LONG RANGE PROPAGATION OF FINITE AMPLITUDE ACOUSTIC WAVES IN AN OCEAN WAVEGUIDE

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Background: The nonlinear progressive wave equation (NPE) [McDonald and Kuperman, JASA, 1987] was developed to obtain accurate and affordable simulations of shock propagation in the deep ocean out to convergence zone ranges.

__Abstract__ The Nonlinear Progressive Wave Equation (NPE) [McDonald and Kuperman, 1987] computer code was coupled with a linear normal mode code in order to study propagation from a high intensity source in either shallow or deep water. Simulations using the coupled NPE/linear code are used to study both harmonic (high frequency) and parametric (low frequency) generation and propagation in shallow or deep water with long-range propagation paths. Included in the modeling are both shock dissipation and linear attenuation in the bottom.

Conclusion

What is the main difference between shallow and deep water ?

In shallow water,
- => lower number of modes (bottom interaction), faster time-separation of modes.
- => lower geometrical spreading, higher amplitudes, stronger nonlinear effects

How can we identify at long ranges a nonlinear acoustic propagation path ?

Redistribution of the energy during the propagation

Frequency-Mode Coupling
- frequency distribution
  - → parametric and harmonic generation
- modal distribution
  - → larger number of modes excited
  - → tendency toward modal equipartition
  - → changes in the arrival time structure

Nonlinearities can give effects similar to long-range propagation in random media:
- → modal distribution + arrival time structure
- → increased sea-bottom coupling (NL candidate for T-phase generation)

Nonlinear Progressive wave Equation (NPE)

McDonald & Kuperman, *J. Acoust. Soc. Am.* **81**, 1406-1417, 1987.

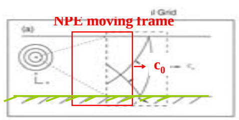
$$\partial_t p = -\partial_x\left[c_1 p + \frac{\beta}{2\rho_0 c_0} p^2\right] - \frac{c_0}{2}\int_{+\infty}^{x} \nabla_\perp^2 p\, dx + \frac{\delta}{2}\partial_x^2 p + 0.02\,\alpha_{(dB/\lambda)}\,\frac{c_0}{2}\int_0^{+\infty}\frac{p(x')}{x-x'}\,dx'$$

Bottom attenuation

Diffraction : Crank-Nicholson

Thermoviscous dissipation : Finite difference scheme

Refraction + Nonlinear steepening : Second order upwind flux corrected transport scheme [B. E. McDonald, *J. Comp. Phys.* 56, 448-460, (1984)]



moving frame time incremental step $\Delta t = \Delta x/c_0$

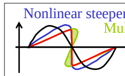
Important for an ocean waveguide:
- Refraction included.
- Porous medium attenuation in the bottom

Integration region (moving spatial frame) :

$x_{min} < x < x_{max}$

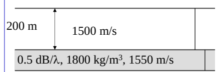
Nonlinear effects

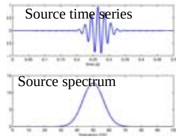
- Additional frequencies — harmonic generation (2f, 3f, 4f,...)
- Broader frequency spectrum — parametric interaction ($f_1 \pm f_2$)
- Structure changes during propagation — shock dissipation



- more uniform modal distribution
- self-refraction

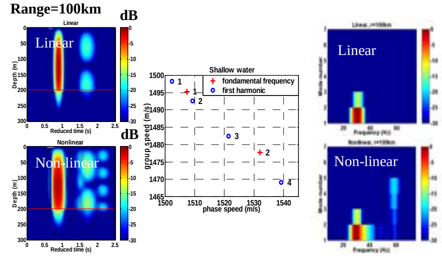
Shallow water Pekeris waveguide



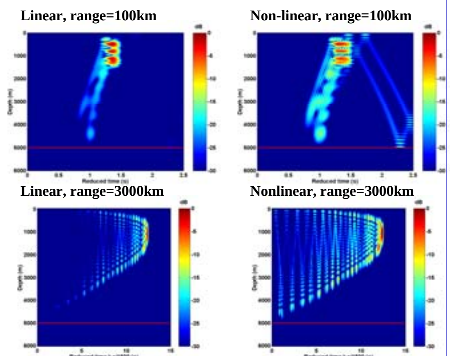


Source 50Hz narrowband, depth 100m

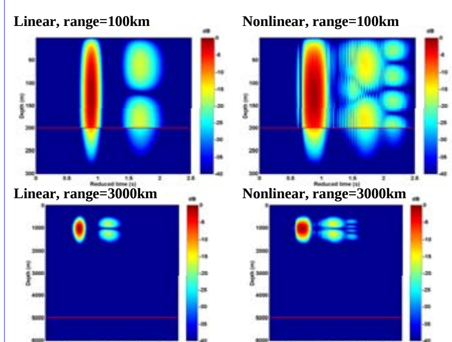
Source over density Rm=3.5 10^{-3}.



