行政院國家科學委員會補助專題研究計畫成果報告

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※地震波傳遞和全球走時層析成像：香蕉-甜甜圈理論 ※
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計畫主持人：洪淑蕙

共同主持人：

計畫參與人員：

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- □赴國外出差或研習心得報告一份
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- □國際合作研究計畫國外研究報告書一份

執行單位：台灣大學地質科學系

中 華 民 國 91 年 10 月 29 日

Abstract

This report summaries the result from global seismic tomographic study of shear velocity heterogeneity in the lowermost mantle using a new, advanced Frechet kernel theory. Wavefront healing and finite-frequency diffractive effects for a seismic pulse propagating within the heterogeneous earth that have been ignored in conventional ray theory are now properly taken into account in this so-called banana-doughnut theory, which accurately constructs the actual 3D sensitivity for a traveltime shift measured by cross-correlation of an observed broad-band seismogram with a spherical-earth synthetic. Furthermore, the kernel theory yields a linearized relation between a measured traveltime residual and wave-speed perturbation which is applicable to seismic traveltime tomographic inversion of mantle shear velocity heterogeneity. We use both 3D banana-doughnut theory and 1D linearized ray theory to build the derivative matrices that express the traveltime sensitivity of S_d-*SKS* and *ScS*-*S* differential residuals with respect to inverted wavespeed perturbations. The model space of whole mantle is parameterized into two configurations: one is discretized by equally-sized spherical blocks and the other is multi-resolution formulation that aims to remove biased and artificial features in the resolved images due to nonuniform data coverage.

Introduction

Lateral variation in shear velocity perturbations near the core-mantle boundary (CMB) has been unraveled exclusively by travel times of diffracted *S* waves. From an infinite-frequency ray-theoretical point of view, the S_d wave emerging in the core shadow uniquely samples the grazing ray segment along the CMB. Synthetic experiment suggests that the traveltime shift measured by an actual finite-frequency wave can differ substantially from the prediction of ray theory because of intrinsic wavefront healing effects (Hung et al., 2001; Baig et al., 2001). Frechet kernel theory based on the Born single scattering approximation has been developed lately to correct such deficiency (Dahlen et al., 2000; Zhao et al., 2000). A *S* traveltime residual yields unexpectedly zero sensitivity right at the geometrical ray; rather, it is most sensitive to the surrounding off-path heterogeneity. The SH_d traveltime kernel exhibits even paradoxical features on the CMB where the S_d ray glides; it has the opposite (or positive) sign suggesting that a S_d arrival could speed up by a slow anomaly at the CMB.

Constrained mostly by compelling seismic evidence, the remote D" zone is thought to be one of the most heterogeneous and dynamic region in the earth's interior. Recent ray-based tomographic inversion of long-period differential *S* (or S_d)-*SKS* traveltimes revealed a global distribution of anomalous D" shear velocity on the scale length ~1000 km (Kuo et al., 2000). To assess the potential bias of the resolved D" structure due to inadequate interpretation of finite-frequency arrivals, we invert 1495 *S*-*SKS* (Kuo et al., 2000) and 8255 *ScS*-*S* (Masters et al., 2000) differential residuals for global mantle shear heterogeneity using both ray theory and 3D kernels. A computationally-efficient paraxial formulation based on body-wave propagation together with full wave theory is implemented to construct the kernels for geometrical *S*, *ScS* and *SKS* waves as well as diffracted S_d waves. The model of the whole mantle is divided into equally-sized spherical triangles in lateral dimension with constant thickness. Shear velocity or slowness perturbations have been parameterized in terms of spherical pixels or blocks and multiscale formulation that invokes the biorthogonal genearized Harr wavelets on a sphere (Chiao and Kuo, 2000). We discuss the difference among the resulting models as a result of wave diffraction and model parameterization.

