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Finite-Difference Simulation of Atmospheric Acoustic Sound Through a Complex Meteorological Background Over a Topographically Complex Surface

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Why Finite-Difference?

- **We have developed a high quality algorithm for 3D finite-difference wave propagation in moving-media (wind)**
- **Finite-difference advantages**
  - **Can use arbitrary gridded models**
    - **Point by point variation of material parameters is allowed**
  - **Directly solve the governing equations—generate all physical arrival types**
  - **Domain decompositions can be used to efficiently solve FD problems on parallel computers**
  - **Atmospheric and source dynamics are easily incorporated**
- **Disadvantages**
  - **Computationally intensive, large (realistic) models require supercomputers**
  - **Complicated stability and dispersion relations must be understood to run models correctly**

Physical and Mathematical Assumptions

- **Linearize equations with respect to small-amplitude acoustic wavefield fluctuations**
  - **Fundamental equations of continuum mechanics**
    - **Balance of mass, momentum, entropy**
  - **Constitutive relations (ideal fluid)**
  - **Equation of state (pressure)**
- **Ambient medium**
  - **Adiabatic (no energy sources or heat transfer between fluid parcels)**
    - **Details of derivation in 4pPA4 from Nashville meeting and paper in preparation**
  - **Divergence-free motion (incompressible fluid)**
    - **Must be enforced by model builder**
- **Gravity and pressure gradients ignored in acoustic equations**
  - **Uncouples p and w from fluctuations in mass density ρ**

Acoustic Velocity-Pressure System for Moving-Media

$$\frac{\partial \mathbf{w}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{w} + (\mathbf{w} \cdot \nabla)\mathbf{v} + b\,\nabla p = b\,\mathbf{f}$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \kappa\,\nabla \cdot \mathbf{w} = \frac{\partial e}{\partial t}$$

Wavefield variables:

- $\mathbf{w}(\mathbf{x},t)$ - particle velocity vector
- $p(\mathbf{x},t)$ - acoustic pressure

Body sources:

- $\mathbf{f}(\mathbf{x},t)$ - force density vector
- $e(\mathbf{x},t)$ - energy density scalar

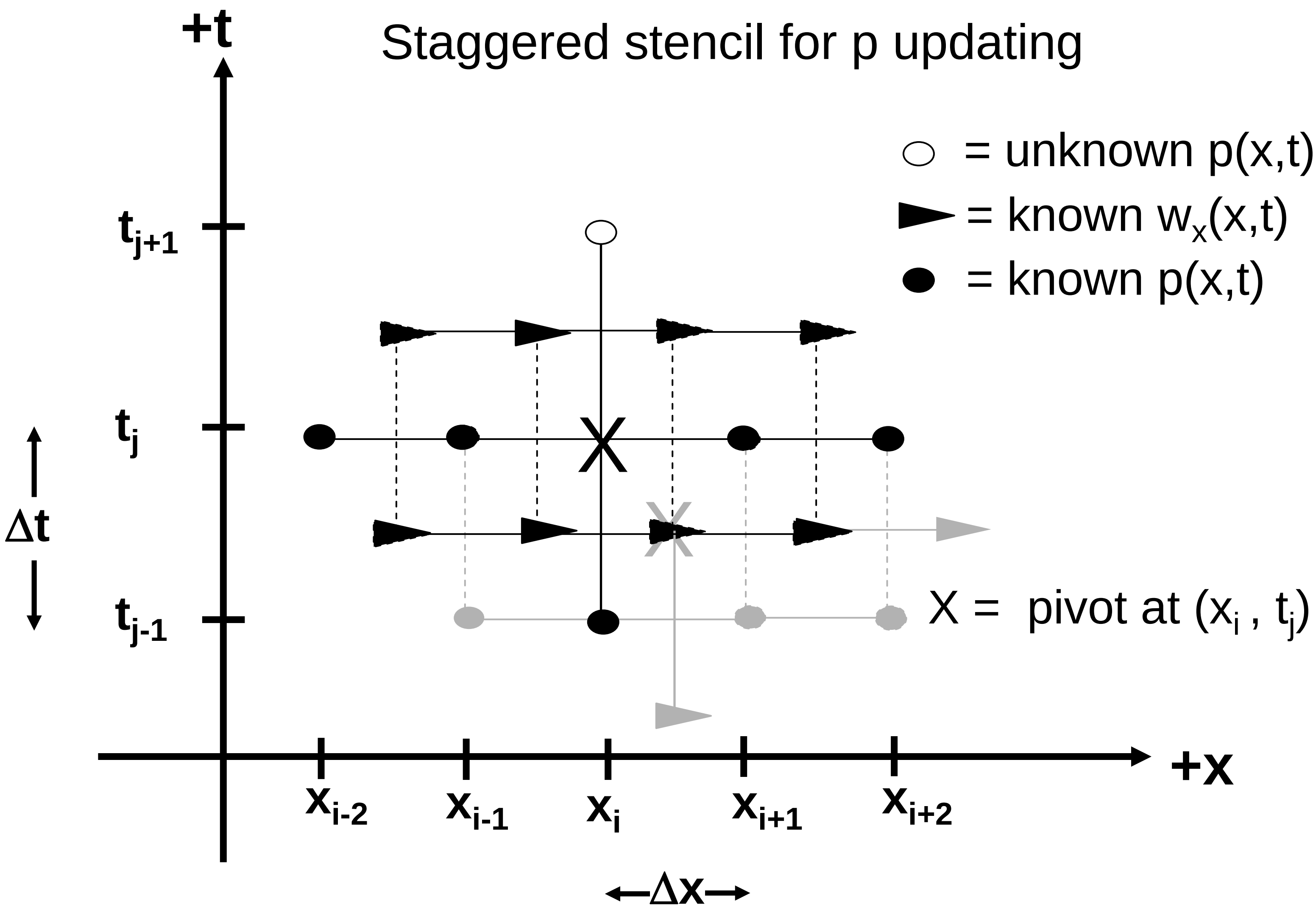
Acoustic model parameters:

