Early Skywave Detection Network: Preliminary Design and Analysis

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A skywave signal is one has propagated by reflecting off the ionosphere. These signals are common in low frequency (LF) broadcast. However, in Loran, these signals are nuisances since they interfere with the more stable groundwave signal. Loran-C was designed with mitigations for the most common forms of skywave interference. However, these mitigations are not adequate to mitigate early skywave, a short delay skywave that interferes with the tracking point of the Loran signal. The interference can affect both the measured envelope and phase (timing) of the Loran signal. These effects can be deleterious for the accuracy and integrity of a Loran position solution. Preserving integrity is critical for safety of life application such as aviation landing. As such mitigations for early skywave need to be designed.

It is difficult for a mobile user receiver to detect and eliminate the effect of early skywave in Loran-C. For eLoran, a monitor network will be used to provide the necessary early skywave warning to protect integrity. The resulting reduction in availability is acceptable since early skywave is reasonably rare in the conterminous United States (CONUS).

This paper describes early skywave and the phenomena that cause the event. It describes some characteristics that can be used for identifying and analyzing early skywave events. It also details the preliminary design and analysis of the monitor system.

There are two major components to the network. The first is the monitor receiver that has to detect the skywave event locally. These receivers will use the current system area monitor (SAM)locations. The second is the monitor network, algorithm and message. This part of the design determines the overall coverage of the skywave event and provides warning to the user.

1.0 Introduction

Long Rang Navigation, or Loran, is one of the few position, navigation and timing (PNT) systems capable of providing back up to the Global Positioning System (GPS) in multiple modes of operation. The capability is critical as redundancy for GPS is vital to the national infrastructure. The Volpe GPS vulnerability study indicated that the current GPS is susceptible to deliberate or inadvertent interference [1]. As such, it recommended examining various alternatives to providing redundancy to GPS, particularly in safety critical applications. The 2004 FAA Loran Technical Evaluation examined the capability of Loran for providing GPS redundancy [2]. It offered several recommendations and changes, that if followed, would yield a Loran system that is capable of meeting requirements for non precision approach (NPA) for aviation, harbor entrance approach (HEA) for maritime, and highly synchronized timing and Stratum 1 frequency for timing and frequency users. The preferred NPA is Required Navigation Performance 0.3 (RNP 0.3).

1.1 RNP 0.3 Integrity

For Loran to provide redundancy to GPS for aviation, Loran must meet aviation requirements. Three areas of primary concern are meeting required levels of integrity, availability, and continuity. Integrity is the fidelity of the system – the reliability that the information provided is true. For RNP 0.3, the requirement is that the probability of hazardously misleading information (HMI) is less than 10^{-7} per hour. An instance of HMI is defined as when the horizontal protection level (HPL), the bound on horizontal position error (HPE) generated by the system, is exceeded by the true HPE. Meeting the integrity requirement is the most challenging task in demonstrating the ability of Loran to serve RNP 0.3.

Availability and continuity are the other two principle requirements. Availability represents how often the system can be used for the desired application. To use a system for RNP 0.3 approach, HPL must not exceed the horizontal alert limit (HAL) of 556 meters (0.3 nautical miles). The requirement for RNP 0.3 is that availability (HPL < HAL) must be at least 99.9%. The requirement must be met at every point in the coverage area and cannot represent a spatial average. Continuity is the ability to complete the specified operation using the system if the system is initially available. For RNP 0.3, the approach is 150 seconds in length and the requirement is for at least 99.9% continuity. Table 1 summarizes the requirements.

Requirement	**Definition (Metric)**	**Minimum Requirement**
Integrity	HMI is when HPL > HPE	Probability HMI ≤ 10^{-7}/hour
Availability	HPL ≤ HAL (556 m) No HPL means not available	99.9%
Continuity	Given HPL ≤ HAL initially HPL must exist & HPL ≤ HAL for 150 seconds	99.9%

Table 1. Primary Requirements for Aviation (RNP 0.3)

The system integrity is determined by ones ability to accurately estimate the range or timing error. Other papers discuss how the position errors are bounded [3]. However, there are some events which can result in errors that cannot be adequately bounded or detected by the user receiver. A form of skywave interference, early skywave, can result in such errors. Hence, one of the recommendations made in the Technical Evaluation was for the inclusion of an early skywave detection network for the conterminous United States (CONUS) [2]. The detection network is required to provide an integrity warning to users who will be affected by early skywave.

1.2 Skywave and Early Skywave

A skywave is a signal that has propagated by reflecting or "hopping" off the ionosphere. Loran skywave interferes with the more stable Loran groundwave signal. The groundwave is the primary signal. These two forms of propagation are shown in Figure 1. Skywave interference is common in low frequency (LF) broadcast. Loran-C was designed with many mitigations for skywave inference. Long delay skywaves (greater than 250 μsec) are mitigated by phase coding [4][5]. Shorter delay skywaves are mitigated by a signal design that allows for tracking before the arrival of typical skywaves. The tracking point is usually 30 μsec from the start of the pulse and is shown in Figure 2. This is the sixth zero crossing location. The tracking location is early enough so that skywave interference is not an issue but late enough to there enough energy in the signal. The envelope power at the tracking point is approximately 4.08 dB lower than the peak envelope power.

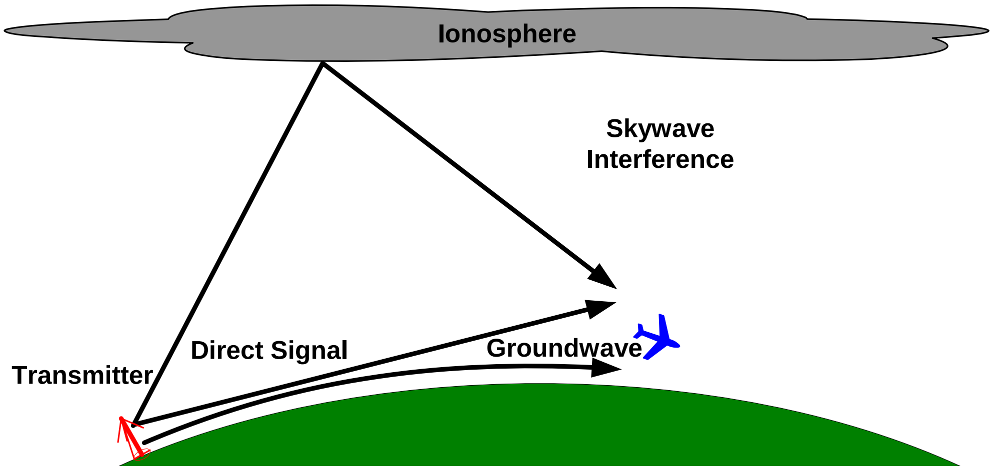

Figure 1. Skywave and Groundwave

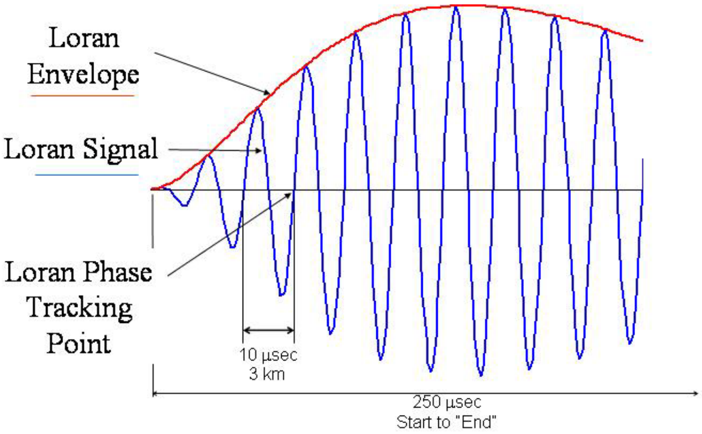

Figure 2. Loran Pulse, Envelope, and Tracking Point

Skywave delay varies depending on ionospheric conditions. As such, it can arrive prior to the 30 μsec tracking point. The term "early skywave" has been used to describe skywaves with a delay of less than 30 μsec with respect to the groundwave. Because of the short delay, it affects tracking point of the Loran signal. This interference adds vectorially to groundwave thereby distorting signal envelope and/or phase. The distortion depends on the relative delay and the skywave to groundwave ratio (SGR). Figure 3 shows the envelope to cycle difference (ECD) and phase distortion caused by various delays for a skywave with SGR of 0 dB.

