Analysis of the Enhanced LORAN Data Channel

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BIOGRAPHY

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Abstract

Many concepts have been proposed to increase the data rate of LORAN. Enhanced LORAN modulation schemes can provide many benefits to navigation including the transmission of GPS integrity information from GPS augmentation systems. The United States Federal Aviation Administration will soon conduct flight trials to assess these modulation and augmentation concepts. However it is important to understand the data channel and to predict the performance of the modulation schemes. An understanding will help determine both system performance and the design tradeoffs involved. This paper will detail the analysis of the LORAN data channel. Included in the analysis are the development of a model for the enhanced LORAN data channel and an examination of the performance of enhanced LORAN modulation schemes.

1. INTRODUCTION

The Global Positioning System (GPS), augmented by systems such as the Space Based and Ground Based Augmentation Systems (SBAS, GBAS), will become the primary means of aircraft navigation. SBAS such as the Wide Area Augmentation System (WAAS) enables GPS to provide the performance and safety for necessary for en route flight and many landing procedures. However, it is possible to lose the WAAS signal, especially at high latitudes such as Alaska. It has become important to develop alternate data links for the data provided by WAAS since the loss of that information would result a loss of operational capability or a reduction in safety. In addition, an alternate data link can provide additional redundancy in the system, increased coverage and additional radio frequency interference (RFI) rejection.

The transition to GPS as primary means of aircraft navigation also suggests that some established navigation systems will be either eliminated or downsized. The United States Federal Aviation Administration (US FAA) is evaluating the utility and effectiveness of the established systems within the new GPS based navigation architecture. If these existing terrestrial systems can broadcast GPS integrity information and provide navigation redundancy, then it could be advantageous to retain some of them. LORAN (Long Range Navigation) whose long term future within the GPS primary means architecture is being assessed.

The US FAA is currently evaluating the performance and capabilities of LORAN within the future GPS based architecture. Technologies such as the H-field antenna and all in view receivers will be fully evaluated. As important is the test and further development of the LORAN GPS Integrity Channel (LOGIC) to transmit WAAS based information to aviation users. Since WAAS messages are applicable to a larger area and require less bandwidth than GBAS messages, it is more suitable for transmission using LORAN. LOGIC will make LORAN more promising to future users by providing additional redundancy to the GPS aviation architecture.

LOGIC requires the design of higher data rate modulation methods as well as message algorithms for those modulation methods. Previous papers have discussed means of modulating data onto LORAN at a rate that can support WAAS information [1,2]. Furthermore, papers have also described how to use the LORAN data channel to provide WAAS information even if it is not capable of achieving the WAAS data rate [3]. This paper will focus on the theoretical performance of the system and the trade-offs involved in increasing the data rate.

2. LORAN COMMUNICATIONS

There are differences between LORAN communications and LORAN navigation. Data communications with LORAN require higher SNR levels than navigation due to several factors. For example, in LORAN communications, signals cannot be averaged over time and their exact forms are not known a priori. In addition, if all LORAN stations are transmitting modulated data, LORAN communications cannot use the cross rate blanking or canceling techniques employed in LORAN navigation. On the positive side, LORAN data communication is not dependent on precise time differences between stations and only one strong signal is necessary. Hence the receiver can use the strongest signal that it receives, even if the signal is from sky wave propagation or if the signal is a combination of the ground wave and sky wave signal from the same station.

Since it may be unclear which station or signal is being used for data, the station that is being used will be denoted as either the “primary” or “desired” station and likewise its signals are the “primary” or “desired” pulses. Any other stations are a source of interference to the primary signal and they are denoted as “interfering”. Also for this paper, the term “corresponding” will be used to denote the signal that is the sky wave manifestation of the ground wave signal. Similarly, the term, when used to describe two pulses refers to the ground wave and sky wave pulse generated by the same transmitted pulse

Three basic LORAN modulation methods were presented in [1,2]. The schemes can coexist and may 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. The second scheme is Intrapulse Frequency Modulation (IFM) whereby modulation is encoded within the pulse by slowly frequency shifting the signal. The third method is supernumary or interpulse modulation (SIM) whereby additional signals are generated in between the current pulses.

Each modulated pulse carries data that has not been decoded by error correction coding (ECC) or forward error correction (FEC). The data on the pulse is denoted by the term symbol. If block FEC methods such as Reed-Solomon (R-S) are used, a block of symbols may form a Reed-Solomon symbol. The initial analysis will only examine the symbol error rates before FEC.

