Nonlinear Propagation of Infrasound from Large Explosions

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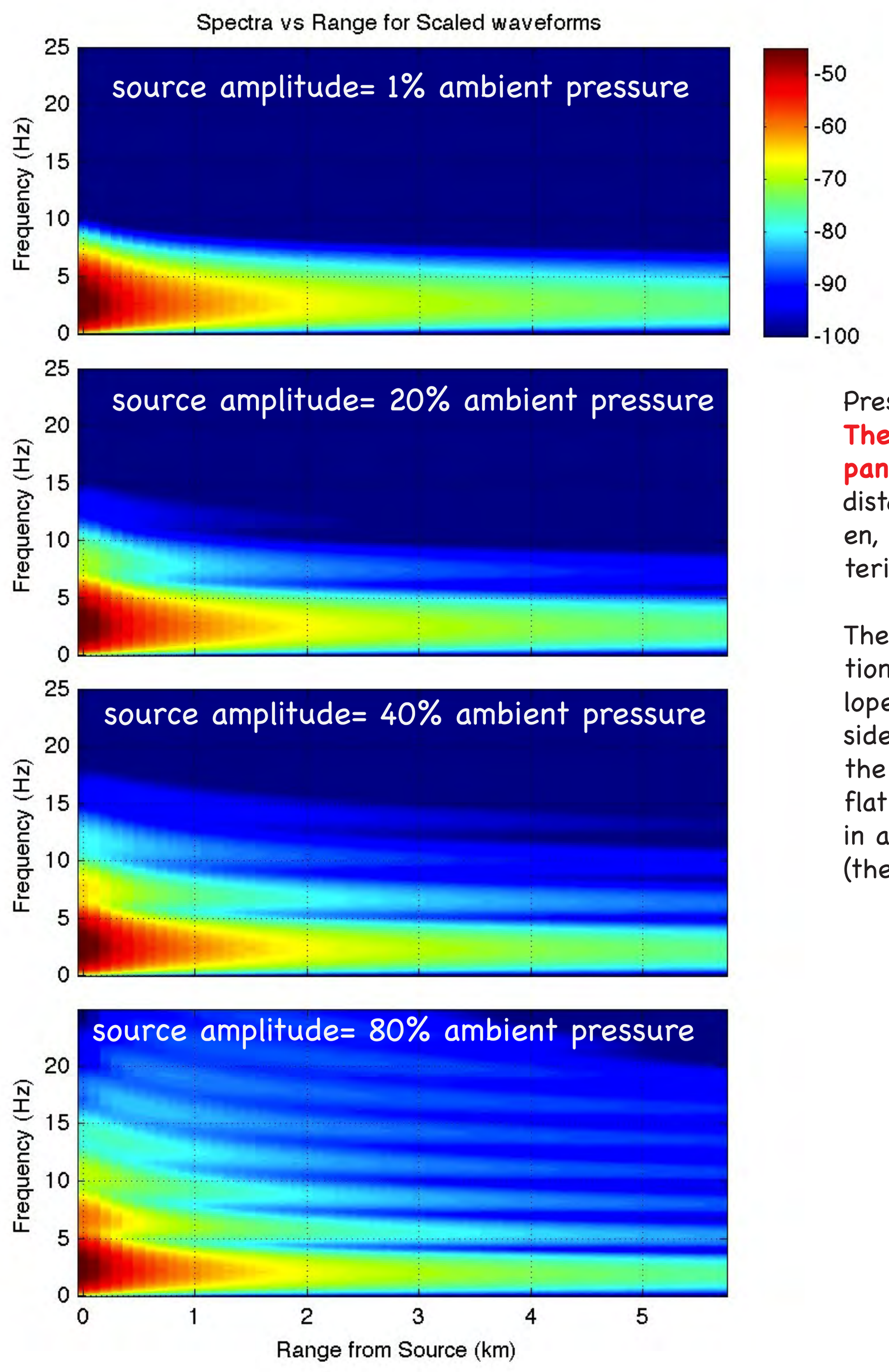
Abstract

