



Photos placed in horizontal position  
with even amount of white space  
between photos and header

# Christian Poppeliers, Leiph Preston, David Schodt

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# Tomography: two fronts

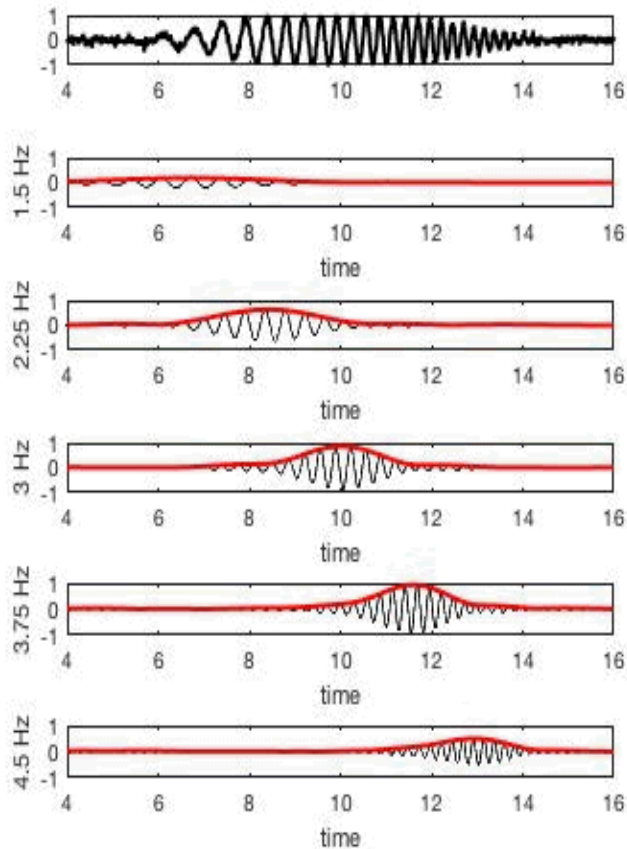
1. Ambient noise, surface wave
  1. Uncertainty estimation using multiwavelets
  
2. Active source: full waveform
  1. Specfem3D
  2. Seisflows

# Surface wave tomography

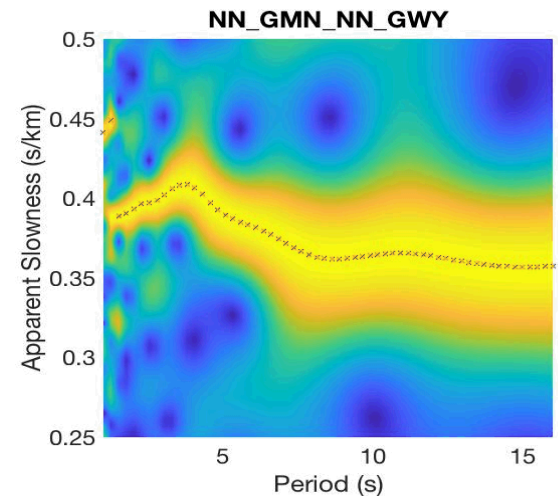
1. Surface waves are dispersive, due to (generally) increasing seismic velocity with depth.
  1. Surface waves sample different depths of the Earth, depending on their wavelength.
2. Determining speed of a given narrow-band surface wave can be used to infer Earth's seismic velocity structure.
3. PROBLEM: What's the uncertainty on measured wave speeds?

# Background: Surface Wave Analysis

- “Filter banks” to decompose surface wave train to narrow band realizations.
- Knowing time of arrival and source-receiver distance yields frequency dependent wave speed.



envelope and  
normalize



# Background: filter banks versus the wavelet transform

Question: What's the difference??

filter bank

$$S(t, f_c) = \int_{t_0}^T H(t, f_c \pm \Delta f) s(t - \tau) d\tau$$

center frequency      filter

time

wavelet

position scale

wavelet

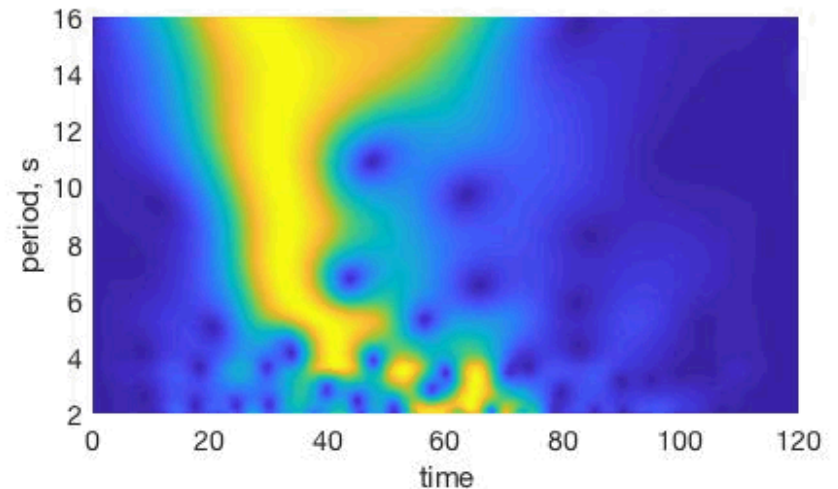
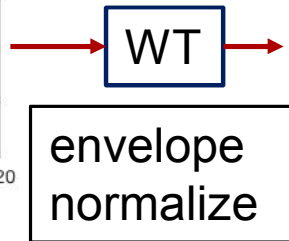
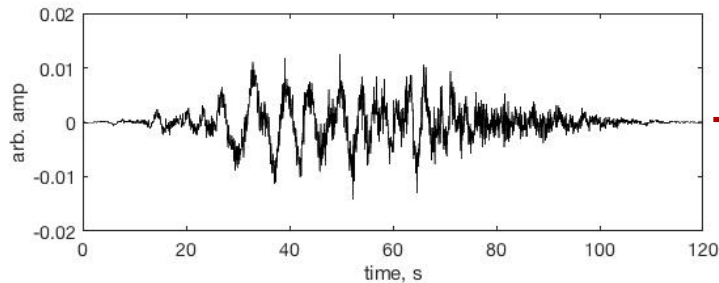
wavelet transform