2.1 Error Rates in the Presence of Noise

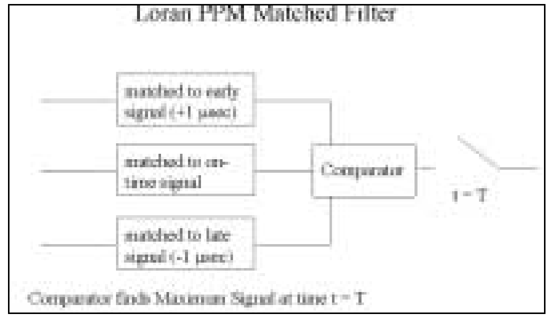

Figure 1. Matched Filter for PPM

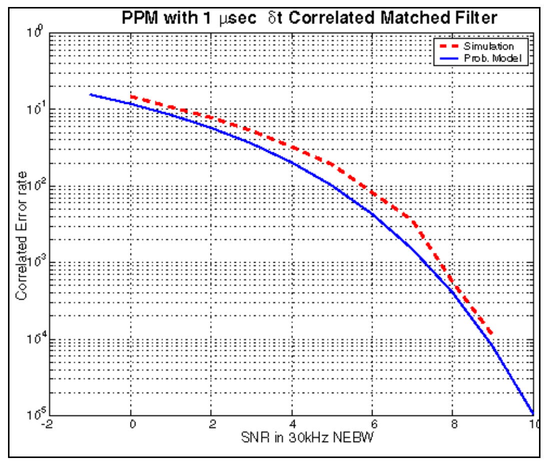

Figure 2. PPM Probability of Symbol Error vs. SNR

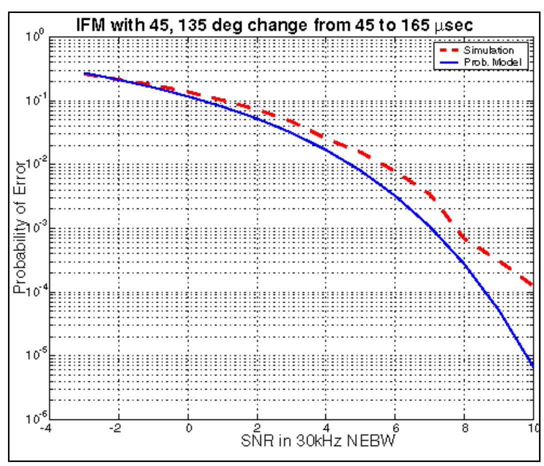

Figure 3. IFM Probability of Symbol Error vs. SNR

The performance of each modulation method is dependent on its probability of error with respect to signal to noise ratio (SNR). Matched filters are used to model the receiver's data demodulation. One major cause of data error is atmospheric noise. This is the dominant form of noise in the LORAN band. Generally, this noise is relatively low compared to the LORAN signal and is generally modeled as band limited white noise. Since atmospheric noise is ubiquitous, it is generally assumed to be present. The analysis of the LORAN modulation scheme and data channel uses the LORAN signal specification [4] 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. Details of the analyses are given in [1]. Figure 1 shows the basic match filter design while Figures 2 and 3 show the results for a specific implementation of PPM and IFM respectively.

2.2 Interference Sources

Aside from noise, there are also interference sources that may cause data errors. LORAN sky wave and cross rate transmissions represent the major source of interference on LORAN. Single hop sky wave is the only form of sky wave that is included in the model. There are a few reasons. Multiple hop sky wave usually have longer delays which means that the sky wave interference will affect the tails of the signal. Since the tail contains a lower percentage of the modulation energy, the effect will be generally less. The only issue for long delay sky wave is if the sky wave pulse interferes with the following data pulse. However, long delay multiple hop sky wave is generally weaker than the single hop sky wave. Furthermore, multiple hop sky wave can easily be incorporated into the model if observations show it to be an important issue for LORAN communications. Section 3 will discuss the models used to represent LORAN propagation and atmospheric noise.

Since the signal strength of the data signal along with cross rate and sky wave interference varies from location to location, one characteristic of the LORAN data channel is that the performance will vary from area to area. Section 4 will examine which areas have the highest levels of interference. The final sections will examine the results of the data channel.

2.3 Interference Error Rates.

Whereas figures 2 and 3 illustrate the performance of the modulation methods in the presence of noise, the performance of the modulation with respect to interference from other LORAN signals need to be examined. This section details the error rates due to the addition of interference from another LORAN station.

The interference of due to another LORAN pulse can be examined by using the match filter model again. The interfering pulse is an additional noise source and it modifies the shape of the desired pulse. The modified pulse is still subject to noise and the modified pulse and noise is passed through the matched filters and compared with the unadulterated data pulses. Figure 4 illustrates the process. If the only source of interference were the undesired LORAN pulse, then knowledge of the relative arrival time of the pulse and the relative signal strength of the pulse would make the error deterministic. Since the relative arrival time may vary due to variations in propagation path characteristics. A range of arrival times is analyzed with a given probability for each value in the range. Variations in arrival times and the addition of noise yield in a probabilistic result.