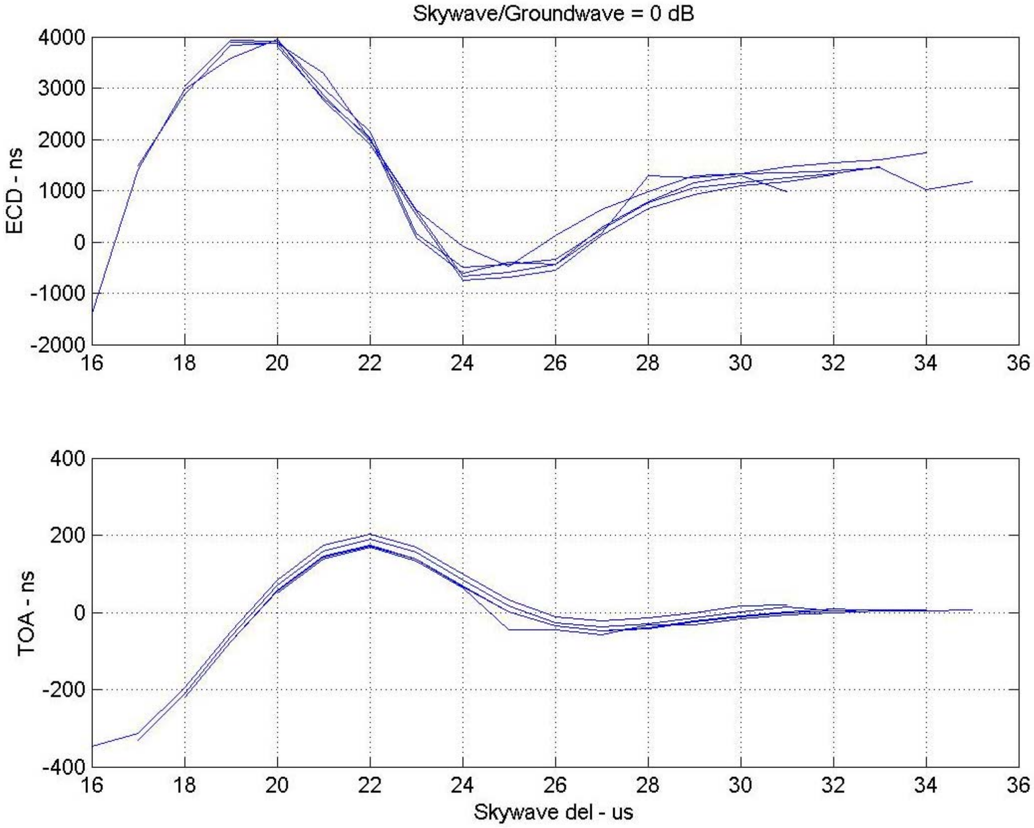

Figure 3. ECD and TOA Error due to Early Skywave (Simulated Locus LRS IIID Performance)

1.3 Early Skywave and RNP 0.3 Integrity

Distortion of the signal envelope and/or phase can be deleterious for accuracy and integrity. The problem is compounded because the effect is difficult for the user to detect and estimate. The signal envelope shape is used to make a coarse determination of the sixth zero crossing. It provides the location of the correct cycle of the pulse to examine. The ECD measurement represents the value of envelope distortion relative to the carrier. A reasonable estimate of ECD results allows for a high confidence determination of the sixth zero crossing. Since early skywave can distort the envelope to large but unknown extent, it can result in an undetected erroneous cycle selection. This is an integrity problem since the receiver generally cannot detect it. An undetected erroneous cycle selection will result in HMI. An erroneous cycle selection result in errors of roughly three kilometers or more. Similarly, phase error induced by early skywave is difficult to detect or predict. The difficulty in prediction can result in the HPL not properly accounting for the error. The result is that the HPL will not bound the HPE with the proper integrity level. Early skywave thus can cause loss of integrity. As such, mitigations for early skywave need to be designed for Loran to meet aviation integrity requirements.

The paper will discuss early skywave mitigation for CONUS. If the user receiver cannot detect early skywave, mitigation can reduce availability. Fortunately, Morris found that early skywave is a rare though not insignificant event in CONUS. It was encountered approximately 0.1% of the time during the peak of the solar cycle[6]. Since it has such a low occurrence rate, mitigation that results in loss or reduction in availability only during these periods is acceptable. Alaska will require additional mitigation to maintain reasonable availability[1].

2.0 Background on Early Skywave

This section presents background on the characteristics and behavior of phenomenon leading to early skywave. The physical events that lead to early skywave are described. Studying these physical events helps determine the extent and frequency of early skywave events. More detailed discussion of early skywave characteristics and causes is given in [6]. Mitigation strategies are discussed in the last part.

2.1 Atmospherics Events Leading to Early Skywave

Early skywave conditions occur when the ionosphere regions (D and E) that normally acts to reflect the Loran signal is lowered. This results in shorter skywave propagation paths for single hop skywaves resulting in a decreased delay. Early skywave conditions originate from solar events that increase the ionization in the ionospheric layers. The increase causes a lowering of the ionosphere regions. Thus, the same ionization level which acts to reflect the Loran signal is found at lower altitudes than typical. Several solar-terrestrial related phenomena can lead to early skywave inducing conditions. Foremost among these are polar cap disturbances (PCDs), sudden ionospheric disturbances (SIDs), and geomagnetic storms.

Sudden ionospheric disturbances (SIDs) are caused by large x-ray flares on the solar surface. These x-rays (high-energy photons) cause excess ionization in those regions directly exposed to the sun. As a result, these events affect only the Earth's dayside with the effect being proportional to cosine of solar zenith angle. SID related effects typically

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[1] Early skywave is more common in Alaska since the region has a very low effective ionospheric reflection height which results in the difference between the skywave and groundwave path lengths becoming relatively small. This results in a high incidence of early skywave when compared to CONUS.   Early skywave is encountered in Alaska with incidences of 5%.

last about 30 to 45 minutes. Figure 4 shows an example of a SID event. The figure shows measurements of the x-ray flux as well as measurements of ECD and TOA from the Alpha-1 system area monitors of the 8970 Loran chain.

