

Early Skywave Detection Network: Preliminary Design and Analysis



Sherman Lo*, Peter Morris**, Per Enge*

* Stanford University, Department of Aeronautics and Astronautics

** Raytheon Company, Integrated Defense Systems

Supported by the Federal Aviation Administration, Office of Communications,
Navigation, and Surveillance (AND-702)



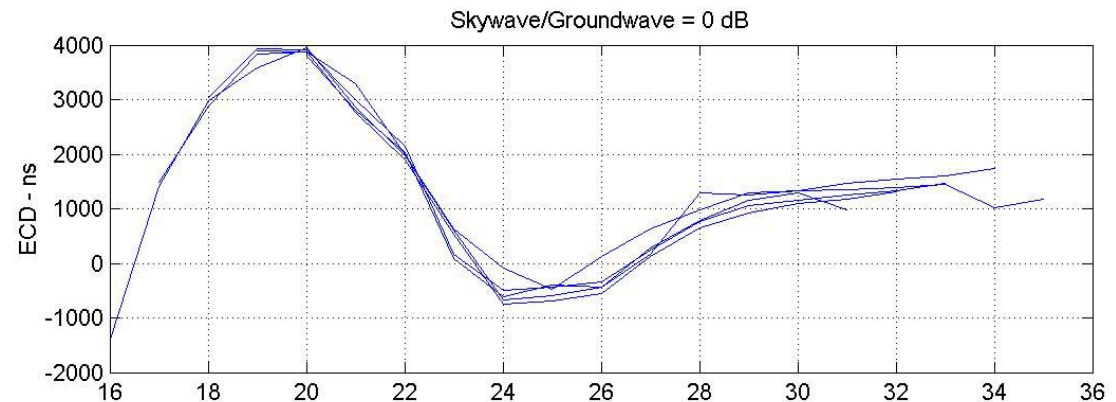
Why have an early skywave detection network

- Early Skywave can have deleterious effects on Loran ECD and/or phase measurements that are not easy to predict
 - Integrity threat if not bounded by the user
 - But, it is difficult to for the user receiver to bound/correct
 - Luckily, it is rare in CONUS (10^{-4} event)
 - A early skywave detection system can
 - Tell users which signals likely are affected by early skywave
 - Allow users to exclude those signals while still being able to use other unaffected signals (preserving availability)
-

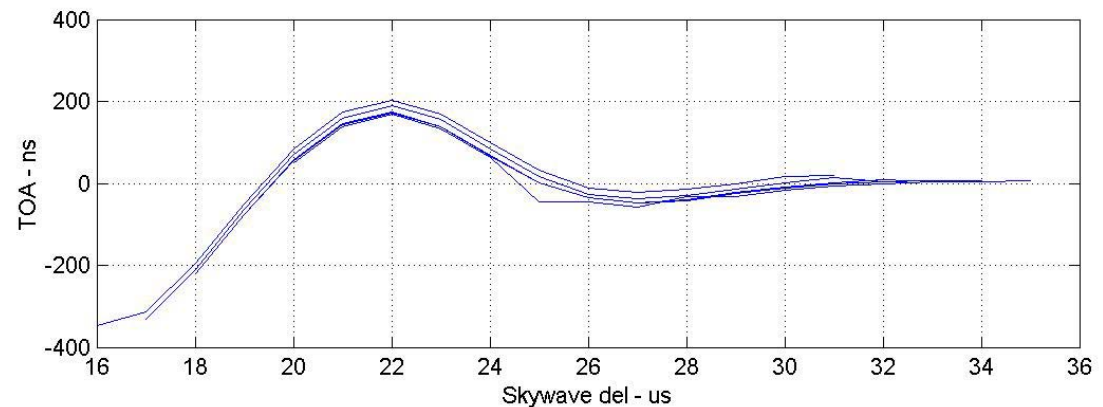


ECD and TOA Error due to Early Skywave

**Skywave and
Groundwave Peak
Amplitudes are Equal**



**Receiver is a Simulated
LRS IIID**





Two Caveats

- The presentation and comments expressed herein are those of the presenter and are not to be construed as official or reflecting the views of the US Coast Guard, the US FAA, the US DOT or the US DHS.
 - This is work in progress
-

Early Skywave Background: Effects & Causes

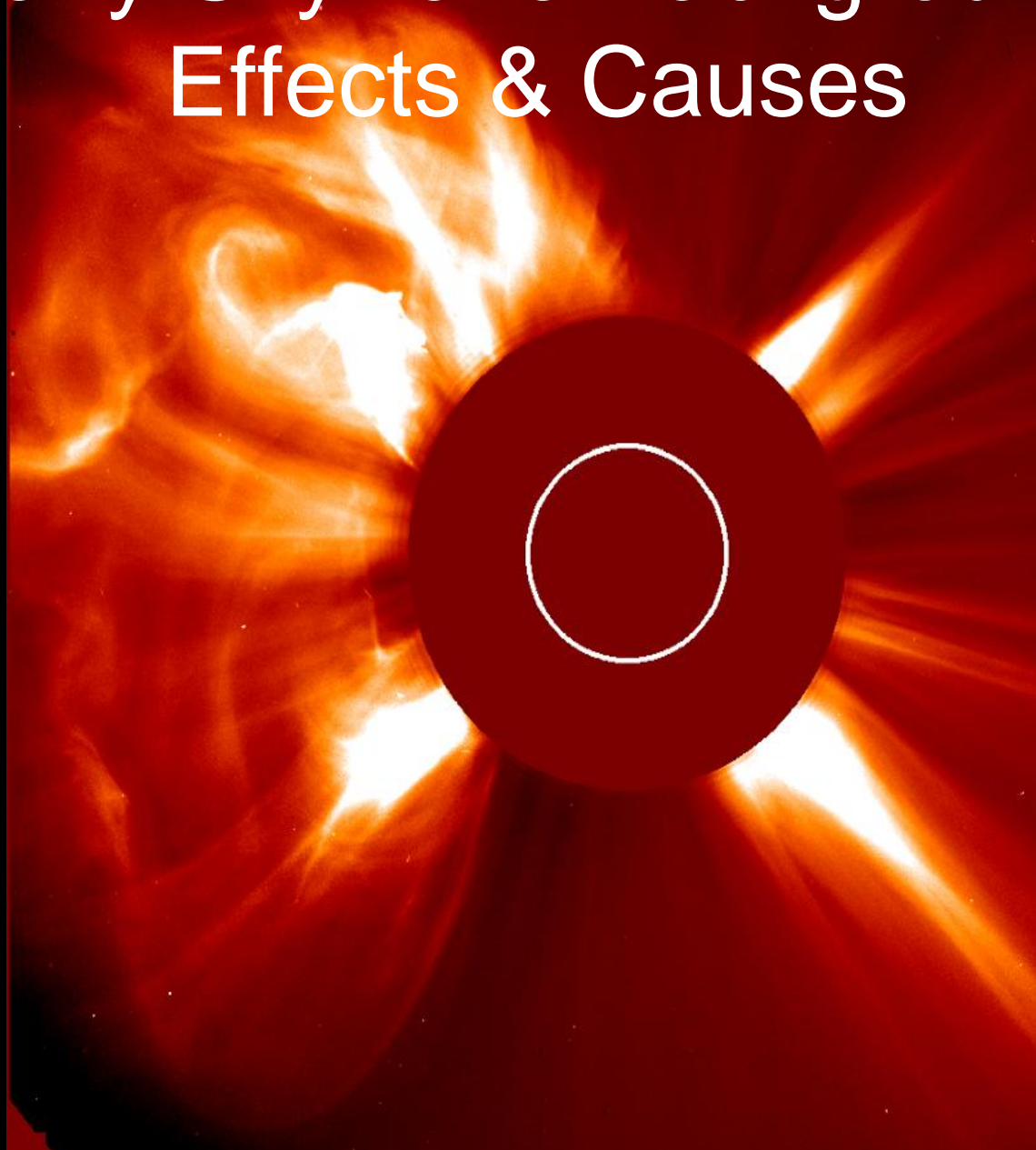
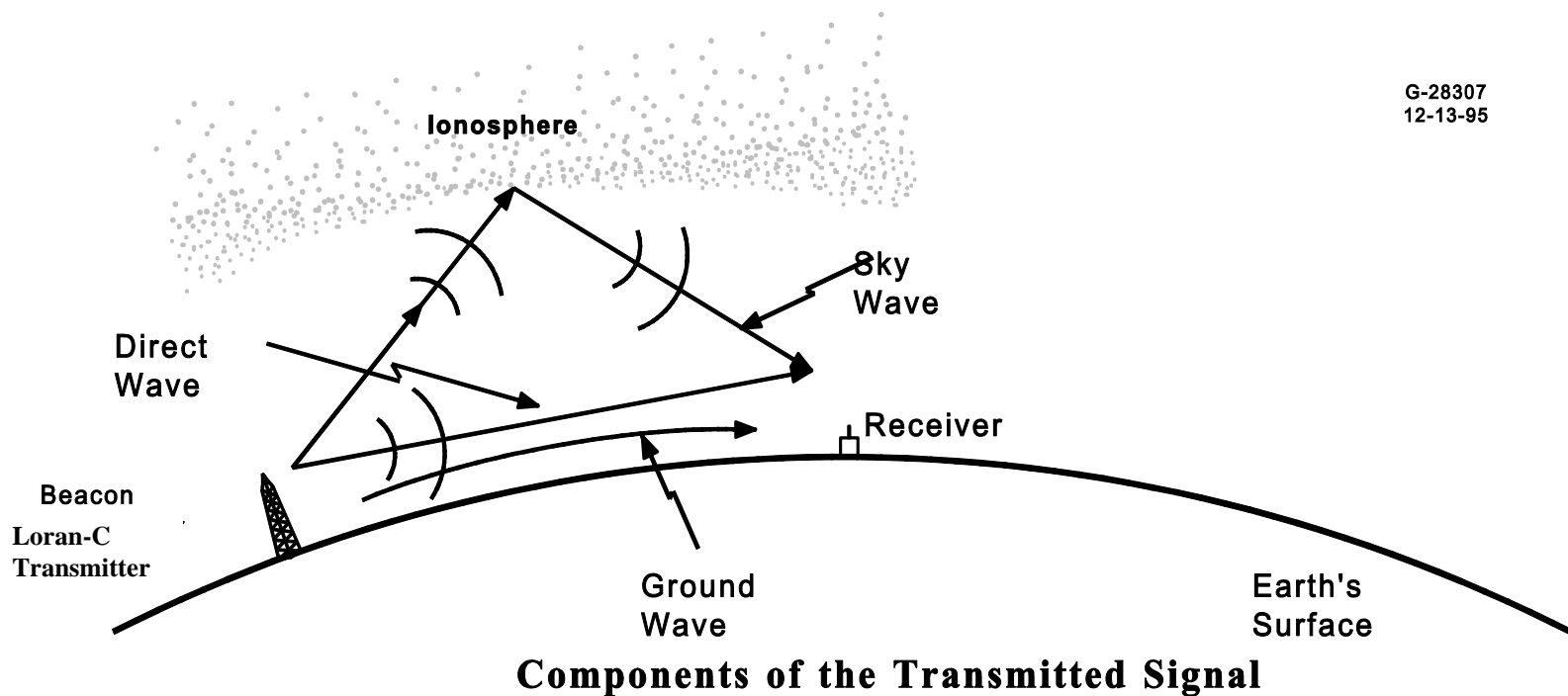




