Analysis and Modeling of Skywave Behavior

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Technical Symposium of the International Loran Association
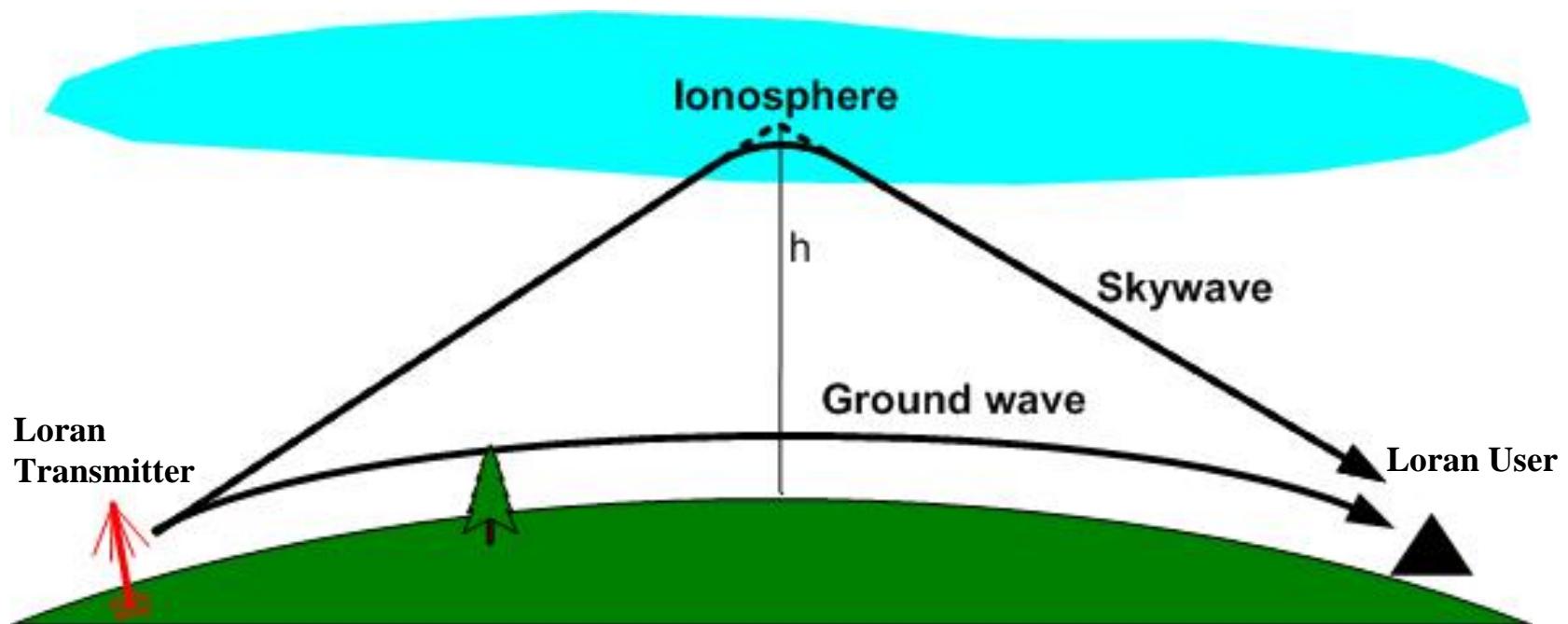October 13-15, 2009
Portland, ME

Outline

- ## Skywave and Early Skywave
  - Utility of characterizing skywave for detection
- ## Modeling Skywave (delay, strength)
  - Effects of Filtering
  - Modeling & Results
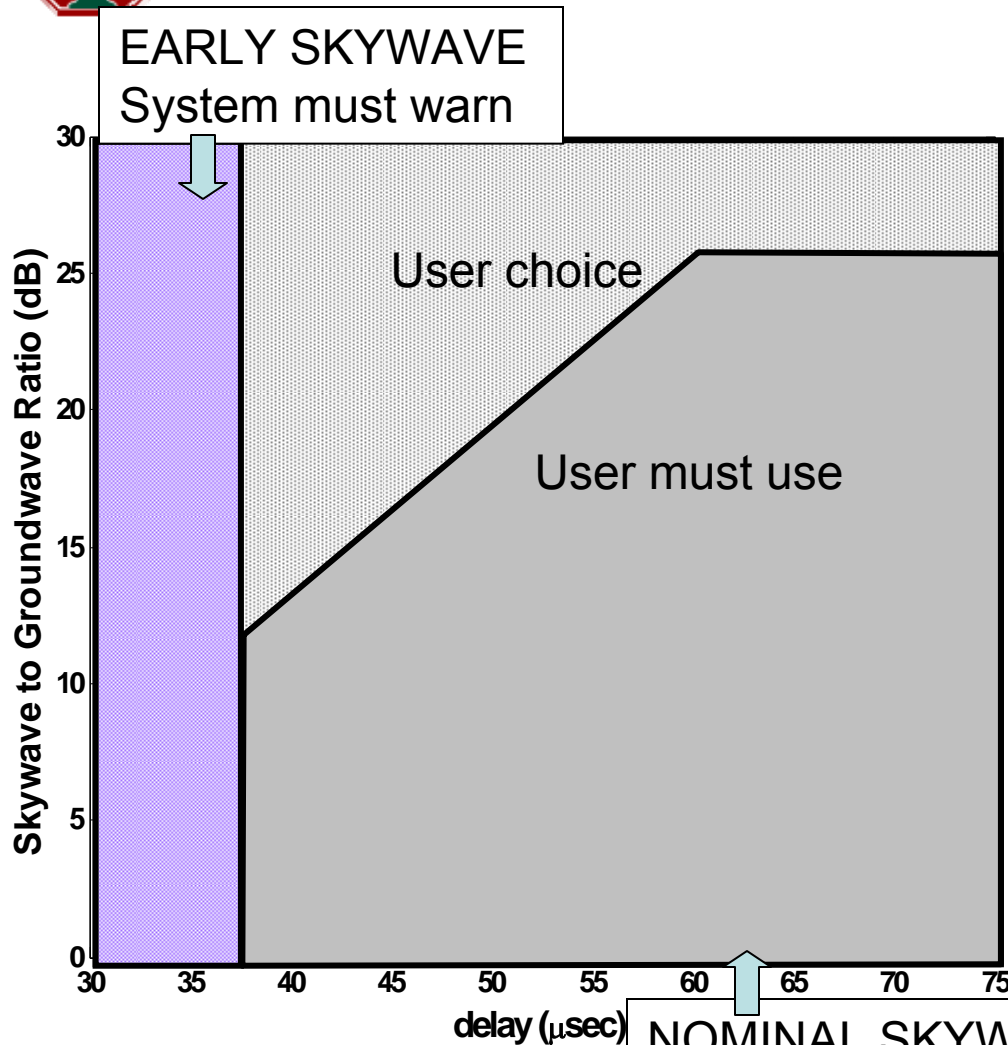 - Phase reversal & skywave ECD

Skywave

Single hop skywave is shown

Early Skywave

EARLY SKYWAVE
System must warn

Skywave to Groundwave Ratio (dB)

User choice

User must use

30 35 40 45 50 55 60 65 70 75

delay (μsec)

