Signal Excess Uncertainty in Multistatic ASW Performance Prediction

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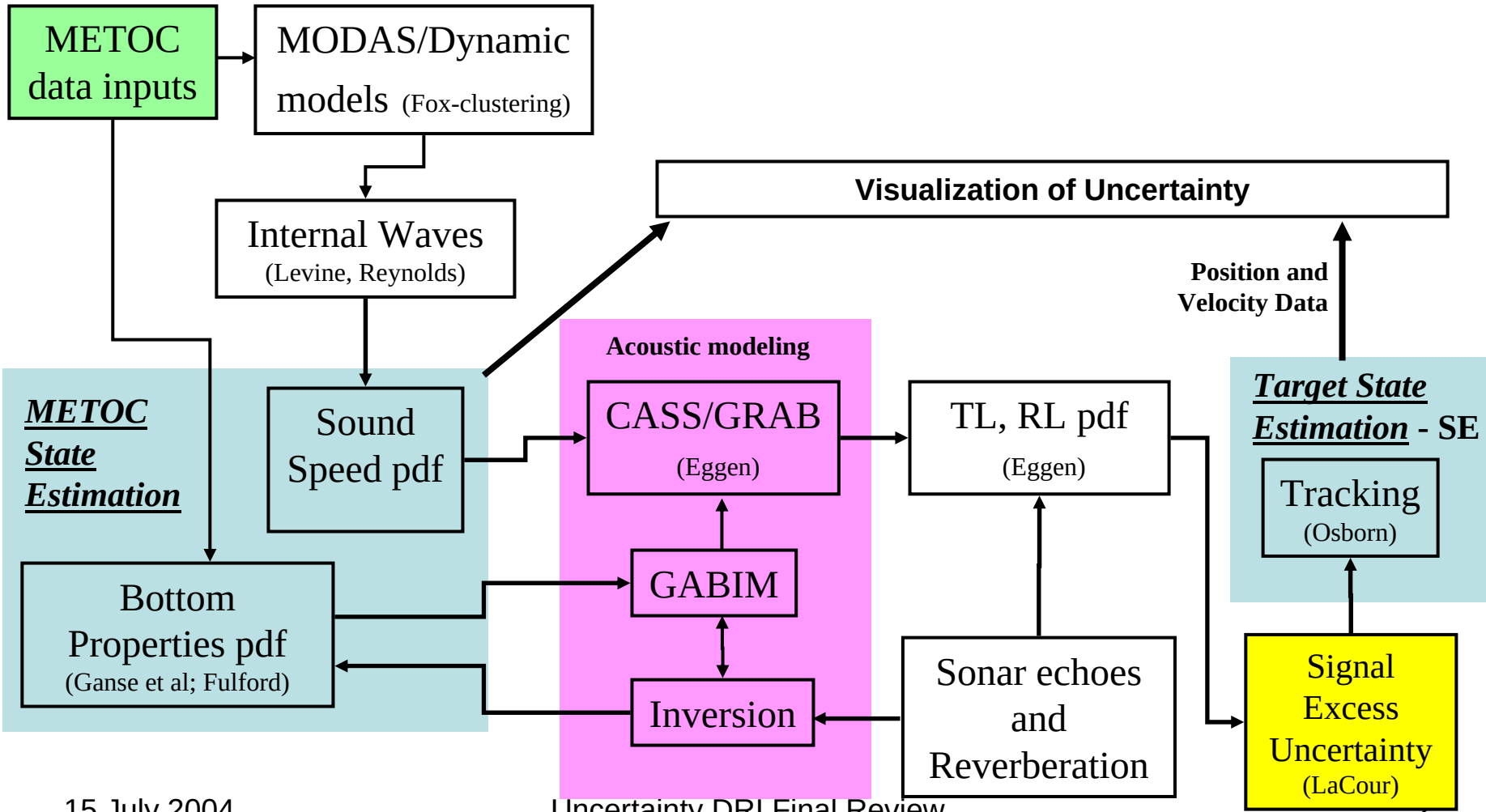
Architecture – Big Picture



Overview of Presentation

- Uncertainty in Active Sonar Signal Processing
  - "Off-Target" Statistical Clutter Modeling
  - "On-Target" Uncertainty in Signal Excess
    - TL Uncertainty
    - RL Uncertainty
    - TS Modeling and Uncertainty
- Summary/Conclusions
- Future Work/Transitions

Log-Likelihood/Normalized MF

$$\Lambda(s) = \left|\int r(t) z(t-\tau(s))^* dt\right|^2 \Big/ E\left[\left|\int r(t) z(t-\tau(s))^* dt\right|^2\right]$$

$$\approx \frac{\left|\alpha(s_0) A_z(\tau(s)-\tau(s_0))\right|^2}{R(\tau(s))^2} + \left|n(\tau(s))\right|^2$$

$$\approx \begin{cases} 10^{[SL - TL_1(s_0) - TL_2(s_0) + TS(s_0) - RL(\tau(s_0))]/10} & \text{on target} \\ \left|n(\tau(s))\right|^2 & \text{off target} \end{cases}$$

