Modeling of Sound Wave Propagation in the Random Deep Ocean

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  - Rytov Theory
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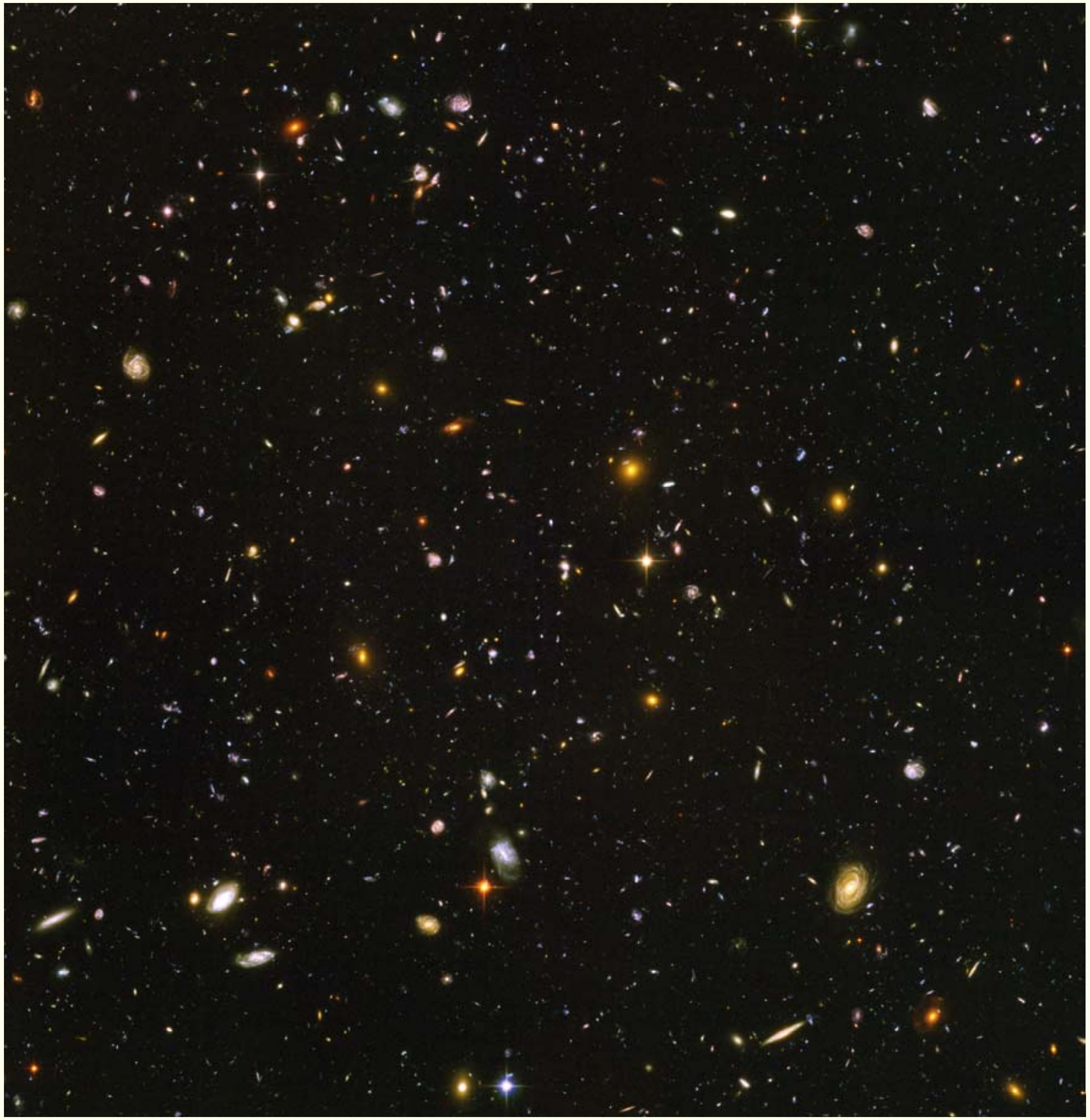
Introduction

- Hubble Ultra Deep Field



- It is an Image of a small region of space composited from Hubble Space Telescope.
- It is the deepest image of the universe ever taken in visible light, looking back in time more than 13 billion years.
- It is contains an estimated 10,000 galaxies.

Introduction (continued)

- **We know quite a lot about out space, but how much we know about our ocean?**

- **Why do we need a space-based observatory rather than a ground-based telescopes?**

"… it remains a fact that human beings crossed a quarter million miles of space to visit our nearest celestial neighbor before penetrating just two miles deep into the earth's own waters to explore the Midocean Ridge."

The Eternal Darkness: A Personal History of Deep-Sea Exploration, Robert D. Ballard

"We know a lot more about moon surface than our deep ocean."

Introduction (continued)

- **The angular resolution of the ground-based telescope is limited by the turbulence in the atmosphere, which causes stars to twinkle.**

- **Acoustic waves are today the only practical way to carry information underwater, and it is has analogical limitations imposed by the "random fluctuating medium" in the ocean as electromagnetic wave put by the turbulence in the atmosphere.**

- **Motivation and Application**
  - **Quantitatively understand the limits that randomness imposes on the practical uses of wave propagation**
  - **Global underwater navigation and communication**
  - **Global Ocean temperature monitoring**

Review

- **1970′s and 1980′s, ocean acoustic WPRM focused on high acoustic frequency and short-range experiments. There were successful finding based on weak fluctuations theory and internal wave models, but it is limited in the short-range, high acoustic frequency, narrowband. [Munk et al., 1976].**

- **From late 1980′s to present, low-frequency basin scale experiments were motivated to measure ocean climate change, which requests the low frequency, broadband and long range acoustic transmission. Some puzzles were found that, such as :**

  - **<u>Acoustic fluctuations were much stronger than previously predicted</u>**, especially for acoustic energy which traveled within a few hundred meters **<u>vertically</u>** from the sound-channel axis in SLICE89 [Duda et al, 1992]

  - In ATOC AET94, It showed surprising **<u>vertical and temporal coherence for the early ray-like arrivals</u>** which were far in excess of the currently predicted values pulse time spreading to be far lower than predictions; intensity fluctuations were slightly larger tan predicted.

  - **<u>Shadow zone arrivals</u>** recorded in the NAVY SOSUS extended significantly in depth and in time. [Colosi 1996,1999; Dushaw,1999]

- **It is a twofold problem, which includes two interrelated topics: Sound Propagation and Random Media.**

  - "It is fair to say that essentially no progress has been made by anyone attempting a direct attack on the general theory without a deep physical understanding of a particular medium".- Stanley M. Flatte, 1983

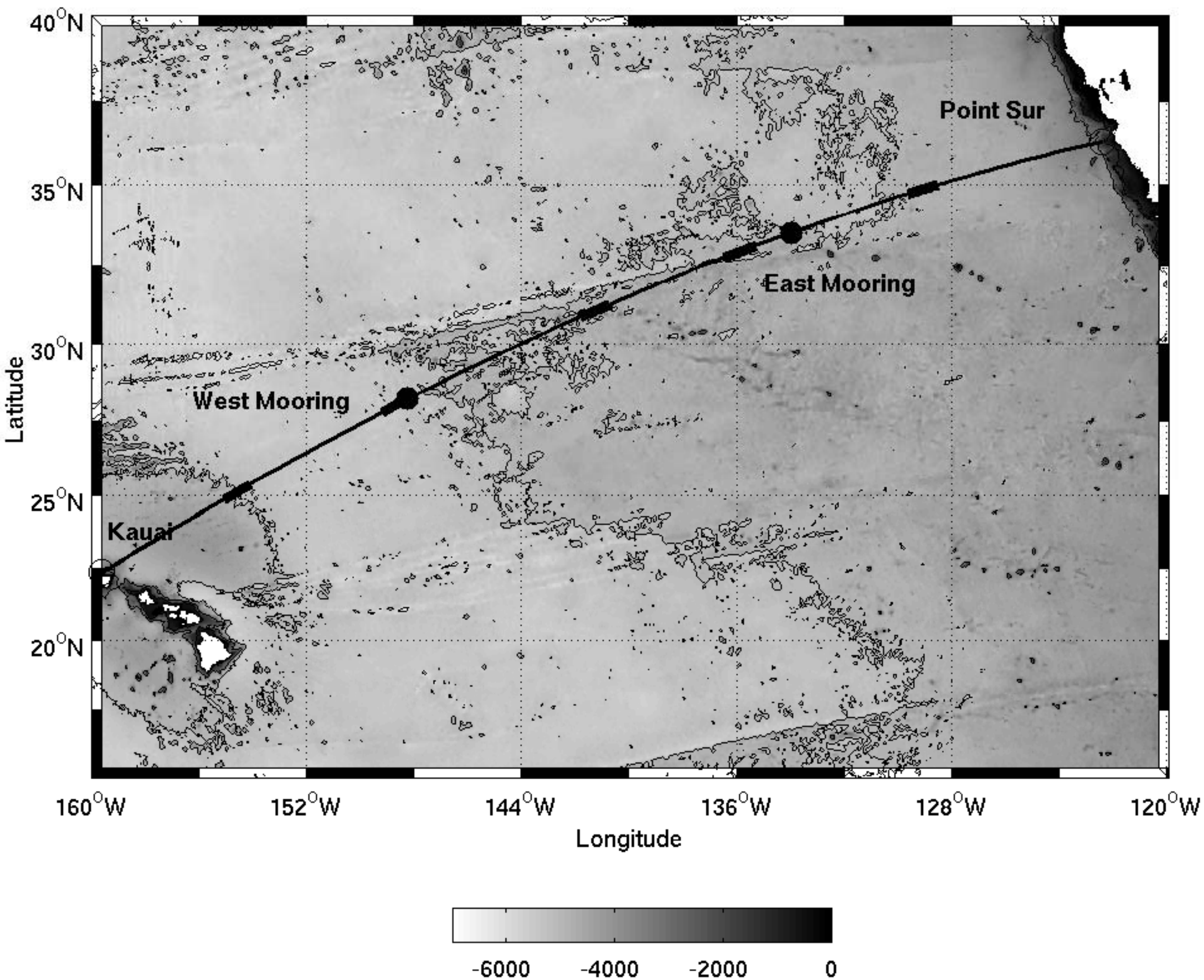
Objectives

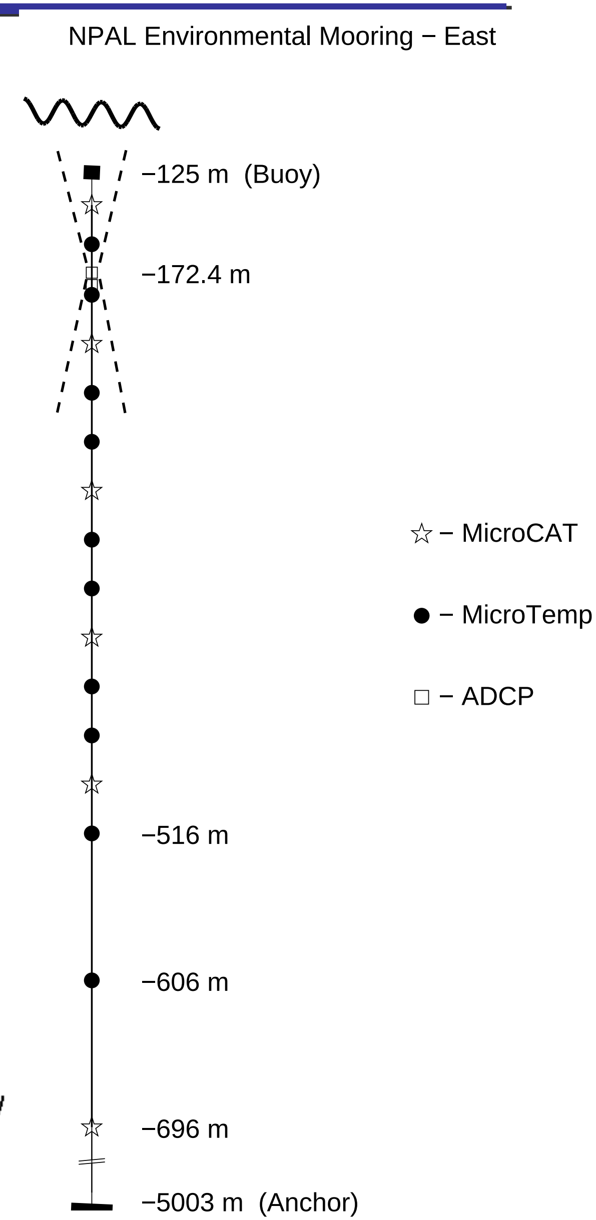
- First is quantification of ocean sound speed space-time scales due to internal waves continuum, near inertial waves, internal tides and sub-inertial motions from the North Pacific Acoustic Laboratory(NPAL)98 -99 environmental data.

