Broadcasting Data from an SBAS Reference Network over using LORAN

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BIOGRAPHY

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ABSTRACT

Space Based Augmentation Systems (SBAS) have been developed principally to augment the Global Positioning System (GPS) for aviation and other safety of life applications. An SBAS reference network generates corrections and integrity information that are broadcast primarily using geostationary satellites. However, SBAS information may also be transmitted on auxiliary data links which could increase the availability and coverage area of the overall system. This paper will discuss how LORAN (Long Range Navigation) may be used to provide an auxiliary data link for SBAS integrity and correction messages. It will begin by examining means of placing data and the SBAS based messages onto LORAN. Since the LORAN data channel does not behave like a satellite data channel, LORAN data channel models will be derived and used to examine the system's performance.

1. INTRODUCTION

Several Space Based Augmentation Systems (SBAS) are currently being developed and fielded. Using geostationary satellite data links, an SBAS will broadcast information that will provide increased accuracy and safety to users of the Global Positioning System (GPS). The information provided by an SBAS may also be broadcast on another data link. This paper will explore how LORAN (Long Range Navigation) can be used to provide an alternate data link for SBAS information.

1.1 SBAS Background

SBAS increases the performance of the basic GPS navigation system by providing differential corrections, confidence bounds, and additional ranging signals. An SBAS uses a ground reference network to calculate an inverse GPS solution. The inverse solution involves the SBAS master station using measurements from the reference network to derive the location and clock bias of the GPS satellites. From that information, corrections to GPS ephemeris and GPS clock and selective availability (S/A) errors are derived. Long-term corrections correct for satellite ephemeris errors while fast corrections correct for satellite clock errors including S/A. The reference stations use dual frequency receivers that permit the calculation of ionospheric corrections. While generating the corrections, the SBAS master station also determines confidence bounds for the corrections and monitors the health of the GPS satellites. The SBAS master station then packages the information for broadcast.

The SBAS master station decides which set of corrections or information should be transmitted and packages the data using predefined message types. The Wide Area Augmentation System (WAAS) messages are set and defined by the WAAS Minimum Operation Performance Standards (MOPS) [1]. For the purposes of the paper, WAAS is used as our model SBAS. The message is 250 bits in length and is transmitted once per second resulting in a required data rate of 250 bits per second (bps). The overall transmission rate is 500 bps since a 1/2 rate convolutional coding is employed for forward error correction (FEC). The message is uplinked to WAAS geostationary satellites where the signal is then retransmitted back to earth at the GPS L1 frequency (1575.42 MHz). The signal is modulated with both data and a spread spectrum pseudorandom signal. The WAAS spread spectrum code and the GPS coarse/acquisition (C/A) codes are from the same family of Gold codes. More information on the WAAS messaging system is given in [2]. The WAAS geostationary signal provides the wide area correction, correction confidences, and an additional GPS-like ranging signal thereby increasing the performance and capabilities of GPS.

1.2 LORAN Background

LORAN is a hyperbolic navigation system capable of horizontal positioning. Originally developed by the United States during World War II, the current incarnation of LORAN, LORAN-C, first became operational in 1958 [3]. LORAN-C accuracy varies depending on receiver implementation. The 1 σ position error is roughly a few hundred meters with repeatable accuracy around 50 meters or better. Positioning is generally done using signals from one LORAN chain.

LORAN stations are grouped together into chains, which provide coverage to a certain geographic region. In each chain, there is a master station and several secondary stations. In LORAN-C, each station transmits a group of eight pulses (nine for the master station) at a specified interval. Each chain has a unique group repetition interval (GRI), which designates the amount of time between transmissions of the pulse groups. Figure 8 shows the West Coast LORAN chain denoted by GRI 9940. Some stations are dual rated and transmit pulses for two different chains. Each pulse is 250 microseconds long and spaced 1 millisecond apart. Receivers generally use the sixth zero crossing of the carrier in each pulse for timing and hence positioning. These pulses are transmitted at 100 kHz and can generally be received by users 800 km away. Position is solved using differences in pulse group arrival times between signals from the master station and the secondary stations.

While LORAN and GPS are both radionavigation systems, there are many differences between the systems. LORAN is terrestrial, low frequency and has high signal strength. These characteristics allow LORAN to operate in conditions that may impede GPS operations. The addition of differential GPS correction data onto LORAN would increase the utility of a combined GPS-LORAN navigation system. However placing DGPS corrections requires modifying LORAN to carry data.

LORAN was not originally designed to carry data. Starting in the late 1960s, there have been many proposals to place data on LORAN-C [4, 5]. In 1989, Dr. Durk van Willigen proposed the Eurofix system where DGPS corrections would be placed onto LORAN-C using pulse position modulation (PPM) [6]. PPM can be done with minimal effect on the navigational capabilities of LORAN and it can enable a relatively low data rate (~35 bps). The low data rate limited the amount of DGPS information transmitted. In 1998, several ideas were proposed to increase the data capacity of LORAN [7]. These schemes will be discussed later in the paper.