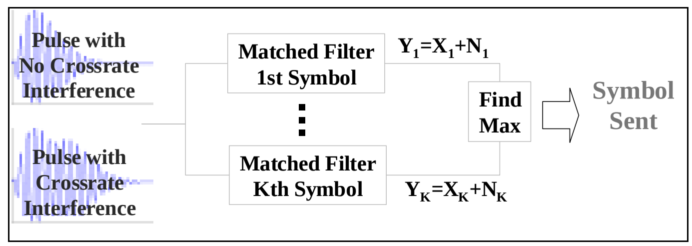

Figure 4. General Match Filter for Interference and Noise on LORAN

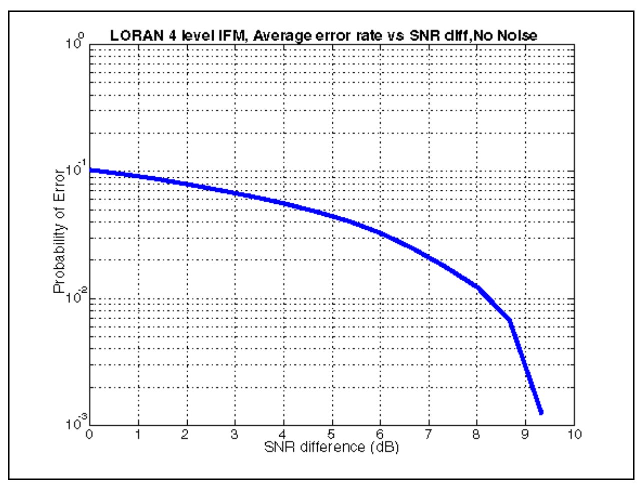

Figure 5. Average Error Rate for Interference from another LORAN signal

Interference from another LORAN pulse can affect the primary signal in different ways. For a primary signal with SNR around 10 dB, the major determinant of data error will be the interfering pulse. Figure 5 shows a plot of data error versus relative difference in SNR for interference from another LORAN pulse with no noise. Since noise is assumed to have a negligible effect, the relative difference SNR is important. This curve is a different from the previous SNR versus error plots in that it is an aggregate average over all possible pulse interference times. The assumption is that all interference times are equally likely. Figure 5 is only useful for illustration purposes since, for a given set of SNRs for the desired and interfering pulse, the probability of error can vary greatly depending on the time offset between the desired and interfering pulse. In fact, given the location of the user, the offset can be estimated to within a few microseconds. Figure 6 shows a curve for a specific noise level and specific interference level for a pulse that interferes at 70 μseconds after the beginning of the primary pulse.

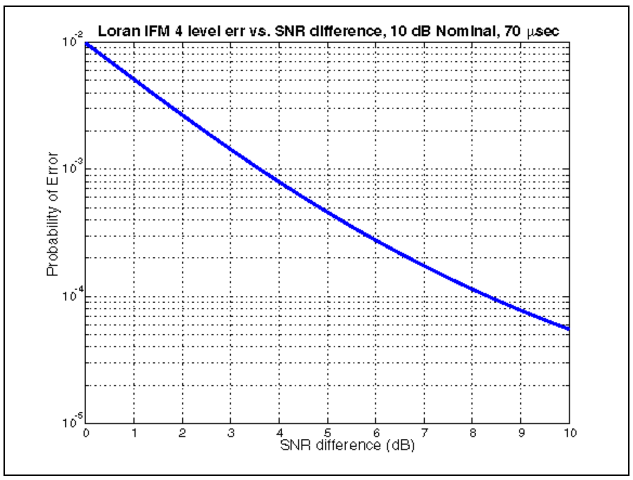

Figure 6. Error Rate vs. Relative SNR difference for a 10 dB LORAN signal and an interfering signal that is delayed 70 microseconds

2.4 Modification of Received Signal when Sky wave is Present

A LORAN communications receiver can use either the sky wave and ground wave signal and should generally take the stronger of the two. However, the sky wave pulse and the ground wave pulse may interfere with each other. Generally, the interfering sky wave signal is the sky wave pulse that corresponds to the ground wave pulse. Hence, they both contain the same symbol or piece of data. The combined signal, while it contains the same information, is modified. The user can acquire knowledge of the modified signal if templates of each modulation are sent. This can be accomplished using the first two pulses. However the modified signal may also affect the signal strength of the pulse. The signals may combine constructively or destructively. The model incorporates some features of the sky wave pulse modification while making some simplifications. It is assumed that the LORAN signal retains its original shape for error rate calculations. However, the signal strength of the combined pulse is modified to the lowest value generated by varying the sky wave delay up to 5 microseconds in time. Hence destructive interference is always assumed.

