Surface wave tomography with USArray based on phase front tracking and amplitude mapping: isotropic, anisotropic, intrinsic attenuation, and density

Fan-Chi Lin[1], Michael H. Ritzwoller[2] & Victor Tsai[1]

1: Seismological Laboratory, California Institute of Technology

2: Department of Physics, University of Colorado at Boulder

1. Abstract

The deployment of the EarthScope/USArray Transportable Array has permitted the detailed study of crustal and upper mantle structures in the western US based on surface wave measurements. In this poster, we present three different applications that incorporate empirical surface wave wavefield determined by phase front tracking and amplitude mapping. In the first application, we demonstrate how local directionally dependent phase velocities can be measured by solving the real part of the wave equation. This method, referred to as Helmholtz tomography, accounts for the finite frequency effects, reduces both random and systematic errors, and improves the resolved of isotropic and azimuthally anisotropic structures at long period (>50 sec) compared to its ray theoretic based predecessor, eikonal tomography. In the second application, we demonstrate how intrinsic attenuation can be studied by solving the imaginary part of the wave equation. The method, in principle, accounts for the focusing/defocusing and local amplification effects and should result in better estimation of intrinsic attenuation structure compared to ray theoretic based methods. In the third application, we demonstrate the potential of using local surface wave amplification to evaluate impedance variation and constrain density structure.

2. Basic equations

The 2D damped wave equation:

$$\frac{1}{c(\mathbf{r})^2}\frac{\partial^2 u(\mathbf{r},t)}{\partial t^2}+\frac{\alpha(\mathbf{r})}{c(\mathbf{r})}\frac{\partial u(\mathbf{r},t)}{\partial t}=\nabla^2 u(\mathbf{r},t) \quad (1)$$

where u, c, and α are the wavefield, phase velocity, and attenuation coefficient for surface waves respectively.

The single frequency wavefield can be described by:

$$u(\mathbf{r},t)=\frac{A(\mathbf{r})}{\varepsilon(\mathbf{r})}e^{i\omega[t-\tau(\mathbf{r})]} \quad (2)$$

where A and τ are the observed surface wave amplitude and phase travel time and ε is the local amplification.

The real part of the solution:

$$\frac{1}{c(\mathbf{r})^2}=\nabla\tau\cdot\nabla\tau-\frac{\nabla^2(A/\varepsilon)}{\omega^2(A/\varepsilon)} \quad (3)$$

phase velocity — apparent slowness — finite frequency correction

Ray theory approximation at high frequency, the eikonal equation:

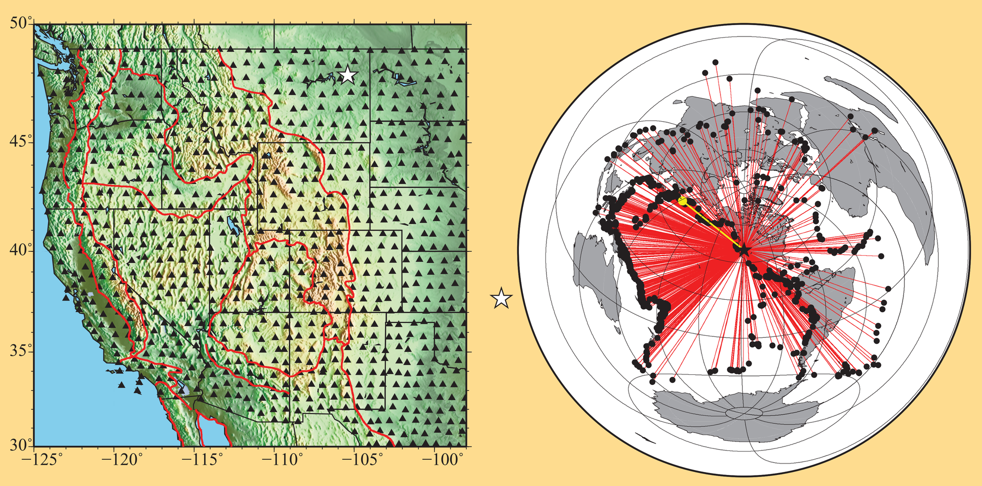
$$\frac{\hat{k}_i(\mathbf{r})}{c_i'(\mathbf{r})}\cong\nabla\tau_i(\mathbf{r}) \quad (4)$$

The imaginary part of the solution:

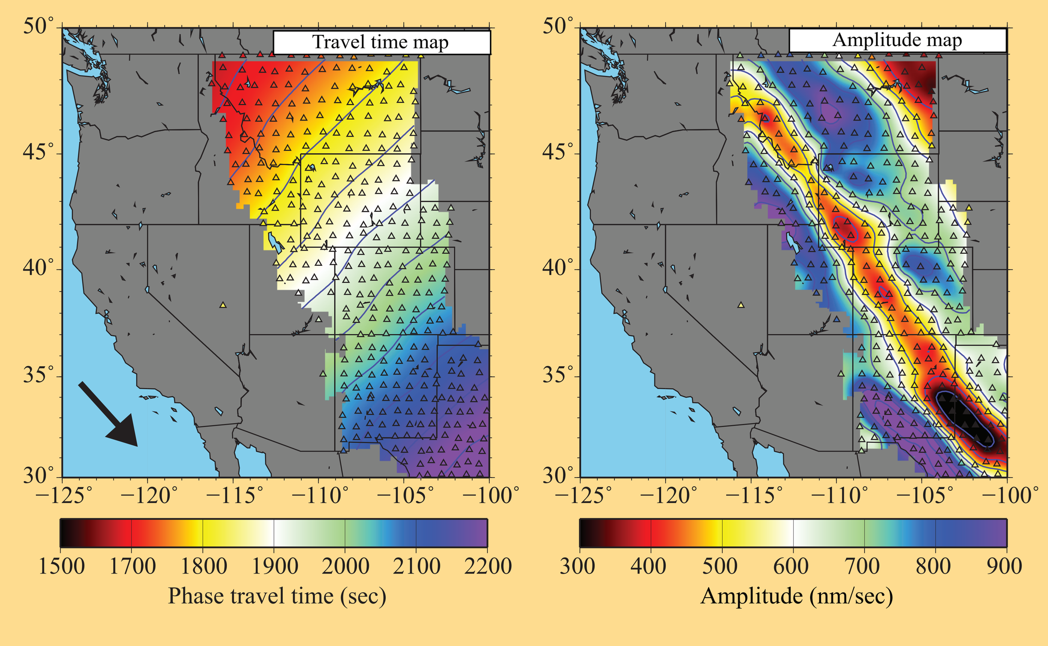
$$\frac{\alpha(\mathbf{r})}{c(\mathbf{r})}+\frac{2\nabla\varepsilon^{-1}\cdot\nabla\tau}{\varepsilon^{-1}}=-\frac{2\nabla A\cdot\nabla\tau}{A}-\nabla^2\tau \quad (5)$$

intrinsic attenuation — local amplification — apparent amplitude decay — focusing/defocusing correction

The stations and earthquakes used.