Finite-Frequency Traveltime Kernel

In conventional ray theory, the finite-frequency traveltime shift of a body wave depends only on the wave-speed anomaly along its infinitely-thin geometrical raypath and therefore the measured traveltime residual is simply given by the 1-D line integral along the path:

$$\delta T = -\int c^{-2} \ \delta c \, dl \qquad (1)$$

However, it is well known that the traveltimes of actual finite-frequency seismic waves differ from the predictions in equation (1) because of intrinsic wave diffraction effects (e.g., Wielandt, 1987; Gudmundsson, 1996). A recently-developed banana-doughnut theory properly takes into account such wavefront healing effects which yields a linearized relation between a measured traveltime residual and the wave-speed perturbation :

$$\delta T = \iiint K \, (\delta c / c) d^3 x \qquad (2)$$

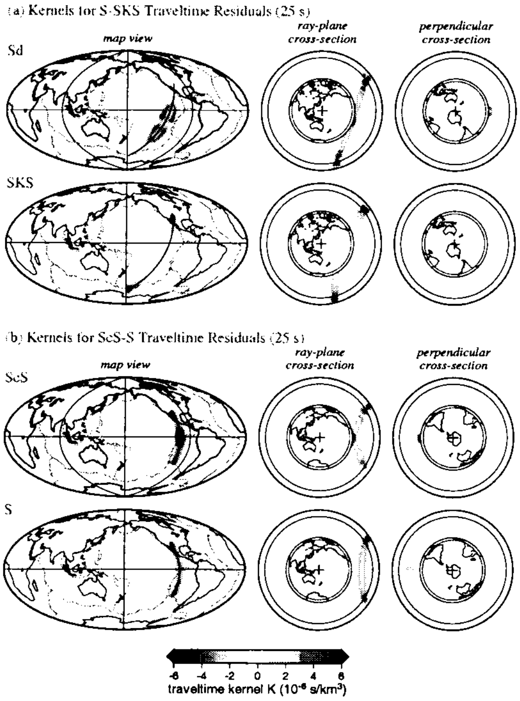

Fig. 1. Finite-frequency traveltime kernels for a pair of S_d and SKS waves at an epicentral distance $\Delta = 114°$ and for a pair of ScS and S waves at $\Delta = 71°$. The waveforms for traveltime measurements have a dominant period of 25 s. The kernels for differential S_d–SKS and ScS–S residuals are simply the differences of two corresponding kernels. On map view of the S_d wave only shows the kernel near CMB.

Fig. 1 depicts cross-sectional views of the 3D Frechet sensitivity kernels K for a pair of S_d and *SKS* and a pair of *S* and *ScS* traveltime shifts measured by cross-correlation of long-period (~25 s) waveforms with the corresponding spherical-earth synthetics in the PREM background model. The most unintuitive feature is that the traveltime sensitivity of a turning S and a reflected *ScS* wave is identically zero everywhere along the raypath. The cross-path width for an *S*-wave kernel with the banana-shaped geometry empirically depends on the frequency content of the observed pulse and its progagation distance. For actual differential traveltime measurements, differential S_d-*SKS* and *ScS*-*S* kernels are simply the differences of two individual traveltime kernels.

Inversion Results

Equations (1) and (2) that describe the linearized relations between the observed traveltime residual and the derived wave-speed perturbation are usually expressed in the matrix notation for the inverse problem:

$$G_{ij} m_j = d_i \qquad (3)$$

where d_i is the traveltime residual for the *i*th source-receiver path and m_j is the *j*th model parameter equivalent to the 3D wave-speed variation. In a ray-based inversion with a block-discretized parameterization, the traveltime derivative G_{ij} is simply a constant value proportional to the length of the *i*th raypath passing through the *j*th block; in a kernel-based inversion, G_{ij} is the 3D integral of the *i*th kernel over the *j*th block, An alternative, more sophisticated multi-resolution parameterization based on generalized Harr wavelets (Chiao and Kuo, 2001) is implemented in the inversion to homogenize the 3D resolution throughout the mantle. This experiment is used to justify the spatial resolution of resolved tomographic images constrained by differential traveltime residuals.