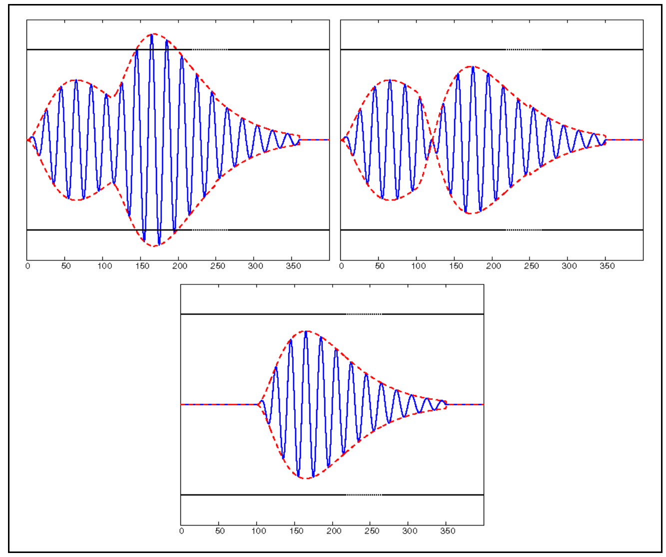

Figure 7. Modifying the Received Signal. From top left clockwise - 1) Strongest Combined Signal 2) Weakest Combined Signal 3) Modified Signal based on Weakest Combined Signal. Lines represent Nominal value of Sky wave

3. MODELS

3.1 Ground Wave Model

A ground wave model for LORAN is necessary to determine the signal strength of the desired and interfering signals. It is known that the propagation of low frequency (LF) ground wave varies with ground conductivity. The field strength of the LORAN ground wave was modeled using curves from [5] assuming nominal ground conditions. A ground conductivity (σ) of 3 x 10^{-3} Siemens per meter and ground permittivity ε_r of 22 is used. The received field strength for a signal propagating on a perfectly conducting surface is given by:

$$E_{sig}^2 = \left(\frac{9.48}{1000 r_{t,km}}\right)^2 P_{rad,W}$$

where $P_{rad,W}$ is the radiated power in watts

E_{sig} is the received signal field in volts/meter

$r_{t,km}$ is the range to the receiver in kilometers

A curve fit rather than a data look up table is used to represent the data in [5]. The two additional terms are used to modify the equation for a surface with finite conductivity [6].

$$E_{sig}^2 = \left(\frac{9.48}{1000 r_t}\right)^2 P_{rad} 10^{-.1a(r_t/1000)^b} V/m$$

r_t is the transmitted distance (km)

P_{rad} is the radiated power (W)

A least squares curve fit for the nominal/average land conductivity curve for 100 kHz yields values of

a = 17.52; b = 1.1036

Figure 8 shows the curve generated by the model. More sophisticated models can better account for the effects of terrain and variations in ground conductivity. However, the incorporation of these details is not necessary for the analysis since the goal is to get a nominal value.

3.2 Single Hop Sky Wave Model

Sky wave interference has been modeled in many ways. International Radio Consultative Committee (CCIR) proposed a model for single hop sky wave [7]. A nominal value of ionosphere height of 90 km is used. The model yields an average field strength and average propagation delay.

$$F = P + G_V + G_H + G_S - L_p + A - 20\log p - 10 k_R p - L_t$$

P - radiated power (dB above kW)

G_V - TX antenna gain (dB) due to vertical directivity

G_H - TX antenna gain (dB) due to horizontal directivity

G_S - additional signal gain when terminal(s) are near the sea

L_p - excess polarization coupling loss

$$A = 106.6 - 2\sin\left(\frac{\varphi_T + \varphi_R}{2}\right)$$

φ_T, φ_R - geomagnetic latitude of TX, RX

$p = \sqrt{\left(d^2 + 4h_r^2\right)}$ slant propagation distance

$k_R = k + 10^{-2} bR$

R- 12 month smoothed Zurich sunspot number

L_t - hourly loss factor

The sky wave delay model is derived from geometry and can be found in [7, 8]

$$t = \frac{2\sqrt{\left(R_e + h_{iono}\right)^2 + R_e^2 - 2R_e\left(R_e + h_{iono}\right)cos\left(\frac{d}{2R_e}\right)}}{.3} - \frac{d}{.3}$$

t is the sky wave delay (in μsec)

h_{iono} is the height of the ionosphere (km)

R_e is the radius of the earth (km)

d is the distance between the user and transmitter (km)