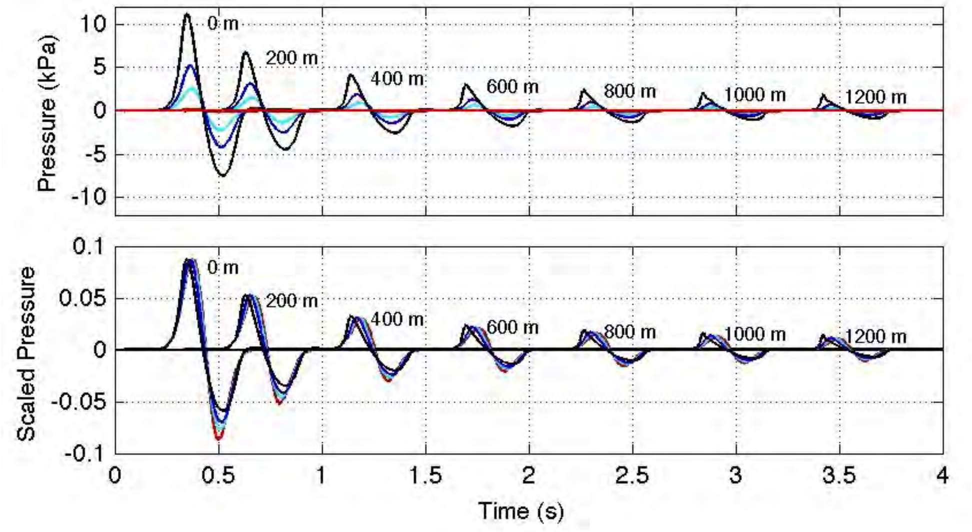
Atmospheric explosions generate huge infrasound signals that can be detected thousands of kilometers away. Standard methods of estimating source yields from infrasound signals use simplified empirical source-yield relations that account for stratospheric winds along the source-receiver path but apply only to direct and stratospherically ducted arrivals. Progress has recently been made in applying numerical modeling techniques to develop more accurate source-yield formulations for realistic sound and wind speed profiles. However, these methods assume linear infrasound propagation along the travel path even though nonlinear effects – which arise when the amplitude of the acoustic pressure perturbation is a finite fraction of the ambient atmospheric pressure – are known to significantly alter infrasound frequencies, velocities and amplitudes, and thus can affect derived source yield estimates. For realistic atmospheric profiles, nonlinearity is significant either near a large explosive source, at caustics created by ducting in the stratosphere, or in the thermosphere where the ambient pressure is very low.

In this study, the effects of nonlinearity on infrasound signal amplitudes and frequencies are simulated using a nonlinear finite difference, time-domain (FDTD) method. The key features that allow for accurate and efficient nonlinear synthesis of infrasound propagation through realistic media are that 1) it includes for atmospheric viscosity, and 2) it computes solutions on an axially symmetric 2D grid in Cylindrical coordinates, yielding solutions relevant to a point source in 3D space. Comparing linear and nonlinear propagation shows the extent to which nonlinearity alters stratospheric or thermospheric returns, or infrasound penetration into zones of silence. Comparisons of linear and nonlinear propagation through realistic representations of the atmosphere show that thermospheric returns are affected by nonlinearity even for very low source amplitudes. Thus an understanding of the effects of nonlinear propagation on infrasound signals is required to develop source-yield estimates, particularly for thermospheric returns.

Nonlinear Infrasound Propagation in a Uniform Halfspace

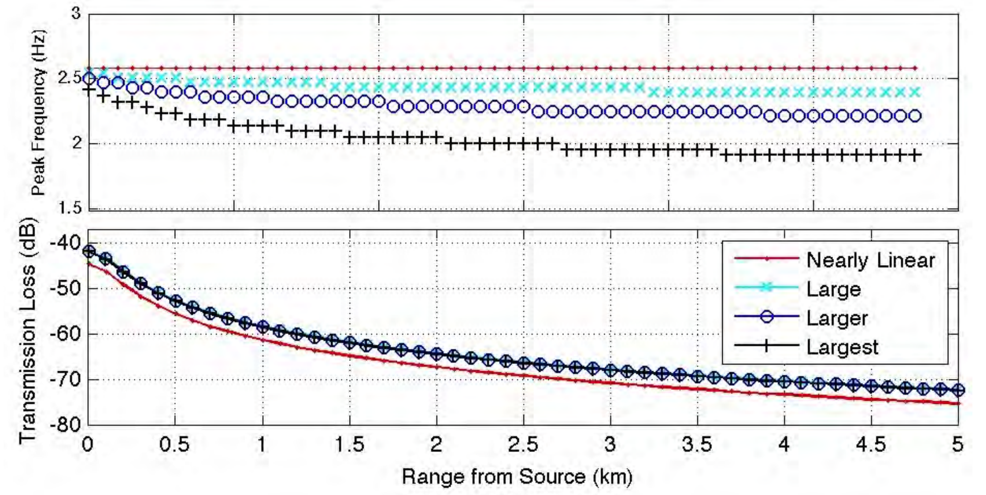
In this panel, nonlinear effects are shown for infrasound propagation in a uniform half-space model with no attenuation. Results are shown for 4 sources with varying amplitude; one is nearly linear, the others have pressure amplitudes on the order of the ambient pressure.