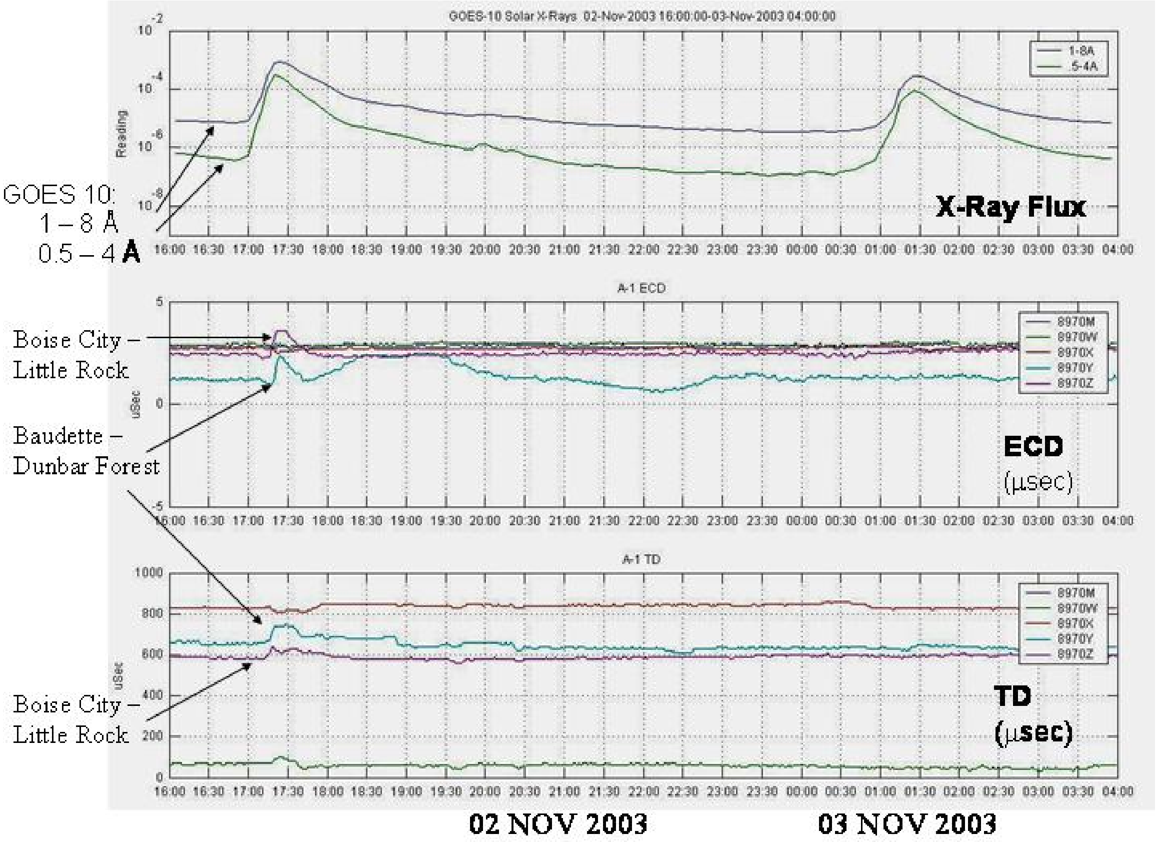

Figure 4. Measurements of 2 November 2003 SID event from GOES 10 and Loran Alpha 1 monitor for 8970

Polar Cap Disturbances (PCDs) are caused by excess protons emitted from the sun during Solar Proton Events (SPEs). Protons are not deflected by the geomagnetic field in the auroral zones (AZs) which leads to very high ionization in these regions. This can result in lowering of ionosphere's D region effective reflection heights to roughly 50 km. These events can last as long as five days poleward of the auroral zone, e.g., Alaska and occasionally in CONUS. PCDs are thus the primary source for conditions leading to anomalously early skywave for ionospheres poleward of the AZ. PCDs are also a leading cause of early skywave conditions in CONUS since they are often accompanied by a southward movement of the AZ in the northern hemisphere. The movement can result in a much larger area, including much of CONUS, being subjected to a PCD ionosphere for a period of one to two hours. The movement of aurora zone boundary equatorward roughly follows lines of geomagnetic latitude. PCDs are also dayside phenomena. More details are given in [6].

Geomagnetic storms result from solar corona mass ejections that distort the interplanetary magnetic field. Large storms compress the dayside geomagnetic field, thereby causing an equatorward movement of the AZ boundary. During these events, CONUS is exposed to the full PCD ionization but the boundary excursion only persists for a few hours.

2.2 Limits of Early Skywave

Analysis shows that early skywave only affects the user on signal paths with a range greater than roughly 800 km. This conclusion is from assessment of propagation models and collected data for a strongly ionized PCD and SID ionosphere. Under PCD ionosphere conditions, Figure 5 shows that the skywave delay is less than 30 μsec for ranges greater than 500 km. However, as seen in Figure 6, the skywave has little effect on the received signal for ranges up to 800 km because the SGR is low. On the upper end, one-hop early skywave has maximum range of about 1500 km for a substantially ionized *D*-region.

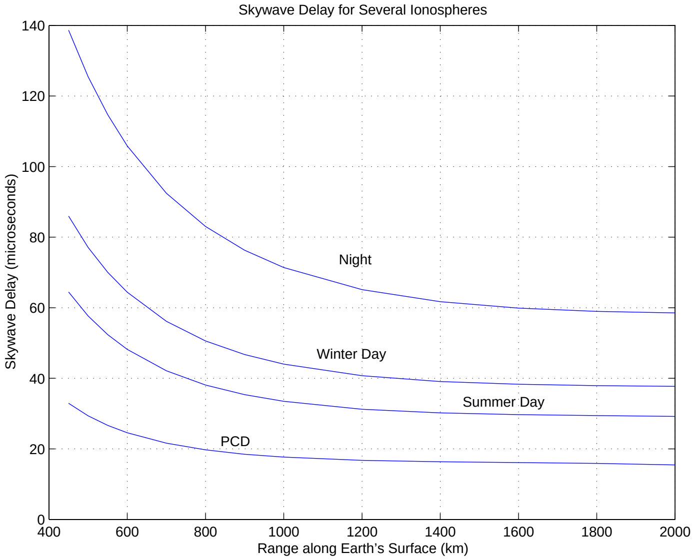

Figure 5. Skywave Delay for Night, Winter Day, Summer Day, and PCD Ionospheres

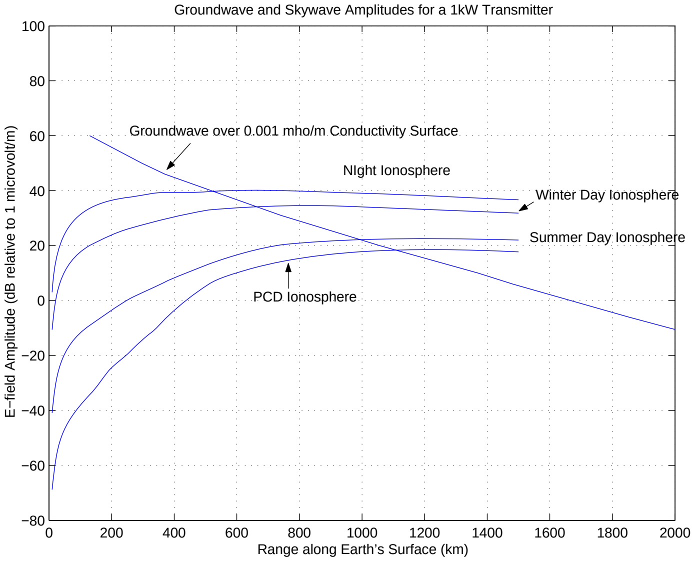

Figure 6. Skywave and Groundwave Amplitudes for Various Diurnal/Seasonal Conditions (1 kW Transmitter at 0.001 mho/m)