$$W[s(u, C)] = \int_{t_0}^T \phi(u, C) s(t - u) du$$

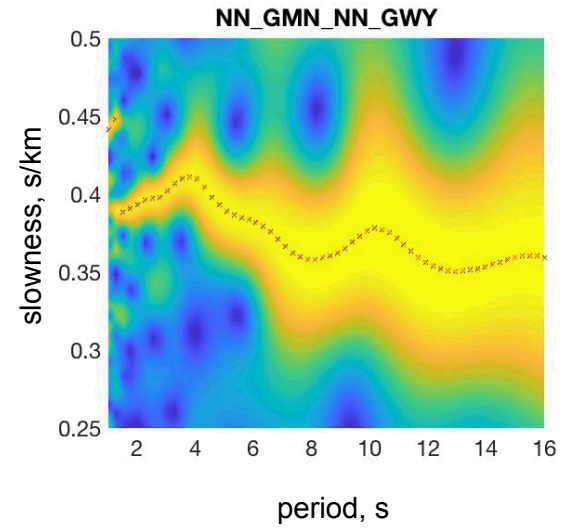
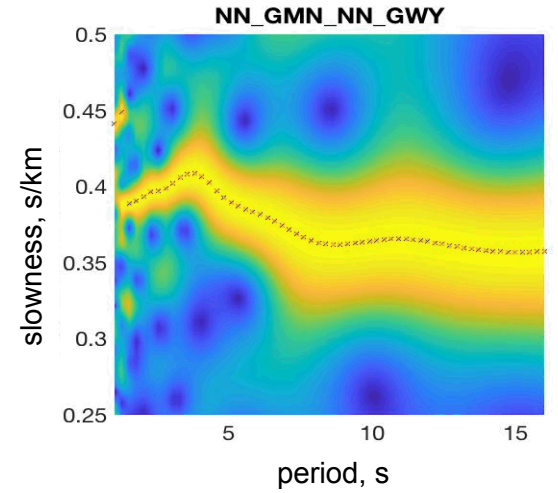
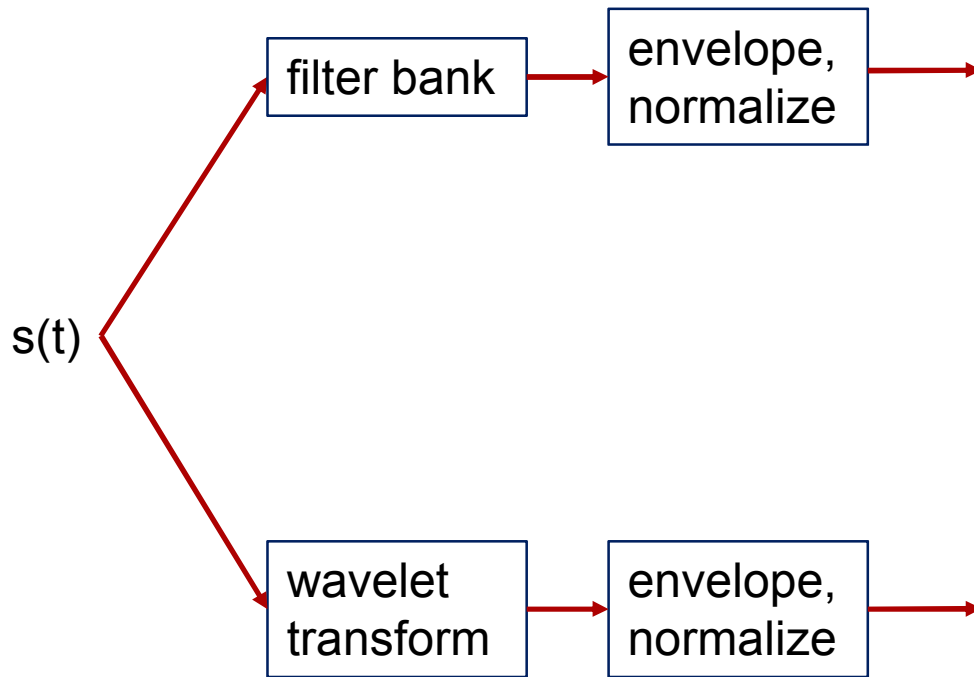
Answer: Not much, in this context

# Implementing the Wavelet Transform

- Implemented exactly the same as a filter bank:
  1. Construct wavelet of scale (C relates to frequency)
  2. Convolve wavelet with signal  $\rightarrow$  store
  3. Construct wavelet of scale  $C+\Delta C$
  4. Repeat



# Compare



# Multiwavelet Transform

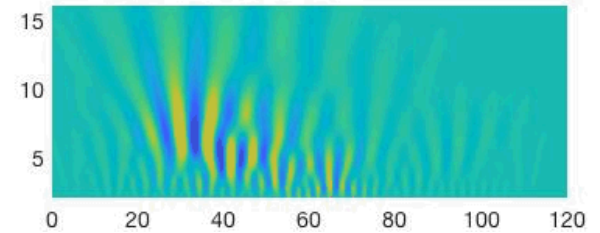
wavelet transform

$$W[s(u, C)] = \int_{t_0}^T \phi(u, C) s(t - u) du$$

one wavelet



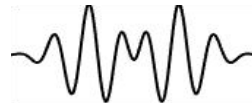
one transform



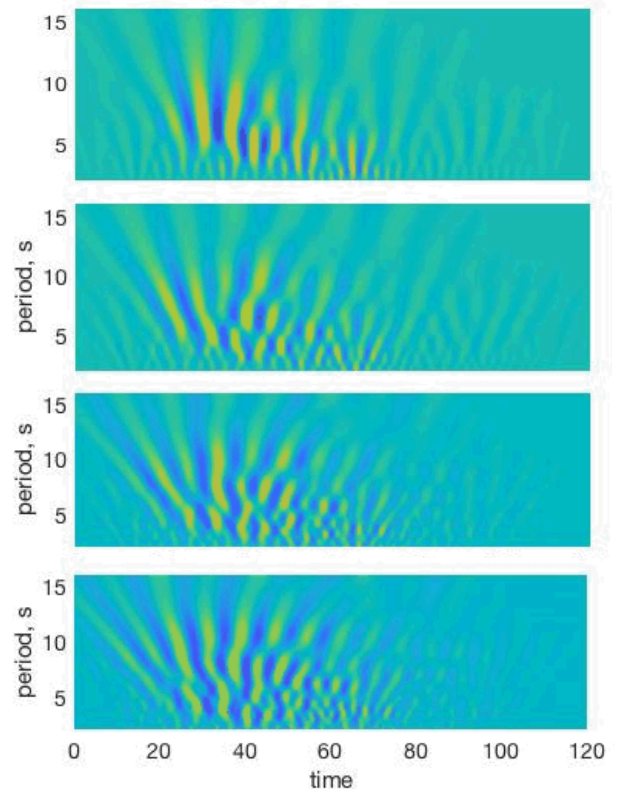
multiwavelet transform

$$W^{\{k\}}[s(u, C)] = \int_{t_0}^T \phi^{\{k\}}(u, C) s(t - u) du$$

$k$  wavelets



$k$  transforms



# Slepian Wavelets

Formed by solving the eigenvalue problem:

$$A\Phi = -\lambda\phi$$

where

$$A_{mn} = \frac{\sin[2\pi(f_c + f_w)\Delta t(m - n)]}{\pi(m - n)} - \frac{\sin[2\pi(f_c - f_w)\Delta t(m - n)]}{\pi(m - n)}$$

- Forms N wavelets
- Even-odd pairs that are  $\frac{\pi}{2}$  out of phase
- Each wavelet pair forms a single complex wavelet

$$\phi^{\{k\}} = \phi_e^{\{k\}}(t, C) + i\phi_o^{\{k\}}$$

Slepian, D., 1983, SIAM Rev. 25 379-393

Lilly, J. M., J. Park, 1995, GJI 122 1001-1021

Bear, L. K., G. L. Pavlis, 1997, BSSA, 87(4), 755-769

# Properties of Slepian wavelets

1) Spectrum of each wavelet pair centers at frequency  $f_c$  with bandwidth  $f_w$ , but different portion of the spectrum is emphasized.