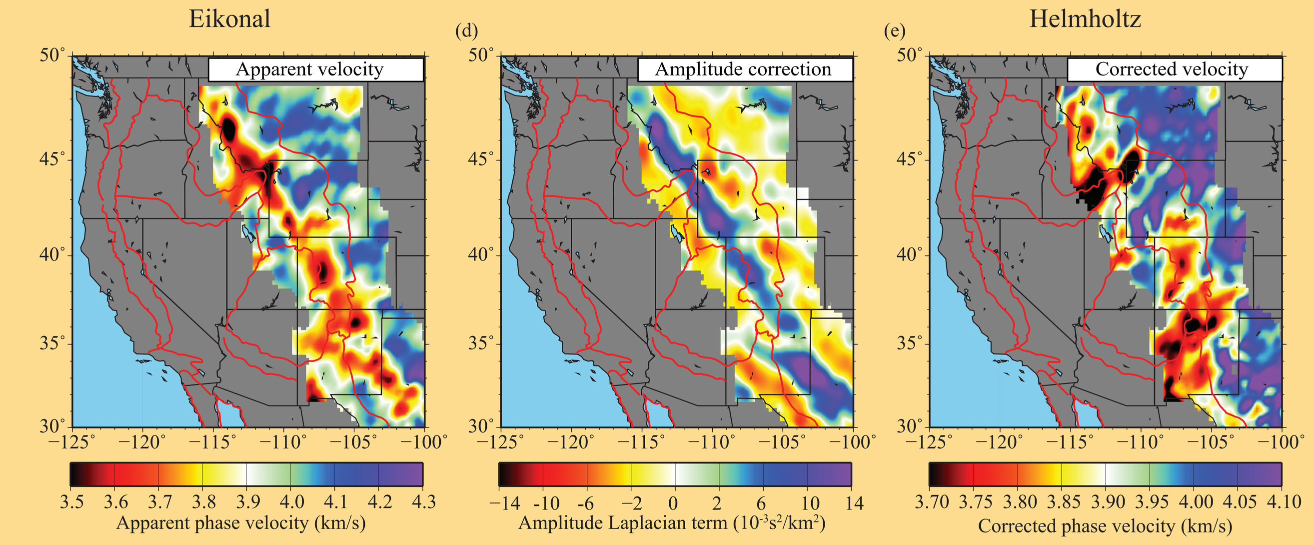


The observed 60 sec Rayleigh wave phase travel time and amplitude maps for the April 7th, 2009 earthquake near Kuril Islands. We use this event to demonstrate our methods.

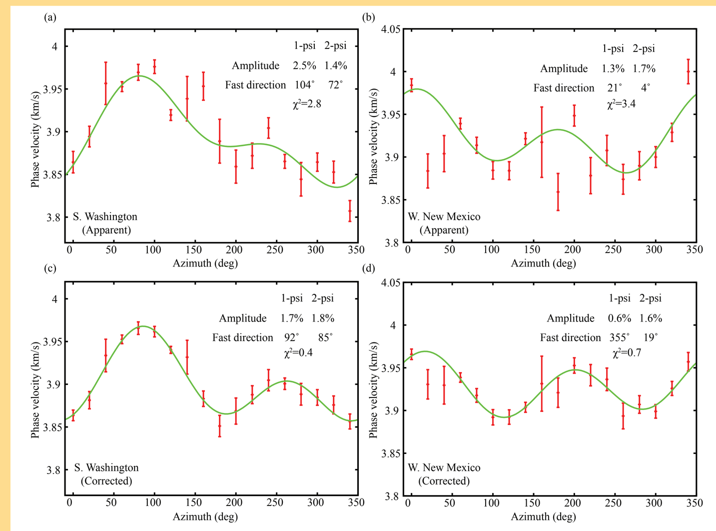


3. Directionally dependent phase velocity measurements

Measureing 60 sec Rayleigh wave phase velocity based on eq. (3) and the Kuril Islands event.



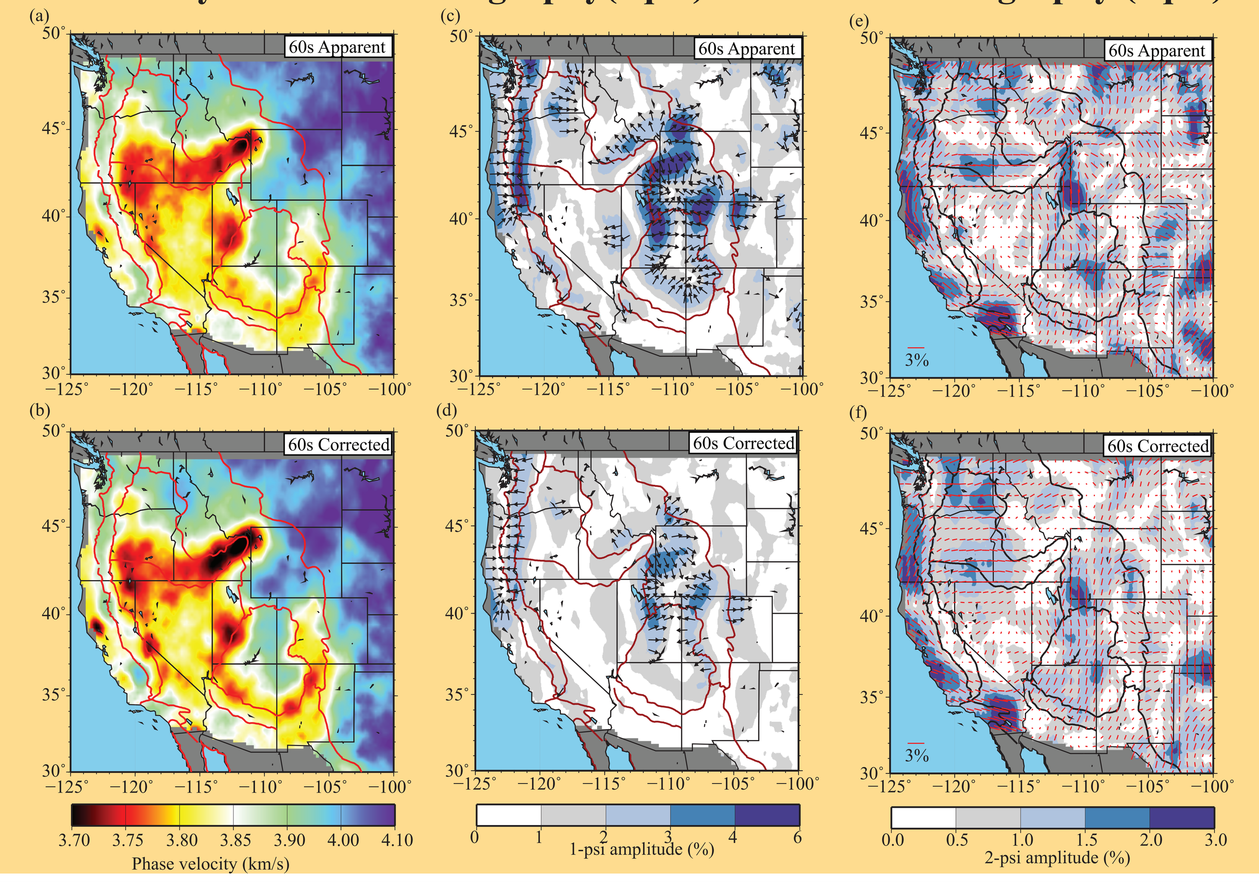
Example of directionally dependent phase velocity measurements based on eq. (3) and (4) at two locations.