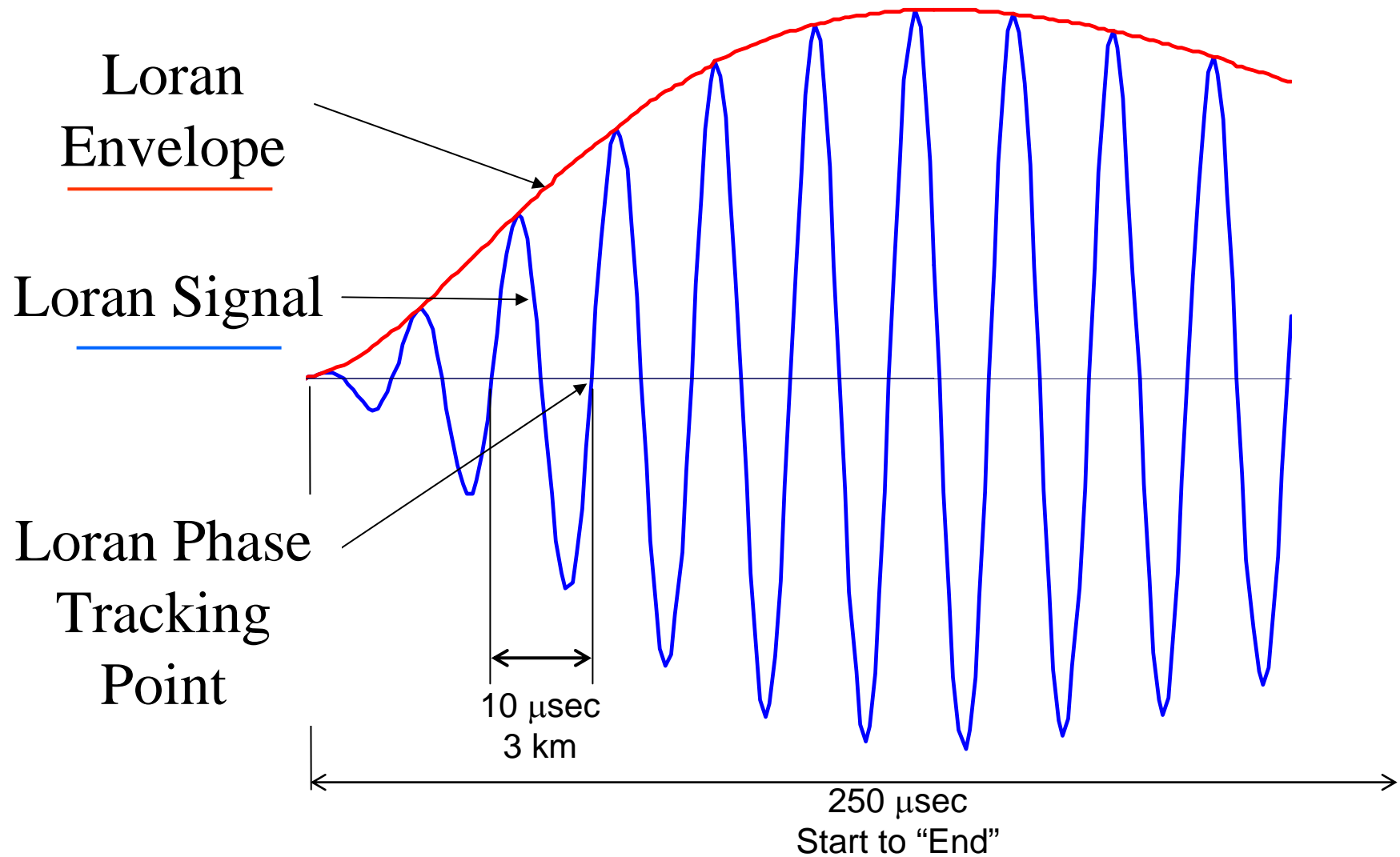
Illustration of Skywave



One-hop skywave is shown



Loran Signal Pulse





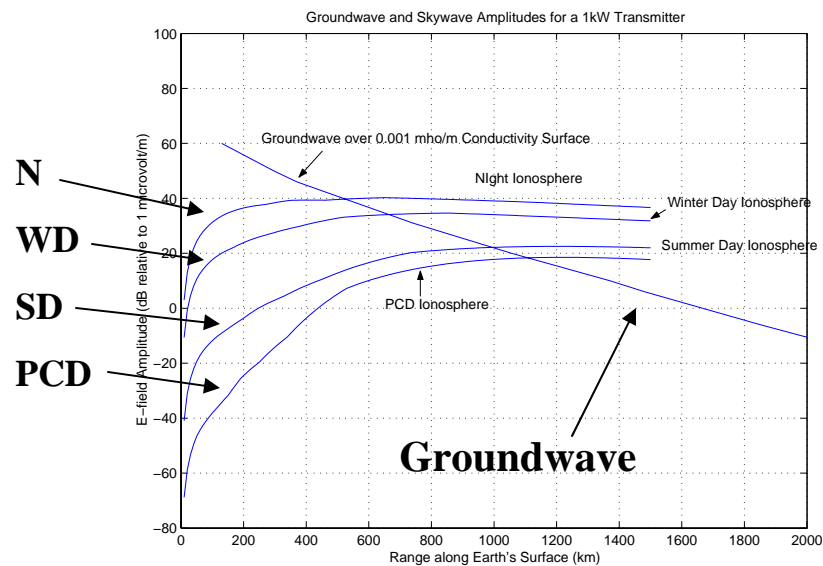
What is Early Skywave?

- Skywave that has a delay of $< 30 \mu\text{sec}$ with respect to the groundwave
 - Only occurs on signal paths with a range $> \sim 800 \text{ km}$
 - One-hop skywave has maximum range of about 1500 km (for substantially ionized *D*-region)
 - Affects tracking point of the Loran signal
 - Vectorially adds to groundwave thereby distorting signal envelope and/or phase
 - Distortion depends on relative delay & magnitude
 - Caused by solar-terrestrial events that result in
 - Sudden Ionospheric Disturbances (SIDs) – Events typically of 15-30 min. duration on Earth's dayside ; worst at sub-solar point
 - Polar Cap Disturbances (PCDs) – Events can last several days poleward of the auroral zone, e.g., Alaska and occasionally in CONUS
 - More details are given in Morris, "Conditions Leading to Anomalously Early Skywave," ILA 2003
-

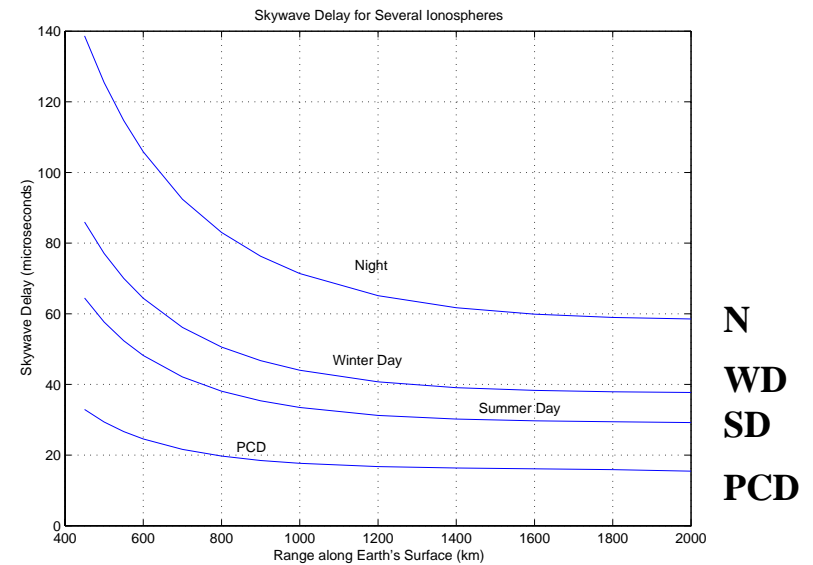


Skywave/Groundwave Relative Amplitude and Pulse Arrival Time for Various Illumination Conditions

Amplitude Comparison



Delay Comparison

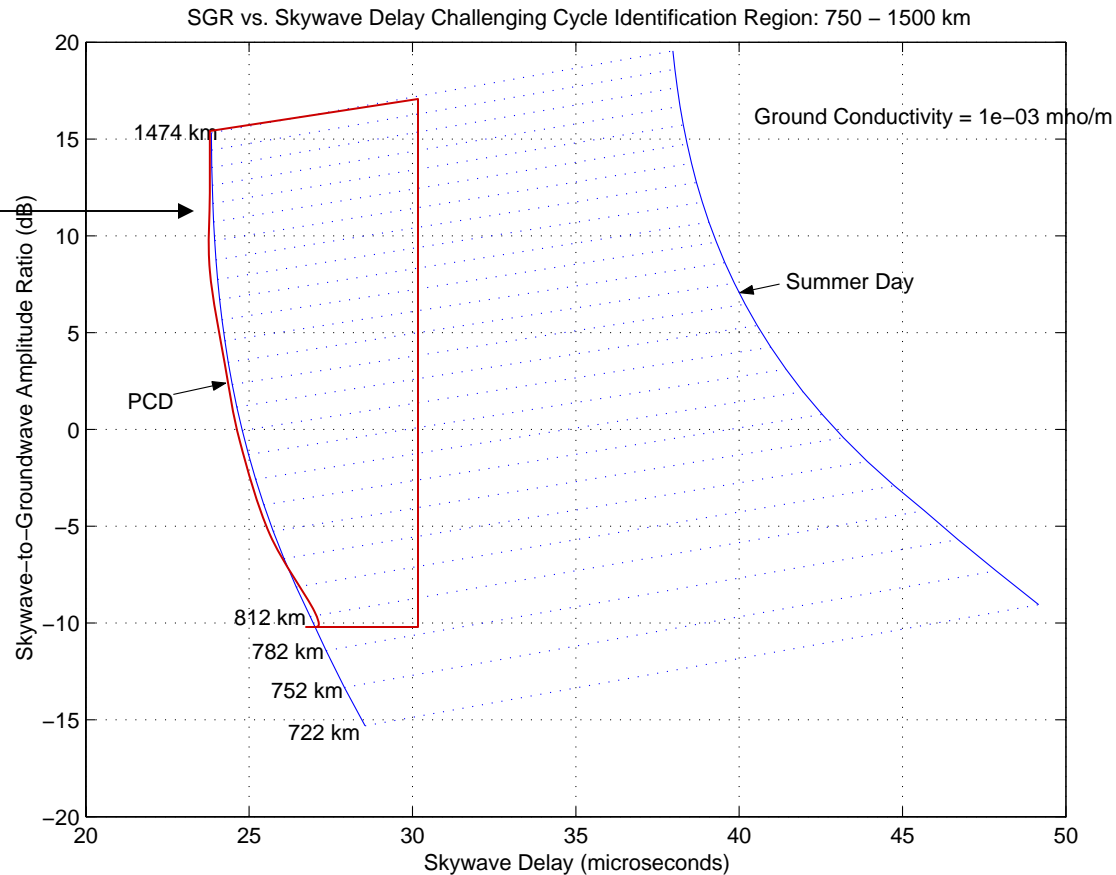


Ionospheric Illumination Conditions: Night (N), Winter Day (WD), Summer Day (SD), and PCD



Rationale for 800 km Minimum Range for Skywave “Danger Zone”

Area enclosed in red is the skywave “danger zone”

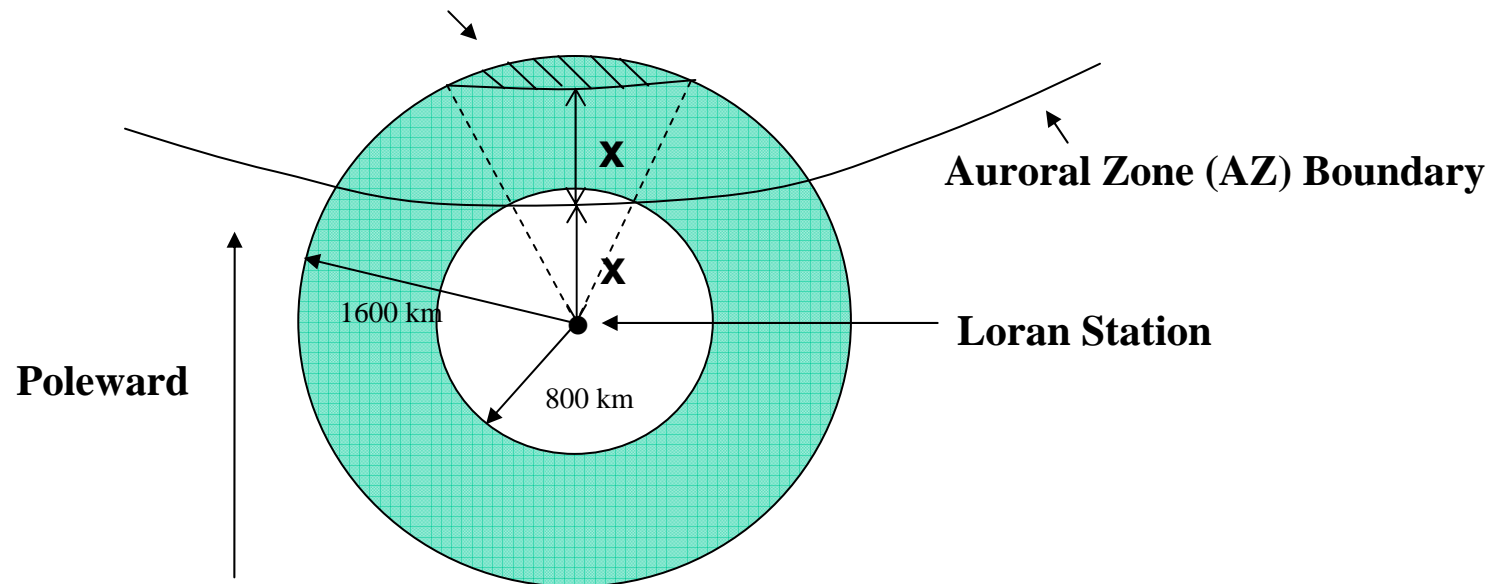


Early Skywave danger zone begins at about 800 km



User Receiver Locations Subject to Early Skywave during a PCD Event

User region subject to early skywave



If a large geomagnetic storm occurs during a PCD event, the AZ boundary sometimes moves toward the equator and the region subject to early skywave on a Loran station signal grows non-uniformly until the entire annular region is affected



