Data Transmission Using LORAN-C

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BIOGRAPHY

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ABSTRACT

In this paper, we examine considerations involved in data transmission schemes on LORAN. Given the considerations, we propose several schemes to encode data onto the LORAN signal. One major purpose of the communications using LORAN is to augment the primary means GPS system envisioned by the Federal Radio Navigation Plan (FRP). The goal is to achieve a data rate approaching 250 b/s, which is the minimum required for carrying the Wide Area Augmentation System (WAAS) signal. Analysis will examine the required signal to noise ratio (SNR) necessary for each of the schemes to achieve their specified data rates.

1. INTRODUCTION

LORAN (Long Range Navigation) was developed in the 1940s as a navigation with a chain of transmitters operational by 1943 [1]. Constant improvements led to the creation LORAN-C in 1958. In the 1970s, the Global Positioning System (GPS), a satellite based navigation system, was introduced. The growing popularity, ubiquity and use of GPS have led the Federal Aviation Administration (FAA) to develop it for aviation purposes. Under the Federal Radio Navigation Plan (FRP), GPS, augmented by Local and Wide Area Augmentation Systems (LAAS & WAAS), is being developed for use as the primary means of navigation for all flight regimes. WAAS and LAAS provide information that ensures the safety and integrity of the GPS navigation solution. LORAN, with its long history and capabilities, can be useful in the new radio navigation infrastructure both as a backup navigation system and a redundant source of GPS integrity information as provided by WAAS. This paper will discuss means of enhancing LORAN to achieve data rates necessary for broadcasting redundant WAAS information.

This paper is a revised and updated version of an unpublished 1998 paper that presented the concepts and analysis of the LORAN modulation schemes presented.

1.1 Background

LORAN-C transmissions from each station travel in sets of 8 (9 for a master station) pulses spaced one millisecond apart. The pulses are carried on 100 kHz signals and LORAN is required to maintain 99% of its energy between 90 to 110 kHz. The pulses can propagate by two means. The pulses propagate as a ground wave where they travel along the surface of the earth. They also propagate as a sky wave by bouncing off the ionosphere. Typically, sky wave pulses arrive at least 32-35 microseconds after the reception of the ground wave [2]. The pulse group is repeated every group repetition interval (GRI) with each chain having a unique GRI. Timing is generally done on the sixth zero crossing (30 microseconds after arrival) to ensure accuracy. Time differences are calculated using the ground waves however sky waves may cause interference.

Data transmission using LORAN-C is not a new concept [3]. The topic has become increasingly important with the coming of GPS as primary means of navigation. The addition of communication signals on to LORAN will enhance the functionality and robustness of the Global Navigation Satellite System (GNSS). The addition allows LORAN to provide navigation solution, differential corrections to augment the accuracy of standard positioning service of GPS (SPS) and potentially GPS integrity information while providing a failure mode that is different from that of GPS. One system, Eurofix, which provides differential GPS (DGPS) corrections, is being tested and fielded. Eurofix is a scheme for encoding LORAN-C with raw transmission rate up to about 70 bit symbols per second for worst case GRI. The data rate is about 35 bits per second (b/s) due to the use of error correction codes. It is currently used to carry a RTCM Type 9 DGPS correction. The paper proposes schemes that are able to increase the data rate to about 250 b/s. The increased data rate will allow LORAN to carry WAAS signals thereby enabling the use of LORAN to supplement both GPS and WAAS. The goal is to have LORAN act as a GPS Supplementary Navigation System (GPS-SNS) providing redundant means of obtaining position and WAAS corrections. The enhancement will increase the utility of LORAN and the robustness of the GPS system.

1.2 Outline

Three basic schemes will be outlined. The schemes can coexist and can be combined to from a hybrid signal design. The first scheme is Pulse Position Modulation (PPM). In PPM, the LORAN pulse is time advanced/delayed. An example of the scheme is Eurofix. The second scheme is Intrapulse Frequency Modulation (IFM) whereby modulation is encrypted within the pulse by slowly frequency shifting the signal. The third method is interpulse or supernumary modulation whereby additional signals are generated in between the current pulses.

2. SIGNAL DESIGN CONSIDERATIONS

Before examining the LORAN communication (LORANCOMM) schemes, there are several important factors that need to be considered for signal design. One must consider the signals effect on current and new LORAN receivers. Encoding data involves changes to the LORAN signal and such changes may have adverse effects on receivers even if the receivers can adequately obtain the new signal. New signals also involve altering the LORAN transmitters. The signal designer must be aware of the changes and how it affects the operation and costs of LORAN receivers and transmitters.

2.1 Date Rate

The prime consideration for the signal design is data rate. LORANCOMM is not very useful if it can only achieve a low data rate. Since DGPS corrections are time sensitive, a low data rate may not be able to transmit time dependent corrections in a manner such that they will still be useful when they arrive at the user. Furthermore, a data rate that is too low may not provide the integrity and safety alarms to the user within 6-10 seconds as specified by International Civil Aviation Organization (ICAO) [4]. At the same time, trying to get a data rate that greatly exceeds the need may require excessive alterations to the signal. Since the desire is to use LORAN for WAAS signals, there is a desired data rate in mind. The goal leads to a required data rate of at least 250 b/s. So our goal is to attempt to achieve the data rate with minimal impact on LORAN navigators.