$$c(\psi)=c_{iso}\left\{1+\frac{A_{1psi}}{2}\cos(\psi-\varphi_{1psi})+\frac{A_{2psi}}{2}\cos\left[2(\psi-\varphi_{2psi})\right]\right\}$$

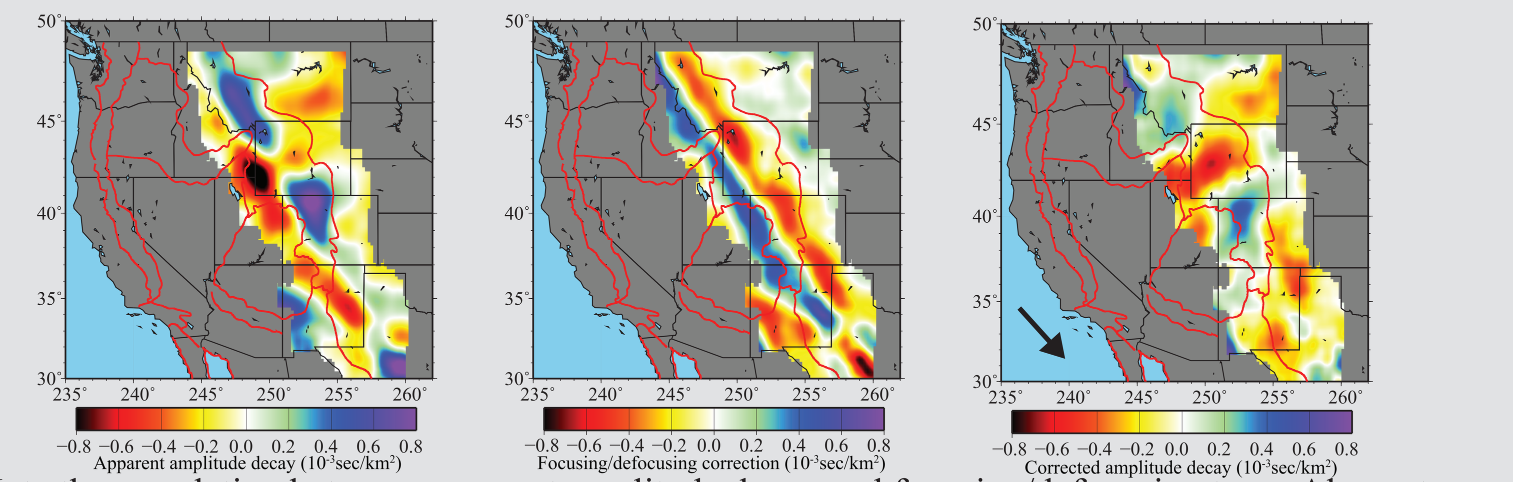
Both 180° (2-psi) and 360° (1-psi) periodicities are observed where the 1-psi anisotropy signal is non-physical and can be considered as apparent bias due to finite frequency effect and large isotropic velocity contrast.

