EVALUATION OF UNCERTAINTIES AND BIAS IN SURFACE WAVE TOMOGRAPHIC MAPS AND TRAVEL TIME CORRECTION SURFACES

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ABSTRACT

Group velocity travel time correction surfaces (TTCS) are computed easily from group velocity tomographic maps. The TTCSs are then used to create phase-matched filters, designed to detect and extract weak surface wave signals immersed in ambient and signal-generated noise as a basis for spectral amplitude measurements essential to discriminate explosions from earthquakes. A long-standing problem in surface wave tomography is that both TTCSs and group velocity maps would be more useful if their uncertainties could be estimated rigorously. The estimation of formal uncertainties is complicated by the fact that the level of uncertainty depends on the spatial length-scale of the modeled features as well as unknown theoretical errors and unmodeled structures. Our purpose is to take steps toward understanding uncertainties in both the tomographic maps and the TTCS constructed from them. All analyses are based on data coverage for 15 s - 20 s Rayleigh waves in Central and Southern Asia.

We have developed a new method to construct tomographic maps that permits estimation of resolution and scale-dependent amplitude bias corresponding to a given data coverage. Based on the resolution matrix formalism, this method produces more reliable estimates of the quality of the tomographic maps than more popular checkerboard tests.

These estimates do not propagate naturally into uncertainties in predicted travel times. To gain insight into the uncertainties in the TTCSs, we perform two synthetic experiments to determine the effects of limited spatial resolution of the tomographic maps and unmodeled azimuthal anisotropy. In the first, we evaluate how the effects of random noise in measurements and unmodeled sub-scale inhomogeneities present in an input model (e.g., sedimentary basins, Moho topography) distort the TTSCs computed from estimated tomographic maps. We estimate that the accuracy of group velocity maps and TTCSs for the part of the region to the north of 25°N is typically better than 0.03-0.04 km/s. In the second, we estimate errors in the TTSCs produced by azimuthal anisotropy not modeled in the tomographic maps. The effect of unmodeled azimuthal anisotropy across large areas, such as the Tibetan plateau, on group velocity maps and TTCSs is in general small: rms of group velocity errors for the region in the presence of 2% anisotropy is less than 0.025-0.035 km/s.

Key Words: surface waves, group velocity tomography, correction surfaces

OBJECTIVE

This research is dedicated to the study of uncertainties and bias in constructing surface wave travel time correction surfaces (TTCSs) computed from group velocity tomographic maps. TTCSs are necessary for the design of phase matched filters used to detect and extract weak surface wave signals in the CTBT monitoring environment. Knowledge of uncertainties in tomographic maps and TTCSs provide estimates of efficiency of phase matched filtering and accuracy of quantitative evaluation of surface wave signals. To acquire such knowledge, we perform synthetic experiments simulating data analyses for intermediate period surface waves propagating across Central and Southern Asia.

RESEARCH ACCOMPLISHED

Introduction

Estimation of surface wave amplitudes plays an important role in the discrimination of explosions from earthquakes. For small seismic events surface wave signals are often too weak to be directly measured or even detected on seismograms. The most efficient technique for extracting such signals from ambient and signal-generated noise is phase-matched filtering (Herrin & Goforth, 1977; Russel *et al.*, 1988; Stevens & McLaughlin, 1997; Leach *et al.*, 1998; Levshin *et al.*, 1998). Lateral inhomogeneity of the crust typical for tectonically active regions, such as Central and Southern Asia and the Near East, produces a variability in surface wave propagation from seismic sources to recording stations. To design efficient phase-matched filters, it is necessary to account for this diversity by tuning filters to a particular wave path. This can be done for each station using travel time correction surfaces (TTCSs) for a set of intermediate periods (10 - 30 s). TTCS may be constructed using regional group velocity tomographic maps for these periods obtained as a result of the tomographic inversion of numerous surface wave dispersion measurements (Levshin *et al.*, 1996, 1997, 1998; Ritzwoller & Levshin, 1998; Ritzwoller *et al.*, 1995, 1998, 1999; Vdovin *et al.*, 1999). The efficiency of phase-matched filtering based on TTCSs strongly depends on the their quality and the quality of the group velocity maps used for their generation. One of the ways to estimate the quality is to use ground-truth events for which hypocenter parameters are well known (Harkrider *et al.*, 1998). Unfortunately there is only a limited number of ground-truth events located in Central and Southern Asia (Engdahl, 1998). Most of them are nuclear explosions at well known test sites. Subsequently, the azimuthal coverage of wave paths for ground-truth events to the existing network of stations is quite poor, and does not provide sufficient information for verifying TTCSs.