NOMINAL SKYWAVE
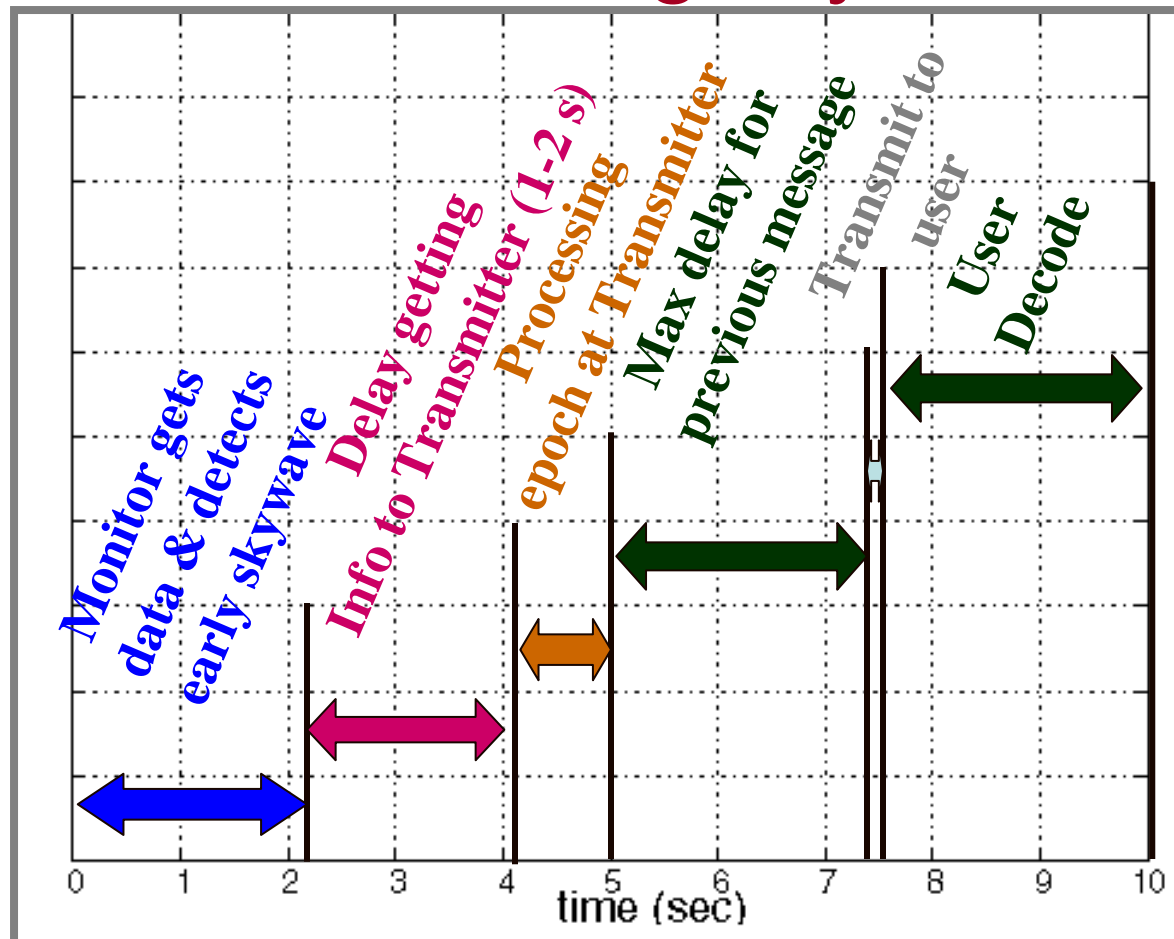User responsible for mitigating

- Early skywave has smaller delay than typical
  - More adverse effect on receiver
  - Harder to detect
- Aviation & maritime specifications have used 35 & 37.5 μs as demarcation line
- System should provide warning
  - Network based solution reduces missed detection
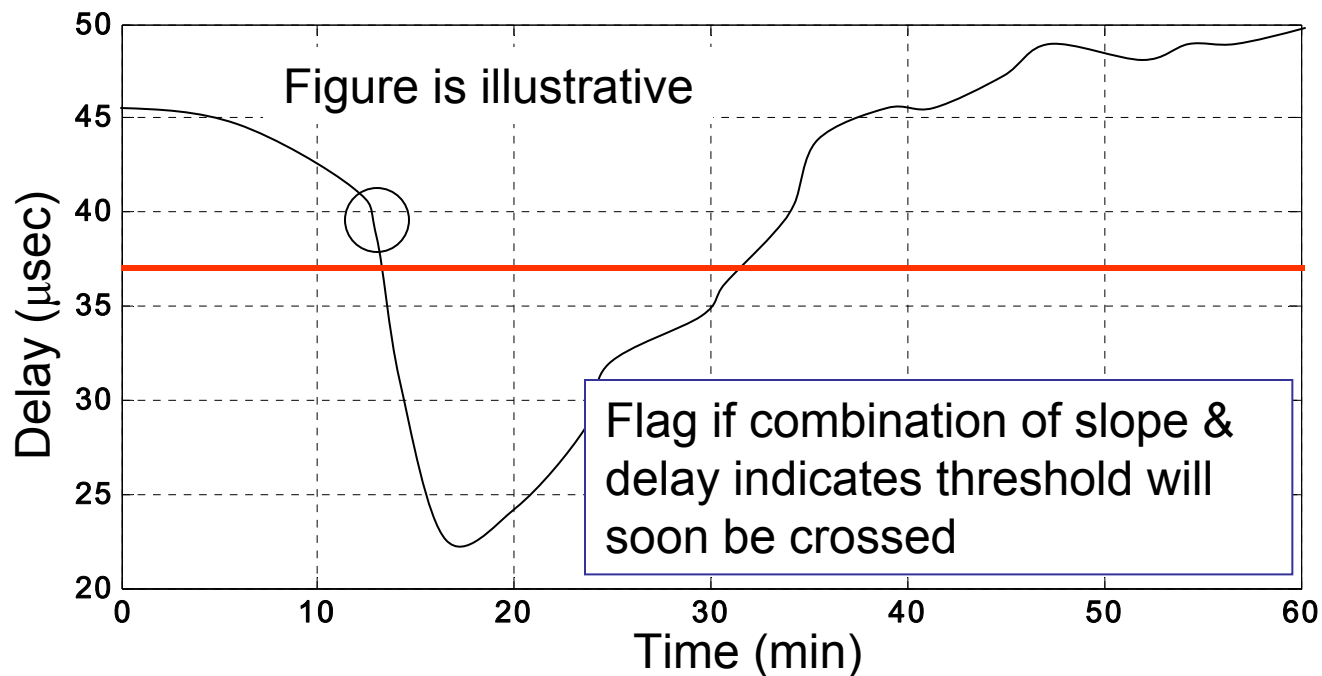 - Skywave modeling to aid TTA

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Time To Alert & Need for understanding skywave

- Meeting 10 sec TTA means detection within a few seconds
- Even a 60 sec TTA means detection in ~ 50 seconds

Example of Use for Detection

The figure shows a plot of Delay (μsec) vs Time (min). The y-axis "Delay (μsec)" ranges from 20 to 50, and the x-axis "Time (min)" ranges from 0 to 60. Text on the figure reads "Figure is illustrative". A horizontal orange threshold line is drawn near 37 μsec. A boxed annotation reads: "Flag if combination of slope & delay indicates threshold will soon be crossed".