The summary of isotropic, 1-psi anisotropic, and 2-psi anisotropic structures determined by Helmholtz tomography(eq. 3) and eikonal tomography (eq. 4).



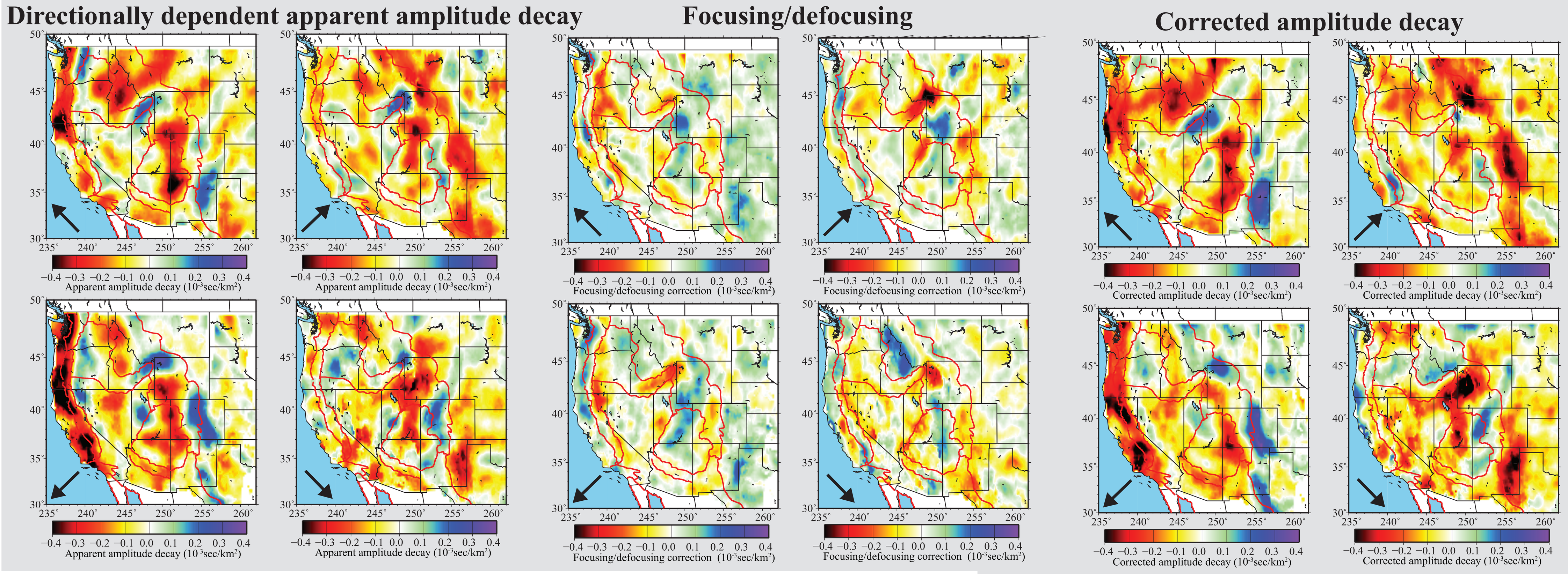
4. Intrinsic attenuation measurements

Measureing 60 sec Rayleigh wave amplitude decay based on eq. (5) and the Kuril Islands event.

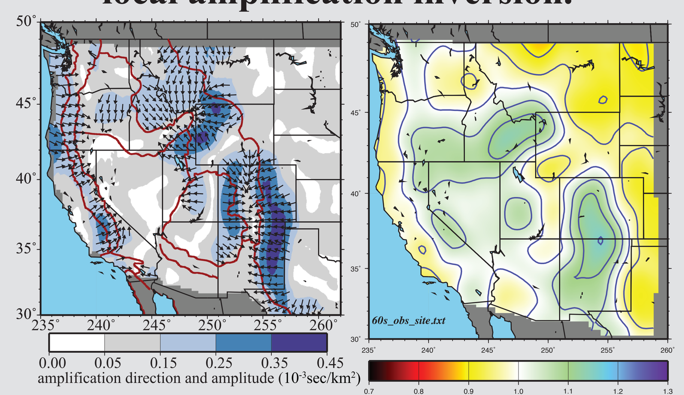


Note the correlation between apparent amplitude decay and focusing/defocusing term. Also note that the corrected amplitude decay is affected by both intrinsic attenuation and local amplification.