However, it is evident that both TTCSs and group velocity maps would be more useful if their uncertainties could be estimated rigorously. The estimation of formal uncertainties is complicated by the fact that the level of uncertainty depends on the spatial length-scale of the modeled features as well as unknown theoretical errors and unmodeled structures. Our purpose is to take steps toward understanding uncertainties in both the tomographic maps and the TTCS constructed from them. All analyses are based on data coverage for 15 s - 20 s Rayleigh waves in Central and Southern Asia as the region of main CTBT monitoring efforts.

We have developed a new method to construct tomographic maps that permits estimation of resolution and scale-dependent amplitude bias corresponding to a given data coverage. This method will be briefly described below and in more detail in Barmin *et al.* (1999). Based on the resolution matrix formalism, this method produces more reliable estimates of the quality of the tomographic maps than the more popular checkerboard tests.

Unfortunately, these estimates do not propagate naturally into uncertainties in predicted travel times. To gain insight into the uncertainties in the TTCSs, we performed two synthetic experiments to determine the effects of limited spatial resolution of the tomographic maps and unmodeled azimuthal anisotropy. In the first experiment we evaluate how the effects of unmodeled sub-scale inhomogeneities present in an input model (e.g., sedimentary basins, surface or Moho topography) and random noise, which is always present in real measurements, distort the TTSCs computed from estimated tomographic maps. In the second experiment we estimate errors in the TTSCs produced by azimuthal anisotropy unmodeled in the tomographic maps. We plan to continue this study in the future using the latest model of the Central and Southern Asia region (Villasenor *et al.*, 1999).

New technique for a 2-D tomographic inversion of surface wave dispersion measurements.

We developed a new technique to invert regional surface wave group or phase velocity measurements into 2D isotropic and azimuthally anisotropic tomographic maps. Such maps are important for monitoring purposes in two aspects: (1) for constructing 3D velocity models of regions under study that are essential for accurate location of seismic events (Villasenor *et al.*, 1999); (2) for constructing surface travel time correction surfaces for a set of monitoring stations. These correction surfaces then can be used for designing phase-matched filters.

The main features of this technique are:
Geometry: spherical, no flattening approximation is applied.
Parameterization: a nodal model of basic functions to parameterize velocity distribution on a spherical Earth surface is used. This model is defined at a finite number of discrete points and the intervening spaces are determined by a specific interpolation algorithm in the inversion matrix and travel-time accumulation codes. Nodes are spaced at constant distances from one another, interpolation is based on the three nearest neighbors. Typical internodal distances for regional inversions are 100 km or less.
Theoretical Assumptions: surface waves are treated as rays, sampling an infinitesimal zone along the great circle linking source and receiver, scattering is ignored. The method generalizes naturally to non-great circular paths, if they are known, e. g., as a result of ray tracing across preliminary phase velocity maps obtained after the first 3D inversion of group velocity data.
Regularization: application of spatial smoothness (with a specified correlation length) plus model amplitude constraints, both spatially variable and adaptive, depending on data density. The regularization scheme that we have effected involves a penalty function composed of a spatial smoothing function with a user defined correlation length and a spatially variable constraint on the amplitude of the perturbation from a reference state. The absolute weight of each component of the penalty function is user specified. The model amplitude constraint smoothly blends the estimated model into a background reference in regions of low data density. This dependence on data density is also user specified.
Azimuthal Anisotropy: can be estimated with isotropic structure. Both 2ψ and 4ψ terms (Smith & Dahlen, 1973) can be evaluated.

