eLoran 102: Introduction to Propagation Hazards

Sherman Lo, Stanford University

33rd Technical Meeting of the International Loran Association (ILA-33)

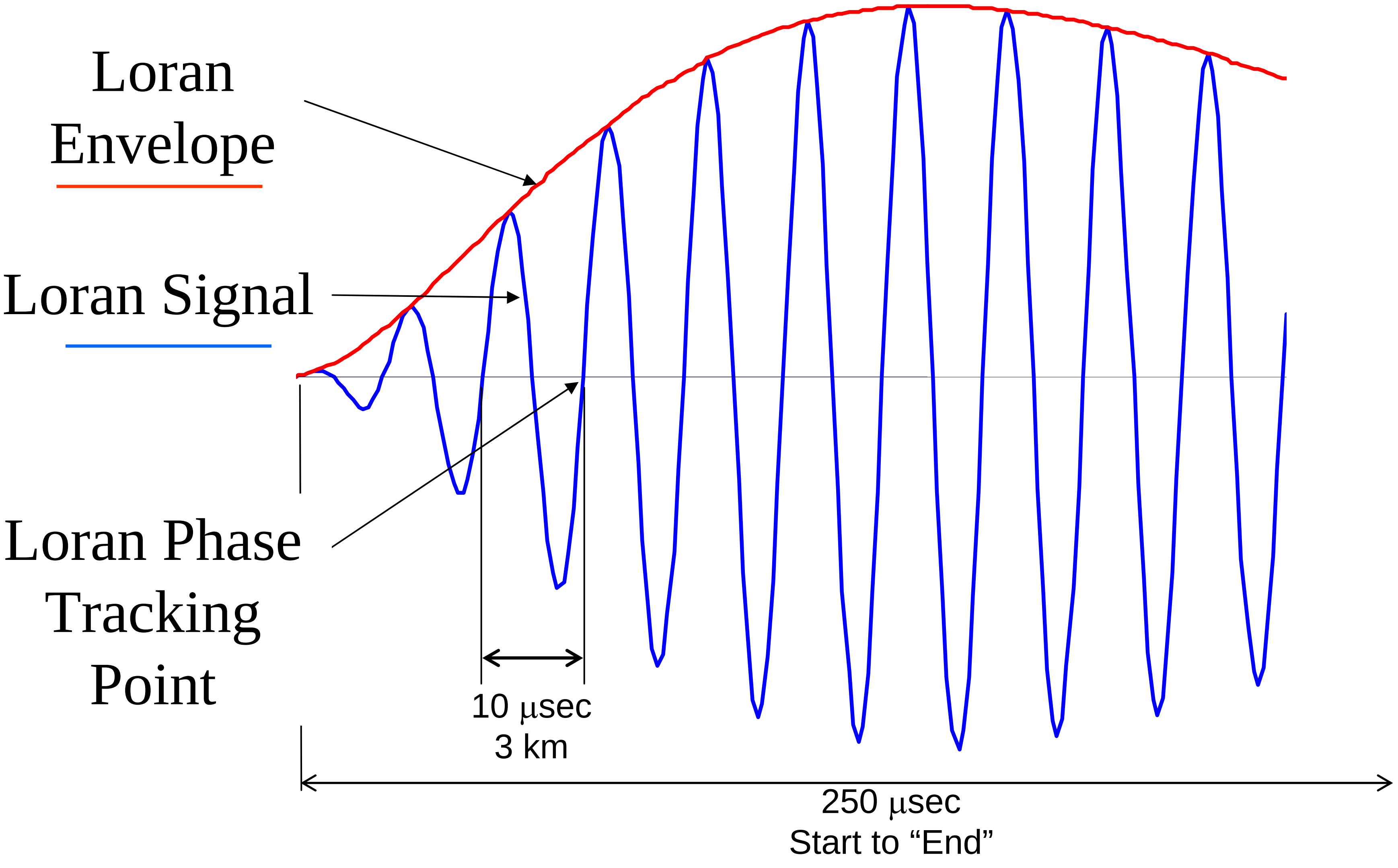
Tokyo, Japan October 25-27, 2004

Outline

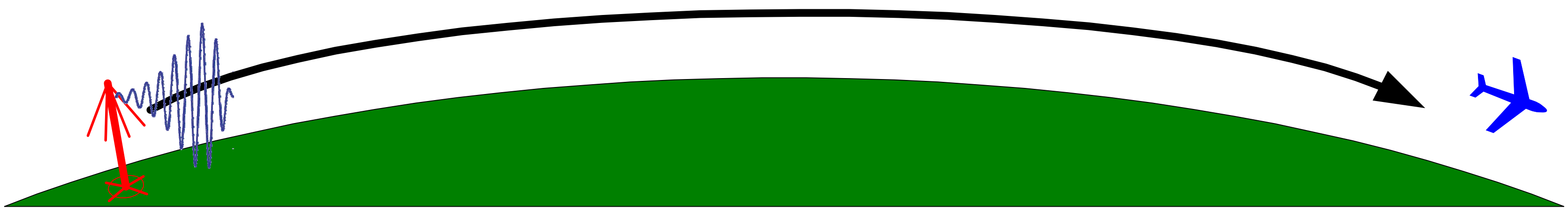
- Introduction to the Loran Signal
- Loran Propagation & Effects
  - ✈Propagation
  - ✈Interference
- Requirements for eLoran
- Modeling and Assessing Propagation Effects for eLoran
- Conclusions

Propagation Effects

Ideal Loran Pulse

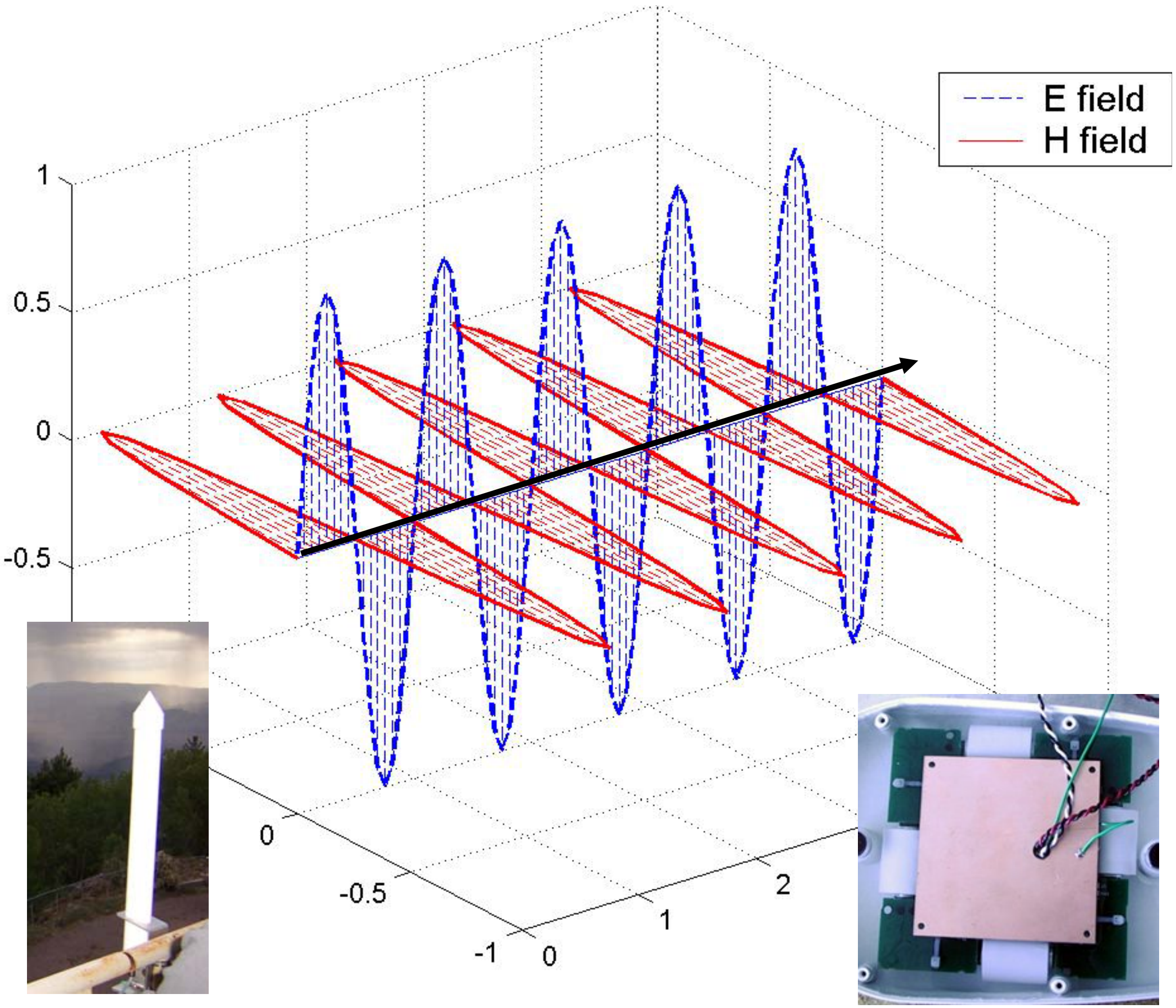


Propagation of LF Signals



- *Low Frequency (LF) signals propagate along the ground (groundwave or surface wave)*
  - ✈ *Follows the earth, not line of sight*
- *Signal bends/diffracts around most objects since they are smaller than the wavelength of the LF signal*
- *Signal can also reflect off the ionosphere (more later)*

E and H field (Radiation Field)



- ***Signal propagates as electric and magnetic field***
  - ✈ *In phase in time*
  - ✈ *90 deg out of phase in space*

Loran Groundwave Propagation Effects

- ***The signal is delayed, distorted and attenuated as wave propagates over ground***
  - ✈ ***Dependent on factors such as ground conductivity, permittivity, roughness, etc.***
- ***Delay: General trend - it is "slower" when hot and humid, it is "faster" when cold and dry***
- ***Distortion: Different frequencies have different delay – envelope delay different than carrier***
- ***Attenuation: Poor electrical conductivity and rough terrain results in greater attenuation***

Propagation Delay

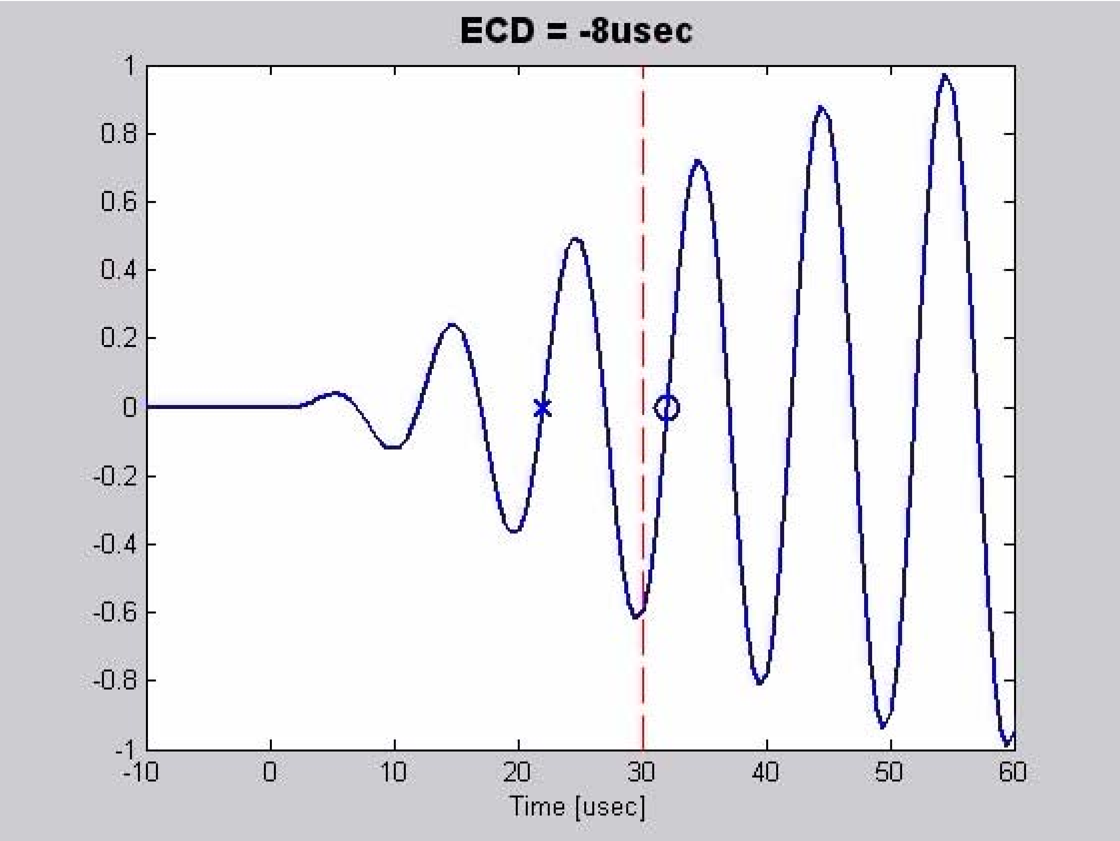
True Propagation Time = $PF + SF + ASF$

Primary Phase Factor (d/v)	SF(d)	ASF(d,σ,ε, etc.)

