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High resolution global phase velocity distributions

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Abstract.
We present global phase velocity distributions for fundamental mode Love and Rayleigh waves in the period range 40 to 150 seconds. The models, expressed in terms of spherical harmonic expansions up to degree and order 40, have beed derived from 28,479 Love wave and 33,662 Rayleigh wave measurements. The measurements were made using an automatic procedure based on non-linear waveform inversion. We show that the results are characterized by lateral resolving radii between 500 and 850 km, a significant reduction from previous work. The improved global resolution is largely due to the inclusion of many more major arc measurements. The power spectra of the models are much whiter than has previously been found. The results show great similarity to the phase velocity distributions derived from the recent *a priori* model 3-SMAC, in which the primary relevant features are the crustal thickness and crustal velocity distributions, the cooling oceanic lithosphere and the thick (300km) lithosphere of the continental cratons. The results thus confirm these features. Differences, for example, in the strengths of the crust, ridge and craton signatures should lead to refinement in the thermal and constitutive parameters upon which the *a priori* model depends.

Introduction

Recently constructed global phase velocity models for fundamental mode Love and Rayleigh waves, in the period range 40 and 150 seconds, [*Trampert and Woodhouse,* 1995, referred to hereinafter as TW] were obtained using 9,640 G_1, 339 G_2, 12,525 R_1 and 1,324 R_2 waveforms. In order to analyze such a large number of seismograms, we developed a procedure, using a non-linear waveform inversion, in which phase velocity and amplitude, as a function of frequency, are expanded in terms of B-splines. The introduction of an explicit smoothness constraint and the use of group velocity information allows the method to be completely automatic. The algorithm incorporates built-in protections to simulate decisions which would normally be taken by an interactive operator (such as whether or not a signal is too noisy, the data fit is satisfactory, ...). In TW, these protections were chosen to be quite conservative, to ensure that the data did not violate the approximations used in the theory. This resulted in the rejection of many waveforms, including a high proportion of the data for major arcs, and thus in quite uneven global ray coverage. We have found that many of the previously rejected waveforms can, in fact, be used to make phase measurements within the ray theoretical framework. The corresponding resolution maps showed an average lateral resolution of more than 2000 km with a significant decrease of lateral resolution in the Southern hemisphere, as would be expected in surface wave tomography based on minor arc data only.

In the present study, we show that lateral resolution can be significantly improved by relaxing the rejection criteria and thus including many more waveforms and a greater proportion of major arc data. Global lateral resolution is now between 1000 and 1700 km.

The primary results of this study are the coefficients of the spherical harmonic expansion of phase velocity, to degree and order 40, for fundamental mode Love and Rayleigh waves at the periods 150s, 100s, 80s, 60s, 40s. These are available by anonymous ftp to 'sismo.u-strasbg.fr' or 'ftp.earth.ox.ax.uk' and are contained in the file /pub/twgrl95.tar.Z.

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Data and resulting models

We used all GDSN and GEOSCOPE seismograms recorded between the years 1980 and 1993 available on-line on a WORM jukebox and corresponding to events with magnitudes M_w between 5.8 and 6.6. A detailed description of the theory and the algorithm may be found in TW. In the present study we follow exactly the same procedure, with differences only in the criteria used to reject unsatisfactory data.

The rationale of the measurement algorithm is to derive a filter, characterized by phase and amplitude functions varying smoothly with frequency, which maps a synthetic seismogram into the observed one. The rejection criteria are as follows. An amplitude variance reduction of less than 85% indicates the presence of notches in the amplitude spectrum which may correspond to a poorly defined phase signal. We chose to reject such seismograms which eliminated 10% of the data. We believe that a group velocity anomaly (used to derive a starting model) or a final phase velocity anomaly of more than 10% with respect to PREM [*Dziewonski and Anderson,* 1981], averaged over the minor or major arc, is unlikely and reject seismograms which exceed this limit. This eliminates 7% and 12%, respectively, of the original data. If the total variance reduction (amplitude and phase) is less than 85%, the seismogram is deemed to be not well enough modeled, and rejected. This test eliminates a further 9% of the original waveforms. In this study we have relaxed the smoothness constraint which makes that a number of measured dispersion curves showed 2π-jumps and we were obliged to eliminate a further 31% of the original waveforms, mostly corresponding to major arc data.

It is interesting to note that the proportion of rejected data decreased slowly from 1980 to 1993. After application of the rejection criteria, there remain 31% of the data originally considered, numbering 28,479 Love wave measurements (23,489 G_1 and 4,990 G_2) and 33,662 Rayleigh wave measurements (26,012 R_1 and 7,650 R_2).