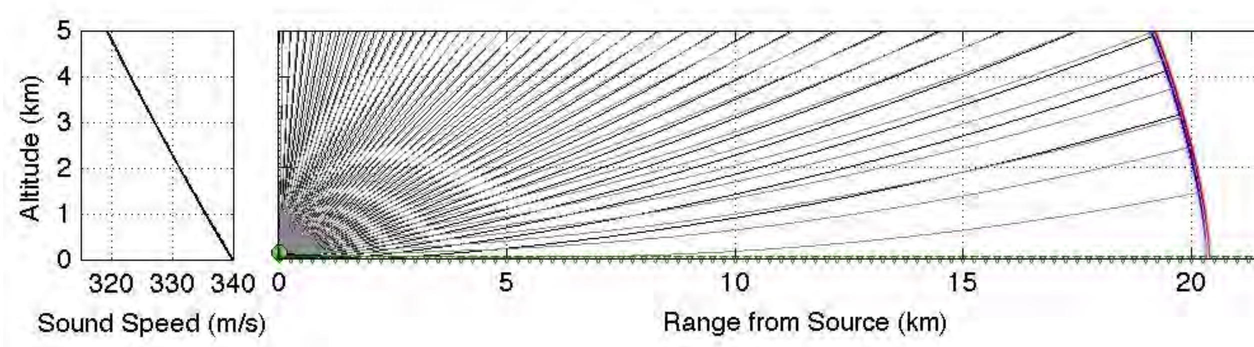


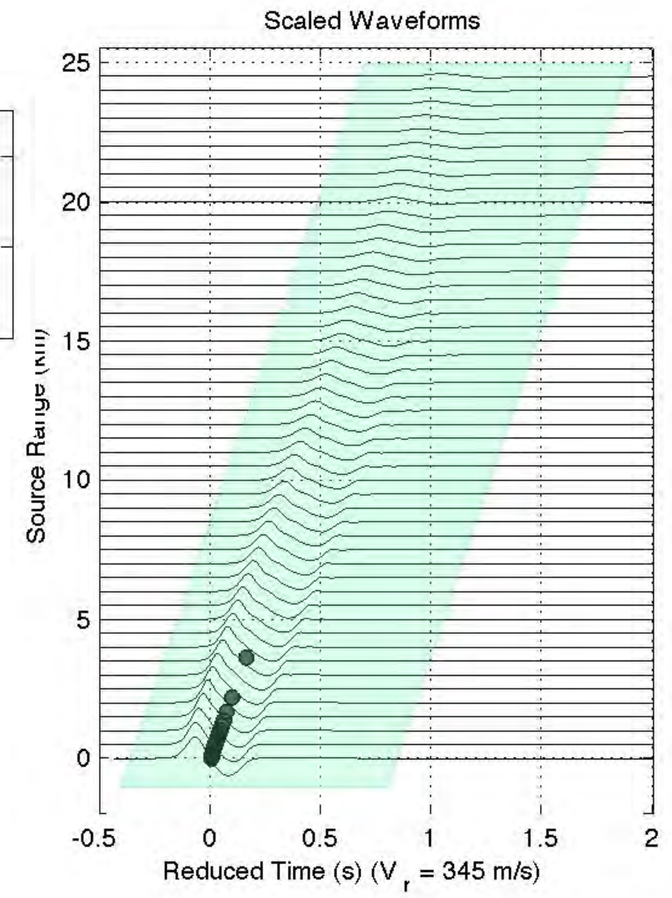
Pressure pulses are shown for receivers at increasing distances in **the figure above**. **The top panel** shows the pressures in kPa. The waveforms are replotted in the **lower panel,** scaled by the source amplitude. As shown, the pulse shape does not vary with distance for the low amplitude source. For the larger sources, the pressure pulses steepen, and the trailing negative excursion in pressure decreases in amplitude, as is characteristic of nonlinear propagation. Amplitudes scale as 1/R, as expected in a 3D space.