- Detection enabled by accurately estimating delay
  - Can use delay estimate to determine progression of skywave event
  - Example: Use delay and delay rate to "predict" onset of early skywave
- Need to understand skywave well for estimation

Estimating Skywave

- Determine the skywave properties
  - Delay, Skywave/Groundwave Ratio (SGR)
  - Rates of change
- Two sources of data from GRI 9940
  - US Coast Guard SAM data ("out")
  - Enhanced Loran Receiver (ELR)
- First need model for skywave
  - Also filter effects

Basic Skywave Model

$$g(t) = A_g \left(t - \tau_g\right)^2 e^{\left(\frac{-2\left(t - \tau_g\right)}{65\,\mu\sec}\right)} \sin\left(\frac{2\pi t}{10\,\mu\sec}\right)$$

$$g(t) = B_g(t) \sin\left(\frac{2\pi t}{10\,\mu\sec}\right)$$

$$s(t) = sign_s A_s \left(t - \tau_s - d\right)^2 e^{\left(\frac{-2\left(t - \tau_s - d\right)}{65\,\mu\sec}\right)} \sin\left(\frac{2\pi(t - d)}{10\,\mu\sec}\right)$$

$$s(t) = sign_s B_s(t) \sin\left(\frac{2\pi(t - d)}{10\,\mu\sec}\right)$$

$$c(t) = B_g(t) \sin\left(\frac{2\pi t}{10\,\mu\sec}\right) + sign_s B_s(t) \sin\left(\frac{2\pi(t - d)}{10\,\mu\sec}\right)$$

- Model based on standard Loran signal definition
  - Generalize envelope
- Skywave is replica of groundwave with few differences
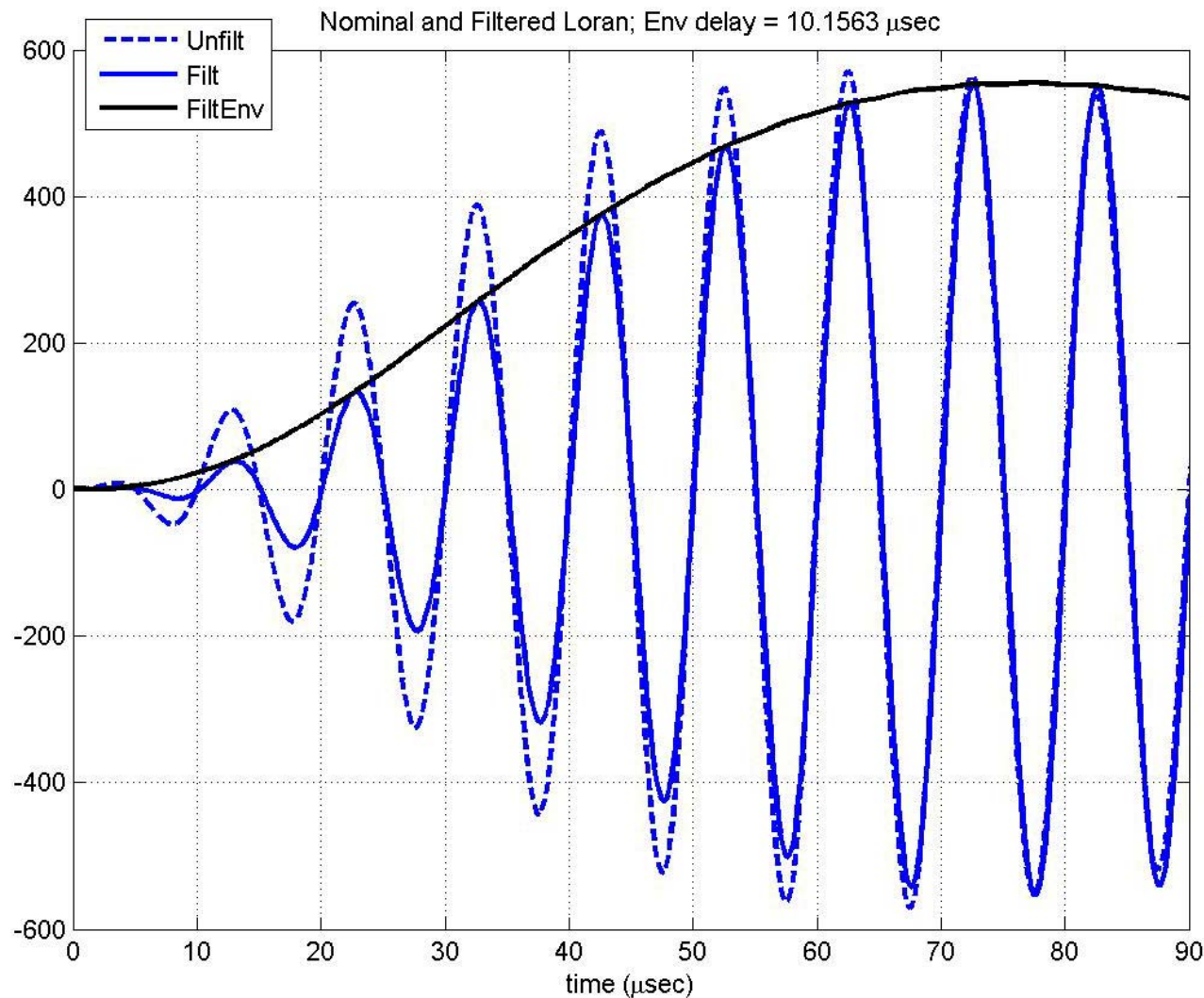 - ECD, phase code, amplitude, delay
- Form composite model

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Preliminary analysis

- Use USCG "out" data (Locus LRS IIID)
  - Provides TDOA and ECD
- Assumptions
  - Filter: 2nd order Butterworth
  - Skywave ECD can be different from groundwave
  - Skywave is phase reverse from groundwave
  - No other attempt was made to replicate LRSIIID performance
    - ECD is calculated using the ratio of the envelope at 17.5 to 22.5 μsec and extrapolated
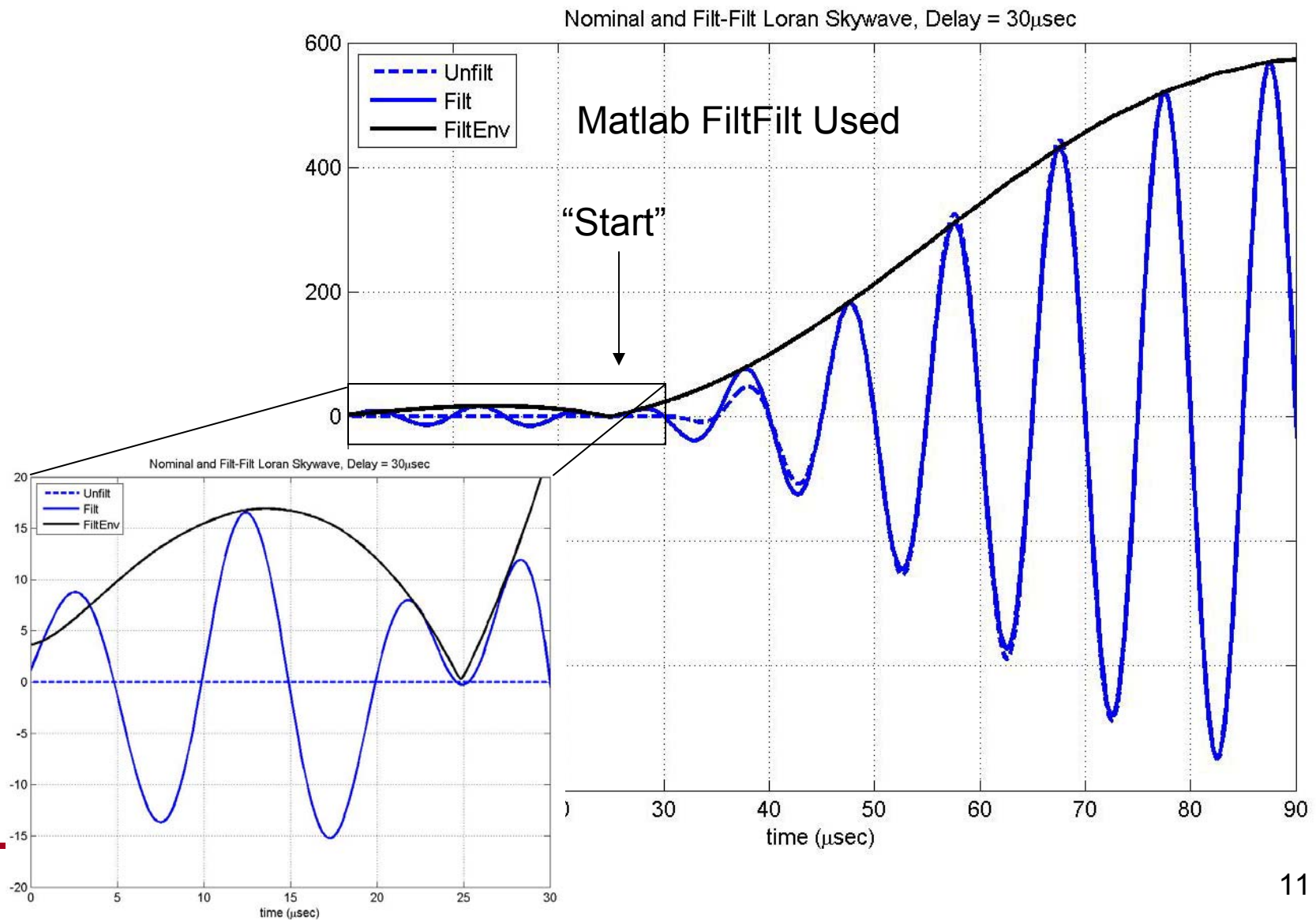- Next 4 slides show the effects of skywave given the filter assumptions