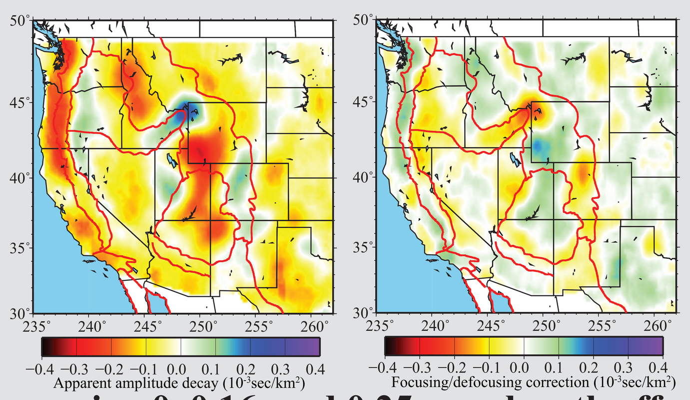
Directionally dependent apparent amplitude decay / Focusing/defocusing / Corrected amplitude decay



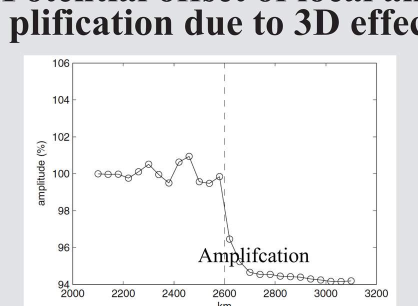
Direction of amplification and the local amplification inversion.



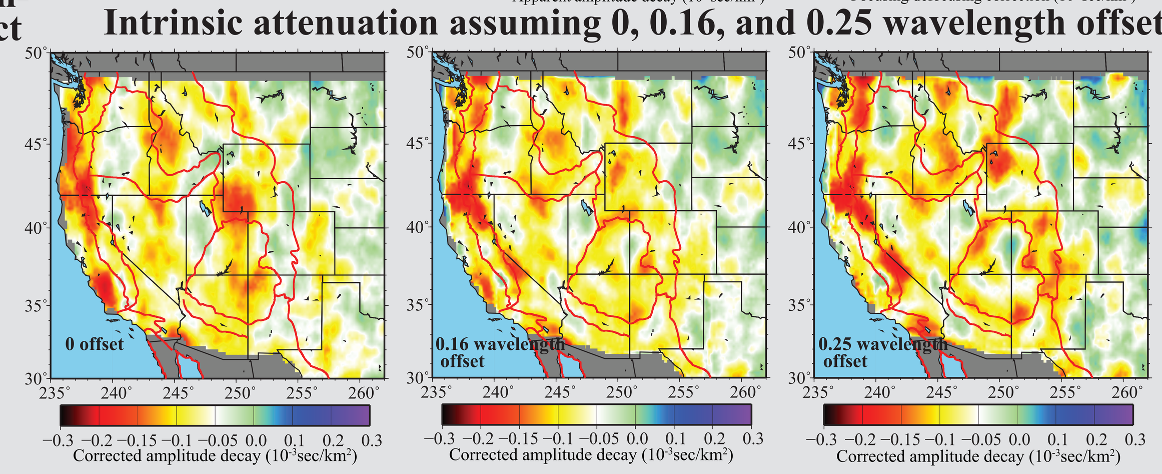
Isotropic component of apparent amplitude decay and focusing/defocusing correction.