Detection & Mitigation of Early Skywave





Mitigation of Early Skywave via a Warning System and Signal De-selection

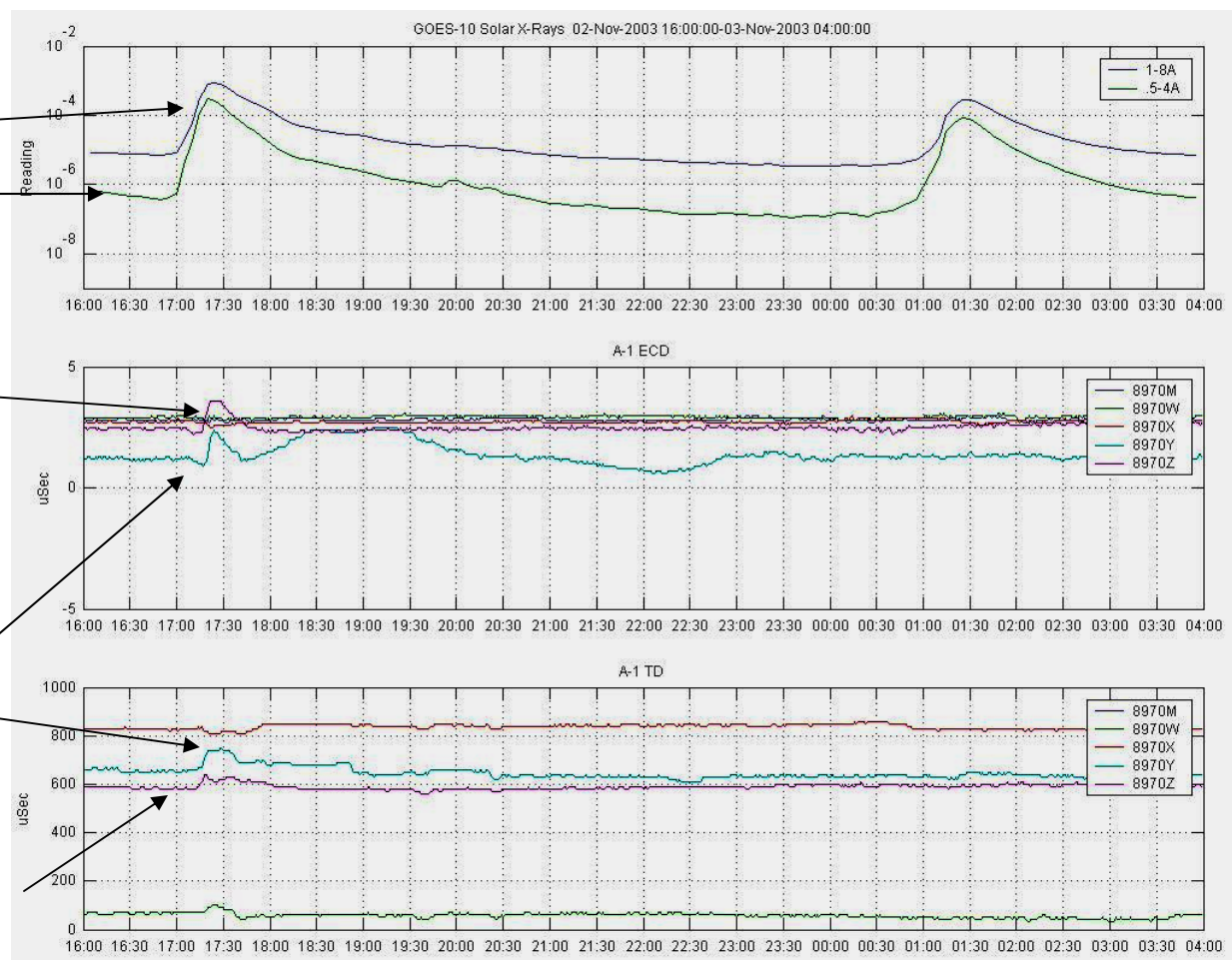
Elements of a Warning System

- Monitor Receiver
 - Examine signal characteristics, e.g., changes in ECD, phase, and signal strength to determine possible occurrence of event
 - Monitor Network
 - Process data from current monitor stations to determine event type & extent (affected area)
 - Time and spatial history of monitor data can help determine type of event
 - Warning Message
 - Event warning can trigger receiver to de-select corrupted signal if conditions indicate presence of event
 - Assures integrity of Loran signal
-



Detecting Early Skywave resulting from SID Events

GOES 10:
1 – 8 Å
0.5 – 4 Å



X-Ray Flux

Boise City –
Little Rock

ECD
(µsec)

Baudette –
Dunbar Forest

TD
(µsec)

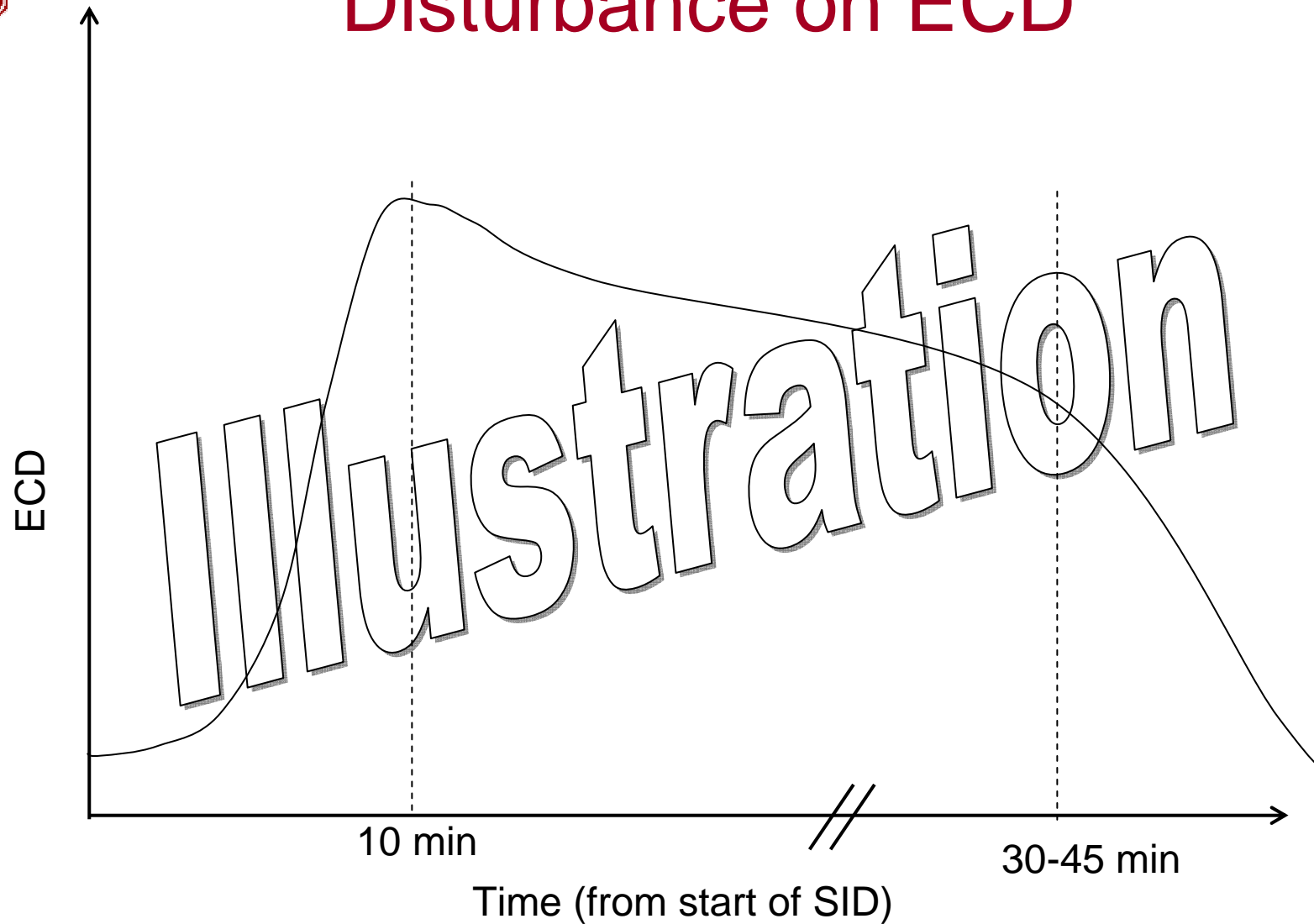
Boise City –
Little Rock

02 NOV 2003

03 NOV 2003



Effect of Sudden Ionospheric Disturbance on ECD



Effects of ECD temporal gradient for SID greater for longer baselines



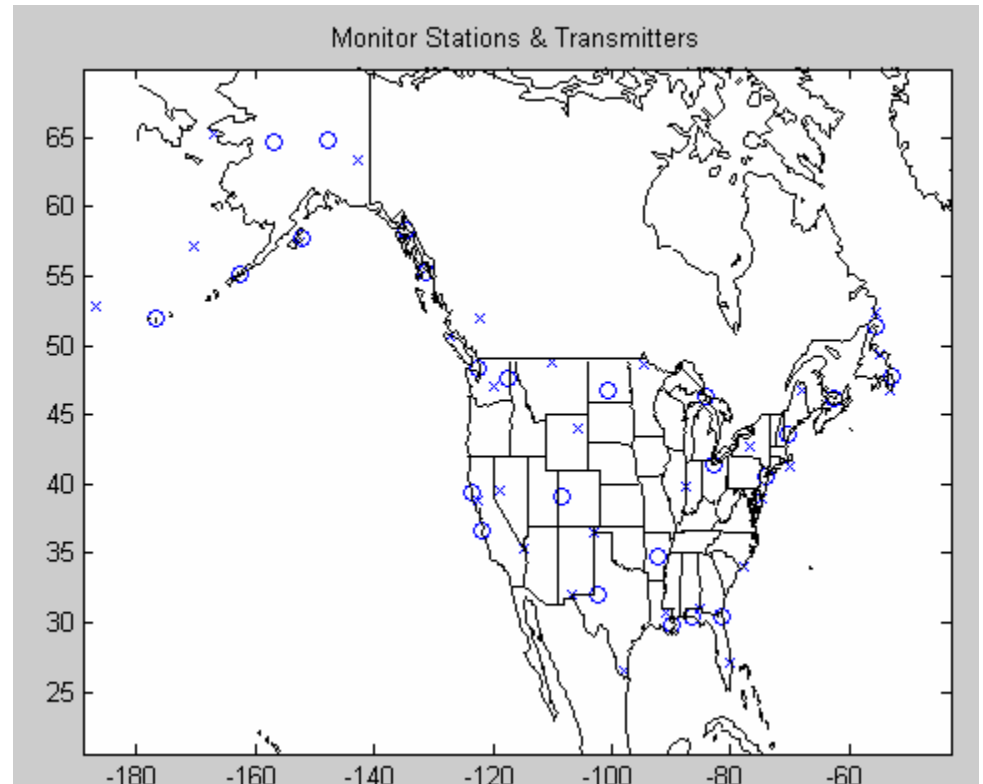
Future Monitor Receiver Development

- Prototype early skywave detection receiver to be developed
 - Algorithms for determining detection
 - A simple metric may be a linear combination (LC) of TOA and ECD error could be chosen as an error measure that always increases as skywave delay decreases
 - May pass measurements (TOA, ECD, etc.) to network
-



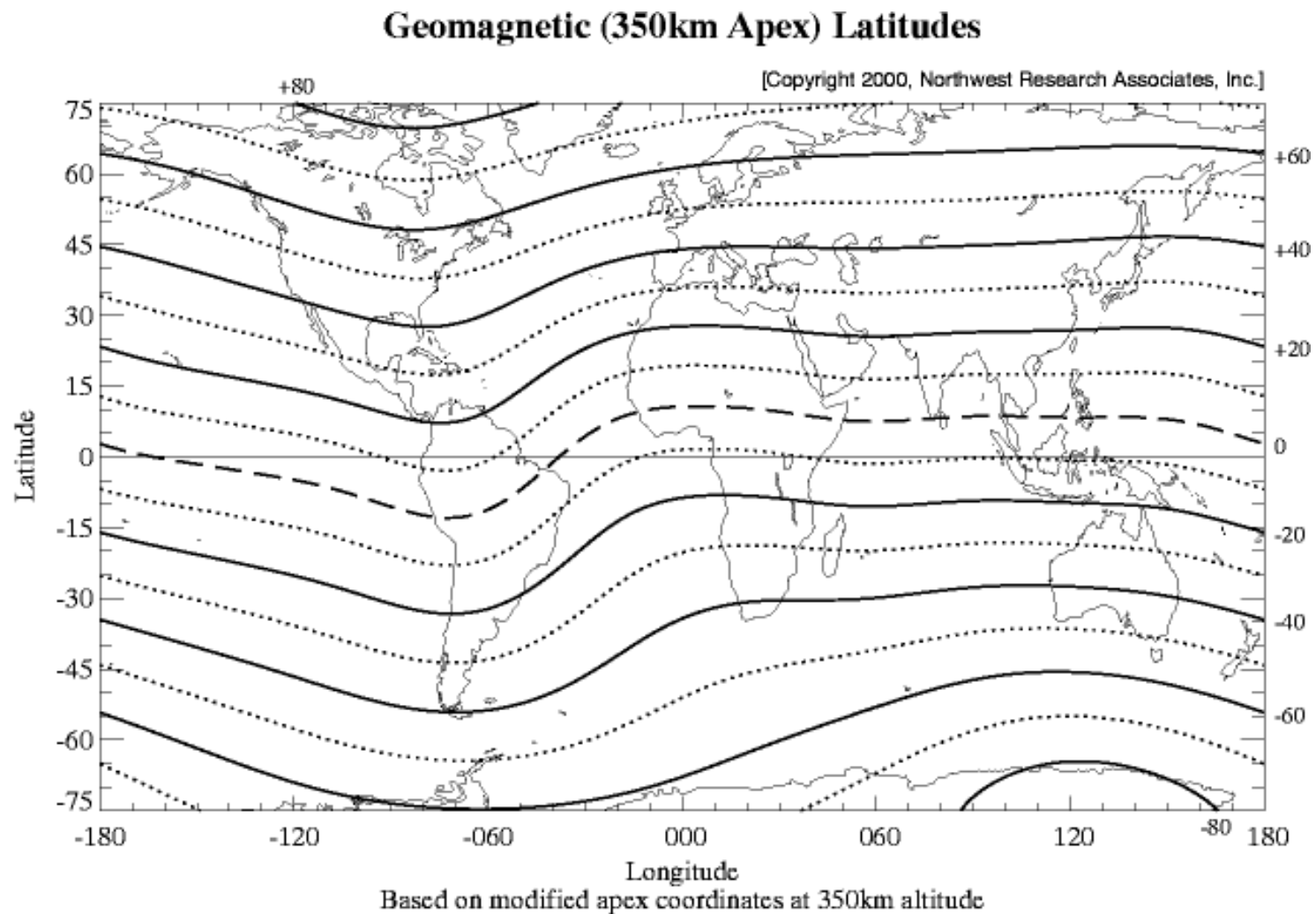
Early Skywave Network

- Uses current transmitter and SAM sites
- Determines the GMLAT and type of event
- NOTE: GMLAT is the bound for the geomagnetic latitude of the AZ for the event