We inverted the phase velocity measurements for global phase velocity distributions in the same way as described in TW. The misfit of the model to the data is similar to that reported in TW, notwithstanding the threefold increase in the number of data. Representative variance reductions are, for Love waves: 40s, 77%; 80s, 51%; 150s, 27%; and for Rayleigh waves: 40s, 75%; 80s, 50%; 150s, 28%.

We have performed a number of tests involving changing the damping and down-weighting data corresponding to similar paths. The effects were not significant, indicating the intrinsic stability the modeling procedure.

The models are shown in Fig. 1 for the periods 40s, 80s, 150s. In general, they show more detailed structure than those presented in TW. The degree by degree correlation between both sets of models decreases with increasing degree (Fig. 3), indicating that the models in TW are long wavelength approximations of the present models. The increased lateral resolution shows this to be entirely information extracted from the data, largely from the major arc measurements.

Resolution

As in TW the inverse problem for phase velocity distributions is regularized by introducing a penalty function based on optimization of model smoothness. This leads to resolving kernels without prominent sidelobes which can be characterized by their resolving radius. Fig. 2 shows the distribution of the resolving radii for Love waves in comparison with the corresponding one of TW. There is a substantial improvement, particularly in the Southern hemisphere where the contribution of the more numerous major arc data is evident. The lateral resolution for Rayleigh waves is generally better than for Love waves. In most parts of the world the averaging radius is between 500 and 850 km, which is the highest lateral resolution achieved in a global surface wave tomographic study to date.

The amplitude spectra (Fig. 3) corresponding to the models in Fig. 1 are much whiter than has been found so far by surface wave tomography. The regular decrease beyond degree 20 is probably not a feature of the real Earth, and is a function of the damping applied in the inversion. Tests with increased damping made the higher degrees decay more rapidly, and *vice versa.* However, the effect of damping on degrees less than 20 is small. For comparison, we also plotted the amplitude spectra corresponding to the models in TW. Both spectra are very similar at lower degrees, with the current ones decaying less faster at higher degrees. The good lateral resolution, together with the homogeneous dataset (all data have been automatically analyzed and selected with the same objective criteria) and the insensitivity of the spectra below degree 20, indicate that at these degrees the shape of the spectra reflects that of the Earth.

The degree 0 term for Love waves is very small, indicating that the spherically averaged earth is in close agreement with the reference model PREM. For Rayleigh waves, on the other hand, a significant degree 0 term is recoved. For example, for 40s Rayleigh waves, the spherically averaged phase velocity is 0.85% faster than PREM.

Discussion

In TW, we made a detailed comparison of the models with previous studies and found that at longer periods, the models were very similar, among others, to structure coefficients measured by *Smith and Masters* [1989]. A recent comparison of three-dimensional seismic models of the Earth's mantle [*Ritzwoller and Lavely,* 1995] with the same structure coefficients, together with the correlation coefficients and the similarity of the amplitude spectra at lower degrees (Fig. 3), indicate that at longer periods our present models are indeed similar to most other global models. At shorter periods, it is interesting to compare the phase velocities derived in this study with the predictions of the recently proposed *a priori* upper mantle model 3-SMAC of *Nataf and Ricard* [1995]. 3-SMAC is based on compilations of thicknesses of chemical layers, 3-dimensional temperature distributions from thermal plate models, mineralogical models and solid state laboratory measurements. A comparison of 3-SMAC with phase velocity data has already been made [*Ricard et al.,* 1995] at longer periods and for expansions at lower degree. Fig. 4 shows 3-SMAC phase velocity predictions (to degree 32) which are directly comparable to the distributions in Fig. 1. We have carried out a test in which the resolution operator characterizing our models is applied to the 3-SMAC