2.2 Receiver Considerations

While it is important for a signal design to carry a large amount of data, it is also important to maintain the position fixing capabilities of LORAN. Keeping current LORAN capabilities is important since it retains the current LORAN user base. Furthermore, a new design may result in lower received signal power thus reducing the coverage of LORAN. Any proposed design should attempt to minimize its impact on the LORAN receiver operations while being able to maintain a reasonable data rate and operational range. It should try to be compatible with currently existing receivers.

Altering the LORAN signal will have some impact on navigation so there needs to be some discussion of the potential impacts that various LORAN communication schemes may have on navigation performance. A good scheme should try to mitigate effects that alter LORAN receiver phase. Induced phase errors lead to greater errors in positioning. We will discuss the effects in greater detail when we describe each scheme.

2.2.1 Sky wave Offsets

The LORAN pulse structure is designed to minimize the effects of sky wave interference. Interference is usually due to substantially delayed (1 milliseconds or more) sky wave. Such interference could lead to a bias error in the receiver. LORAN-C pulses are phase coded (0 or 180 degree shifts denoted +/-) to minimize the effects of sky wave interference. The phase coding ensures that the LORAN signal is complementary over two GRI. To accomplish this, there is one set of coding for the first GRI and another set for the second GRI. They are denoted in the literature as A and B respectively. The auto correlation of a two GRI sequence results in a value of zero except when there is no time shift. Master stations and secondary stations have different coding.

Analysis of sky wave offsets begins by examining how LORAN typically rejects sky wave interference. The received ground wave or sky wave during two (GRI) is

$$s(t)=\sum_{i=1}^{8} x_i p(t-iT)+\sum_{i=9}^{16} x_i p(t-iT)$$

where x_i is the i-th phase code, p(t) is the LORAN pulse, and T is the LORAN pulse separation period (1 millisecond). Sky wave interference occurs when a delayed LORAN pulse (the sky wave) arrives coincident with a ground wave. The delay is some integral number of pulse separations, known as the "coarse delay", plus a remainder term denoted as the "fine delay". The coarse delay time should not exceed one GRI. The fine delay of the sky wave, represented by τ, is the relative phase between the sky wave and ground wave. Hence, after going through the receiver's correlator, the interference is

$$I_s=\sum_{i-d=1}^{i-d=8-d} x_i x_{i-d} c(\tau)+\sum_{i-d=9}^{i-d=16-d} x_i x_{i-d} c(\tau)=\sum_{j=1}^{j=8-d} x_{j+d} x_j c(\tau)+\sum_{j=9}^{j=16-d} x_{j+d} x_j c(\tau)$$

$$I_s=c(\tau)\left[\sum_{j=1}^{j=8-d} x_{j+d} x_j+\sum_{j=9}^{j=16-d} x_{j+d} x_j\right]=0$$

$$\text{since } \sum_{j=1}^{j=8-d} x_{j+d} x_j+\sum_{j=9}^{j=16-d} x_{j+d} x_j=0 \text{ for } d>0$$

Where I_s is the interference due to sky wave and $c(\tau)$ is the auto correlation of the LORAN pulse p(t). LORAN employs complementary phase coding that drives the summation to zero for a "coarse" delay of one of more pulse separation. The design discussed will alter the pulse structure or timing and thus change the correlation function.

2.2.2 Phase Offsets

The coding design may induce phase offsets. The transmission of a sequence of time shifted LORAN signals whose total time advances is not equal to its total time delays during a period equal to or greater than the receiver's time constant could induce phase errors [5]. This type of transmission is known as an unbalanced transmission. For example, Eurofix employs a code where three symbols, denoted by +1, 0, -1, are represented by a microsecond advance, no time shift, and a microsecond delay respectively. If such a sequence has more +1's than –1's over a specified period, then the transmission is unbalanced. The solution is to use balanced coding.

Balanced coding is a scheme where every time/phase shift is made so that the sum of the time/phase shifts is zero over a cycle. Suppose only six of the eight pulses per GRI are used. If six pulses (one GRI) constitutes a basic set, a three level (three symbols per pulse) modulated code has 141 (7.1 bits) balanced sequences while a five level modulated code has 1751 (10.8 bits) balanced sequences. The calculation can be done for twelve pulses. Twelve pulses would constitute two GRI for LORAN-C or one GRI for LORAN-D. LORAN receivers typically have integration times that equal or exceed two GRI so being balanced over one or two GRI is adequate to eliminate the phase offset.

Pulses per set	Levels	Balanced Sequences	Bits
6	3	141	7.1396
6	5	1751	10.7740
7	3	393	8.6184
7	5	8135	12.9899
12	3	73789	16.1711
12	5	19611175	24.2252

Table 1. Balanced Sequences

Note that using increasing complex balanced coding schemes involves storage of more and more balanced sequences. The additional knowledge needed requires the receiver more storage and processing power. So while using a balanced code over two GRI yields better data performance than using two sets of code balanced over one GRI, it requires more powerful receiver hardware.

2.2.3 Sky wave and Phase Fluctuation

Changes in the LORAN pulse can have other deleterious effects. The combined effects of sky wave and modulation can induce some random position fluctuation known as sky wave fluctuation [5]. There can also be an increase in the standard deviation of the received phase known as phase fluctuation. If balanced modulation is guaranteed for a time period less than the phase lock loop time constant then phase fluctuation is eliminated [5].