- $b(\mathbf{x},t)$ - mass buoyancy
- $\kappa(\mathbf{x},t)$ - bulk modulus
- $\mathbf{v}(\mathbf{x},t)$ - fluid velocity vector

A system of four, coupled, linear, first-order, partial differential equations.

V. E. Ostashev, D. K. Wilson, L. Liu, D. F. Aldridge, N. P. Symons, and D. H. Marlin, "Equations for finite-difference, time-domain simulation of sound propagation in moving inhomogeneous media and numerical implementation," *J. Acoust. Soc. Am.* **117** (2), 503-517 (2005).

O(2,4) Staggered-Grid Finite-Differences

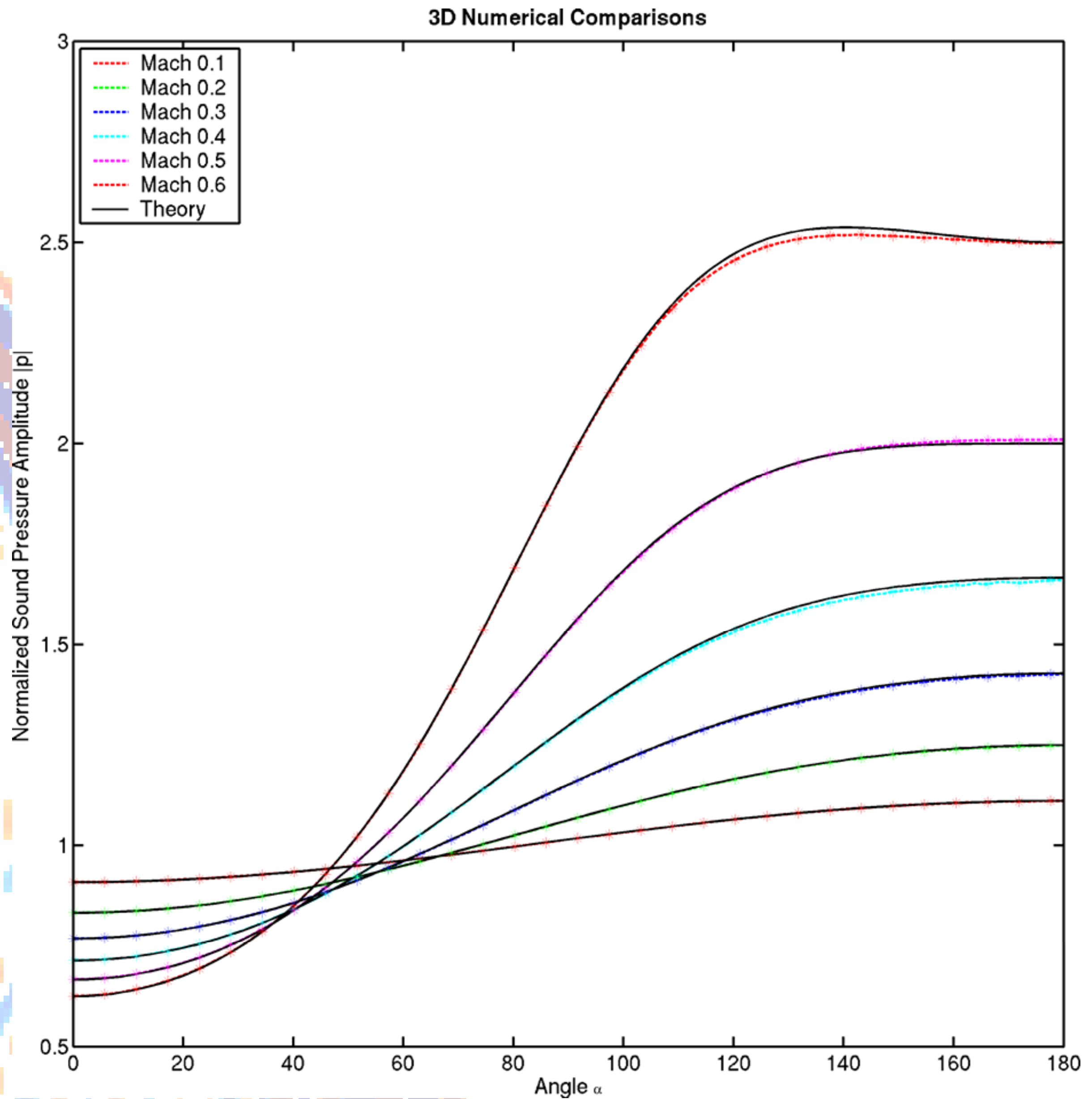


Dispersion and Stability

- **5 nodes/propagating wavelength is the normal rule of thumb with 4th order spatial finite-difference algorithms**
  - **Determine the highest frequency in the far field (may be 1 or more differentiations of the source waveform)**
  - **Determine the slowest velocity in the model and pick a grid spacing such that λ/dx is ~5**