The **spectrograms at right** show the associated spectra of the scaled signals as a function of distance from the source. They show that the spectra become increasingly scalloped as source amplitudes increase. The energy shift from lower to higher frequency sidelobes results in a decrease in the signal's dominant frequency as is propagates from the source, as shown in the **upper panel of the figure below**. That is, the spectrum flattens out somewhat for large source sizes. **The lower panel below** shows the change in amplitude with range, indicating a 1/R decrease with range for all source scales shown (there is no attenuation).

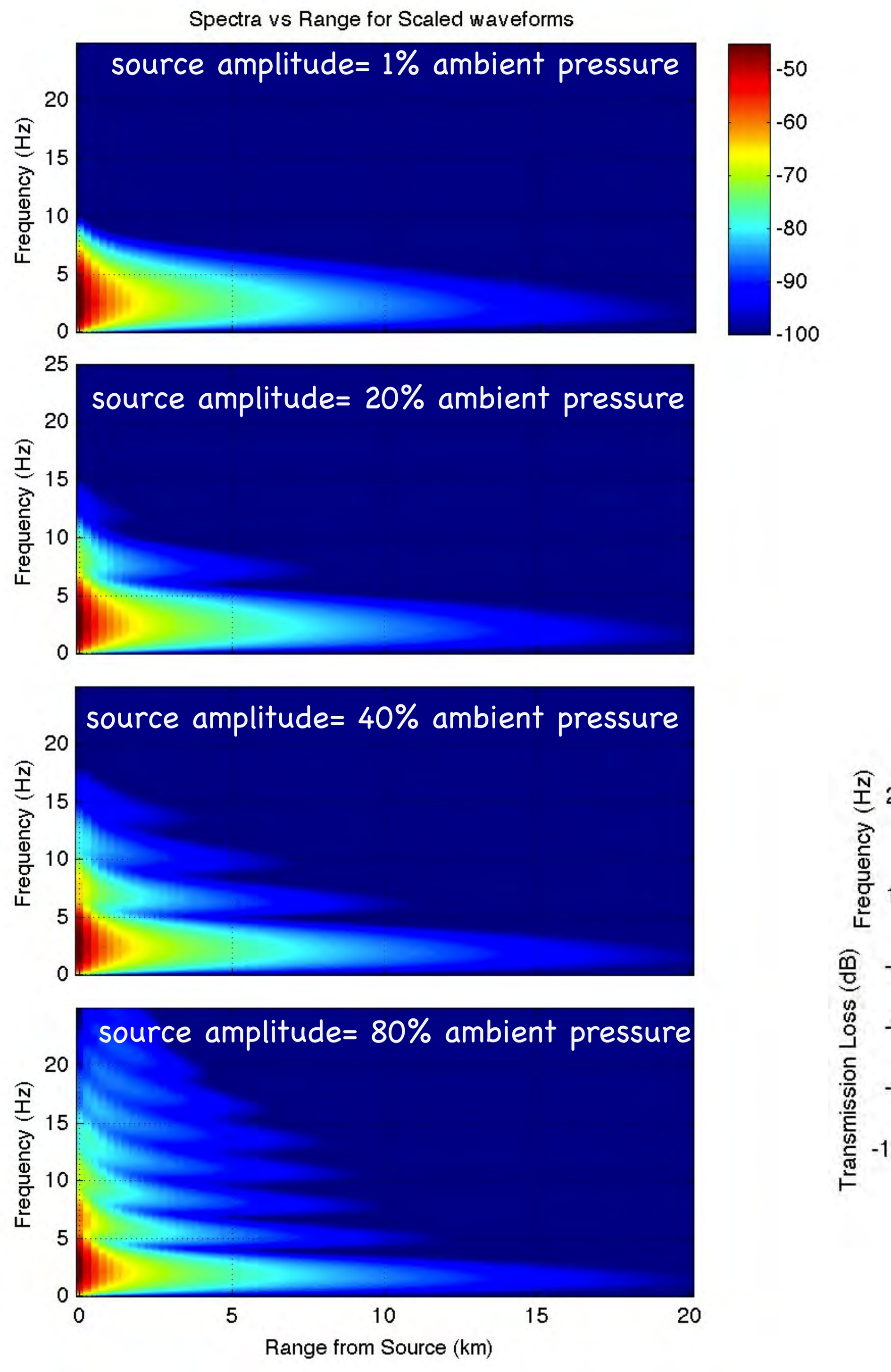


Nonlinear Infrasound Propagation in a Shadow Zone



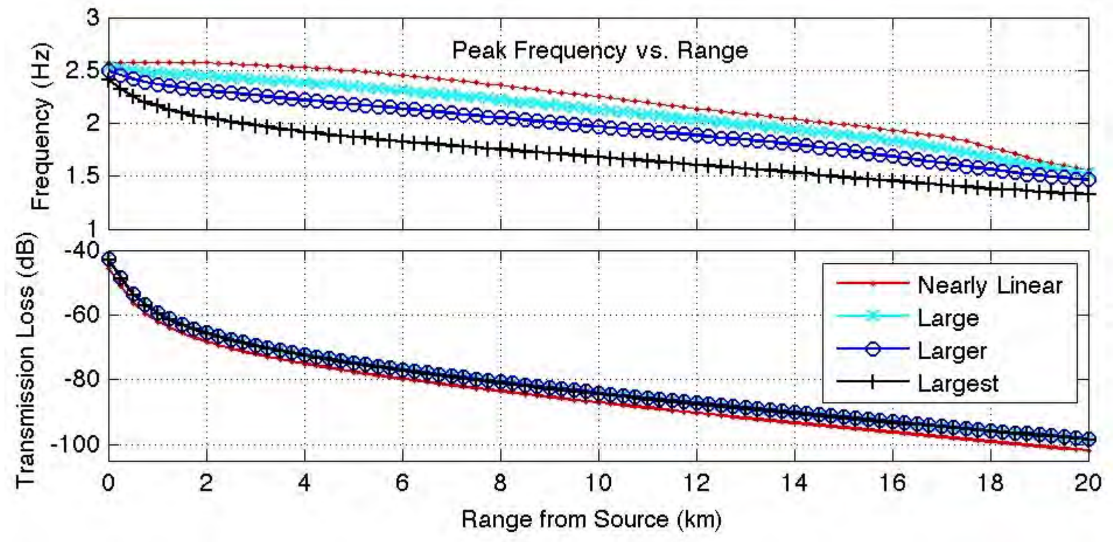


This panel shows nonlinear infrasound into a shadow zone for a bilinear profile, with decreasing sound speed with altitude. This model has an analytic solution for linear propagation showing that high frequencies are attenuated with increasing range from the source due to the upward refraction of sound waves. The source is at an alitude of 150 m. **The figure above** shows the sound speed profile and ray solution, along with the FDTD pressure field