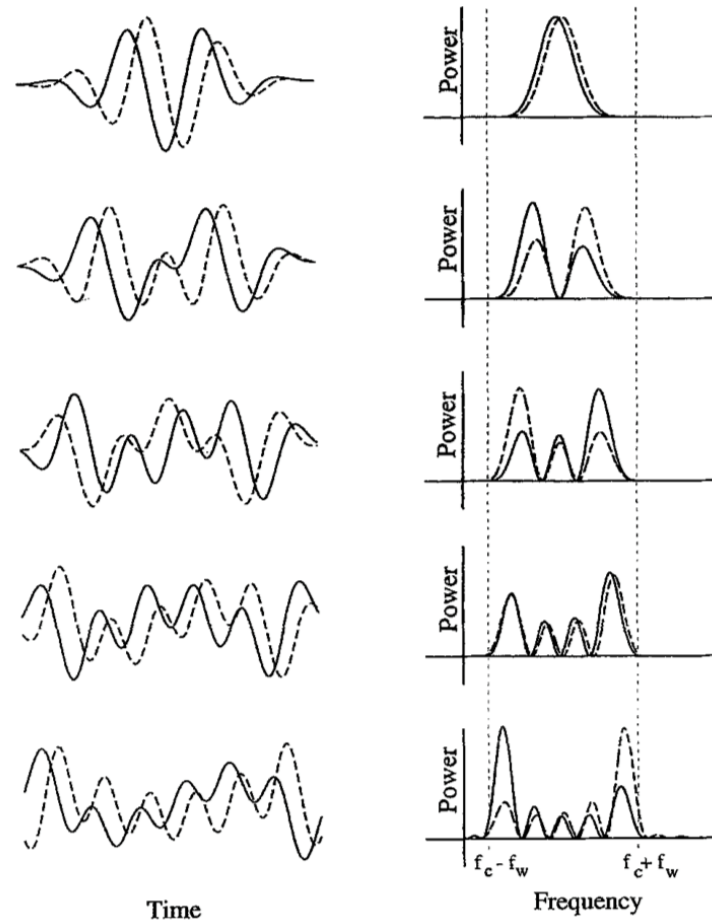
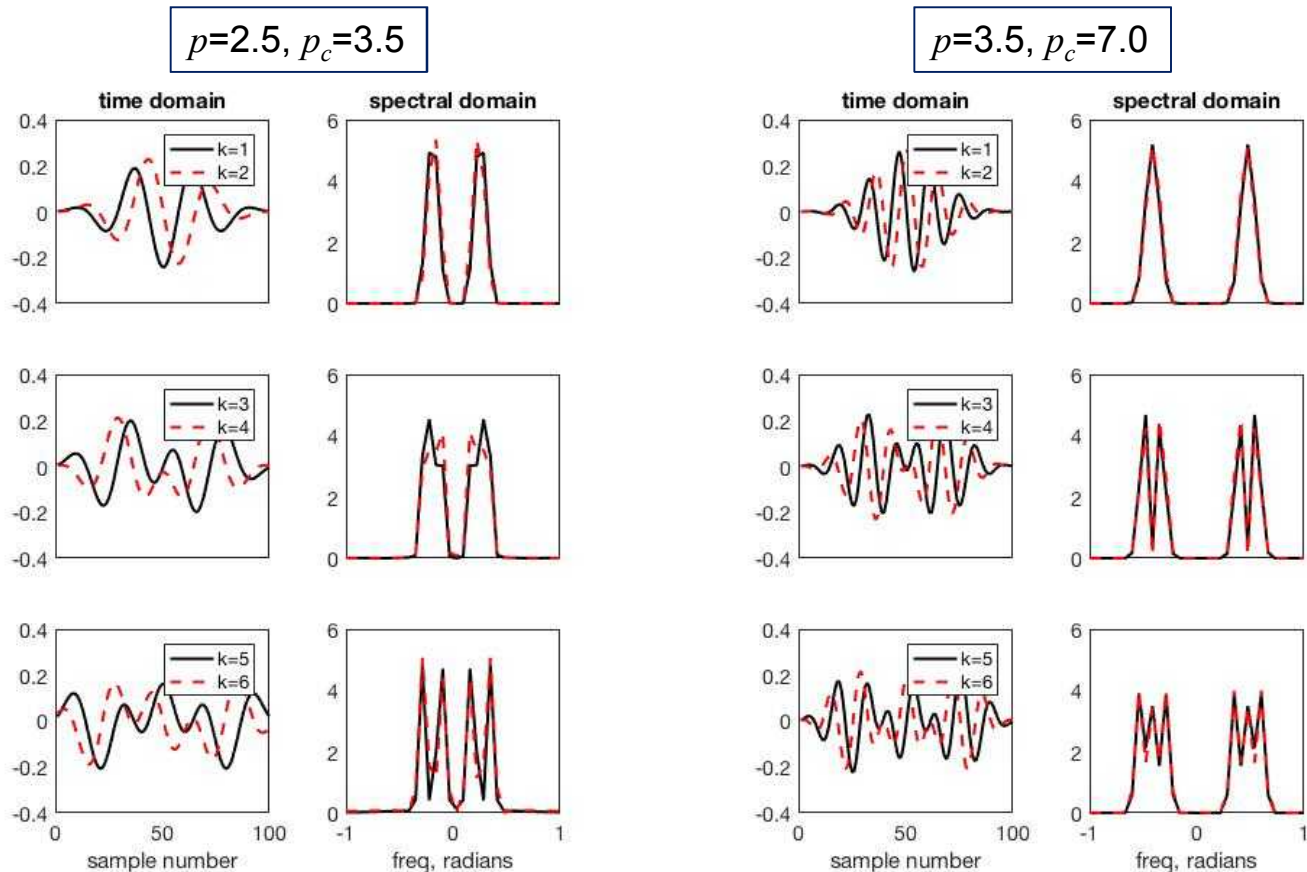


figure from Lilly and Park, 1995

# Properties of Slepian wavelets

- 2) Can control time-frequency resolution,  $f_c$  and  $f_w$  using two parameters:
- 1: time-bandwidth product:  $p = f_w n \Delta t$
  - 2: time-bandcenter product:  $p_c = f_c n \Delta t$



# Properties of Slepian wavelets

3) Wavelet pairs are mutually orthogonal!!