This technique has advantages in comparison with our previously used method by Yanovskaya and Ditmar (1985) in at least in two aspects: (1) there is no spatial bias due to the Earth's flattening; (2) there is more efficient smoothing, depending on data density. Figures 1 and 2 demonstrate new isotropic tomographic group velocity maps for the target region between 15° and 50° N, 25° and 105° E for Rayleigh and Love waves at the 15 s period obtained by this technique from surface wave dispersion measurements described at Ritzwoller & Levshin (1998), Ritzwoller *et al.* (1998). The numbers of independent paths used for the inversion are 3160 for Rayleigh waves, and 2160 for Love waves. The same figures show the path density (defined as a number of rays crossing 2°x 2° bin), estimated spatial resolution of these maps, and amplitude bias resulting from smoothing. We define the amplitude bias as the relative difference (in percents) between the amplitudes of the observed output anomaly and of the input local perturbation of the group velocity. Zero bias corresponds to the undistorted amplitude imaging. We see that the spatial resolution for the territory defined above is quite high. We resolve features of the size 250 - 300 km on Rayleigh wave maps almost everywhere to the north of latitude 30°N, except NW Iran. The resolution on Love wave maps is slightly worse but still better than 300-350 km virtually everywhere in the same territory. We are able to contour even relatively small sedimentary basins, like the Dzhungarian basin and some others, as slow velocity spots on group velocity maps. The amplitude bias characterizing these group velocity maps is rather small, less than ±10%, except the southern part of the region characterized by poor ray coverage. We used these maps as input to construct the travel time correction surfaces for several seismic stations deployed in this region and belonging to the IMS network, namely AAK (Kirgizstan), ABKT (Turkmenistan), BRVK, KURK, MAKZ (all in Kazakstan), LZH, WMQ (China), and TLY (Russia). Examples of TTCSs for four of these stations are shown in Figure 3 for the 15 s Rayleigh wave. These figures show group velocity corrections δU for the path from any point on the map to a given station. The predicted travel time t for a selected path is found using the formula:

$$t = \Delta/(U^\circ + \delta U),$$

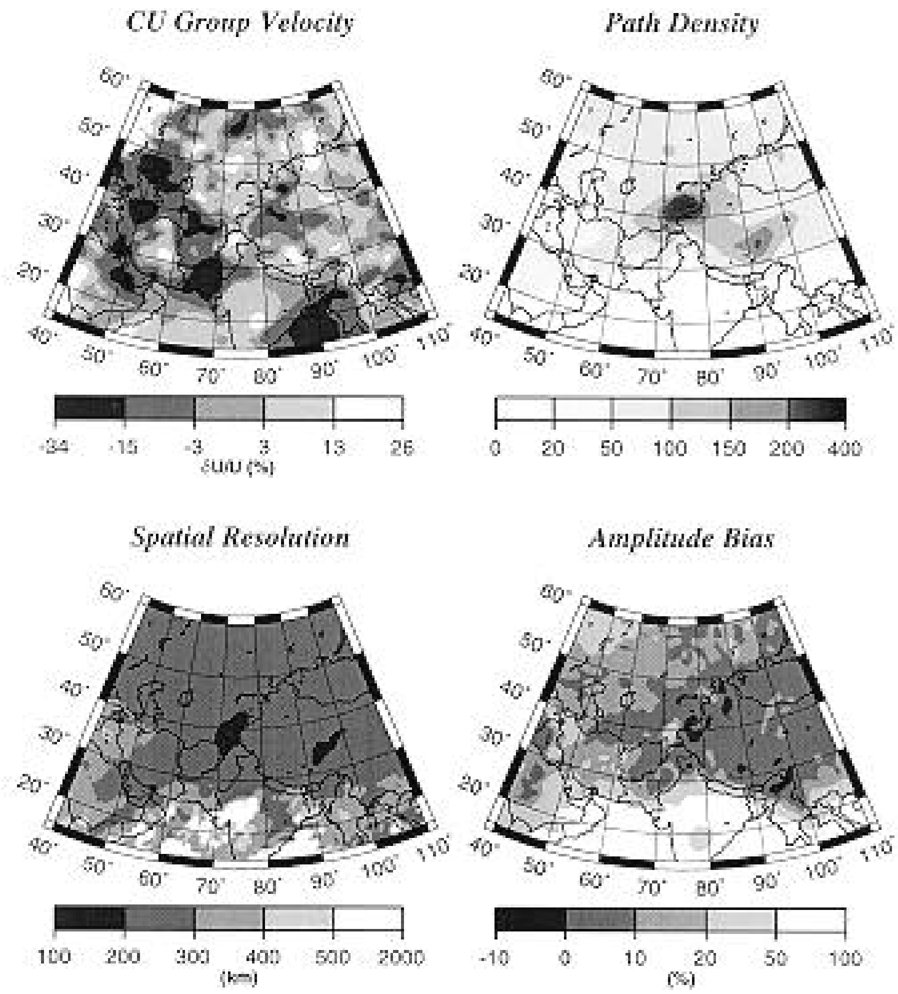

Figure 1. Estimated Rayleigh wave group velocity map and its assessment at the 15 s period. Path density is defined as the number of rays intersecting a 2° square cell.

where Δ is the epicentral distance and *U*° is the reference value obtained by averaging the group velocities across the input map. Both group velocity maps and TTCSs exhibit significant variations in surface wave group velocities and group travel times across the region.