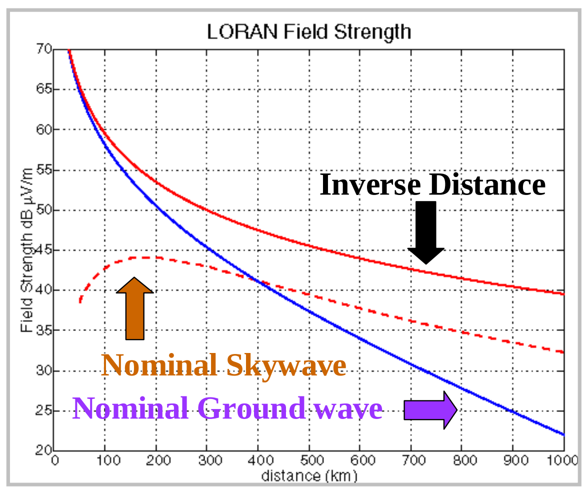

Figure 8. Average Ground wave and Single hop sky wave signal strength

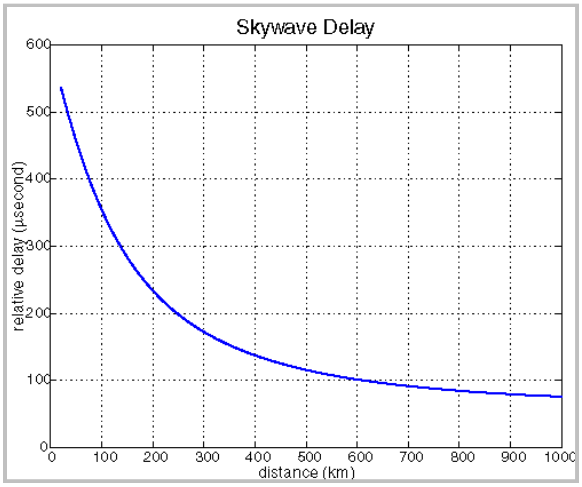

Figure 9. Nominal Sky wave delay

3.3 Ambient Noise Level

Ambient atmospheric noise varies with conditions and location. Average levels of atmospheric noise can be calculated from data and in the model results from [4, 9]. It is assumed that the noise bandwidth of the receiver is 30 kHz

4. DATA CHANNEL ANALYSIS

LORAN coverage can be determined from the propagation and noise models. The models can also help determine areas of high cross rate interference. An examination of the difference in SNR between the strongest and 2nd and 3rd strongest stations gives a reasonable estimate of the interference signal strengths. In general, the primary signal is far stronger than any other LORAN signal. However, there exist some areas where the SNR of the 2nd and 3rd strongest signals are within 2 dB of the primary signal. The plots overstate the case a little because the second and third strongest signals are often from stations in the same chain. Those signals will not cause cross rate interference. Since many stations are dual rated, a station that is in the same chain as the primary station may still interfere with the desired signal if it operates as part of another chain.

Ideally, one would like to test every region in the coverage area. However it is neither feasible in a short amount of time nor necessary. In a safety of life application, the concern is often for the worst case. Using Figure 10 and prudent selection of test cases, one can gain a reasonable understanding of the performance of the data channel. Five locations were selected for testing. The first two locations are in areas of strong cross rate interference. The second two are in areas of medium cross rate interference. The last one is located in an area of low cross rate interference. The last case seems typical of most of the country.

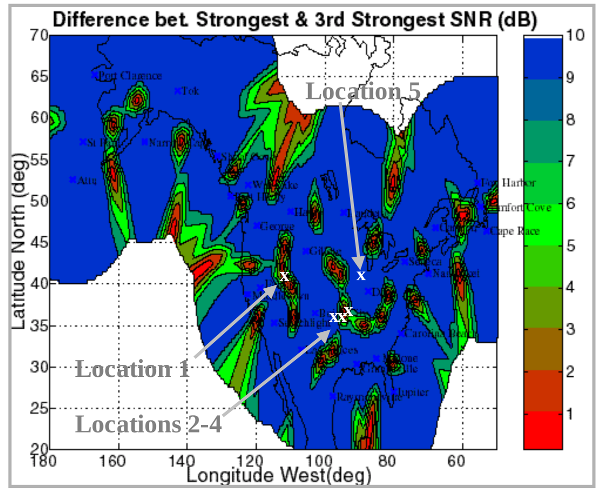

Figure 10. Relative Strength of LORAN interference signals (vs. strongest signal)

4.1 Creating the Model

Figure 11 shows the basic structure of the model. The model takes the location of the LORAN station and the user/test location as inputs. The ground wave and sky wave models are used to calculate the signal strength of LORAN signals received by the user while the location of the user determines the noise level. The station with the highest signal power, whether from sky wave or ground wave, is selected as the desired station. If there is sky wave, then the SNR of the desired signal is modified (see section 2.4) to reflect the condition. All interference sources within a threshold, usually 10 dB, of the desired signal are retained for interference calculations.

