NONLINEAR EFFECTS IN LONG RANGE PROPAGATION

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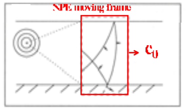
Background: The nonlinear progressive wave equation (NPE) [McDonald and Kuperman, JASA, 1987] was developed to obtain accurate and affordable simulations of shock propagation in the deep ocean out to convergence zone ranges.

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 Results presented here suggest that undersea explosions may be characterized by studying their spectral evolution over long-range nonlinear acoustical propagation. In shallow water, the signal interacts with the bottom earlier than in deep water, thus initially lower geometrical spreading is obtained (cylindrical versus geometric spreading). Therefore, signal amplitudes are initially higher than in the deep-water case, causing stronger nonlinear effects. The nonlinear effects will cause the frequency spectrum to be broader and will usually excite a broader spectrum of modes, with more relative energy for the high order modes. In shallow water, low order modes travel faster than high order modes and the nonlinearity will give a larger time spread of the received pulse.

NPE algorithm


NPE moving frame

$$\partial_t p = -\partial_x\left[c_1 p + \frac{\beta}{2\rho_0 c_0}p^2\right] - \frac{c_0}{2}\int_{-\infty}^{x}\nabla_\perp^2 p\,dx$$

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

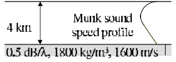
Diffraction Step :
Crank-Nicholson scheme

time incremental step $\Delta t = \Delta x / c0$ of the moving frame

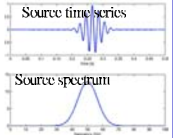
Integration region (moving spatial frame) :
$x_{min} < x < x_{max}$

Self-refraction included. Important for ocean waveguide.

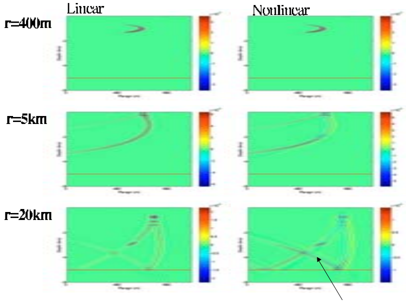
Deep-water waveguide



Source: 50Hz narrowband, depth 100 m
Source over density Rm=3.5 10^{-3}.

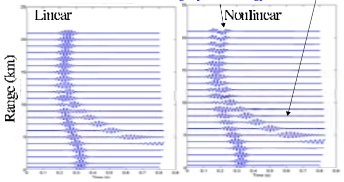


Snapshots



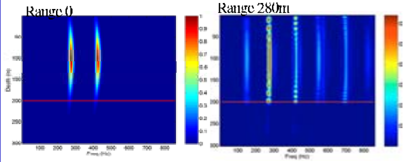
Bottom bounce

Slightly more energy in tail

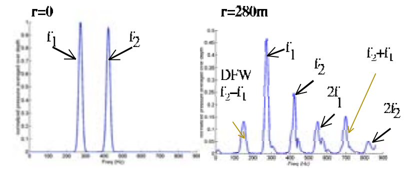


Two narrowband sources in shallow water

Normalized spectrum for two narrowband sources (275 Hz, 425 Hz)



Normalized depth averaged spectrum.

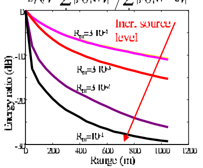


The nonlinearities generate additional frequencies:
harmonic energy and parametric energy

Energy

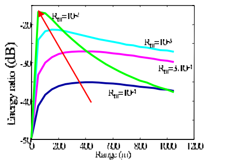
Source strength is measured in dimensionless dynamic density, Rm=r'/r_0,
where r_0 is the static density

Total Energy
$E_t(r)=\sum|p(f_i,r)|^2 / \sum|p(f_i,r=0)|^2$



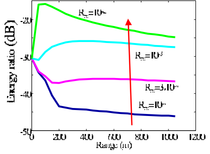
Higher source levels have more relative energy dissipation

Harmonic energy
$E_h(r)=\left(|p(2f_1,r)|^2+|p(2f_2,r)|^2\right)/E_t(r=0)$

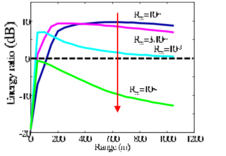


Maximum of the harmonic energy corresponds to shock wave formation distance.