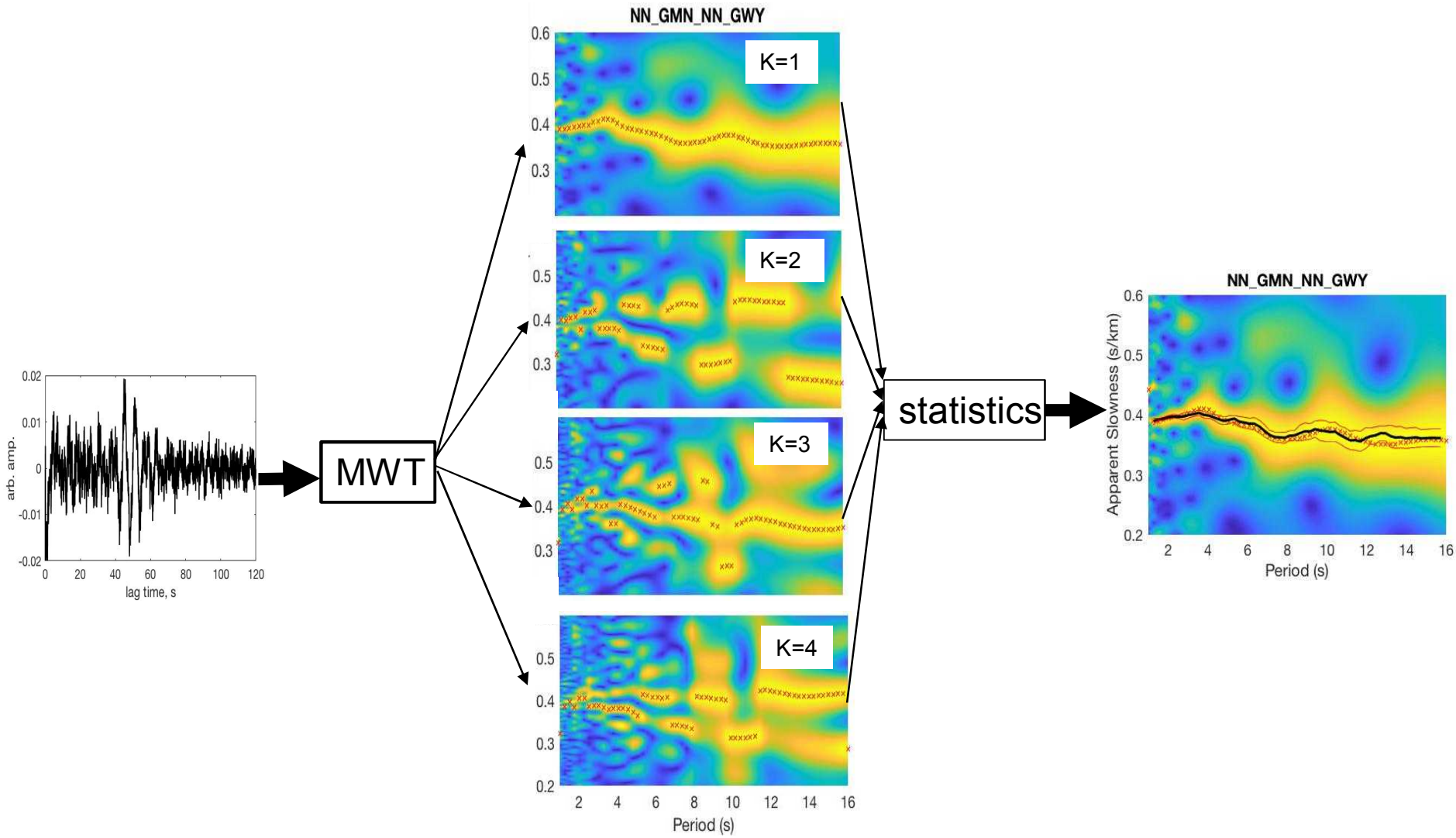
$$\text{If } \int_{n=1}^{n=M} \phi^{\{k\}} \phi^{\{l\}} dn = 0, \quad k \neq l$$

then  $W^{\{k\}}[s(u, C)]$  and  $W^{\{l\}}[s(u, C)]$

are statistically independent (Bear and Pavlis, 1997)

The point: by constructing K complex wavelet transforms of a given signal, we have statistically independent estimates of its time-frequency content. → use this to estimate uncertainty!

# Multiwavelet transform in action

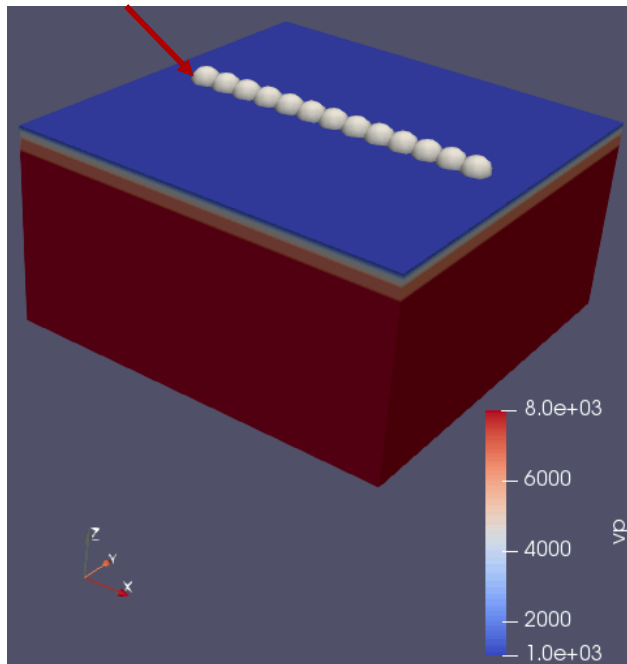


# Test: Synthetic data

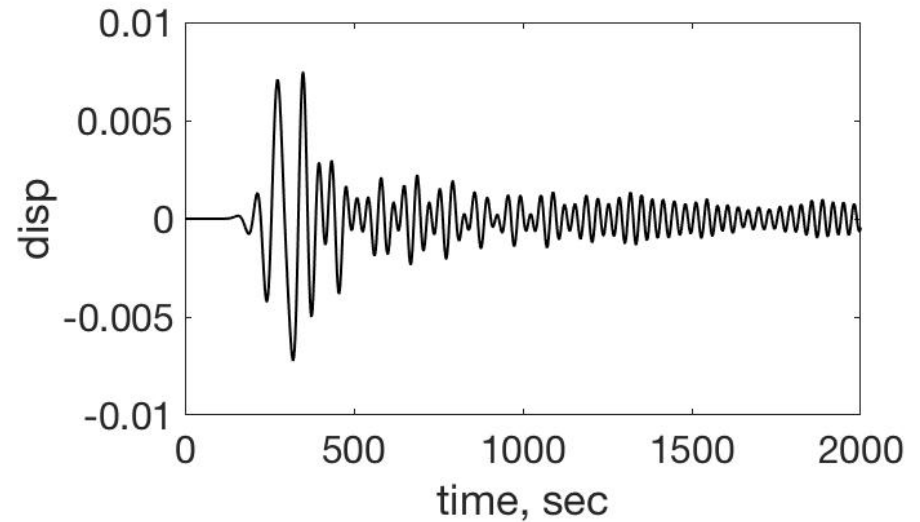
## Specfem3D

- Specfem is used to model wave propagation in a variety of media
- Used to create sensitivity kernels used for full-waveform inversions