Explained: Butterworth Filter

Nominal and Filtered Loran; Env delay = 10.1563 μsec

- 2nd order Butterworth filter
- Envelope peak delayed ~ 12.5 μsec
- Carrier is visible after 5 μsec
- Skywave effect greater & earlier than without filter
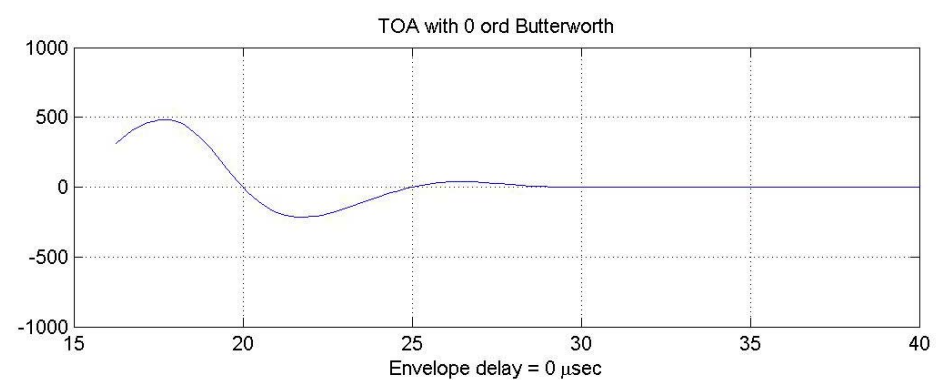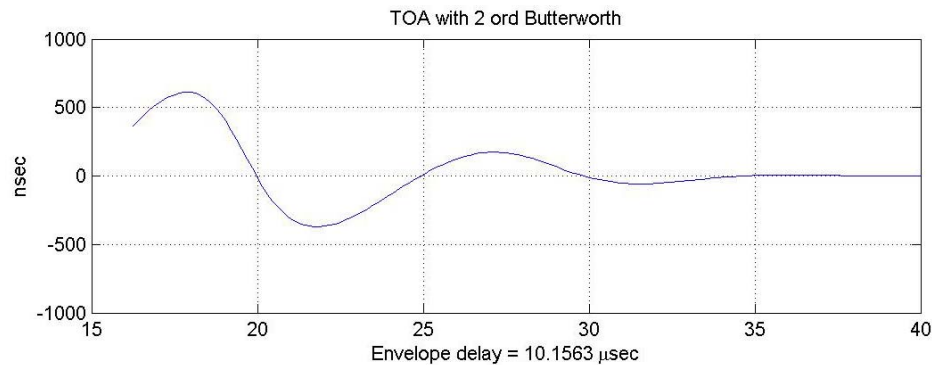 - 35 μsec delay can effect 30 μsec tracking point

Nominal and Filt-Filt Loran Skywave, Delay = 30μsec

Matlab FiltFilt Used
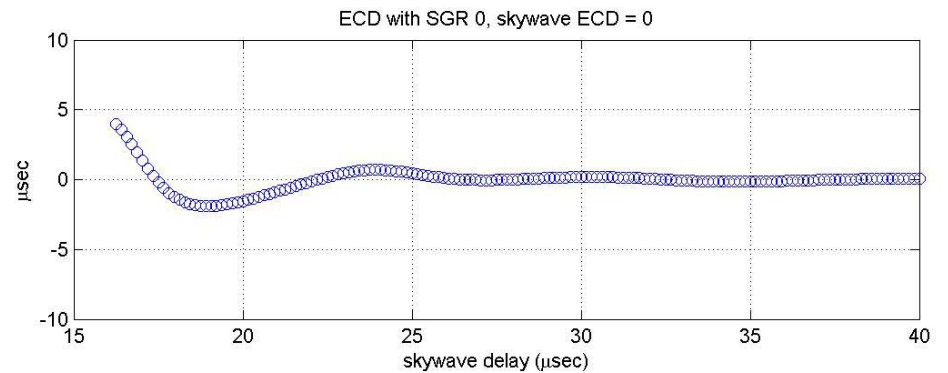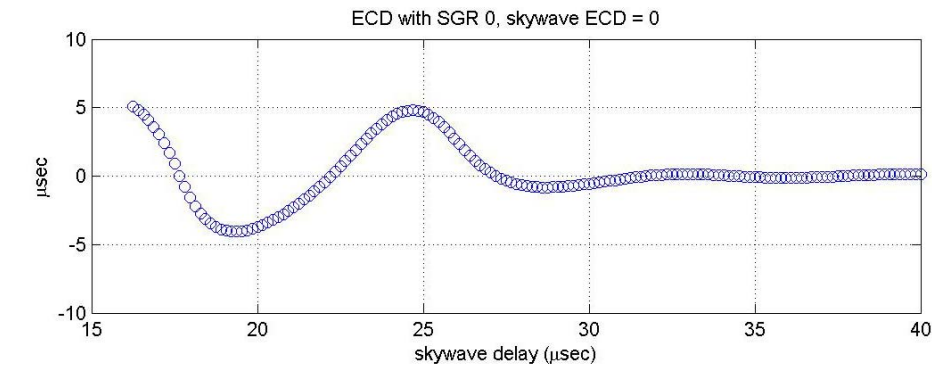
"Start"