Synthetic experiments with isotropic tomographic maps.

To estimate uncertainties in tomographic maps and TTCSs constructed from them due to unmodeled sub-scale heterogeneities and random noise in measurements, we performed the following numerical simulations:

(1) the group velocity maps described above were considered as “exact” maps representing the real structure. We traced our set of rays across this model, assuming that waves follow great circle paths, and then introduced the random noise into the resulting average group velocities along each path. The rms of noise was selected to be equal to 0.03 km/s. This noise level is typical for group velocity observations along “clustered” paths (Ritzwoller & Levshin, 1998).

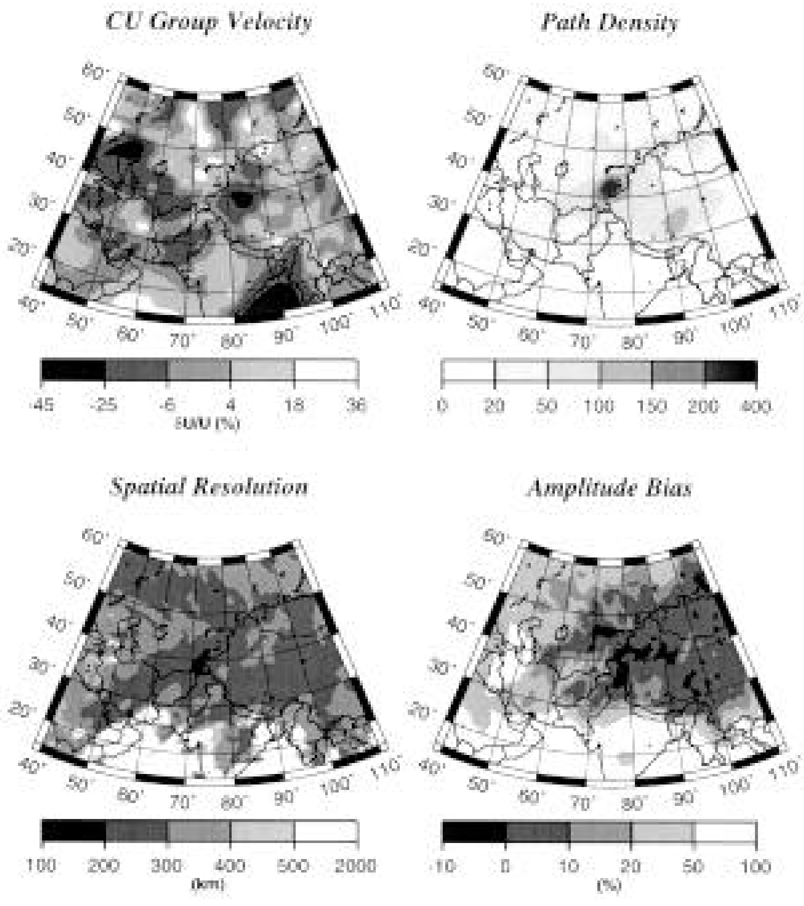

Figure 2. Estimated Love wave group velocity map and its assessment at the 15 s period .

(2) This new set of "data" was then used as the input for the tomographic inversion code. We ran this code several times using different smoothing parameters and different background reference models: "exact" maps and maps predicted by the global crustal model of Mooney *et al.* (1998) . Smoothing parameters were chosen to get slightly "overdamped" tomographic maps. Resulting maps are distorted due to the random noise in input data, unaccounted sub-scale heterogeneity of the medium, and bias caused by the inhomogeneous path density. If we use our "exact" model as the background reference model in constructing the map, the distortion is caused only by the random noise and smoothing. In this case, the bias is minimized due to the rule for a local smoothing imbedded into our code: the less the path density the stronger the penalty for local deviation of a solution from the background model. The rms deviations of obtained maps from the "exact" ones are two or three times higher than the input noise level and slightly decrease with increase of smoothing. The rms deviation of "observed" group velocities from predicted by the constructed model is of the same order as the input noise level. In the realistic case of the absence of a good background model and nonhomogeneous path density, distortions become more significant. Such an example is presented in Figure 4, where we used as the reference models group velocity maps predicted by the crustal global model of Mooney *et al.* (1998). This figure demonstrates difference between the input and constructed maps for the 15 s and 20 s Rayleigh waves and 20 s Love wave. The rms differences between the two maps are much higher than the level of random noise (of the order of 0.1-0.2 km/s), weakly depending on the smoothing parameter. The significant distortions correspond to the parts of the region characterized by poor coverage: the Caspian Sea, NW Iran, Oman Bay. At the same time, for most of the region, including all of Central Asia and Western China where the path coverage is good, the distortions are relatively small (1-2% of velocity values.) Note that the rms deviation of "observed" group velocities along individual paths from those predicted by the constructed model is only slightly higher than the input