    - **Slowest velocity is the apparent velocity *V(1-Mach)***
    - **Can be much smaller than lowest velocity for high wind speeds**
    - **Can get excessive dispersion for upwind propagation if this is ignored**
- **CFL ($\sim[dt \times V_{max}]/dx$) must be less than 1 for stability**
  - **Must use the highest apparent velocity *V(1+Mach)***
  - **Algorithm will “blow up” if this ignored**

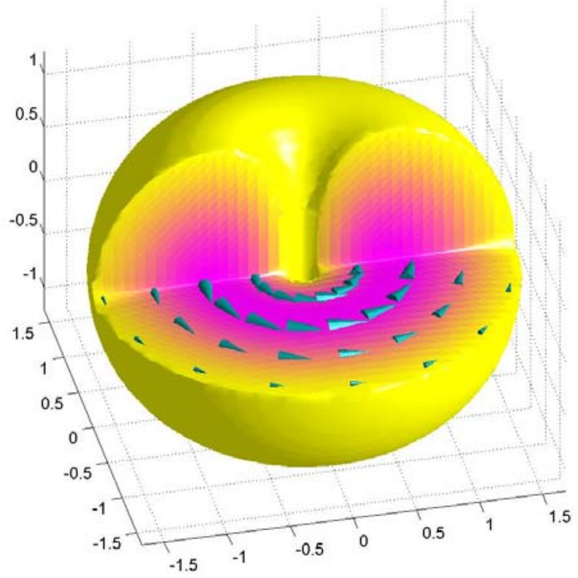
Comparison to Analytic Solution (1)

- **Black lines are the theoretical pressure verses azimuth at a variety of Mach #**
- **Colored lines are the results of this algorithm**
  - **Needed to grid up a very fine model to get good results at the higher Mach numbers**
- **These are** wholespace **results**
  - **At 50m from the source**



Quasi-Wavelet Turbulence

Quasi-wavelets: Technique that mimics the conceptual picture of turbulence consisting of discrete eddies of different sizes.