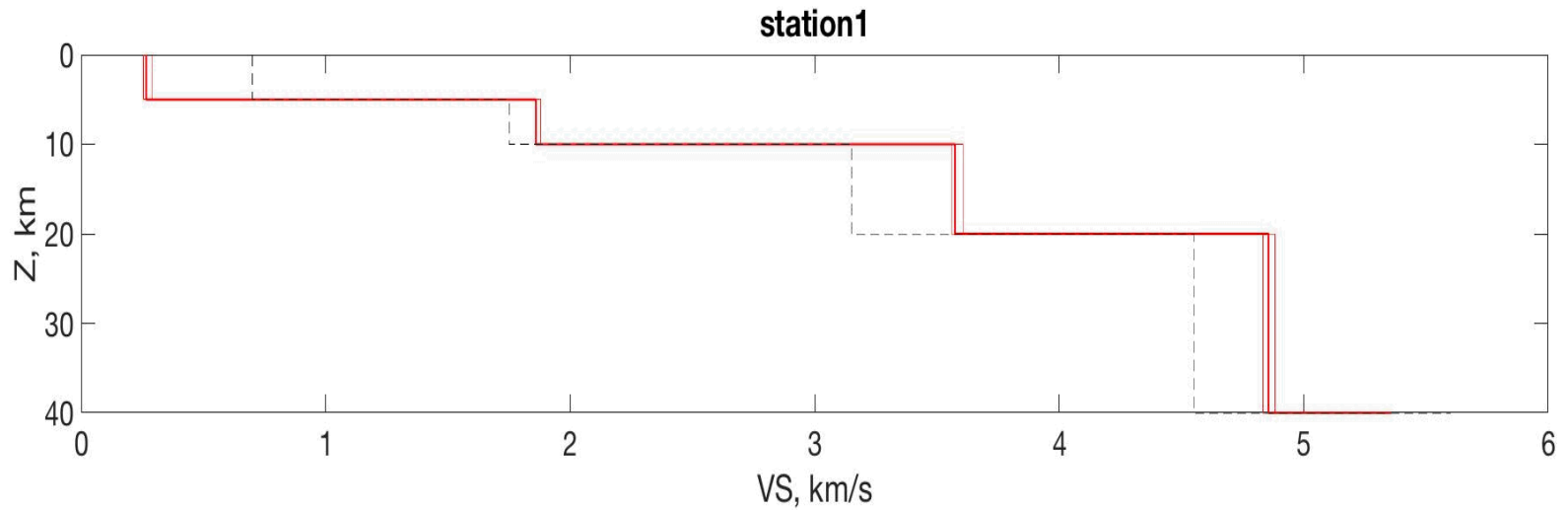
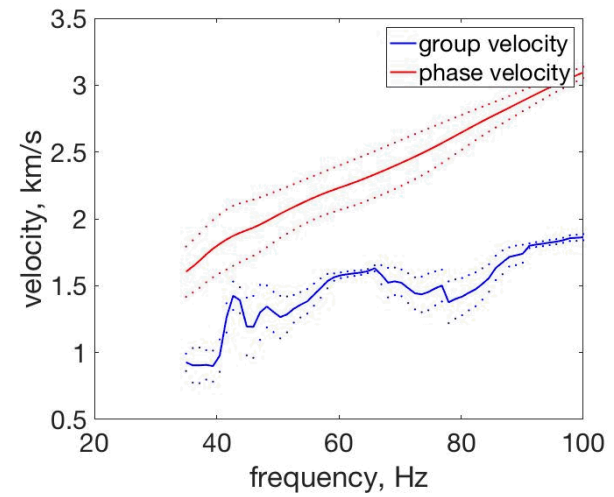
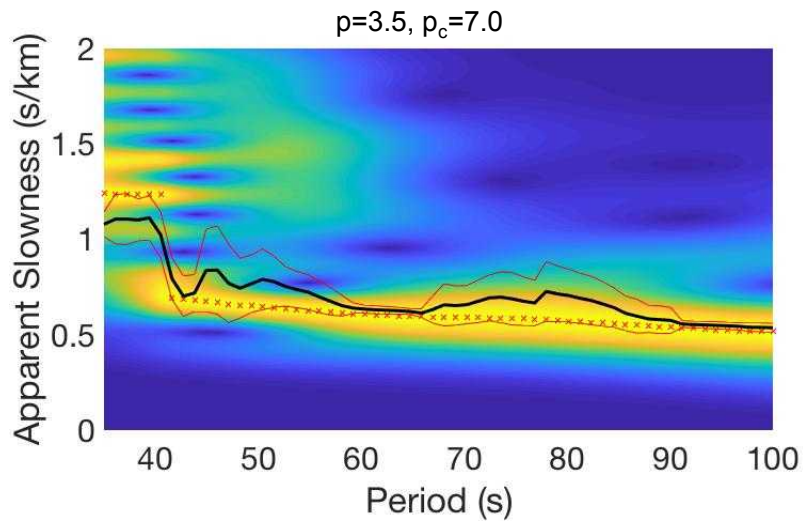
surface shot



800x800x400km

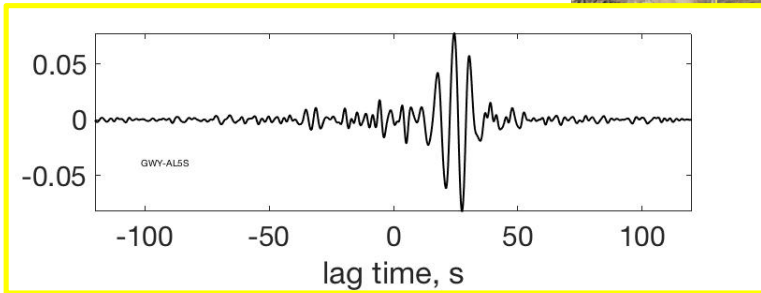
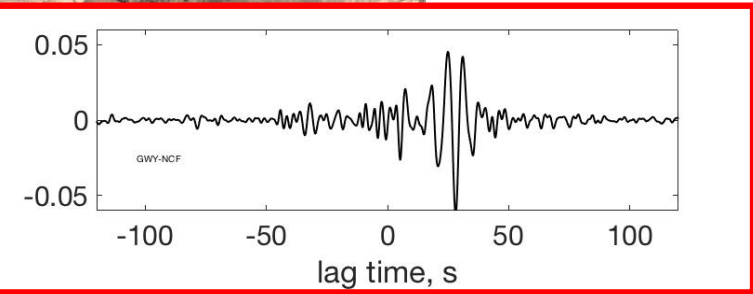
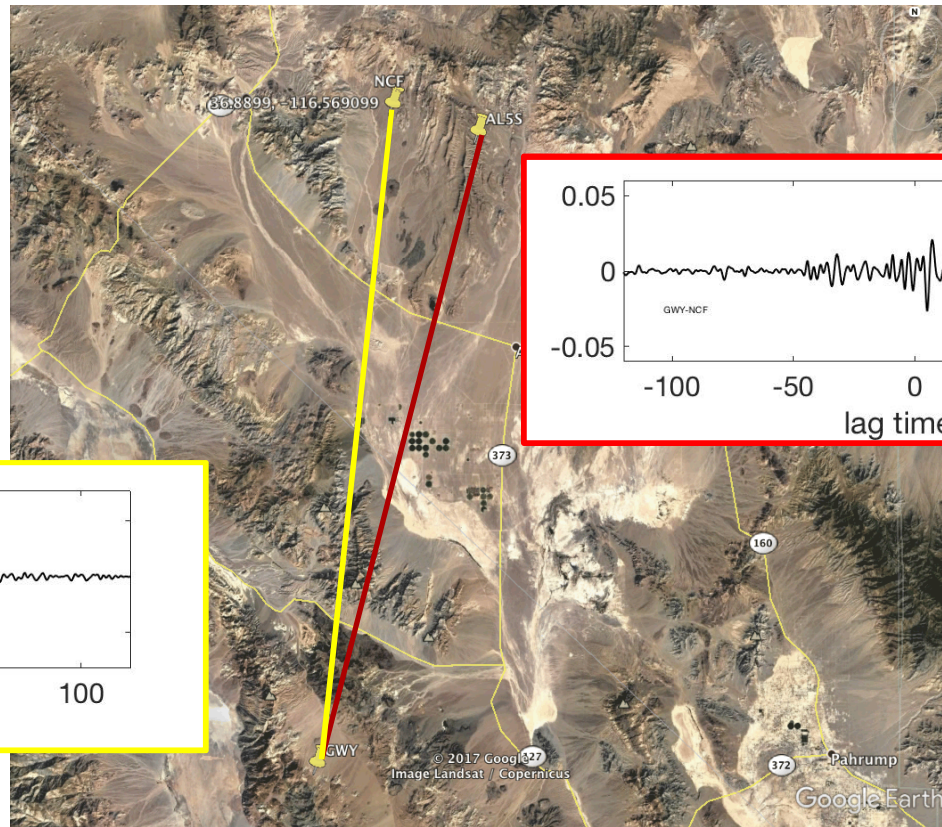
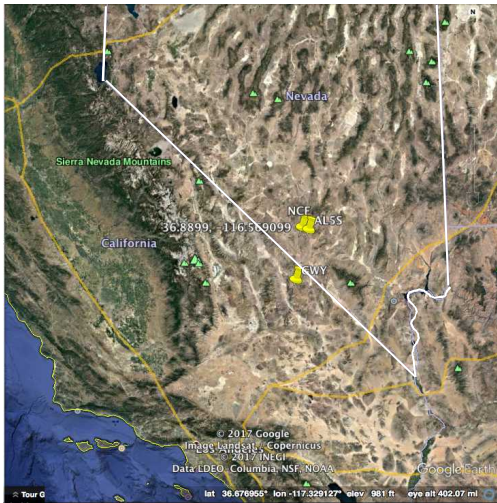