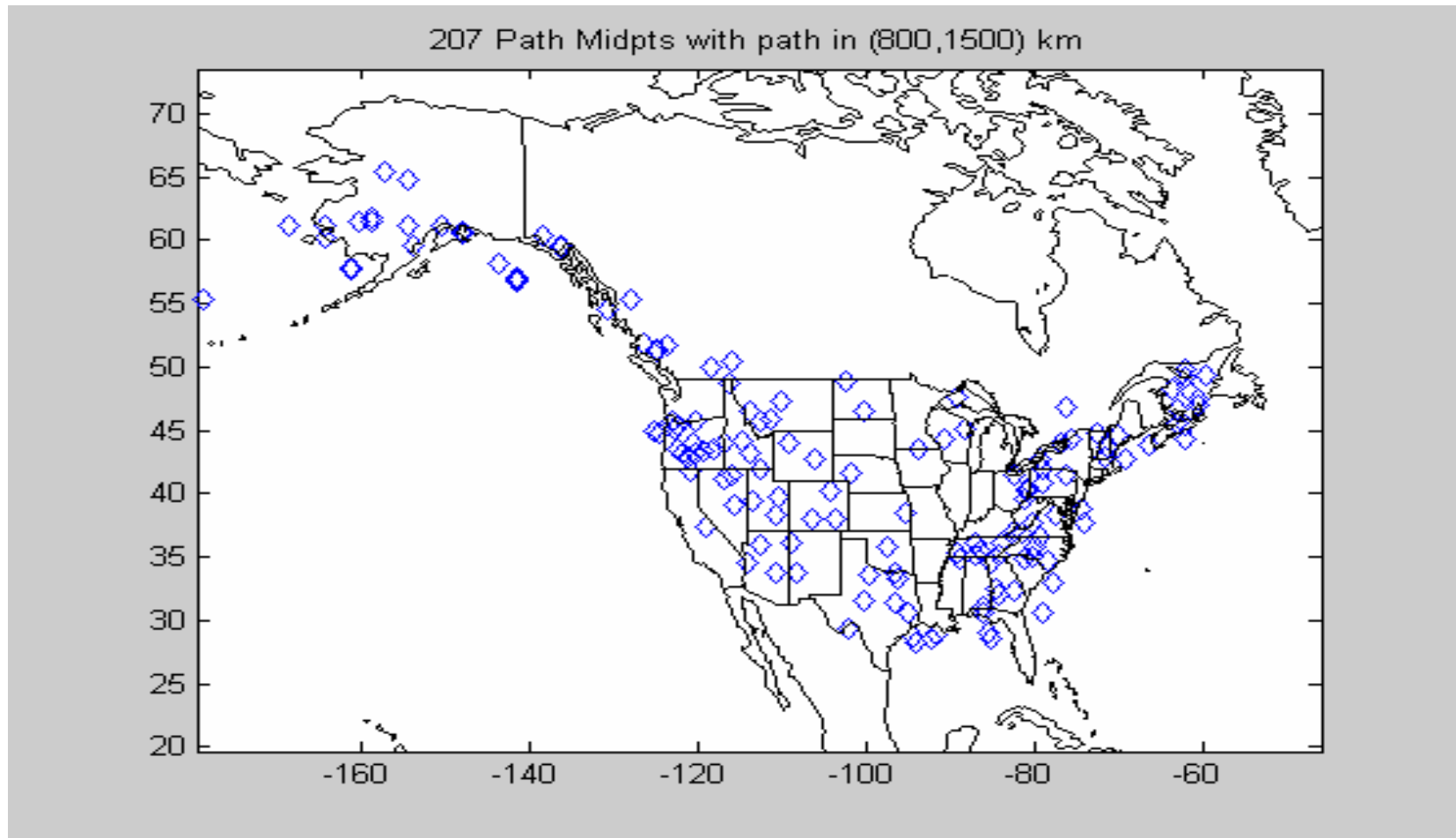


Geomagnetic Latitudes



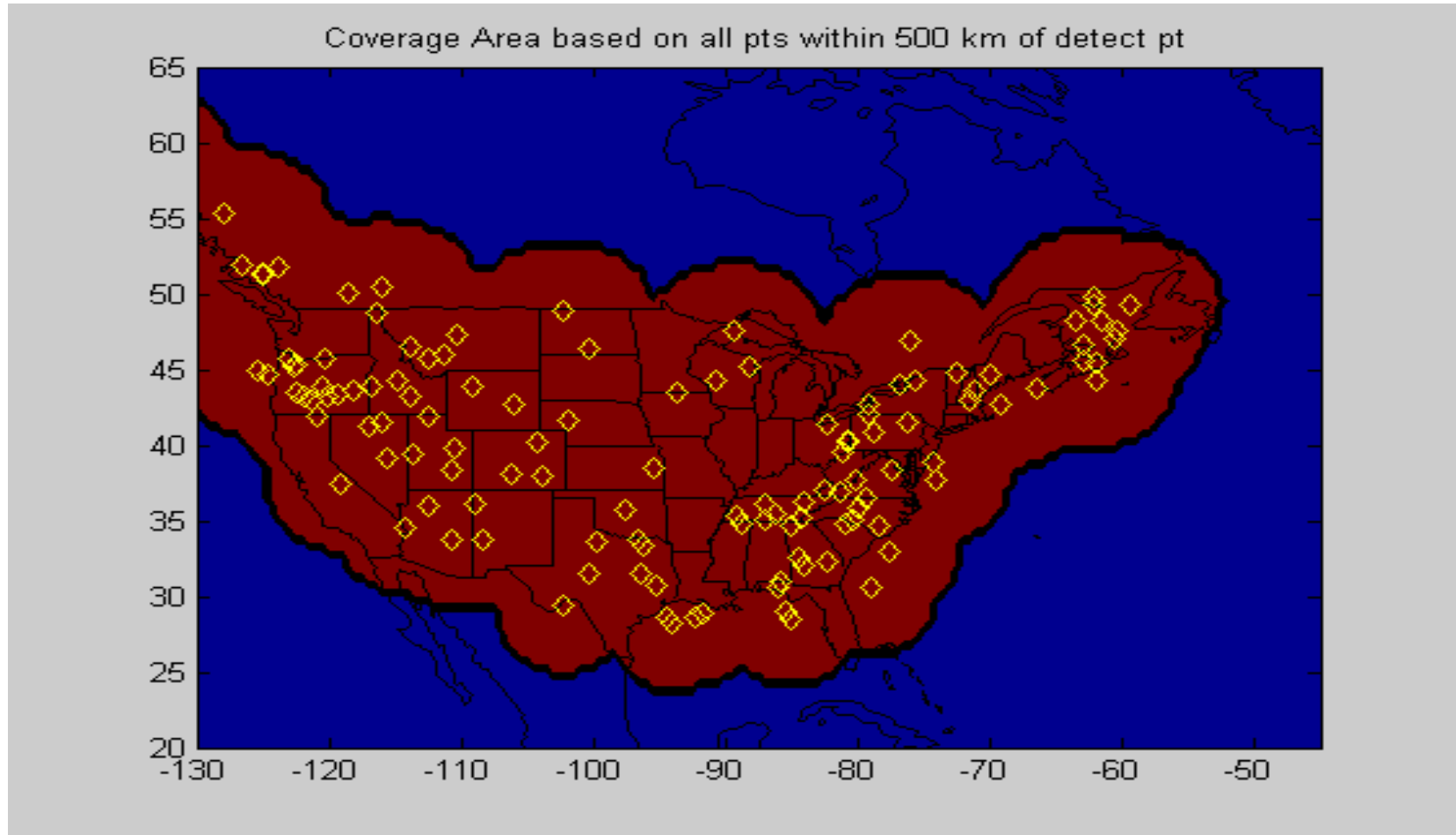


Path Midpoints Capable of Detecting Early Skywave





Detectable path midpoints at 800 to 1500 km





Network Simulator

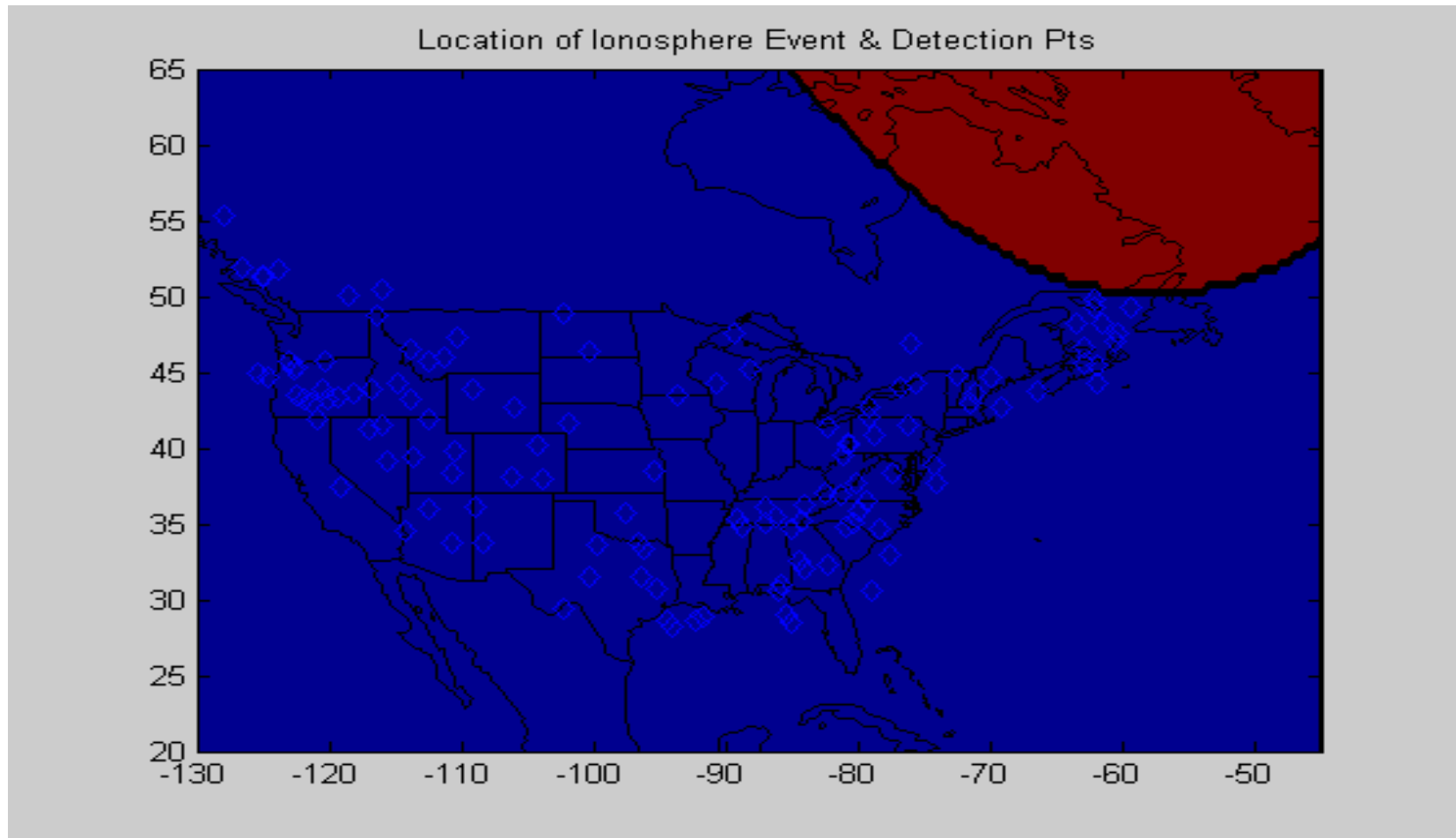


Purpose & Inputs

- Create a tool to test system architecture and a *priori* rules for early skywave warning
 - Need to know the effectiveness of the rules for warning users following detection of early skywave
 - Need to set a rule for coverage area boundary (unobservable area)
 - Tool used to visualize affected areas for missed detection and false alarm given either rule form
 - Input some model of ionosphere event
 - Only boundary of PCD/SID event
 - Assume event always occurs within the boundary
 - Time lapsed event can be used
-