Increased data capacity and data rates can enable LORAN to carry WAAS information. Because LORAN signals have a large range, WAAS information is well suited for LORAN. WAAS correction is designed to be used over a large geographic area whereas scalar local area differential GPS (DGPS) corrections degrade spatially as one moves further away from the reference station. However, the most important feature provided by WAAS is addition of integrity to the GPS solution allowing GPS to be used for safety of life applications.

2. TRANSMITTING SBAS INFORMATION ON LORAN

Before turning to the transmission of WAAS based integrity information on LORAN, two areas need to be examined. First, one must be able to place data on LORAN. The following section will briefly discuss means of placing data on LORAN-C while maintaining backward compatibility and positioning capabilities. Second, one has to determine how to place WAAS integrity information on LORAN. The second step is important since the data rates enabled are not adequate for the full WAAS correction. It is necessary to study means of repackaging the WAAS information to fit on LORAN.

2.1 LORAN Data Communications

In order to use LORAN-C as an alternate data link, we need to examine the data transmission capabilities of LORAN-C. Eurofix has demonstrated the capability of LORAN-C to carry a small amount of data with minimal impact on current LORAN users. Eurofix uses PPM where the LORAN pulse is time advanced/delayed [8]. Balanced modulation, whereby an equal number of delayed and advanced signals are used per GRI, is employed to mitigate receiver phase offsets. If only six of the eight pulses are modulated, there are 141 unique balanced sequences per GRI. The first two pulses are not modulated to preserve some navigation functions and the blinking service [8]. In Eurofix, LORAN-C is encoded to have a transmission rate of about 70 bps for the worst case GRI. The actual data carried is lowered by the overhead required for error correction and error detection. Assuming that half the symbols are used for error correction, this leads to a data rate of roughly 35 bps.

2.2 Enhanced LORAN

Higher data rates on LORAN are achievable. The data rate increases need to be accomplished while still allowing legacy users to operate. There are schemes that can increase the raw transmission rate to about 350 bps or more. Again, the data rate will be lower due to the use of error correction and detection coding. The details and analysis of these schemes are presented in [7].

One method to increase the data capacity on LORAN signals is to combine a variety of basic modulation schemes. Three basic schemes have been examined in [7, 9]. The schemes can coexist and can be combined to form a hybrid signal design. The first scheme is aforementioned PPM. One can examine the performance of PPM in noise using either simulation or a probabilistic model. The signal to noise (SNR) ratio versus symbol error of PPM signals through a matched filter is shown in Figure 1. For the analysis, the standard definition for LORAN SNR [10] is used and a three level PPM with time shifts of +1/0/-1 microseconds is used. The model however does not include the effect of timing errors and the effect of additional modulation on to the signal. These effects may be significant and would increase the error rate.

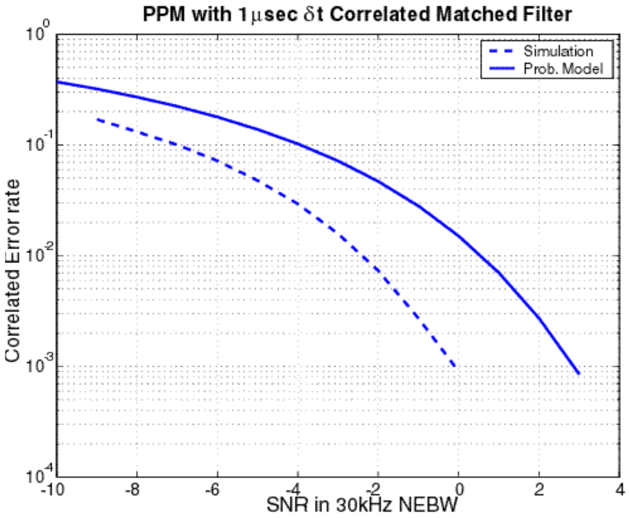

Figure 1. Pulse Position Modulation SNR vs. Symbol Error Rate (3 levels +/0/- 1 microsecond)

The second scheme is Intrapulse Frequency Modulation (IFM) whereby modulation is placed within the pulse by a slow frequency shift in the signal. The gradual change insures that the frequency content of the transmission remains mostly between 90-110 kHz. The change should occur after the sixth zero crossing to reduce the effects of the coding scheme on the navigation performance of LORAN. There are many ways to implement IFM. Initially, a phase shift of 90 degrees in 100 microseconds was examined. Peterson examined modified version where the phase is shifted 120 degrees and then restored [9]. This was shown to perform better. Simulations and probabilistic model were done to examine the symbol error rate for various SNR.