$$\boxed{SE(s) = 10\log_{10}\Lambda(s)}$$

Modeling Reverberation Clutter Statistics

Active Sonar Reverberation

$$r(t) = \alpha_0 \, z(t - \tau_0) + \sum_{n=1}^{N} \alpha_n z(t - \tau_n)$$

<u>Contributions from</u>

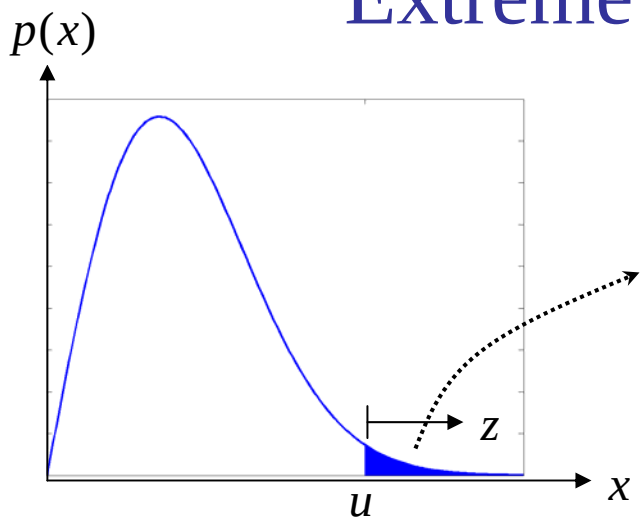
- bottom clutter
- bottom roughness
- biomass (fish, etc)
- volume inhomogeneities
- surface roughness
- etc.

Model as a mean reverberation $R(t)$ times a zero mean, unit variance random factor:

$$\sum_{n=1}^{N} \alpha_n z(t - \tau_n) = R(t) n(t)$$

random

Extreme Value Theory



$$p_u(z) = \frac{p(u+z)}{\int_u^\infty p(x)dx} \xrightarrow{u\to\infty} g_\gamma(z/\sigma)$$

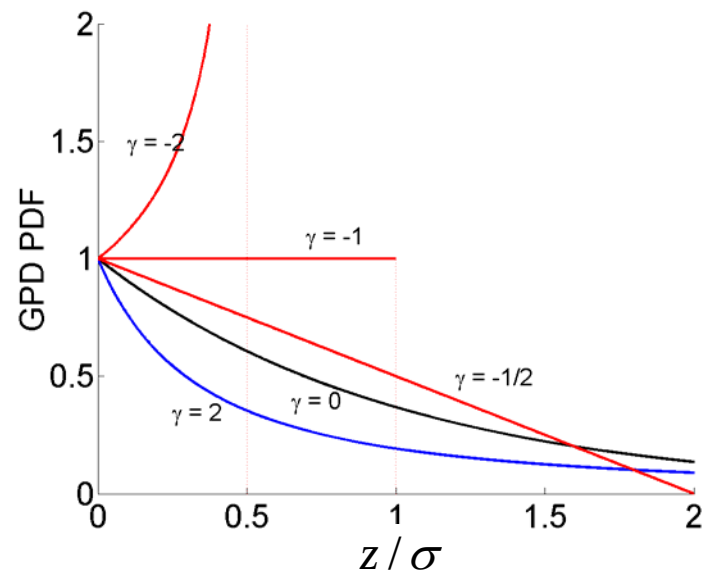
Generalized Pareto PDF

$$g_\gamma(z/\sigma) = \frac{1}{\sigma}(1+\gamma z/\sigma)^{-(\gamma+1)/\gamma}$$

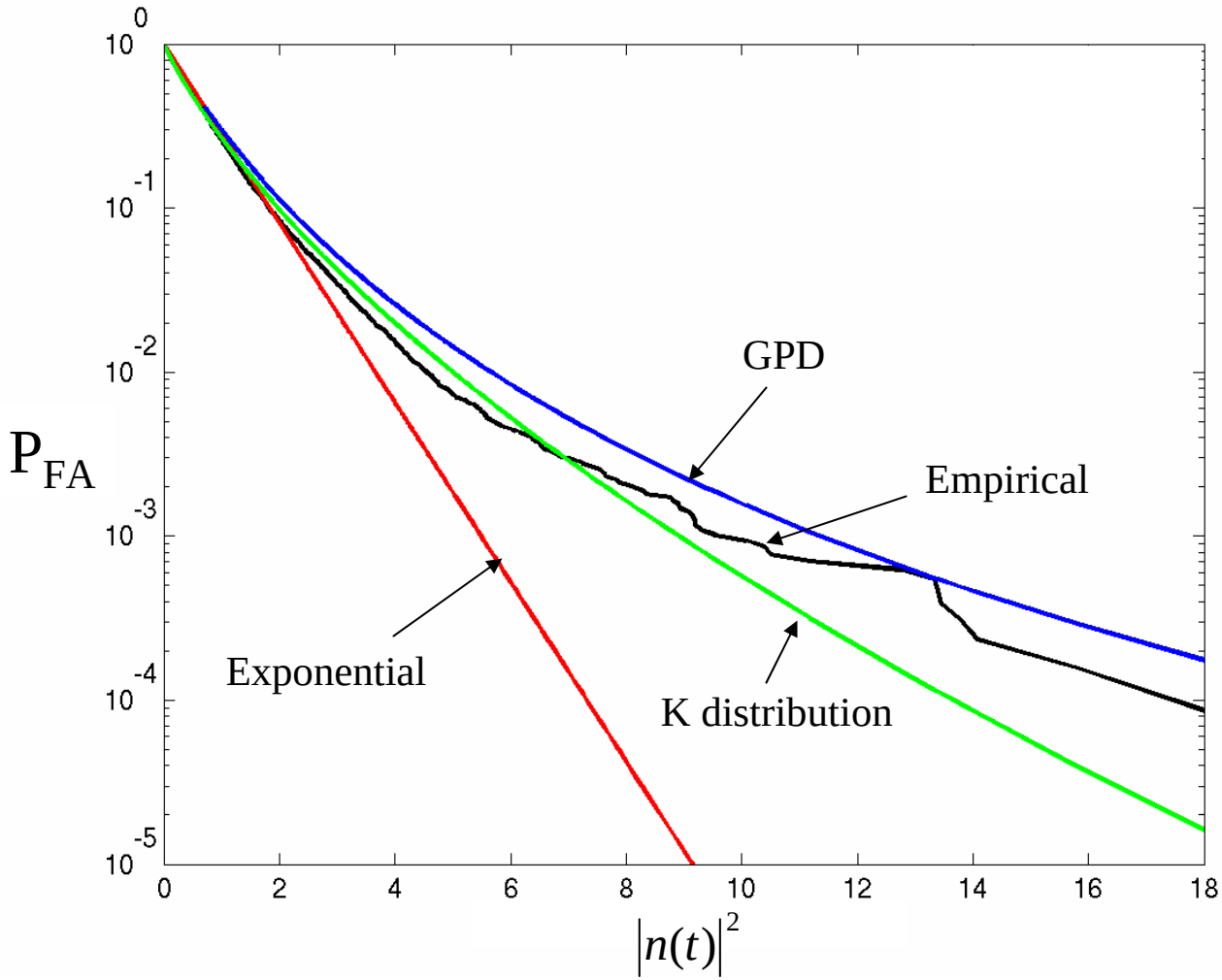
$\gamma = 0$: Type I (exponential)