Potential offset of local amplification due to 3D effect

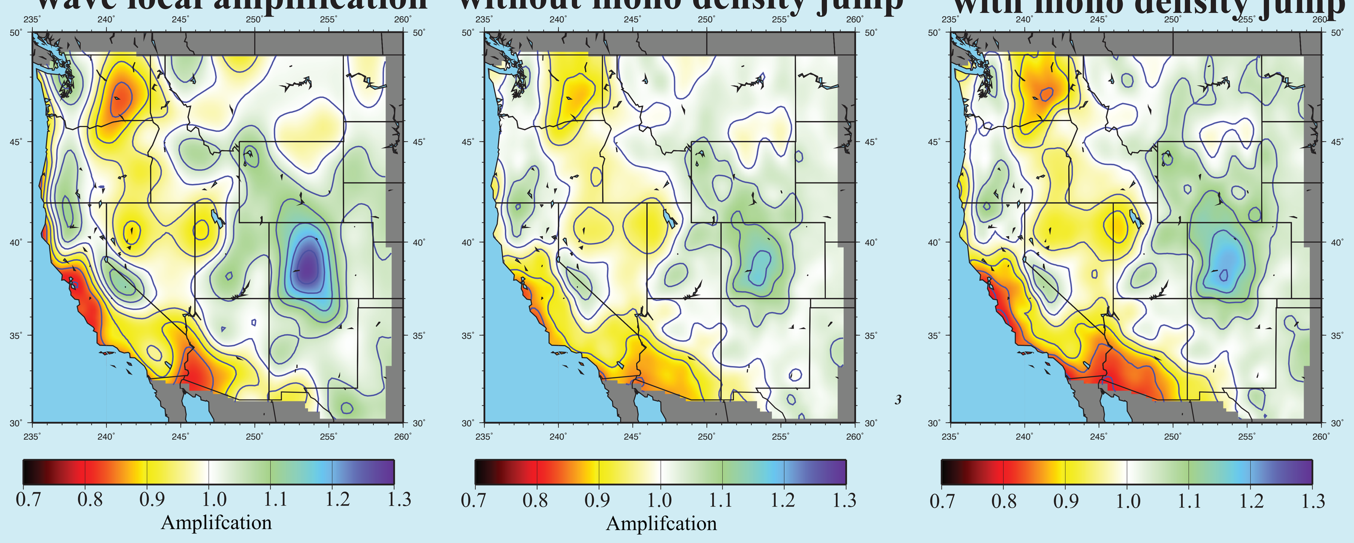


Intrinsic attenuation assuming 0, 0.16, and 0.25 wavelength offset



5. Constraint on density structure?

Observed 30 sec Rayleigh wave local amplification / Prediction based on model without moho density jump / Prediction based on model with moho density jump



$$\varepsilon\propto\frac{1}{\sqrt{CI_1}}$$

$$I_1=\int_0^a\rho(U^2+V^2)r^2\,dr$$

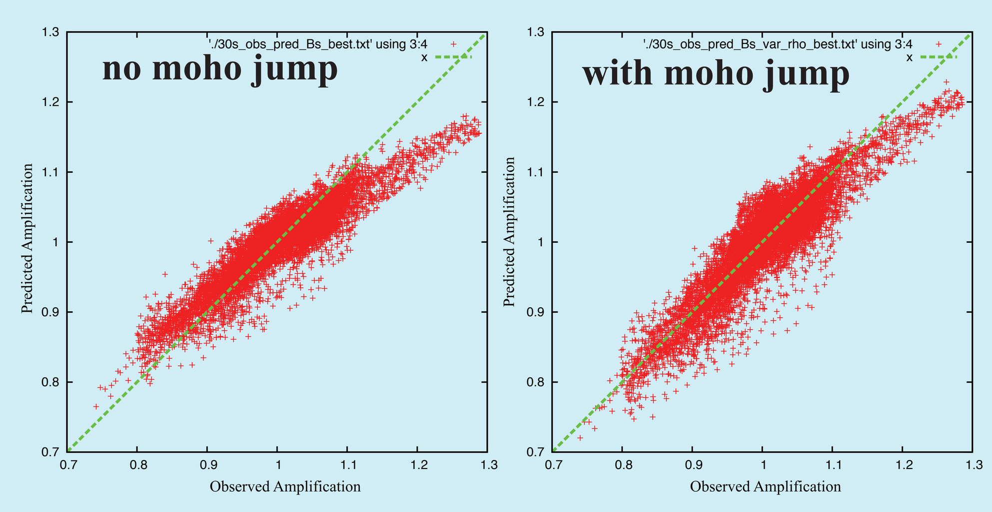
C: group velocity

U: normalized horizontal eigenfunction

V: normalized vertical eigenfunction

Tromp & Dahlen (1992)

Comparison between observed and predicted amplification for 30 sec Rayleigh wave



Comparison between observed and predicted amplification for 60 sec Rayleigh wave