- ***First two delay factors (PF, SF) can be determined knowing the distance from transmitter to receiver***
- ***Additional Secondary Factor (ASF) is dependent on***
  - ✈ ***Terrain: i.e., ground conductivity, permittivity, moisture content, elevation, etc.***
    - *Changes with time (temporal) and travel path (spatial)*
  - ✈ ***ASF represents a major uncertainty: 300 m or more of range error***
  - ✈ ***ASF estimate required for better accuracy, bound on variation from nominal necessary for integrity***

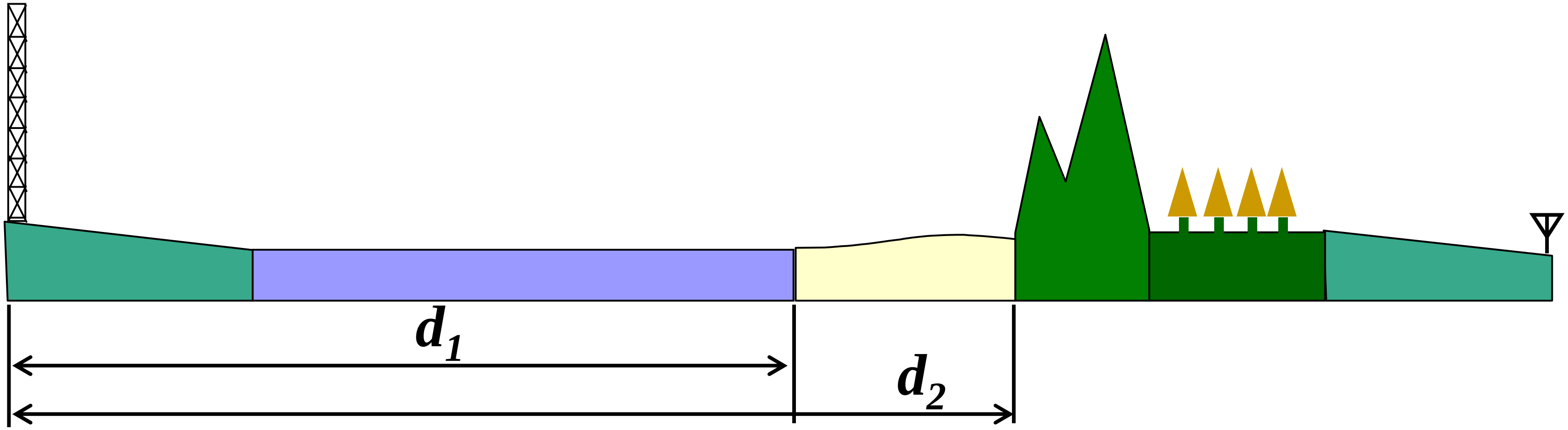
Variation of Envelope Relative to Carrier

X	***true tracking point (6th zero crossing)***
O	***tracking point used***



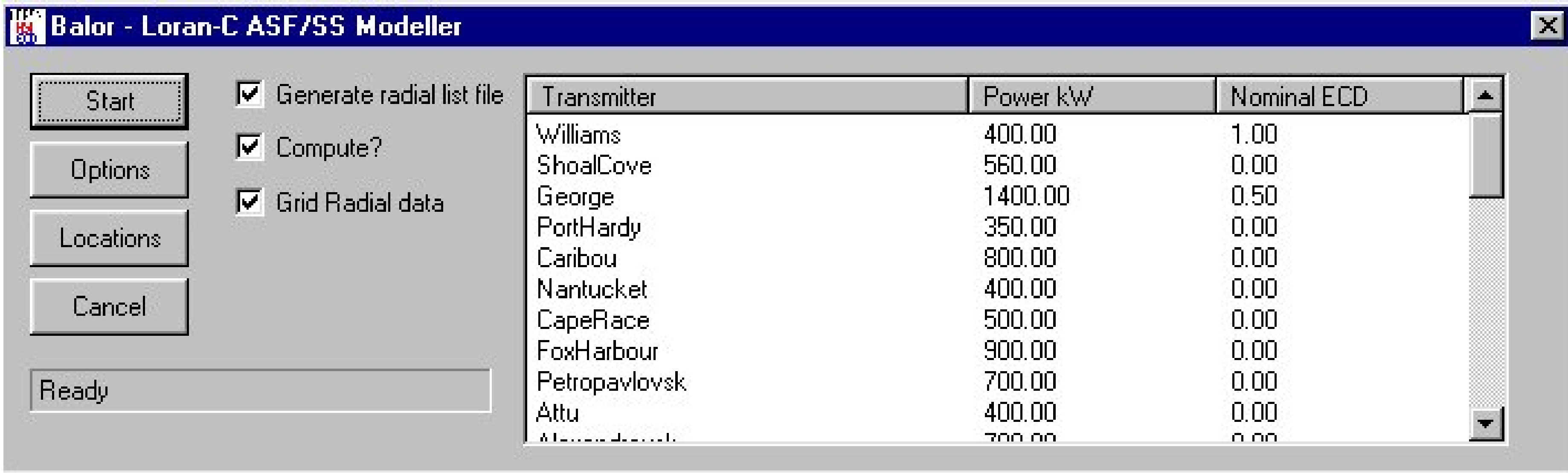
- ***The envelope of the signal is used to determine the zero crossing used for tracking***
- ***If ECD differs from prediction by more than 5 microsecs, misidentification of tracking point will occur***

Millington's Method



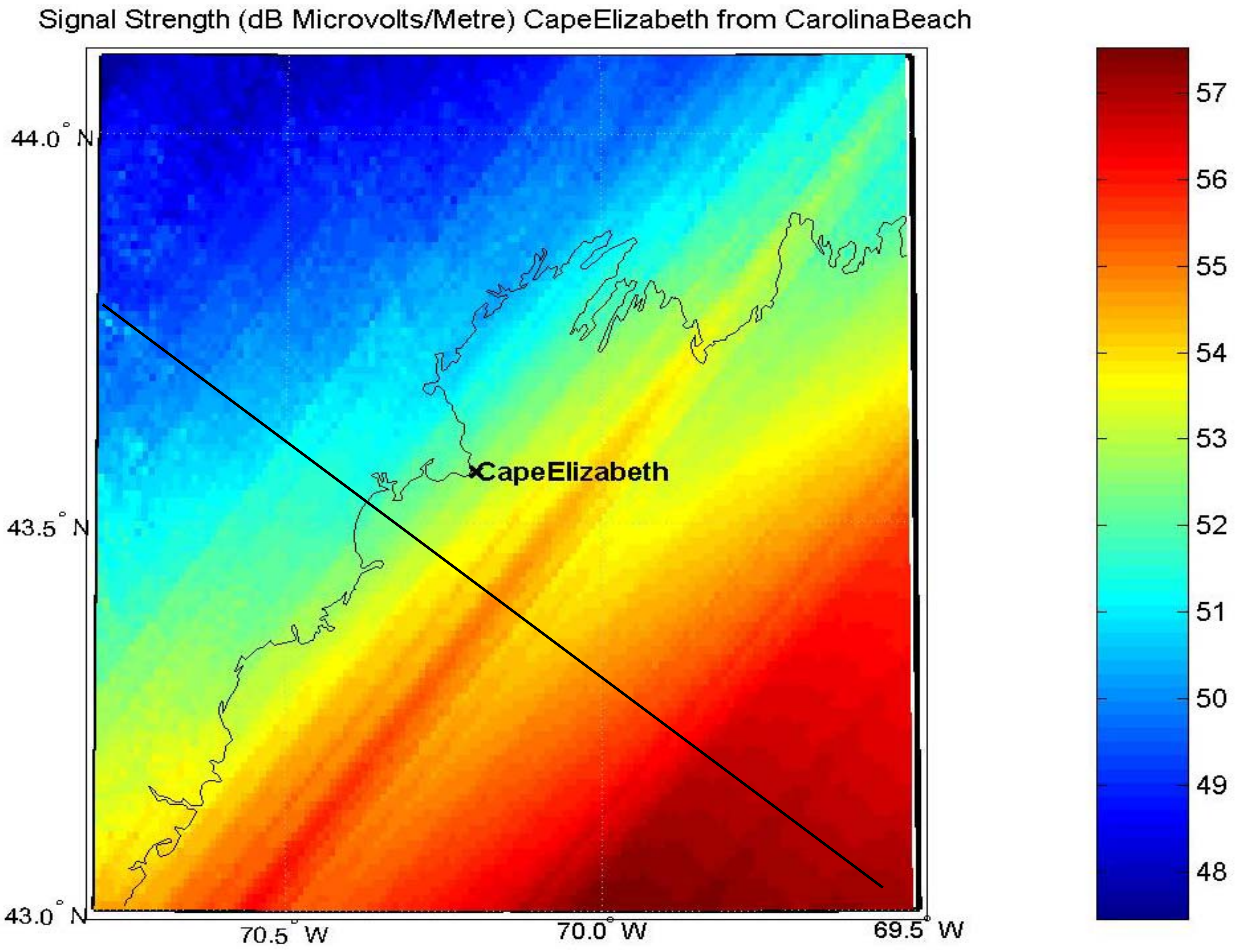
- *Millington's Method determines ASF, attenuation by dividing heterogeneous terrain into distinct homogeneous segments of different conductivity*
- *Calculate differential attenuation, delay assuming due to the segment*
- *Reciprocal path values calculated and averaged*

Newer ASF Methods



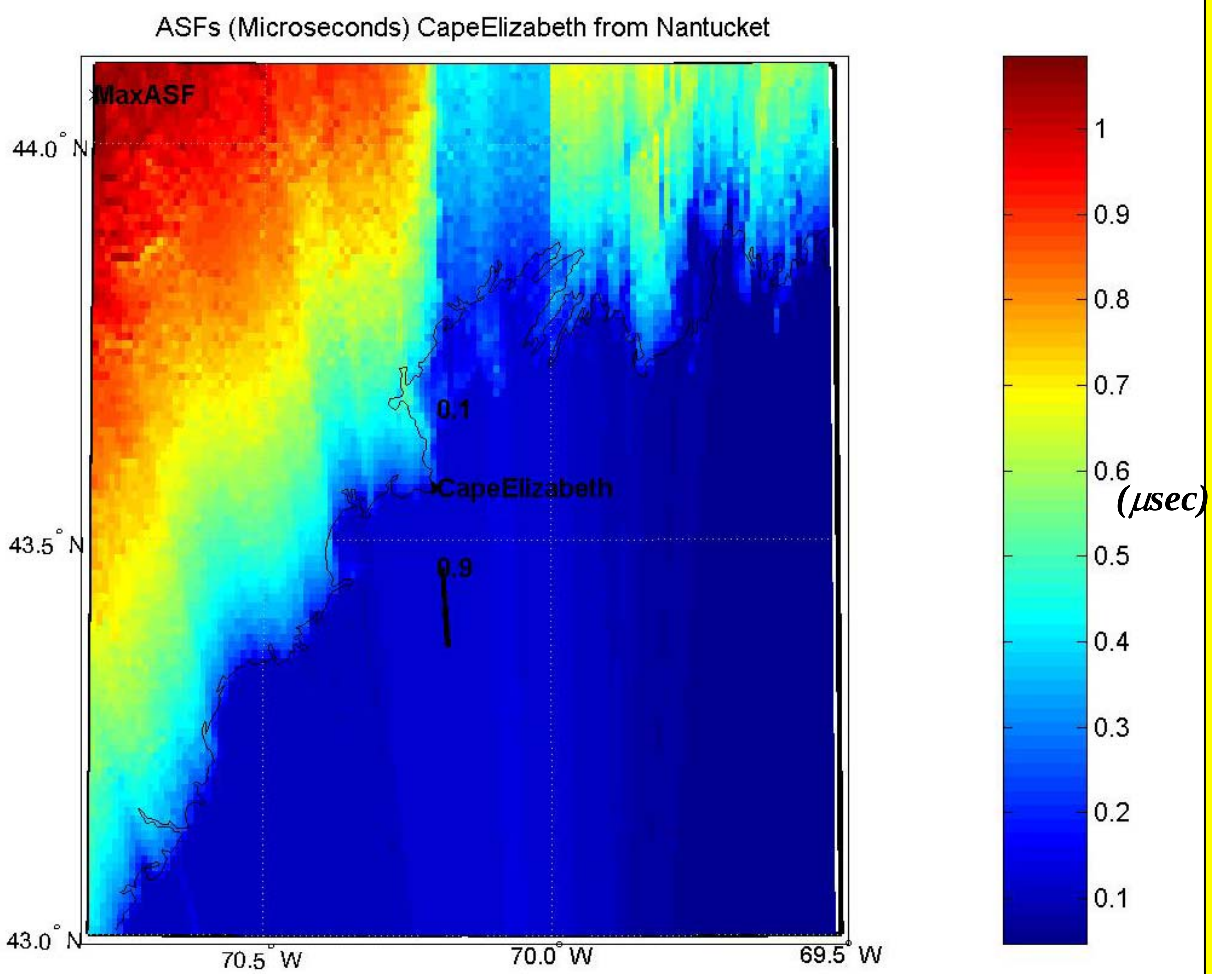
- ***Terrain is known to greatly effect ASF, attenuation, phase delay***
- ***Bangor, Wales Balor model***
  - ✈ ***Uses Monteath Method***
    - *Being modified to account for earth curvature*
  - ✈ ***Conductivity, elevation, and coastline databases***

Spatial Variation of Signal Strength: Portland, ME from Carolina Beach



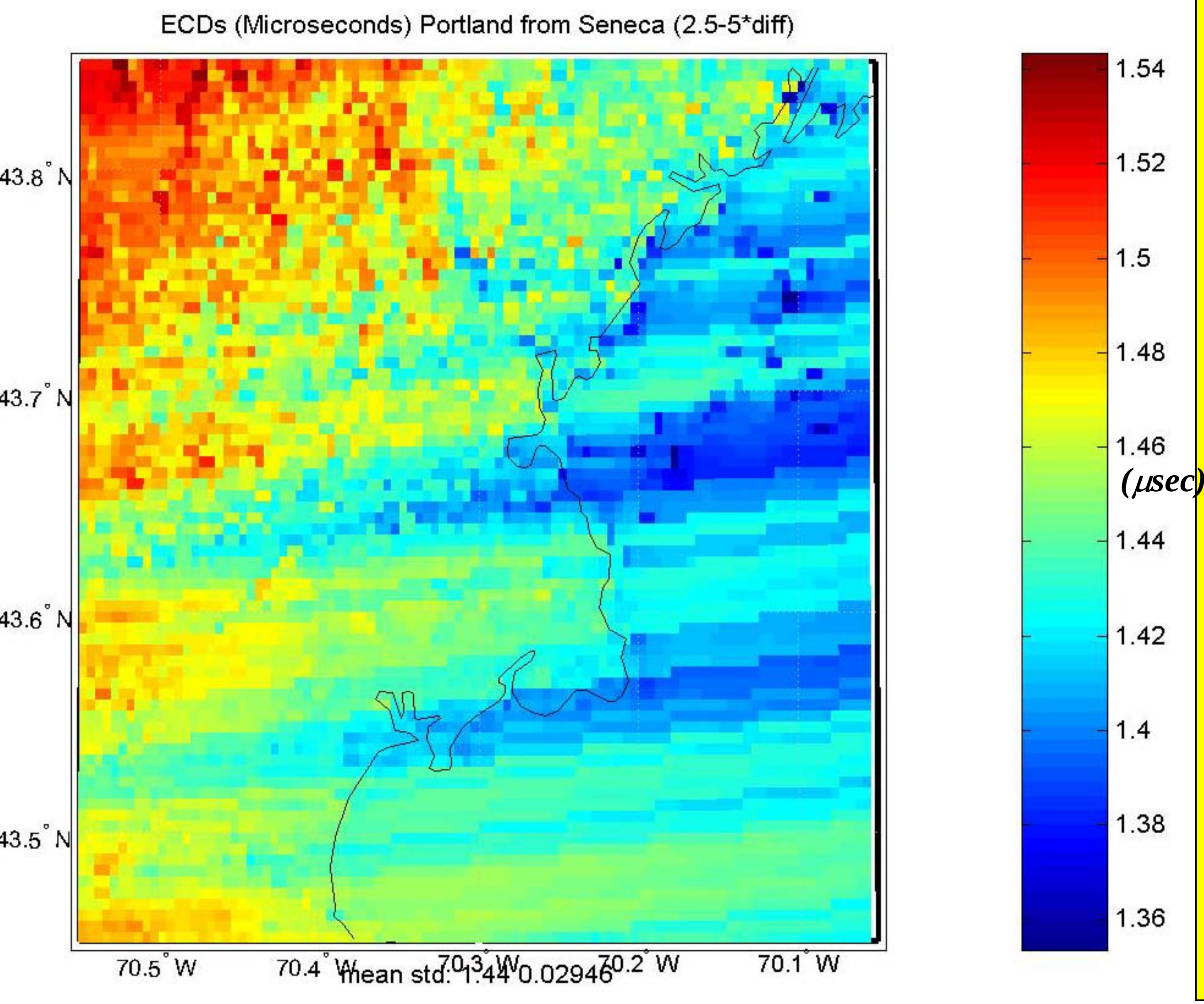
- *Portland, ME*
- *Extreme case - junction of sea and land; mountainous terrain*
- *10 dB difference for the same range*