$\gamma > 0$: Type II (power law)

$\gamma < 0$: Type III (bounded)

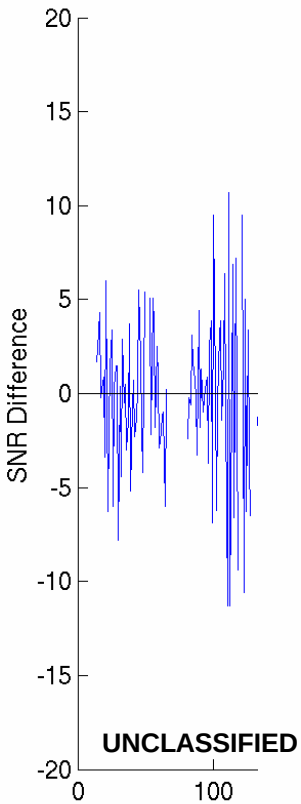


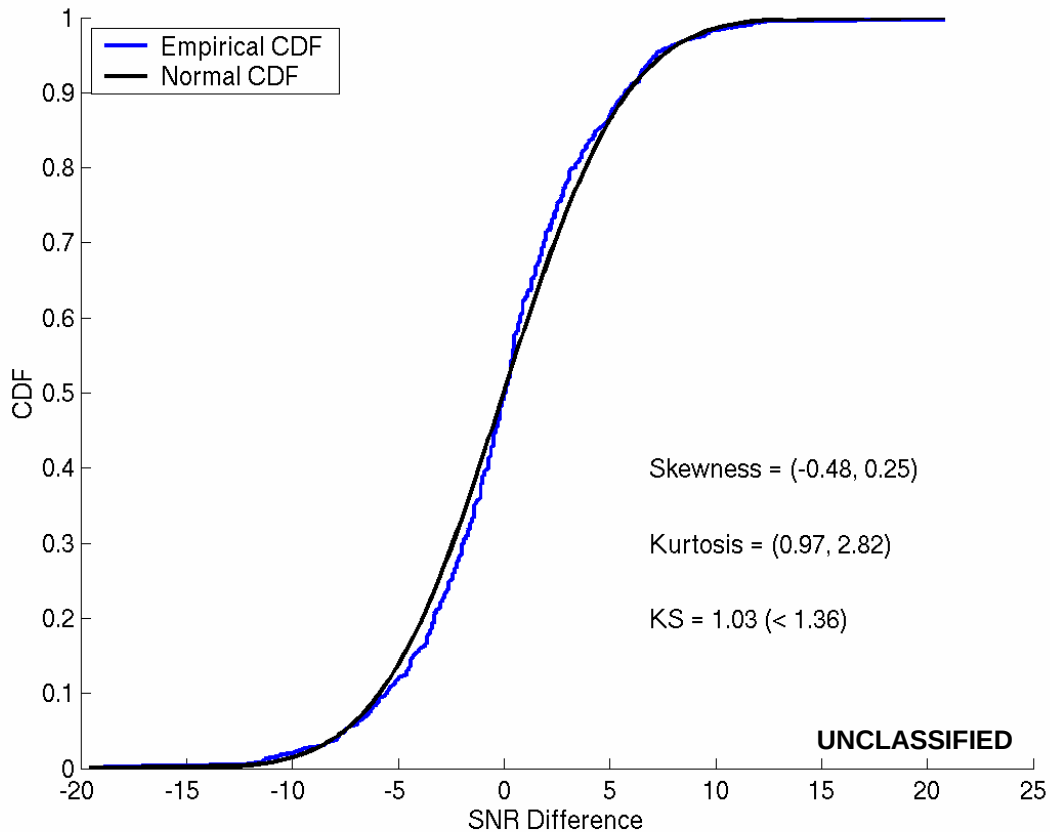
Example of Normalizer Output



Uncertainty in TL and RL

Observed Variability in TL





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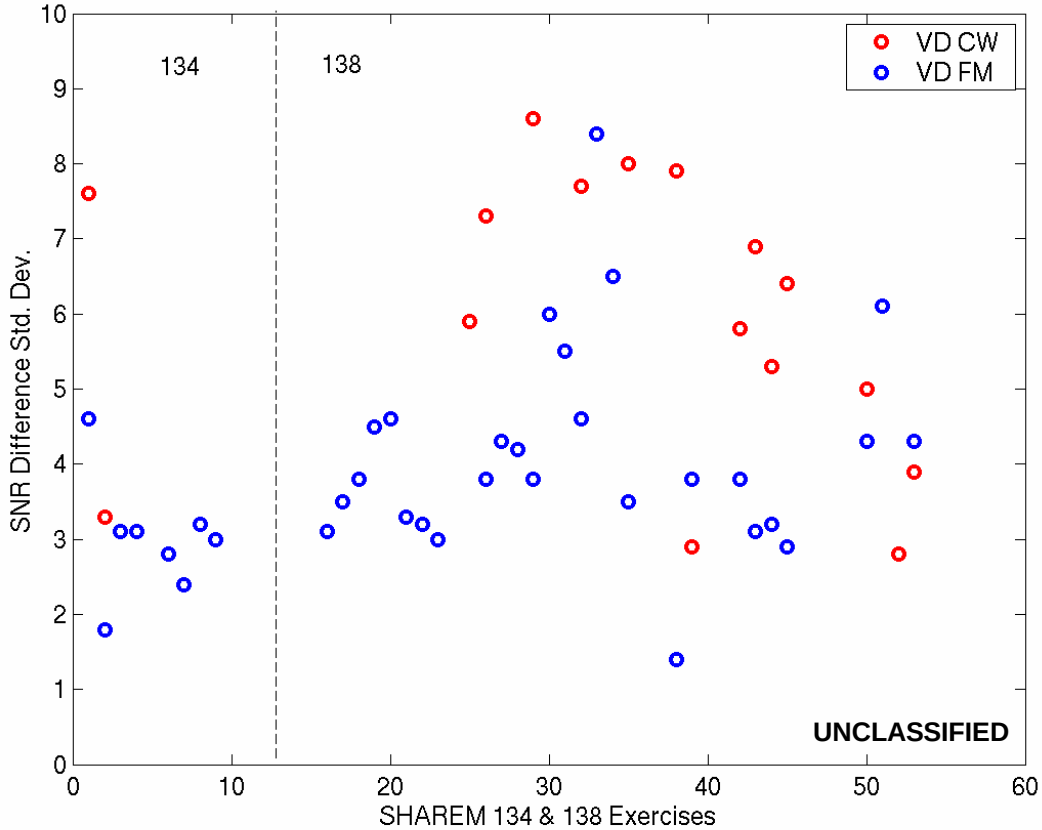
Comparison of FM vs. CW



