Body Wave Tomography

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Seismic Tomography Mini-FAQ

• **What is it?**
  • Earth sciences “CAT-scan”
  • Measure of seismic wavespeeds or wavespeed variations

• **Why do we care?**
  • Understand phase/temperature/compositional variations
  • Relate geology and mantle dynamics to regional processes
The reference Earth: Radial models

Courtesy Frederik Simons
Seismic Velocity Relationships

- Determined by
  - Pressure (depth)
  - Temperature
  - Composition

Matsukage et al. [2005]
Forward modeling of the wave field, Part I:

Ray tracing, most 1-D

Before

Kennett, GJI, 1995

After

Bullen & Bolt, 1985

Buland, BSSA, 1983
Relative Delay Time Example
Relative Delay Time Example
Relative Delay Time Example
Relative Delay Time Example
Relative Delay Time Example
What is $f(x, y, z)$? Seismic wavespeeds.

Travel-time tomography

The Earth is made of a heterogeneity of seismic velocities $v(x, y, z)$. Travel-time anomalies go as

$$\delta t = \int_{\text{ray}} \frac{1}{\delta v(x, y, z)} \, ds.$$  

(3)

Waveform tomography

Arrival times depend on the wavelength of the seismic phases. All raypaths curve and coverage is far from perfect.

Courtesy Frederik Simons
Non-continuous source coverage

The CMT catalog of large events

Courtesy Frederik Simons
Ray Theory Paths

- Spaghetti, bananas, and doughnuts

Hung et al. [2004]
Hung et al. [2004]

Finite Frequency Paths

- Spaghetti, bananas, and doughnuts
**Letting it simmer: Solving inverse problems**

We have: \( G \cdot m = d \), which is **linear**.

You think: \( m = G^{-1} \cdot d \), but we **can’t invert** a non-square \( M \times N \) matrix.

You think: \( G^T \cdot G \) is square, let’s solve \( G^T \cdot G \cdot m = G^T \cdot d \).

You try: \( m = (G^T \cdot G)^{-1} \cdot G^T \cdot d \).

**Alas!** \( G^T \cdot G \) may be singular, ill-conditioned, under/over-determined, have (near-)zero eigenvalues, and thus be **not-invertible**.

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**over-determined, \( M>N \)  mixed-determined  under-determined, \( M<N \)**
Resolution issues

- Different models, same results (underdetermined)
- Need crossing rays (unique information)

Allen and Tromp [2005]
Body Wave Tomography: Strengths

- Many methods: great when they agree!
- Results can be easy to interpret visually
- Dense arrays provide higher level of resolution
- Surface wave inversions can provide absolute velocities
- Complementary observations:
  - Receiver functions
  - Seismic anisotropy
  - Combined surface wave/body wave inversions
Body Wave Tomography: Weaknesses / Caveats

- Resolution: Model will always be a blurry (smoothed) image of real structure
- Regularization: How much bias does model have from damping and smoothing?
- Misfit: How well does model fit data? Is it unique?
- Many methods: What happens when they don’t agree?
- Be cognizant of:
  - Very small features: avoid interpretation!
  - Color schemes and isocontours
  - Streaks pointing in direction of earthquakes used in inversion
Model Sampling

- Array aperture and raypath density are very important

Ritsema and Allen [2003]
Uncertainties and Resolution

• Checkerboard test
• Spike test (Resolution matrix)
• Statistical test (bootstrapping, Jack-knifing methods)
• Synthetic test (simple model checking)
• Probabilistic Bayesian approach (Tarantola & Valette, 1982)
• Covariance matrices (model and data space)
TOMOGRAPHY TARGETS

• Local scale (20 km x 20 km x 10 km)
  • characteristic DH ~ 4 km and DZ ~ 1 km

• Lithospheric scale (100 x 100 x 50 km)
  • DH ~ 15 km and DZ ~ 5 km

• Mantle scale (3000 x 3000 x 600 km)
  • DH ~ 50 km and DZ ~ 50 km

• Global scale (Whole Earth) D ~ 500 km

From http://www-lgit.obs.ujf-grenoble.fr/~virieuxj
Global Tomographic Images of the Africa “Superplume”

Ritsema et al. [1999]
3-D Model: NW U.S. Tomography

- Inversion of relative delay times
- Ray-based method
- ~300,000 cells (knots)
- ~56,000 rays (P)
- ~58,000 rays (S)

Roth et al., *GRL*, 2008
Apparent gap in Juan de Fuca slab (inversion artifact)

High velocities beneath cratonic North America

Low velocities beneath central Oregon and SRP/Y

Central Nevada anomaly

Roth et al., GRL, 2008
Cross Section: N. Oregon

- *Apparent* missing Juan de Fuca slab (likely inversion artifact)
- Large zone of high velocities beneath Blue Mountains/Idaho Batholith

Roth et al., *GRL*, 2008
• Juan de Fuca slab extends to 500 km and perhaps deeper
• New discovery: Secondary slablike structure evident beneath Oregon/Idaho border
• Discovery: Large high velocity cylinder beneath the central Great Basin (interpreted by West et al., 2009)
Lowest S velocities beneath Yellowstone
Low velocities persist through eastern Snake River Plain
Colocated with Holocene volcanism

James et al., in prep, 2009
Yellowstone and Snake River Plain have identical (weak) signature at 200 km and deeper.

Weaker signature than Juan de Fuca wedge and Great Basin / Rio Grande Rift asthenosphere.

Central Nevada anomaly evident.

James et al., in prep, 2009
No Simple Mantle Plume Beneath Yellowstone

James et al., in prep, 2009
Complex Slab Morphology Beneath Snake River Plain / Yellowstone System
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Same Model, Different Colors

P Velocity Perturbations

Depth = 150 km

Velocity Perturbation (%)
Same Model, Different Colors

P Velocity Perturbations

SAF05abcdefghi
Depth = 150 km
Same Model, Different Colors
Isocontours: +/-0.6%
Isocontours: +/-0.4\%
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