2.2.4 Received Power

Another outcome in altering LORAN pulses is a potential reduction in received power. A reduction in received power can result in either reduced LORAN coverage or reduced LORAN availability. If reductions are significant, then the change has effectively eliminated the navigation utility of LORAN. So a good design should minimize the loss of received power.

2.3 Transmitter Considerations

New designs should try to minimize changes to LORAN transmission stations. One reason that LORAN is being considered as an alternate data link for WAAS is costs. Since LORAN stations was being maintained and operated, there can be a lot of cost savings from utilizing this equipment for the alternate data link if few costly changes are necessary. Software changes are relatively easy (time shifting pulses, etc.) however significant changes to transmitter hardware such as the half cycle generators could make the endeavor economically unpractical. Hence a new design should not require any expensive change in LORAN transmission stations.

3. COMMUNICATION SCHEMES

Before examining the proposed communication schemes, a few assumptions are made for the analysis. Since the system is being considered for WAAS applications, no one particular GRI can be assumed and so a worst case GRI of 9990 microseconds (roughly 10 Hz) is assumed. In fact, some stations transmit at nearly twice that rate and all dual rated stations transmit at more than twice that rate. Depending on the desired implementation, we may assume that the data rate can be nearly doubled. However we will first proceed with a more conservative assumption. In addition, we propose to leave the first two pulses unadulterated to preserve the blinking service [6].

The analysis of the LORAN modulation scheme uses the LORAN signal specification [7] to reference standard definitions for LORAN signal strength and noise. Hence a 5.91 dB correction is used to go from the maximum signal power to the 25 μsecond point. Also 30 kHz noise equivalent bandwidth (NEBW) is assumed.

4. PULSE POSITION MODULATION (PPM)

Pulse Position Modulation is a system where LORAN pulses are time shifted to code information. Eurofix is an example of the technique. In Eurofix, only the last six pulses are used and the code is balanced for every LORAN transmission (eight pulses per GRI). The current Eurofix system employs three levels of coding as described before. However other variations of the system such as five level coding can be employed.

Balanced coded PPM helps to ensure there is no induced phase offsets. Sky wave induced offset is dependent on the size of the time shifts. Using the equations developed in section 2.2, sky wave interference on PPM is

$$I_s = \sum_{i-d=1}^{i-d=8-d} x_i x_{i-d} c\left(\tau + n_{i-d}\Delta t\right) + \sum_{i-d=9}^{i-d=16-d} x_i x_{i-d} c\left(\tau + n_{i-d}\Delta t\right)$$

$$I_s = \sum_{j=1}^{j=8-d} x_{j+d} x_j c\left(\tau + n_j\Delta t\right) + \sum_{j=9}^{j=16-d} x_{j+d} x_j c\left(\tau + n_j\Delta t\right)$$

where n_j is the coding on the j-th signal and Δt is the size of time shift. An examination of the LORAN auto correlation function reveals it to be a periodic function with a period of 10 microseconds. For each GRI, we assume that we receive at most seven pulses having sky wave interference. Now we can calculate the worst case value of I_s. The table shows I_{sn} which is I_s as a fraction of the un-interfered output. I_{sn} is equal to I_s divided by 16 (two GRI) times the maximum auto correlation value.

Max n_j Δt (μsec)	I_{sn}
0.5	0.0150
1.0	0.0551
2.0	0.1561

Table 2. Sky Wave Interference due to PPM

The results are overestimates of the error since only the last six pulses are modulated.

The interference is significantly worse as we increase either spacing (Δt) or code levels (n_j). Modulation spacing governs how easily the receiver can identify the different symbols (hence probability of error) and code level governs how much data can be included on a pulse. Later we will see that probability of symbol error is directly related to required SNR. A trade off in PPM is sky wave rejection for probability of error or data rate.

There is some degradation on normal LORAN-C receiver signal power due to the time shifts but test have shown these changes to be small (.79 dB) [6]. Future systems with knowledge of the Eurofix modulation can eliminate the loss. Small modulation also reduces undesirable loss in tracking signal power. [6]

4.1 Analysis of Performance

The performance of PPM needs to be analyzed to assess the trade off between data rate and SNR. The analysis is based on the discussion of M-ary Modulation Techniques found in Haykin[8]. The method was used both to analyze PPM and to give a preliminary estimate on the next scheme, Intrapulse Frequency Modulation.

The method outline in [8] is for phase coded data. Pulse Position Modulation time shifts are equivalent to a phase shifts. For example, a 2.5 μsec shift equivalent to a $\pi/2$ radian shift (since LORAN has 10 μsec period). Since the different levels of the PPM signal are not evenly spaced in phase, modifications were to be made to the basic M-ary PSK calculations. One needs to transform phases to symbols. A phase/symbol constellation helps to visualize the transformation. Figure 1 represents the signal constellation for some sample PPM designs. Large phase shifts (greater than π/2 for the figure) are not used to reduce the alteration on the signal. The exclusion of those phases results in an unevenly spaced constellation.

Examine the three symbol constellation. In an ideal noiseless world, only three phases, ideal received phases, would be seen by the receiver. The reception of π/2 is equivalent to getting the symbol 1. From a series of six pulses a user can get a series of symbols such as 1,-1,0,0,1,-1. Since there is noise, the receiver needs interpret phases do not correspond to π/2,0,or -π/2. The phase plot is divided so that any received phase can be interpreted to be a symbol (1, 0, or –1). The ideal received phase that minimizes the absolute difference between the received phase and ideal received phase is chosen as the transmitted phase. So a phase of 3π/4 is interpreted to be a corrupted form of a transmitted phase of π/2. The received symbol is then 1.