Like wavelets, they…

- **Are based on a self-similar, localized function**

Unlike wavelets, they…

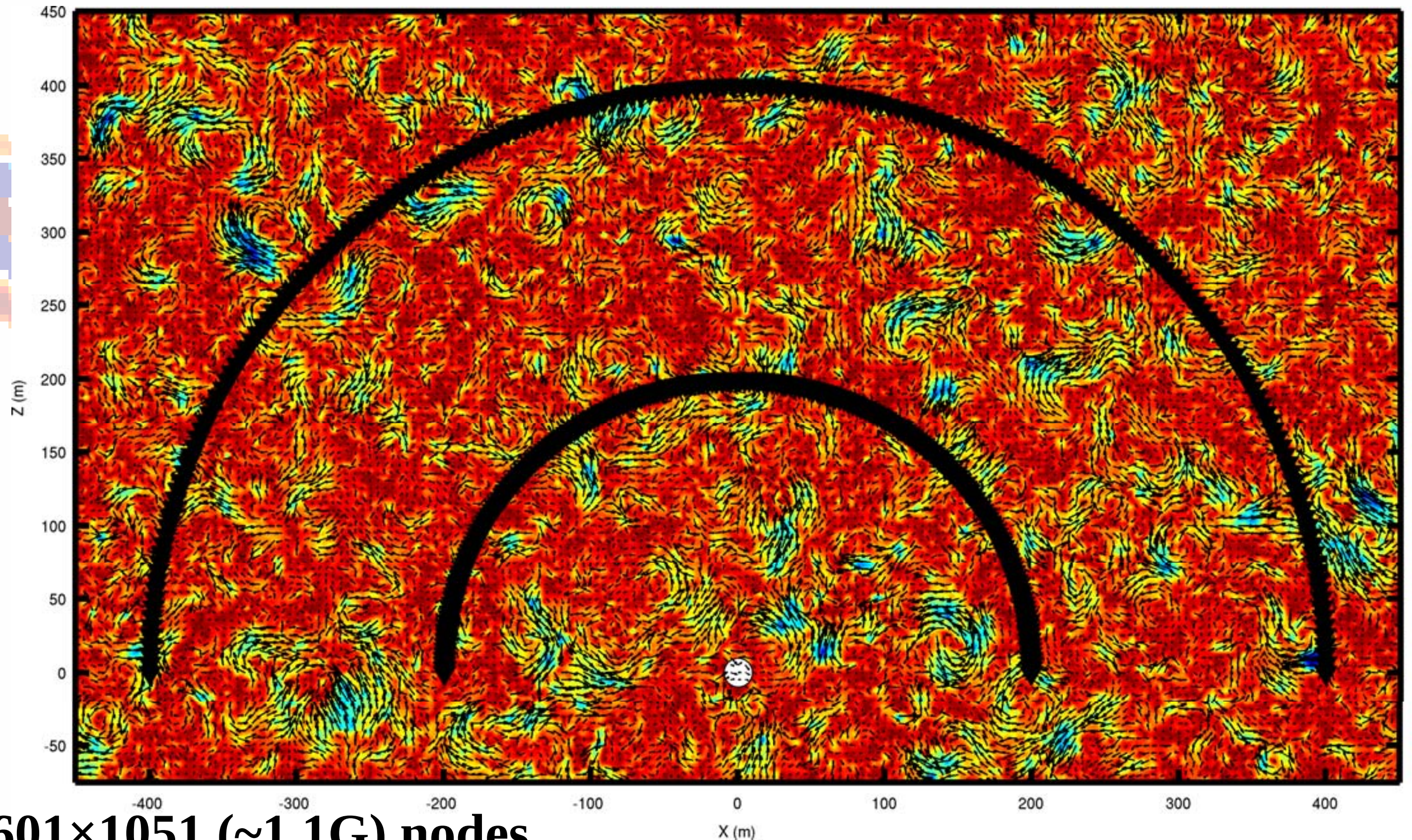
- **Have random orientations and positions**
- **Are not required to be zero-mean functions**
- **Do not form a complete basis**

Parallel implementation:

1. **Generate a "master list" of QW positions, sizes, and orientations.**
2. **Each processing element searches the list for the QWs within its domain. Fields associated only with local QWs are calculated.**

Test of the QW Implementation

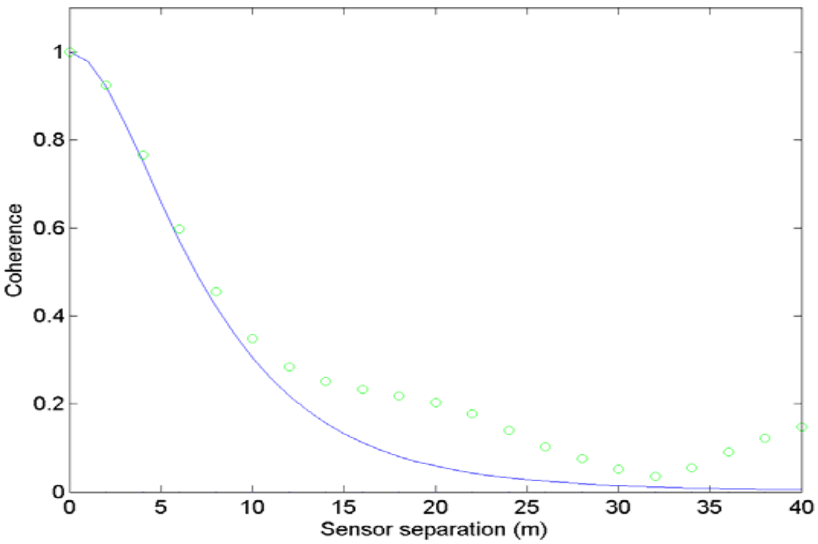
- Receivers at two fixed distances from the source
  - This is the upper half of a band around a sphere
  - Total of 8400 receivers