Spatial Variation of ASF: Portland, ME from Nantucket



- ***Portland, ME***
- ***Extreme case - junction of sea and land; mountainous terrain***
- ***ASF Variations over map ~ +/-0.5 μsec***
- ***Variation about approach is significant ~ 0.1 to 0.6 μsec***

Spatial Variation of ECD: Portland, ME from Seneca



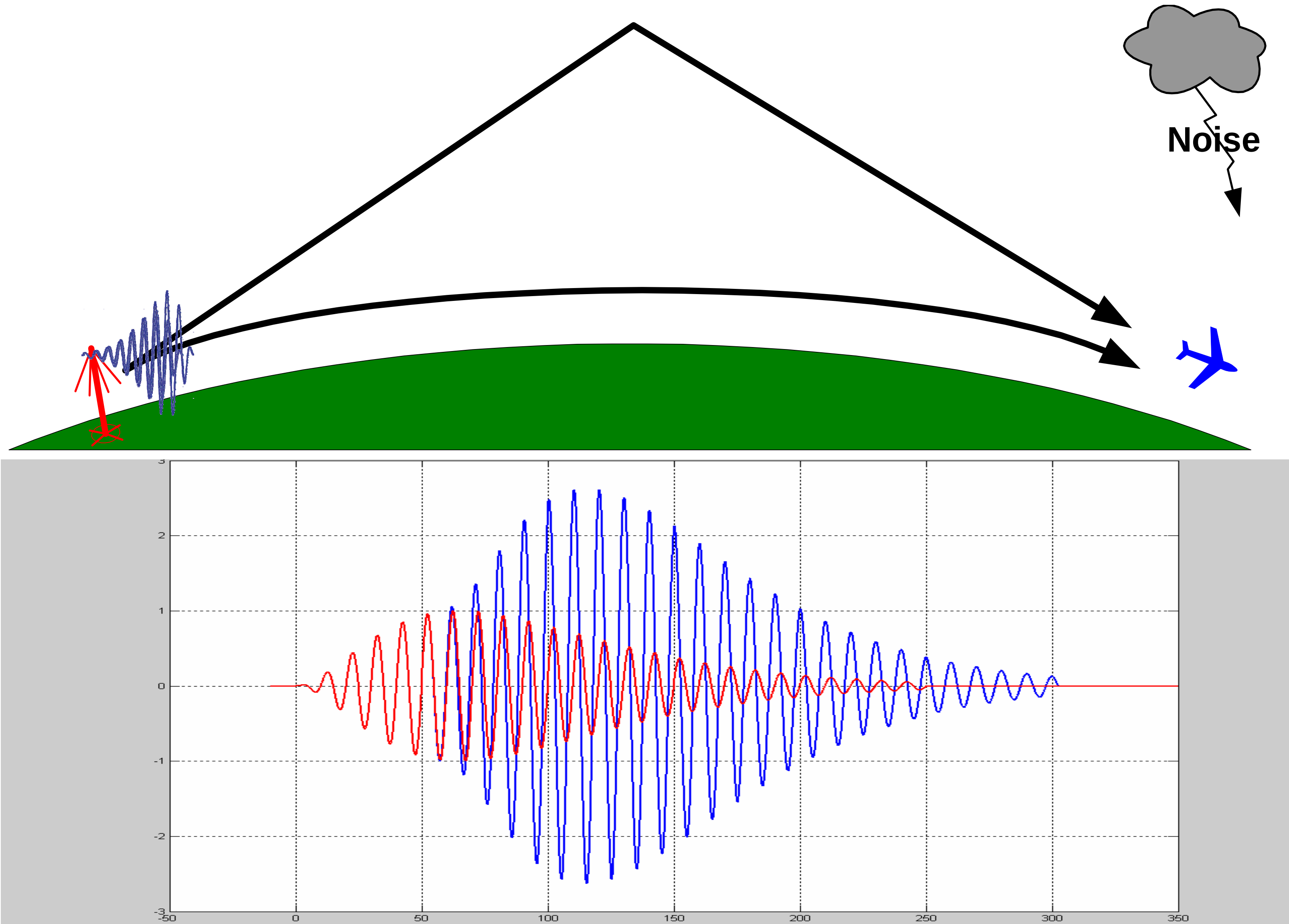
- ***Portland, ME***
- ***Extreme case - junction of sea and land; mountainous terrain***
- ***ECD Variations over map ~ +/- 0.12 μsec***
- ***Probably varies less than 0.1 μsec over approach***

Errors in Estimating Propagation Induced Effects

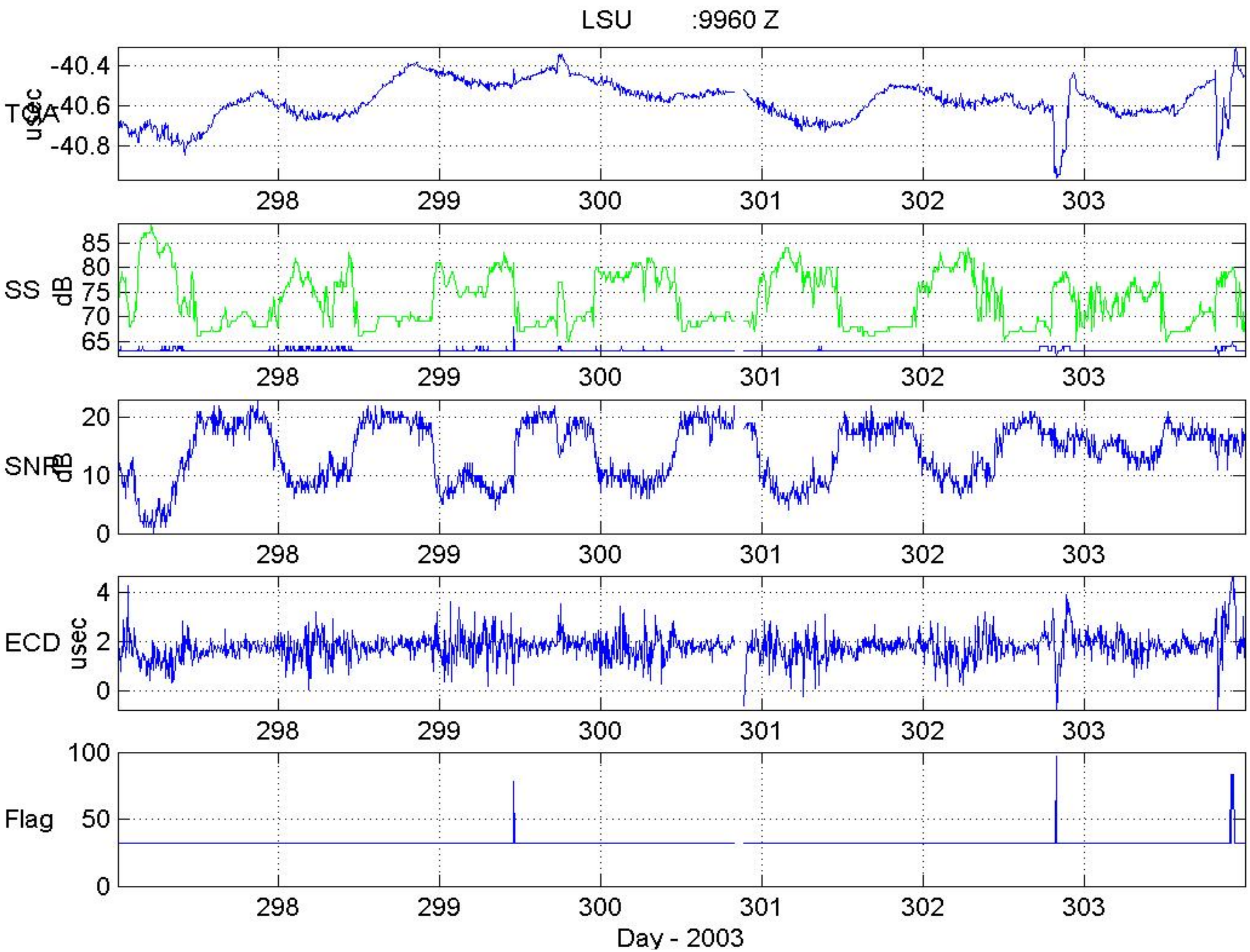
- **Error in estimating phase delay (ASF)**
  - ✈ Results in range error and reduced accuracy
  - ✈ Actual integrity level does not meet requirement if bound is inadequate to cover error
- **Error in estimating ECD**
  - ✈ Can result in improper cycle determination
  - ✈ Range error of 3 km or more
  - ✈ Undetected integrity fault
- **Error in estimating SNR**
  - ✈ Reduced availability

Interference

Loran Skywave



Extreme Example of Early Skywave Dana, IN to Wildwood, NJ (591 NM)



Loran and GPS Propagation Errors Analogy

Loran	GPS	Effect
ASF (phase delay)	Ionosphere, Tropo delay	Signal delay that varies spatially, temporally
ECD	Code-Carrier Divergence	Reduces ability to track signal
Signal Strength Variations	Ionosphere Scintillation	Degrades SNR
Skywave	Multipath	Interferes with signal
Reradiation	Reradiation	Signal distortion
CW interference	Man Made interference	Jamming, etc.
Atmospheric Noise	Background Noise	Degrades SNR

- ***Can use analogy and experience in designing integrity for GPS to help with Loran integrity***

Mitigating Errors

RNP & HEA Requirements for Loran

Performance Requirement	RNP Value	HEA Value
Accuracy (target)	307 meters	20 m, 2 drms
Monitor/Alert Limit (target)	556 meters	50 m, 2 drms
Integrity	10^{-7}/hour	3×10^{-5}
Time-to-alert	10 seconds	10 seconds
Availability (minimum)	99.9%	99.7%
Availability (target)	99.99%	
Continuity (minimum)	99.9% (150 seconds)	99.85% (3 hrs)
Continuity (target)	99.99%	

- *Meeting Integrity (with adequate availability & continuity is the most challenging and critical requirement for aviation*
- *Integrity drives many of the design choices for enhanced Loran*

Timing and Frequency

Performance Requirement	Value
Frequency Accuracy (target)	1 x 10^{-13} averaged over 24 hours
Frequency Accuracy (desired)	1 x 10^{-12} averaged over 6 hours
Frequency Accuracy (minimum)	1 x 10^{-11} averaged over 1 hour
Antenna	No External Antenna (desired)
Legacy Use	Backward Compatibility (desired)
Integrity Data	Minimum "Use/No Use" flag
Timing Data	Time Tag, Leap Second Info
Timing Accuracy at the user's receiver	< 100 nsec (RMS)
Differential Data Update Rate	< once/hour

Philosophy

- Treatment of hazards determines whether they effect integrity/accuracy/availability
- Bound errors due to various hazards (to integrity)
  - ✈Collect data and determine models for hazards
  - ✈Determine if corrections are necessary and how they should be implemented (HEA)
  - ✈Map model for hazards into range domain bound using integrity (HPL) equation
- Warn/Alert on hazards that are not bounded
  - ✈System unavailable during warning (best for rare events)
  - ✈SNR penalty (affects both availability & integrity)

Loran Hazards & Mitigation

Category	Hazard	Mitigation
Transmitter	Timing and Frequency Equipment Transmitter and Antenna Coupler Transmitter Equipment Monitoring	Bounds (Testing), Monitoring Bounds (New Equipment), Monitoring N/A
Propagation	Spatial variation of phase along approach Temporal variation of phase Spatial variation of ECD along approach Temporal variation of ECD Temporal variation of SNR	Error Bound (Position Domain) Error Bound (Correlated & Not) Error Bound Error Bound Debit to SNR
At the Receiver	Platform dynamics Atmospheric Noise Precipitation Static Skywaves Cross-Rate Interference Man-made RFI Structures Receiver Calibration	N/A Receiver Processing H field Antenna Integrity Monitor & 9th Pulse Receiver Processing Survey & Calibration Survey & Calibration Error Bound

Bounding Phase/ECD Errors

Bounding Phase Error

$$HPL = \kappa_{RNP}\sqrt{\sum_i K_i \alpha_i^2} + \left|\sum_i K_i \beta_i\right| + \sum_i \left|K_i \gamma_i\right| + PB$$

$$\alpha_i^2 = \sigma_i^2 = \sigma_{f(SNR)}^2 + \sigma_{tx}^2$$

$$\gamma_i = k_i^{terrain} k_{TempPhase}^{uncorr}$$

Correlated Temporal Phase

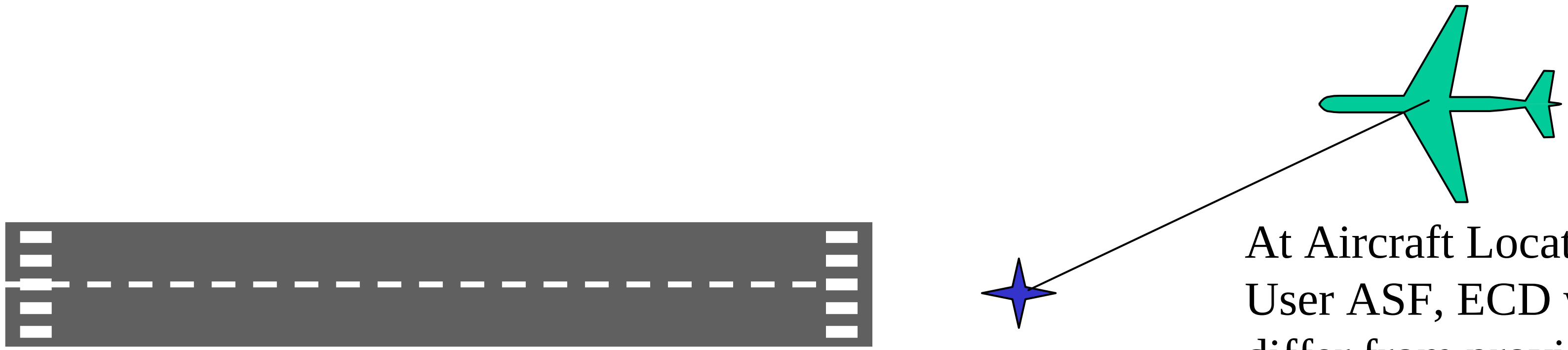
$$\beta_i = k_i^{terrain} k_{TempPhase}^{correlated} \left| d_{i,land} \right|$$