2.3 Methods of Protecting Against Early Skywave

Early skywave can affect both ECD and phase measurements. As mentioned previously, both undetected ECD and phase errors will result an HMI. Hence the aviation Loran user must be protected from early skywave. There are several methods of providing protection. The simplest is to provide a warning message indicating the location of the early skywave affected signals. This reduces the number of signals for available for the receiver. Another means of mitigation is to reduce the effect of skywave. Faster rise time signals similar to the Chayka signal can be used. Finally, receiver detection is a final mean of mitigation. With the current signals, this is difficult for non stationary users. Some of the transmitted signal can be modified to aid with receiver detection. For example, a sounding signal can be used to help users detect and potentially mitigate the effect of skywave. This sounding signal could be placed on a non navigation signal such as the Ninth Pulse Communication signal.

Fortunately for CONUS, the incidence of early skywave is relatively low. Historical data indicates that this occurs about with a probability of 0.001. As a result, a warning message will be adequate to protect integrity with only a minimal effect on availability. (Since early skywave events are reasonably rare, the loss of availability is acceptable.) This is the solution indicated in the Loran Technical Report [2]. An early skywave detection network needs to be developed to generate the warning message. This network will consist of three components: warning message, monitor detection receiver, and monitor network.

3.0 Warning Early Skywave

The interface between the early skywave detection network and the user is the warning message. The section will discuss preliminary design for the message and how it will be transmitted. It will also discuss algorithm and processing in the user receiver.

3.1 Warning Message and Algorithm

An early skywave warning message will notify users of early skywave conditions. The early skywave warning message is to be carried on the modulated Ninth Pulse. The message will share that data channel with differential Loran corrections and station identification and timing message. The message will be broadcast by all transmitters so the user will only need to receive data from any one station. It will use the format developed for the differential Loran corrections for harbor entrance approach (HEA).

The Ninth Pulse message uses 24 group repetition intervals (GRIs) to transmit one message. Each GRI contains five bits yielding a raw data content of 120 bits per message. Forward error correction (FEC) is employed to enhance robustness and results in 45 bits of data. Since 24 GRIs are used, a message is transmitted every 1.6 to 2.4 seconds. More details on the modulation are given in [7].

The purpose of the early skywave warning message is to provide information to the user on the presence and absence of early skywave. The information is constructed to maintain as much availability as possible while fitting into one Ninth Pulse message. The message will contain the following information: a flag indicating an event, the geomagnetic latitude limit of the event (denoted in this paper as GMLAT or λ), and the type of event. The geomagnetic latitude limit is the broadcast bound on the extent of a PCD event. PCD events generally follow along a geomagnetic line of latitude. Lines of constant geomagnetic latitudes are shown in Figure 7. SID events occur throughout the dayside Earth. As such, a SID ionosphere has no distinct latitudinal boundary. In the warning message, a SID event is indicated by setting the geomagnetic limit to zero degrees which indicates that it exists everywhere. Hence, the transmitted geomagnetic latitude limit also indicates the type of event.

The message transmission rate is designed so that the user can quickly determine if early skywave conditions exist. The early skywave message will be repeated at a specified interval (N messages), regardless of skywave condition. Hence, a receiver that has just started up will have to wait for at most N messages to determine if early skywave exists. A receiver only needs to process one warning message to ascertain the current early skywave condition. Processing the message helps provide a guarantee on the transmitted Loran signal.

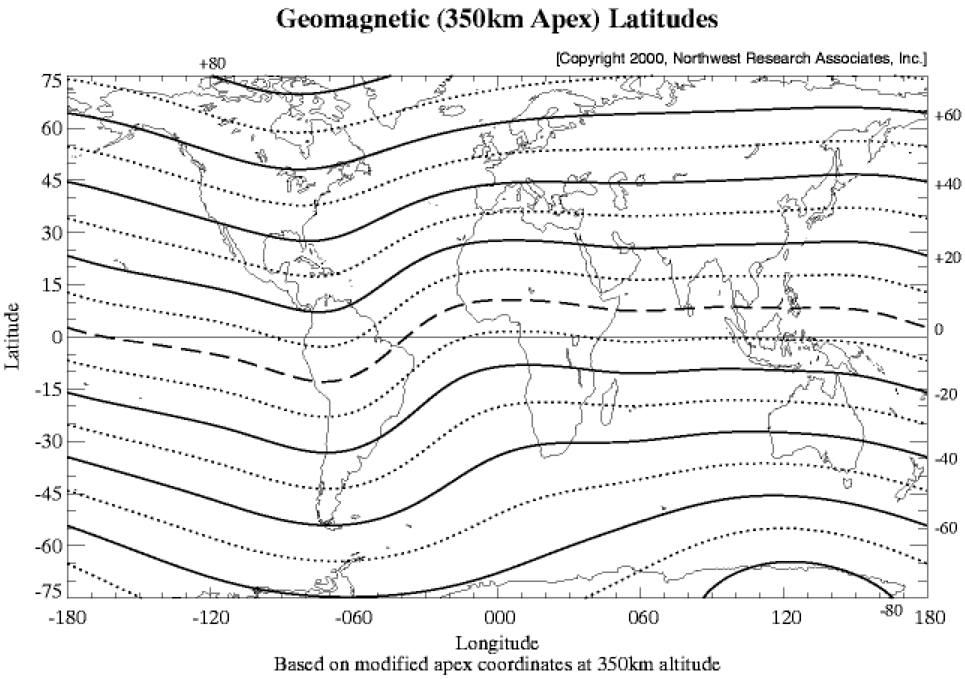

Figure 7. Geomagnetic Latitudes (http://www.nwra-az.com/ionoscint/maps/maplats.html)

3.2 User receiver processing

Once the receiver gets the message, the receiver needs to be able to properly process it. First, that means the receiver needs to decode and parse the contents of message. If the warning indicates there is early skywave, the receiver needs to determine which signals are affected. For each transmitter used, the user receiver will follow a process similar to that shown in Figure 8 to determine if the signal can be used. It first checks if the transmitter is the correct (800 to 1500 km) distance away for early skywave to exist. If true, then the receiver calculates the midpoint location between the user and the transmitter. The receiver, based on the time and date, will determine if the midpoint is on the daylight side of the Earth. Next, if the midpoint is on the daylight side, the receiver will convert that midpoint location to a geomagnetic latitude and compare the latitude with the limit given in the early skywave message. If the midpoint's geomagnetic latitude is greater than the geomagnetic latitude limit (GMLAT), then the signal cannot be used.