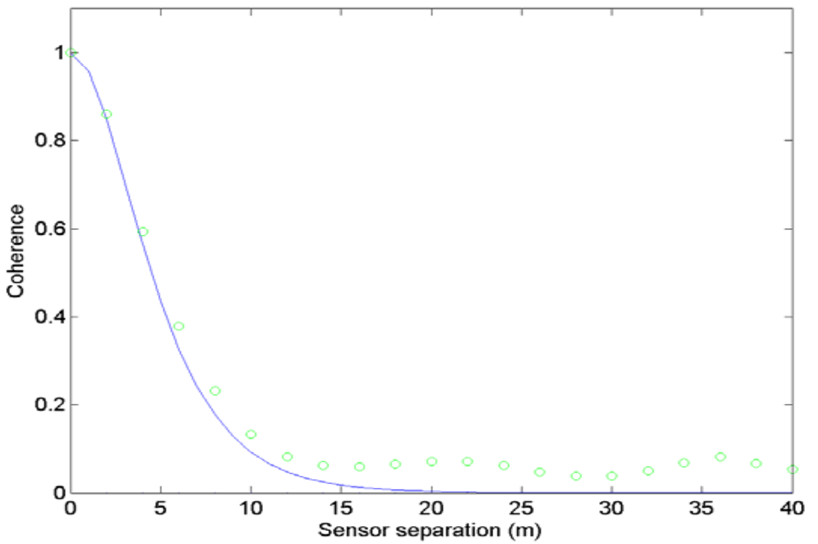


- Model is 1801×601×1051 (~1.1G) nodes
  - Whole space
  - 590000 QW
    - Kinetic Energy Dissipation Rate 10
    - Size range from 1-10m
    - Maximum Velocity ~10m/s

QW Results

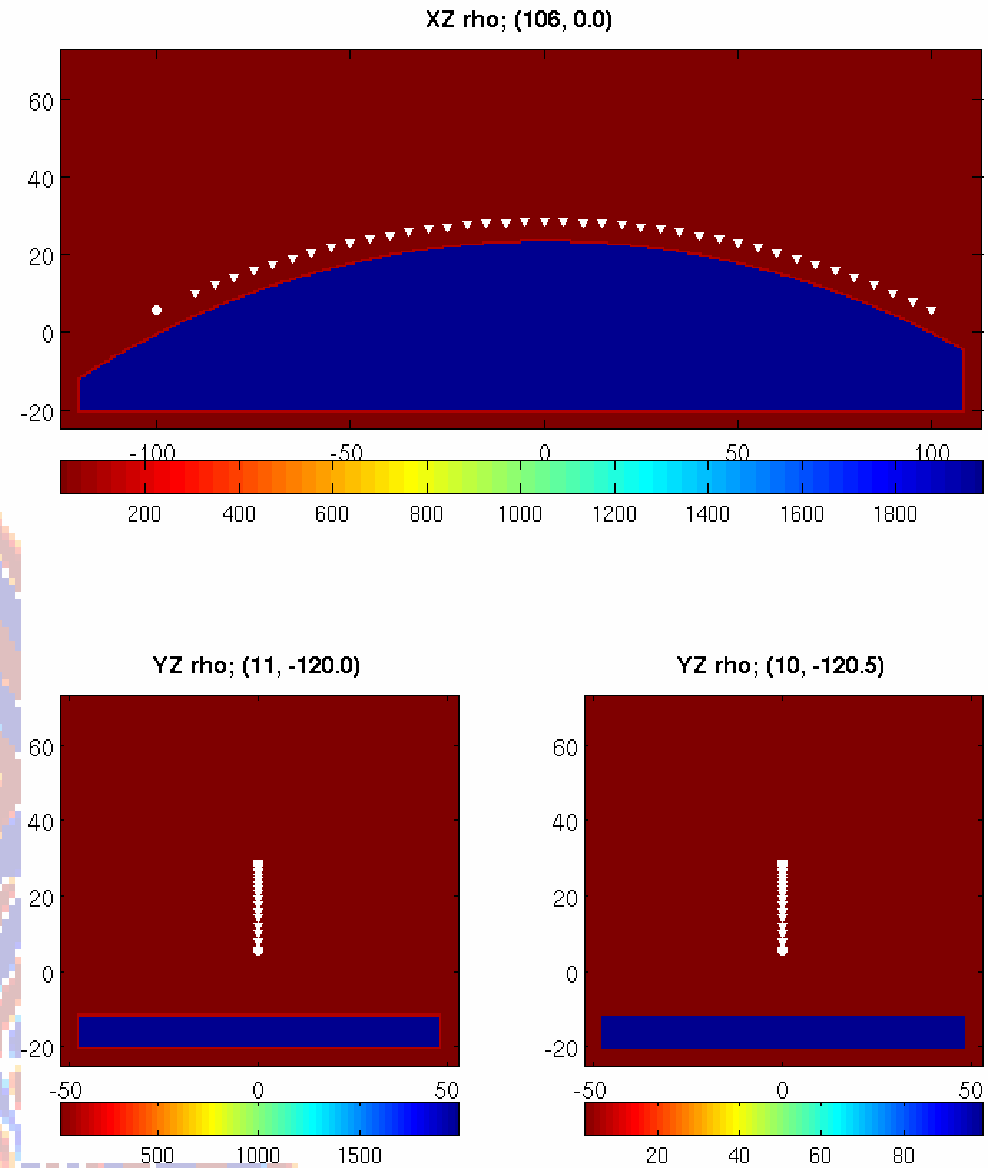
- Fairly good fit to the analytic solution
  - Coherence
    - 200m -11%
    - 400m -15%
  - Extinction
    - 200m 26%
    - 400m 7%
- Over the propagation distances of this test, for a dissipation rate of 10
  - The extinction is very high
  - The signal phase has essentially zero mean
  - This makes it very difficult to estimate meaningful phase statistics from a small number of samples
  - Results for this scenario probably reflect limitations due to the random nature of the test