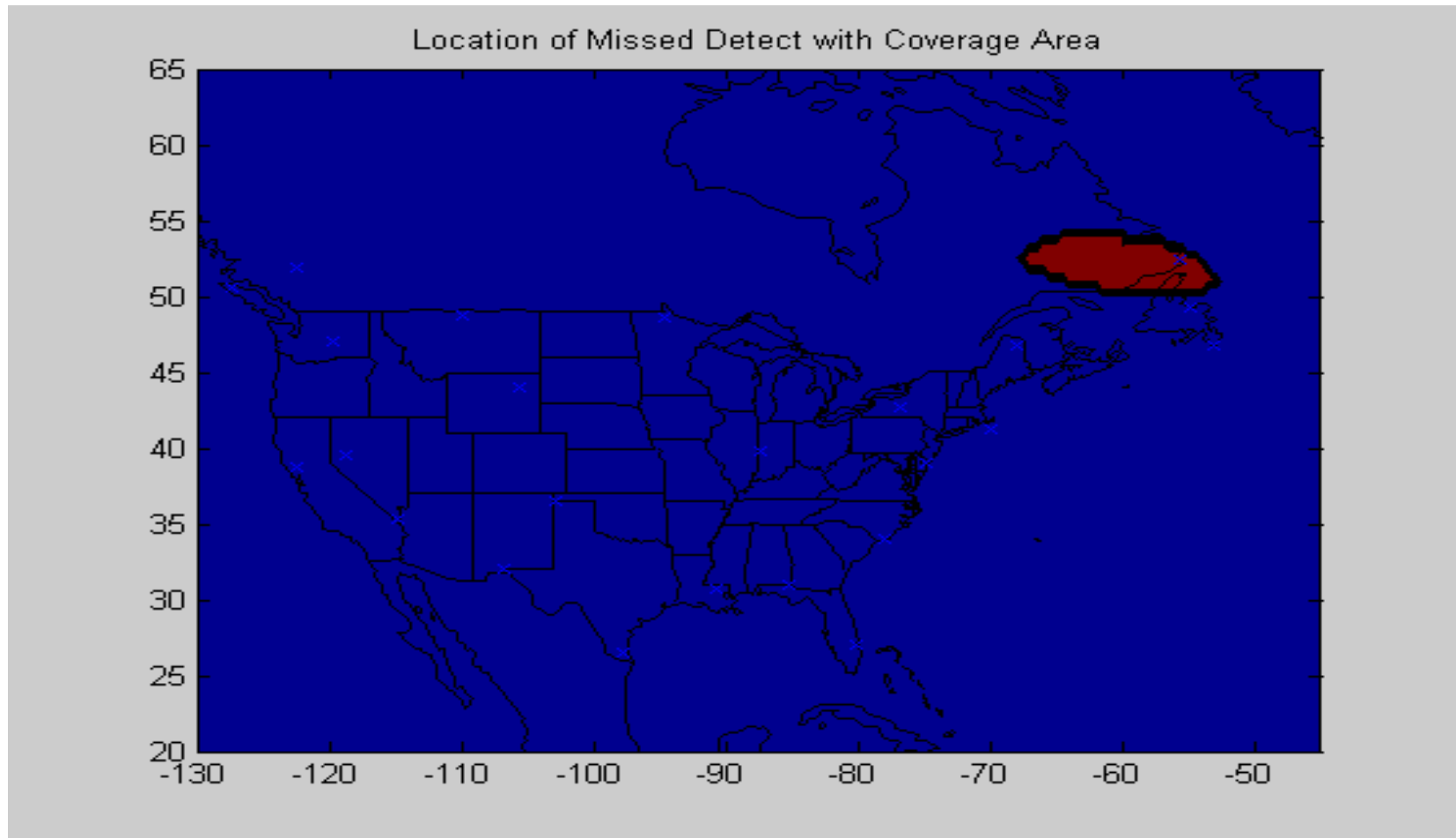


Unobservable Ionosphere Event



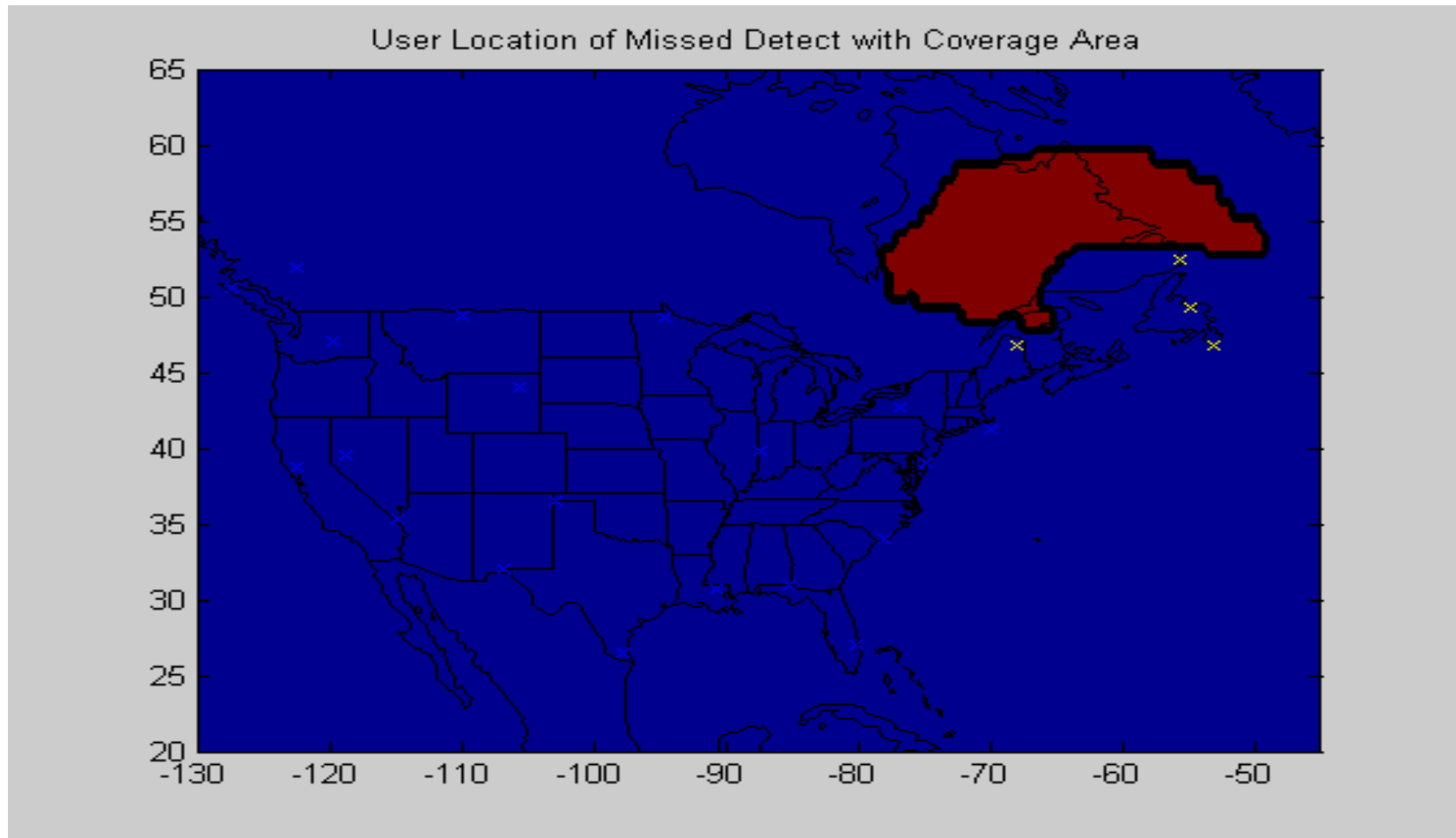


Affected Ionosphere Area (with coverage limits)