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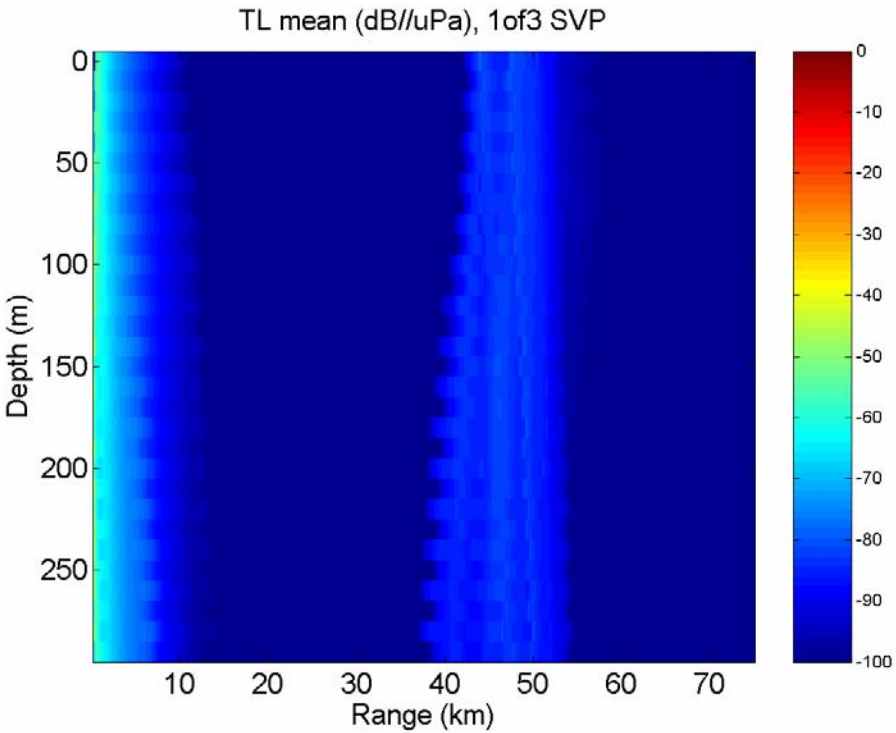
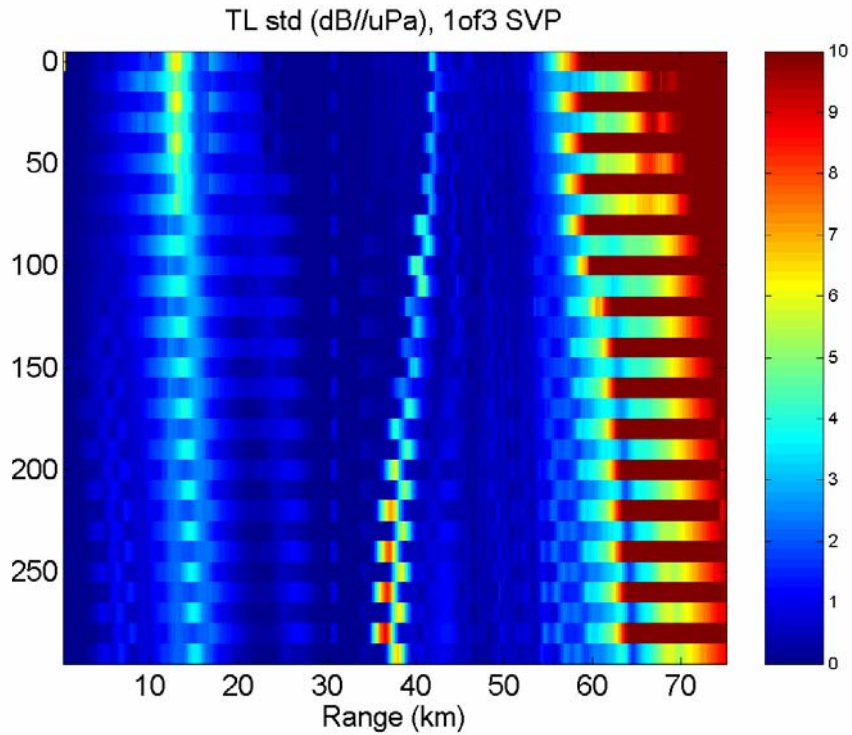
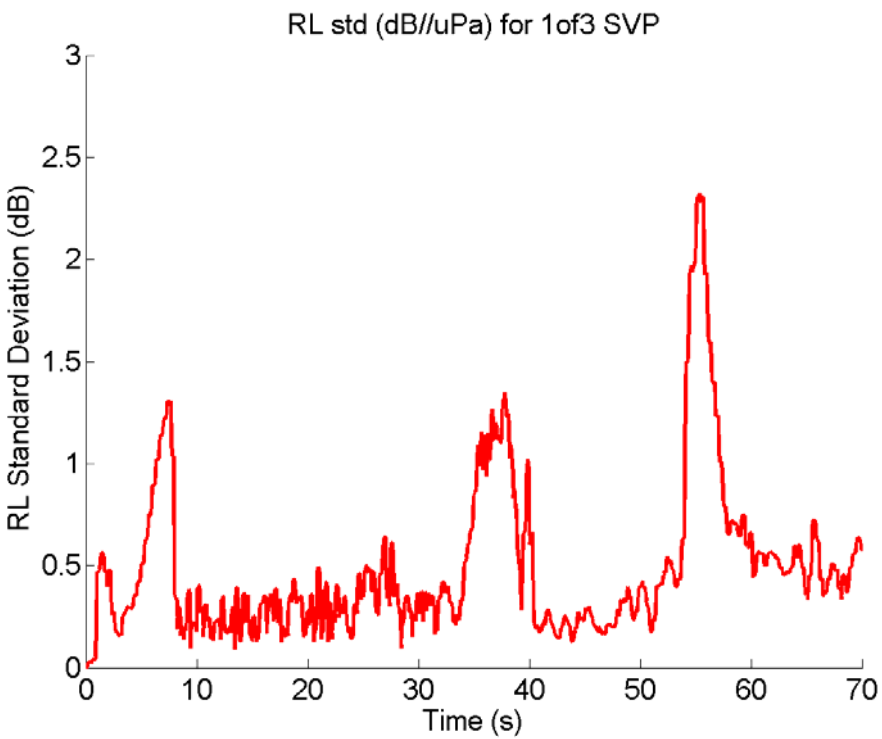
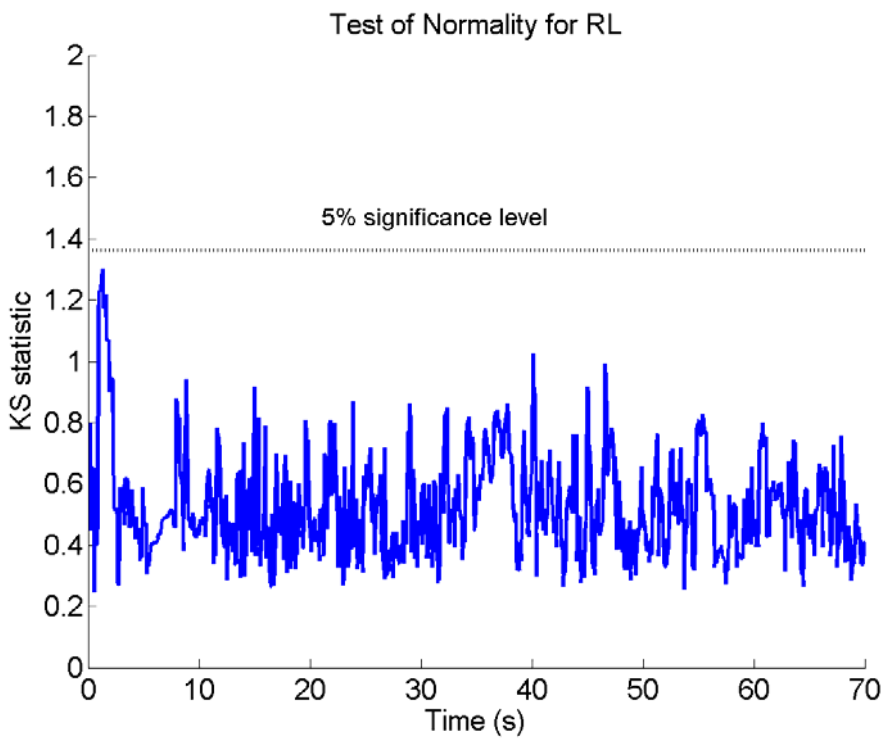
TL Uncertainty due to Internal Waves





RL Uncertainty due to Internal Waves





Uncertainty in Target Modeling

Two Models for Bistatic Target Strength

BASIS (previous model)

- Model the target as a collection of primitive shapes.
- Assume only specular reflections.
- Compute bistatic TS using the Bistatic Theorem.
- Compute forward scattering using Babinet's Principle.
- Assume the final received signal has a Rician distribution.