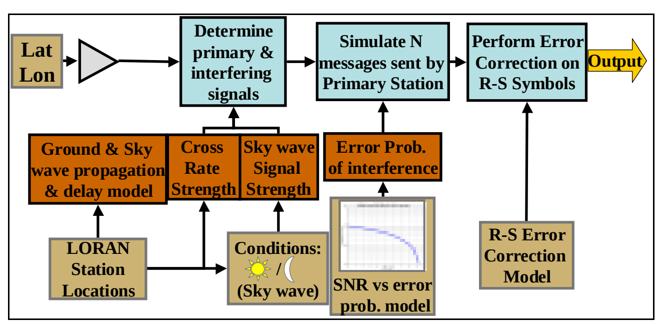

Figure 11. Data Channel Model Flowchart

The probability of error when there is no interference from other LORAN sources can be immediately calculated from the SNR. The probability of error when there is cross rate or sky wave interference from another LORAN station needs to be examined on a case by case basis because the error rate depends greatly on the offset time between the desired and interfering pulse. Simulations are used since they can represent such offset time variations. The relative difference in initial transmission time between chains and the nominal emission delays (NEDs) of each station are used to initialize the simulation. For the sake of the simulation, interfering sky wave signals are treated as a separate from its corresponding ground wave. In essence, it is another station in the chain whose NED is the NED of the station generating the signal plus the sky wave delay. And its received signal strength is the sky wave signal strength.

For each GRI, the interference on each pulse is calculated for each interfering signal rather than for the aggregate of all interfering signals. This is because there is rarely more than one or two interfering signals. If there is no cross rate or sky wave interference, then the error probability is determined from the SNR vs. error curve and can be calculated a priori.

If there is interference from another LORAN station, then the error probability is calculated by using the relative difference in arrival times of the desired and interfering pulse. The variation in the difference in arrival times is accounted for by assuming that the difference in arrival time can vary by a given amount of microseconds, usually 2, either early or late. The distribution of the variation is assumed to be uniform. Furthermore, the interfering LORAN pulse has one of two phase coding. The phase code of the interfering signal can be the in phase or completely out of phase relative to the desired signal. Since there is no a priori knowledge of the relative phase code, it is assumed that each relative phase code has equal likelihood. Furthermore, there is no a priori knowledge of the data on the desired pulse so each modulation is assumed to be equally likely. The desired and interfering LORAN pulse form modified pulse. Each set of different time offset, relative phase code and modulation creates a modified pulse. A probability of symbol error for each modified LORAN pulse is calculated using the analysis for each modulation scheme discussed in section 2.3 and knowledge of the noise level. Weighted by the overall probability of each modified LORAN pulse, the overall probability of symbol error is calculated.

It is more meaningful to describe the symbol error rather than the probability. The symbol error probability and distribution is collapsed to actual symbol errors by taking a random draw. This is done for the each GRI.

4.2 Forward Error Correction

Symbol errors need to be translated into message error since that is our primary concern. In order to do that, the effect of the FEC needs to be modeled. The effects of various FEC models can be tested once the symbol and GRI error rates and distribution is known. The performance of a Reed-Solomon (R-S) was modeled here. The assumption was that every set of six pulses represented one R-S symbol. For data without supernumary modulation, each GRI contains 1 R-S symbol. For supernumary modulation, each GRI contains 2 R-S symbols. A complete message is contained an integer number of R-S symbols.

A number of schemes are simulated. In the simulation it is assumed that each message is 30 R-S symbols in length. The error correction coding is capable of correcting for 7 R-S symbol errors out of a set of 30 R-S symbols. For schemes using supernumary modulation, the message requires .75 to 1.5 seconds while for schemes without supernumary modulation, the message requires 1.5 to 3.0 seconds. The transmission time calculation assumes that only one of the two rates of a dual rated station is used for the message. Otherwise, a dual rated station may transmit the required symbols in even less time.

Simulations lasting 1000 messages (30000 GRI) are conducted for two cases. The one case has cross rate interference but no sky wave interference and the other has both forms of interference. Six different modulation schemes are tested, three with supernumary pulses and three without. The test modulation schemes (with and without supernumary pulses) are:

- Three level pulse position modulation with time shifts of -1, 0, 1 μsec
- Three level IFM with phase shifts of –120, 0, +120 degrees
- Four level IFM with phase shifts of –135, -45, +45, +135 degrees