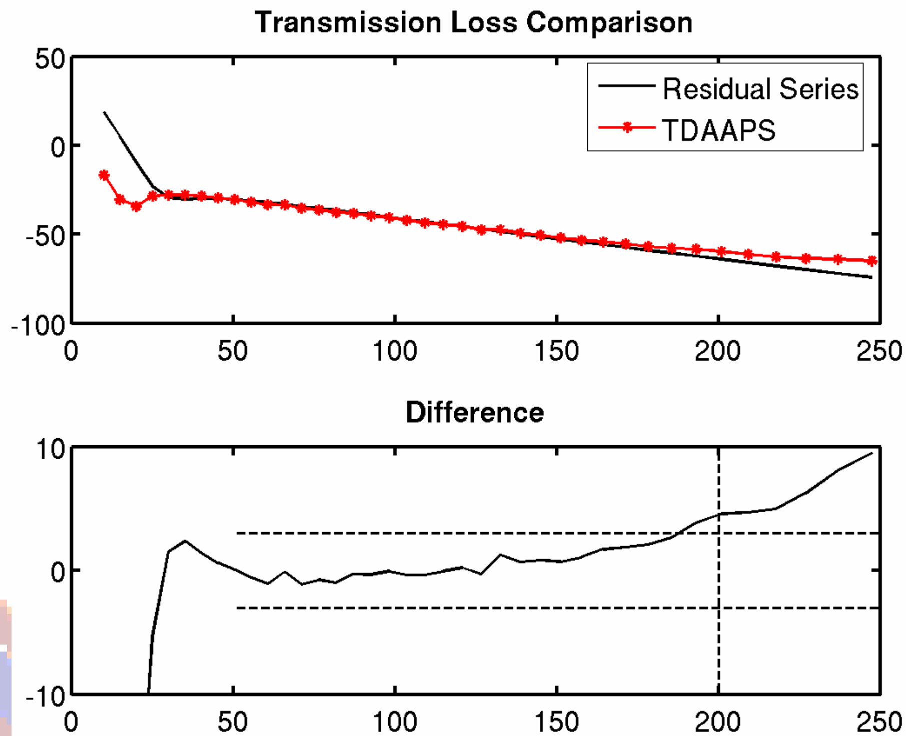
Test of Topography

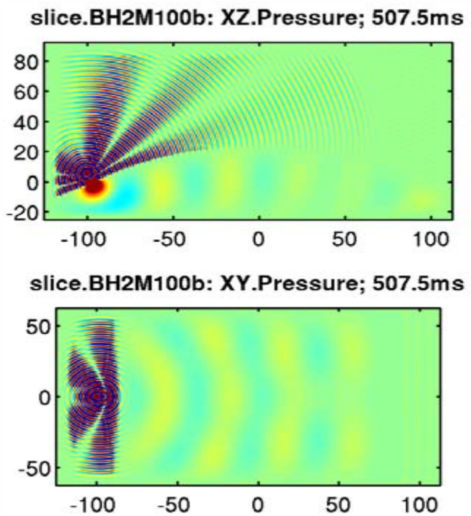
- **2 ½ D Hill**
  - **3D propagation**
  - **Cylindrical 2D Hill**
- **Receivers at 1m intervals (along the surface)**
- **2 m above the surface**



Topography Test Results

- Another difficult test
  - The only energy that reaches the more distant receivers has refracted over the hill
  - We get slightly higher amplitude than predicted
    - Possibly energy that propagates through the hill
    - Possibly energy reflected from boundaries

