Joint inversion of teleseismic body and surface waves:
a simple technique for recovering full upper mantle velocity structure

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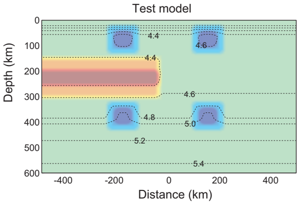
1.The problem

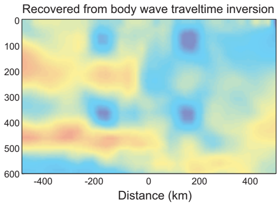
Seismic surface waves are sensitive to the absolute velocity structure of the Earth. However, the long periods required to sample the upper mantle are sensitive only to broad lateral features. This lateral resolution deteriorates rapidly with depth (right fig.)

Teleseismic body waves typically have frequencies one to two orders of magnitude higher than accompanying surface waves and can reveal much narrower features (center fig.) While finite frequency content limits resolution at depth, the effect is far less deleterious than for surface waves. In order to account for whole Earth structure however, the mean traveltime residual from each earthquake is usually removed. As a result, regional body wave inversions can recover only lateral perturbations relative to an arbitrary 1D background model.

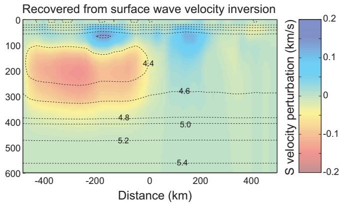
It has long been noted that these two types of data are highly complimentary for regional surveys. Though several studies have synthesized independently-derived surface and body wave velocity models [e.g. Dueker et al. 2001; Achauer and Masson 2002], many structures are better recovered by jointly inverting the two data types.



Synthetic Earth model. 1000 km wide by 600 km deep - a geometry similar to many broadband experiments. Contours label absolute shear velocity in increments of 0.2 km/s, while shades represent departures from 1D background model.



Inversion recovers the high velocity point anomalies at all depths. However the tabular feature is not resolved, and its low velocities are distributed throughout the left side of the model. Note the absence of absolute velocity information.



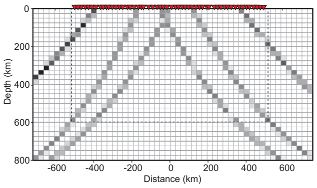
Tabular feature is well-resolved. However, the absence of the deeper point anomalies highlights the surface waves' inability to recover short wavelength features at depths.

Achauer, U., and F. Masson, Seismic tomography of continental rifts revisited; from relative to absolute heterogeneities, Tectonophysics, 358, 17-37, 2002.
Dueker, K., H. Yuan, and B. Zurek, Thick-Structured Proterozoic Lithosphere of the Rocky Mountain Region, GSA Today, 11, 4-9, 2001.

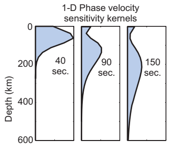
2. A simple approach to joint inversion

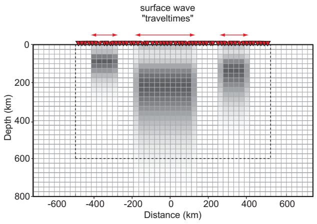
A simple scheme for jointly inverting the two types of data is made possible by treating the observed surface wave velocities as traveltimes between stations. This allows surface wave sensitivity kernels to be written in terms of traveltime delay relative to a starting model, δt_k, and model slowness, δs_j. This form is indentical to that used in most inversions of teleseismic body waves. These extra constraint equations can be added directly to the G matrix of Frechet derivatives. Though we demonstrate the technique using kernels derived from 1D models, more sophisticated kernel calculations (3D ray tracing, banana-doughnut kernels, etc.) could be incorporated using the same methodology.

$$G = \begin{bmatrix} \delta t_i^{\text{body wave}} / \delta s_j \\ \delta t_k^{\text{surface wave}} / \delta s_j \\ \text{smoothing eq.} \end{bmatrix}$$



Six representative teleseismic body wave sensitivity kernels.



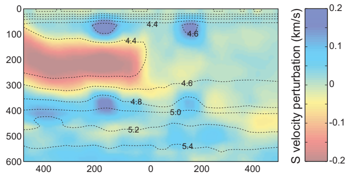


Three representative Rayleigh wave phase velocity sensitivity kernels. The depth sensitivity of the kernel is determined by the period. Longer periods are typically measured over larger distances.

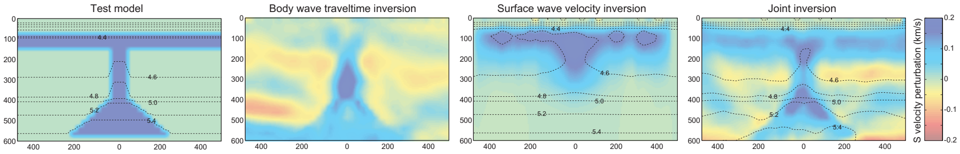
3. Synthetic tests

Results of joint inversion for test structure shown in section 1. Synthetic data calculated using ray and surface wave distribution from RISTRA project discussed below. S-wave traveltimes have been perturbed with +-0.05 s of random noise. The surface wave "traveltimes" have been perturbed by +-0.25 s in accordance with measured errors.

The joint inversion incorporates the strengths of both methods. The body waves constrain short wavelength lateral structures, such as the high velocity spots. The surface waves provide the absolute velocity structure and help place long wavelength anomalies at the appropriate depth, as represented by the low velocity channel.



A further comparison of the methods:



Model which contains a hypothetical downwelling feature with ponding in the transition zone. This model is typical of features which benefit from the joint inversion approach.

Body wave tomography recovers the portion of the structure that is laterally discontinuous but does not capture the uniform mantle lid above 200 km. The low velocity artifacts are unavoidable since the traveltime residuals must be demeaned prior to inversion.

Surface wave tomography recovers the shallow laterally continuous structure but fails to detect the narrower features at depth. The inversion returns reliable absolute velocities above ~400 km depth.

The joint inversion returns absolute velocities and the basic structure of the anomaly at all depths. Some low velocity artifacts are still present since the surface waves have limited sensitivity to the deeper model. Longer period surface wave data could be used to minimize this.

4. Application to PASSCAL-style data

We apply the method to data collected by the RISTRA project in the southwestern U.S. This 57-station broadband experiment recorded data during a 21-month deployment in 1999-2001. *Gao et al.* [in review] used S, ScS and SKS phases from 61 earthquakes in-line with the array to derive a set of 2164 traveltime residuals. They have inverted this data (as well as P wave data) for upper mantle structure (see poster S31E-0810, this session). *West et al.* [in review] analyzed Rayleigh wave phase velocities (10-150 s periods) from 29 events in-line with the array to derive 750 interstation velocity measurements.

We use the joint inversion method described here to simultaneously invert the two datasets. As expected, the derived images share features unique to each dataset. The surface wave inversion misses many of the finer details picked up by the body waves. However, the surface waves capture the difference in average velocity between east and west. Fast shield-like velocities of the Great Plains transition to the warmer U.S. west. The joint inversion includes this long-wavelength transition because of the inclusion of surface waves. Examination of the absolute velocities shows that at a depth of 200 km, the shear velocity transitions from 4.3 km/s in the west to nearly 4.8 km/s in the east.