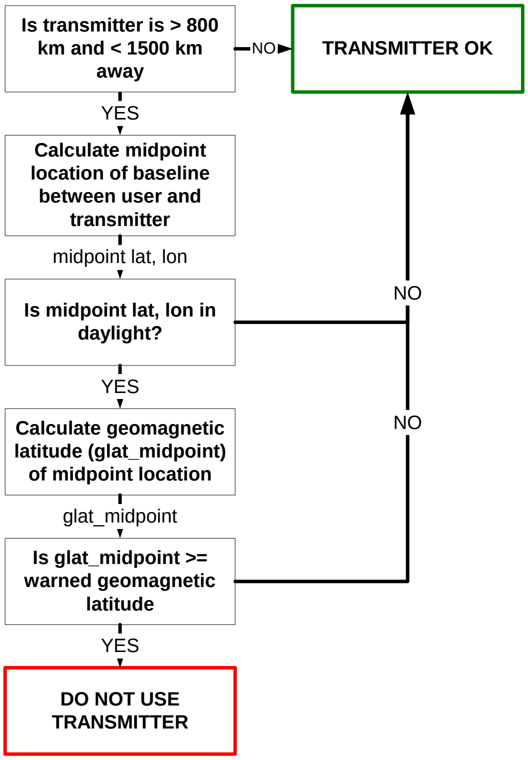

Figure 8. Flow Diagram for Determing Effect of Early Skywave

4.0 Monitor Receiver

The monitor receiver is responsible for initial detection of early skywave conditions. Its design must have fidelity enough to detect early skywave conditions before it affects the user. A new type of monitor receiver will have to be developed for early skywave detection. A prototype receiver known as the Enhanced Loran Research Receiver (ELRR) is being built to explore some of capabilities required by the monitor receiver. It is also being used to assess type and quality of information that can be gathered on early skywave.

The monitor receiver will examine several markers to help identify the onset of early skywave conditions. Phase and ECD measurements, as seen in Section 2.1, are useful markers. Other indicators such as signal strength should be used. Detection of the event and type of event will be based on examining all of this data. Detection will require utilizing as much information as possible. This is because the early skywave events must be detected very early – before the event can significantly affect the user. Therefore, the detection must occur during the onset of the event when effects are small. Gradients and assessment of time history will also be used in identifying the onset of an event (see Figure 9). Furthermore, comparison of neighboring baselines/detection points can provide additional verification. The detection process may occur at the monitor receiver or at the network level or both.

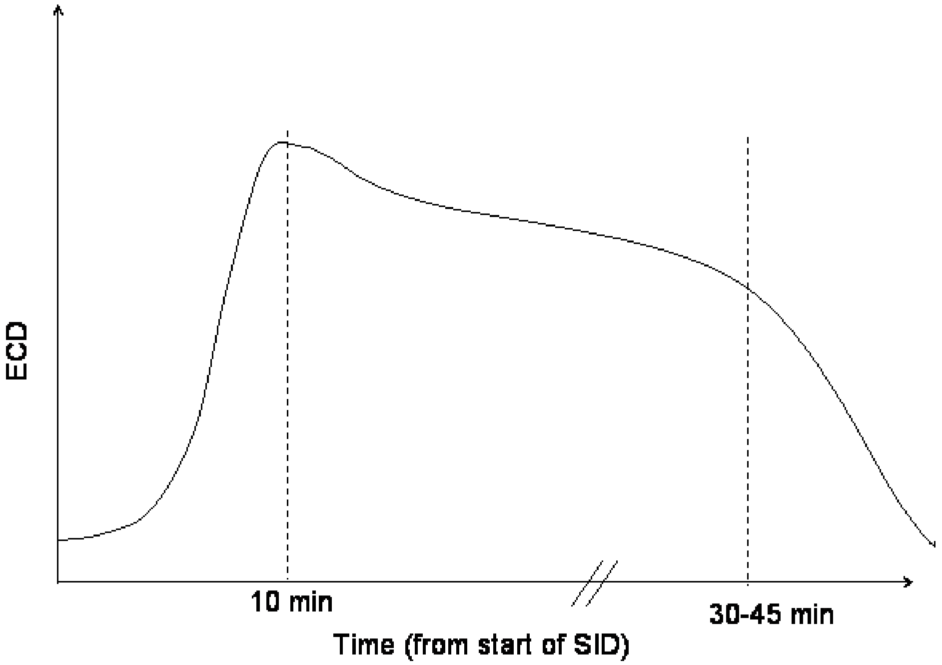

Figure 9. Illustrative Plot of the effect of an SID event on ECD

In the 2006, the ELRR and other data collection receivers should be collecting more data on early skywave. As more data is collected on early skywave, analysis will be necessary to determine when to alert. A set of parameters based on the receiver measurements will be calculated and warnings will be issued once the parameters exceed set thresholds. Research will determine the parameters and the thresholds that best trades off between false warning and missed warning.

5.0 Early Skywave Monitor Network

The network segment of the early skywave warning system collects and assesses the information gathered by the monitor receivers. The assessment is used to determine if and where early skywave conditions exists. It also should help determine the type of early skywave event (PCD, SID). The results are then transmitted via the warning message.

Ideally, the design should only use the existing infrastructure of Loran transmitter sites and system area monitor stations. These current monitor sites are shown in Figure 10. New monitor receiver and communication infrastructure will be needed. Ideally, no additional sites will be necessary. The early skywave network simulator was created to test the capabilities and limitations of the design. It will determine if the current monitor locations provide sufficient coverage. It will also test the algorithms used by the network.

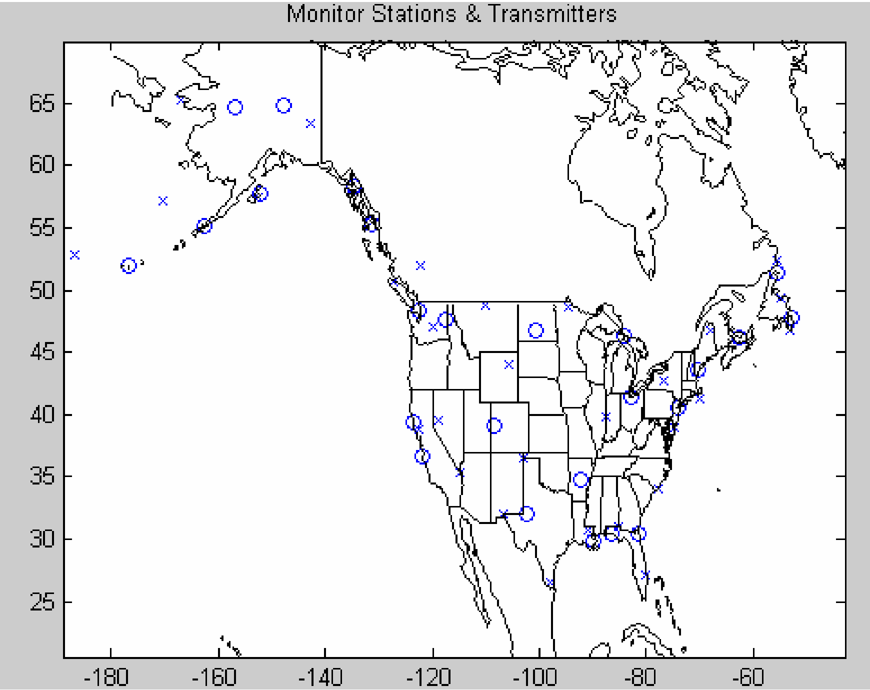

Figure 10 Map showing current Loran infrastructure of transmitters (x) and system area monitors (o)

5.1 Early Skywave Network Simulator

The capability of the network depends on its observability and coverage. The observed locations are the path midpoints that can be affected to early skywave. Using the currently existing Loran monitor sites, there are 207 paths with distances between 800 to 1500 km between the transmitter and monitor. The midpoints for these paths are shown in Figure 11 and represent the location in the ionosphere examined by the monitor receiver. These points will be referred to in this paper as observation points. The 207 paths and hence observation points are not unique as some of these paths are reciprocal paths. That means some midpoints are doubly monitored – once by the monitor at transmitter A looking at transmitter B, once by the monitor at transmitter B looking at transmitter A. The redundant paths are the ones between two transmitters.