TEST (current model)

- Allows more complex highlights, not just simple geometric primitives
- Includes specular, diffractive, and elastic effects.
- Target Engine:
  - Uses a target "blueprint" of primitive highlights
  - Can specify monostatic or bistatic
  - Can vary frequencies, source/receiver range, aspect, and elevation
  - Produces a Matlab data file containing target impulse response
- Post Processing:
  - Select waveforms and highlights
  - Time-domain target signature
  - Integrated or peak bistatic target strength for given waveform

Bistatic, Broadband Target Strength

$$\mathrm{TS}(S,R) = 10\log_{10}\left|u(S,R)+n\right|^2$$

complex Gaussian noise
$E(n) = 0, \quad E(n\,n^*) = \sigma^2$

scattering function
$u(\theta)$

waveform spectrum

$$u(S,R) = \int_B \sum_n \left[g_n(S,R,f) + \tilde{g}_n(S,R,f)\right] S(f)\,df$$

highlight
backscattering
function

highlight
forward scattering
function

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Integrate target strength uncertainty into LRT

- A description of the individual processes and variations as appropriate
  - Develop TEST blueprint for specific target
  - Run TEST over source/receiver aspect pairs to obtain frequency response
  - Convolve frequency response with given waveform to compute TS
  - For TS uncertainty, run TEST over different source/receiver elevations
- Computational hardware and software requirements as we've implemented those steps/alternates
  - PC running Windows XP
  - Copy of the TEST software
  - Matlab script to configure TEST run
  - Matlab scripts to perform post-processing
- Some indication of the flexibility of the H/W and S/W to run elsewhere
  - TEST is restricted to Windows XP in current form but may be ported to Linux
  - Matlab scripts are useable on virtually any platform
  - Best to form look-up tables rather than attempt to compute TS on the fly.

Integrate target strength uncertainty into LRT

- Man hours and expert knowledge level needed to execute the steps
  - Construction of blueprint file requires expert knowledge of general submarine design and technical specifications for the specific target
  - Running TEST requires about a day with user oversight
  - Post-processing is easy to set up as a batch job, may take several hrs
- Input data format requirements
  - Target identity (or target blueprint, if available)
  - Transmit waveform, specified parametrically or otherwise
- Output data format
  - Matlab binary data files (.mat) of
    - Source and Receiver Aspects (degrees bow to port -180 to 180)
    - Integrated and Peak Target Strength (dB)
    - Target Strength uncertainty in the form of a standard deviation (dB)
- Recommended next steps:
  - Use a non-Gaussian model of TS in the LRT (e.g., Rician distribution)
  - Determine distribution of source/receiver elevations from acoustic propagation

Summary/Conclusions

- Non-Rayleigh “off target” SE may be adequately modeled in the tails by a generalized Pareto distr.
- RL/TL variations wrt internal waves are Gaussian distributed and comparable to observed variability.
- TEST provides more detailed target modeling, particularly for low frequency bistatic TS.
- TS uncertainty may be determined from grazing angle dependence, related to mean TS.

Future Work/Transitions

- Publications
  - La Cour, "Statistical characterizationn of active sonar reverberation using extreme value theory," *IEEE J. Oceanic Eng.*, vol. **29**, no. 2, April 2004.
  - Stone, Osborn, Miyamoto, La Cour, “Incorporating Performance Prediction Uncertainty into Detection and Tracking,” abstract submitted for JUA Theme Issue: Sensor Performance Prediction and Analysis.
  - Luter and La Cour, “Chaotic acoustic rays in littoral environments due to background internal waves,” to be prepared for submission to JASA.
- Tentative Transitions
  - Modeling non-Rayleigh clutter in support of CBASS system
  - TS uncertainty for incorporation into SPPFS Target Model

Uncertainty due to Chaotic Propagation

Hamiltonian Formulation

Forward propagating acoustic rays as a Hamiltonian system:

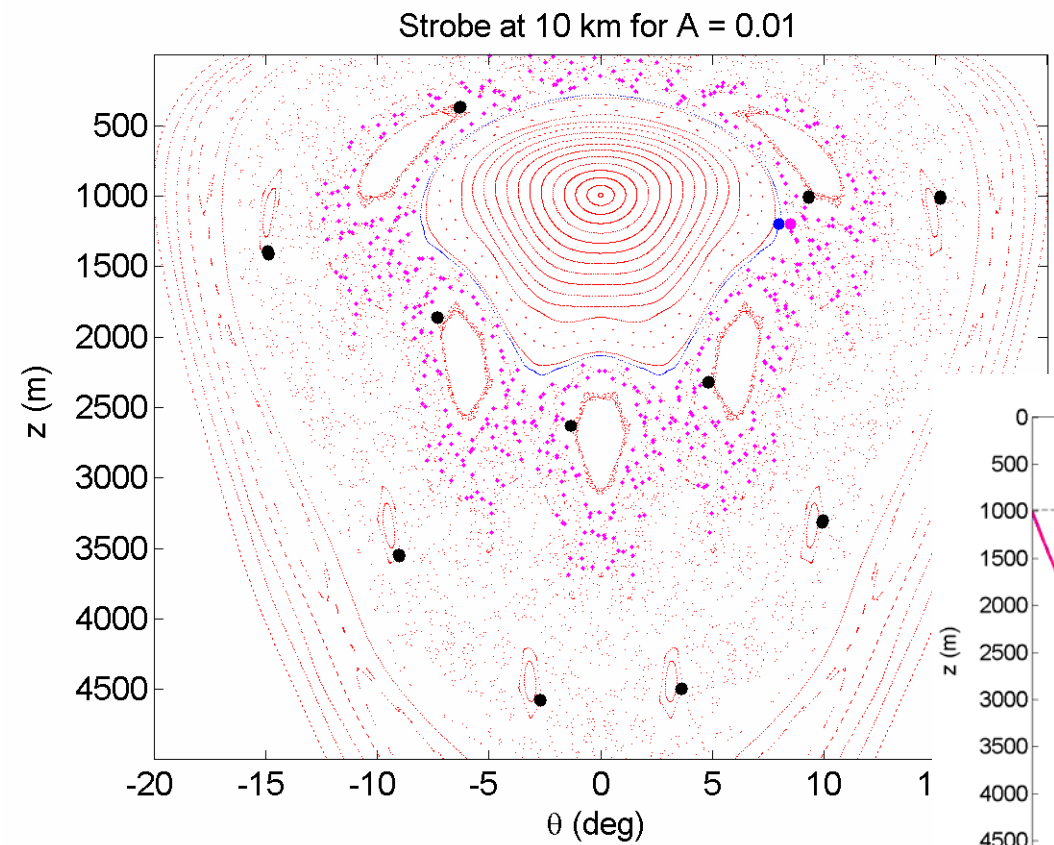
$$H(z,k_z;r) = -\sqrt{\frac{\omega_0^2}{c(z,r)^2} - k_z^2}$$