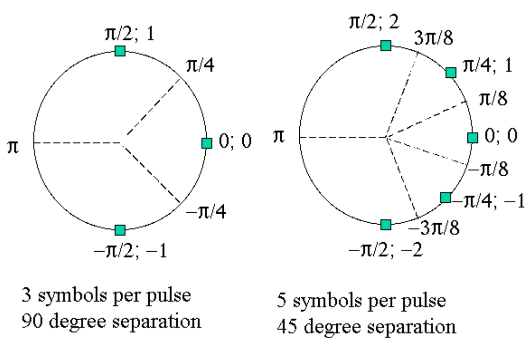

Figure 1. PPM Signal Constellation

The received signal is broken into a quadrature and an in-phase signal portion using a pair of correlators. The optimum receiver for coherent M-ary PSK uses a phase discriminator on the two signal segments. The random variable in the in phase and quadrature signals is assumed to be additive white Gaussian noise (AWGN).

$$\hat{\theta} = \arctan(X_Q / X_I)$$

$$X_Q = \sqrt{E}\sin(2\pi n / M) + W_Q \text{ (quadrature signal)}$$

$$X_I = \sqrt{E}\cos(2\pi n / M) + W_I \text{ (in phase signal)}$$

where W is the noise and n is the symbol level. M is the number of evenly spaced divisions about a circle provided that the modulation index is extended about an entire period. Examine the five symbol constellation on Figure 1. M equals eight since the phases are spaced π/4 radians apart between π/2 and -π/2. Again, θ > |π/2| are not transmitted so any phase in that region is due to noise.

Let P_c represent the probability of reading a symbol correctly (correct reception).

$f_\Theta(\hat{\theta})$ = probability density function of the random variable Θ whose sample value equals the phase discriminator output $\hat{\theta}$ produced in response to a received signal that consists of the signal plus AWGN

$$\text{If } \theta = 0,\ Pc = \int_{-\pi/M}^{\pi/M} f_\Theta(\hat{\theta})\,d\theta$$

$$\hat{\theta} = \arctan\left(\frac{W_Q}{\sqrt{E} + W_I}\right)$$

Now we need to determine the density function for the phase discriminator output.

for $|\hat{\theta}| \le \frac{\pi}{2}$

$$f_\Theta(\hat{\theta}) = \frac{1}{2\pi}\exp\left(-\frac{E}{N_o}\right) + \sqrt{\frac{E}{\pi N_o}}\cos\hat{\theta}\exp\left(-\frac{E}{N_o}\sin^2\hat{\theta}\right)\left[1 - \frac{1}{2}erfc\left(\sqrt{\frac{E}{N_o}}\cos\hat{\theta}\right)\right]$$

otherwise

$$f_\Theta(\hat{\theta}) = \frac{1}{2\pi}\exp\left(-\frac{E}{N_o}\right) + \sqrt{\frac{E}{\pi N_o}}\cos\hat{\theta}\exp\left(-\frac{E}{N_o}\sin^2\hat{\theta}\right)\left[\frac{1}{2}erfc\left(-\sqrt{\frac{E}{N_o}}\cos\hat{\theta}\right)\right]$$

$$P_e = 1 - P_c = \text{probability of error} = 1 - \int_{-\pi/M}^{\pi/M} f_\Theta(\hat{\theta})\,d\hat{\theta}$$

4.2 PPM M-ary Analysis Results

For symbols other than θ = 0, one can solve for the error probability by transforming the problem so that the problem is centered about 0. Assuming that each symbol is equally likely, we can then solve for the overall probability of error. The results were numerically integrated and a SNR versus probability of error plot can be generated. Three forms of PPM are shown below. PPM3 is the current Eurofix scheme. PPM5a and PPM5b are five level scheme where the spacing is .5 μsec (π/8 radians) and 1 μsec (π/4 radians) are used respectively.

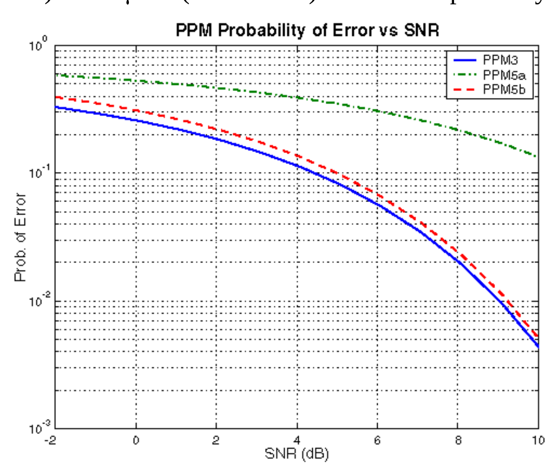

Figure 2. PPM Probability of Error vs. SNR (M-ary)

There are two drawbacks to the M-ary analysis. First, AWGN is assumed whereas actual noise in the receiver is filtered (i.e. 30 kHz NEBW). Also, M-ary analysis only assumes that the phase information is only available at one portion of the signal whereas the phase information is available for the entire length of the pulse. This leads to the next analysis method, which uses matched filters.

4.3 PPM Matched Filter Analysis

Even though we originally used M-ary analysis, to examine LORAN in a 30 kHz NEBW, we decided to employ matched filter analysis. Figure 3 shows set up. Matched filter is a more practical means of implementing LORAN demodulation and is also used to analyze IFM.