- To understand how low frequency sound wave propagates through the random deep water environment, considering that internal-wave-induced sound-speed fluctuations are the dominant source of high-frequency variability of the acoustic wave field in the ocean.

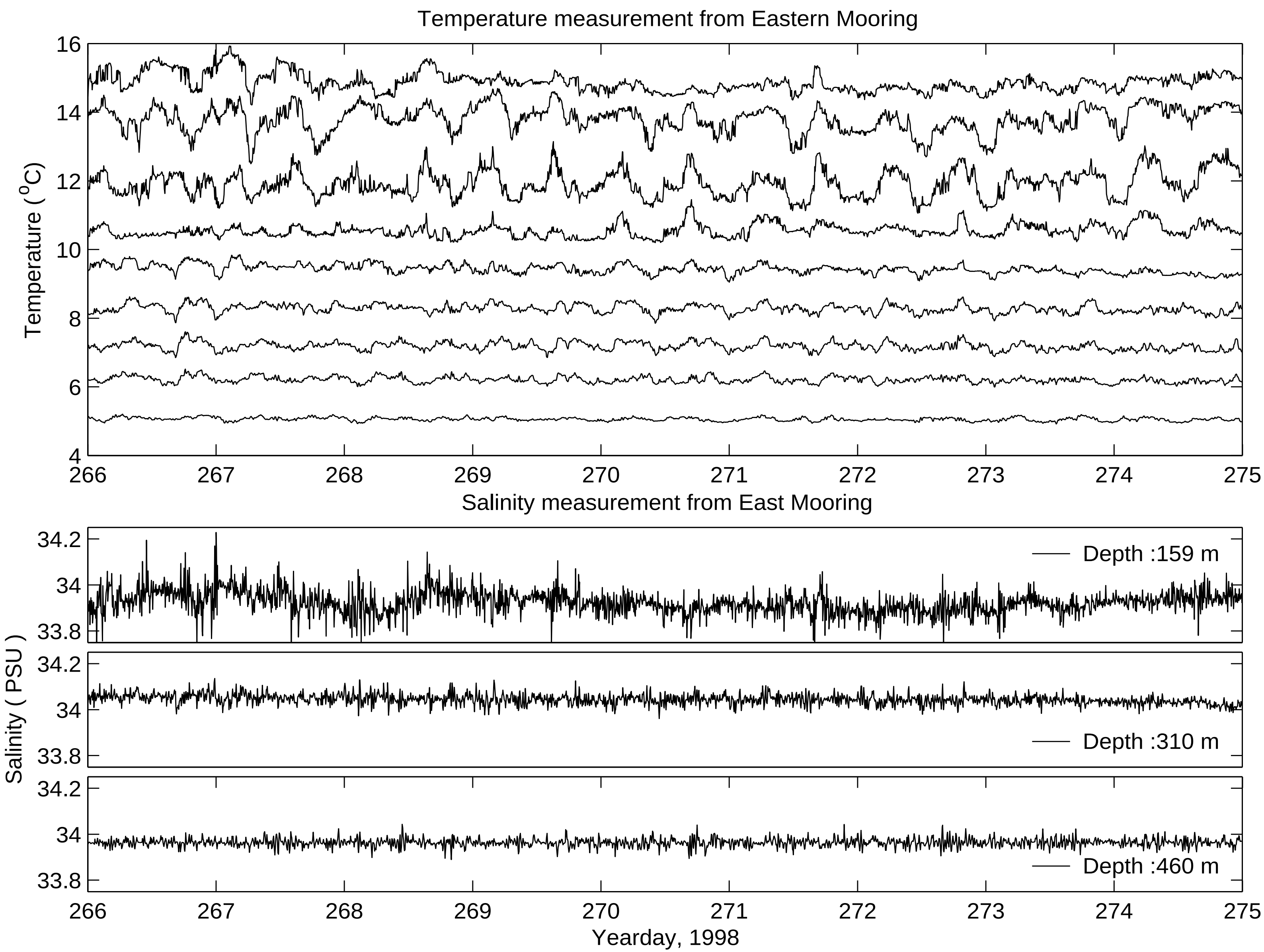
Random fluctuating medium in the Deep Ocean

Quantification of ocean sound speed space-time scales due to internal waves, mesoscale eddies, internal tides

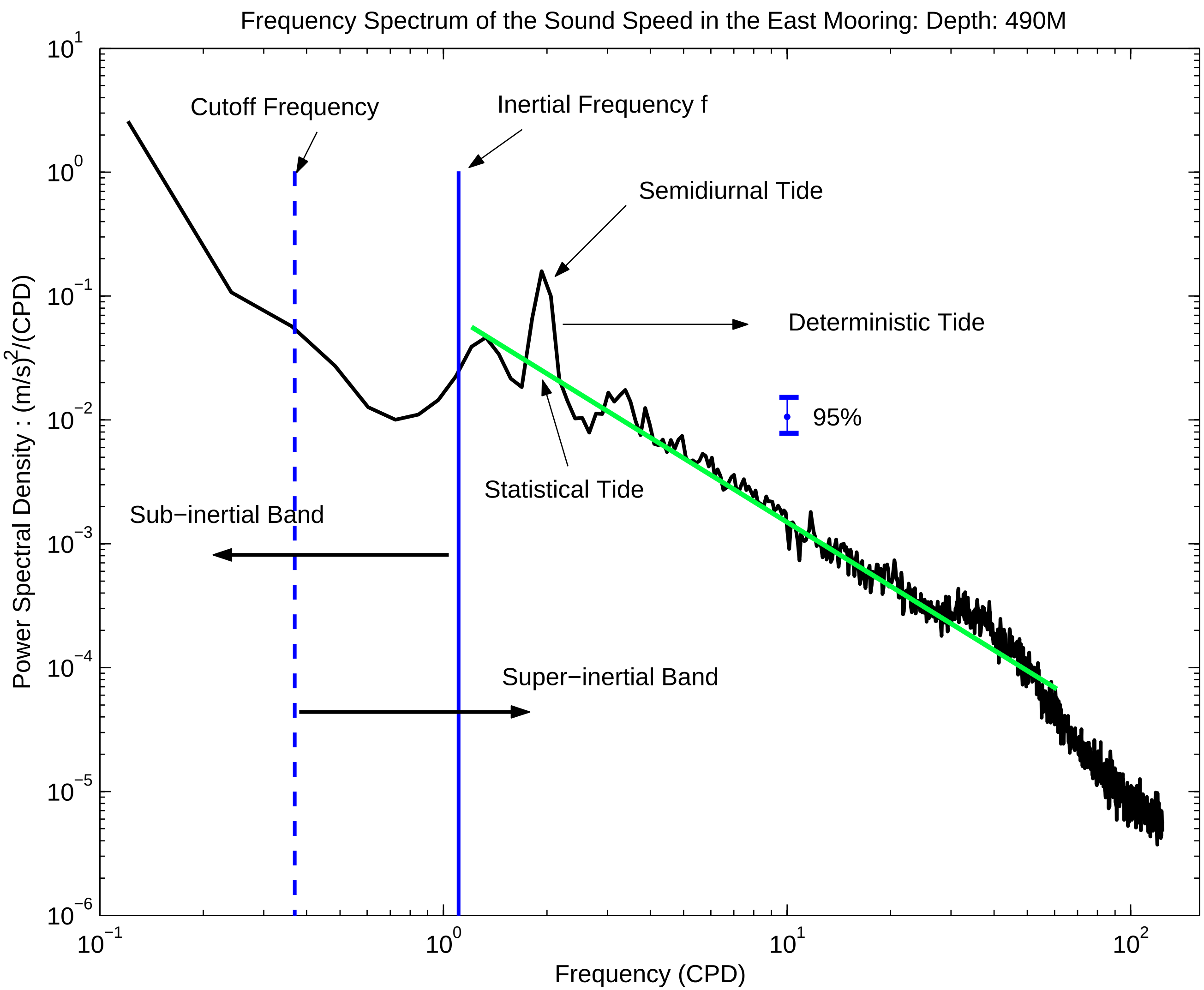




Time series of Temperature and salinity at different depths



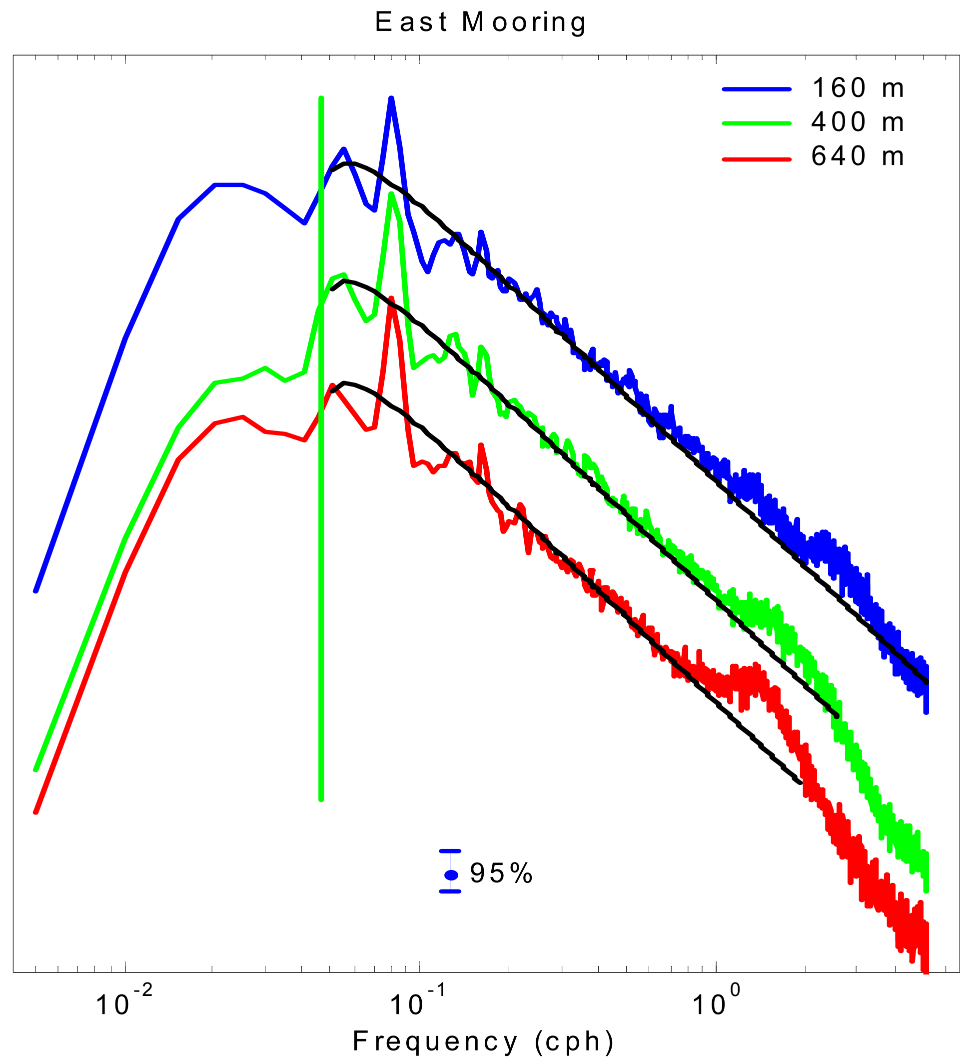
Frequency Spectrum of the sound speed at depth 490m