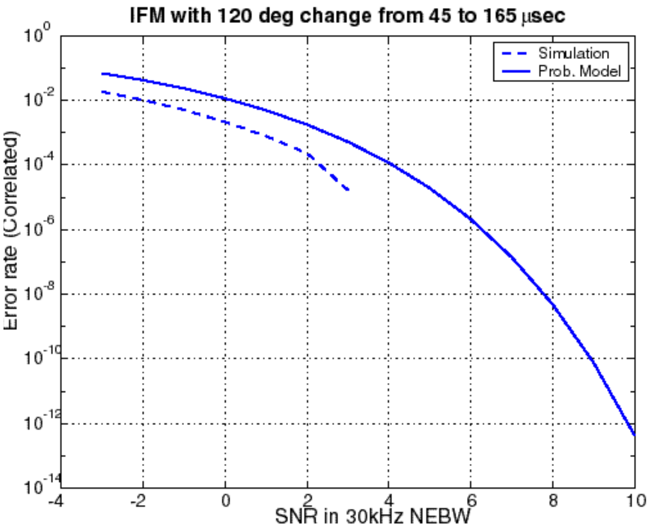

Figure 2. Intrapulse Frequency Modulation SNR vs. Symbol Error Rate (120 phase shift)

The third method is Supernumary LORAN whereby additional pulses are inserted in between the current pulses. Reference [11] demonstrates how the pulses can be added without affecting current LORAN-C users. The additional pulses can be modulated using PPM and IFM. So a hybrid scheme that has 16 pulses per GRI can be created. Data is modulated onto the pulses using PPM and IFM. This results in the hybrid scheme seen in Table 1. It is assumed that the data rate is half the transmission rate (i.e., the code rate is 1/2).

One cost of employing these schemes is increased noise and interference. Table 1 shows that increased data rates on LORAN are achievable though this will entail additional costs. However, the increased data rate allows for more flexibility in designing the WAAS on LORAN messages and a more useful LORAN signal.

Scheme	Data Rate (bps)	Transmitter Costs	Receiver Costs
Pulse Position Modulation	35	Additional logic	Additional processing for PPM
Intrapulse Frequency Modulation	47.5 to 55	Additional logic for half cycle generators. New equipment to modulate IFM	3 matched filters and processing
Preferred Hybrid (with Supernumary)	180	All of the above & 2x Transmission power. New equipment to enable increased number of pulses	All of the above & ability to receive supernumary

Table 1. Data Schemes on LORAN

2.3 Message and System Design

The data modulation methods discussed above result in a data rate lower than the 250 bps data rate required for WAAS messages. Because of the data rate, the information generated by WAAS must be modified to fit onto the LORAN data link. Many techniques such as requantizing corrections, reducing the corrected satellite set, combining messages, compression coding schemes, and repackaging messages were tested.

Two systems are examined - a high data rate system (~ 167 bps) and a low data rate (~35 bps) system. For the high LORAN data rate, all three forms of WAAS corrections are retained however only a subset of satellites (19) are corrected. Analysis demonstrates the amount is more than adequate [12]. For a lower data rate link such as 35 bps, more data needs to be truncated. In this system, only the fast correction is maintained and due to the low bandwidth, the accuracy of the fast corrections is reduced. Both these systems maintain the WAAS MOPS standards for user differential range error (UDRE) and fast correction updates. The UDRE message contains information necessary to place confidence bounds the error on the position solution. The combined data modulation and message schemes are denoted as the LORAN GPS Integrity Channel (LOGIC). Reference [12] discusses the details of how the feat is accomplished. The low and high data rate systems are used to achieve Non Precision Approach (NPA) and Instrument Approach with Vertical guidance (IP-V) respectively. Hence they are respectively denoted by LOGIC-NPA and LOGIC-IPV. The schemes were created before S/A was turned off. A natural question is whether and how WAAS or LOGIC is affected by that S/A being off.

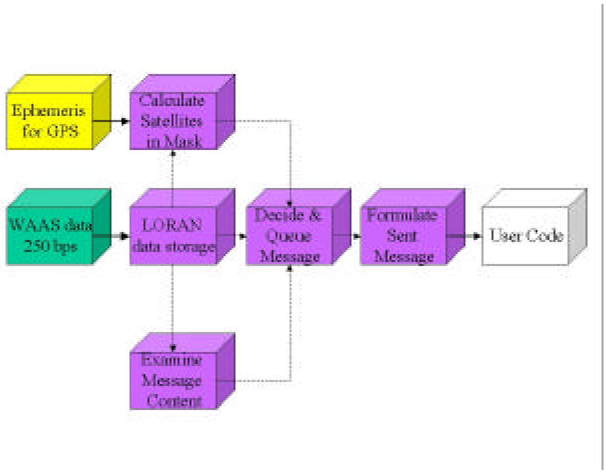

Figure 3. LOGIC System Diagram

2.4 Selective Availability (S/A) off

With S/A off, the drift rates and magnitude of the GPS clock error and hence fast corrections are significantly lowered. This would imply that WAAS and DGPS corrections can be sent less frequently and still maintain the same accuracy resulting in bandwidth savings. However, to maintain integrity requirements specified by the WAAS MOPS, the update rate of the UDRE and fast corrections must be maintained. Since the WAAS standards currently remain unchanged, an S/A off environment does not change LOGIC.