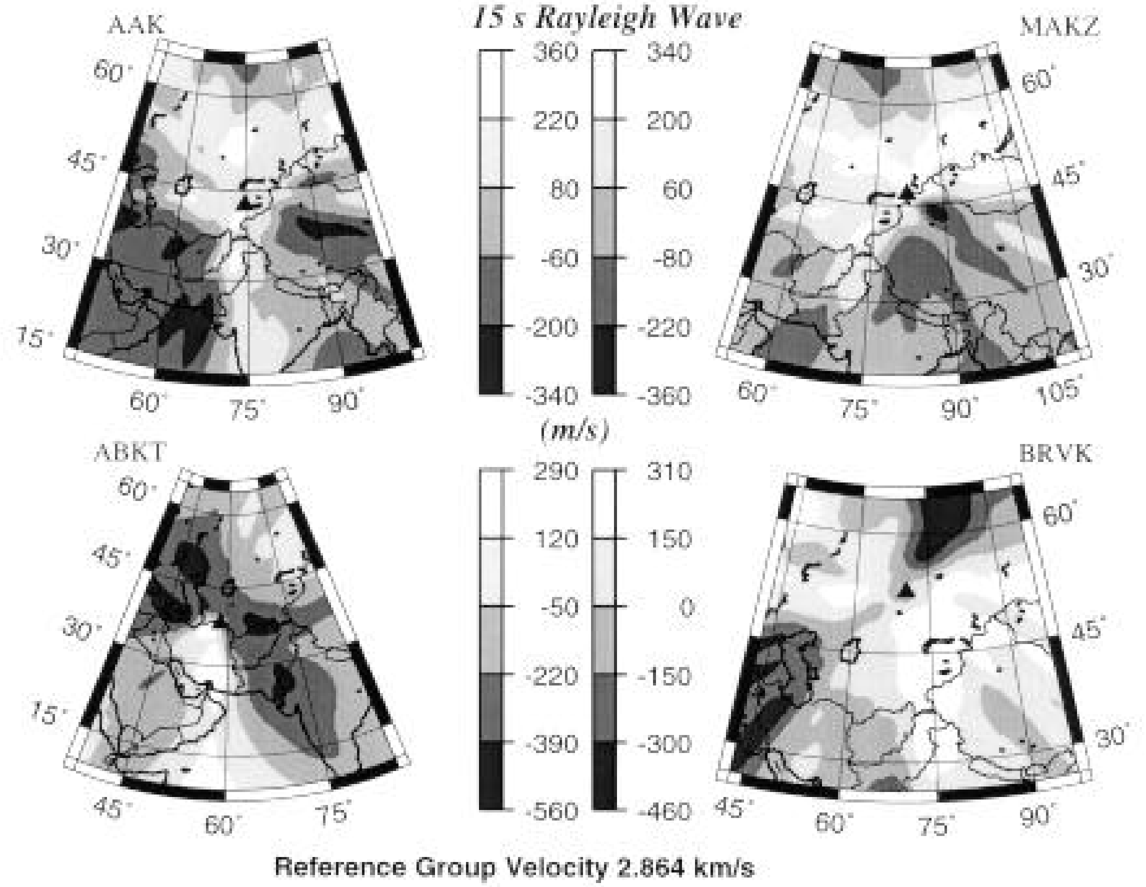

Figure 3 . Group velocity correction surfaces for 4 stations in Central and Southern Asia for the 15 s Rayleigh wave. For each geographical point, maps define the group velocity perturbation that should be applied to a 20 s Rayleigh wave observed at a station if an event were located at the chosen point. Perturbations are relative to the reference value of the group velocity.

noise level. This was expected because distortions of the map caused by the poor coverage have almost no effect on group travel times. This example clearly demonstrates the importance of a reliable reference model when the path density is not homogeneous. In the absence of such a model, maps of spatial resolution and of amplitude bias should be used to outline poorly defined areas.