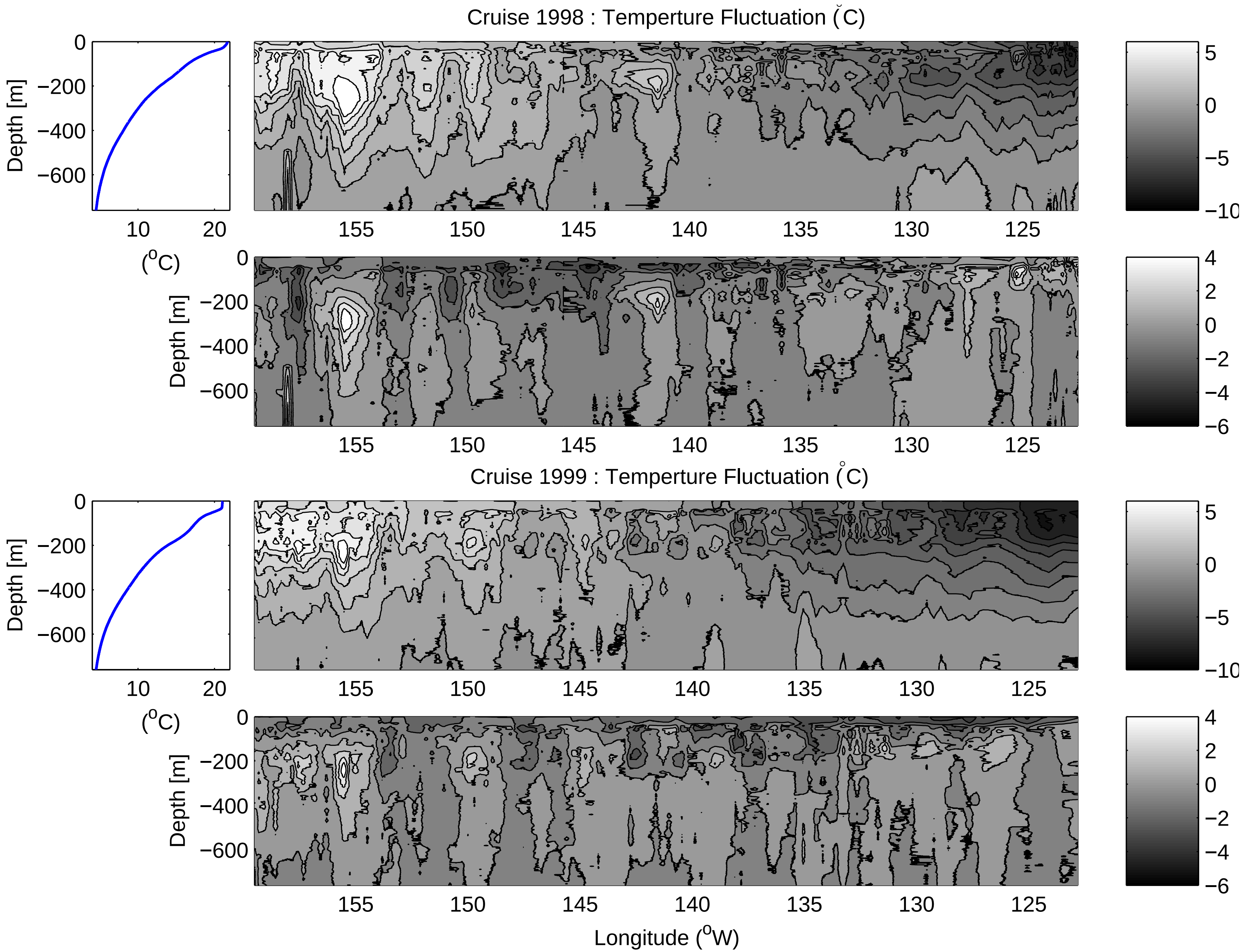
Garrett-Munk universal internal wave spectrum

- In the lower and main thermocline of ocean, the GM spectrum provides a zeroth order description of internal waves.
- The introduction of the GM model was a critical breakthrough in the 1970s to predicting observed acoustic fluctuations.
- There is a standard method to connect the sound speed fluctuation with displacement of internal waves.
  - Internal-wave-induced sound-speed perturbations are proportional to the product internal-wave-induced vertical displacements and potential sound-speed gradient.

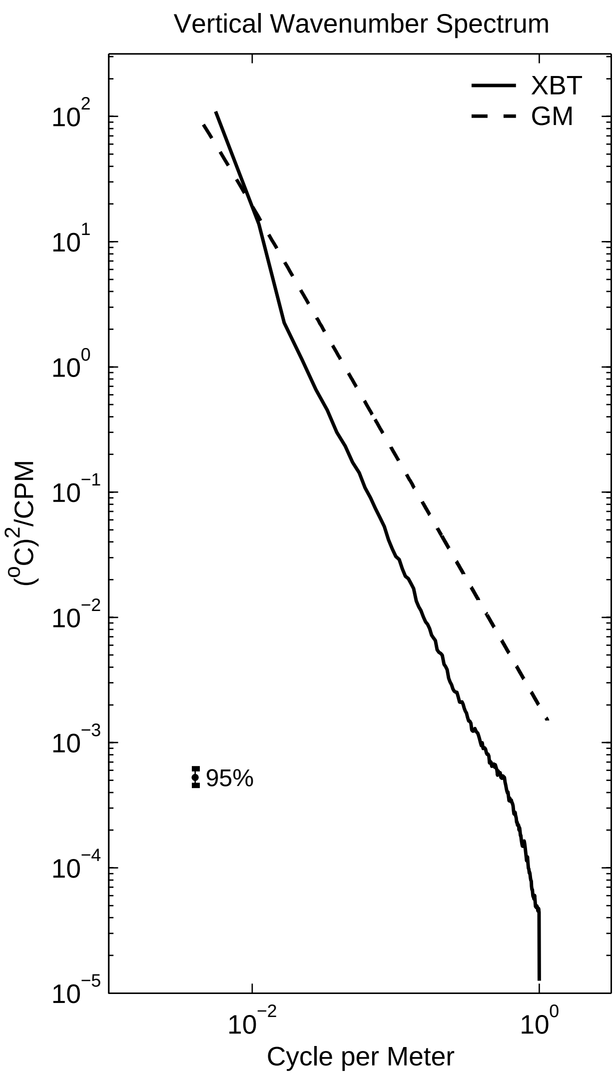
Frequency Spectrum of the Sound Speed Fluctuation in Super-inertial band at different depths / GM Spectrum

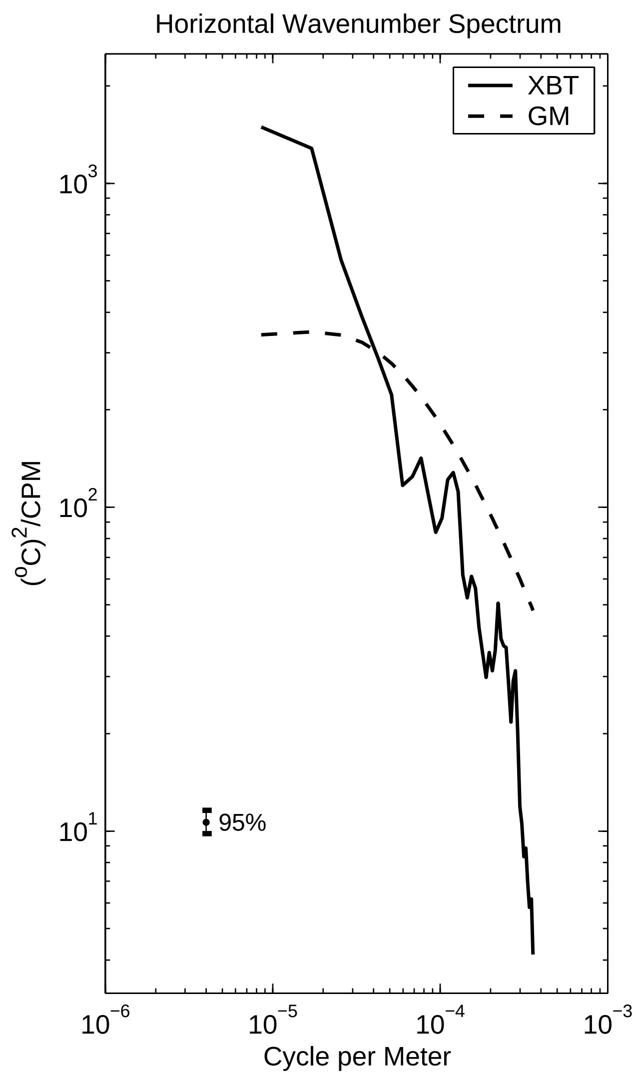


XBT measurements of Temperature in space scale.



Vertical/Horizontal Wavenumber Spectrum of the Temperature





What We Found

- The frequency spectra in the internal wave band are very GM-like.
- Similar observations show GM-like characteristics in the vertical/horizontal wavenumber Spectrum
- Internal wave induced sound-speed fluctuations are the dominant source of high-frequency variability of acoustic wave field in the deep ocean.
- In general, the comparison result shows GM internal wave model is a well set-up model under certain conditions (like in the North Pacific)

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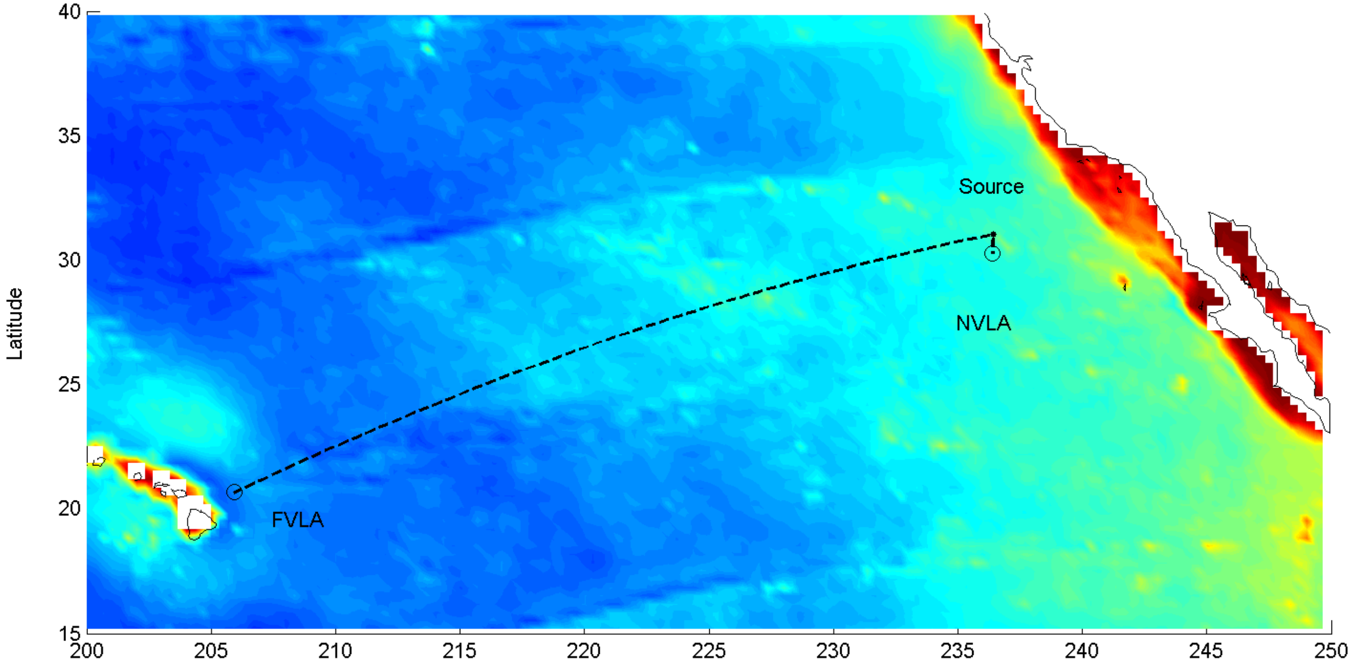
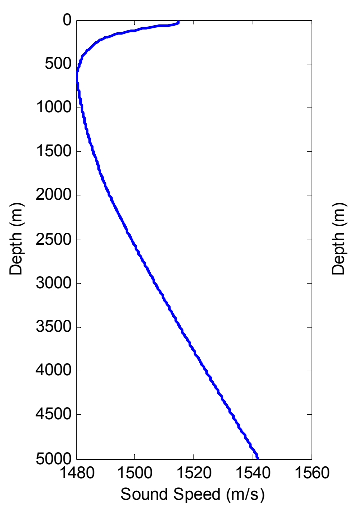
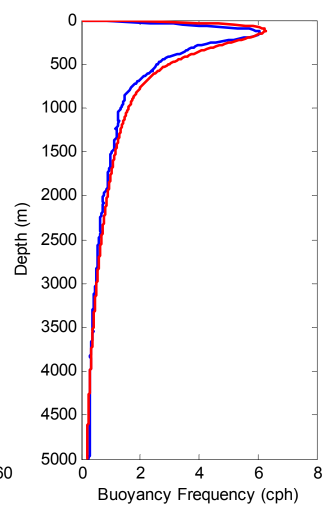
Space-time scales of Acoustic fluctuations for 75-Hz, broadband transmissions to 87-km range in the eastern North Pacific Ocean