Many receivers decode data using matched filters [8]. The matched filters convolve a time reversed version of a desired signal with an input. The result is the same as multiplying the signal with a time shifted version of the desired signal and summing for finite length signals. We proceeded by examining the effects of AWGN as it passes through the filters. Since the problem is stochastic in nature, we derive the random statistics of the output.

Signal variance through filter j from signal i $= \mathrm{E}\left\{(\mathrm{x} - \bar{\mathrm{x}})^2\right\}$

$$= E\left\{\int [s_i(t)+n(t)]s_j(t) - s_i(t)s_j(t)dt \int [s_i(z)+n(z)]s_j(z) - s_i(z)s_j(z)dz\right\}$$

$$= E\left\{\int n(t)s_j(t)dt \int n(z)s_j(z)dz\right\} = \frac{N_o}{2}\int s_j(t)dt \int s_j(z)\delta(t-z)\,dz = \frac{EN_o}{2}$$

= noise variance thru filter j from signal i

Note $\mathrm{E} = \int s_j^2(t)dt$, x = received signal = $[s_i(t)+n(t)]$; $\frac{N_o}{2} = \mathrm{E}\left\{\mathrm{n(t)}^2\right\}$

Assuming that the filters contribute negligible noise to the signal, the signal noise seen by each filter is the same. Hence the output from each of the three filters should be correlated. The largest matched filter output decides which symbol is interpreted. Determining the symbol is equivalent to finding the filter whose output, when differed from the outputs of other filters individually, is always positive. So next we determine the variance of the difference of output from each filter pair.

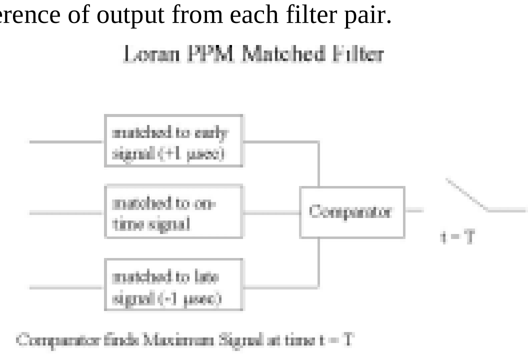

Figure 3. PPM Matched Filter

Signal variance through filter j minus filter k from signal i = $\mathrm{E}\left\{\left(\mathrm{x}-\bar{\mathrm{x}}\right)^2\right\}$

$$= E\left\{\begin{matrix}\int\left(\left[s_i(t)+n(t)\right]\left[s_j(t)-s_k(t)\right]-s_i(t)\left[s_j(t)-s_k(t)\right]\right)dt\,* \\ \int\left(\left[s_i(\tau)+n(\tau)\right]\left[s_j(\tau)-s_k(\tau)\right]-s_i(\tau)\left[s_j(\tau)-s_k(\tau)\right]\right)d\tau\end{matrix}\right\}$$

$$= E\left\{\int\left(n(t)\left[s_j(t)-s_k(t)\right]\right)dt\int\left(n(\tau)\left[s_j(\tau)-s_k(\tau)\right]\right)d\tau\right\}$$

$$= \iint\left[s_j(t)-s_k(t)\right]\left[s_j(\tau)-s_k(\tau)\right] * E\left\{n(t)n(\tau)\right\}dt\,d\tau$$

= noise variance through filter j minus filter k of the transmitted signal i plus noise

Note that the noise/signal variance does not depend on the signal, just the filter
In discrete form, the integral can be approximated as

$$= \sum_{l=0}^{M}\sum_{m=0}^{M}\left[s_j(m\Delta t)-s_k(m\Delta t)\right]\left[s_j(l\Delta t)-s_k(l\Delta t)\right]E\left\{n(m\Delta t)n(l\Delta t)\right\}\Delta t^2$$

Since a 30 kHz NEBW is used, the correlation function $E\left\{n(m\Delta t)n(l\Delta t)\right\}$ is a sinc function (Fourier Transform of an ideal bandpass filter)
if we assumed uncorrelated white noise, the result would be

$$= \frac{N_o}{2}\int\left[s_j(t)-s_k(t)\right]^2 dt \cong \frac{N_o}{2}\sum_{m=0}^{M}\left[s_j(m\Delta t)-s_k(m\Delta t)\right]^2\Delta t$$

Knowledge of the noise variances and covariances can provide a bound on the probability of error.

Denote $P(y_i > y_k \mid k)$ to be the probability that the maximum output from matched filter i is greater than that from matched filter j given that signal k was sent.

Let F_{norm} be the cummulative density function for the standard normal variable.

Let y_{ij} be the maximum signal from matched filter j given signal i

Let σ_{ij} be the standard deviation of the output from matched filter j subtracted from matched filter i.