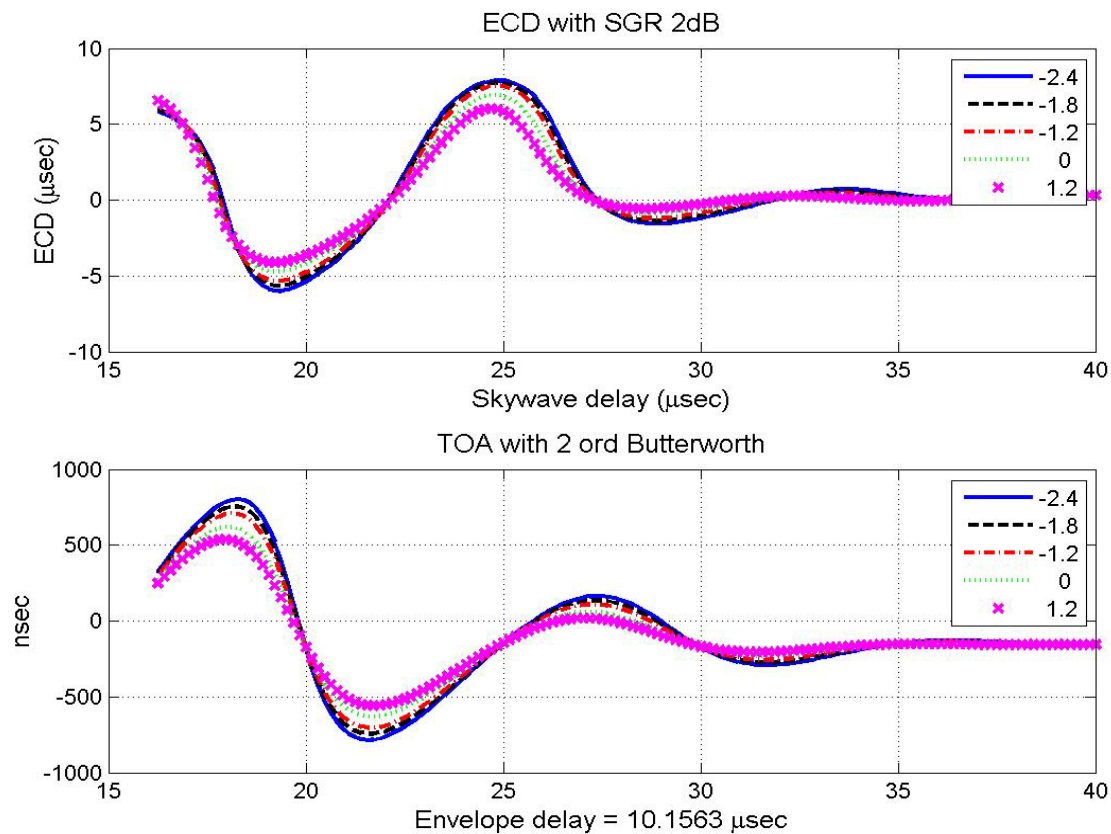# Skywave Effects:
Filtered vs Unfiltered

2nd Order Butterworth Filter   No Filter

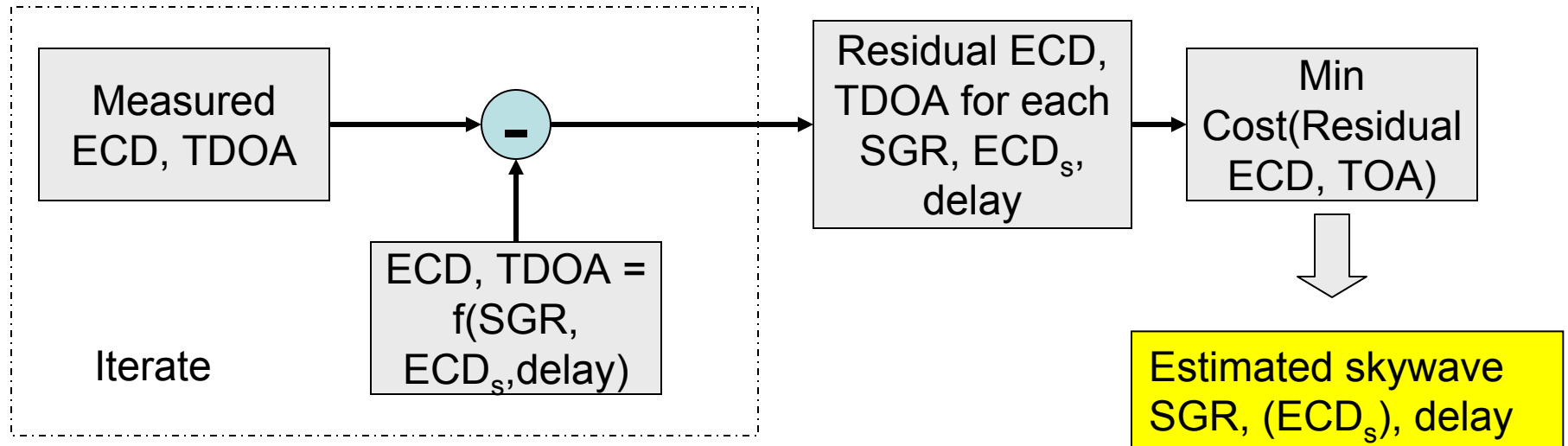Filtering amplifies affect of skywave and results in skywave affect happening earlier

Skywave Effect Curves

- Curves of TOA (TDOA), ECD variations due to SGR, ECD as a function of delay
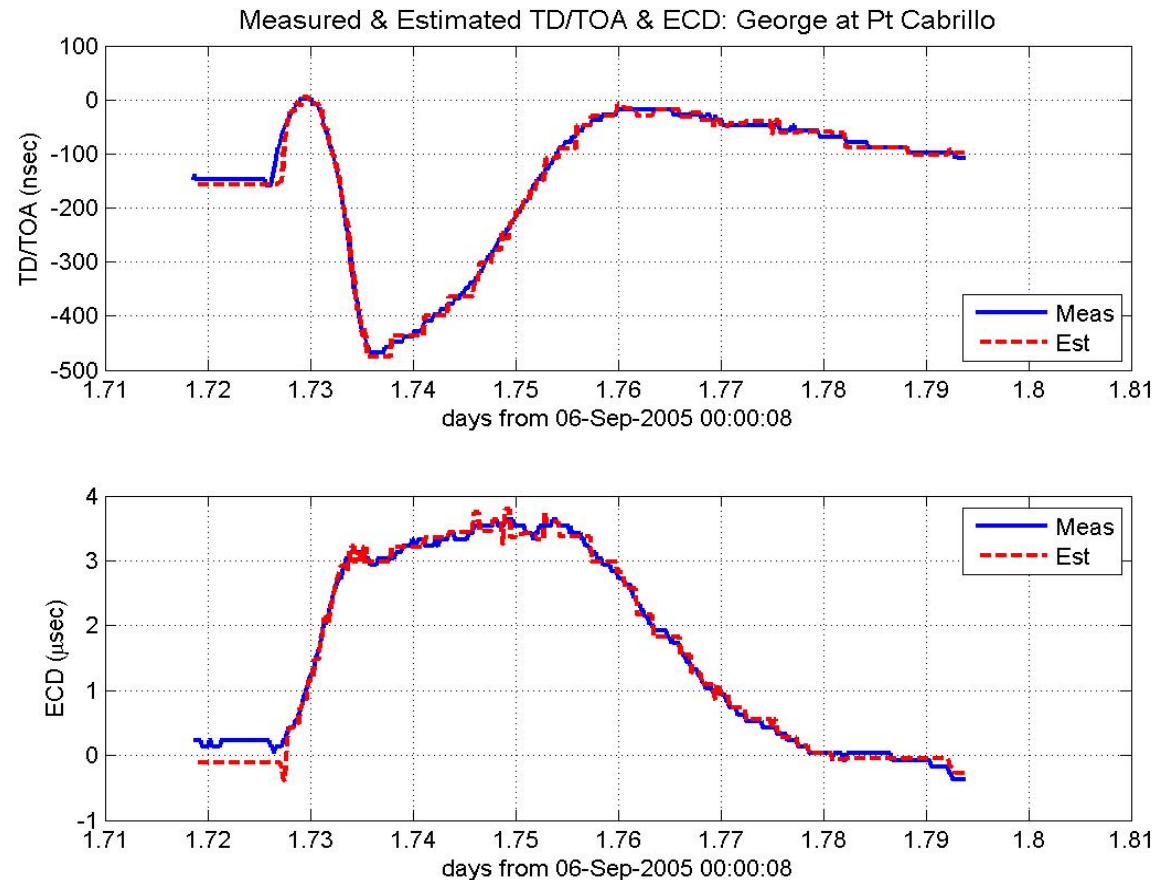
Determining delay and SGR

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| Measured ECD, TDOA | → | (−) | → | Residual ECD, TDOA for each SGR, ECD_s, delay | → | Min Cost(Residual ECD, TOA) |

ECD, TDOA = f(SGR, ECD_s,delay)

Iterate

⇩

Estimated skywave SGR, (ECD_s), delay

- Minimize sum of residual ECD & TOA
- Estimation is made "ad hoc"
  - No interpolation (SGR quantization >= 0.5 dB)
  - Cost function based on roughly equal weighting of ECD, TD, delay change
- Results seems to reasonably replicate
  - Is it just curve fitting or is the physics right?