# Test: Synthetic data



# Test: surface wave correlograms

Univ. of NV Seismic network  
crosscorrelograms: NCF-GWY and AL5S-GWY



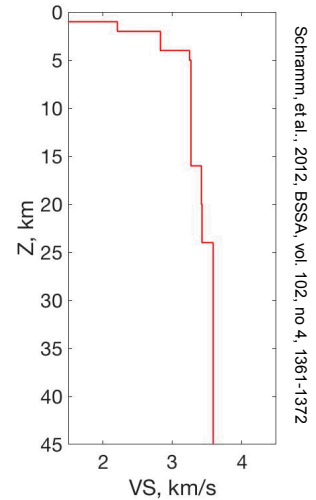
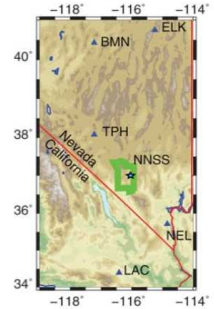
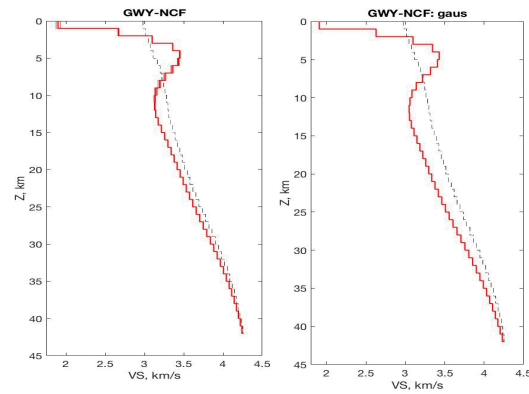
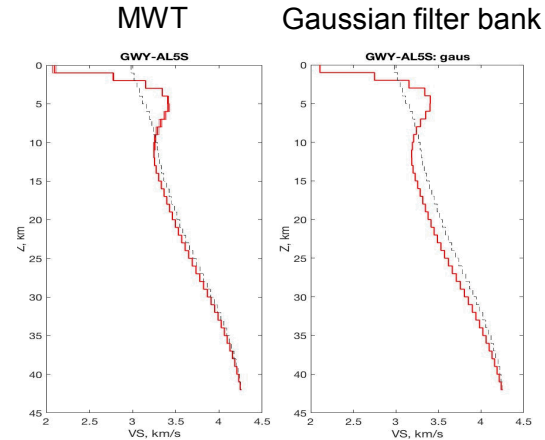
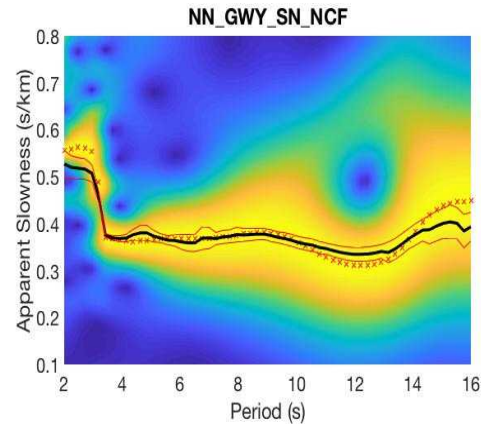
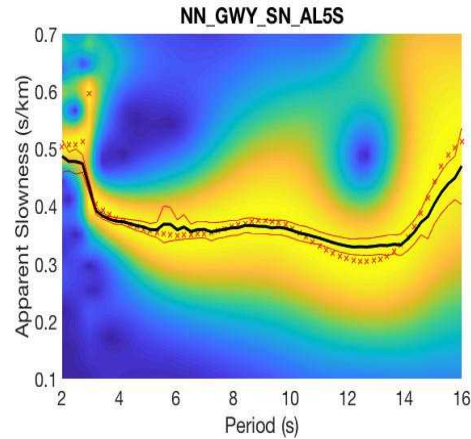
# Test: surface wave correlograms

## Proof-of-concept

Univ. of Reno seismic network:

- 1) Two station-pair noise crosscorrelograms,
- 2)  $|MWT|$  ( $\rho=3.5$ ,  $\rho_c=7.0$ ,  $K=10$ )  $\rightarrow$
- 3) normalize  $\rightarrow$
- 4) automatic peak detection (QC, hand edit)  $\rightarrow$
- 5) group and phase velocity  $\rightarrow$
- 6) 1D SW inversion (CPS: Herrman and Ammon, 2002).

Compare 1D velocity structures:  
MWT versus Gaussian filter bank.



Schramm, et al., 2012, BSSA, vol. 102, no. 4, 1361-1372

## SeisFlows: what is it?

- SeisFlows is a wrapper for Specfem3D (or other suitable software) that explicitly performs the full-waveform inversion.
  - Specfem doesn't have all necessary tools for full-waveform inversion.
- SeisFlows includes working methods for estimating the inverse Hessian and performing line searches.
  - Framework for additional methods is already in place.