at 60 seconds. The ray solution shows a shadow zone beginning at a range of about 5 km from the source, but the FDTD solution shows that low frequencies penetrate well past this range. **The plot at left** shows reduced-time, scaled FDTD-synthesized waveforms (the amplitudes are multiplied by source distance, i.e. the amplitudes would be uniform for a halfspace), along with circles showing arrival times for rays. As shown, low amplitude waveforms extend well into the shadow zone.

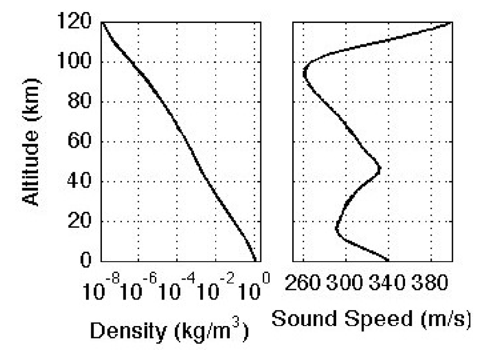


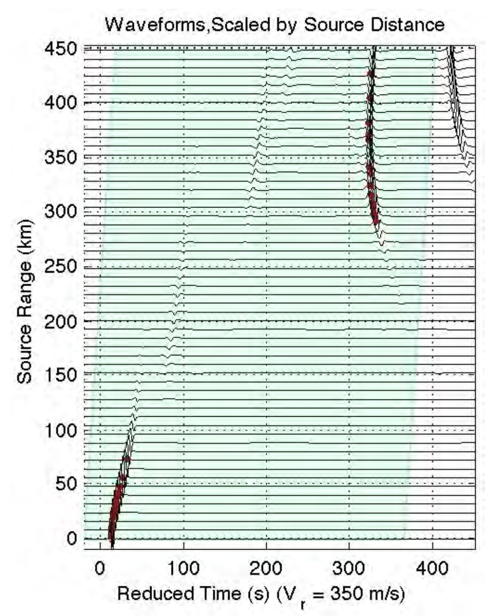
The FDTD computations were done for the same source amplitudes and frequencies as for the half-space model, shown in the previous panel. **The spectrograms at right** show the spectra of the scaled signals as a function of distance from the source (the signal waveforms are scaled by the source amplitude). As for the halfspace model, the spectra become increasingly scalloped as source amplitudes increase. However, comparing these to the spectra for the half-space, the higher frequencies are attenuated far more rapidly, since high frequencies behave in a more ray-like manner than lower frequencies (again, no attenuation is included in these simulations).