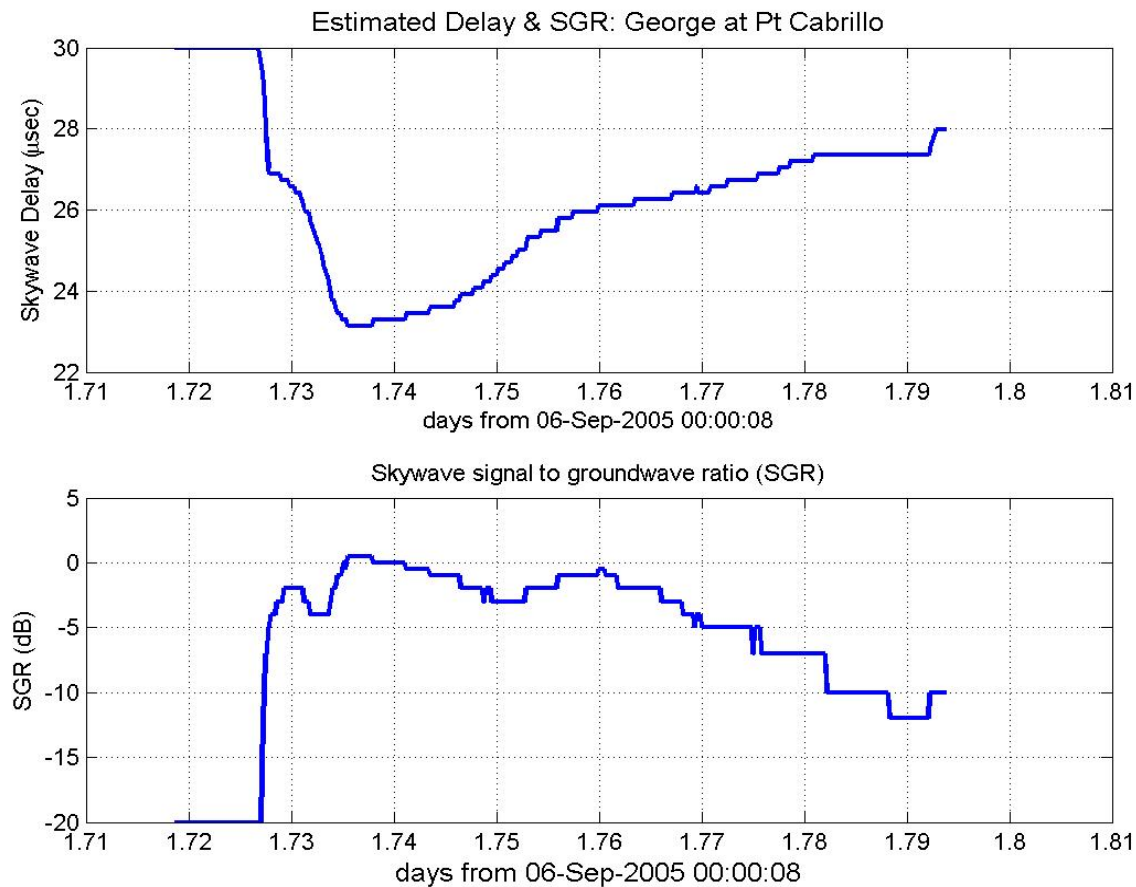# Measured & Estimate Derived TD & ECD at George at Pt. Cabrillo Sept 7, 2005

Phase Reversed

Measured & Estimated TD/TOA & ECD: George at Pt Cabrillo

Baseline ~ 1020 km

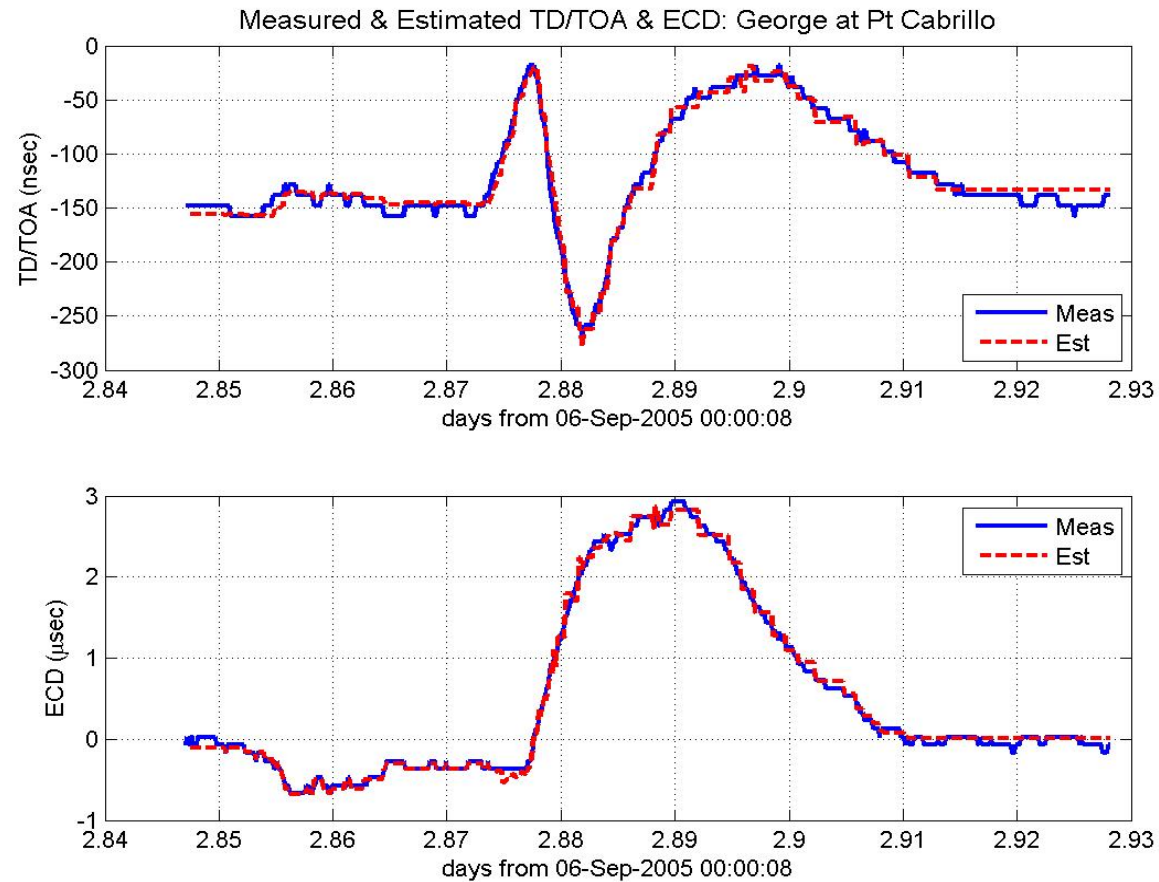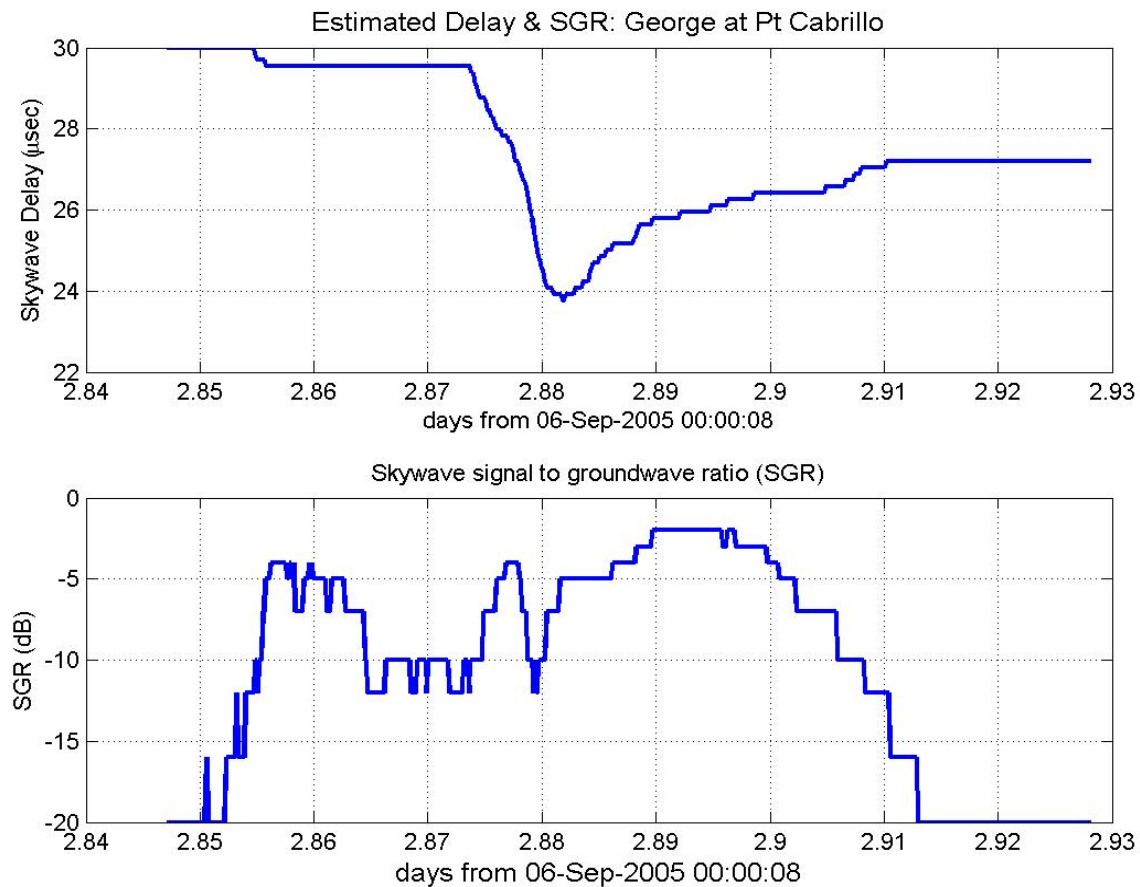# Estimated Parameters at George at Pt. Cabrillo Sept 7, 2005