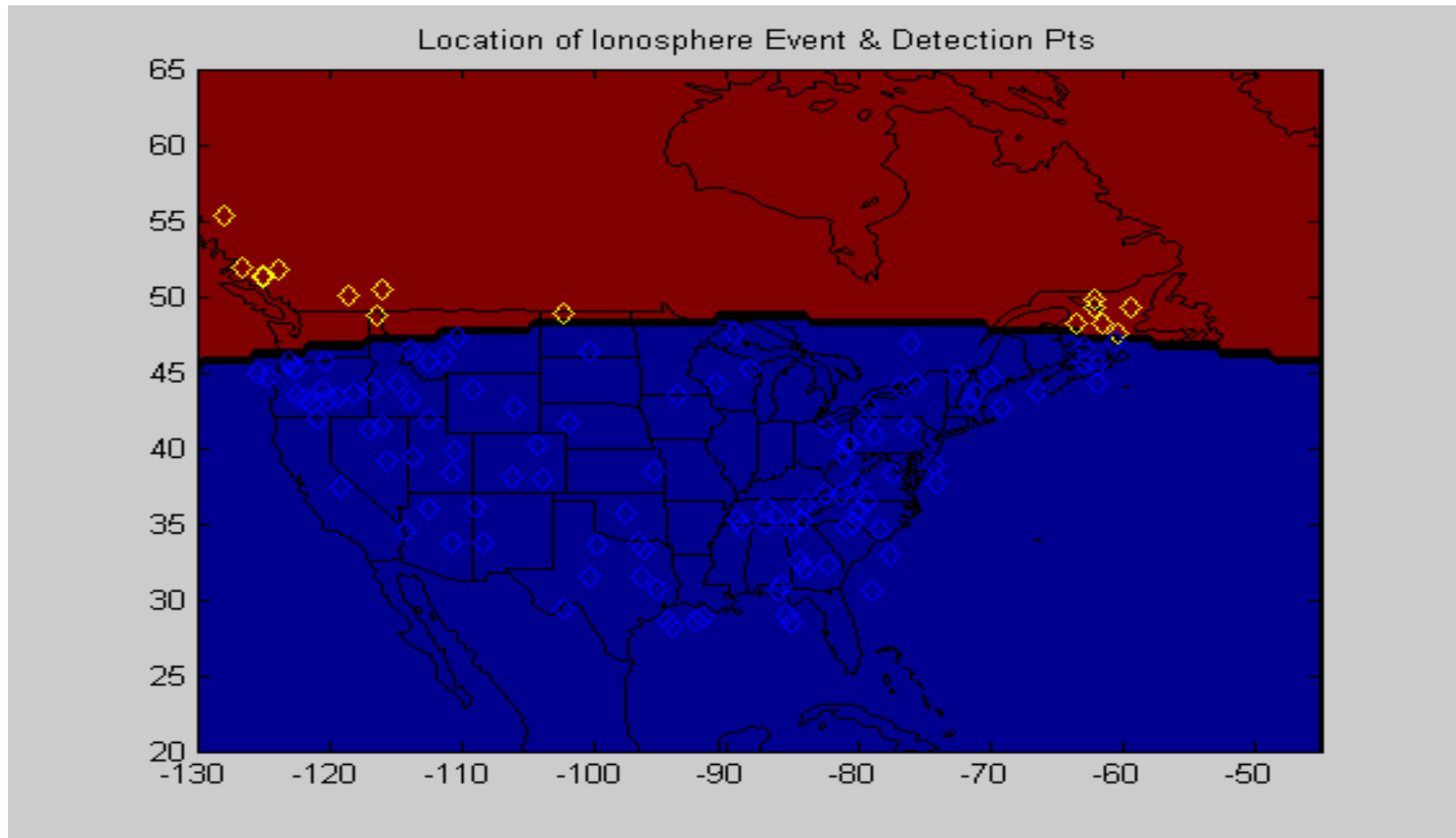


User Locations Affected



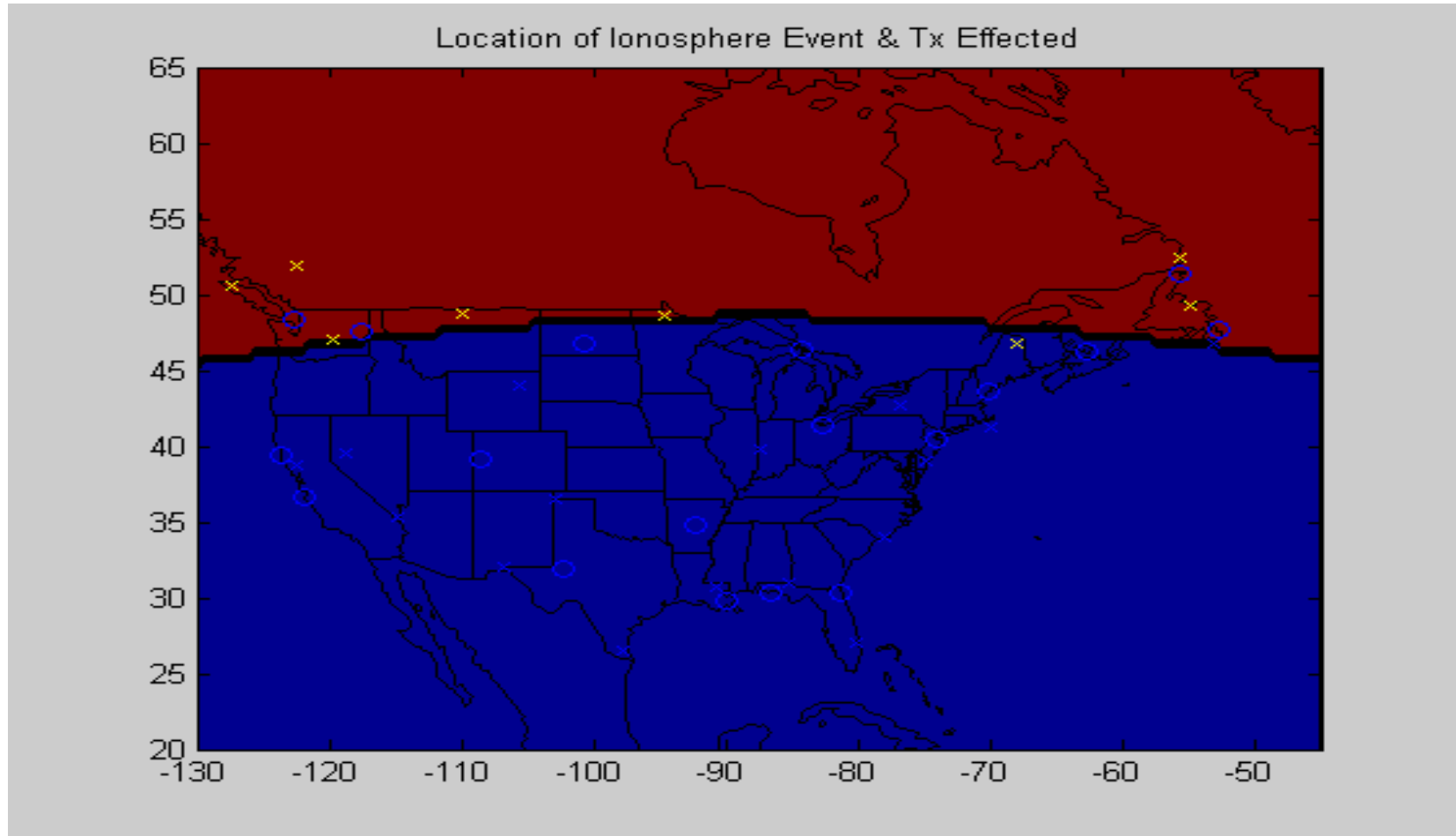


Observed Event & Observed Locations





Observed Event & Affected Stations



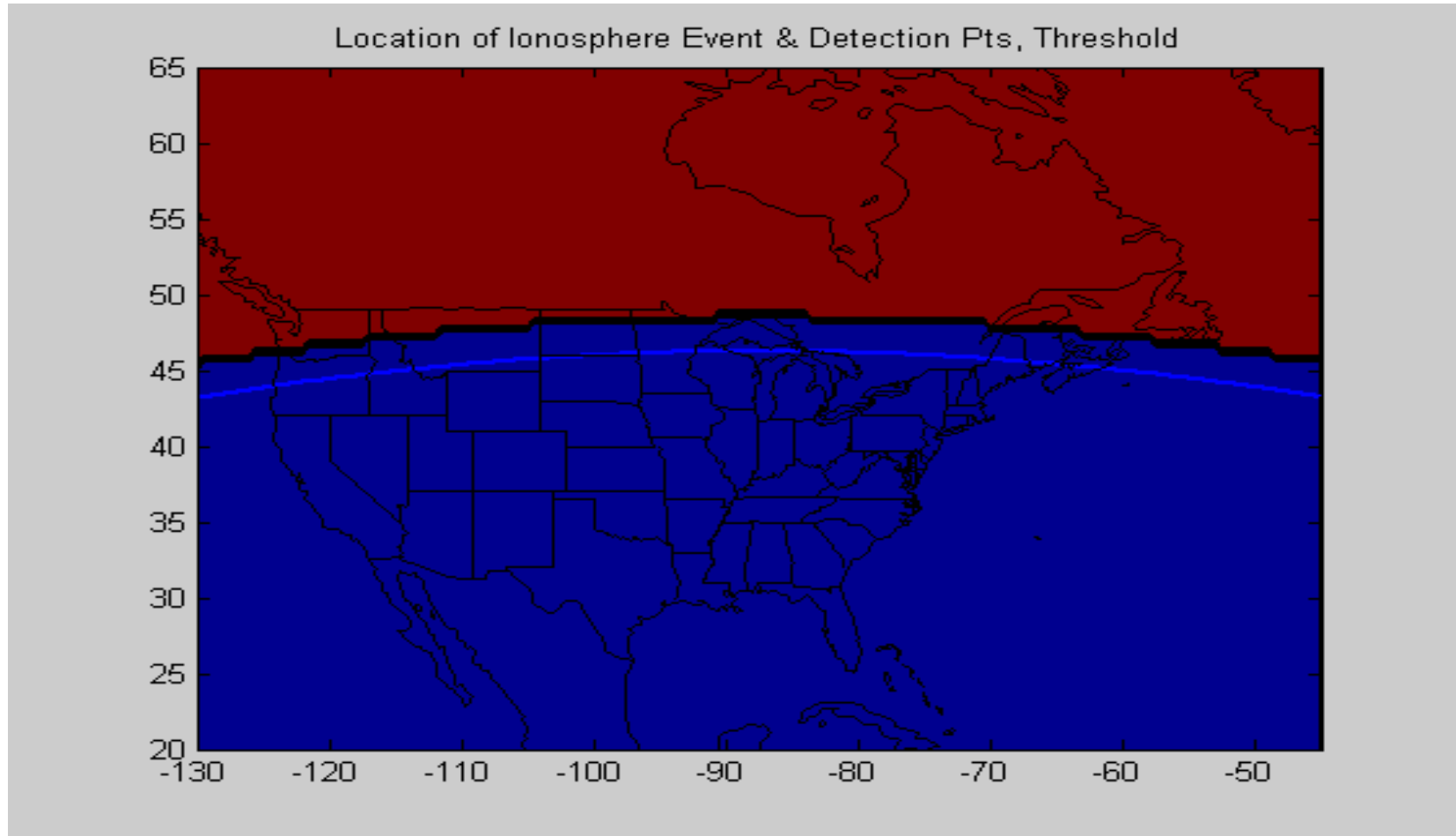


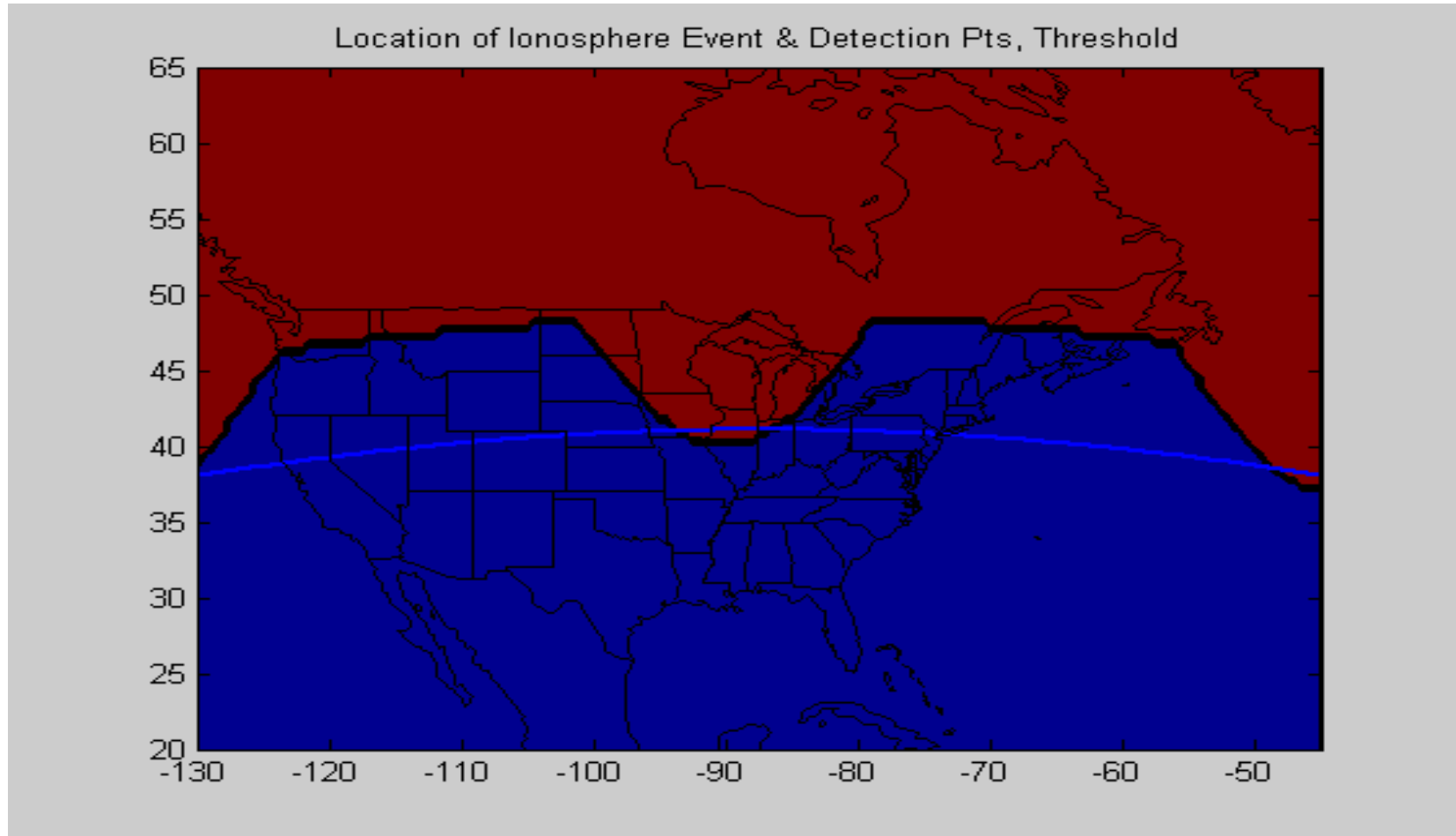
Example Rules for PCD Events

- Select lowest geomagnetic latitude for affected area indicated to users
 - Sample choices for AZ boundary GMLAT:
 - “y” degrees/km below the minimum GMLAT of the monitor stations detecting the event
 - GMLAT of monitor not detecting an event nearest to and equatorward of user
 - Calculate using weighted combination of detected and undetected locations
 - Protect integrity while maximizing availability
-