(3) We used these “noisy” and “overdamped” maps for constructing TTCSs, and compared them with TTCSs obtained from “exact” maps. Examples of differential TTCSs are presented in Figure 5. The rms values of differences between predicted and “exact” TTCSs vary from station to station mostly being of the same order of magnitude as the noise level (0.03-0.04 km/s). These values do not change significantly with changes of the smoothing parameters in tomographic inversion. The smallest differences are for the 20 s Rayleigh waves due to the highest density of paths. The largest differences are observed for the station ABKT in Turkmenistan due to the poor coverage of the western part of the region (NW Iran, Figure 5.)

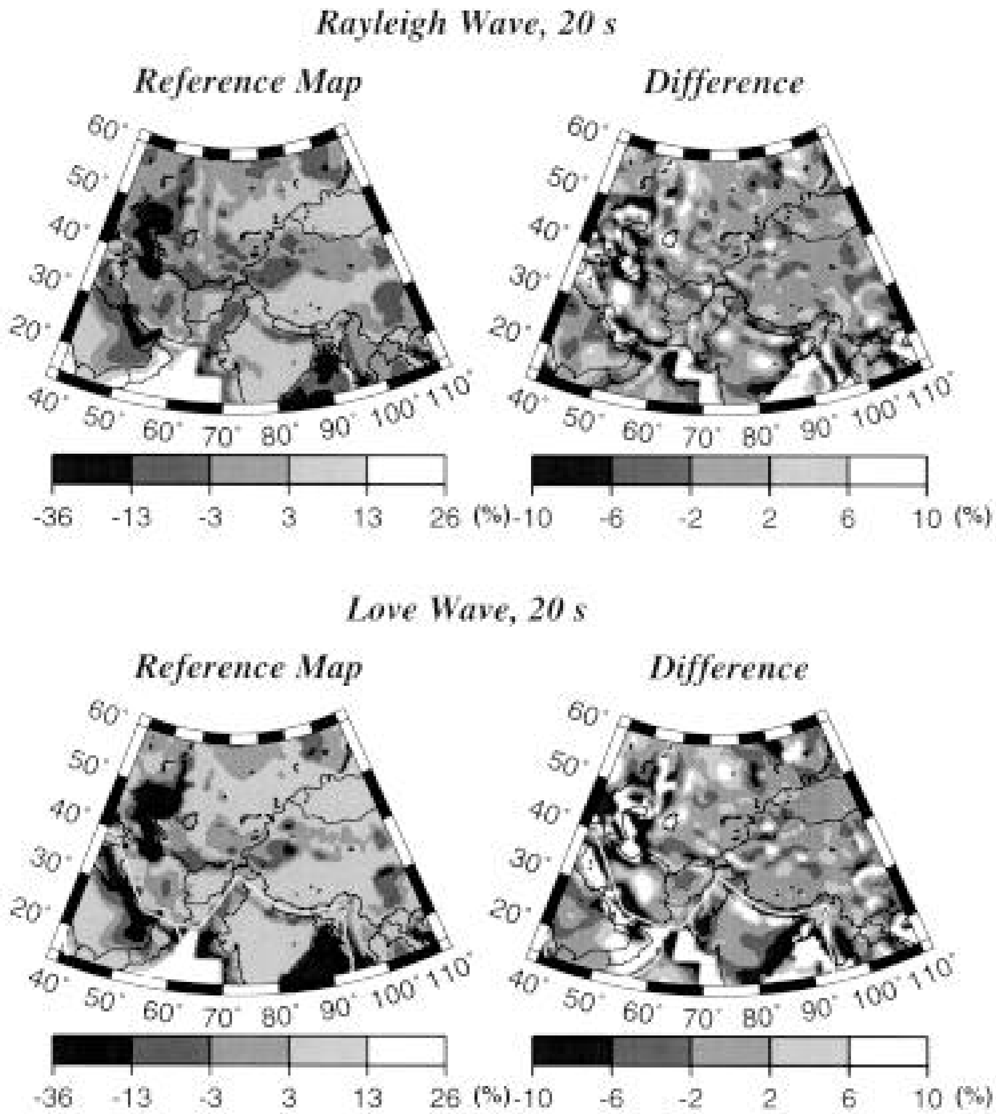

Figure 4 . Synthetic example of errors in the constructed tomographic group velocity map for the 20 s Rayleigh and Love waves. Errors are due to the data noise, poor path density, and unmodeled sub-scale structures. The left map is an "exact" reference map. The right map is a relative difference (in percents) between the "exact" and constructed maps. The background reference map for the tomographic inversion is predicted by the model CRUST5.1 (Mooney *et al.*, 1998).