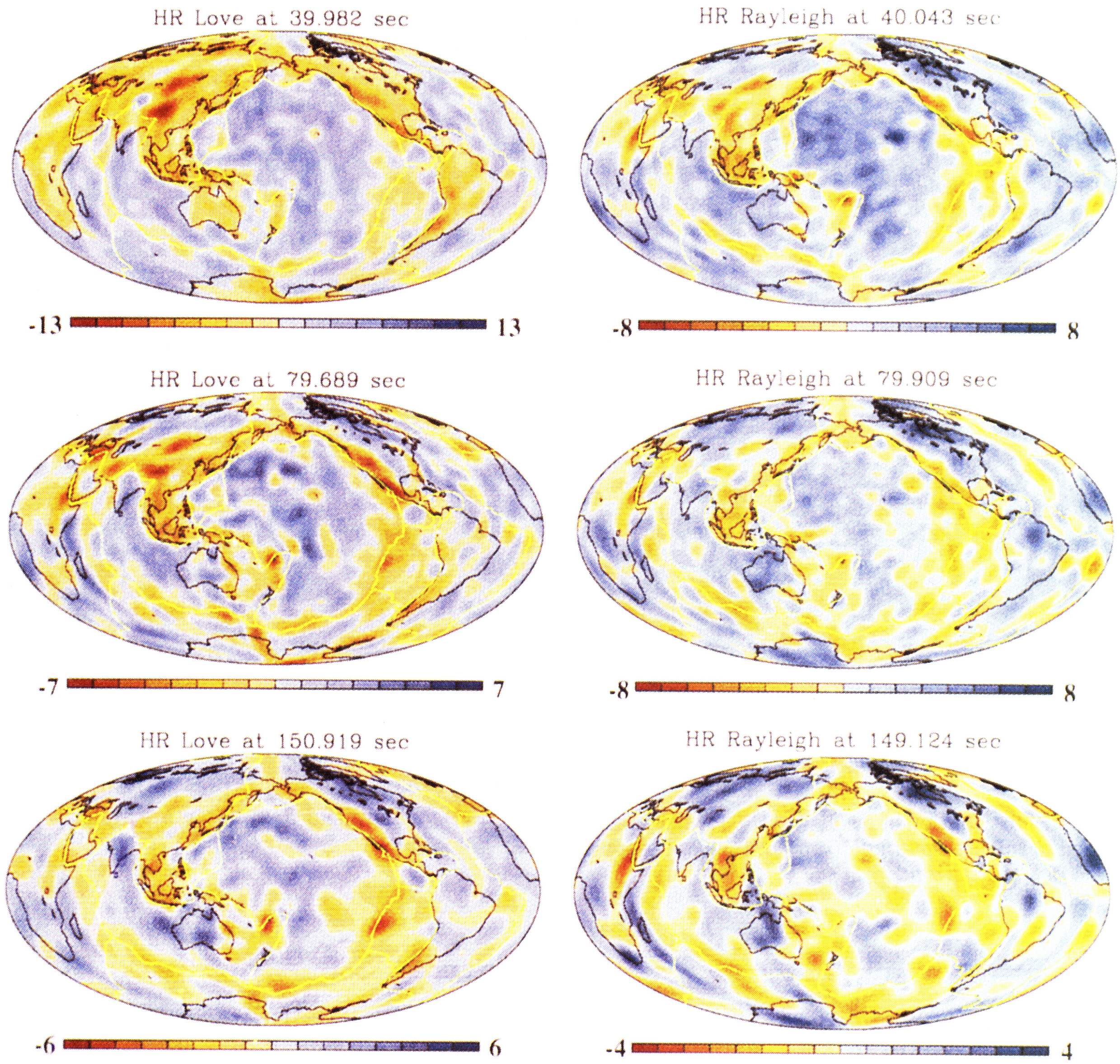

Figure 1. High Resolution (HR) Love and Rayleigh wave phase velocity perturbations for the periods 40s, 80s and 150s. The variations are given in percent with respect to the PREM average. Yellow lines are plate boundaries and yellow circles are hotspots.

predictions. The result is that the correlation coefficient of the output of the resolution operator with the input is 0.99, indicating that the differences between the 3-SMAC predictions and the observations cannot be ascribed to imperfect resolution. If the true Earth were to resemble 3-SMAC (to degree 32), our resolution would allow us to recover it almost perfectly. In general, the agreement in terms of correlation coefficients (0.72 and 0.51 for Love at 40 and 150 s; 0.42 and 0.28 for Rayleigh at 40 and 150 s) is decreasing with increasing period and is higher for Love waves than for Rayleigh waves.

While the similarity between the *a priori* model and measurements is striking some differences apparent. For example, for both Love and Rayleigh waves at shorter periods there is a much greater E-W gradient in velocity across the Pacific, leading to significantly higher measured velocities for the old ocean basins. As is to be expected, it appears that 3-SMAC is a better model for the crust and uppermost part of the mantle than for the deeper structure. It is anticipated that further analysis will lead to a refinement of the parameters entering into the *a priori* model, among the most important of which are the temperature derivatives of seismic velocities in mantle materials and the distribution of crustal velocities.