Spatial Phase in

$$PB = \sum_i K_i k_{SpatialASF,i}^{uncorr}$$

- ***First term = Σ random errors (transmitter jitter, receiver noise). Treated as uncorrelated from transmitter to transmitter.***
- ***Second term = Correlated phase bias error from temporal variation (proportional to range)***
- ***Third term = Uncorrelated phase bias error from temporal variation***
- ***Fourth term = Position domain bound for residual spatial ASF error***

Model for ECD, ASF



At Aircraft Location User ASF, ECD will differ from provided ASF , ECD

Mean ASF, ECD Value At Calibration Point x_o Provided

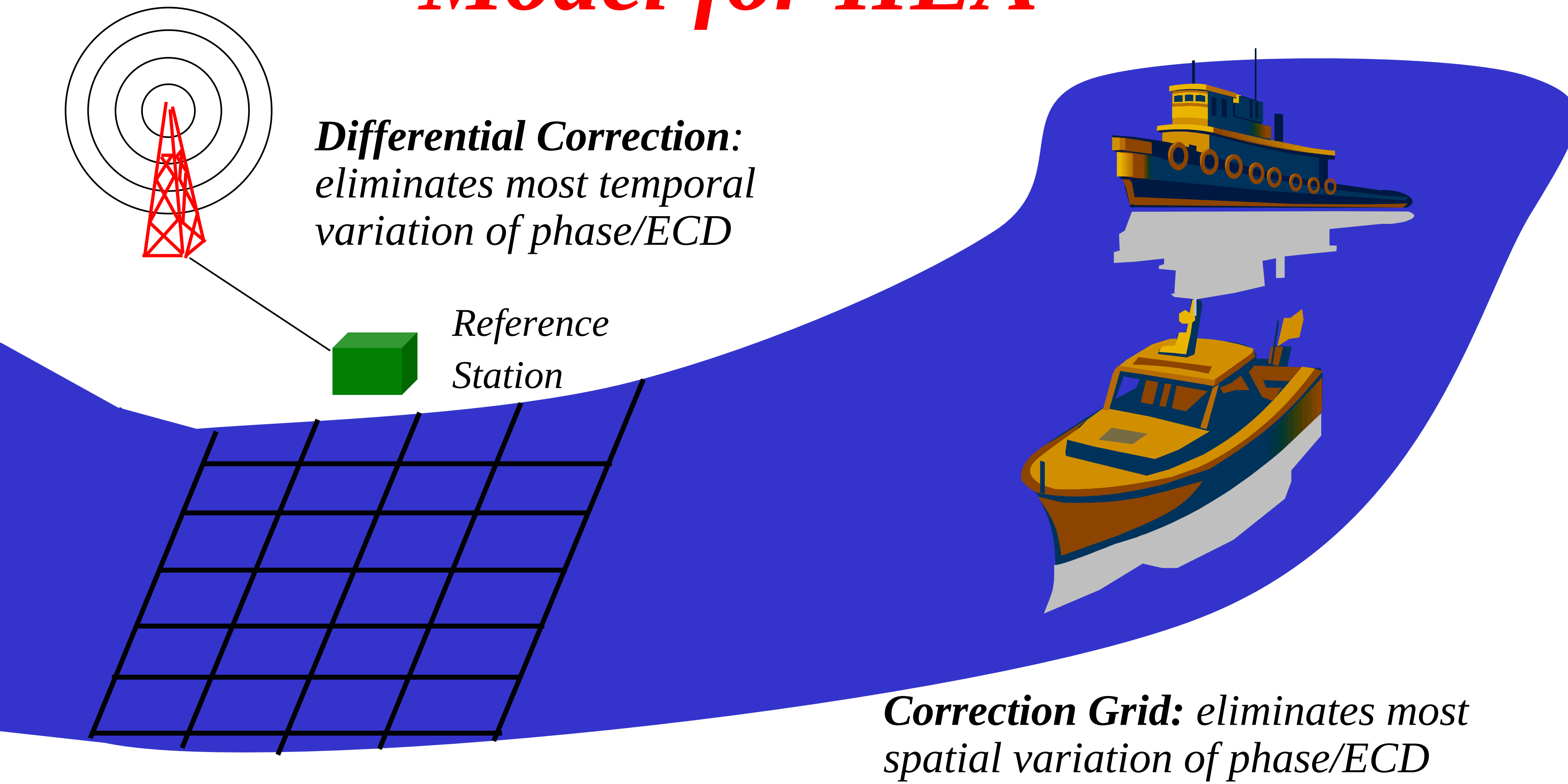
$$ASF = ASF_{nom} + ASF_{temp} + ASF_{spatial} + ASF_{spatial,altitude}$$

$$ECD = ECD_{nom} + ECD_{temp} + ECD_{spatial} + ECD_{spatial,altitude}$$

User rx value	Nominal value at cal pt	Difference from cal pt due seasonal changes	Difference from using a different location	Difference from using a different altitude

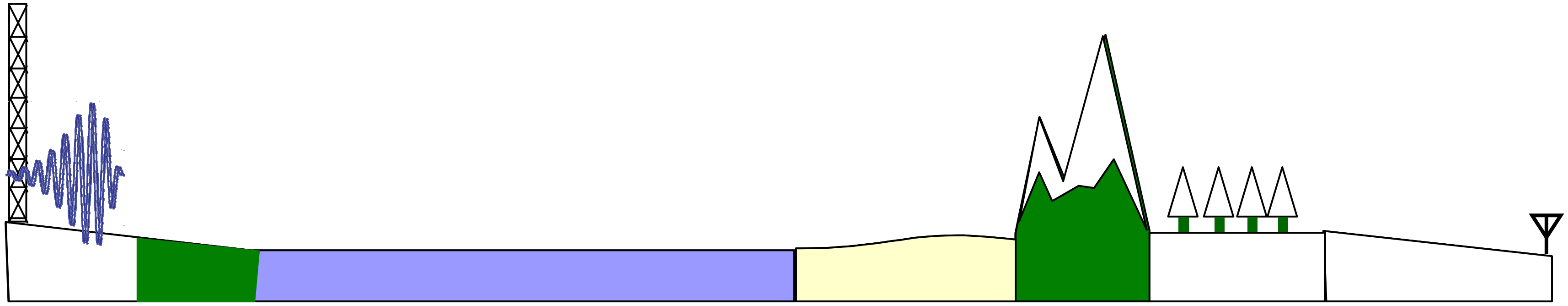
- *Look up table is to be provided to user (at each calibration pt)*
- *Variations from calibration due to spatial & temporal factors*

Model for HEA



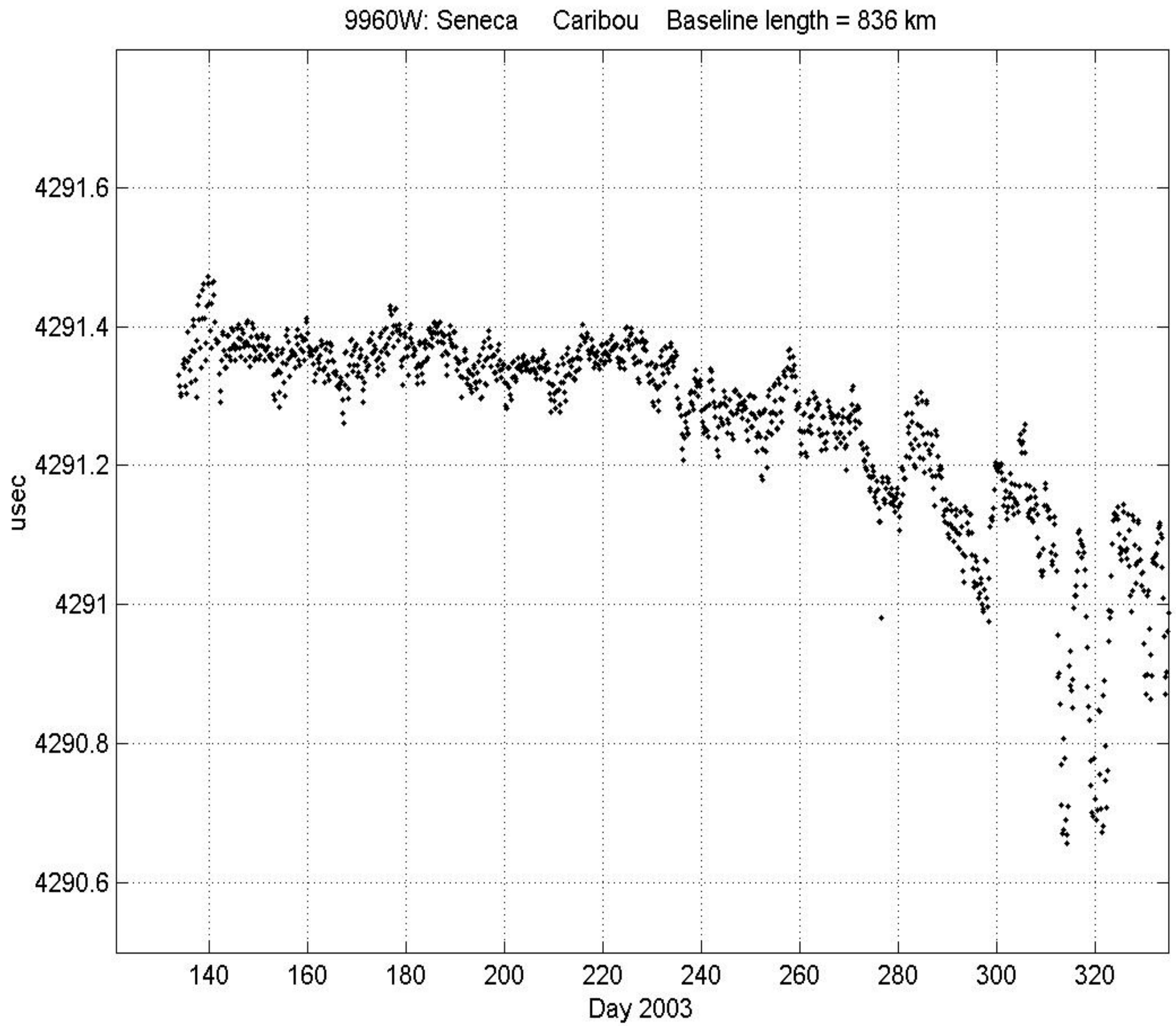
- ***Only small residual phase/ECD uncertainty left***
- ***Currently examining grid density required to achieve HEA accuracy***

Temporal Variations

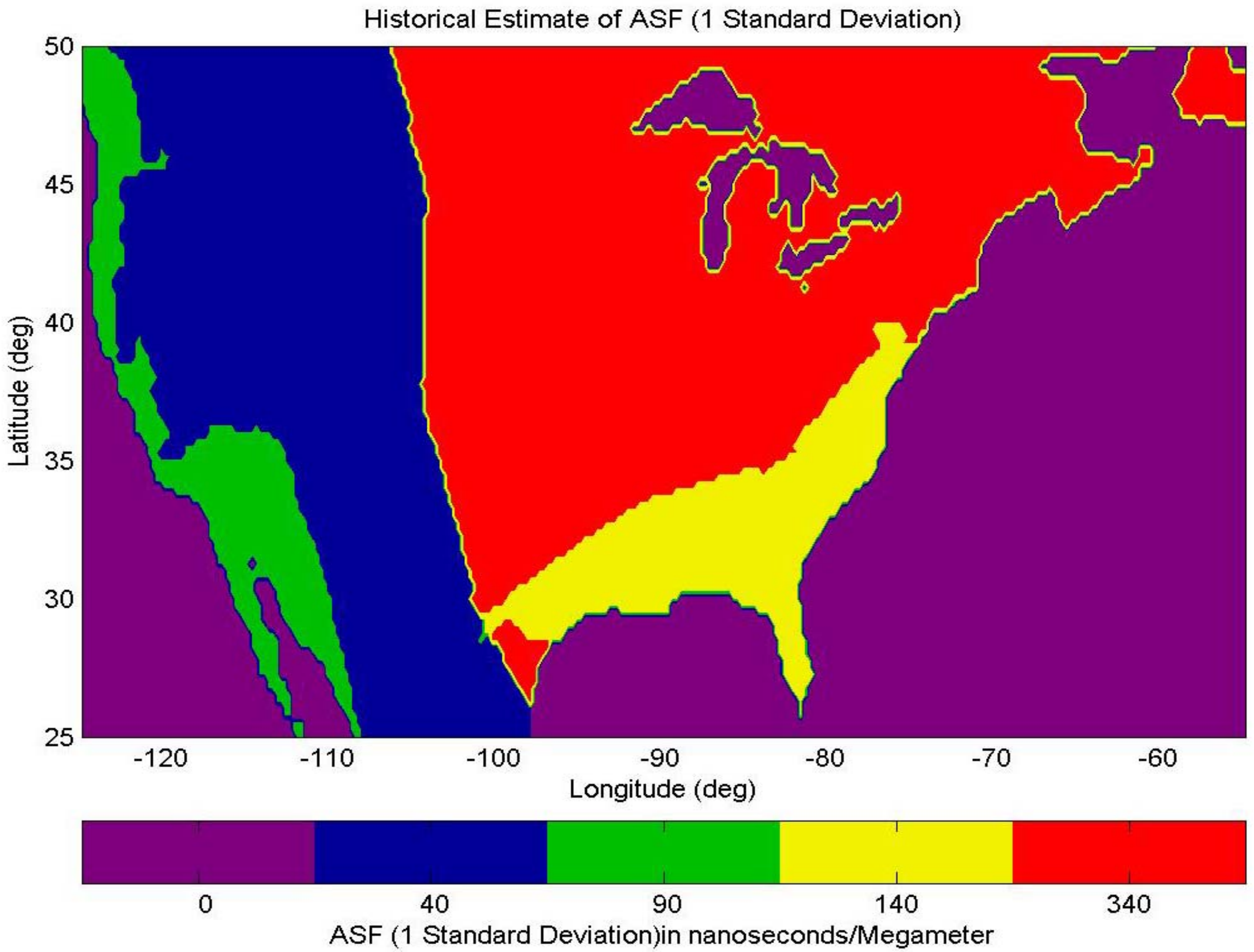


- ***As weather changes, properties such as terrain conductivity, permittivity, moisture level changes***
- ***Results in different propagation speeds and variations in the delay on the pulse***
- ***Hence, the phase delay (ASF) and ECD varies in time***