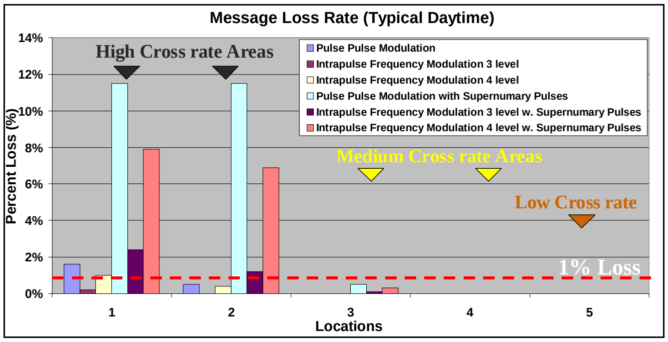

Figure 12. Message Loss Rates with Cross Rate Interference Only (No Sky wave Interference)

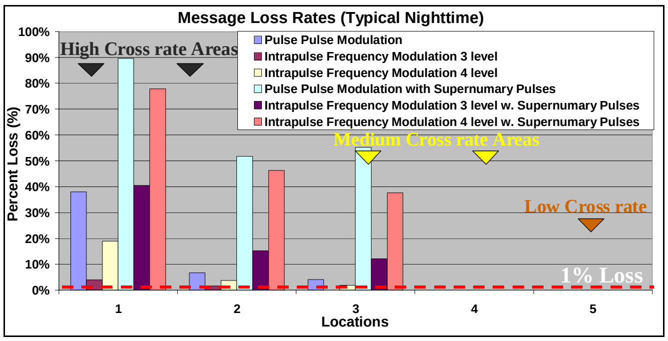

Figure 13. Message Loss Rates with Sky wave Interference

5. DISCUSSION OF RESULTS

The WAAS Minimum Operation Performance Specifications (MOPS) specifies that the integrity solution needs to have at least 99.9% availability for the desired operation even with .1% message loss. If the message loss is random, trials have shown that even a one percent message loss is tolerable [3, 11]. Hence, a one percent message loss is used as a reference measure of performance. Figure 12 shows the results when there is no sky wave interference and Figure 13 shows the result when every transmitter has a sky wave and ground wave signal.

5.1 Cross Rate Only

The cross rate interference case in Figure 12 is a nominal case. First, examine modulation techniques that do not employ supernumary pulses. Without sky wave interference, these modulation schemes, except for one of the PPM cases, performed with less than 1% message loss in even the high cross rate interference areas. However, even in the one instance where message errors with PPM exceed 1%, the message loss is still only 1.5%. Since supernumary pulses increase the amount of pulses being transmitted, the expected result is that there is a higher amount of interference and this is confirmed by the analysis. The effect of adding supernumary pulses is very evident in areas of strong cross rate where almost every modulation technique with supernumary pulses greatly exceeds 1% message error. PPM with supernumary modulation performs the worst with error rates around 11%.

5.2 Sky wave Interference

Figure 13 may be seen as a worst case situation since all stations emit a sky wave signal. Sky wave interference increases the probability of error since there are more signals that can interfere with the desired signal. Again proceed by examining approaches that do not employ supernumary pulses. For those approaches, only IFM 3 level has error rates rarely roughly 1% or lower for all areas. The other two methods exceed the 1% message loss rate in areas of strong cross rate. PPM even fails to meet this specification in an area of medium cross rate interference. The outlook for supernumary pulses is less promising and supernumary pulses perform acceptably only in areas of low cross rate interference.

5.3 Message Length

The message error rates plots present a high level summary of the data channel. A more detail examination yields some interesting conclusions as well. Figure 14 and 15 are histograms of the R-S symbol error rates for a 30 and 60 GRI/R-S symbol respectively. Both R-S symbol error rates are calculated for the same location and modulation method. FEC is assumed to correct for errors in up to 23.3% of the R-S symbols. While the data channel has memory in the sense that there are burst errors within a GRI, the error from one GRI to the next are independent. The independence of these errors from GRI to GRI has an effect on the statistics of the percentage of R-S symbol errors per message. With a longer message, the variance of the quantity decreases. Since only the portion of the distribution of the quantity exceeding the percentage correctable by the FEC contributes to message error, even a small decrease in the variance may have a significant effect in the presence of FEC. The 30 GRI message has a message error rate of 5.0% while the 60 GRI message has a message error rate of 1.6%. The figures show that with only a change in message length, the message error rate with decrease, ceteris paribus. The result is another justification for using the longest allowable.