Assume three different signals i,j,k

$$P_{error} \mid i \le P(y_j > y_i \mid i) + P(y_k > y_i \mid i) = P(y_i - y_j < 0 \mid i) + P(y_i - y_k < 0 \mid i)$$

$$\le P(z_1 = (y_i - y_j) - (y_{ii} - y_{ji}) < (y_{ii} - y_{ji})) + P(z_2 = (y_i - y_k) - (y_{ii} - y_{ki}) < (y_{ii} - y_{ki}))$$

$$\le F_{norm}\left(\frac{y_{ji} - y_{ii}}{\sigma_{ji}}\right) + F_{norm}\left(\frac{y_{ki} - y_{ii}}{\sigma_{ki}}\right)$$

where $z_1 \sim N(0, \sigma_{ji})$; $z_2 \sim N(0, \sigma_{ki})$

Thus, given a signal to noise ratio, we have an upper bound on the probability that a sent symbol is interpreted by the receiver to be a different symbol. Figure 4 shows the bound for various SNRs. Also shown in the Figure 4 are results from simulation based on code written by Dr. Ben Peterson. The difference in the analytic and simulation results is mostly due to the use of an ideal bandpass filter for the analytic model and a 2nd order butterworth filter for the simulation.

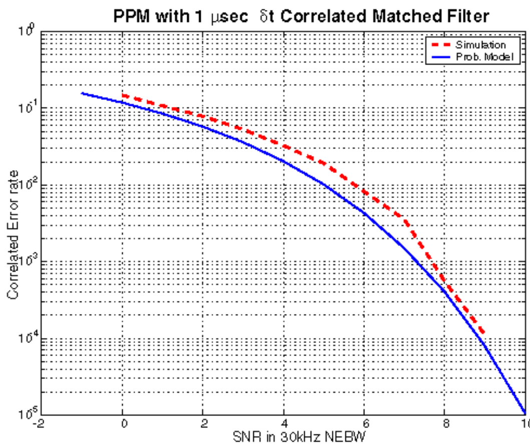

Figure 4. PPM Prob Error vs. SNR (Matched Filter)

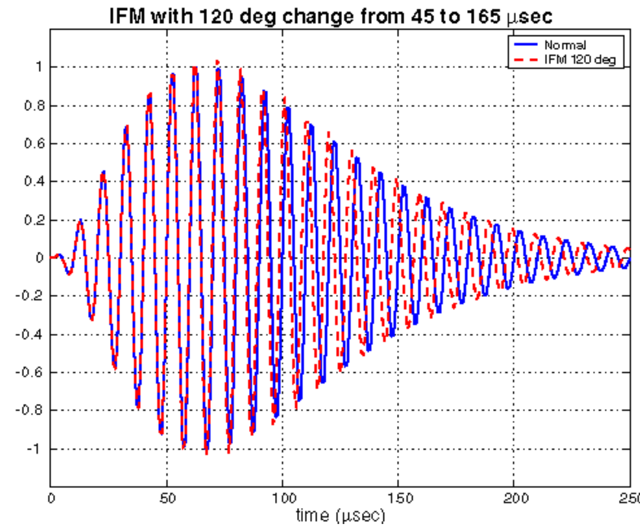

Figure 5. LORAN Pulse & IFM LORAN Pulse

5. INTRAPULSE FREQUENCY MODULATION (IFM)

Intrapulse frequency modulation involves a gradual change in the frequency of the LORAN signal within the pulse (to at least/most 90 or 110 kHz) to induce a different phase and signal pattern. In the original paper, we proposed a gradual change in frequency that would achieve a phase shift of up to 90 degrees in 100 microseconds. A three level (per pulse) system may have 90,0-90 degrees as its levels while a five level system may involve 90, 45, 0, -45, -90 degrees as its levels. I have denoted these schemes as the original schemes. The change should occur after the sixth zero crossing to reduce the effects of the coding scheme on the navigation performance of LORAN. The choice of the starting time and duration time for the frequency shift is arbitrary as is the phase difference for each level. The chosen parameters were selected for testing purposes only and does not represent any sort of optimization. Later, Peterson et. al. [9] suggested the use of a signal that continuously changed frequencies in such a way that the final frequency was 100 kHz. Increasing and then decreasing the frequency (or vice versa) created the various symbols. The end result being that after the frequency changes, the pulse is offset from a normal LORAN signal by a certain fixed phase. A three level system may have phase shifts of 0, +120, -120 degrees and a four level system may have phase shifts of –135,-45,+45,+135 degrees. These schemes shall be denoted in this paper as the new IFM schemes. This is shown on Figure 6 and detailed in reference [9].

As with PPM, a M-ary analysis was used to get a preliminary estimate on IFM performance. Then we carried out a matched filter analysis of IFM. The analysis was originally carried out on a three level IFM modulated signal using +90, 0, -90 degree shifts to represent each symbol though the newer schemes have also been tested. Three matched filters (one matched to each of the possible signals) are used to decide which signal was transmitted. The setup is shown on Figure 6. The choice of a three level IFM signal is based on two criteria. The concept can be extended to the four level IFM currently being proposed.

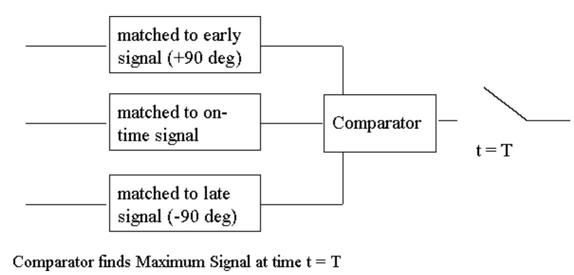

Figure 6. Matched Filter Set Up

5.1 Matched Filter Analysis

Figure 7 shows the results of the analysis for the proposed 4 level IFM scheme. The 3 level scheme performs better due to the increased phase separation. The results confirm that IFM can be accomplished with error rates comparable or better than PPM for a given SNR. Again, simulation and analytic results are shown and the difference between the results is probably due to the difference in filters used.