## Data Processing

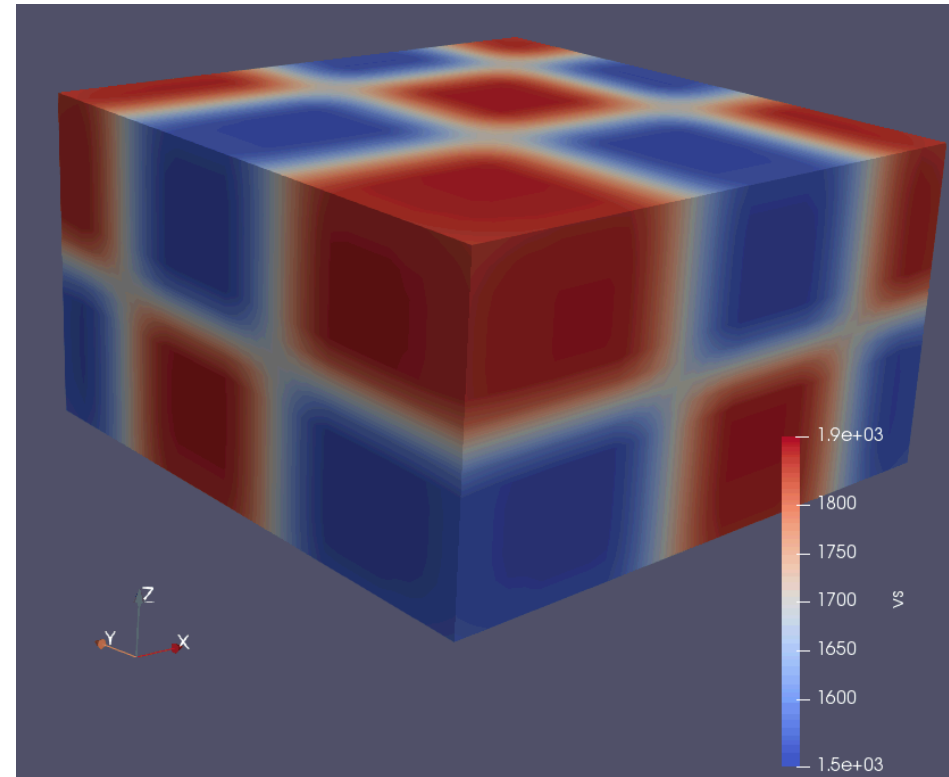
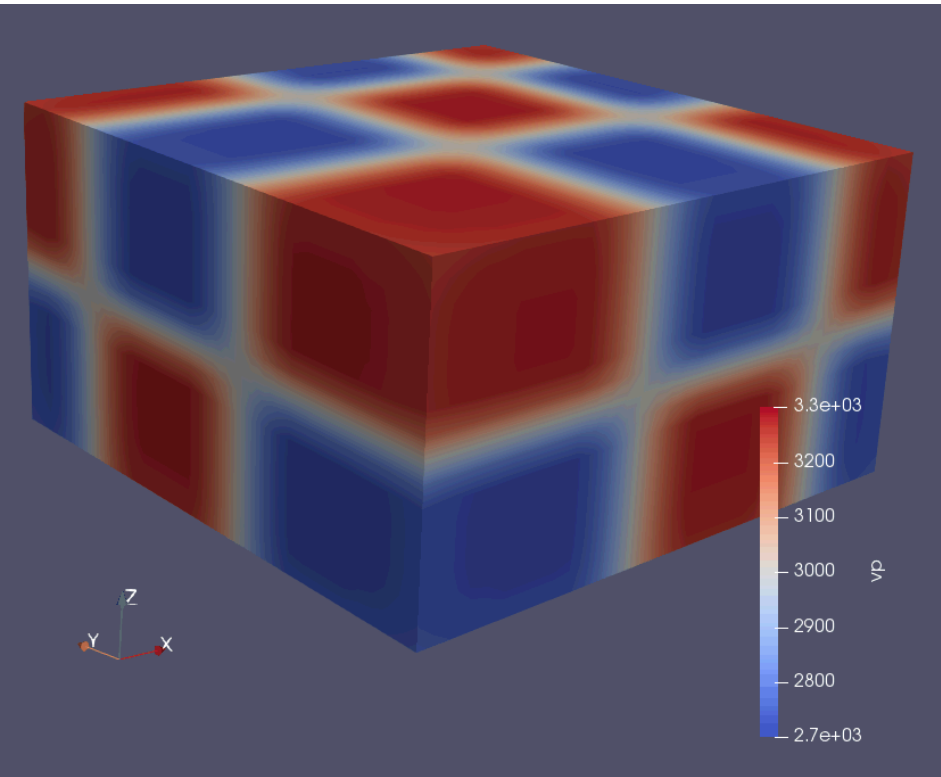
- Seisflows requires displacement data, SPE measurements are velocity.
  - Seismograms are demeaned/detrended and then integrated
- Timestep of data is greater than maximum stable timestep of simulations (by a factor of 2).
  - Seismograms are upsampled with a linear interpolation.
- Signals contain too much information to be used directly.
  - Seismograms are high-cut filtered.
  - Filter band is widened with each successive inversion.