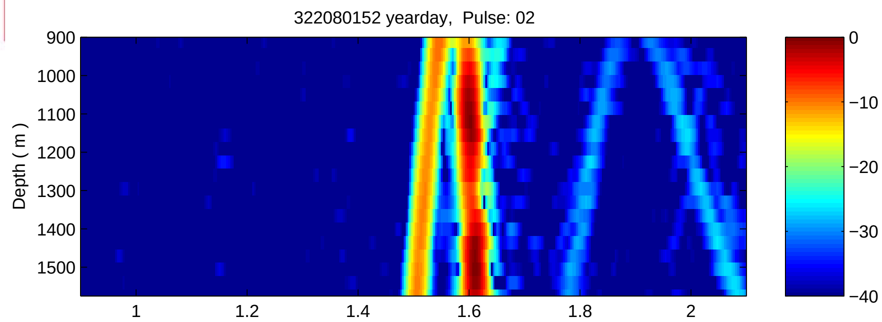


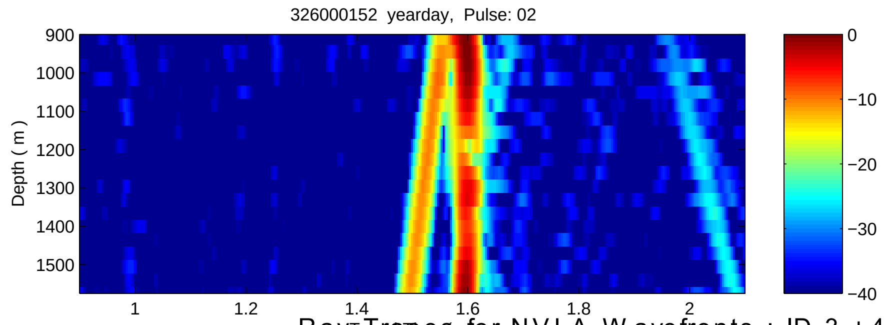


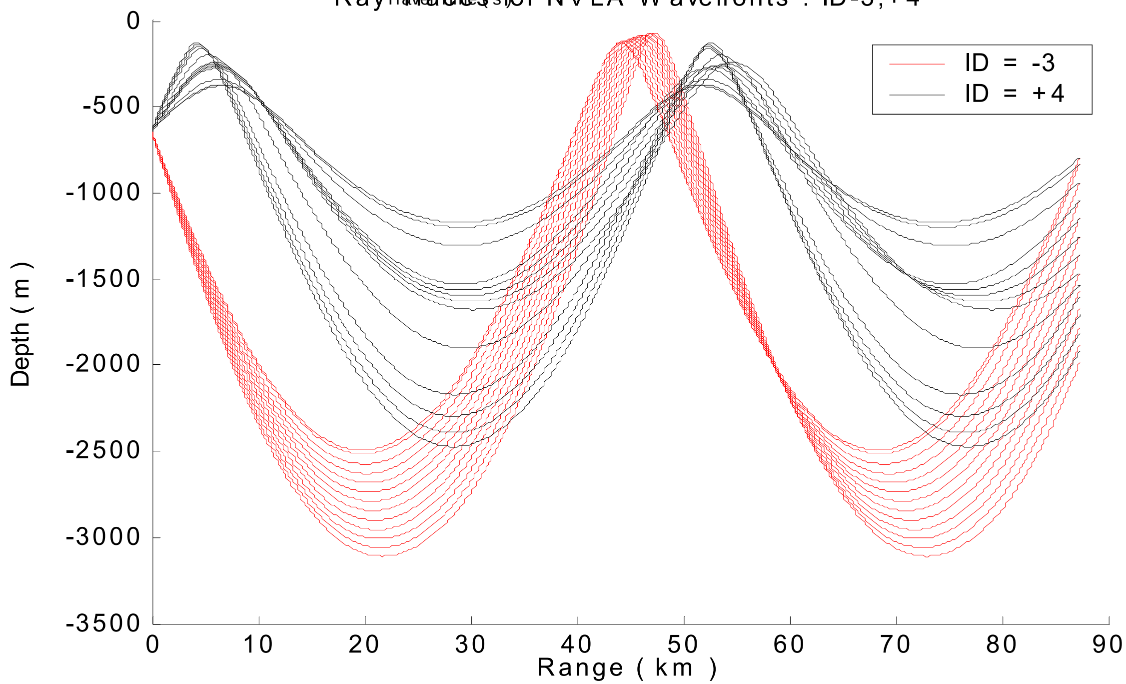


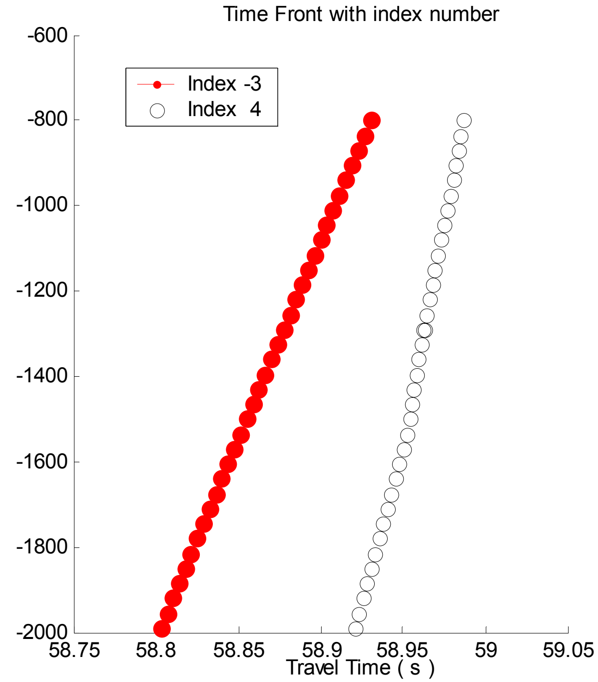
- **North Pacific, November, 1994**
- **Over 6 day period**
- **Broadband 75 Hz@ 650 m depth,**
- **20-element, 700-m long VLA @87Km distant, spanning the depth 900- 1600m**
- **70 transmission, 40 pulses 20 minute**