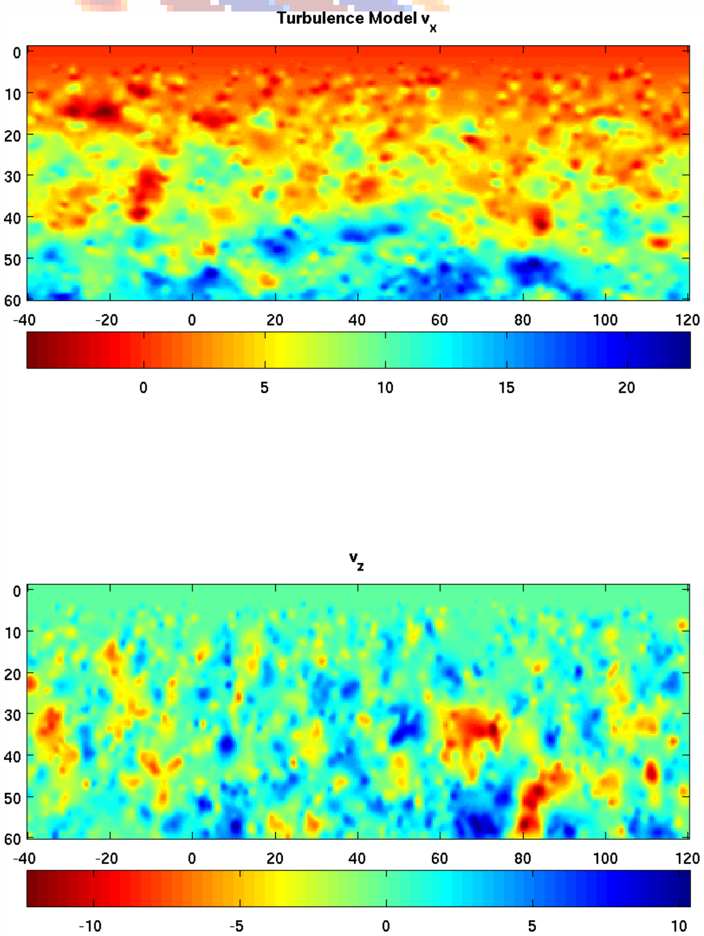


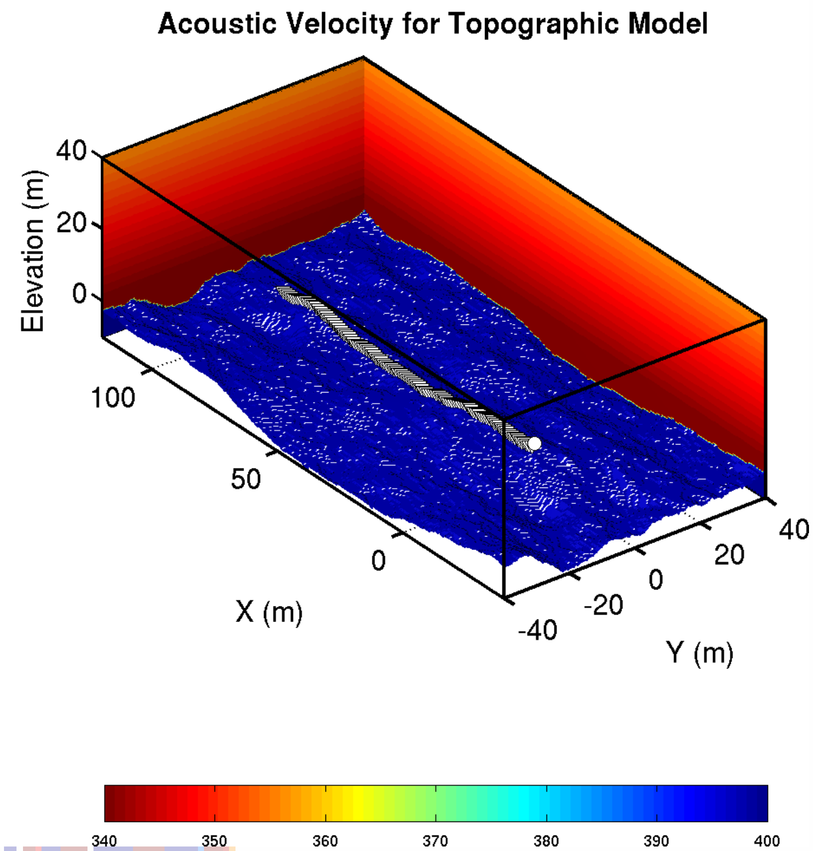


- Analytic solution
  - Not expected to reproduce the near-source complications
  - M. Berengier, G.A. Daigle, Diffraction of sound above a curved surface having an impedance discontinuity, Journal of the Acoustical Society of America, **84**, September 1988, pp 1055-1060

