit the geomagnetic latitude of lower limit of the auroral zone for Polar Cap Disturbances (PCDs) and zero for Sudden Ionospheric Disturbances (SIDs). Receivers more distant than 800 km from the transmitter and where the midpoint of the propagation path is both illuminated by the sun and at a geomagnetic latitude above the transmitted lower limit should not use the signal. Since these warnings can be triggered by observing data from a sufficiently dense array of far field monitors, the intent is to deny the use of the signal to all users who could be affected but to allow users who are not affected to continue to use the signal.

The LDC phase correction message has a skywave warning flag. This flag will be set when a skywave warning message is needed. A skywave warning message will soon follow with the latitude of lower limit of the auroral zone. The receiver then decides which Loran signals are effected. The format of the early skywave warning message has not been finalized. Also the method to detect an early skywave warning condition has not been identified.

CONCLUSIONS

The LDC modulation and coding technique has been presented. The LDC message format was briefly described. The current status and future plans of the LDC project was discussed. The LDC project is still in the engineering development phase. The current status is available at the U. S. Coast Guard Navigation Center web site as the Coast Guard continues to evaluate the LDC

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ACKNOWLEDGEMENT

The effort was funded by the Federal Aviation Administration Loran Evaluation project; Mitch Narins, project manager.

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FOR FURTHER INFORMATION, PLEASE CONTACT:

Dr. Ben Peterson
Peterson Integrated Geopositioning, LLC
30 Pond Edge Drive
Waterford, CT 06385
860 442-8669, FAX 447-2987
BenjaminPeterson@ieee.org