Examples of Observed Wavefronts

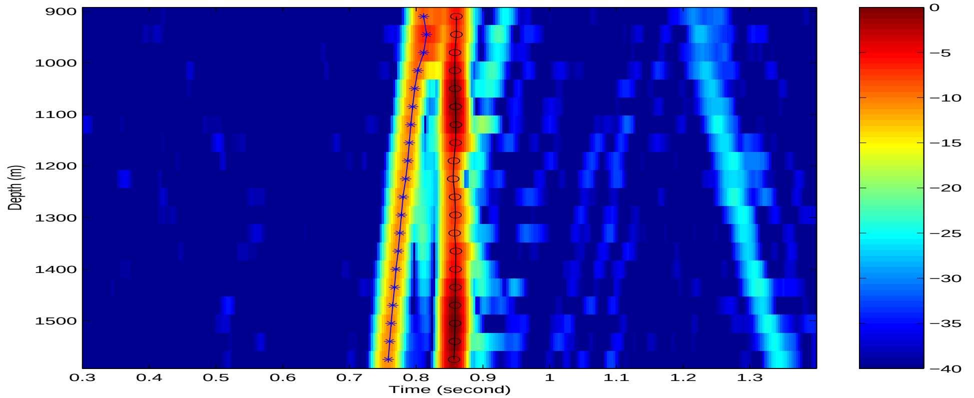


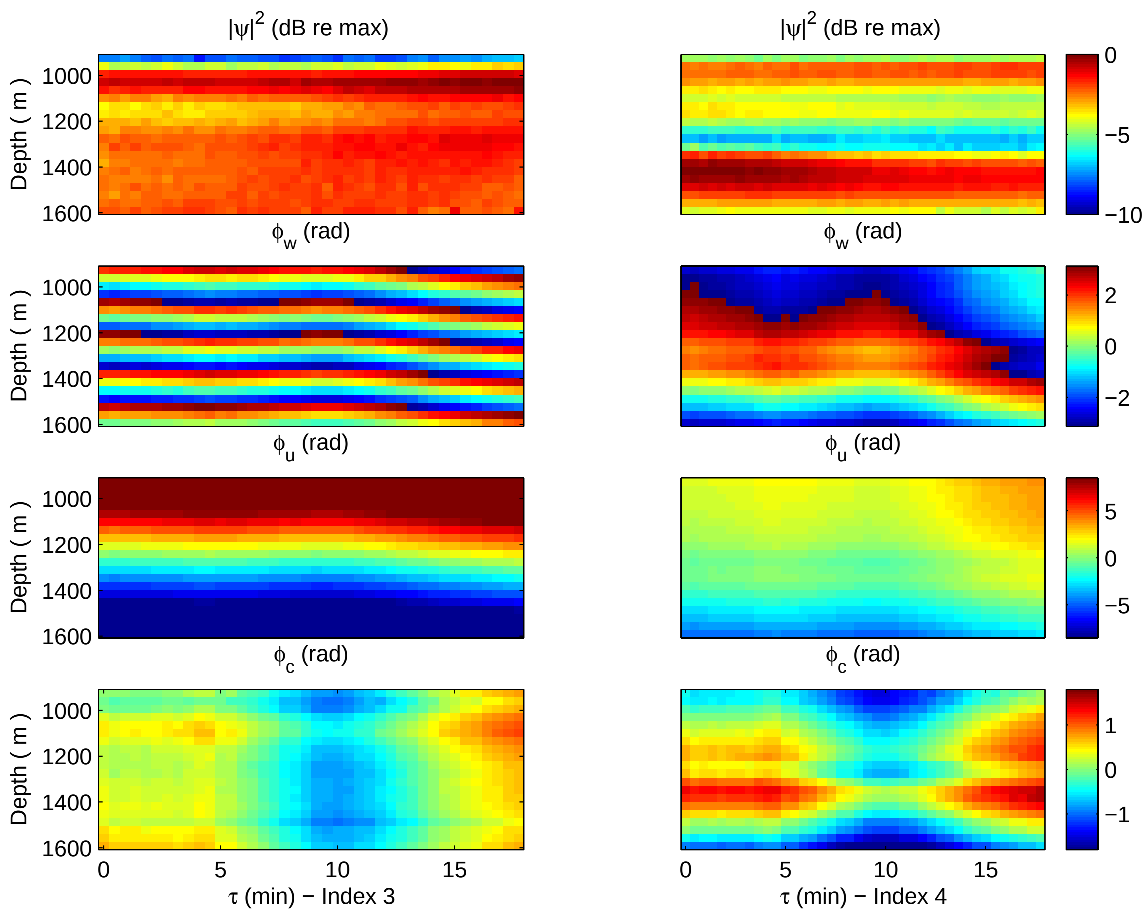






Procedure of Processing Data





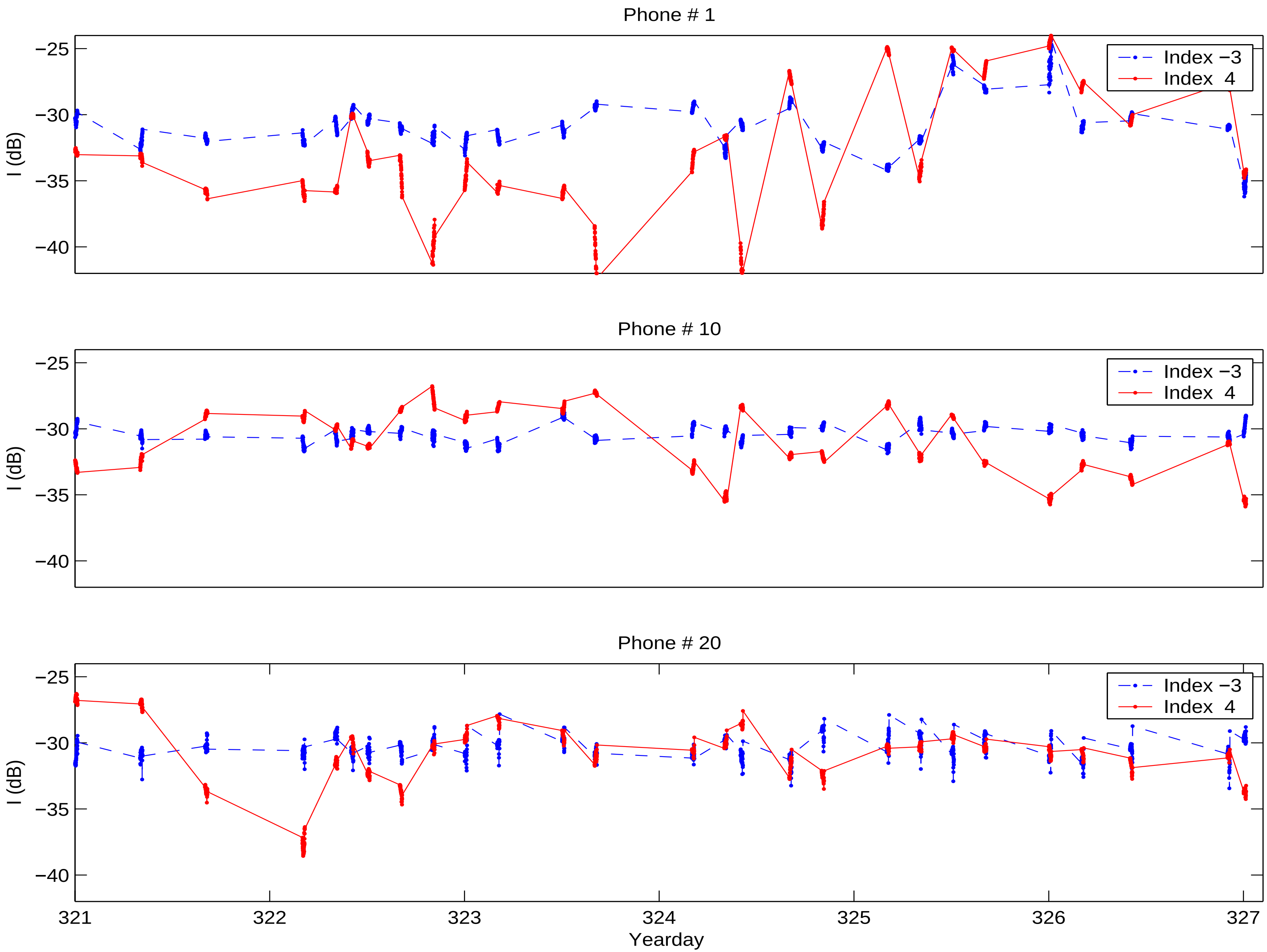
30 Good transmission

40 pulse per transmission

20 Hydrophone

30X40X20= 24000

Observed Intensity Time Series from Different Hydrophones



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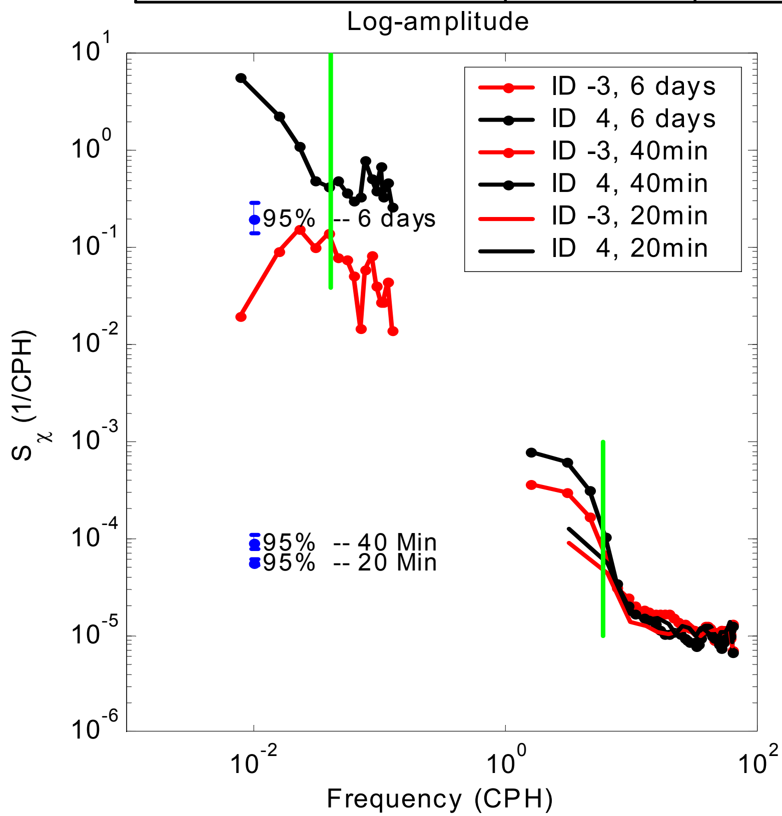
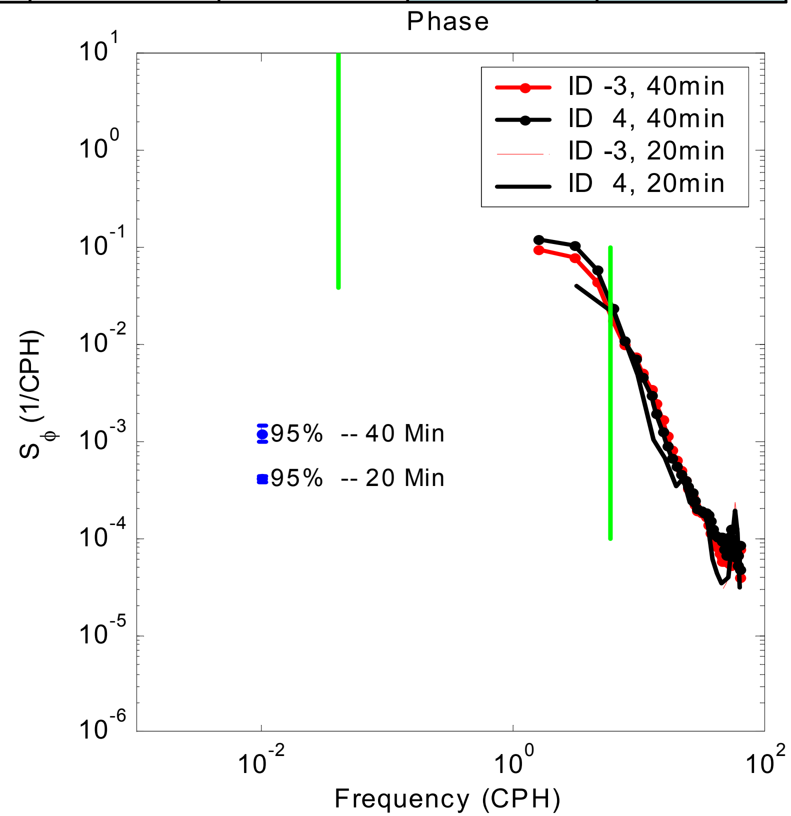
Three different time scales: 20, 40 minute and 6 day.

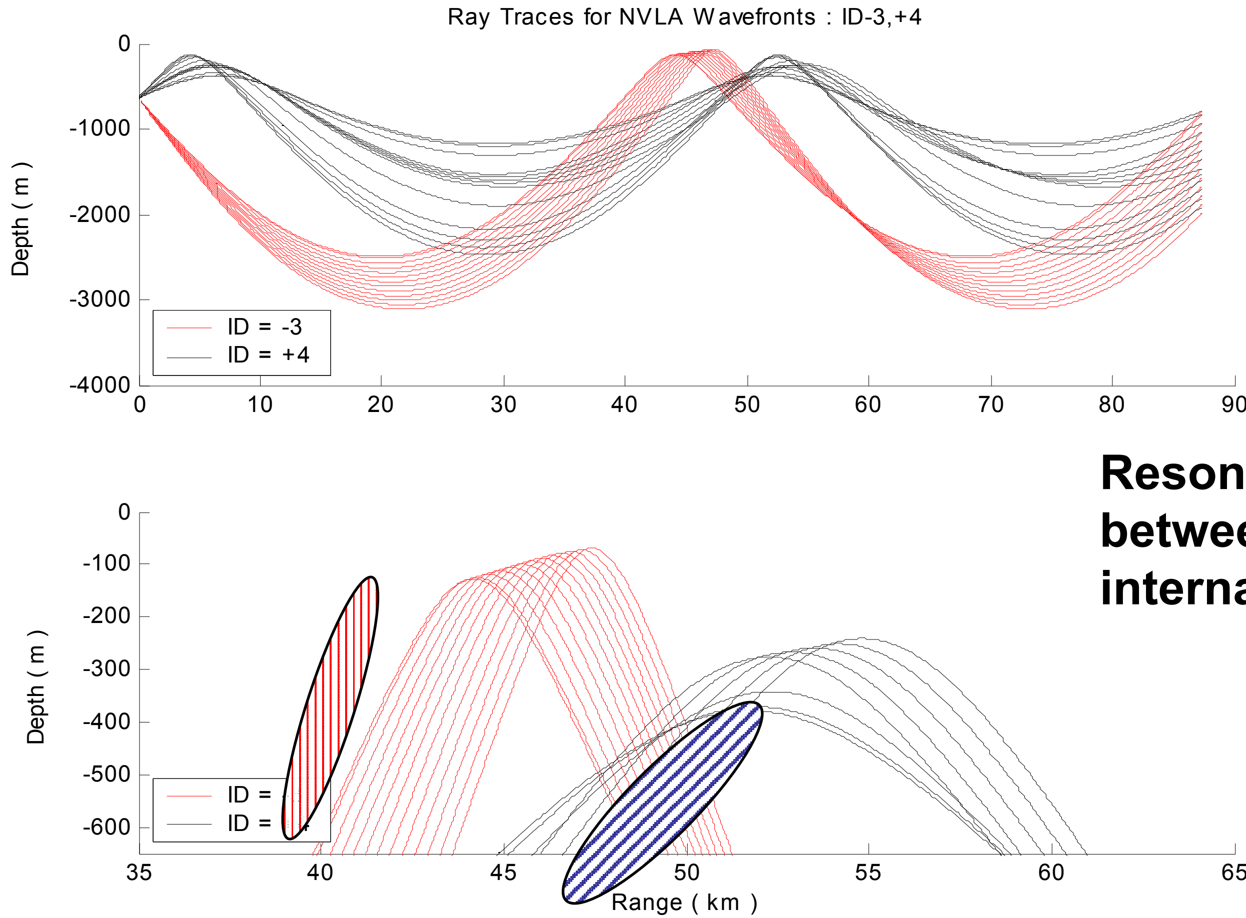
	20 Mins		40 Mins		6 Days	
	ID -3	ID4	ID -3	ID4	ID -3	ID4
$<Phi^2>^{1/2}$ (rad)	0.439	0.441	0.619	0.684		
$<I^2>^{1/2}$ (dB)	0.256	0.258	0.382	0.402	0.797	3.059
SI	0.004	0.005	0.009	0.013	0.044	0.43





Rytov theory (Munk& Zachariasen, 1976, JASA)

Why there is such big difference between arrivals in the low frequency region ?



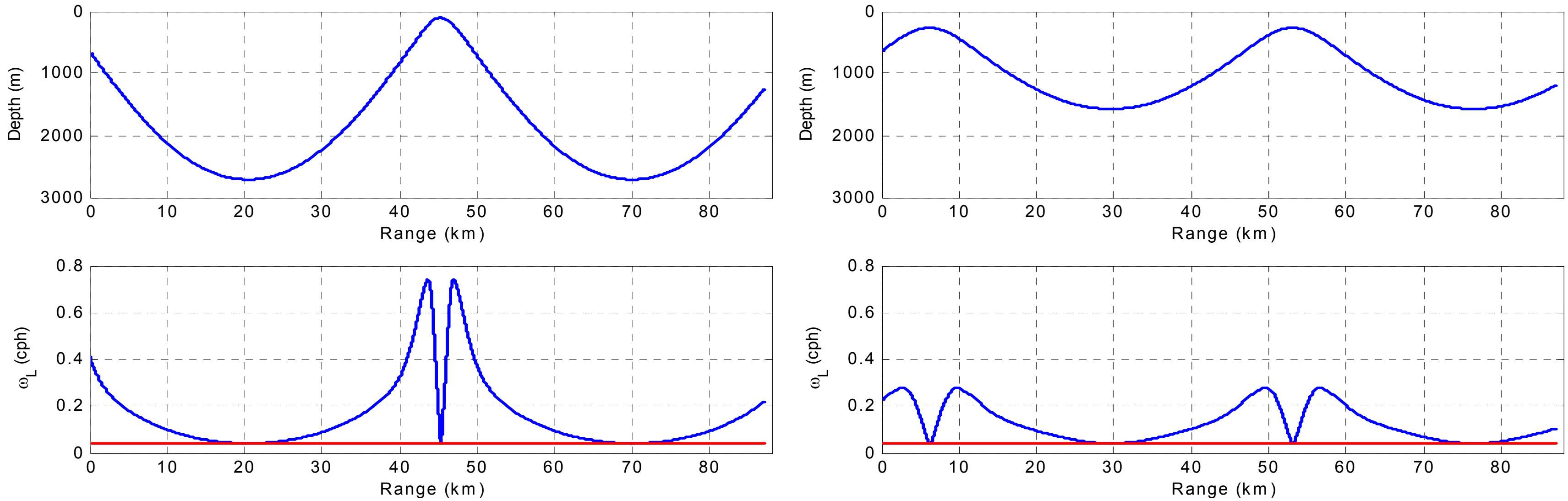
Resonance condition between ray and internal waves

Rays with high grazing angles do not acquire scattering contribution due to low frequency internal waves