Effect Comparison

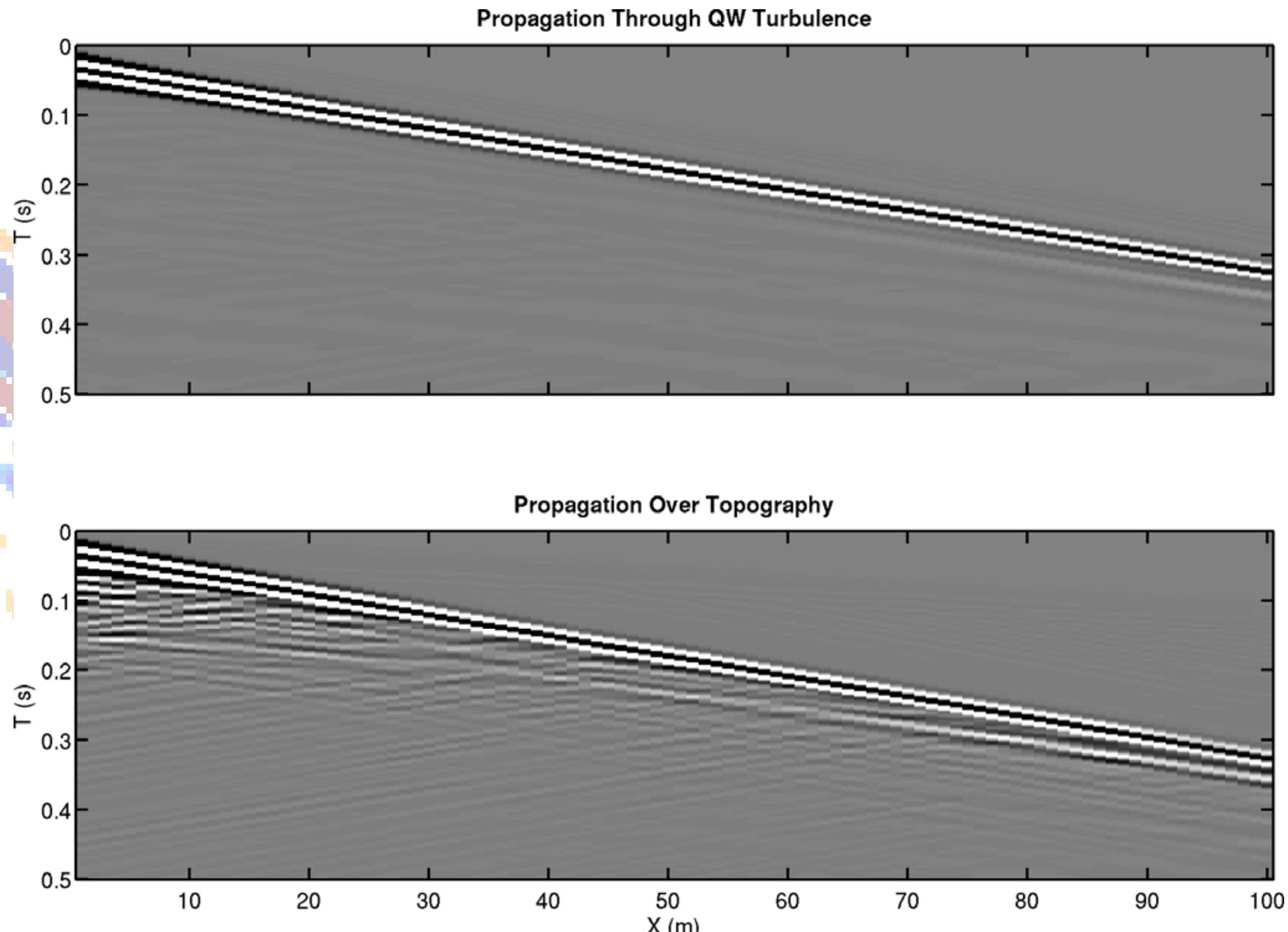
- Compare the contribution of turbulence and topography
  - Two effects that are hard to seperate in the real world





Comparison

- These results clearly show that for this particular geometry and frequency range the effect on the sound due to the topography is much larger than the effect from the turbulence
- In the topographic model the direct arrival and the scattered energy trailing is of a similar magnitude



- The signal energy scattered by the turbulence, even for the unrealistically intense turbulence used here, is much lower and is barely visible at this plot scale

Conclusions

- We have successfully implemented FDTD calculations of sound propagation through moving media
- Accuracy of the algorithm has been demonstrated for propagation over topography and through turbulence
- A highly realistic atmospheric turbulence representation based on quasi-wavelets has been incorporated directly into the algorithm

- Demonstrated the utility of modeling to investigate where the complications in our data come from