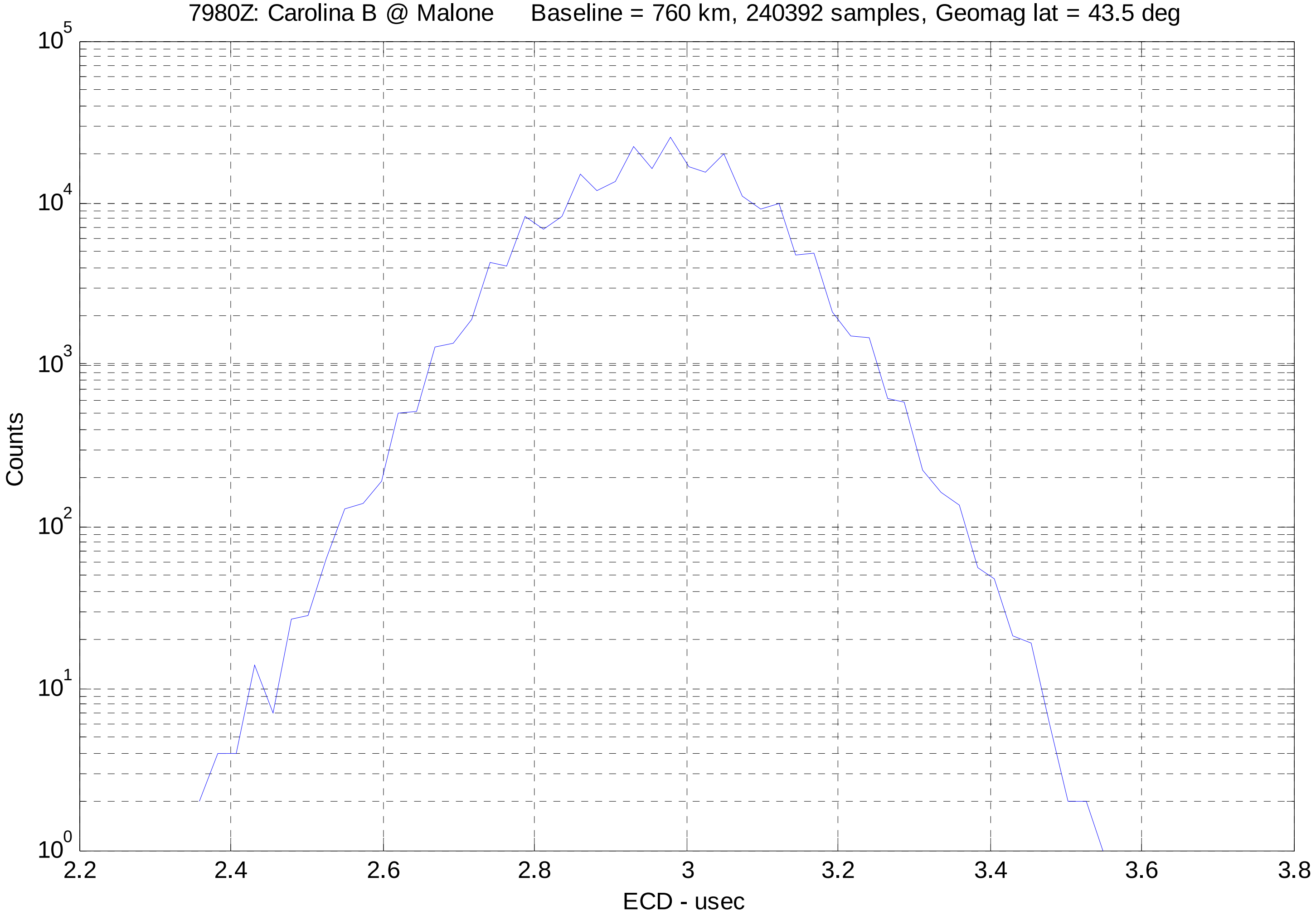
Example of Northeast US temporal variation in phase



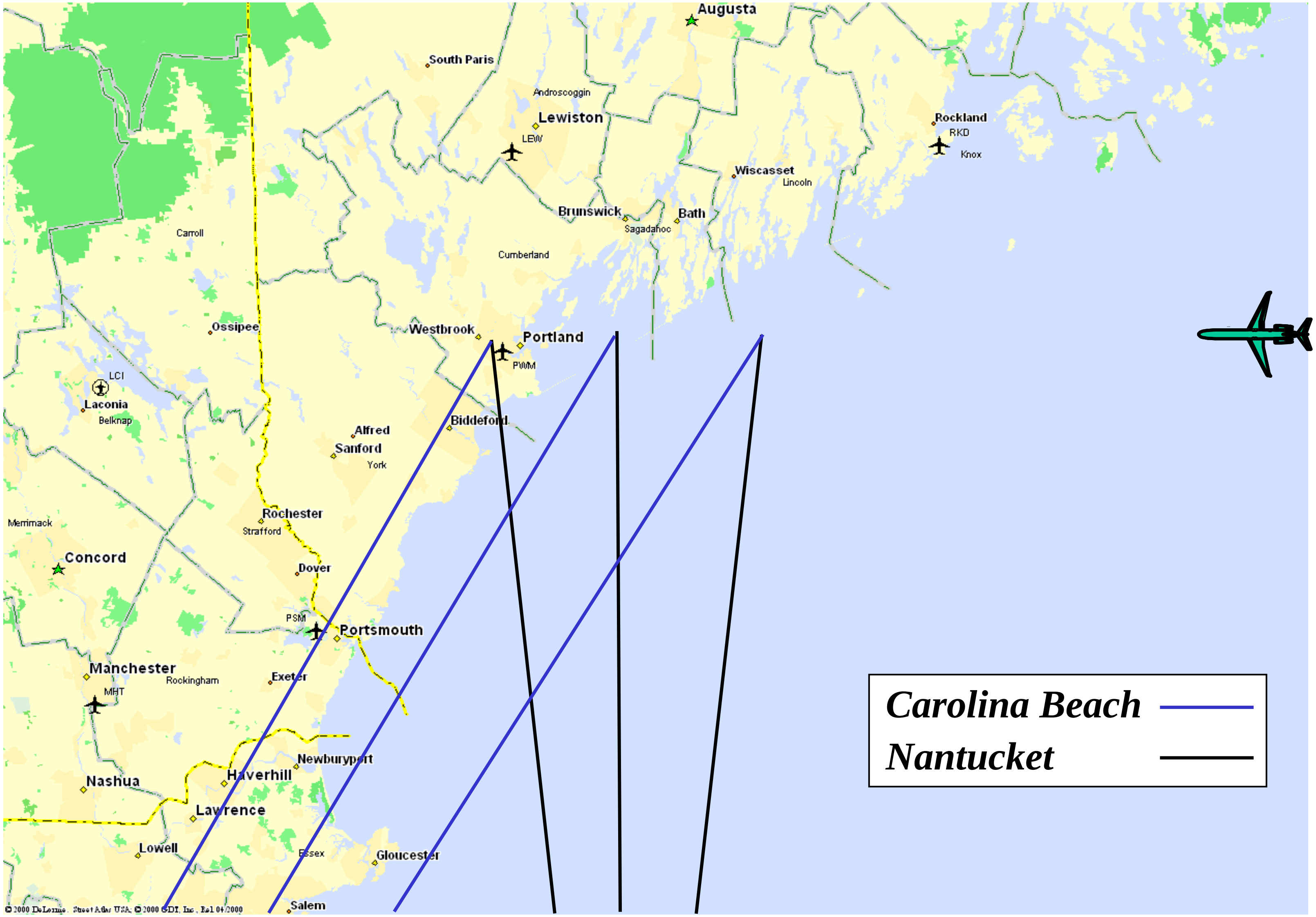
Historical ASF



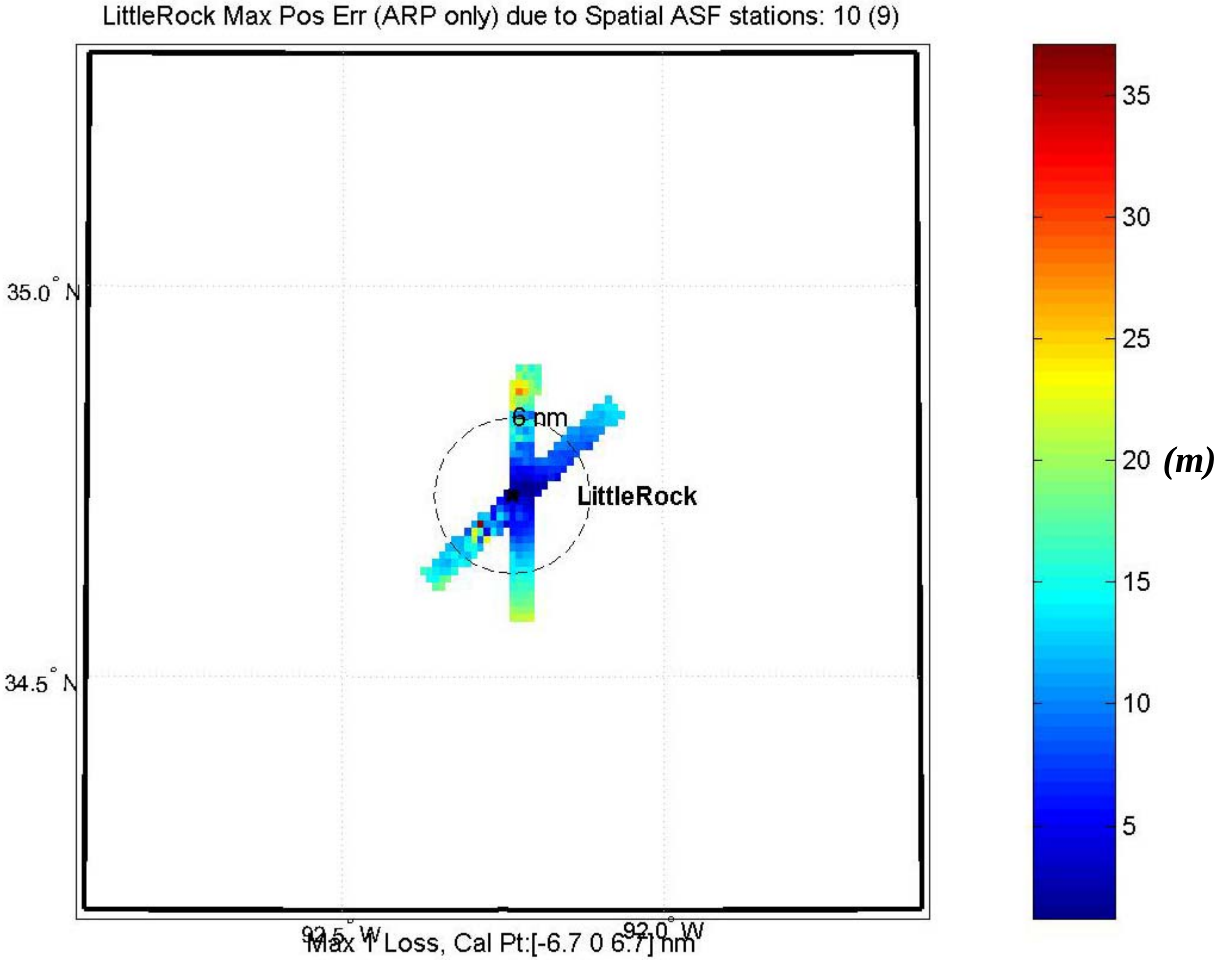
Example of Southeast US variation in ECD



Spatial Path Variations

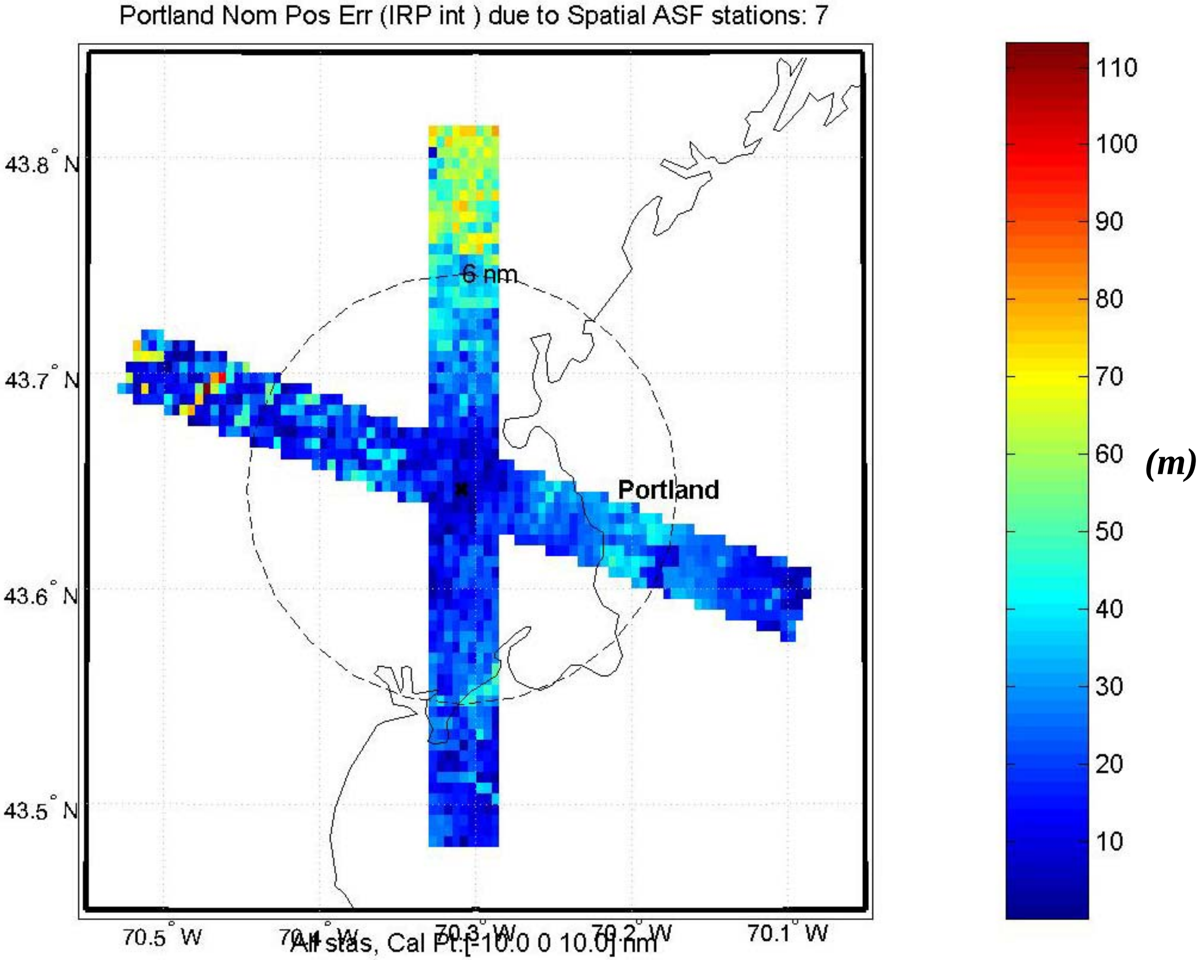


Spatial ASF PD Bounds: Little Rock, AR (Max with 1 Loss)



- ***Little Rock, AR***
- ***9 out of 10 Stations (worst case 1 loss)***
- ***Typical inland (non Rockies) case – Non coastal, no significant terrain***
- ***Max PD Bound: ~37 m***

Spatial ASF PD Bounds: Portland, ME (Nominal – 7 Stations)



- *Portland, ME*
- *7 Stations (Nom.)*
- *Extreme case - junction of sea and land; mountainous terrain*
- *Paths change from mostly land to mostly sea water for Carolina Beach*
- *Max PD Bound: ~110 m*

Summary

- *Propagation effects are responsible for the largest uncertainties in Loran measurements*
- *Interference is also significant*
  - ✈ *Early skywave can cause significant distortion of signal*
  - ✈ *Fortunately rare in non-Alaskan US*
- *Providing integrity requires that adequate bounds on uncertainties are derived*
  - ✈ *Integrity requires that worst case be examined*
- *LORIPP and LORAPP assessments suggests that enhanced Loran can, with proper design, meet the requirements of aviation, maritime, & timing and frequency*

Acknowledgements, etc.