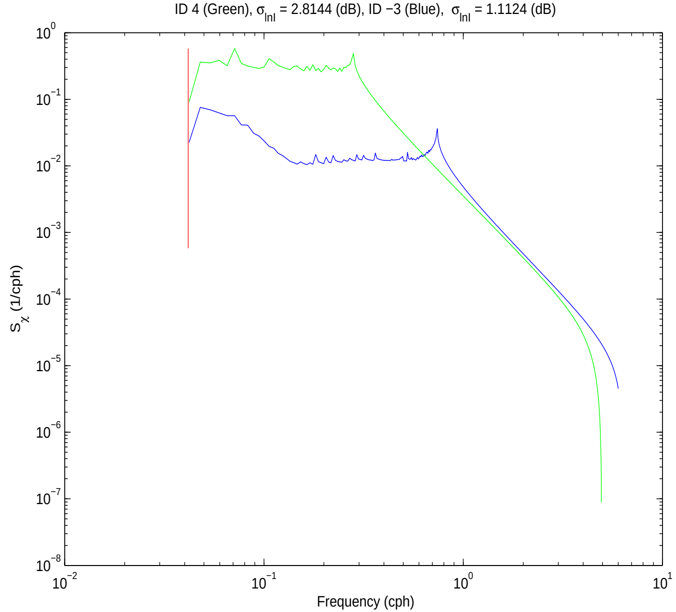
Rytov theory - Acoustic Filer and its cutoff frequency

ID -3

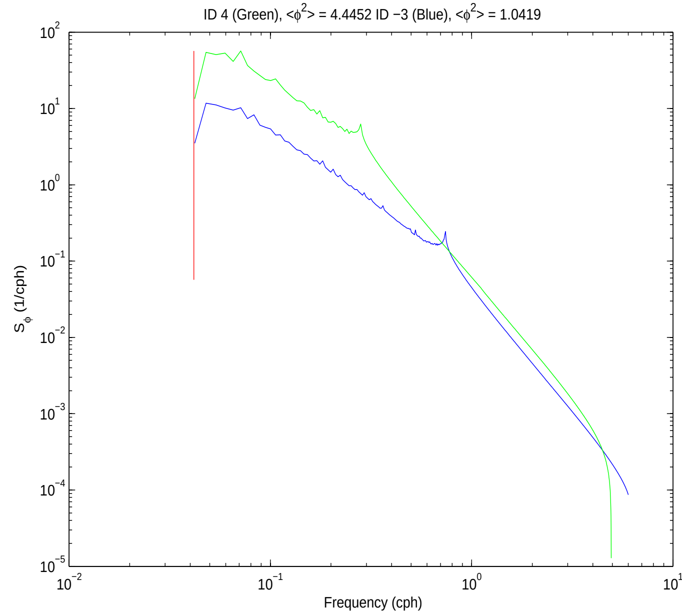
ID +4



ID 4 (Green), σ_{lnI} = 2.8144 (dB), ID −3 (Blue), σ_{lnI} = 1.1124 (dB)



ID 4 (Green), $\langle\phi^2\rangle$ = 4.4452 ID −3 (Blue), $\langle\phi^2\rangle$ = 1.0419



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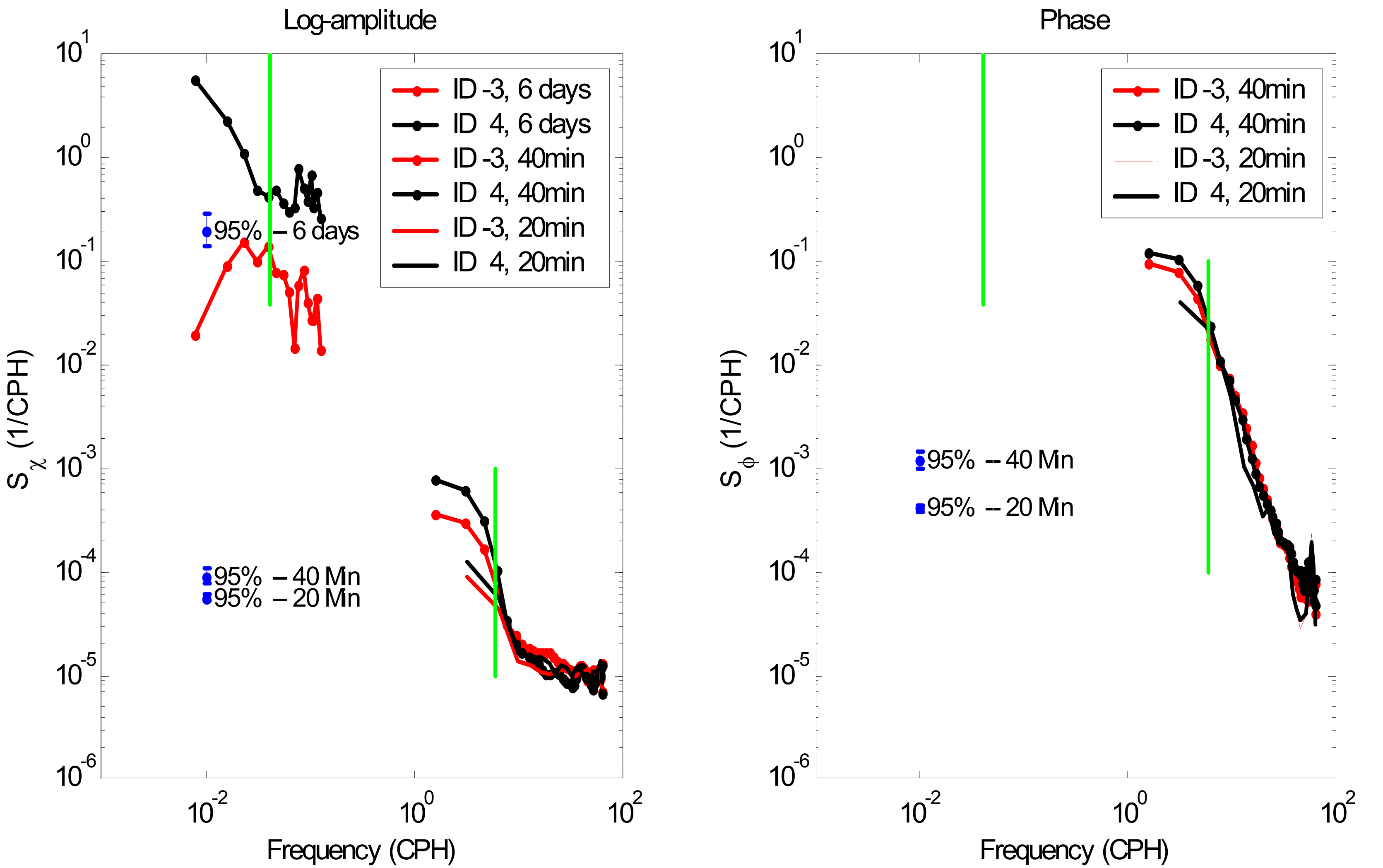
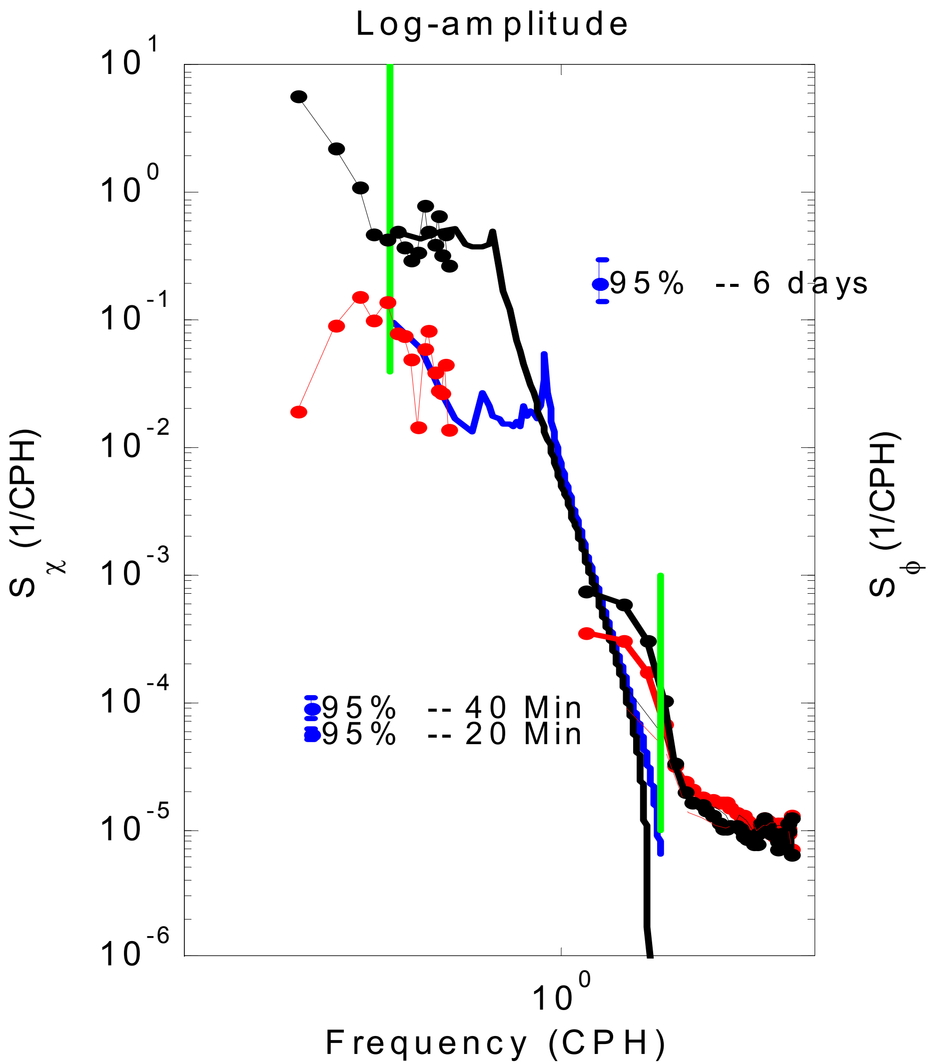
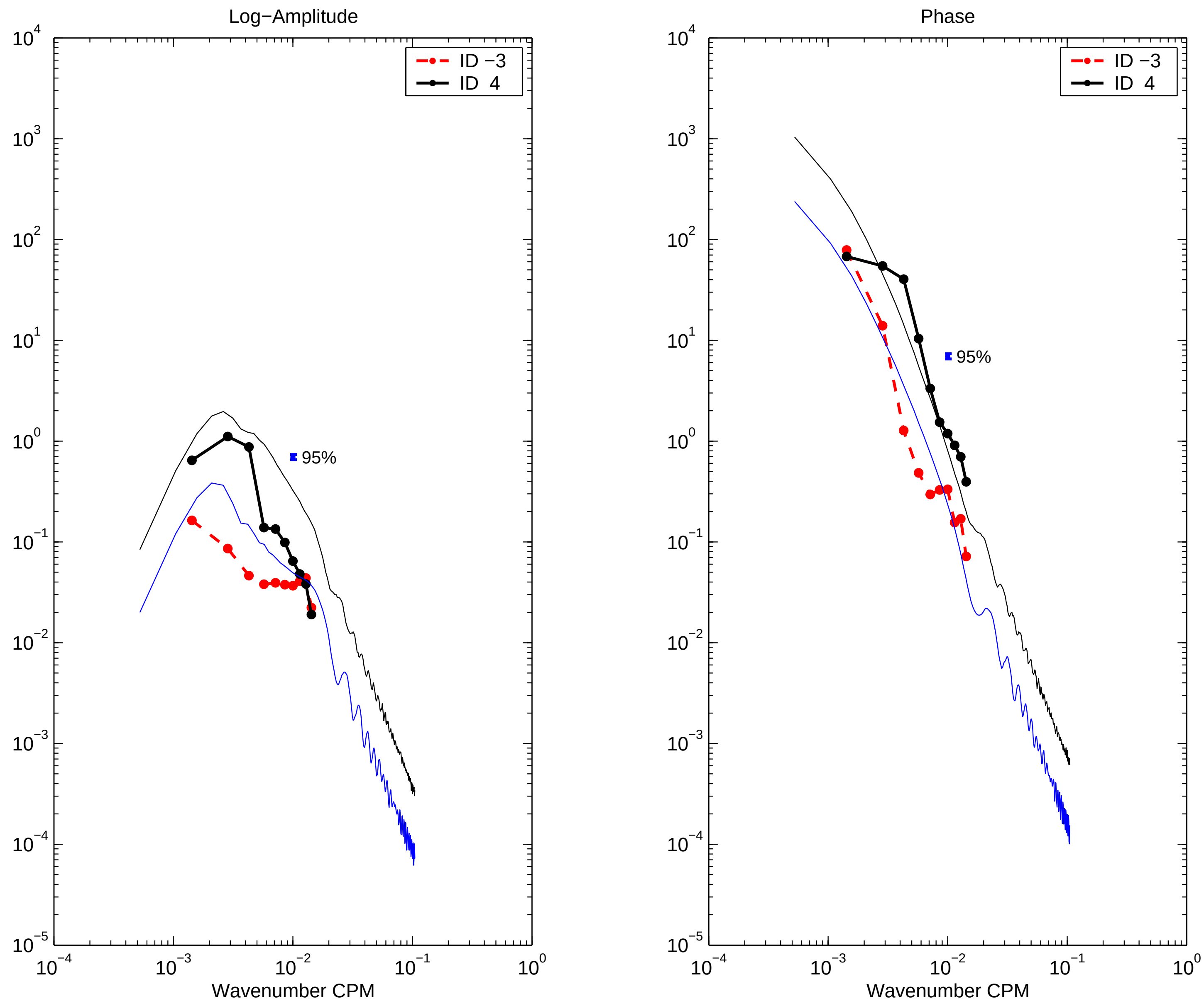