Another consequence of S/A off is that the errors due to the ionosphere are nearly as large as the errors corrected by the fast corrections. This is particularly evident in the vertical accuracy. The result has significant implications. Since the ionosphere is now a primary source of error, the inclusion of ionospheric corrections is important. For example, one can design a message scheme that includes fast corrections and ionosphere corrections for the low data rate channel. While it would not meet the current WAAS MOPS fast correction update requirement, the lower fast correction drift rates in an S/A off environment mitigates the need. Since we are only beginning our S/A off research, the subject still requires more study.

3. LORAN DATA CHANNEL MODEL

One factor that differentiates using LORAN for SBAS information versus a geostationary satellite data link is the data channel characteristics. A memoryless channel is often used to model data and message loss on a geostationary satellite data link. While this may be an adequate model for satellite data links, it may not well represent a terrestrial data link such as LORAN. The data loss on LORAN tends to occur in bursts and should be modeled differently. To model the LORAN data link, one begins by examining the sources of interference on LORAN. There are many sources of interference for LORAN [3]. However, the primary sources of interference come from LORAN itself in the form of cross rate and sky wave interference.

Interference of one station's signal by another station from a different chain is known as cross rate interference. Within the coverage area of a chain, no station operating as part of that chain will interfere with another station in the chain. This is due to careful selection of transmission delays for the stations relative to the master station. However, stations that operate in another chain, particularly dual rated stations, can cause interference.

A dual rated station transmits pulses for two different chains. For example, the Searchlight station is dual rated for GRI 9940 and 9610 (see Figure 8). This means that Searchlight will transmit a group of pulses every 99400 microseconds for GRI 9940 and every 96100 microseconds for GRI 9610. There is no guarantee that the GRI 9610 pulses will not interfere with transmissions from the GRI 9940 chain. Occasionally, the station will have to transmit for both chains simultaneously. When this occurs, the pulses for one chain are not transmitted. This is known as blanking. Cross rate interference with its associated phenomenon of blanking is a primary source of LORAN interference.

Sky wave interference is another major LORAN interference source. In order to examine sky wave interference, it is important to understand LORAN signal propagation. LORAN signals propagate by two means. The signals 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. The ground wave signal is more reliable and is used for position solutions. Sky wave signal is delayed and the delay is dependent on height of the ionosphere. Generally, sky wave is delayed 50 to 400 microseconds [13]. Depending on the distance from the transmitter and other factors, the sky wave signal can be significantly stronger than the ground wave signal. For LORAN communications, sky wave is an issue when the sky wave and ground wave of the primary signal are very close in signal strength. Otherwise, if the two signals differ in signal strength, the receiver can select and use the signal with the greater power to receive data. Hence sky wave can help or hinder LORAN communications.

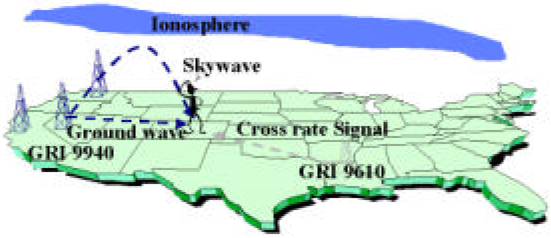

Figure 4. Sky Wave & Cross Rate Interference

To model the data channel, it was assumed that the data transmitted using LORAN are placed into packets. Since the modulation schemes do not employ binary modulation, the LORAN symbols must be converted into bits. One way of packaging the data onto LORAN is to use each GRI to contain an integer number of packets. The packets will be mapped onto a binary data format. In LOGIC-NPA, each GRI contains one packet. In LOGIC-IPV, there are two packets of data per each GRI packaged so that the six consecutive pulses contain one packet. The schemes help mitigate some of the effects of cross rate interference. Multiple packets are combined to form a message.

3.1 LORAN Interference Models

Models were developed to examine the effects of cross rate and sky wave interference. The SNR of North American LORAN stations were predicted. A contour map of this can be seen [9]. The primary station generating the desired message will be the station with the strongest SNR. Any station generating a SNR value within 10 decibels (dB) of the desired signal is assumed to be capable of causing interference. For the purpose of the data link, these stations and signals are undesired.

Sky wave is included in the models by the addition of an extra set of interfering pulses delayed a fixed amount of time from the ground wave signal. The difference in SNR is not currently in the model. The sky wave interference SNR used in the model is the SNR of the ground wave. Future simulations may include a sky wave SNR model.

Two models were developed. A simple model was developed to determine a rough estimated of cross rate interference and the need for error correction. The addition of SNR effects on data reception was added to the simple model to get a more realistic representation of the data channel.