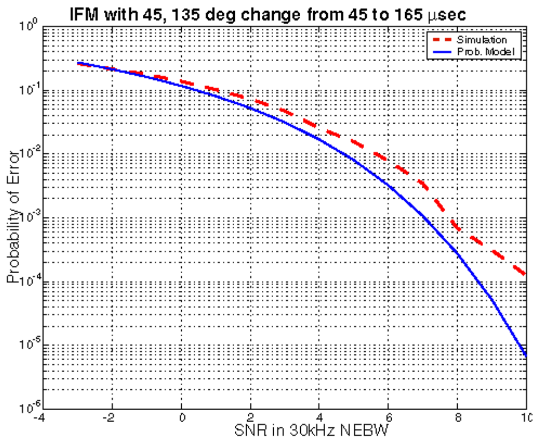

Figure 7. IFM Probability of Error vs. SNR (New IFM Schemes)

5.2 IFM Sky wave Rejection

The scheme will result in some sky wave offset. Using section 2.2 and going through the same matched filter analysis, we determine the component of the matched filter output that is due to sky wave. Now the received sky wave is

$$s(t)=\sum_{i=1}^{8} x_i p_i(t-iT)+\sum_{i=1}^{16} x_i p_i(t-iT)$$

where $p_i(t\text{-}iT)$ is the i-th IFM LORAN pulse. Since IFM alters the pulse, a subscript is used to indicate that the pulses may differ. The sky wave offset can now be shown

$$I_s=\sum_{i-d=1}^{i-d=8-d} x_i x_{i-d} c_{i-d}(\tau)+\sum_{i-d=9}^{i-d=16-d} x_i x_{i-d} c_{i-d}(\tau)=\sum_{j=1}^{j=8-d} x_{j+d} x_j c_j(\tau)+\sum_{j=9}^{j=16-d} x_{j+d} x_j c_j(\tau)$$

The analysis demonstrates that if all the IFM signals were coded the same way, the result of the sky wave interference would be zero since LORAN phase code is complementary. The worst case occurs when half have one form of frequency shifting and half have another. Denote an increase in frequency as "positive" and a decrease in frequency as "negative". Then we can write the cross correlation function of a normal LORAN pulse with each of these signals as c_p and c_n respectively. Assume that the positive products ($x_j x_{j\text{-}d}$) are associated with positive phase and the negative products are associated with negative phase. Let the sky wave be delayed at least one pulse. The worst case has seven positive and seven negative products over two GRI. The summation becomes

$$I_s=\sum_{j=2,\,j\neq 9}^{j=16} x_j x_j c_j(\tau)=\sum_{j=1}^{j=7}\left(c_p(\tau)-c_n(\tau)\right)$$

The results for the initially proposed scheme are shown in table 3. These schemes are not as resistant to noise as the newer schemes proposed by Peterson. The results for those schemes are shown in table 4. Again, note this is an over estimate of the error since only the last six pulses are modulated. A more realistic but less tractable model may be:

$$I_s=\sum_{j=1}^{j=7} x_{j+1} x_j c_j(\tau)+\sum_{j=9}^{j=16} x_{j+1} x_j c_j(\tau)$$

IFM Phase shift in 100 μsec	IFM start time μsec after pulse start	Isn
45 degrees	70	0.1635
45 degrees	100	0.0881
90 degrees	100	0.1342
90 degrees	70	0.2278

Table 3. IFM (Original Schemes) Sky wave Rejection

There is a distinct trade off between sky wave offsets and the ability to distinguish the symbols. The more distinct the symbols are, the less the system will be able to reject long delay sky wave. Making symbols more distinct means that the output from the positive matched filter minus the output from the negative filter is the largest among the IFM schemes in the table. It is the result of its earlier start time and larger phase shift. Hence the same amount sky wave offset has a lower effect on the scheme. Furthermore, lower SNRs are required for a given probability of error for more distinct symbols. Since we have not attempted to optimize the modulation, it is very possible that there are other schemes that have less sky wave offset and lower required SNR for our desired probability of error.

IFM Phase shift in 120 μsec	IFM start time μsec after pulse start	Isn
45 degrees	45	0.1788
120 degrees	45	0.3779
135 degrees	45	0.3958

Table 4. IFM (New Schemes) Sky wave Rejection

In Table 4, a three level scheme (0, 120 degrees) and a four level scheme (45,135 degrees) are being compared. The worst case long delay sky wave rejection for the four level scheme is worse than that of the three level. Furthermore, the four level scheme has a higher SNR requirement for a given error rate. However, it does have more symbols per pulse and hence a higher data rate.

5.3 IFM Data Rate

The Intrapulse Frequency Modulated code does not need to be balanced. The analysis above shows that a balanced code leads to a higher chance of a bad sky wave offset. The amount of data carried per GRI is then n^6 where n represents the number of levels in the modulation.

5.4 Transmitter and Receiver Considerations

At the time of the original paper, no study has been done on the cost of modifying current state of the art LORAN-C transmitters/half cycle generators to produce a gradual frequency change. However, discussions and analysis generated after the introduction of IFM imply that it is possible to modify transmitters such as the AN-FPN/64 to transmit IFM.