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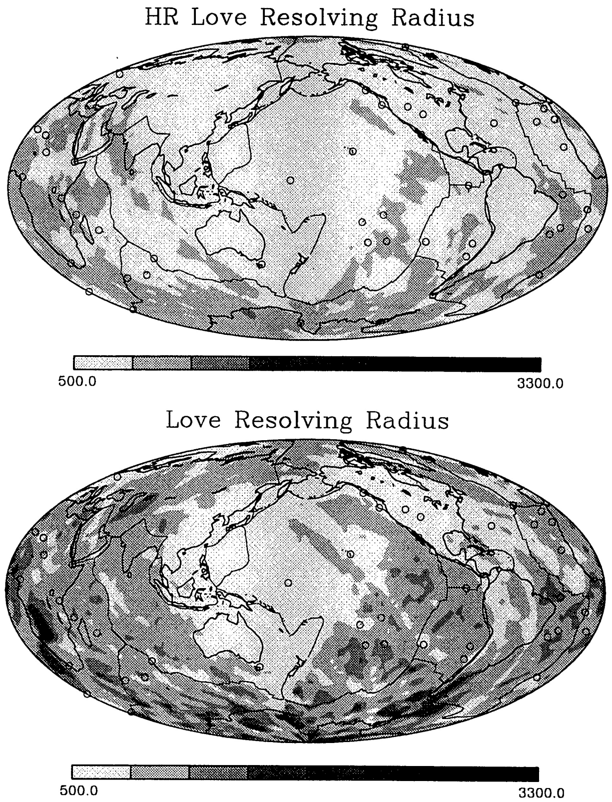

Figure 2. Distribution of resolving radii for Love waves obtained in the present study (top) and the corresponding one of TW (bottom).

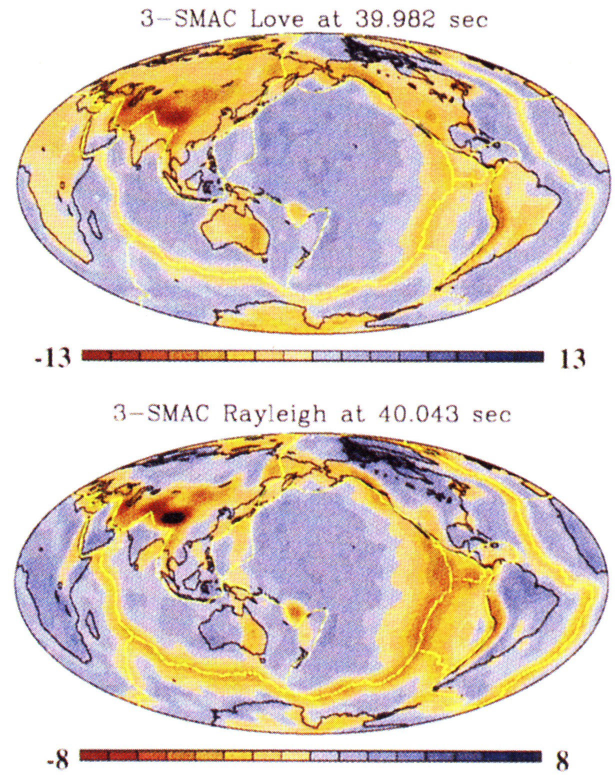

Figure 4. Predictions of 3-SMAC phase velocity perturbations for Love and Rayleigh waves at 40s.

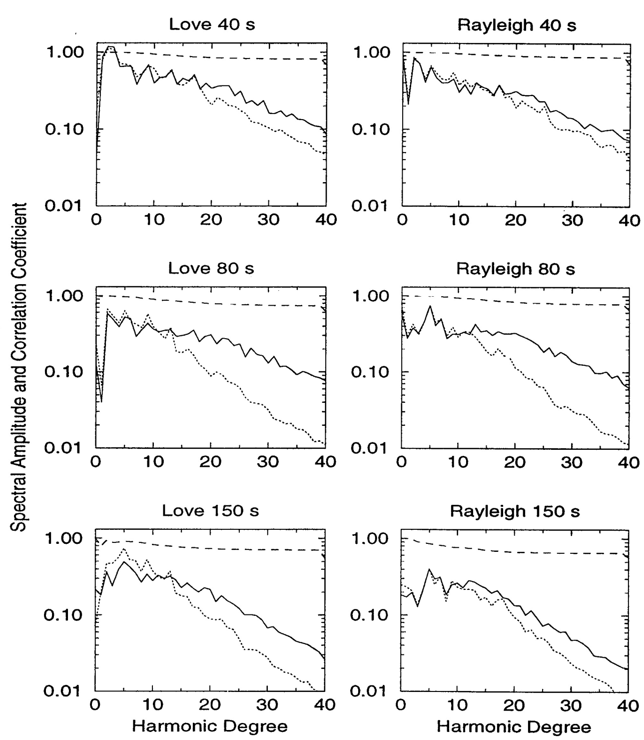

Figure 3. Amplitude spectra corresponding to the models shown in Fig. 1. (solid line) and those presented in TW (dotted line). Also shown are correlation coefficients between the two sets of models (dashed line).

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