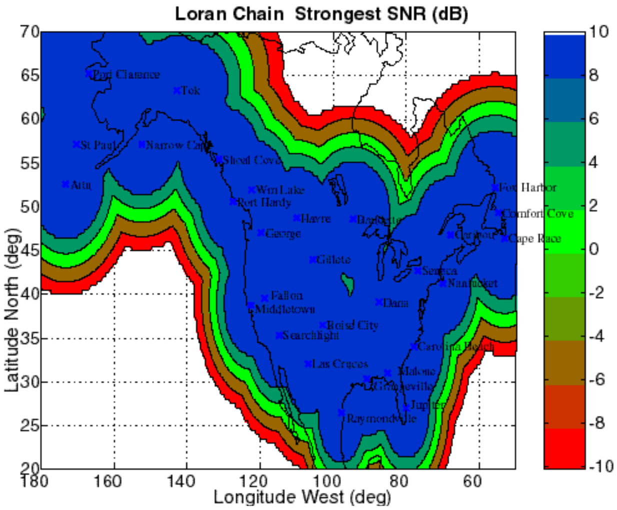

Figure 5. Strongest LORAN SNR

3.2 Simple LORAN Channel Model

In the simple model, if pulses generated by the undesired stations arrives at the same time as the pulses generated by the desired station then there is interference and all data from the pulse and the group that contained the pulse is lost. This is a very conservative model of the effects of cross rate interference. Blanking is also included. Sky wave is also modeled and the only parameter that is set is the sky wave time delay. The difference in SNR from ground wave to sky wave was not modeled. Sky wave interference from the desired station was also not included. The addition of sky wave did not greatly alter the interference rate seen in the model. Since sky wave generally is 50 to 400 microseconds delayed from the ground wave signal, if there is sky wave interference, there typically is ground wave interference and vice versa.

As case studies, three different regions of the United States (Western US, Eastern US, Alaska) are examined. The results showed that with this model of LORAN interference, the channel could only operate effectively with one cross rating station. If there were cross rate interference from more than one station, the percentage of lost packets would generally exceed the percentage correctable by a reasonable amount of error correction. This leads to a large message loss rate. There are very few regions that have less than two cross rate stations whose signals are within 10 dB of the primary signal. Most have two or more such stations. The basic model demonstrates how often one can expect to LORAN signals from different chains arrive nearly simultaneously. Each cross rate station interferes with about 10-20% of the transmitted GRI groups depending on the modulation scheme used and the GRIs involved. Knowledge of the amount of packet loss caused by one or more cross rate interference sources, can be used to analyze the necessary error correction rate needed to ensure low message loss.

The error correction coding selection was based on the belief that an average of about 10-20% of the packets will be lost. This is roughly equivalent to having one cross rate interference source that always causes data loss. A Reed Solomon error correction scheme is assumed to be used in the transmission. The 167 bps message has a Reed Solomon code could produce a correct message even if 1/4 of the packets that formed the message had been eliminated. The same is true for the 35 bps channel.

3.3 Extended LORAN Channel Model

After using the simple model to determine the percentage of signals affected by cross rate interference, a more realistic model was used to analyze the channel. The SNR differences between desired signal and the interfering signals were added. The SNR versus probability of error curves shown in Figures 1 & 2 were used to determine error rates. Note that these models are for white noise whereas the LORAN cross rate interference is of a known frequency and pattern.

Examining the difference in SNR between the strongest and 2nd and 3rd strongest stations will give a reasonable estimate of the interference signal strengths. There are only a few places where the SNR of the 2nd and 3rd strongest signals are within 2 dB of the primary signal. One fact that mitigates the situation is that the second and third strongest stations maybe from the same chain and those signals will not cause cross rate interference. However, the stations may be dual rated thus having the potential of emitting two cross rating signals. From previous analysis, messages can generally be recovered in the presence of one cross rate interference source even if the receiver cannot receive any of the pulse groups where the primary and cross rate signal coincide. There maybe trouble when there is cross rate from many stations.