Measured & Estimate Derived TD & ECD at George at Pt. Cabrillo Sept 8, 2005

Phase Reversed

Measured & Estimated TD/TOA & ECD: George at Pt Cabrillo

Estimated Parameters at George at Pt. Cabrillo Sept 8, 2005

Estimated Delay & SGR: George at Pt Cabrillo
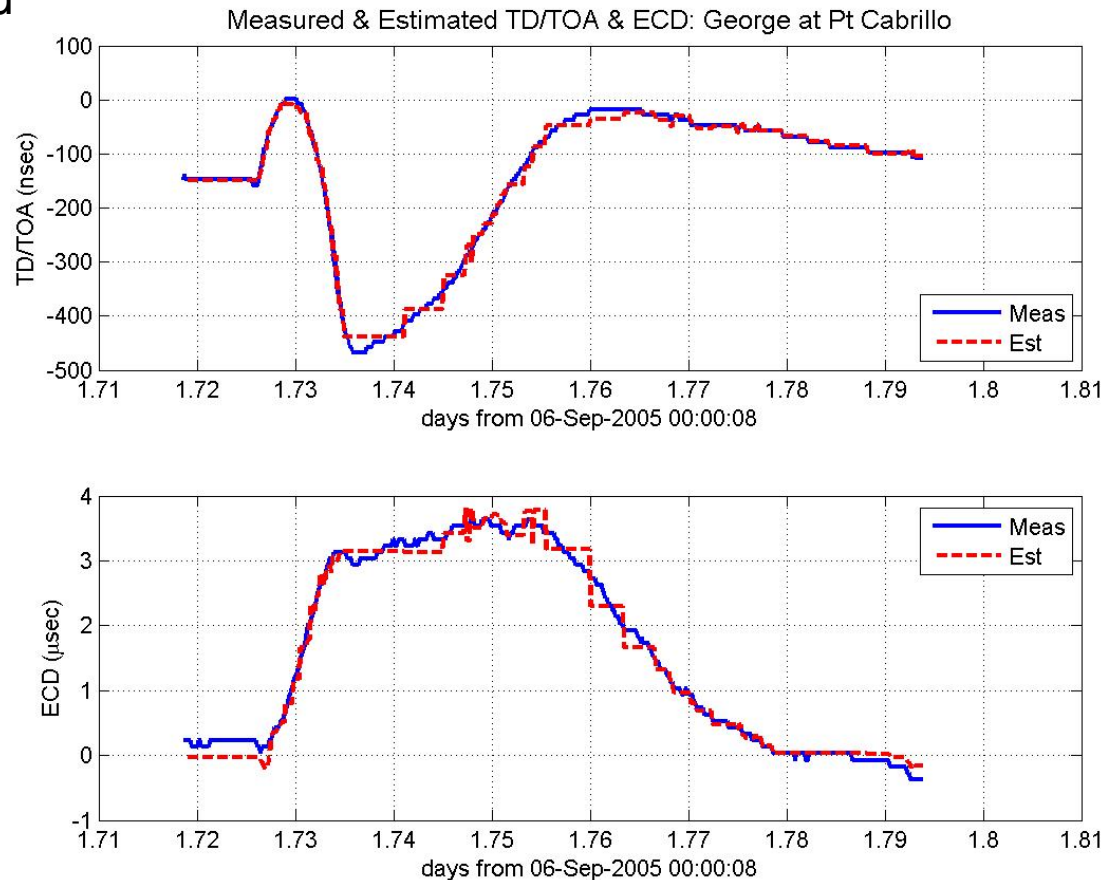
Skywave signal to groundwave ratio (SGR)

How do we know that the is correct? Signal Reversal on Skywave?

- Test model with no sign reversal (phase unchanged) on USCG data
  - Data reasonably well model
  - Implied differences from phase reversed (higher SGR, ~5 µsec)
- Past data
- Examine reversal/no sign reversal on ELR data