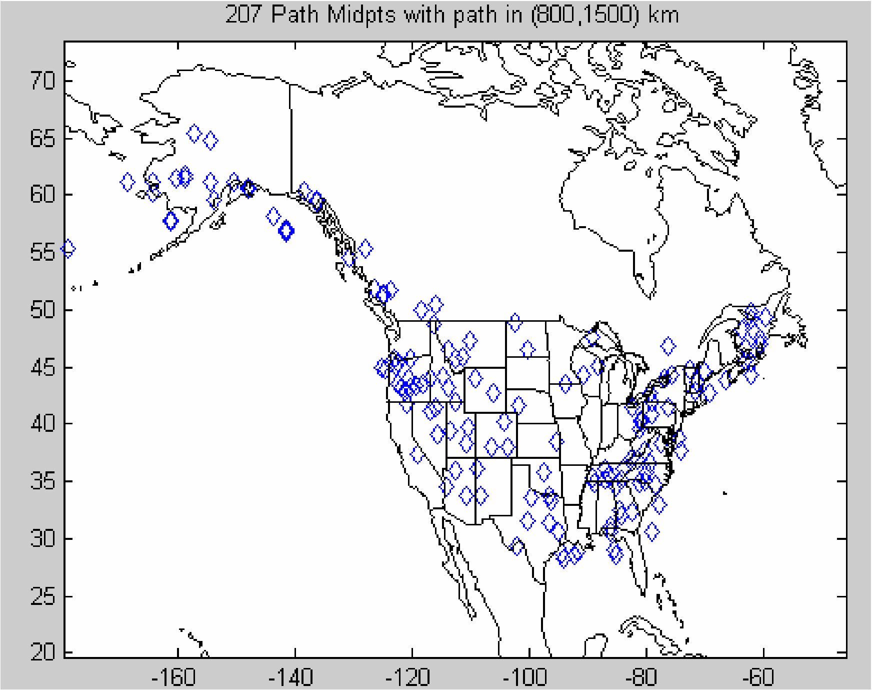

Figure 11. Path midpoints (observation points) monitored by the Loran infrastructure

The observation points are the only ionosphere locations that are directly measured. If there were no spatially correlation to early skywave conditions then the system would not be able to protect beyond the observation points. Fortunately, since the conditions that lead to early skywave are not localized, the observation points can be used to estimate the ionosphere nearby. It is assumed that there is some spatial correlation and that early skywave conditions do not occur in a small regional bubble. From the physics of early skywave ionosphere, we know one of two things should happen. First, in a PCD ionosphere, the conditions descend from the poles, roughly following the geomagnetic lines of latitude. Second, in a SID induced event, the conditions appear throughout the dayside Earth with the strength roughly proportional to the cosine of the solar zenith angle. Knowledge of the physics allows us to extrapolate from the observation point determinations to the surrounding local area.

5.2 Coverage Region & Observability

The ionosphere coverage region is determined by the observation point and its surrounding regions. Most of the ionosphere over CONUS are within a coverage radius of 500 km of an observation point. Figure 12 shows the coverage. This means that we need to protect against roughly a 500 km area from each of our observation. Part of the protection comes from the correlation between local ionospheric conditions. The other part will be built into an additional "padding" or buffer added to the warned geomagnetic latitude.

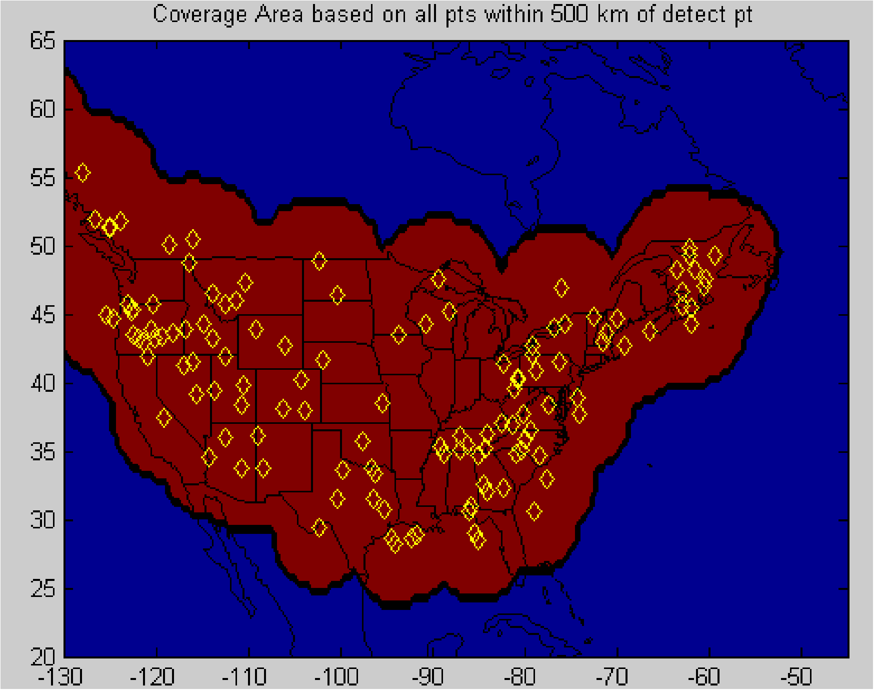

Figure 12. Coverage Area based on a 500 km detection radius

However, one needs to be careful in that the protection, particularly on the northern boundaries of coverage. This is true for a couple of reasons. First, observability is more limited at those locations. Second, PCD ionosphere descends from the poles. Thus, as it moves towards CONUS, it may affect users the before affecting any observation point. The following example illustrates the point. Assume the coverage area is set to any point within 500 km of an observation point. This is the area of the ionosphere that the system is protecting and it is shown in Figure 12. Figure 13 shows a simulation of an event that affects "protected" users in the north even though it cannot be detected by the network. The intersection of the ionosphere boundary and the coverage area is shown in Figure 14.

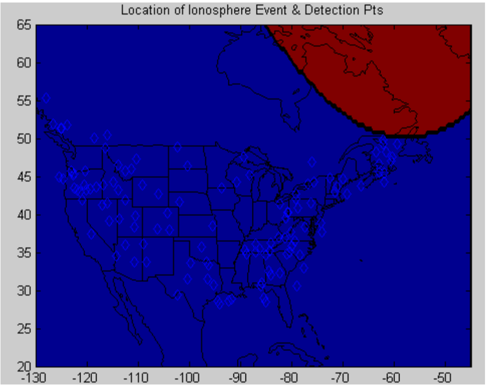

Figure 13. An unobservable AZ Ionosphere

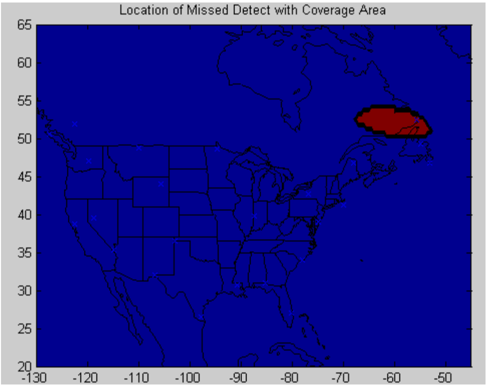

Figure 14. The Intersection Between the Ionosphere Event and the Coverage Area defined above

The location of early skywave ionosphere can be translated to a user location by geometry. Figure 15 shows the geometry of the calculation. First, determine locations of the AZ boundary that are between 400 to 750 kilometers away from a transmitter. This is the path midpoint location and represents the propagation of the skywave signal to the ionosphere. Increase the baseline between of the intersection of the boundary and the transmitter by two. The increase in distance represents the propagation of the skywave down from the ionosphere to the user. Finally, cut off the extent of the event at 1500 kilometer. Using this method on the area in Figure 14, the user location that are affected but not warned is calculated. This is shown in Figure 16.