Time series, deep water ocean waveguide

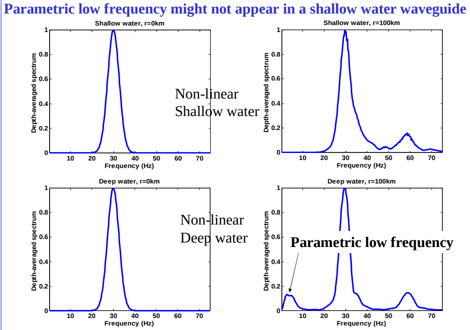


Time series, shallow to Deep water



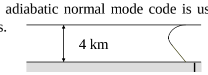
Normalized depth-averaged spectrum

Parametric low frequency might not appear in a shallow water waveguide

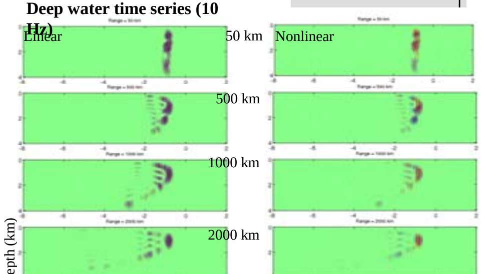


Long range propagation

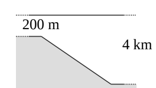
For both shallow and deep water the NPE is propagating the field the first 20 km where nonlinearities are strong. An adiabatic normal mode code is used for propagating the field to longer ranges.

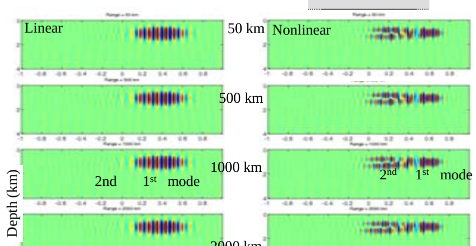


Deep water time series (10 Hz)



Shallow to deep water (10 Hz)

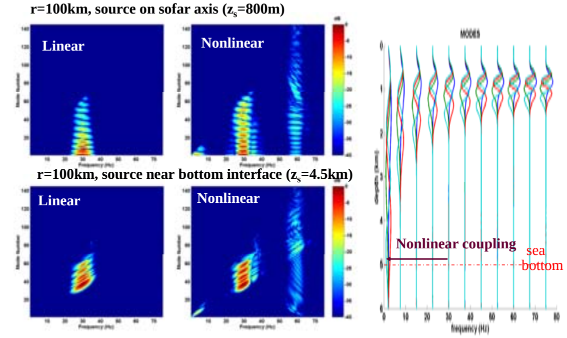




Only few modes excited: little time spread, energy close to sound speed axis.

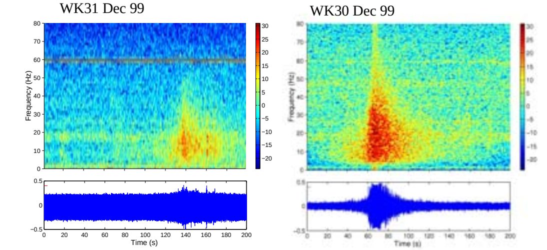
The Nonlinear propagation excite higher order modes

Deep water ocean waveguide: influence of parametric mode conversion on sea-bottom coupling



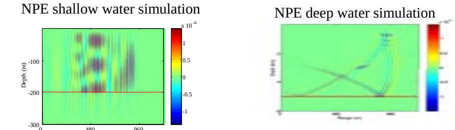
Frequency-mode coupling → Increased sea-bottom coupling (nonlinearities can be candidate for T-wave formation)

But, we also work with real data!



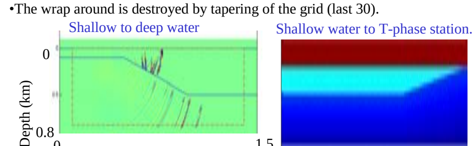
MOVIES!

The nonlinear NPE code and a time domain finite difference code (Cabrillo) and are used to generate movies.



In Depth FDTD modeling: Using Cabrillo

- Staggered Fourier pseudo spectral method
- Fourier spectral methods requires less grid points than classical FD (l/2 vs l/10)
- Can model both acoustic, elastic and poroelastic (Biot) media.
- FD method can better model variations in sound speed (including bathymetry) than classical ocean acoustic propagation codes. Any grid point can have different properties!
- The wrap around is destroyed by tapering of the grid (last 30).



- Cair=0 m/s, Cwater=1500 m/s, Cbot=2500 m/s
- Source at 70 m depth
- Field tapered outside red box