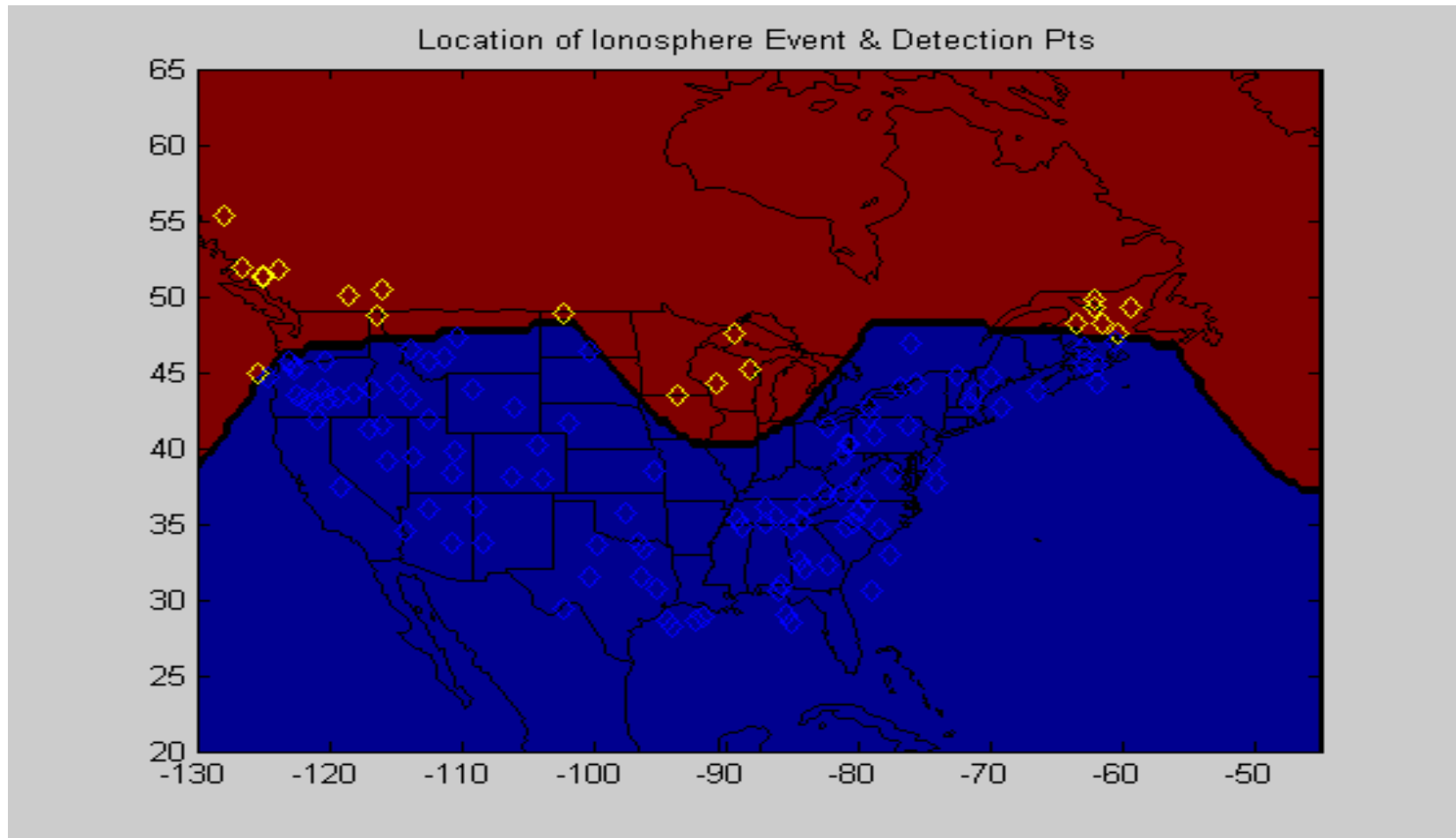
Area Warned





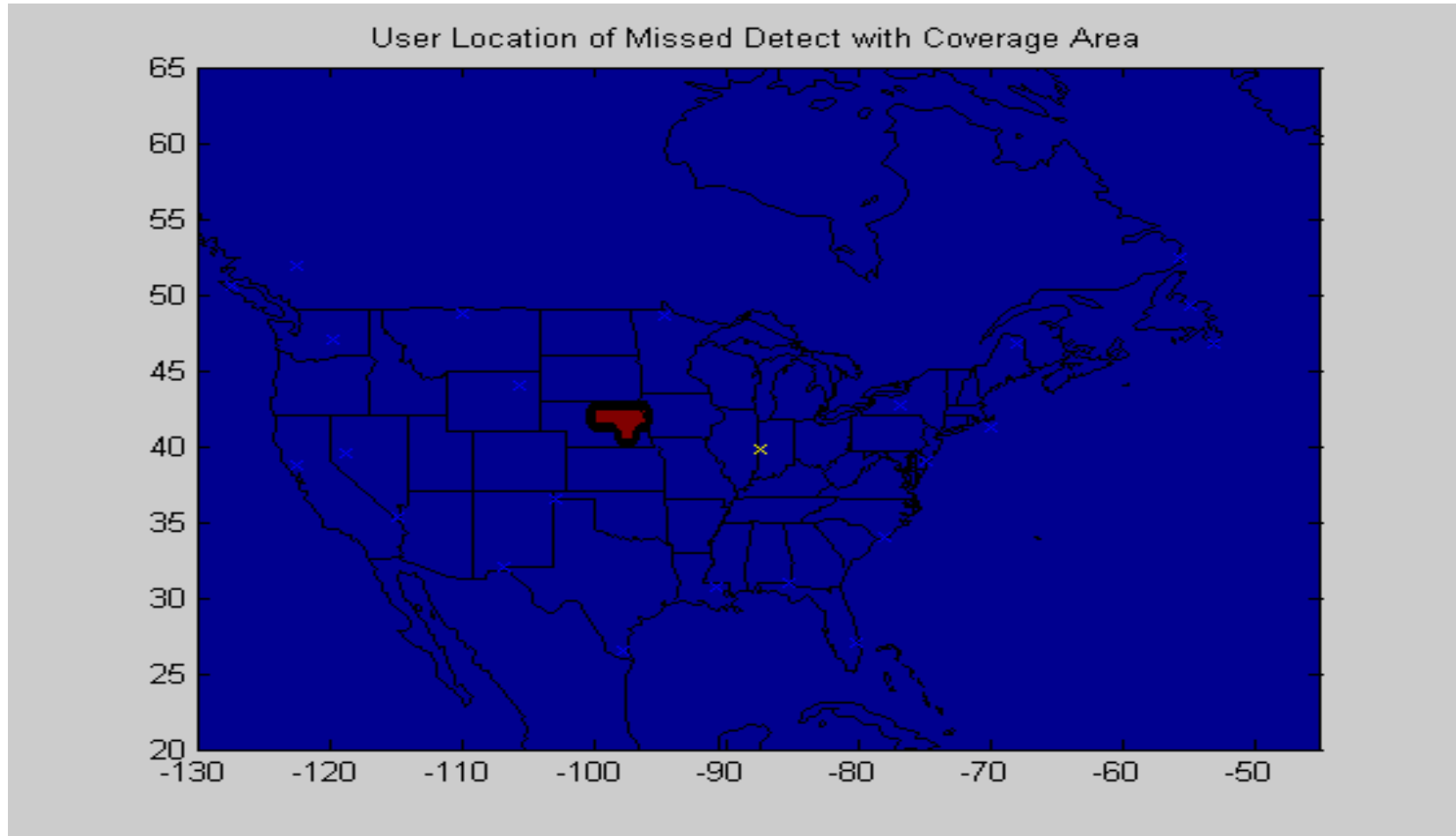


Missed Detection due to Low Density of Detection Pts in Midwest



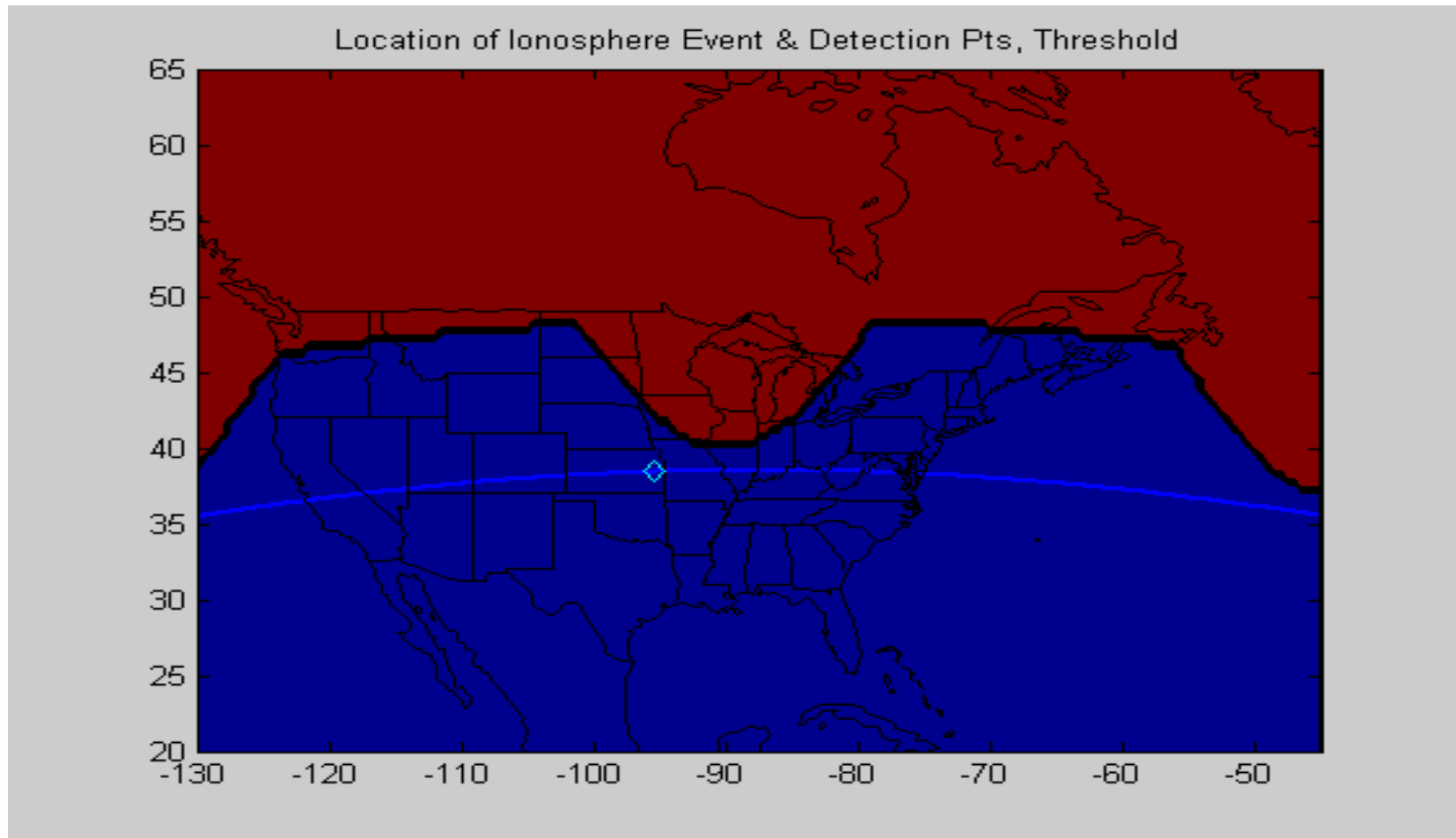


Users Affected by Missed Detection





Bounded Using A Different Rule: Closest Southern Non Detection Location





Additional Parameters Tested

- Monitor False Alarms
 - Local storm may falsely trigger warning
 - Should be evident at network level
 - Anomalies
 - Crosscheck with other monitors
 - Monitor Missed Detections
 - Due to failure of equipment
 - Due to power outage
 - Must be robust to the worst case deprivation of midpoints/monitors
-



Classifying Event Type

- Time history of event spatial configuration
 - Trace evolution of best-fit AZ boundary
 - Is spatial evolution correlated to advance of day-night terminator?
 - Event duration as means of identification:
 - For example, if event persists beyond 45 minutes, event is likely a PCD
-



Early Skywave Warning: Message Transmission

- Need to warn the user when a signal is affected (when LC reaches a certain threshold)
 - Ninth Pulse Communication Broadcast on Loran
 - 1.6 to 2.4 seconds per message
 - Skywave message transmitted 3 consecutive times when event first detected
 - During the event, the warning will be issued every N^{th} message (N to be determined)
 - Provides low-latency warning indicator without excessive overhead
-



Early Skywave Warning: Example Message Content

- Data Item 1 (DI1): 0 = No event ; 1 = Event
 - Data Item 2 (DI2):
 - If (Event = PCD), DI2 = GMLAT (degrees) of AZ boundary
 - If (Event = SID), DI2 = 0
 - If ((Event = PCD) & (Event = SID)), DI2 = - GMLAT (degrees) of AZ boundary
-



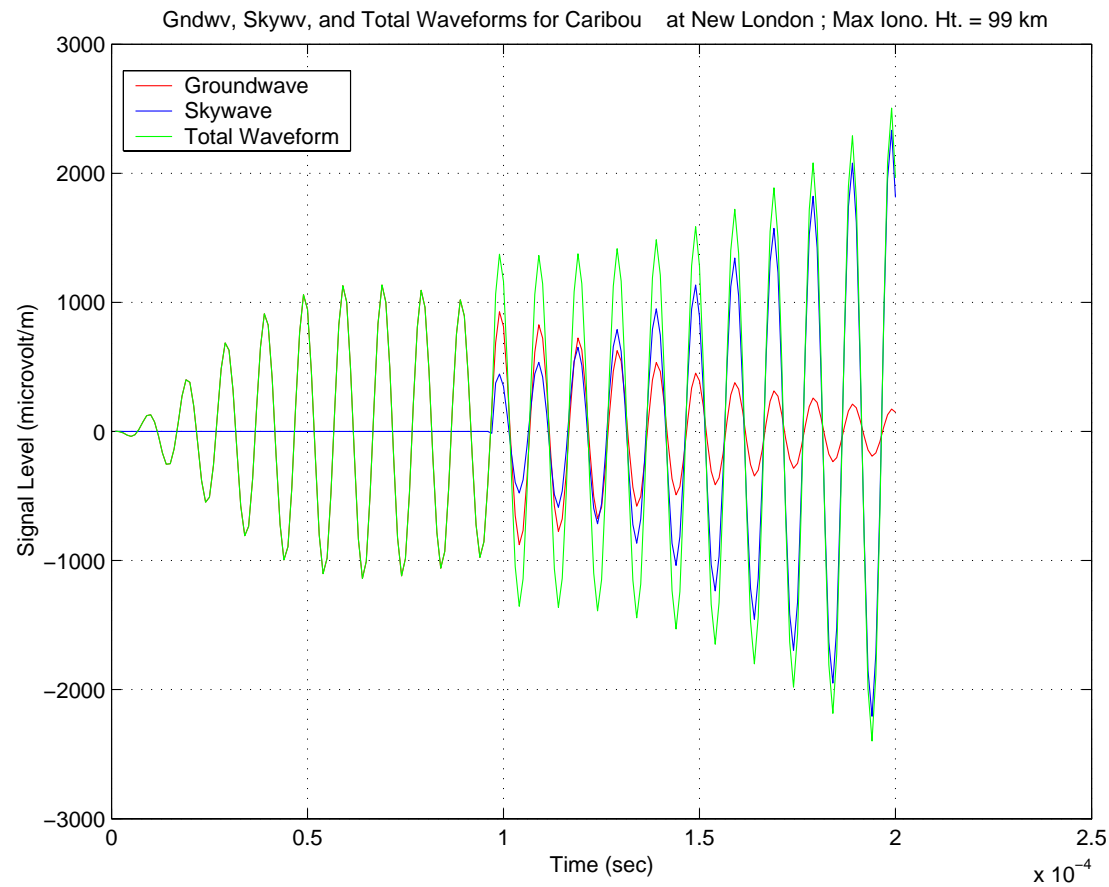
Conclusions

- Early skywave has been identified as one of the most serious challenges to Loran integrity
 - We have determined the sources of the events that result in early skywave
 - We have described a method of resolving the integrity issue using a warning network comprising existing monitor sites
 - The rules and procedures for event detection using this network are currently being formulated
-