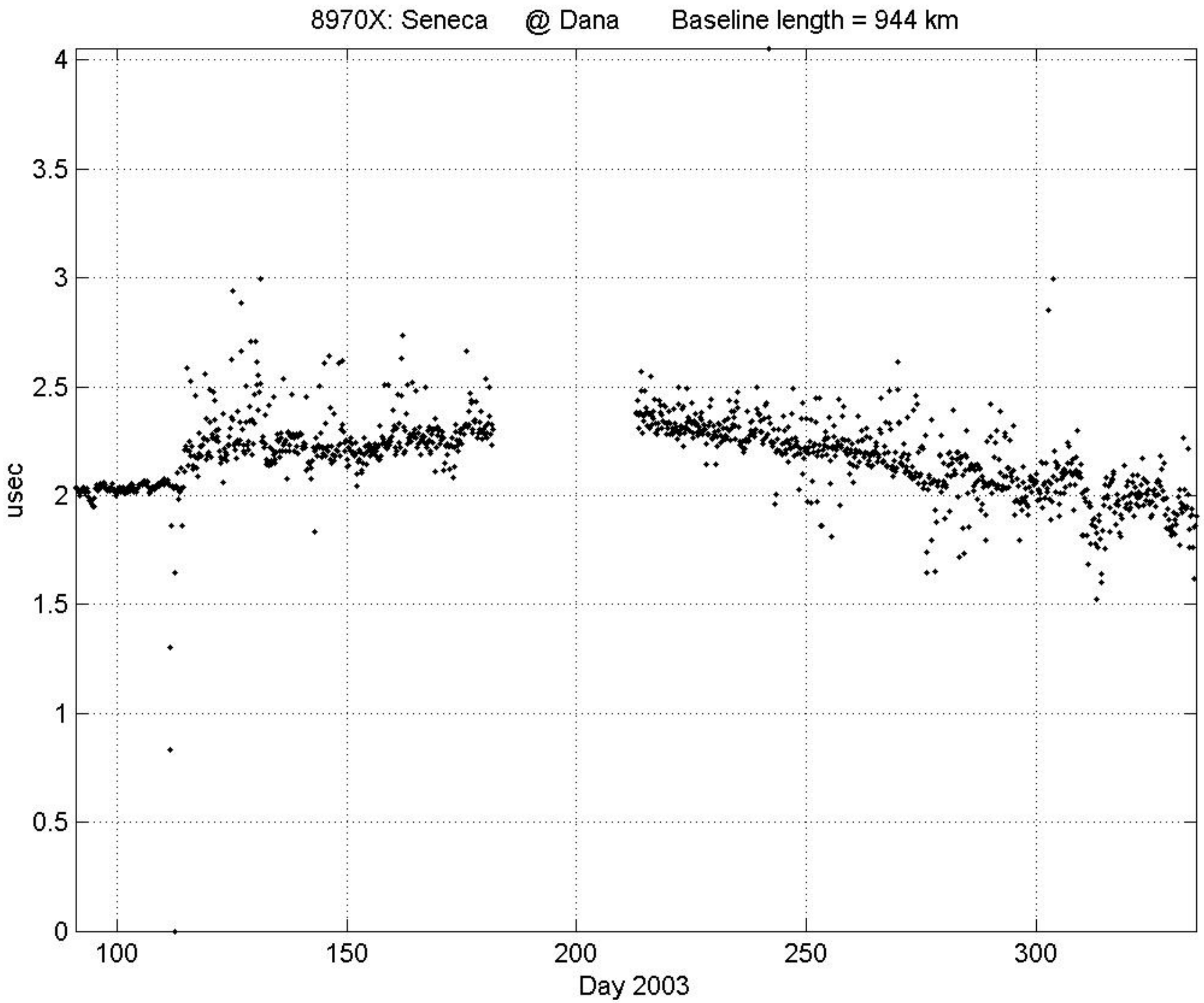
- *Funded by Federal Aviation Administration*
  - ✈ *Mitch Narins – Program Manager*

- *For additional info:*
  - ✈ *Contacts*

    - *sherman.lo@stanford.edu*

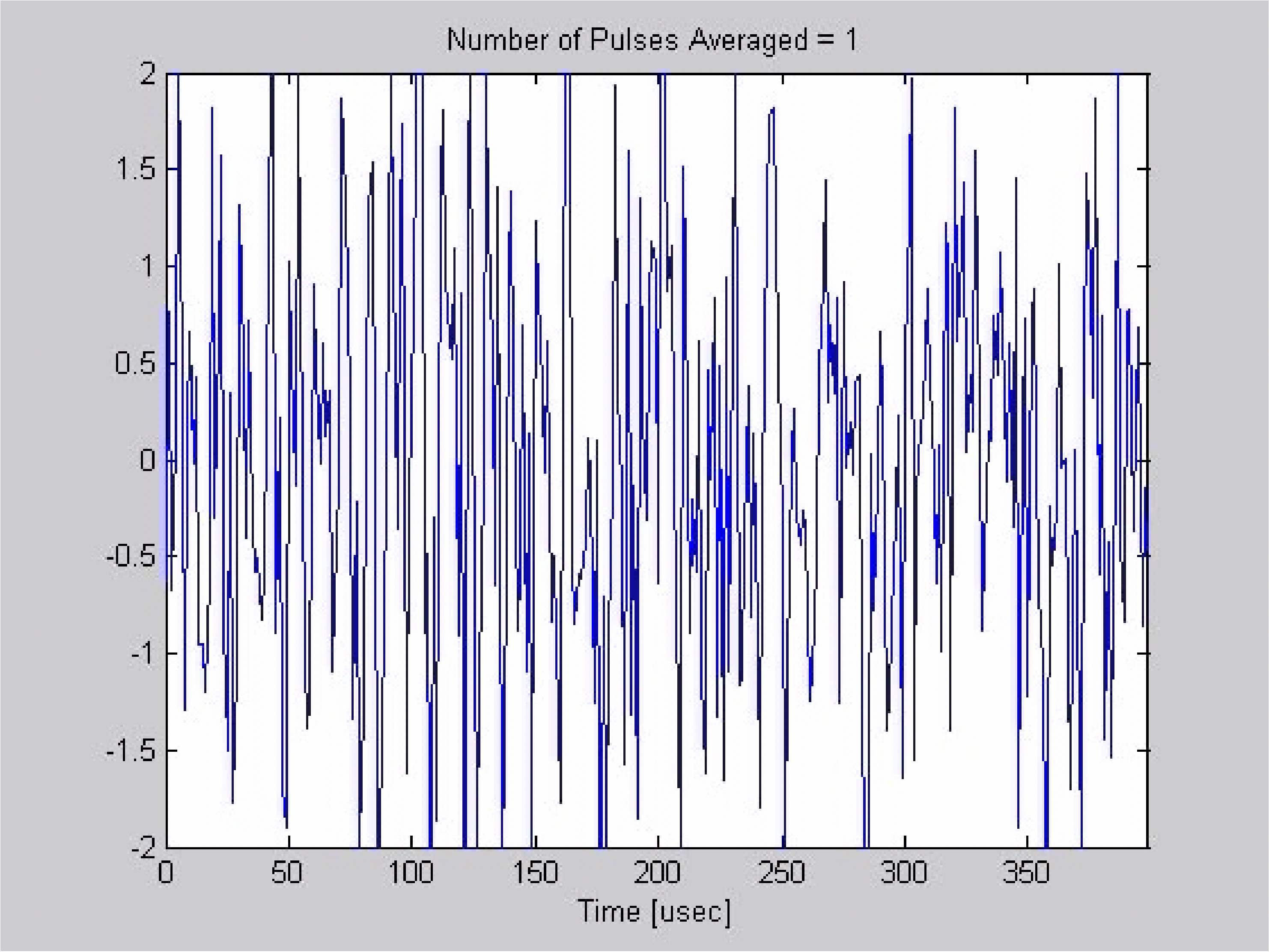
- *-Note- The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, Department of Transportation or Department of Homeland Security.*