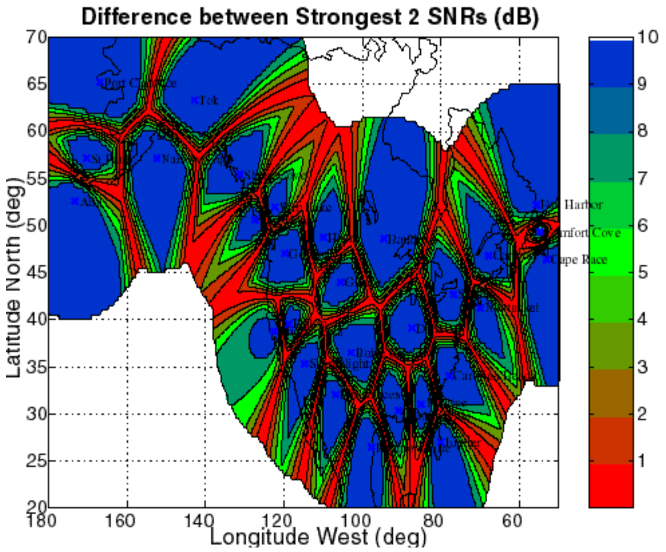

Figure 6. Strongest - Second Strongest LORAN SNR

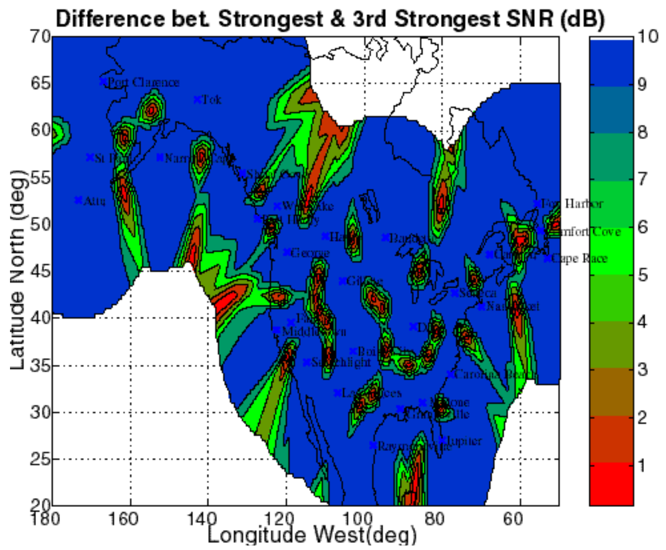

Figure 7. Strongest - Third Strongest LORAN SNR

Since cross rate interference varies greatly from place to place, it is difficult to generalize its effects. Instead, a few cases are examined. Three of the cases examined are that of an area where there are many strong signals (within 3 dB of the primary signal) - which is an extreme and rare case as seen by Figure 7.

The first case is an area near the vicinity of 35.6 N, 119.96 W. In this region the signals from Middletown (primary), Searchlight, and Fallon that are within a few dB of each other. However, in this region, all stations are from the 9940 chain, though Searchlight is dual rated and also operates in the 9610 chain. If Middletown is used as the primary, cross rate interference only comes from Searchlight. For LOGIC-IPV, simulations show a packet loss rate of 2.75% and 3.11% for PPM and IFM respectively and no message loss. For LOGIC-NPA, 2.04 % of the packets are lost but no messages are lost.

More typical is the case of 35.9 N, 109.1 W. Signals from Las Cruces (primary), Boise City, and Searchlight are within 2 dB of each other. In this case, all stations are in the 9610 chain however there are two cross rating signals since both Boise City and Searchlight are dual rated stations. For LOGIC-IPV, simulations show a packet loss rate of 6.41% and 6.89% for PPM and IFM respectively and a message loss rate of 0.4%. For LOGIC-NPA, 4.25% of the packets are lost but no messages are lost.

The third case examines the vicinity of 36.47 N, 94.25 W. In this region, signals from Grangeville (primary), Dana, and Boise City that are within one dB of each other. However, in this case is different from the first case in that there are multiple stations causing cross rate interference and all stations are dual rated. If the Grangeville GRI 9610 pulses are used as the primary data signal, the number cross rate interference signals is minimized. Since Boise City is part of the 9610 chain, the Boise City 9610 signals will not cause interference. However, Boise City still causes cross rate interference because it also transmits on GRI 8970. Dana causes interference because it transmits on both GRI 9960 and 8970. For LOGIC-IPV, simulations show a packet loss rate of 8.53% and 9.55% for PPM and IFM respectively and a message loss rate of 2.1%. For LOGIC-NPA, 5.73% of the packets are lost but no messages are lost.

Location	LOGIC-IPV Msg Loss	LOGIC-IPV PPM, IFM loss	LOGIC-NPA Msg Loss	LOGIC NPA PPM loss
35.6 N, 119.96 W	0%	2.75% 3.11%	0%	2.04%
35.9 N, 109.1 W	0.4%	6.41% 6.89%	0%	4.25%
36.47 N, 94.25 W	2.1%	8.53% 9.55%	0%	5.73%

Table 2. Results of LORAN Channel Case Study

3.4 LORAN Data Channel Results

The data channel models indicate that there will be many cross rate signals. However, there are only a few places where the cross rate signals will be significant. Error correction can compensate for some of the cross rate and sky wave interference. The simulation shows that with error correction that can correct for burst errors, low message error rates may be achieved. Furthermore, proper error correction can result in a message error that is random and independent. This knowledge means that we can use a random message loss model to model the performance of LOGIC. However, the models do not include all possible interference issues. More tests and experiments need to be conducted to validate the models and results. Future tests involving data transmission from an actual LORAN transmitter will help in developing the data link into a robust channel for SBAS information.

4. LOGIC PERFORMANCE

The performance of the LOGIC message schemes can be examined for a data channel with binomial independent message loss. Since the LORAN data channel model shows such a model can approximate the message loss in the LORAN data channel. Actual data is used to assess the performance.

GPS satellite measurements taken from the National Satellite Test Bed (NSTB) from June 24 to June 27, 1998 was used to analyze of the message schemes. From the data, the Stanford WAAS Test bed Master Station (TMS) generated the WAAS correction used and additional code was written to simulate the transmission of the data to the Middletown LORAN station, the processing done by the station, and the transmission to the user. The data link between the WAAS TMS and the LORAN station is presumed to be lossless and to have one second of time latency. As seen in Figure 8, the Middletown station is part of the 9940 chain. Using the station location, the LOGIC code determines which satellites it will correct and then it decides which message to send. The NSTB data contains measurements from the GPS satellites in view at various stations in the test bed. Figure 8 shows the approximate coverage area of the 9940 chain and the NSTB reference stations (designated by stars) for which a LOGIC and a WAAS solution are calculated. Denver is also examined, even though it is outside the coverage area, to test the robustness of the system.