Comparison Between AET experiment and Rytov theory of Frequency spectrum



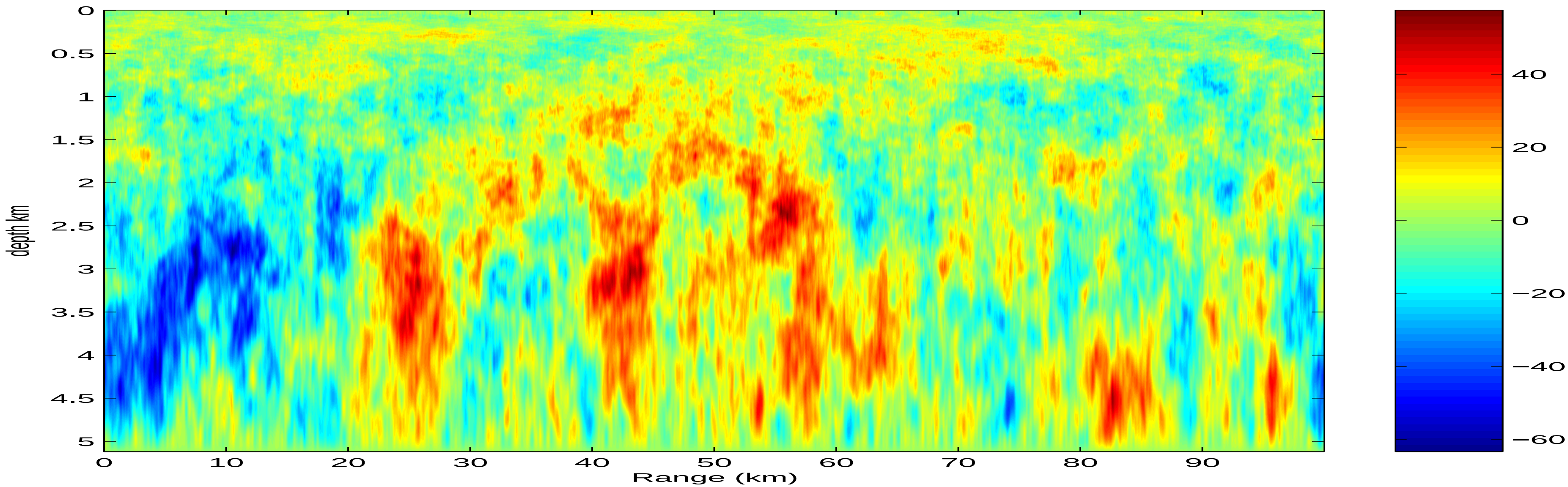
Comparison Between AET experiment and Rytov theory of Vertical Wavenumber spectrum

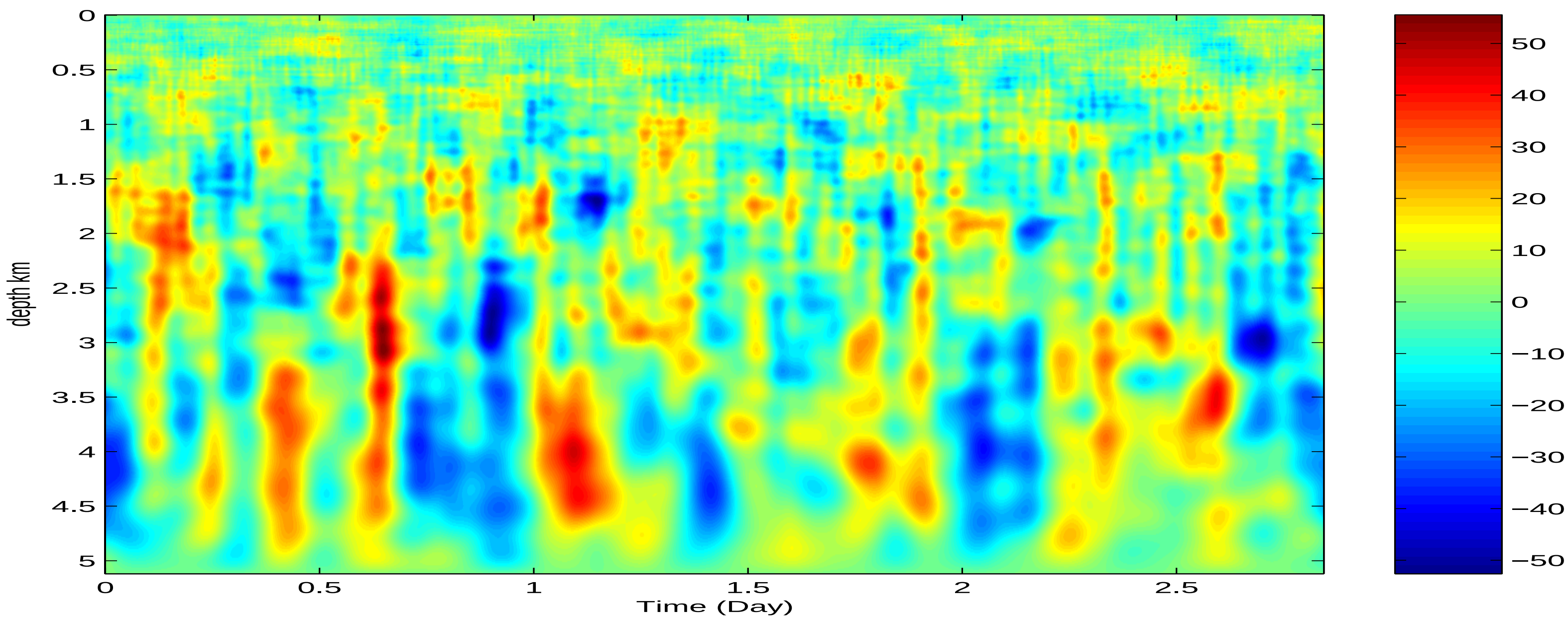


Monte Carlo Simulation

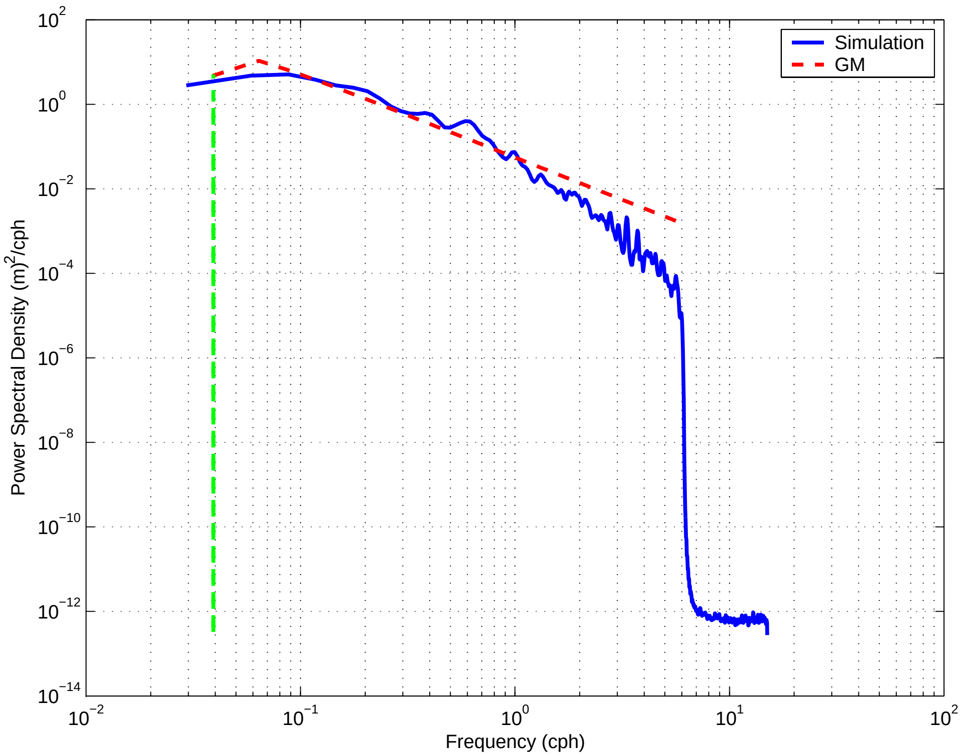
- Monte Carlo simulations are carried out by propagating the sound through the time evolved Internal wave field, which follows the internal wave dispersion relationship.
-
- Two Types of Monte Carlo simulation are implemented: Narrow Band and Broad Band.
-
  - Narrow band simulation is implemented by sending out two narrow beams with different beam tilt to simulate the multipath effect of AET experiment.
  - Broad band simulation is implemented by Fourier synthesis of CW results, which is composed of 60 different frequencies (from 45 to 105Hz) .