Example of seasonal variation in ECD in Northeast US

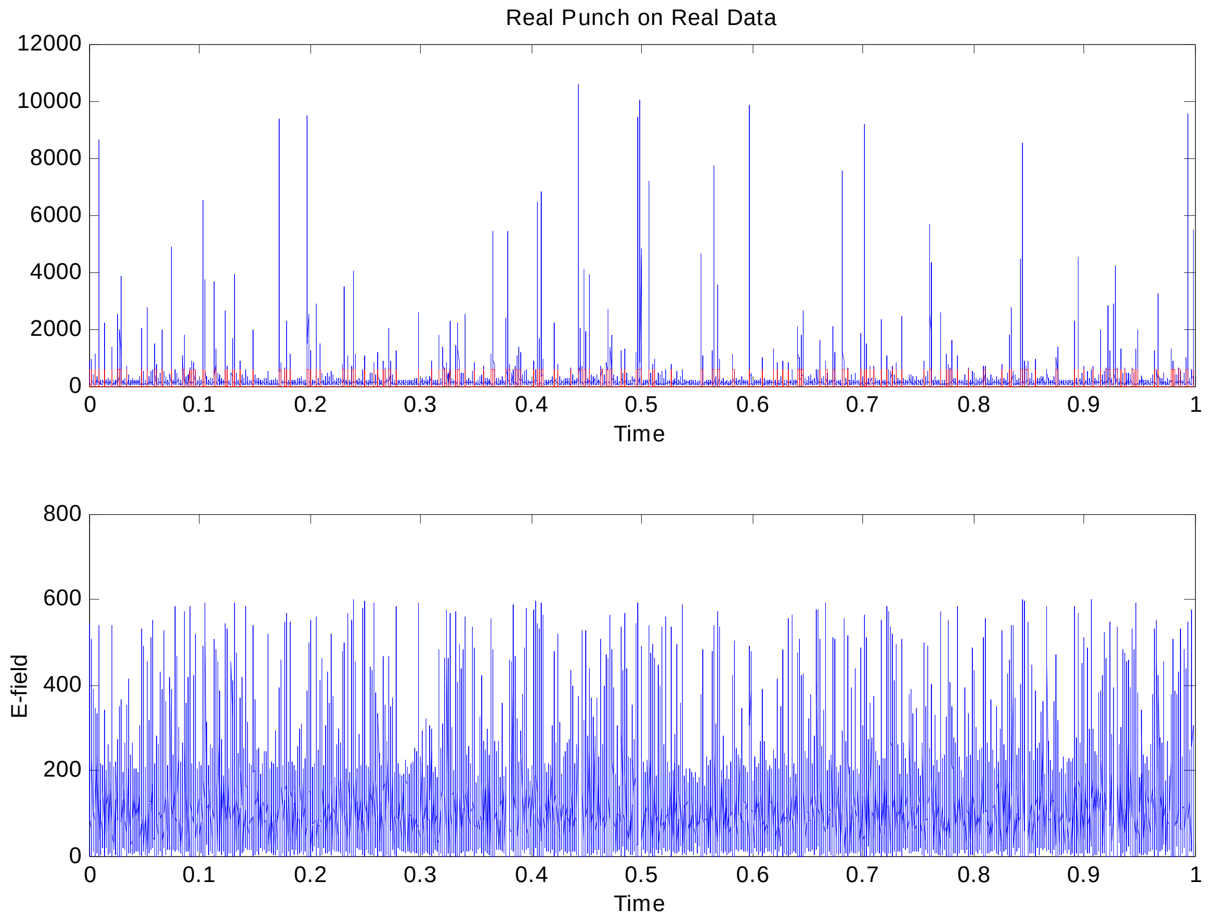


Processing Gain for Atmospheric Noise

Averaging a Pulse



Threshold Time Domain

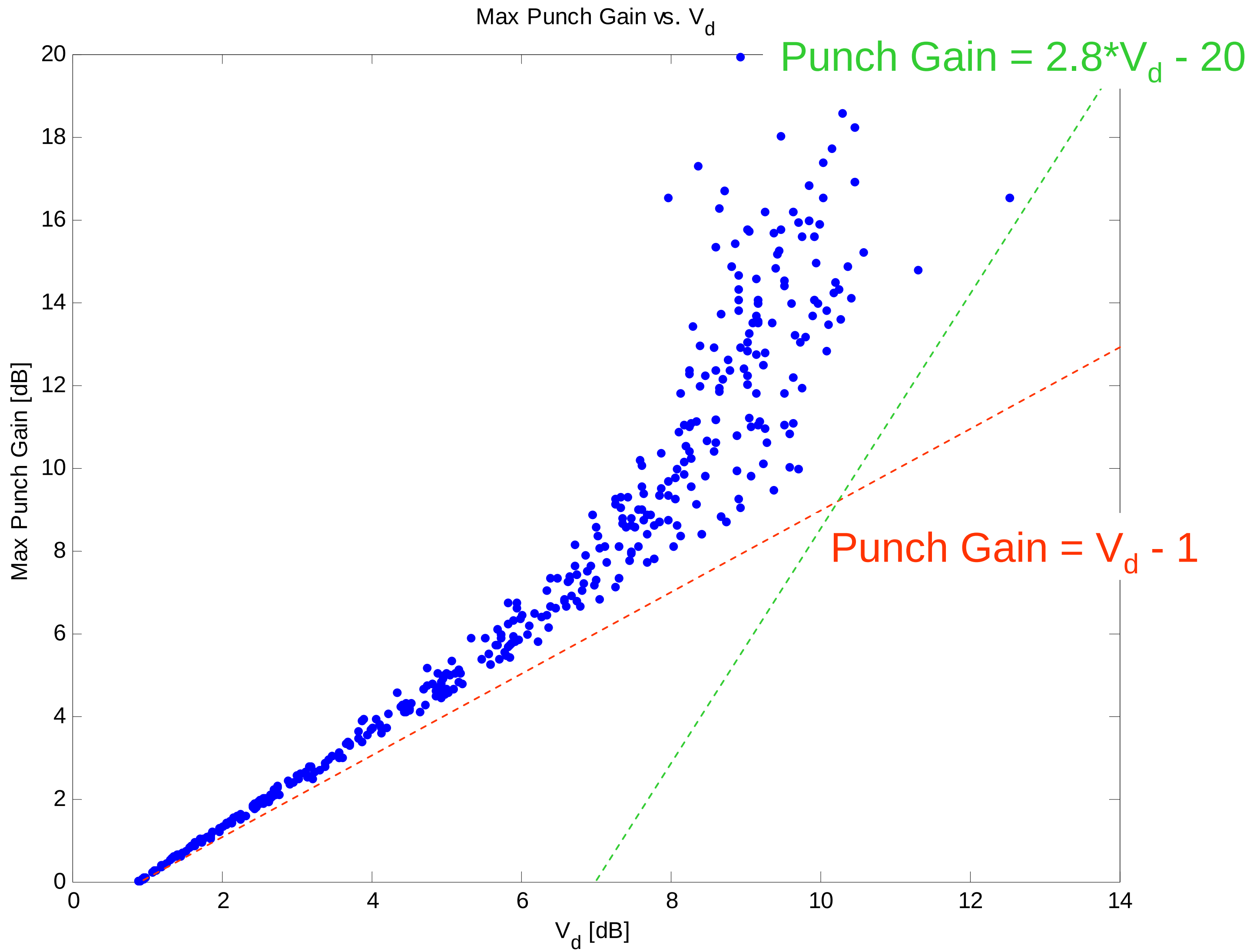


Without Punching

With Punching

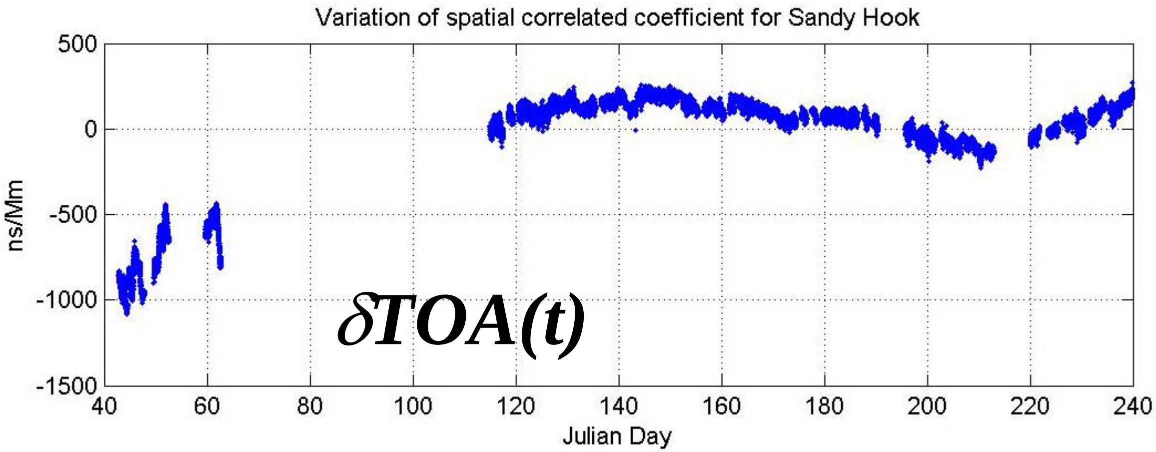
- ***Eliminate (Punch out) time blocks where noise is above a threshold***
  - ***Essentially, eliminate x% of signal and y% of noise energy (y > x)***
  - ***More effective for more impulsive noise***
- ***Threshold can be dynamic – based on expected SNR***

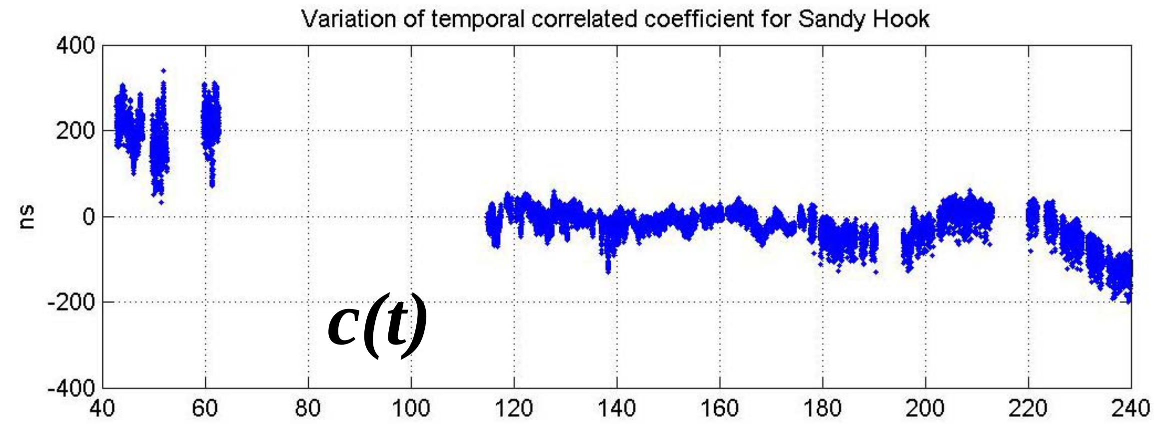
Atmospheric Noise: Gain from Hole Punching



Temporal Variation Model

$$ASF_N(t) = ASF_{N,mean} + \delta TOA(t) * d_{N,land} + c(t) + \varepsilon_N(t)$$





- ***δTOA(t)***

  Changes in s should be very similar for all land near rx

- ***c(t)***

  Common term

- ***$\varepsilon_N(t)$***

  Changes in s more uncorrelated further away from rx

- ***Phase variations at the "calibration" location (no spatial variation)***

Millington's Method

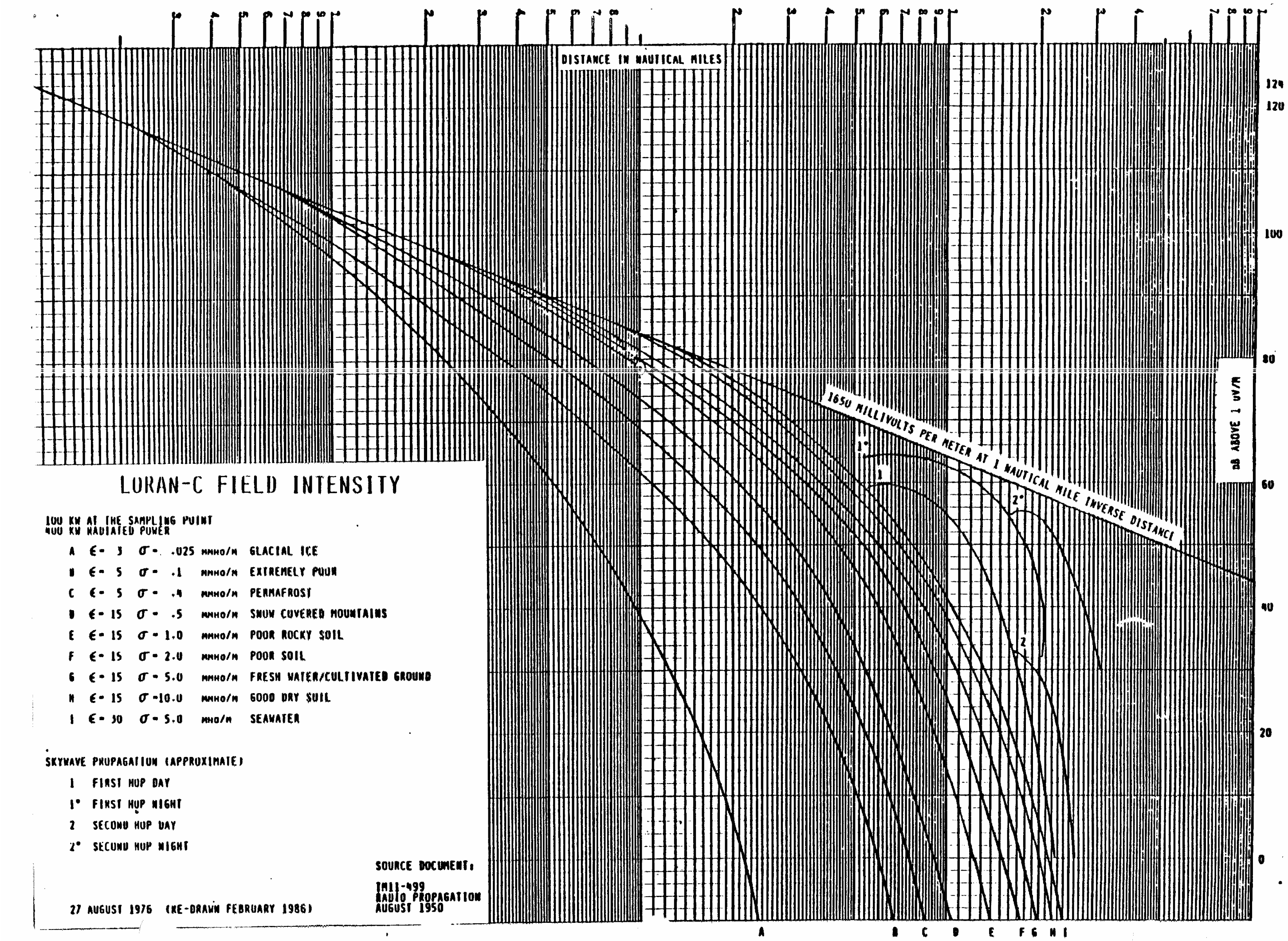
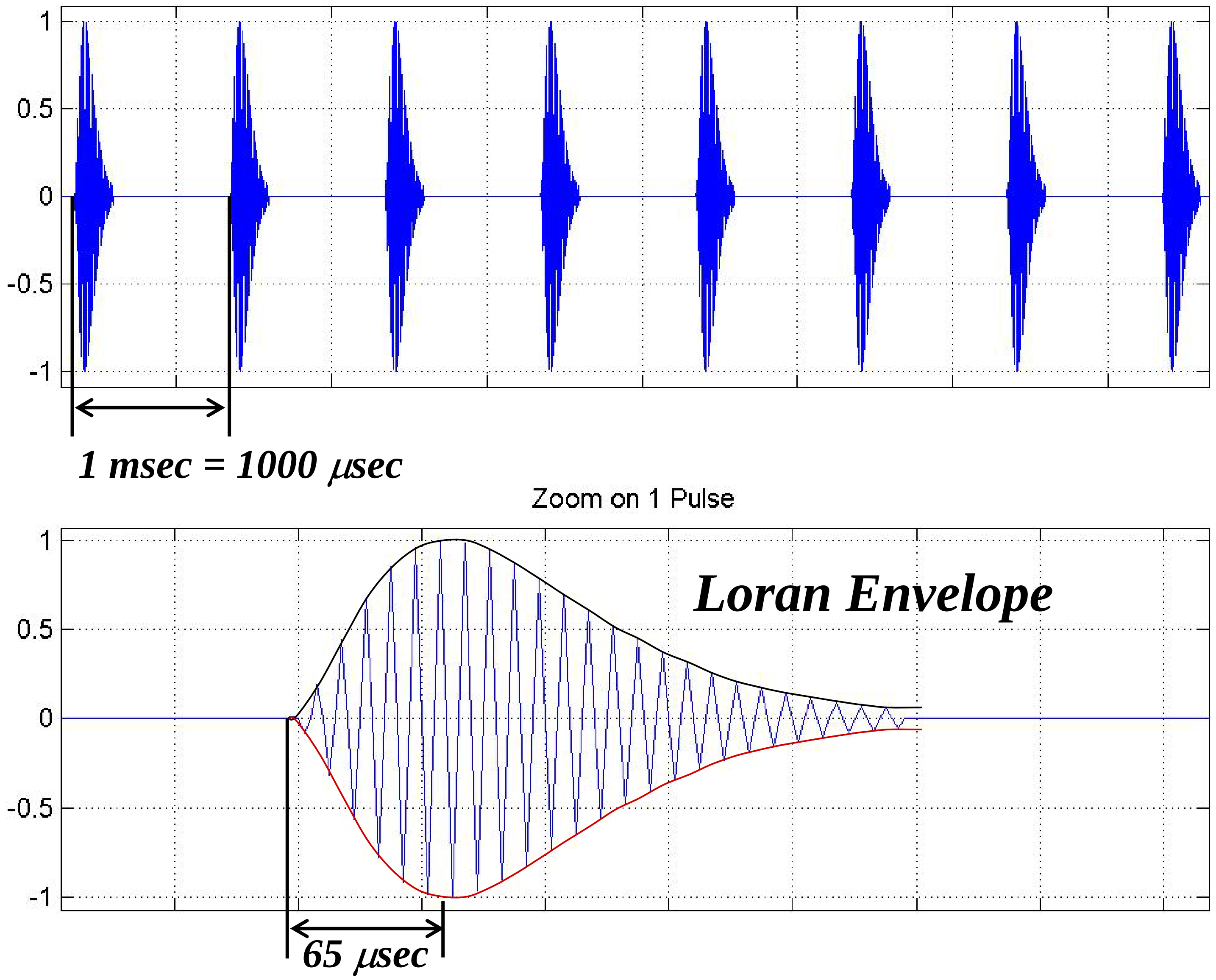