Performance of the system will be assessed using a graphical tool known as a triangle chart. For more information concerning the tool, see either the WAAS website at Stanford University or reference [12].

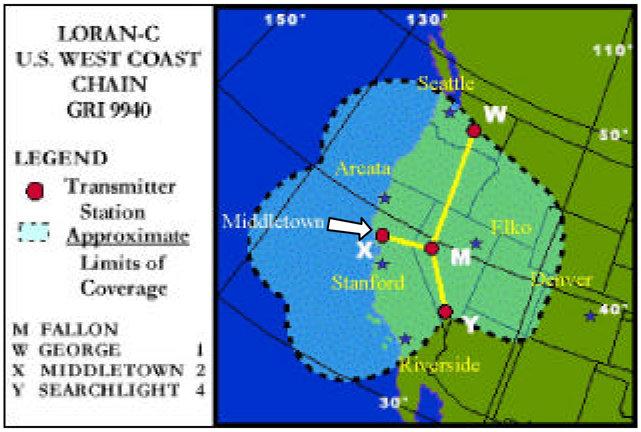

Figure 8. Coverage Area & Test Set Up

4.1 Low Data Rate LOGIC

The performance of the low data rate LOGIC (35 bps) in the absence of message loss can be seen in Figure 9. Figure 9 shows the Horizontal Protection Level (HPL) triangle chart of a user at Seattle, Washington using corrections generated at the Middletown LORAN station. The Stanford TMS used actual measurements to generate the WAAS corrections. These corrections were passed to the LOGIC code that generated the LOGIC corrections and simulated the data link. The position solutions were generated from actual measurements taken at Seattle and the low data rate LOGIC corrections. Similar performance can be seen in Stanford and Riverside, California as well as Denver, Colorado. Note that the protection levels achieved using the 70 bit message is only capable of achieving NPA performance and not capable of achieving IPV, its more stringent counterpart. Hence this system is denoted LOGIC-NPA.

However, the data link is not perfect and in fact the WAAS MOPS dictates a structure that accounts for lost messages. From the previous section, a binomial message loss model was used to simulate the LORAN data link and to test LOGIC-NPA performance with message loss. Results show that the protection levels are not changed very much. The large protection levels are due mostly to degraded corrections and UDREs and because ionospheric corrections are not sent. Even with a 20 percent message loss channel, the low data rate LOGIC system achieved better than 99.999% availability for NPA. Since WAAS was designed to provide high availability for CAT I approaches and since NPA has much less stringent requirements than CAT I or even IPV, it is not surprising that this LOGIC system achieves NPA with such high availability. The difference between LOGIC with low message loss rates (less than 1%) and high message loss rates (between 1% and 20%) shows up more in accuracy rather than availability for NPA.

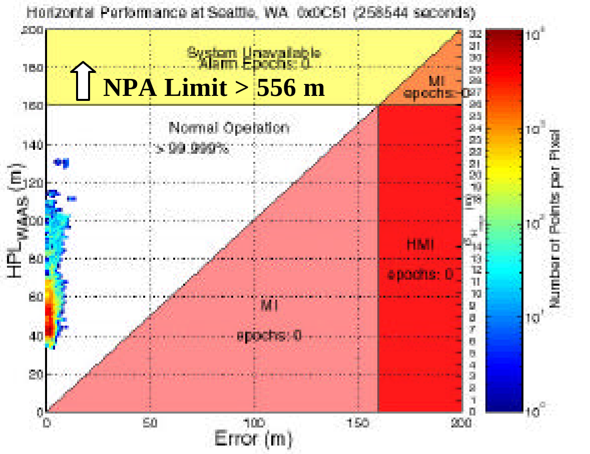

Figure 9. Low Data Rate LOGIC Horizontal Protection Level - Seattle (No Message Loss)

4.2 High Data Rate LORAN

The increased data capacity of the 167 bps data channel allows more corrections to be sent and other improvements. Hence, it should achieve better performance. Again, we present results from both a lossless and a lossy transmission cases. The performance of the system in the coverage area is adequate to meet IPV (Instrument Landing with Vertical Guidance) specifications, which specifies both vertical and horizontal performance. This system is denoted LOGIC-IPV. Only the vertical performance results are shown since the horizontal specifications are not as stringent and were easily met.

The Vertical Protection Level Charts for a lossless data channel (Figure 10, 11) show that the performance is worse than WAAS. Accuracy is slightly worse while error confidence bounds (protection level) are higher. The result is expected since the WAAS MOPS specify the rapid manner by which confidence bounds degrade with time. However, the system does achieve IPV availability for 99.995% of the time. More importantly, the system has no integrity failures, where the error exceeds the protection limit calculated by the user, during the entire period. The performance does degrade when there is message loss.

Figure 12 shows that LOGIC-IPV significantly degrades when the message loss rate is above 1 percent - a result that is similar to the performance of WAAS [14]. Using the 2.1% message loss rate seen in the worst case from the previous section, the system has a better than 99.8% availability. For lower loss rates, the system has greater than 99.99% availability for IPV for all test locations in the coverage area.