# Waveform tomography: SeisFlows

Checkerboard Model (2.64x2.64x1.44)km

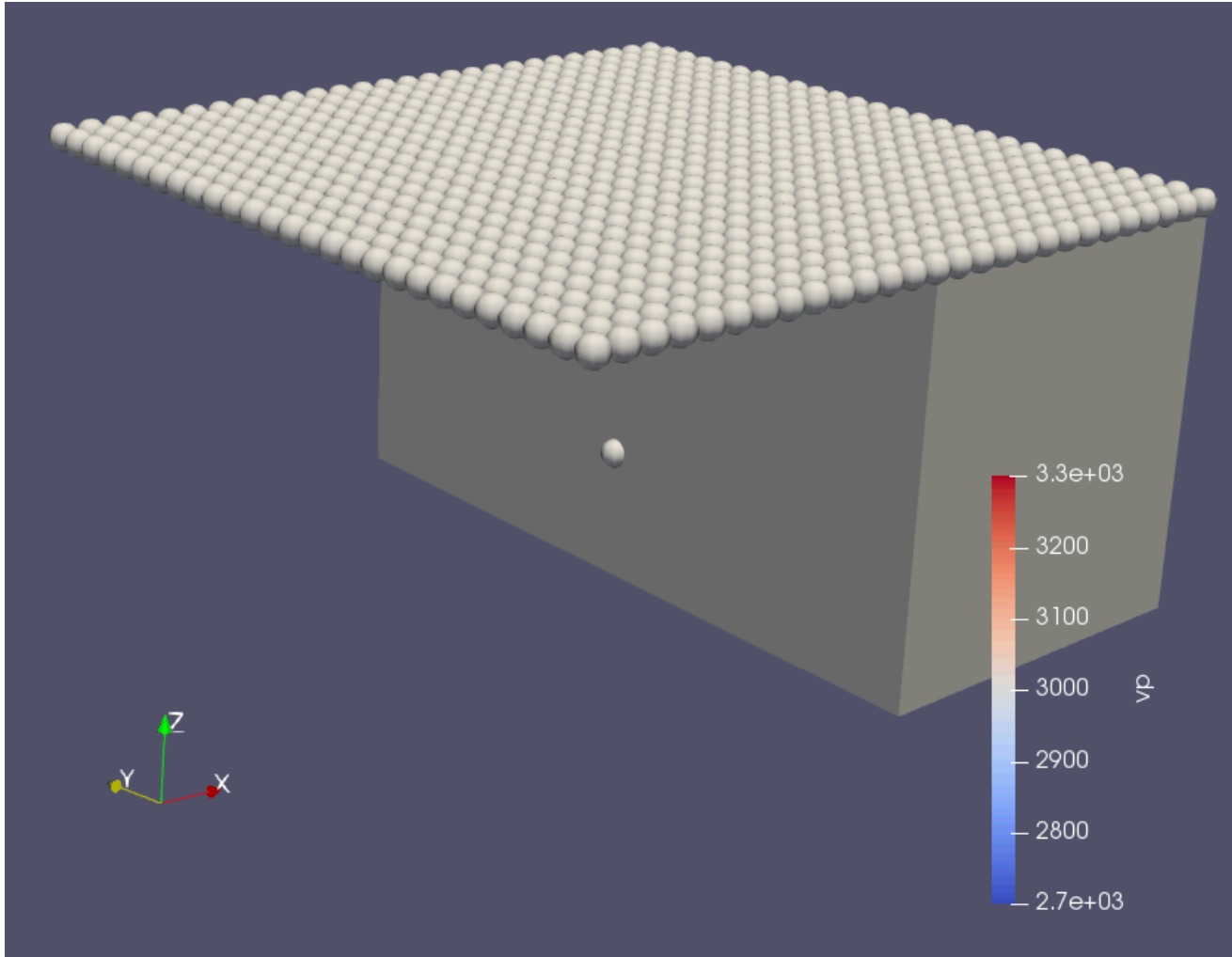
Vp

Vs



shot and receiver geometry: next slide

source: centered in x-y, z=1km

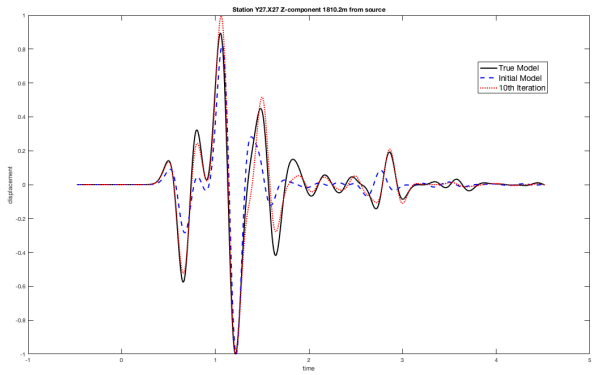
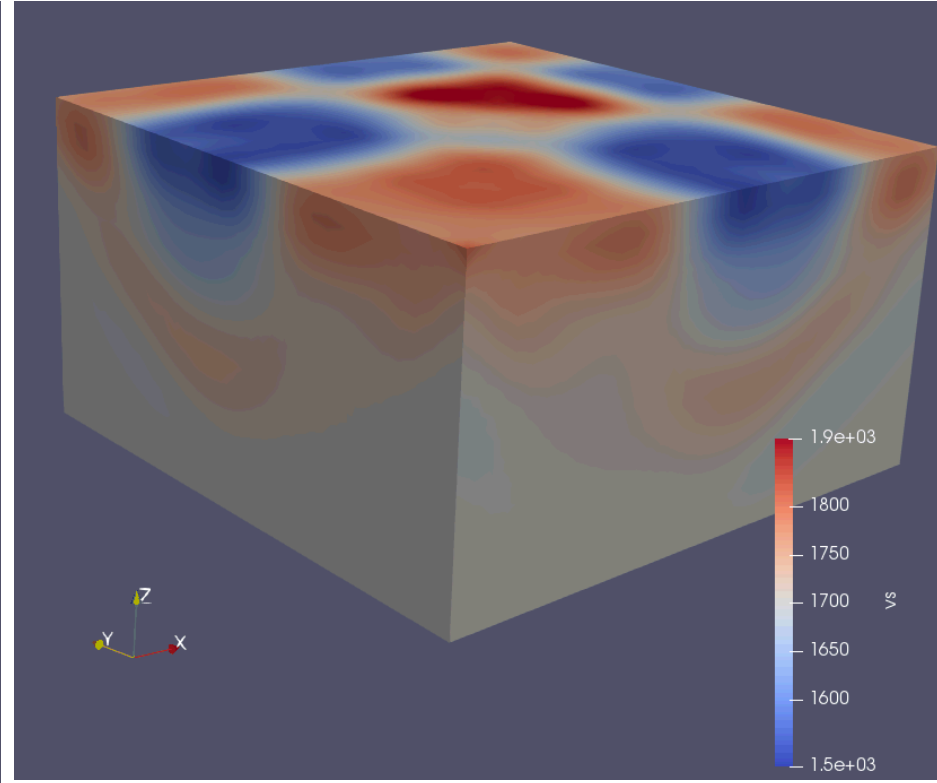
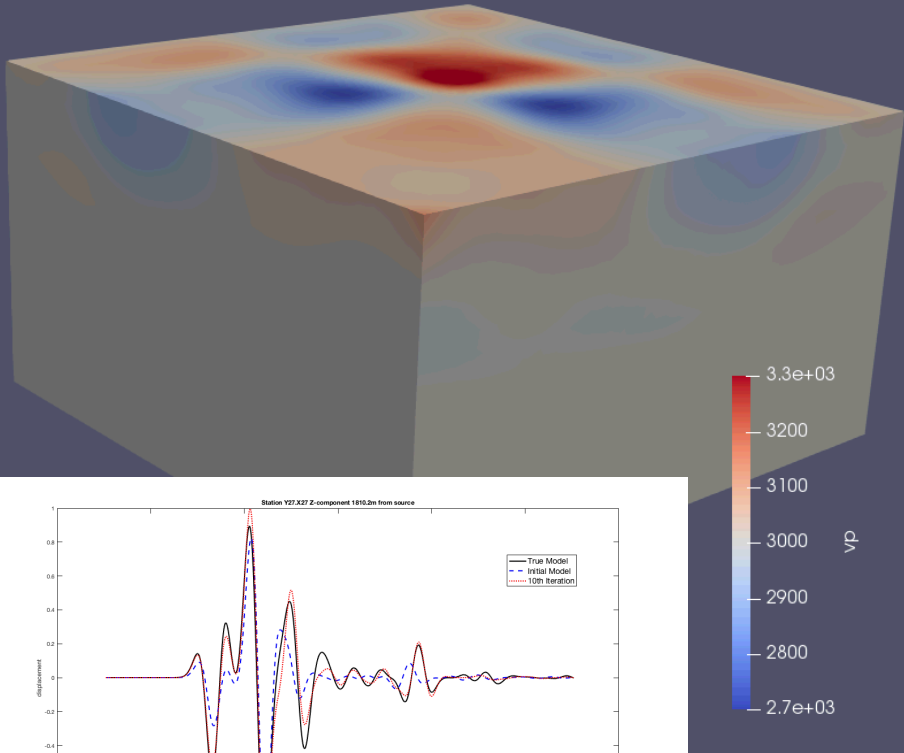


# Waveform tomography: SeisFlows

Model after 10 iterations

Vp

Vs



# Summary

- Surface wave tomography
  - Multiwavelet surface wave analysis + 1D inversion
  - up and running
  - provides uncertainty
- Full waveform tomography
  - Can generate seismograms using SPECFEM
  - Using Seisflow to invert simple models
  - Beginning to process SPE-1 data for full waveform tomography

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- Thank you