Synthetic experiments with anisotropic tomographic maps.

Effects of unmodeled azimuthal anisotropy on tomographic maps and TTCSs were evaluated by the following way:

(1) We introduced 2% of the 2ψ azimuthal anisotropy (Smith & Dahlen, 1973; Trampert & Woodhouse, 1995) into our "exact" maps across the Tibetan plateau , creating "exact anisotropic maps". Then, we traced rays across these maps to get a new "data" set for tomographic inversion.

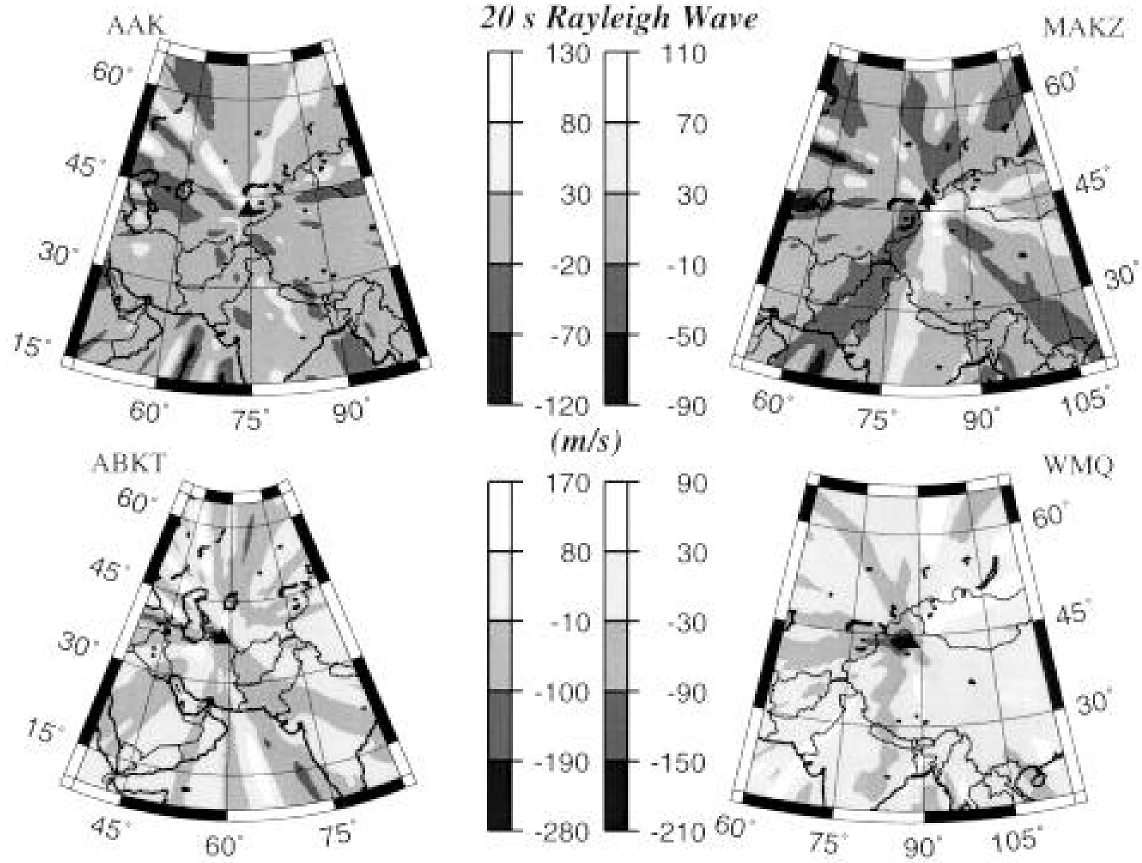

Figure 5. Errors in the travel time correction surfaces for the 20 s Rayleigh wave at four seismic stations. Errors (in m/s) are obtained by subtraction of "exact" correction values of group velocity from values found using the maps shown in Figure 4.