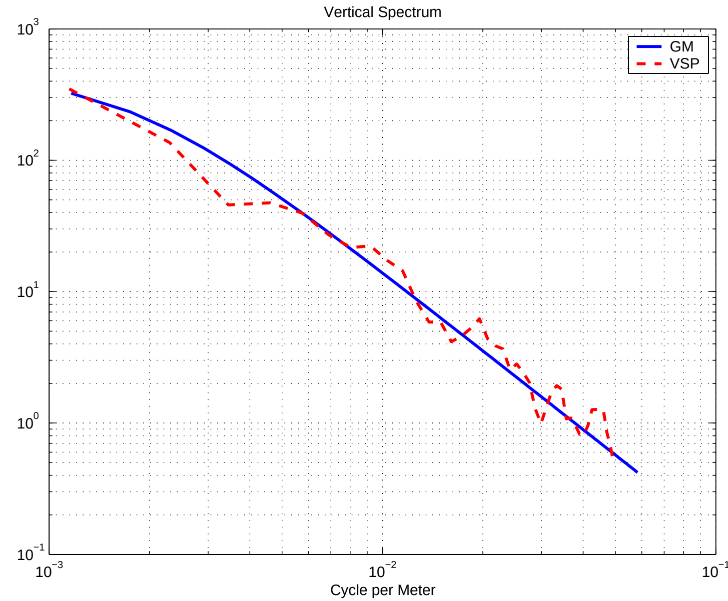
Internal wave field simulations

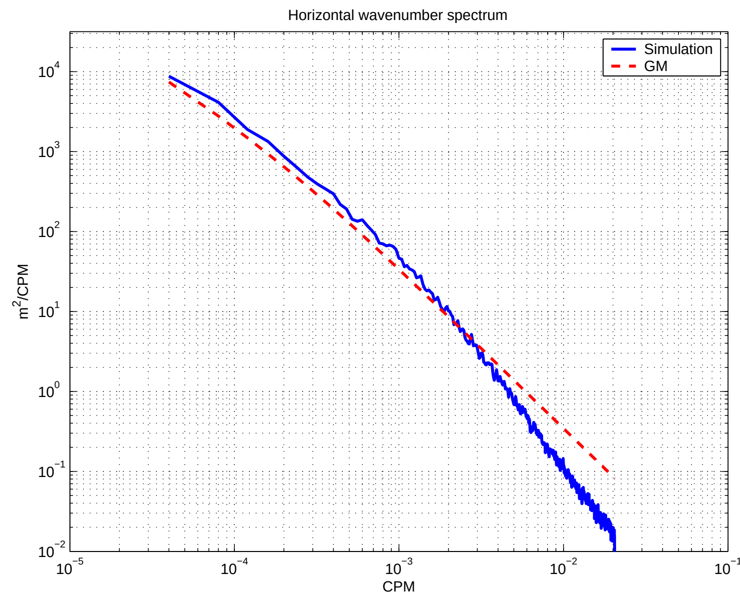




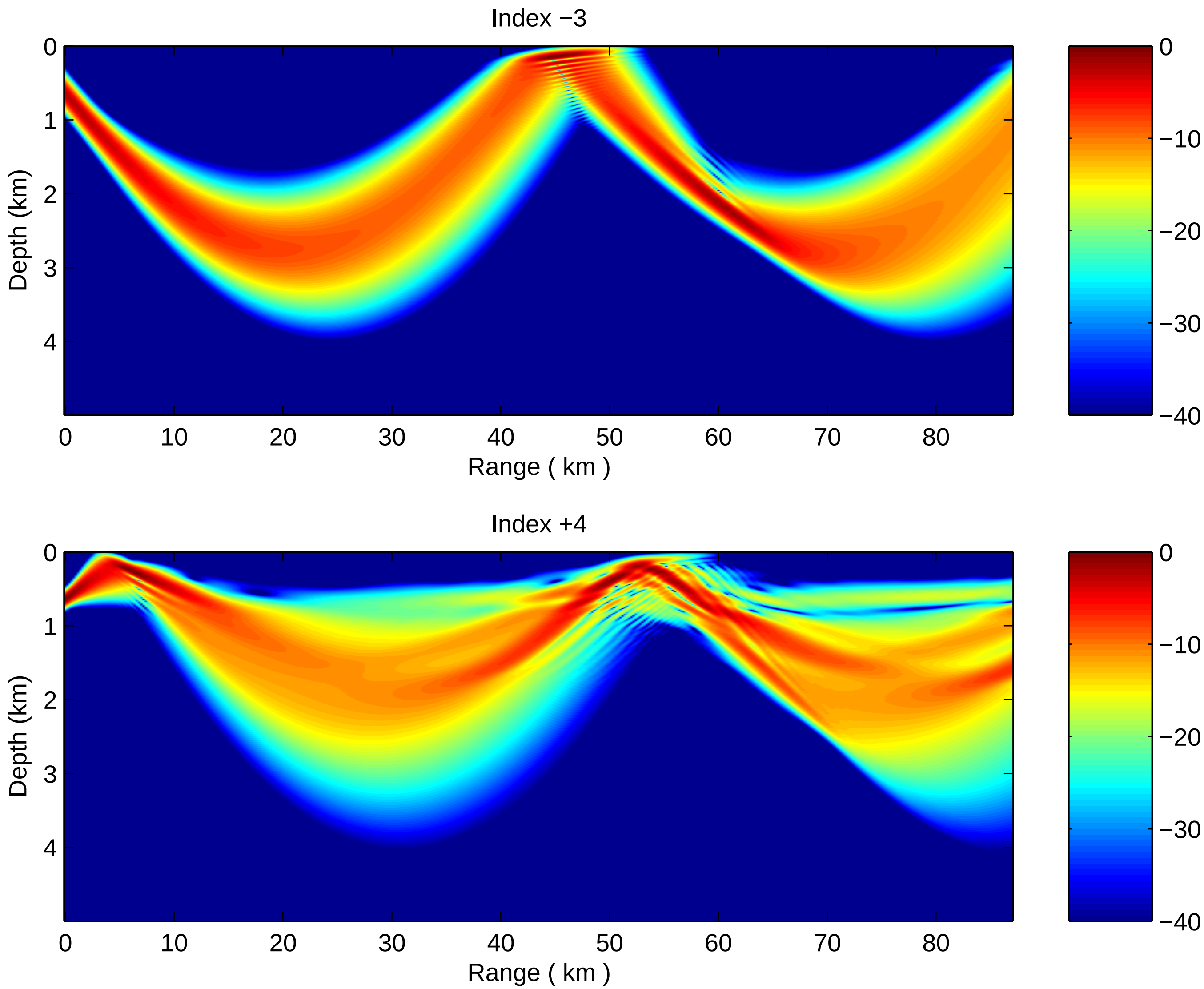
Spectra of Simulated Internal Wave



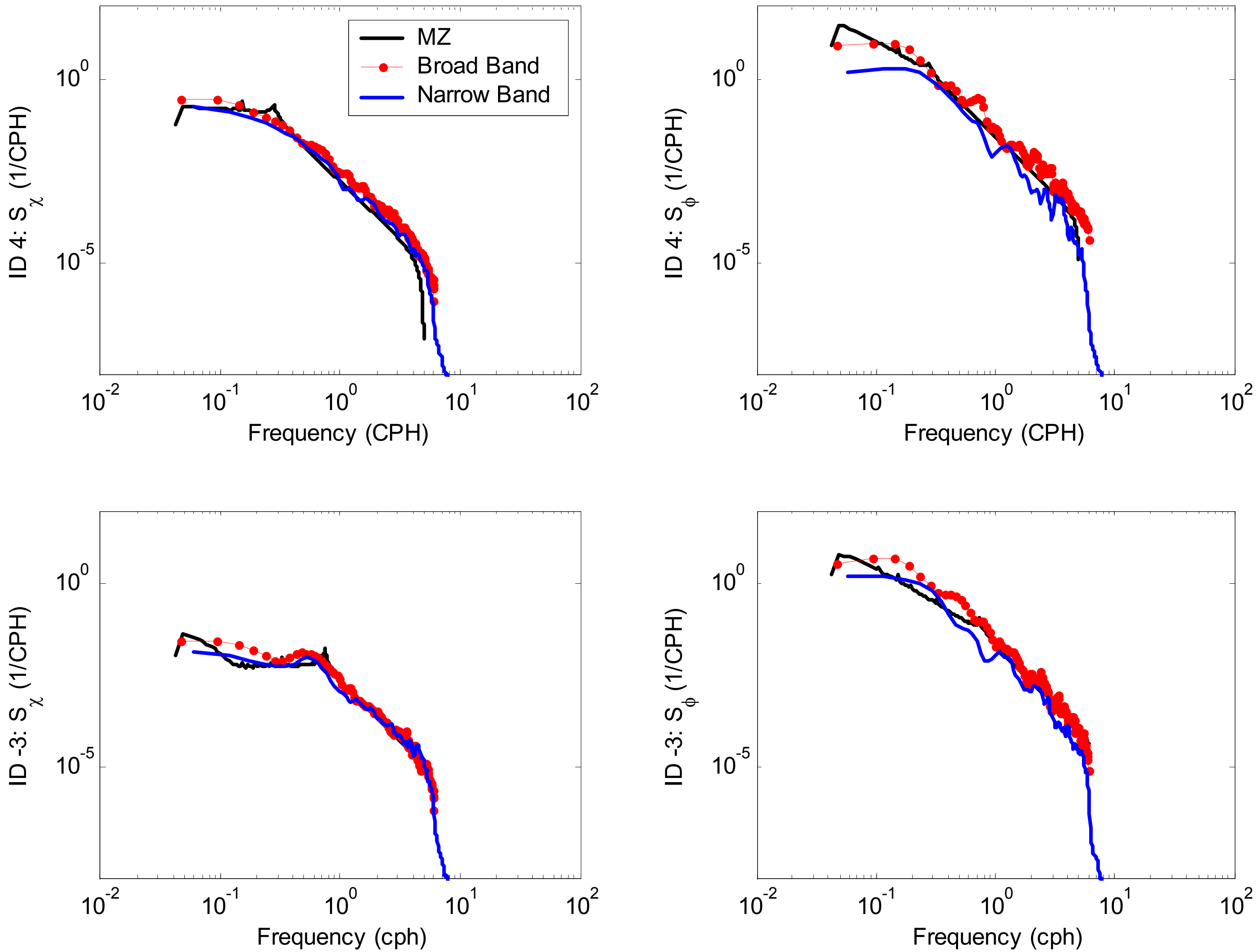




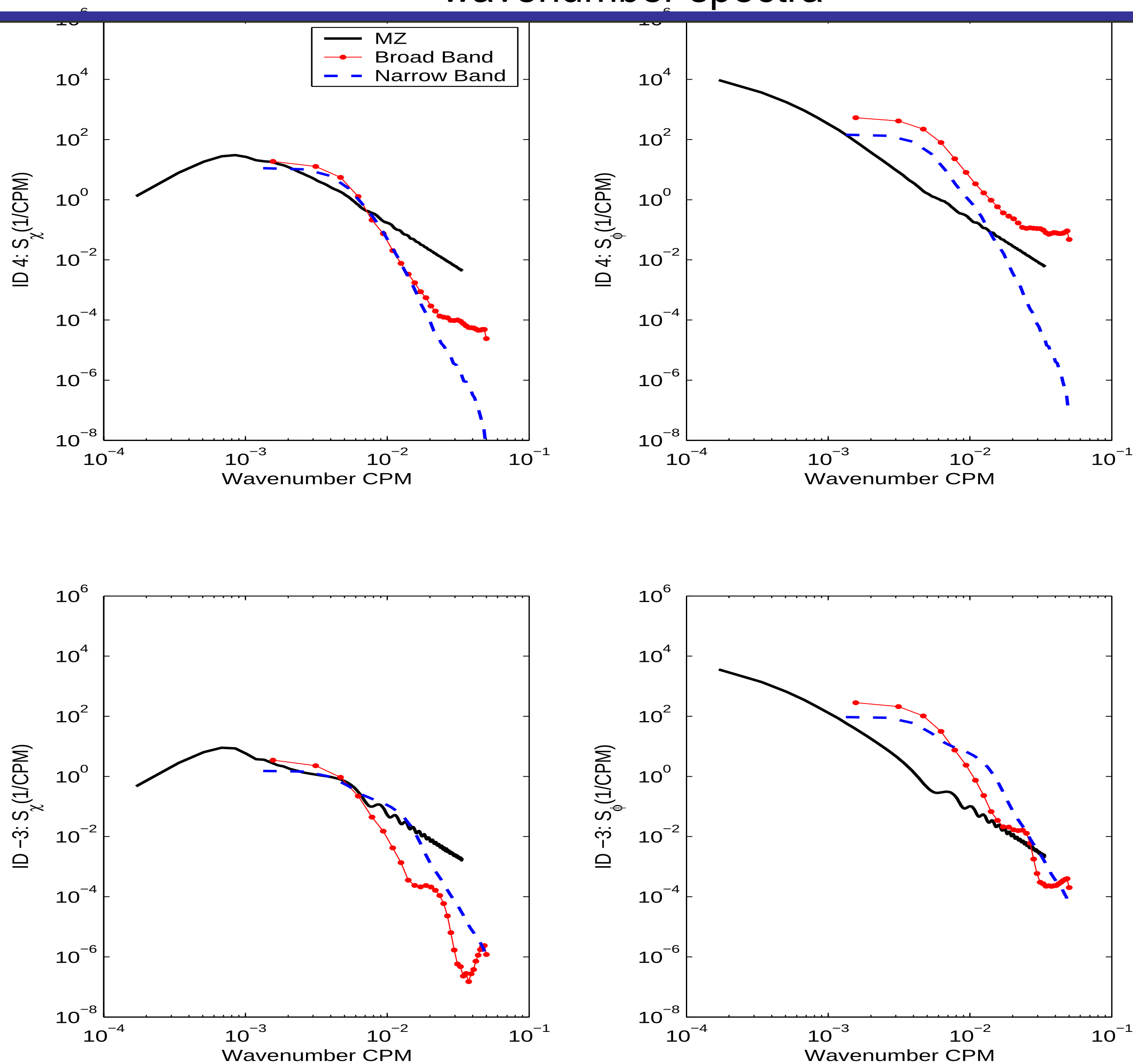
Narrow Band Beam Simulations



Comparison Between MZ theory and Monte Carlo Simulation



Comparison Between Rytov theory and Monte Carlo Simulation of vertical wavenumber spectra



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Summary and future direction

- Ocean Environmental Observations show the GM internal wave model is a well set-up model under certain conditions.
- The Rytov theory model and numerical model based on GM internal wave ocean model successfully describe the statistical variability of the acoustic fluctuations after 87 km range transmission in the deep ocean.
- Importantly the comparisons show that a resonance condition exists between the local acoustic ray and the internal wave field such that only the internal waves whose crests are parallel to the local ray path will contribute to acoustic scattering.
- This effect leads to an important filtering of the acoustic spectra relative to the internal wave spectra, such that rays with high grazing angles do not acquire scattering contribution due to low frequency internal waves.
- We believe that this is the first observational evidence for the acoustic ray and internal wave resonance.

- We have solved the acoustic scattering case after a one and two upper turning points. For long range acoustic propagation of order 1000-km involves order 10 or 20 scattering events, so can we push this theory prediction to further range?
- Improve ocean sound speed fluctuation model. GM internal wave model is still dominant, but we know there are some other processes other than internal waves.
- Broadband modeling of acoustic wave propagation.