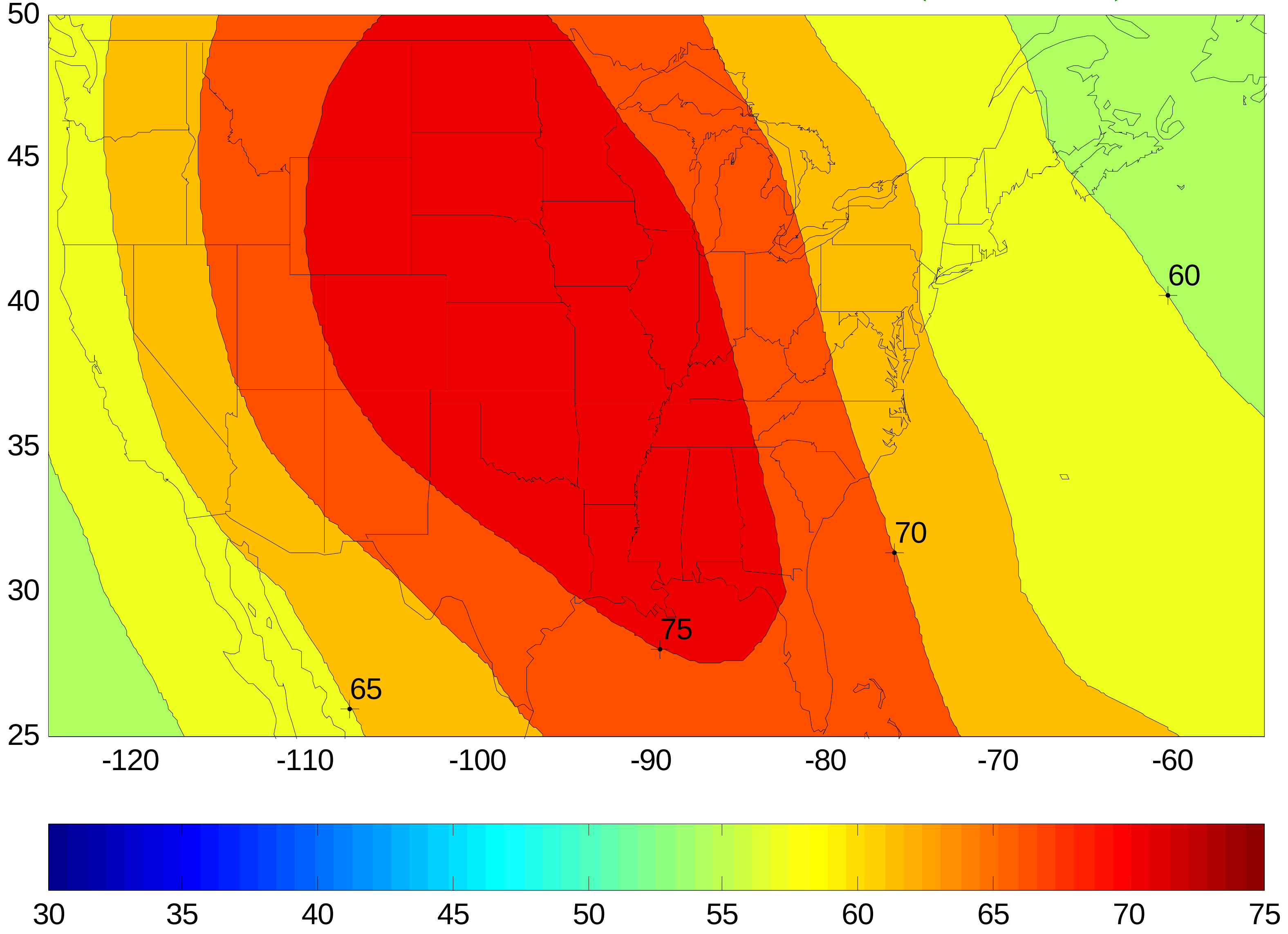
Figure 2 LORAN-C Field Strength vs. Distance

The Ideal Loran Signal

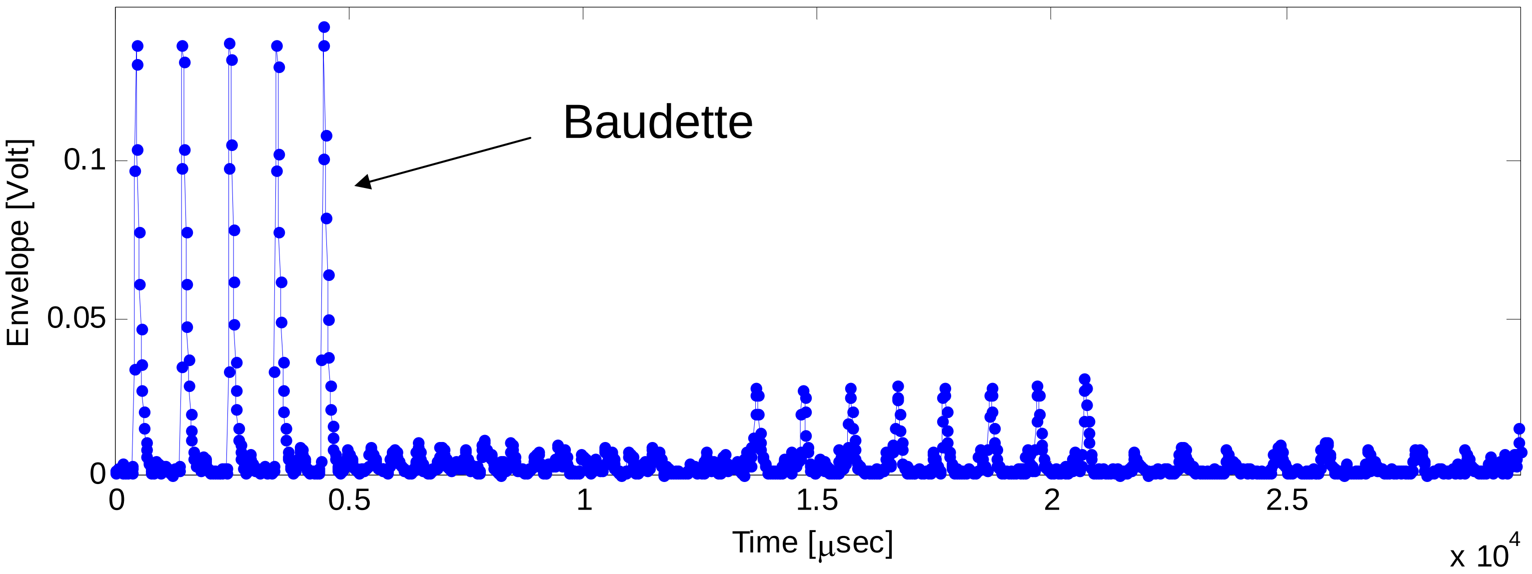


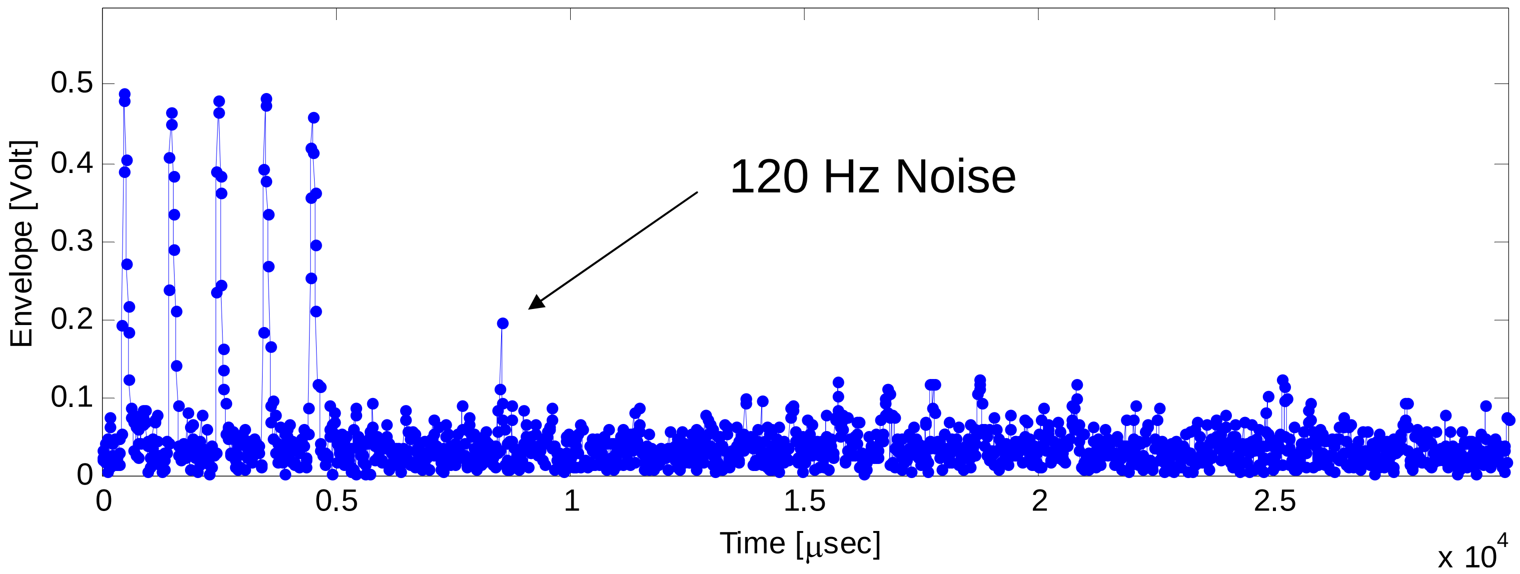
Atmospheric Noise

95% CONUS Noise Map During Worst Period at Each Location (CCIR)

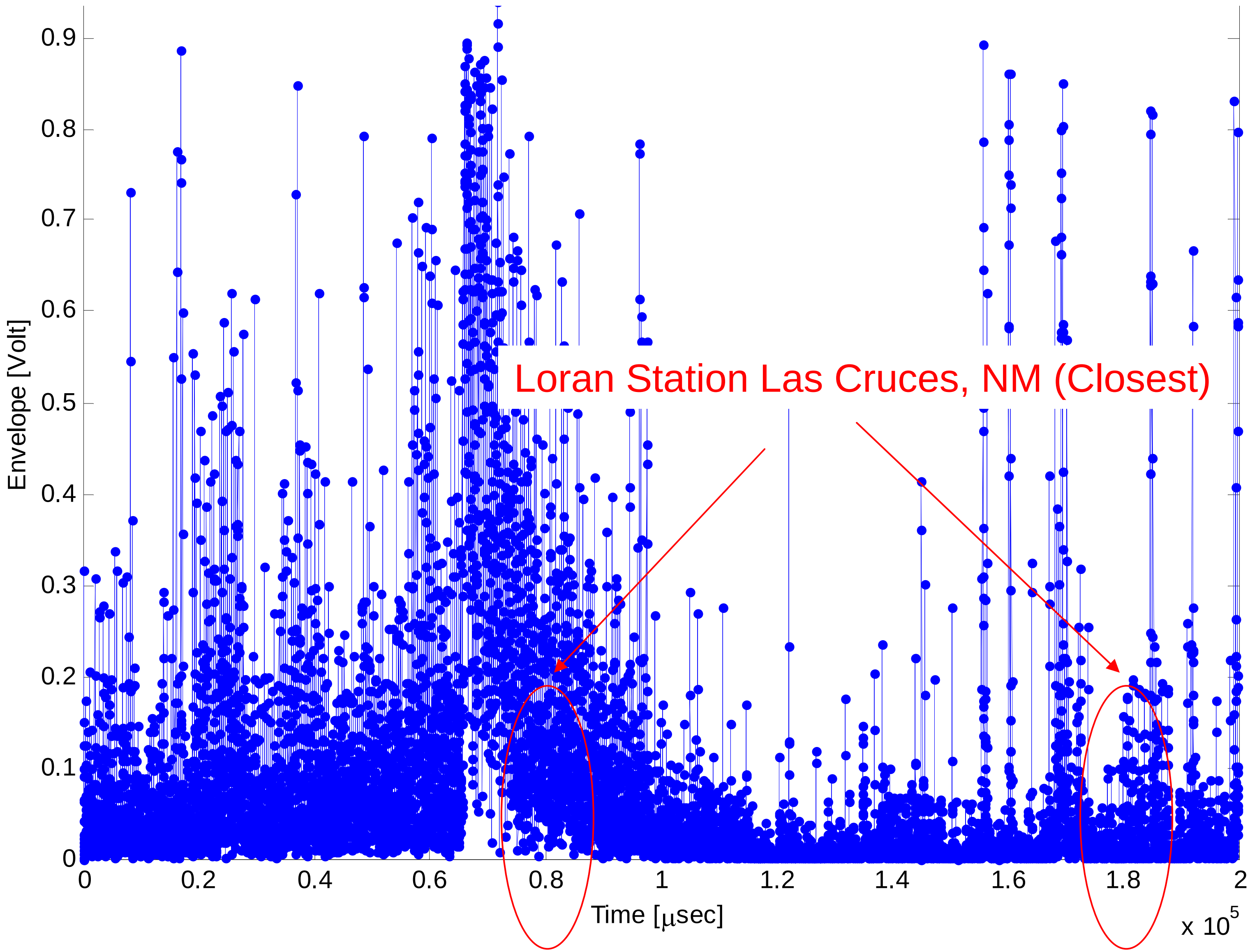


Loran Envelopes with Noise

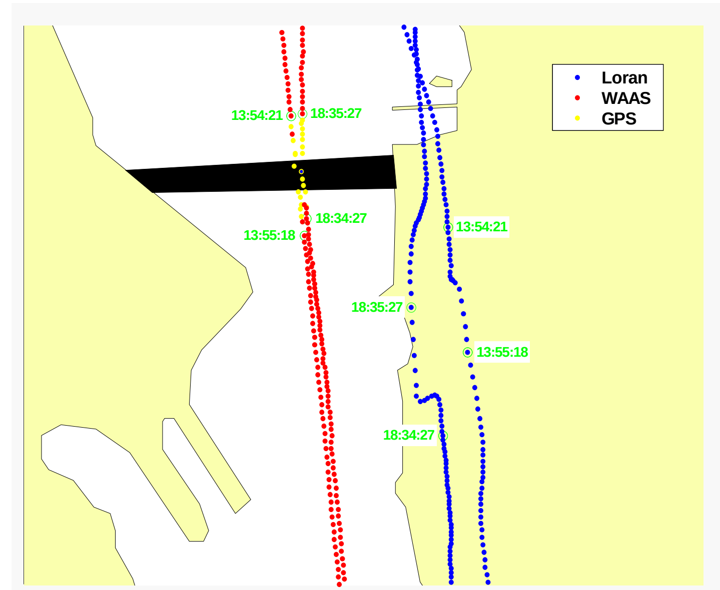


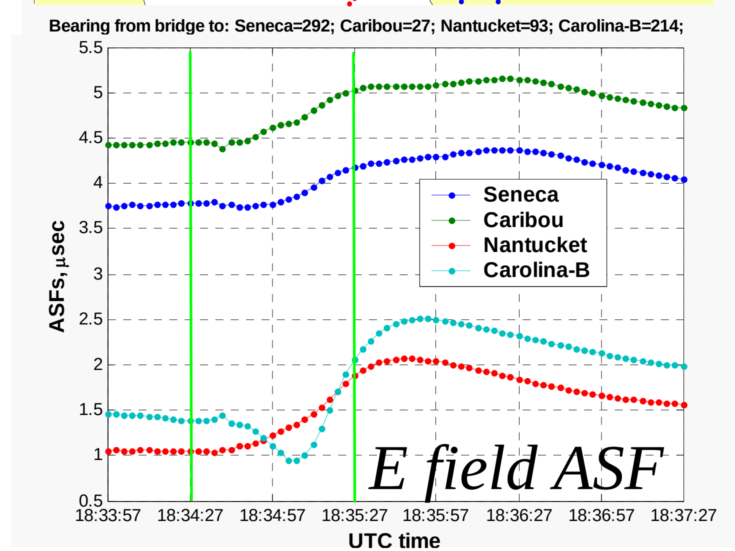


High Noise Measurements



Reradiation Effects





- ***A severe (negative) effect of bridges with E-field antennas – within a good distance to either side***
- ***Data collected shows that the H-field antenna experiences some effect, but only when in the immediate vicinity of the bridge.***