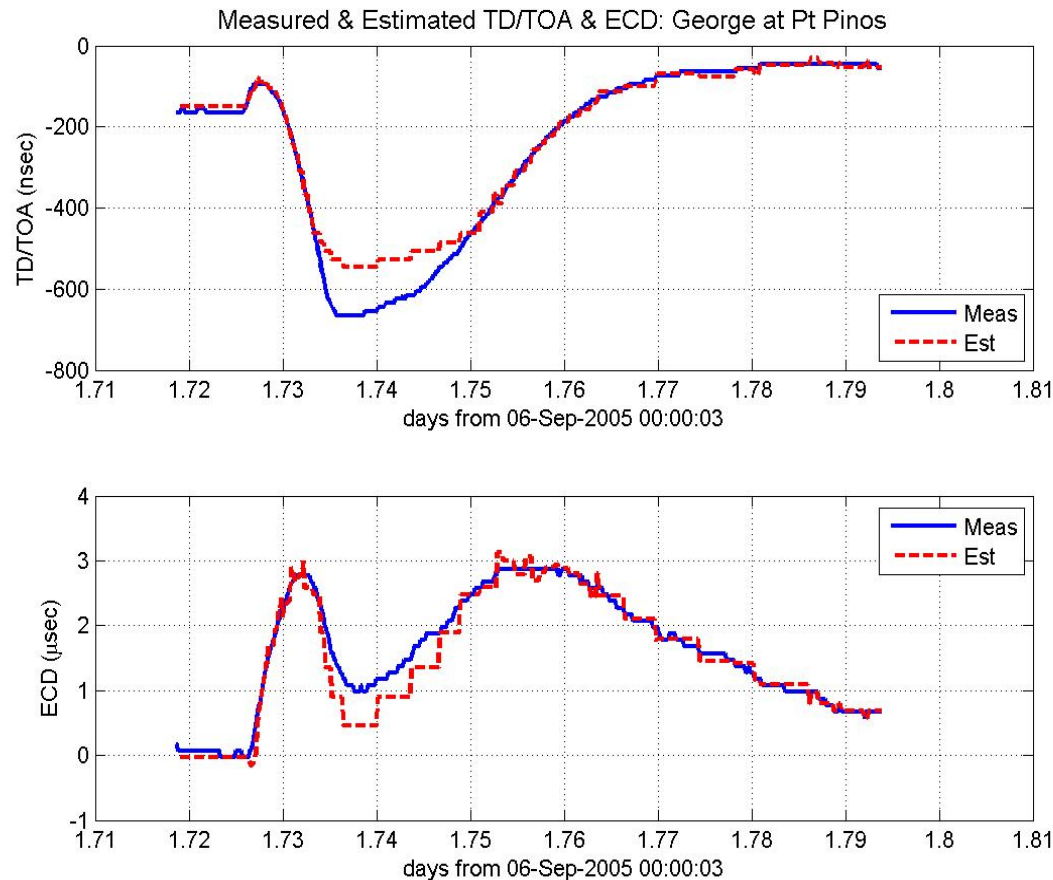# Measured & Estimate Derived TD & ECD at George at Pt. Cabrillo Sept 7, 2005

Phase Unchanged

Measured & Estimated TD/TOA & ECD: George at Pt Cabrillo

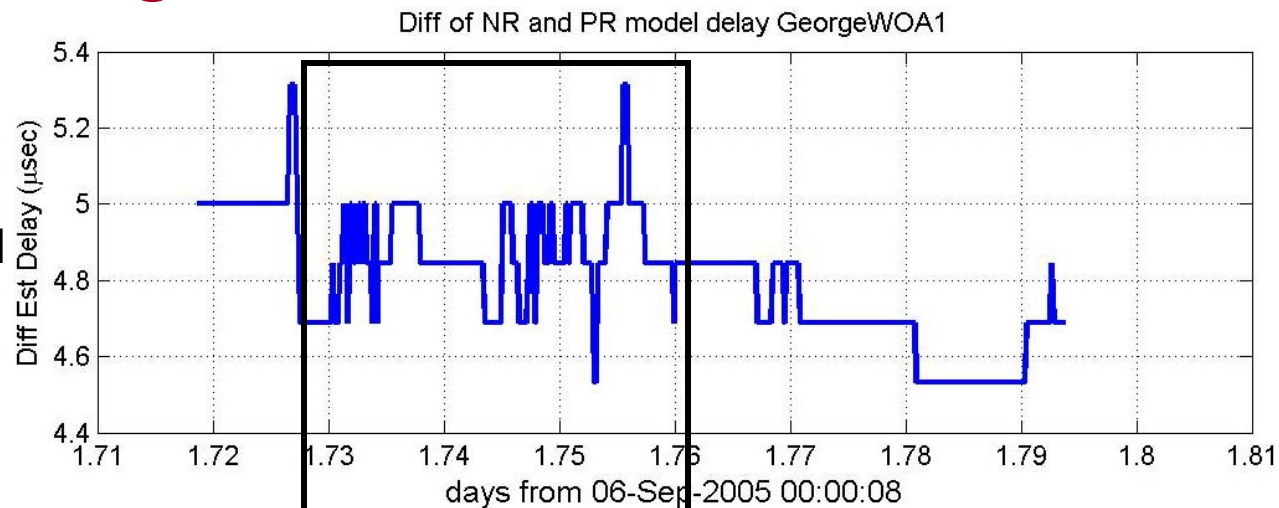# Measured & Estimate Derived TD & ECD at George at Pt. Pinos Sept 7, 2005
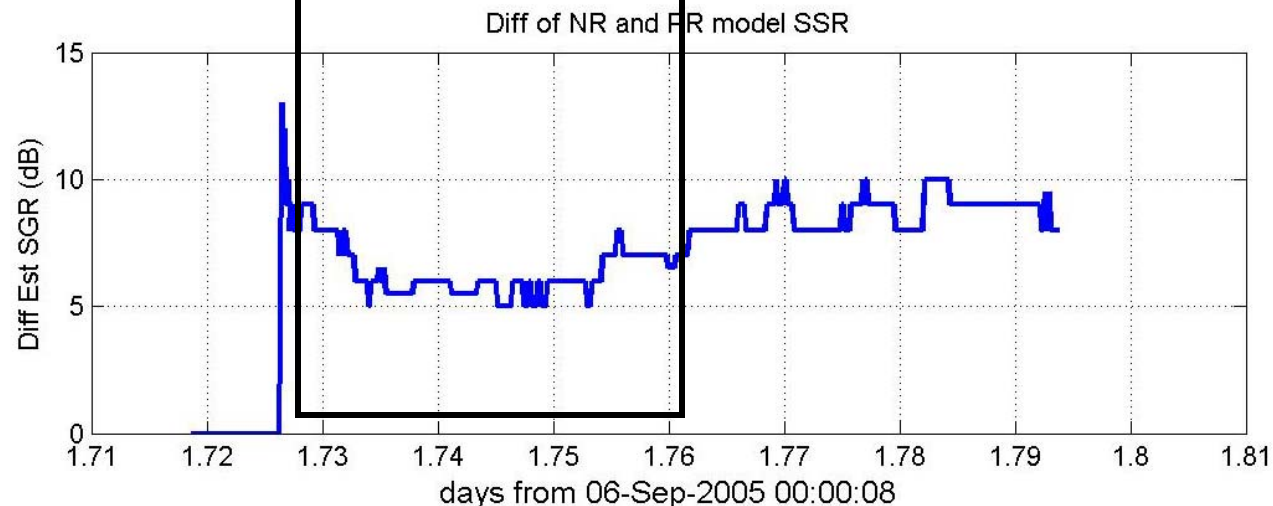
Phase Unchanged

Baseline ~ 1050 km

Difference between Phase Unchanged & Phase Reversed Model

Phase unchanged delay is +5 µsec

Phase unchanged SGR is 4-10 dB higher

Diff of NR and PR model delay GeorgeWOA1

Diff of NR and PR model SSR

Phase Reversal in Past Data

SKYWAVE to GROUNDWAVE RATIO vs. SKYWAVE DELAY
7960 Port Clarence observed at A-1 Monitor Fairbanks
24 February – 08 April 1993

~ 900 km

Skywave to Groundwave ECD

Skywave Fit: Fallon measured at SU June 2008, SkyECD = 1.25, GndECD = 2.5

Rev Phase Fit Resid 1.2517

Same Phase Fit Resid 18.0989

Skywave ECD is ~ -1.25 μsec relative to Groundwave
Values that differs results in larger residuals
(i.e. 0 or +/- 2.5) results in min resid ~ 4

Summary

- Filter cause skywave to effect signal even if delay > 30 μsec

- Results show that skywave likely has different ECD than groundwave

- Suspect that there is some phase reversal (single hop)

Acknowledgments & Disclaimer

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- Kirk Montgomery, Benjamin Peterson, and Peter Morris for their help and insight

- 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 or any other person or organization.