$$\frac{dz}{dr} = -\frac{k_z}{H(z,k_r;r)}, \qquad \frac{dk_z}{dr} = \frac{1}{c(z,r)^3 H(z,k_z;r)} \frac{\partial c}{\partial z}$$

Effect of internal waves on sound speed profile:

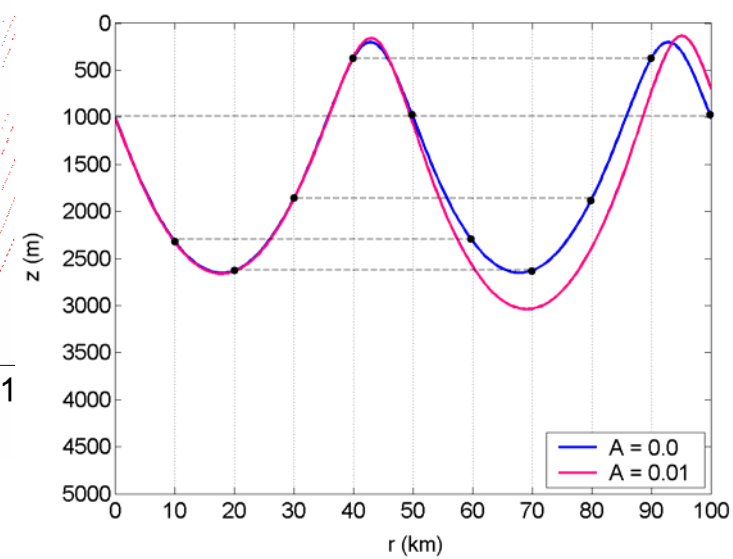
$$c(z+\varsigma(z,r,t),r) \approx c(z,r) + \frac{\partial c}{\partial z}\varsigma(z,r,t), \qquad \varsigma(z,r,t) = \mathrm{Re}\sum_j A_j W_j(z) e^{\mathrm{i}(k_j r - \omega t)}$$