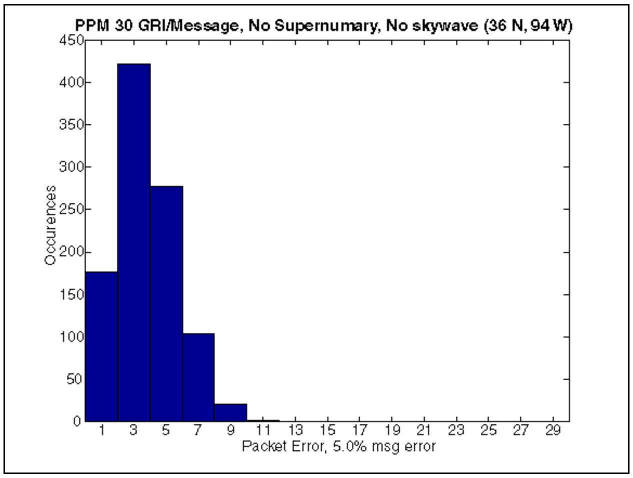

Figure 14. R-S Symbol Error per Message Histogram (PPM with 30 GRI/message)

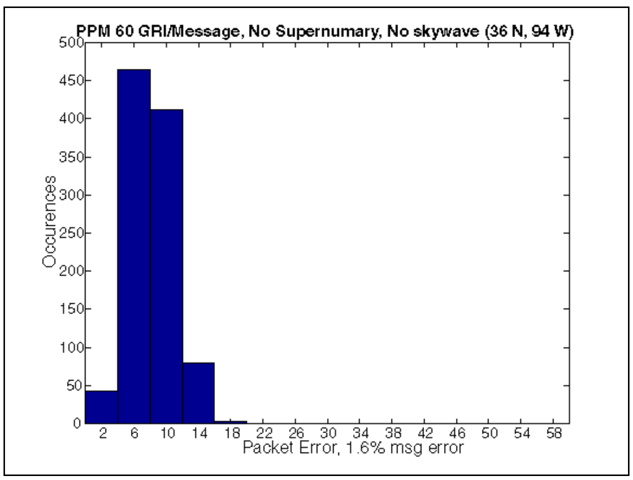

Figure 15. R-S Symbol Error per Message Histogram (PPM with 60 GRI/message)

6. CONCLUSIONS

The only method that performs adequately in all areas is a 3 level IFM. However this does not mean that the other methods are not useable. If one can accept a reduced coverage area, then any of these schemes may be acceptable. Most of the country have low cross rate interference and so any of the methods can be used in this reduced coverage area. However IFM 4 level and perhaps PPM, both without supernumary pulses, can also perform in all areas except for areas of strong cross rate interference. Even if one were unwilling to accept reduced coverage area, there are still means of using these modulation schemes. For example, stronger error correction coding may be used at the expense of data bandwidth. Or, as proposed by Dr. Peterson, the pulse shape can be changed or even lengthened to add more energy in the pulse. The change may be necessary for IFM for other reasons but such a change may help IFM 4 level achieve an acceptable message loss rate in all areas. The changes can be tested using the data channel model.

Some experiments have been conducted with the 4 level IFM concept. For stations in chains with GRI less than 5555 or for dual rated stations, the 4 level IFM results in at least 108 b/s. Research, as seen in Figure 16, has shown that it should achieve LNAV/VNAV Test of a 108 b/s design have been conducted and validates the ideal that a 1% message loss is still tolerable while still maintaining 99.9% availability.

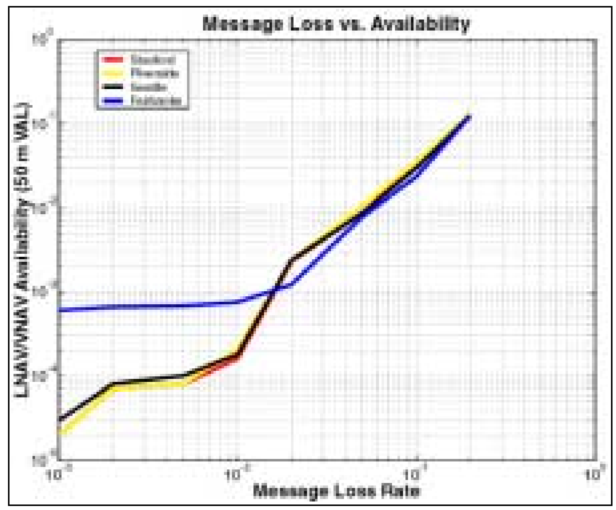

Figure 16. Message Loss vs. LNAV/VNAV Availability (108 b/s message)

As a result, the trials of enhanced LORAN at both Wildwood, NJ and Alaska will examine using IFM only without supernumary pulses. The tails of the LORAN signal will be lengthened to provide maintain frequency requirements and better data loss characteristics. Two versions are tested - a 4 level IFM modulation and 16 level IFM modulation scheme. The data channel results show that LOGIC using the 4 level modulation should be useable in almost all regions. The 16 level method is more aggressive and its useable coverage region may be much smaller than the 4 level method. However it allows for the transmission of 250 b/s which allows for the rebroadcast of the WAAS message with minimal changes. The two systems offer a chance to test the capabilities of LORAN and develop the system to meet the needs of the future aviation user.

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