6. INTERPULSE MODULATION (SUPERNUMARY)

Interpulse modulation interleaves additional pulses between current LORAN-C pulses. The scheme could be done in a manner similar to LORAN-D so that each station transmits a signal with 16 pulses spaced 500 microseconds apart. The additional pulses can be coded in a manner that a normal LORAN-C receiver is oblivious to the existence of those pulses. The pulses can also be coded to aid in sky wave rejection. New LORAN receivers with the ability to use the additional pulses will have the advantage of receiving at a higher average power since they will get twice as many pulses per second [10]. Current LORAN-C transmitters should be able to support 16 instead of 8 pulses per GRI. There would be increased operating costs since more energy is being used per GRI.

It is possible to efficiently include data on a supernumary modulation scheme. One method would be to alter the phase code of the additional eight pulses. The key considerations in the scheme is to make sure that the alterations still keep LORAN phase code complimentary and ensures that the additional pulses remain oblivious to LORAN C receivers. An example of a LORAN-D scheme is shown below

+ + - - + - + -	+ - - + + + + +
++++-+--++-++--+	++-+-++-+-+-+++-
1st Group	2nd Group
+ + - - + - + -	+ - - + + + + +
+-+----++---++--	+-----+++++++-++
3rd Group	4th Group

Figure 8. Phase Code & LORAN-D Altered Code

The pattern for creating the LORAN-D pulses is to choose any phase coding pattern for the first two GRIs and then using the opposite phase coding pattern in the next two GRIs. Hence there are 2^{16} phase coding (2 GRI) per four GRI grouping that are oblivious to LORAN-C receivers with time constants of 4 GRI or more [11]. The difficulty is sky wave rejection and LORAN transmission acquisition during changes from one phase code to another. Acquisition of correct timing and of the master station signal is possible if the additional pulse sequence does not resemble normal LORAN-C pulse sequences.

One scheme that could be used is to switch between the 2^{16} phase coding (per four GRI). The sky wave interference could be very large if the receiver is integrating the signals during a time frame that involves a switch. Care must be taken and so all 2^{16} phase codes cannot be used. A modification is to just use the last bit to modulate data. This would result in 2 bits per 4 GRIs or 5 b/s of data. The sky wave interference would be less since only the last bit is not predicable and may not be integrate out.

Another scheme is to add and modulate an additional pulse at the end of the LORAN master station transmission. Thus the master station now would transmit a pulse after the ninth pulse of LORAN-C master station. The change results in a data rate of 10 b/s.

A more sophisticated attempt would be to include PPM and/or IFM onto the additional pulses. Both PPM and IFM can be encoded together since the schemes should not interfere with one another. Hence one can create a hybrid data scheme with a data rate of over 300 b/s if IFM and PPM are used on a pulse train of 16 pulses.

Supernumary modulation will result in approximately a doubling of the transmission costs. It can also result in at least a doubling of the data rate of a LORANCOMM scheme. Furthermore it also may increase the amount of sky wave and cross rate interference for both legacy and new users. If it can be accomplished in a way that does not greatly diminished utility for current users, it can actually double the received energy for a user with a receiver capable of using the additional signals as well as more than double the data rate. The increased capability may justify its use.

7. CONCLUSION

The table below summarizes the results for Eurofix, the analyzed three level version of IFM, Supernumary modulation, and a hybrid scheme that combines the three above schemes. In Table 5, the data rate column assumes that half the symbols are used for error correction.

Scheme	Data Rate (b/s)	Transmitter Costs	Receiver Costs	SNR (for P(error) < 1e-3)
Pulse Position Modulation (Eurofix)	35.7	Additional logic	Add'l processing for PPM	7.45 dB
Intrapulse Frequency Modulation	47.5 60	Additional logic for half cycle generators	3 matched filters and processing	4.96 dB 7.08 dB
Supernumary (Loran-D)	N/A	2x Transmission power	Ability to receive Add'l signals	N/A
Example Hybrid	>166 >190	All of the above	All of the above	7.45 dB

Table 5. Conclusions on Modulation Schemes

While none of the three schemes alone can provide the required data rate, a hybrid scheme employing all three of basic schemes can provide the necessary data rate. The example hybrids shown uses the following schemes:

- 3 levels PPM with 1 μsec spacing (Eurofix)
- 3 and 4 levels IFM as analyzed in section with frequency/phase shifts from 45 μsec to 165 μsec
- Modulation of at least 12 pulses per GRI
- Example Hybrid is a combination of 1-3 with 3 level PPM and 3 and 4 level IFM also used on the additional pulses.

The resulting of the preferred hybrid system (with 4 level IFM) is a symbol rate of 452 bit symbols per second and 226 b/s data rate. If a dual rated or a lower GRI station was employed, the symbol rate could easily be 800 or more bit symbols per second. With half the bit symbols used for error correction, the data rate is well over the 250 b/s used by WAAS. Even with less than 250 b/s, the system could augment GPS/WAAS. Other follow up research to the work presented in this paper describes how to achieve a useable WAAS based integrity system using a sub WAAS data rate [12] and the development of a LORAN data channel model [13].

The ability to carry communication on LORAN would be of immense use to navigation. The inclusion of the WAAS message can provide the system with back up and using WAAS corrected GPS can help calibrate LORAN. Carrying the WAAS message requires a data rate (250 b/s) that is significantly higher than the data rate available on current LORANCOMM. This paper discussed and analyzed three schemes that can be used to allow LORAN to carry data. It is hoped that these schemes can help improve LORAN and make it an important part of the new National Airspace infrastructure.

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