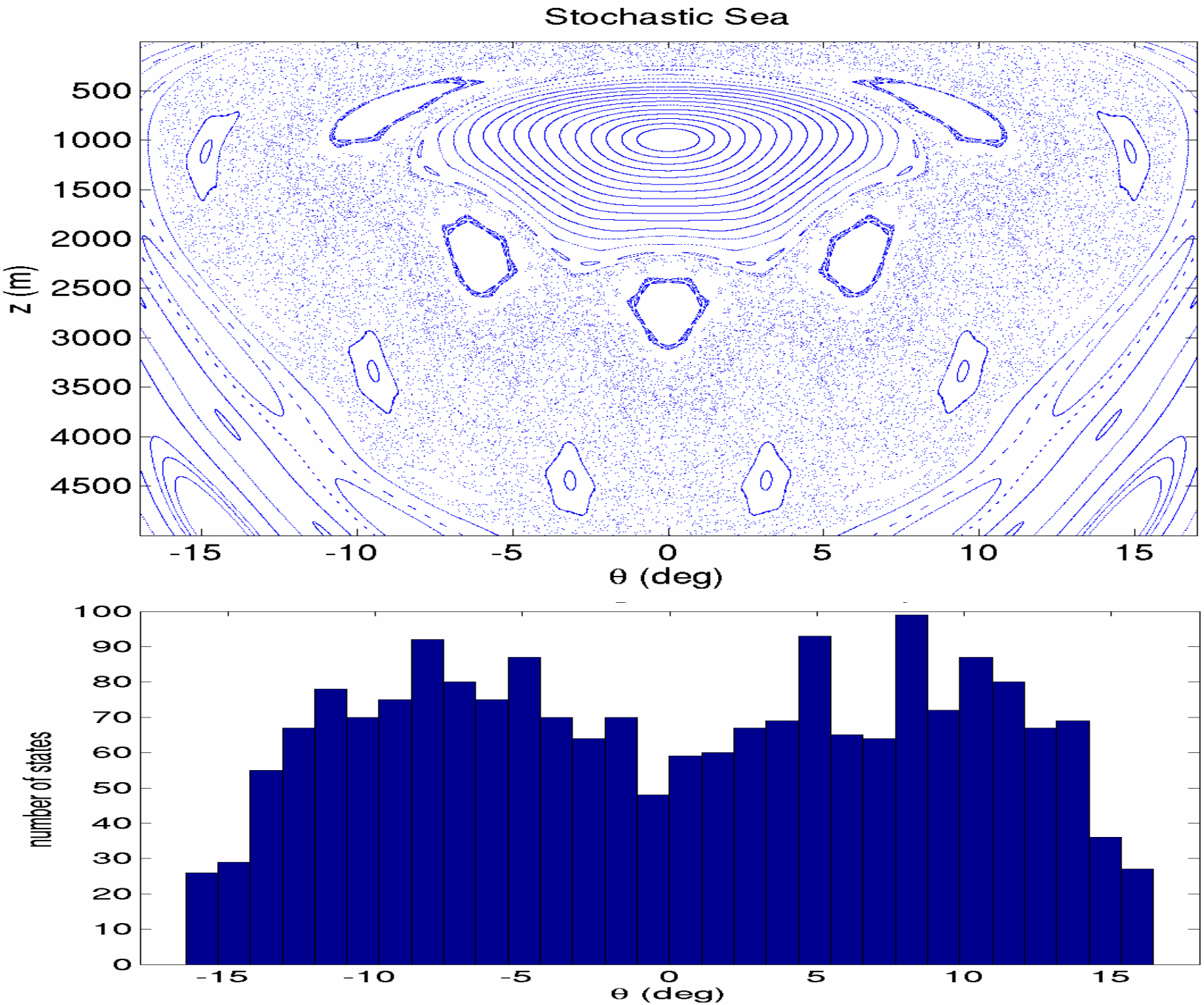
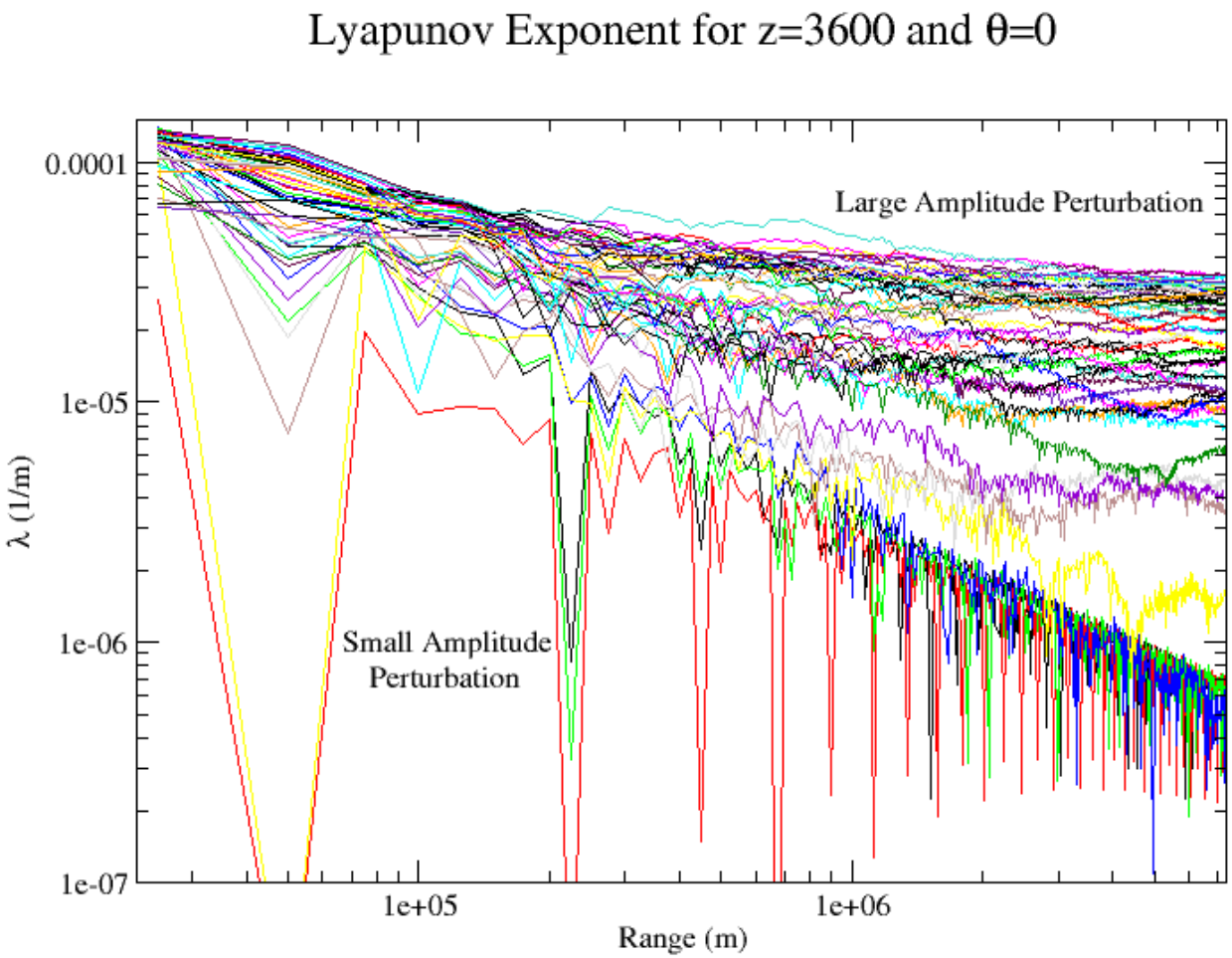
Phase Space Portrait with Internal Waves



Munk SSP w/ IW:

$$c(z,r) = c_a\left[1+\varepsilon\left(e^{-2(z-z_a)/B} + \frac{2(z-z_a)}{B} - 1\right)\right] + A\left(\frac{2z}{B}\right)e^{-2z/B}\cos\left(\frac{2\pi r}{R}\right)$$




Stochastic Sea
z (m)
500
1000
1500
2000
2500
3000
3500
4000
4500
-15
-10
-5
0
5
10
15
θ (deg)
number of states
100
90
80
70
60
50
40
30
20
10
0
-15
-10
-5
0
5
10
15
θ (deg)

Parameter Dependencies