Parametric energy (dB)
$E_p(r)=|p(f_2-f_1,r)|^2/E_t(r=0)$

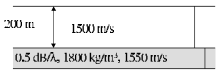


Ratio harmonic/parametric energy,
E_h/E_p



-For high source levels parametric energy is dominating.
-The harmonic energy decays faster in range

Shallow water Pekeris waveguide



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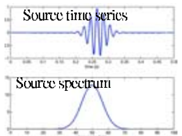
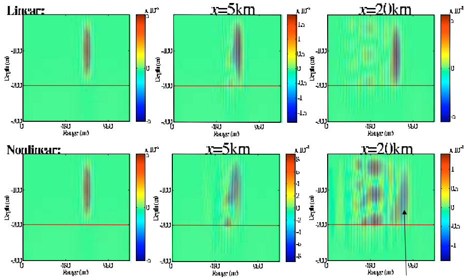
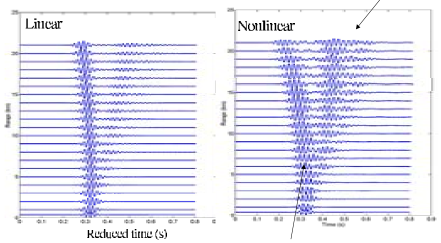


Snapshots



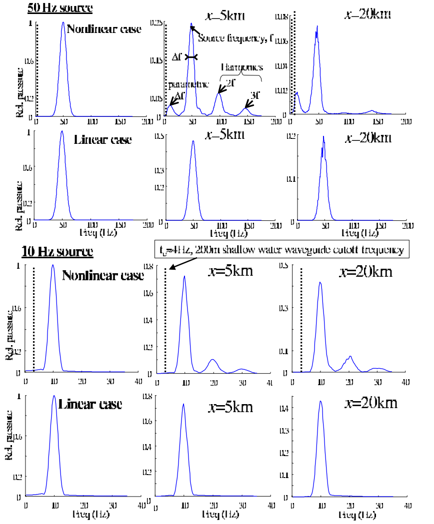
Nonlinear wave has longer tail

Range stacked time series



Steeper waveform at 3-6 km

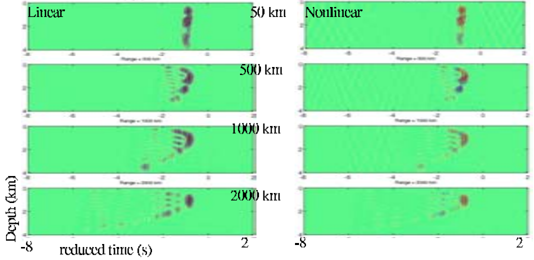
Depth averaged pressure normalized with first range



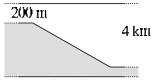
Long range propagation

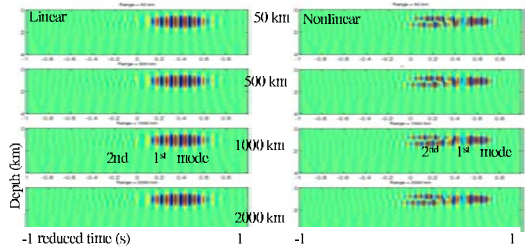
For both shallow and deep water the NPE is propagating the field the first 20 km where nonlinearities are strong. An adiabatic normal mode code is used for propagating the field to longer ranges.

Deep water time series (10 Hz)



Shallow to deep water (10 Hz)



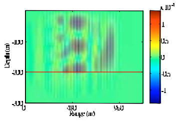


Only few modes excited: little time spread, energy close to sound speed axis.
The Nonlinear propagation excite higher order modes

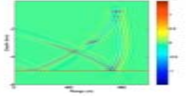
MOVIES!

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

NPE shallow water simulation



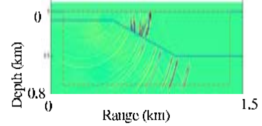
NPE deep water simulation



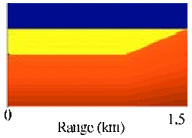
In Depth FDTD modeling: Using Cabrillo

- Staggered Fourier pseudo spectral method
- Fourier spectral methods requires less grid points than classical FD (1/2 vs 1/10)
- 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).

Shallow to deep water



Shallow water to T-phase station.



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