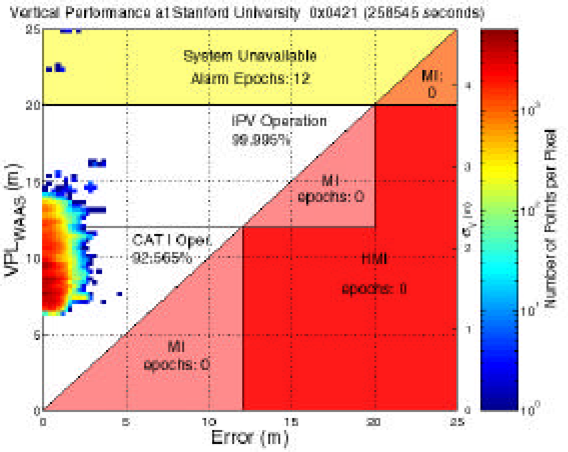

Figure 10. Vertical Protection Level Chart LOGIC-IPV performance on June 24-27, 1998 - No message loss

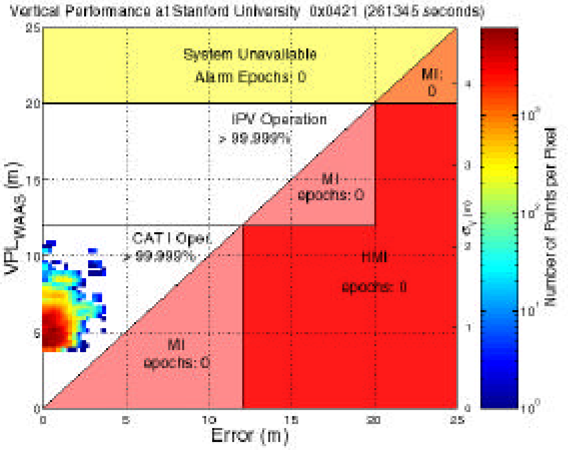

Figure 11. Vertical Protection Level Chart WAAS performance on June 24-27, 1998 - No message loss

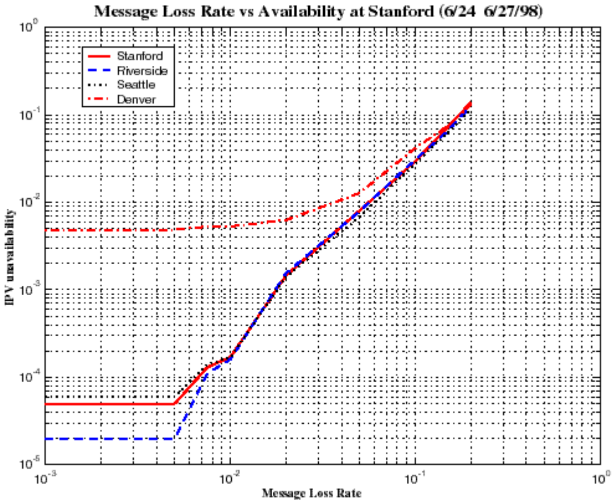

Figure 12. LOGIC Performance with Message Loss

5. RESULTS & CONCLUSION

The research on using LORAN as an alternate data link for WAAS information demonstrates two results. First, a sub 250 bps WAAS derived message can be a useful addition to GPS/WAAS navigation. Second, modeling and understanding the data channel is necessary and important to the design of the system.

The two sub 250 bps WAAS derived integrity messages examined demonstrate that there is utility in transmitting a reduced and truncated set of corrections. The corrections can act as back up for users in safety of life applications or they can be used as differential corrections for non-safety of life applications.

A low bandwidth LOGIC can provide aviation with an alternative data link that can still enable NPA. A 167 bps LOGIC system can provide aviation with an additional means of receiving information necessary to conduct enroute and landing operations down to IPV. Using LORAN to transmit the message mitigates line of sight problems. This makes the system feasible for land and sea applications as well as aviation.

The schemes are general and not limited to LORAN. They can be used on any data channel. Other possible transmission channels are FM subcarrier channels such as the Radio Data System (RDS) or a VHF datalink such as VHF Data Broadcast (VDB). Bandwidth on VDB can be gained from the unused bits of the Local Area Augmentation System (LAAS) Type 1 or differential corrections message. Examining the LAAS Interface Control Document (ICD), there are at least 56 unused bits in the message. Since the message must be sent once per frame or half second, this translates to a minimum rate of 112 bps. Another way of using VDB is to have a message dedicated to WAAS. More study including analysis of the data channels will be needed.

The analysis of the LORAN data channel shows that a user can expect many cross rate interference signals. Only a few signals will be within a few dB of the primary signal. However, one needs to design the channel with error correction coding that can account for burst errors as well as losses of around 10% of the data packets. With proper error correction, LORAN can transmit the LOGIC messages with low message loss rates. The low message loss rates enable the integrity messages to have high availability for users. The ability to have useful and available GPS integrity information on LORAN increases the utility of LORAN and provides an additional feature to a combined GPS/LORAN navigation system.

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