(2) We constructed a new set of *isotropic* tomographic maps using this new set of "data". The resulting maps are distorted due to the unaccounted effect of anisotropy. Differential maps demonstrating the differences between "real" and isotropic tomographic maps are shown in Figure 6. The differences between the "exact" isotropic map and the map constructed from "data" without modeling anisotropy are quite small for all reasonable values of the smoothing parameters. The rms of differences are on the order of 0.025-0.035 km/s, depending on the value of the smoothing parameter used in the inversion. The strongest differences are at some areas around Tibet and the poorly covered southern parts of the region. It is evident from this simulation that azimuthal anisotropy of this level cannot significantly distort the maps and TTCSs.

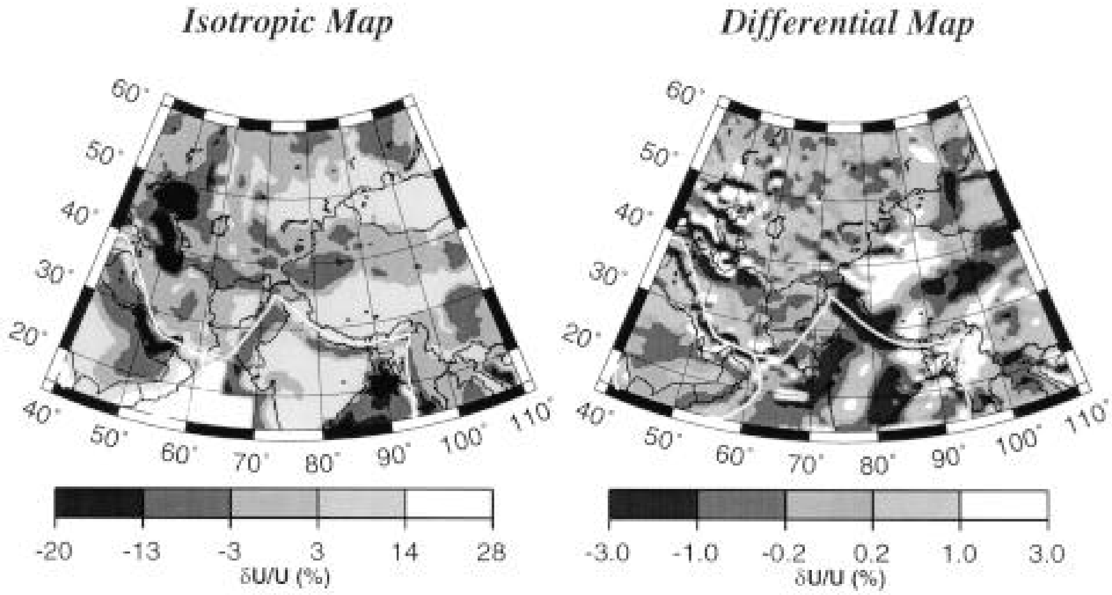

Figure 6 . Errors in the group velocity map due to unmodeled azimuthal anisotropy introduced into the isotropic model for the Tibetan plateau. The left map is an "exact" isotropic map. The right map is a relative difference (in percents) between the "exact" and constructed maps.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The new technique for tomographic inversion of surface wave dispersion measurements provides necessary means for constructing travel time correction surfaces for selected stations and their assessment in terms of spatial resolution and amplitude bias. The existing set of group velocity measurements across the Central Asia and Western China is sufficient for constructing reliable group velocity maps and TTCSs both for Rayleigh and Love waves at periods 15 s and longer. Synthetic experiments show that in areas with dense ray coverage the spatial resolution of these maps is on the order of 250 - 350 km and the amplitude bias is no more than 10%. We estimate that the accuracy of group velocity maps and TTCSs for the part of the region to the north of 25°N is typically better than 0.03-0.04 km/s. The unmodeled 2% azimuthal anisotropy across such large areas as the Tibetan plateau does not generate significant errors in group velocity maps and TTCSs constructed from them.

Recommendations

This study is based on group velocity measurements for periods above 10 s. To construct efficient phase-matched filters able to extract surface wave signals from events with the *Ms* magnitudes less than 3.5-3.7 it is necessary to broaden the period range of measurements to periods of 6-8 s. Such measurements can be done only for relatively short wave paths of less than 2000 km length. We consider that special efforts should be dedicated to making such measurements across the target region, constructing group velocity maps and travel time correction surfaces, and providing their assessment.

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