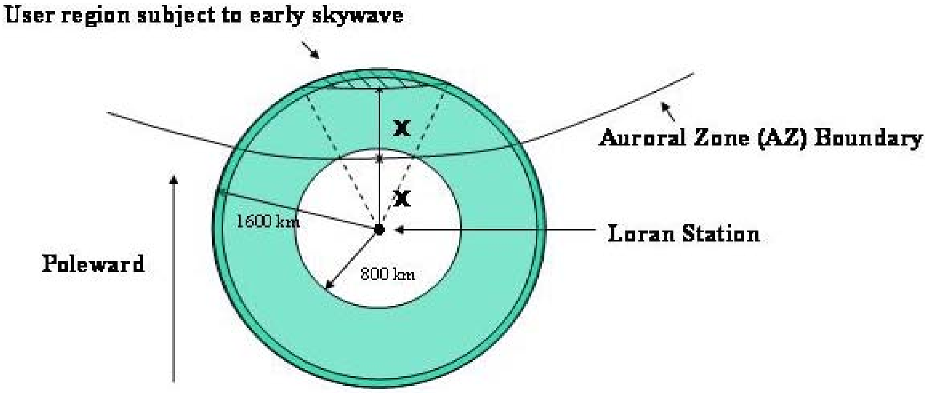

Figure 15. Determining User Affected from the Location of Early Skywave Ionosphere

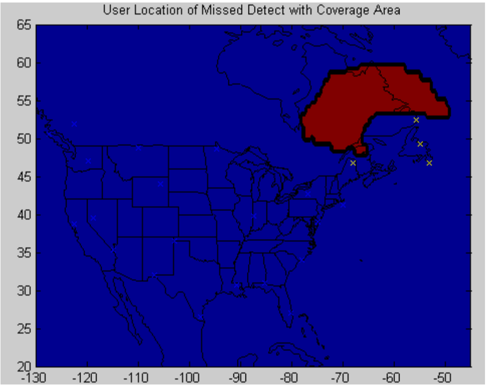

Figure 16. User Location affected by Missed Warning

5.3 Detection Rules

The monitor network must determine the extent of the early skywave conditions throughout CONUS. The determination will provide the user with a geomagnetic latitude limit or GMLAT. GMLAT is a conservative boundary between regions where early skywave inducing ionosphere exists and does not exist. In making the determination, the limited observability of the network, monitor false alarms and missed detections was factored in. Several algorithms for arriving at GMLAT have been examined[2].

Before using the algorithm, misleading information should be eliminated. Cross checking is used to eliminate false alarms. Since false alarms result in an early skywave warning when one is not necessitated, cross checking only prevents loss of availability. Missed detections are harder to determine and must be covered by conservatism in the GMLAT calculation. Three algorithms are described in this paper. One purpose of the simulator is to test the effectiveness of these algorithms.

The first algorithm is to select lowest geomagnetic latitude for affected area indicated to users. GMLAT is then that latitude padded by a given distance (degrees, kilometers). Several values were examined. A very conservative choice is 1000 km. This results from the following logic. Two neighboring observations are necessary to determine a boundary. Since coverage of the CONUS is achieved if all observation points have a coverage radius of 500 km, the two neighboring observations are at most 1000 km apart. Hence, the boundary is at most 1000 km from the nearest detected location. This value does not account for missed detection. The same logic can be used to account for the worst case missed detection by one monitor. The result is a buffer of 2000 km. In a small number of simulations, it has been found that roughly 250 to 500 km (2.5 to 5

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[2] We shall use the term false alarm and missed detection to refer when the monitor stations detect early skywave falsely and misses detection, respectively. The terms false alert and missed warning refers to when the warning message results in the users not using a valid signals or using an early skywave signal, respectively.

degrees of latitude) is sufficient to protect against expected movements of the AZ. The worst region is in the Midwest US where observation density is reasonably sparse.

Results from using the algorithm above lead to a second algorithm that determined the padding based on observation density. Rather than use 1000 km, examine the observation points that detected early skywave conditions. Find the detecting observation point with the lowest geomagnetic latitude. Next find the nearest equatorward observation point that does not detect early skywave conditions. In the implementation, the observation point selected is south of the observation point with a deviation of at most a small angle (~ 20 degrees) from due south. The algorithm uses the geomagnetic latitude of that non detecting observation point for GMLAT. Missed detection by one monitor can be mitigated if the second nearest equatorward non detecting observation point is chosen.

Another method is to find the best fit aurora zone boundary (GMLAT) using weighted least squares. This accomplished by selecting the GMLAT, λ, value that maximizes the sum of two weighted sums. The first is the sum of the difference of between the geomagnetic latitude of the detecting observation points and GMLAT. The second is the sum of the difference of between GMLAT and the geomagnetic latitude of the non detecting observation points. The weighting is proportional to path length. Mathematically, this is given by:

$$S \equiv \sum_{j\in\{j\}} w_j D_1^j(\lambda) + \sum_{i\in\{i\}} w_i D_0^i(\lambda)$$

where:

- D_1 is the difference between (1) the geomagnetic latitude of detecting observation points with geomagnetic latitude less than λ and (2) λ
- D_0 is the difference between (1) λ and (2) the geomagnetic latitude of nondetecting observation points with geomagnetic latitude greater than λ
- w_i is a weight that is roughly proportional to path length

A buffer may be added to this calculation to increase conservatism and protect against missed detection.

5.4 Simulated Events

This subsection shows some results from simulated events and application of the rules. The purpose is purely instructional and should not be construed as the final methodology used. Rather it should be seen as illustrating the effect of a given GMLAT determination. In each case, the first algorithm is applied with a 2.5 degree buffer. Figure 17 shows the AZ boundary and the midpoint locations detecting the event (highlighted). Figure 18 shows the geomagnetic latitude (GMLAT) sent out in the warning message. The warning latitude is 2.5 degrees below the geomagnetic latitude of the most equatorward (geomagnetic) detection location.