The plot in the upper panel below shows the change in the dominant frequency with range from the source at all source amplitudes. The results show that the dominant frequency decreases with range from the source even for a very small source, as predicted by theory, but that decrease is more pronounced for high amplitude sources. **The lower panel in the plot below** shows the transmission loss with range. Larger source sizes result in changes in dominant frequency but less significant changes in transmission losses.



Comparison of Linear and Nonlinear Effects on Stratospheric and Thermospheric Returns

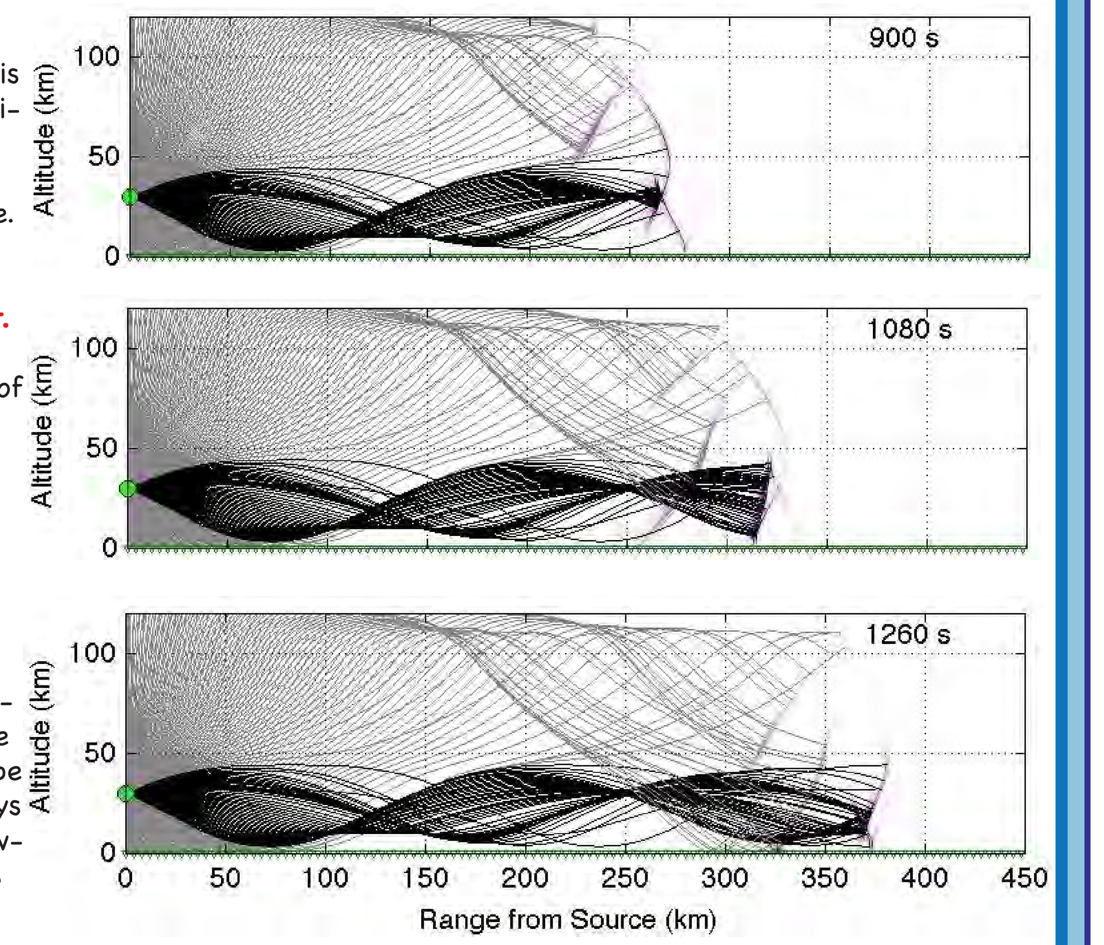


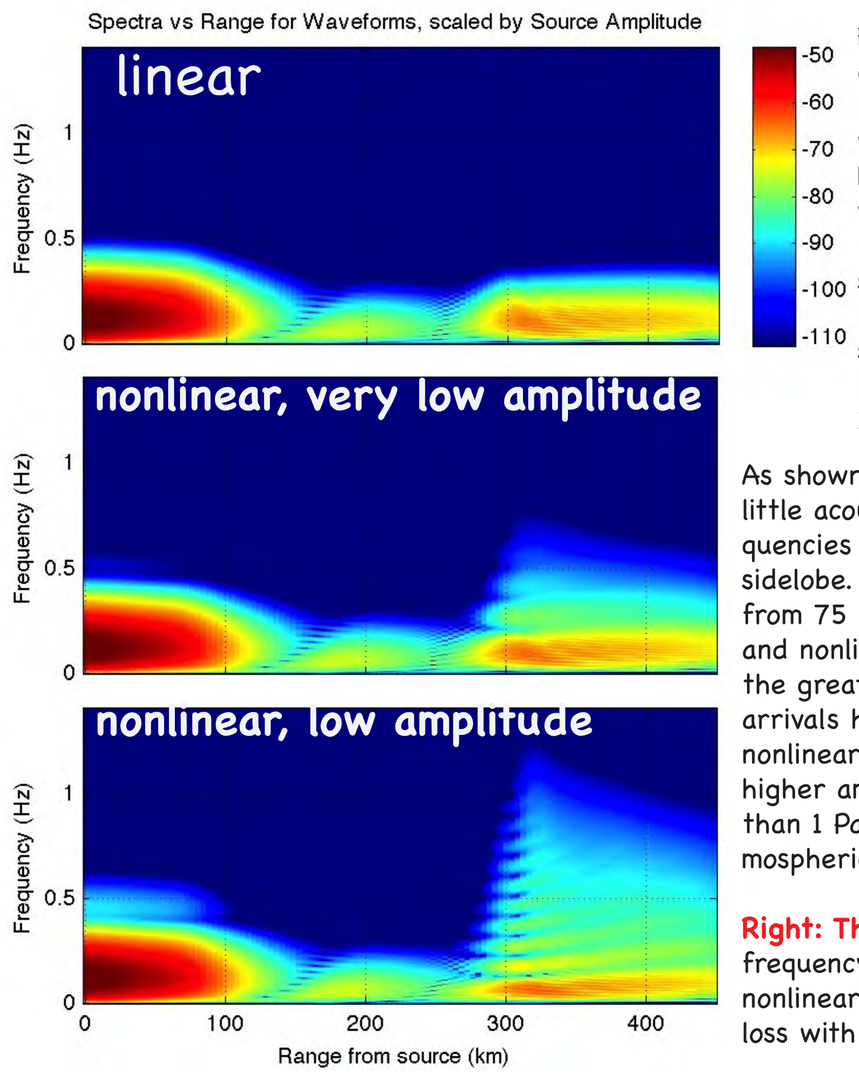


In this panel, infrasound propagation is computed for a realistic static sound speed profile, derived from a standard NRLMSISE-00 model. The purpose of this example is to show that nonlinearity is not only an issue in the vicinity of the source. Nonlinearity could arise for infrasound propagation within the thermosphere where the ambient density is very low, or at caustics within the stratosphere. Atmospheric attenuation is included.

The sound speed and density profiles **are shown at right. Three panels at left** show FDTD pressure solutions at times 900, 1080, and 1260 seconds for a source altitude of 30 km, along with the ray solutions. The ray solution implies the existence of a shadow zone from 75 km to nearly 300 km range, where the first thermospheric returns come in. The FDTD solutions show that some infrasound energy penetrates the shadow zone. Rays ducted within the stratosphere show caustics at ranges of about 125 km and 250 km.

The figure at left shows the reduced-time FDTD synthesized pressure responses, scaled by the distance from the source. Several low amplitude stratospheric arrivals can be seen at ranges where the ray results (left) show that rays nearly reach the ground. Two sets of thermospheric arrivals are evident in the FDTD simulations. The arrival times for rays that reach the ground are plotted as circles. Spectra are computed for the time range in green.