Predicted Groundwave and Skywave Waveforms at Receiver

**Caribou at New
London, CT**

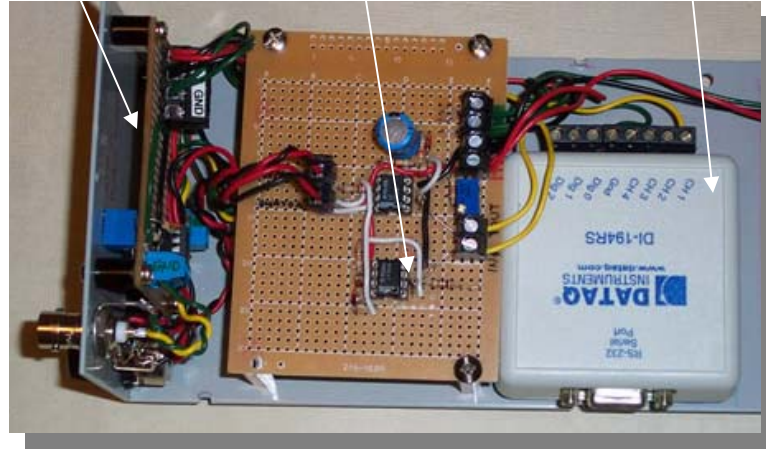
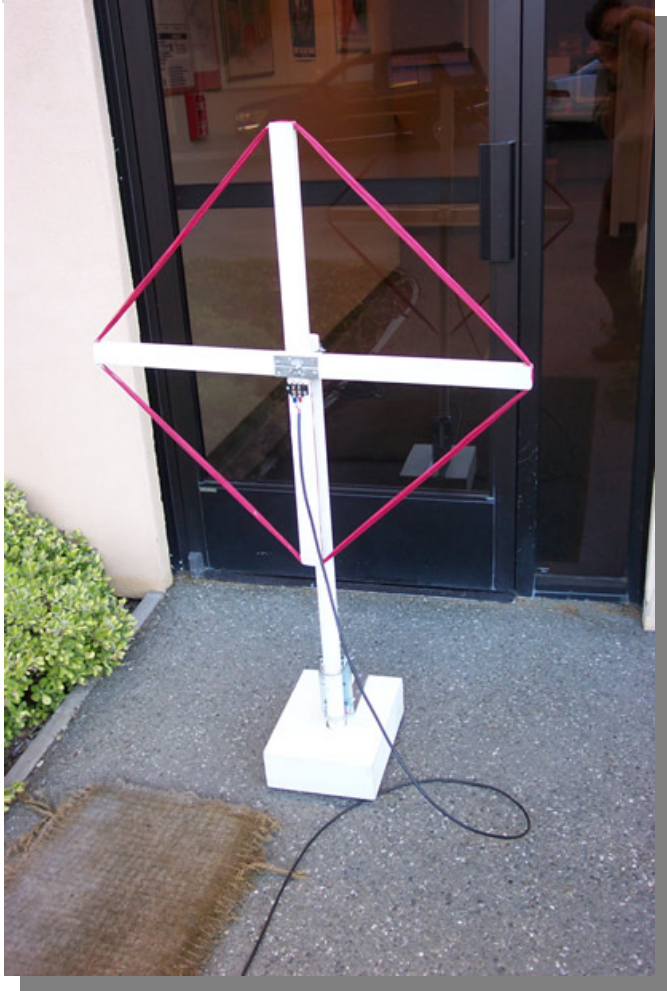




Effective Minimum Range for Early Skywave

From the previous plots, we see that, for a strongly ionized PCD (or SID) ionosphere:

- The skywave delay is less than 30 μsec for ranges > 500 km, *but*
 - The skywave has little effect on the received signal for ranges up to 800 km because the skywave-to-groundwave amplitude ratio (SGR) is so small
 - The net result is that early skywave only affects user-to-transmitter paths > 800 km
-





Causes of Early Skywave I

- Solar events result in increased ionization in the ionospheric layers
 - The same ionization level (which acts to reflect the Loran signal) is found at lower altitudes during events
 - PCDs
 - Caused by excess protons emitted from the sun during Solar Proton Events
 - Protons are not deflected by the geomagnetic field in the auroral zones (AZs) thus leading to very high ionization
 - SIDs
 - Caused by large x-ray flares on the solar surface
 - X-rays (high-energy photons) cause excess ionization in those regions directly exposed to the sun; effect is proportional to $\cos(\text{solar zenith angle})$
-



Causes of Early Skywave II

- 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
 - Nightside Ionosphere
 - Effective height is also depressed (relative to nominal) during PCDs but even a 20 km depression results in a layer at ~ 70 km altitude, not low enough to cause a 30 μ sec skywave delay
-



Outline

- Skywave & Effects
 - Causes of Early Skywave
 - PCD and SID event descriptions
 - Detection & Mitigation of Early Skywave
 - Early Skywave Network
-



Other Rules

- Integrity Paramount
 - When availability is sufficient, false alarms are preferable to missed detection
 - Eliminate monitor false alarms (outliers) (if other stations do not event exists)
 - Find lowest-GMLAT monitor that detects an event
 - Include margin that depends on certainty of estimate
 - Find best-fit geomagnetic latitude to AZ boundary
-



An Algorithm for Network Determination of AZ Boundary

- Find the AZ GMLAT (λ) that maximizes

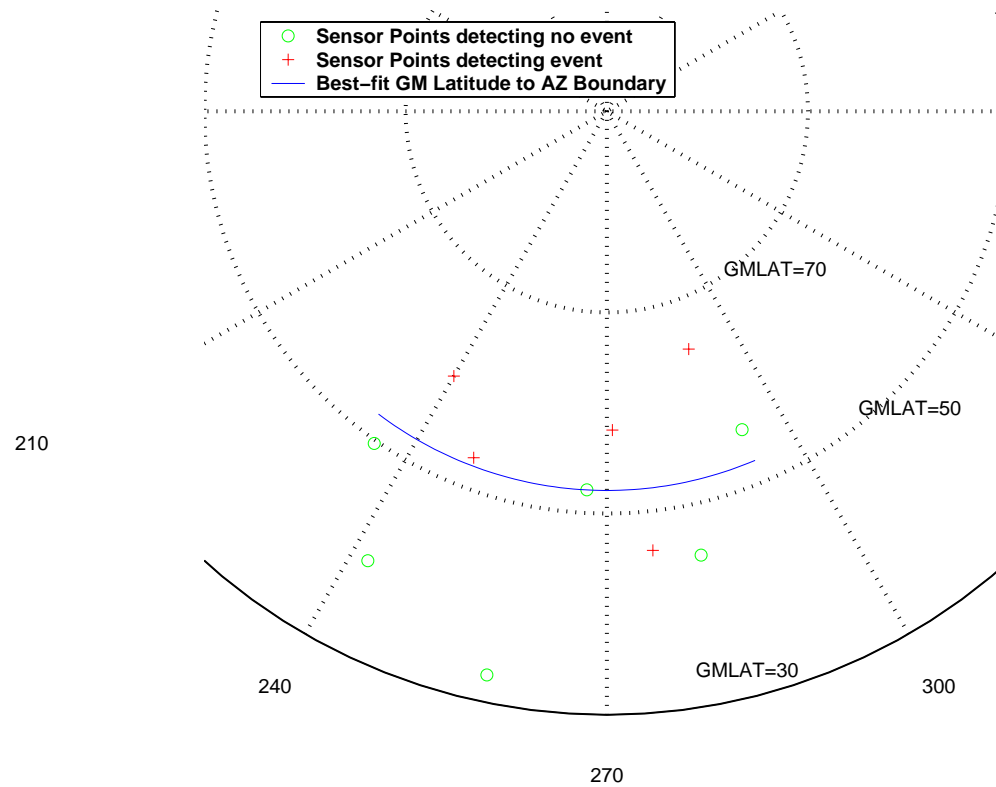
$$S \equiv \sum_{j \in \{j\}} w_j D_1^j(\lambda) + \sum_{i \in \{i\}} w_i D_0^i(\lambda)$$

where:

- D_1 is the difference between (1) the GMLAT of stations less than λ that detected an event and (2) λ
 - D_0 is the difference between (1) λ and (2) the GMLAT of stations greater than λ that did not detect an event
 - w_i is a weight that is roughly proportional to path length
-



Illustration of AZ Boundary Determination based on Alternative Algorithm

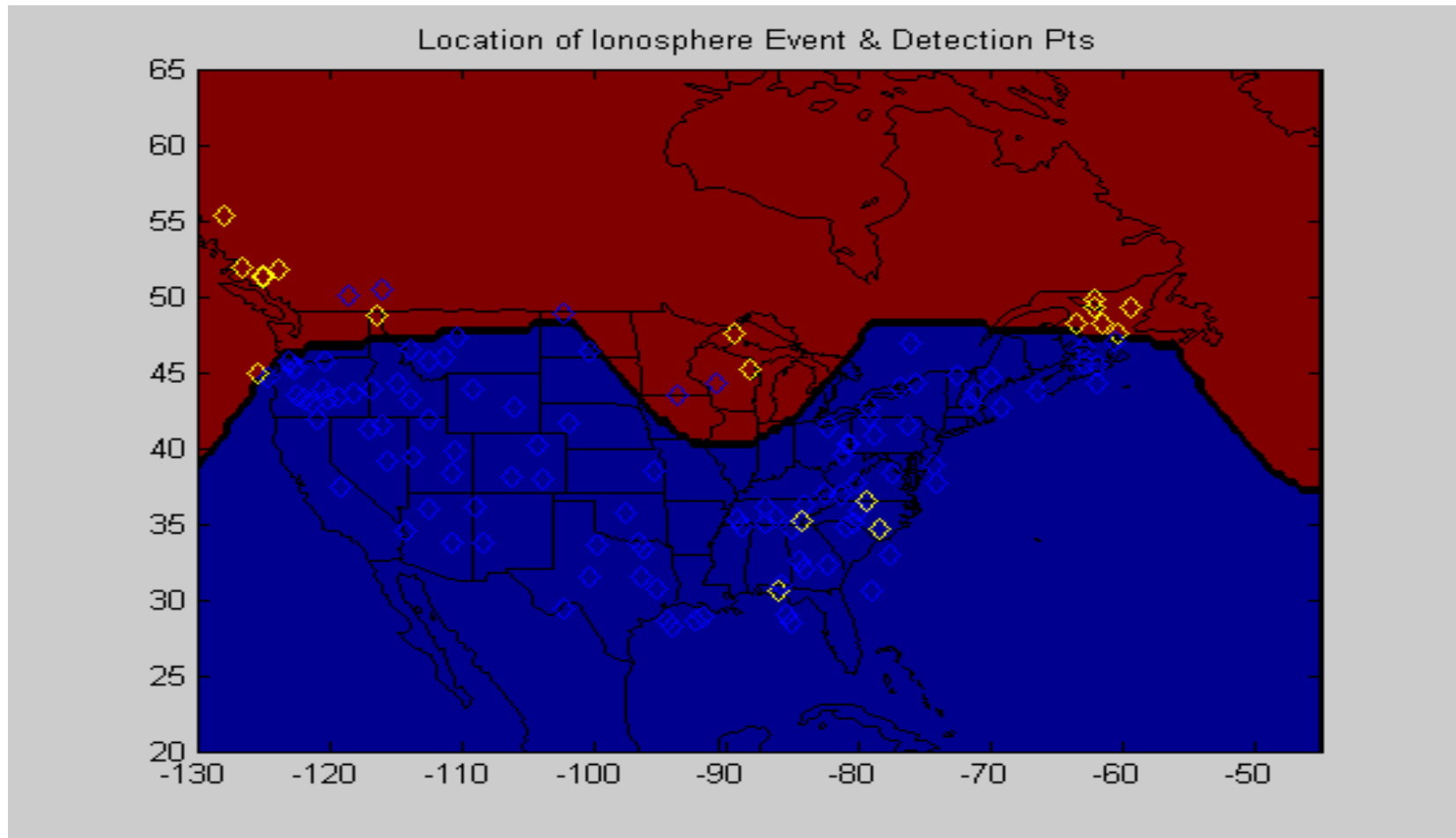




Ideas for Network Solution



Example of False Alarm & Missed Detection





Calculation in the Receiver

- The receiver shall determine
 - If path midpoint is in day ionosphere ($\cos(\text{solar zenith angle}) < -0.157$)
 - If $|\text{GMLAT}(\text{path midpoint})| > |\text{DI2}|$
 - If (Path length to a given station) > 800 km
 - If ($\text{DI1} = 1$) and the above all true, the receiver will automatically deselect the signal
 - The user can be confident about early skywave status as soon as the receiver successfully decodes an early skywave message
-



Event Characteristics & Features

- Sudden Ionospheric Disturbance (SID)
 - Ionization level (effective reflection height) abruptly increases (decreases) to a maximum (minimum) within a few minutes
 - Event decays much more slowly with a total effective duration of ~ 30 - 45 min
 - Polar Cap Disturbance (PCD)
 - Poleward of the auroral zone, the event causes excess ionization of the *D*-region for several days
 - A concurrent geomagnetic storm sometimes pushes the AZ equatorward, thus exposing mid-latitude regions to the PCD
-



Causes of Early Skywave

- Solar events result in increased ionization in the ionospheric layers
 - PCDs
 - Caused by excess protons emitted from the sun during Solar Proton Events
 - SIDs
 - Caused by large x-ray flares on the solar surface
 - Geomagnetic Storms
 - Result from solar corona mass ejections that distort the interplanetary magnetic field
 - More details are given in Morris, “Conditions Leading to Anomalously Early Skywave,” ILA 2003
-