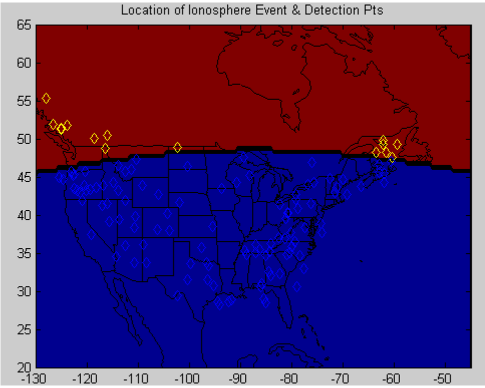

Figure 17. Simulated Event (red) and Detected Location (yellow diamonds)

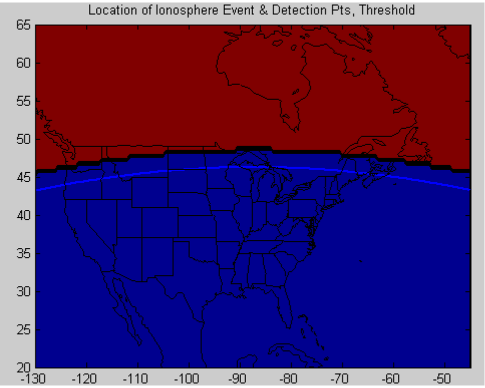

Figure 18. AZ boundary (red) and Geomagnetic latitude in warning (blue line)

Figure 19 shows a fictional case where the AZ exhibits behavior that does not closely follow the geomagnetic lines of latitude. This case was created so that the AZ dips in the Midwest and results in missed detection if the warning was generated in the previous example. The Midwest was chosen because of its low observation point density. Figure 20 shows the resultant warning geomagnetic latitude using the first algorithm. The warning latitude does not adequately protect against the event. However, the conservative 1000 km (or even 500 km) buffer would have easily sufficed. Also, the second algorithm would have protected. This is shown in Figure 23.

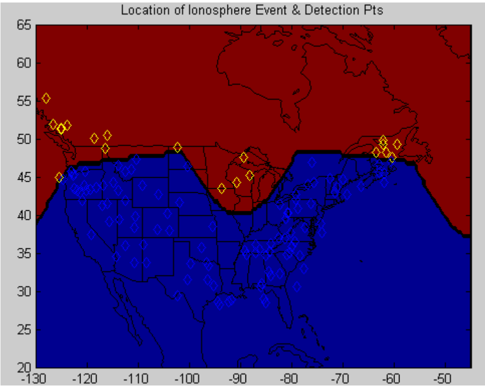

Figure 19. Simulated Anomalous Event affecting Midwest (red) and Detected Location (yellow diamonds)

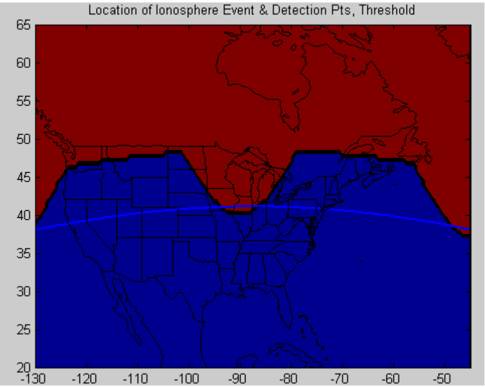

Figure 20. Warning Boundary based on simple 2.5 degree buffer from lowest observation point (AZ boundary (red) and Geomagnetic latitude in warning (blue line))

The resulting ionosphere region that was not warned and user locations affected are shown in Figure 21 and Figure 22, respectively

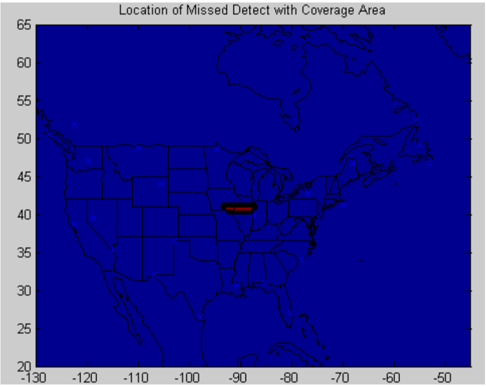

Figure 21. Portion of the Ionosphere Not Covered by Warning

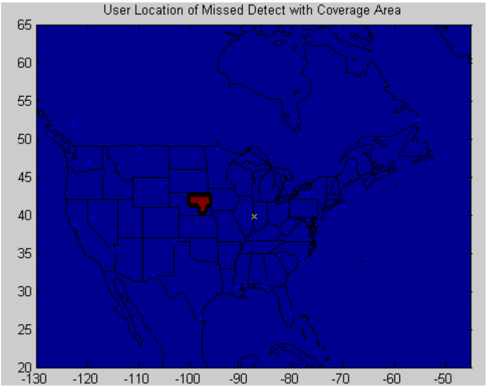

Figure 22. User Locations affected by Missed Alert

Figure 23 shows the result of using the second algorithm. The closest non detecting observation point is shown as a blue diamond. Application of the second algorithm would have protected all users.

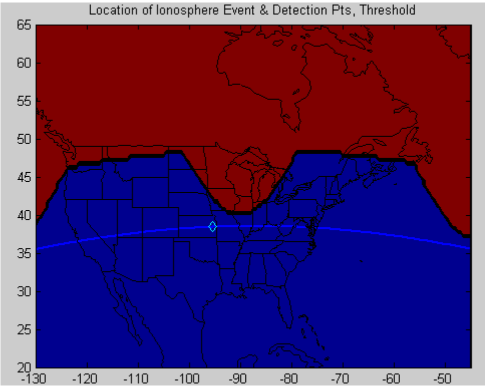

Figure 23. Warning Boundary based on Nearest Nondetection point (AZ boundary (red) and Geomagnetic latitude in warning (blue line))

5.5 Robustness to Faults

As mentioned previously, the network calculation should be robust to monitor failures (missed detections) and false detections. In regards to false detection, worst case deprivation is applied to test robustness. In worst case deprivation, the station that provides the most useful information on the event is loss. For early skywave event, that means losing the station with the most equatorward detected point. Robustness in the algorithm can eliminate the effect of monitor failures or missed detection by the monitor. The goal is to design robustness with low amounts of false warnings.

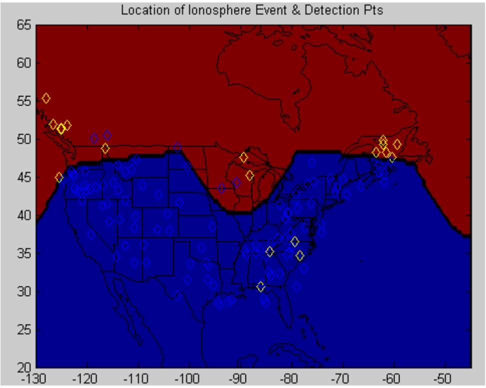

Figure 24. Missed Detection and False Detections

6.0 Conclusions

The early skywave detection network is essential for eLoran to meet RNP 0.3 integrity requirements. Work on the detection network is progressing with development of research receivers for monitor design, simulator for network algorithm design, and ninth pulse message scheme. Since integrity is paramount, the goal is to limit the missed detections and warnings in the system. As seen in the network simulator, integrity can be increased at the expense of availability. We can warn a larger area to ensure that the event is fully covered. Fortunately, early skywave events are rare in CONUS and the increased loss of availability should be acceptable.

7.0 Disclaimer

The views expressed herein are those of the primary author and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, Department of Transportation or Department of Homeland Security.

8.0 Acknowledgments

The author would like to acknowledge Mitch Narins (FAA AND 702) for his support of Loran and the activities of the LORIPP.

The author would also like to acknowledge the help and cooperation of the members of the LORIPP, particularly Dr. Ben Peterson, Robert Wenzel, LT Kirk Montgomery who have all contributed to this work

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