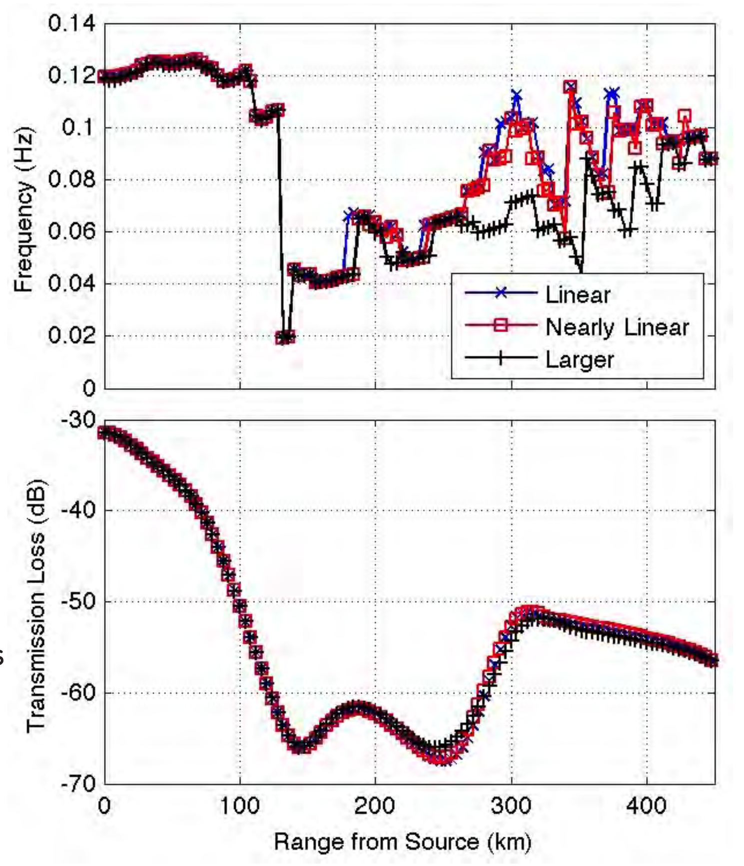




FDTD computations were performed at low frequencies so that viscosity is insignificant for a linear source – the peak frequency is about 0.1 Hz, whereas viscosity becomes significant at 0.2 Hz. Nonlinear computations were performed to examine where nonlinearity plays a stronger role: at caustics within the stratosphere or within the thermosphere, where ambient pressures are very low. Two low amplitude sources were used, with peak pressure of 1% and 4% of the ambient pressure at 30 km. The spectra for the direct, stratospheric, and 1st thermospheric arrivals **are shown at left.**

As shown, the source amplitudes are small enough that very little acoustic energy is shifted from lower to higher frequencies within 100 km of the source, resulting in a single sidelobe. Stratospheric arrivals within the 'shadow zone' from 75 to nearly 300 km are nearly identical for the linear and nonlinear computations. The thermospheric arrivals show the greatest difference; the spectra of the thermospheric arrivals have many sidelobes, indicating a higher degree of nonlinearity. This is especially pronounced for the slightly higher amplitude source. The thermospheric signals were less than 1 Pa in amplitude, indicating that even very small thermospheric returns are subject to strong nonlinear effects.

Right: The upper panel shows the change in the dominant frequency with range from the source for both linear and nonlinear sources. **The lower panel** shows the transmission loss with range.



Conclusions

A code has been developed to simulate nonlinear infrasound propagation in 3D space from a spherical source through a model with realistic atmospheric sound speed and viscosity profiles. The source code, which can be run on a desktop computer, is available for download at http://l2a.ucsd.edu/research/l-propc/lpropc.php, along with an example of its use. The code was used to show the effects of nonlinearity on propagation for 3 scenarios:

For infrasound propagation from a very low amplitude infrasound source **in a uniform halfspace**, the pulse scales inversely with the distance from the source but otherwise the shape in unaltered. With increasing source amplitude, the pressure wavefronts steepen the trailing negative excursion decreases, and acoustic energy is shifted from lower to higher frequencies. These well-known effects are correctly synthesized by this code.

Propagation through **a shadow zone** is not strongly affected by nonlinearity because, although nonlinearity shifts acoustic energy to higher frequencies, this is counteracted by the higher attenuation of high frequencies in a shadow zone. At low frequencies, propagation extends into the shadow zone, well beyond the maximum range predicted by rays, but this is a linear effect.

Infrasound **propagation through the thermosphere** is strongly affected by nonlinearity. Energy shifts from lower to higher frequencies for thermospheric returns with amplitudes as low as 1 Pa. This answers a long-standing question about observations of thermospheric returns at higher than expected frequencies. It was thought that thermospheric attenuation are overestimated. These results show that the higher frequency returns are the effect of nonlinear propagation through the very low ambient pressures and densities within the thermosphere.