The model of the whole mantle is divided into 32 equally-thick layers, each of which is divided into 5120 nearly equal-area spherical triangles in lateral dimension. Shear velocity or slowness perturbations have been parameterized in terms of spherical pixels or blocks and multiscale formulation that invokes a hierachy of

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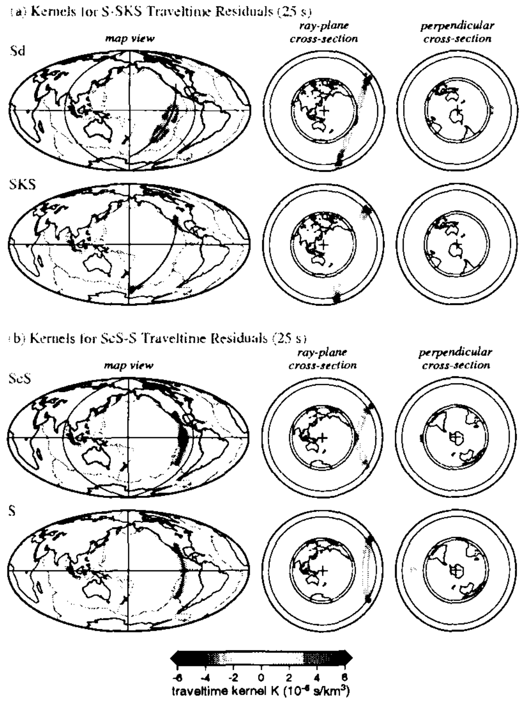

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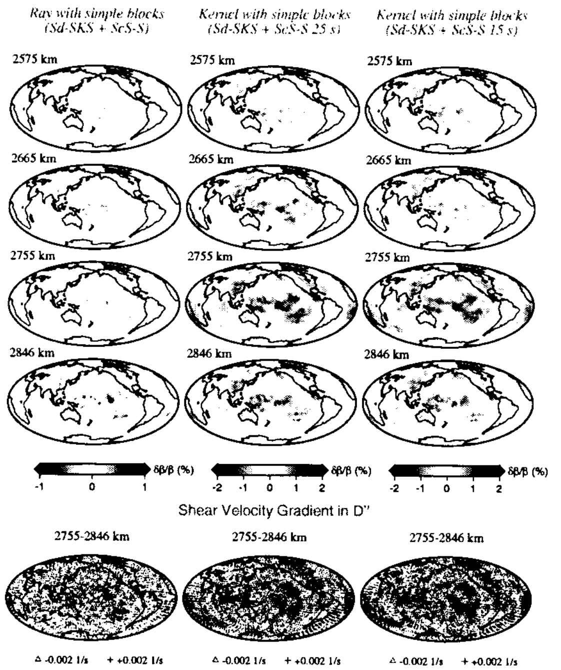

Fig. 2. Comparison of shear velocity perturbations in the four lowerest layers near CMB from block-based inversion. The data kernel that governs the relation between model (velocity or slowness perturbation) and data (S–SKS and ScS–S residuals) is built based upon linearized ray theory and 3-D kernels of a finite-frequency wave with a dominant period of 25 and 15 s, respectively.

Fig. 2 shows geographic views of shear velocity perturbations in the lowermost four layers (2575-2846 km) near CMB, using simple-block parameteriations. Below each column of tomographic images is the derived shear-velocity gradient in D" layer. The traveltime tomographic inversion yields a dominant degree 2 pattern closely related to whole mantle convective current, with low-velocity anomalies beneath the Pacific and Africa, and high-velocity circum-Pacific rings surrounding them. This long-wavelength variation has been found coherently in both compressional and shear velocity heterogeneity from previous global tomographic studies (e.g., Dziewonski, 1984; Su et al., 1994; van der Hilst et al., 1997; Kuo et al., 2000). The most significant difference between the ray-based and kerne-derived models is the magnitude of shear velocity perturbations. Given equally-good fits to the observed traveltime residuals, the magnitude of shear velocity models derived from the kernel tomography is approximately twice larger than that based on ray theory. Because of imperfect data coverage, the smearing feature along ray geometry as well as spotted, local flunctuations often observed in ray-based models are less signicant in the kernel-derived images. Such contrast can be revealed by the difference in the sampling density of finite-frequency traveltime sensitivity, that is, the derivative Gram matrix used in the inversion (Fig. 3).

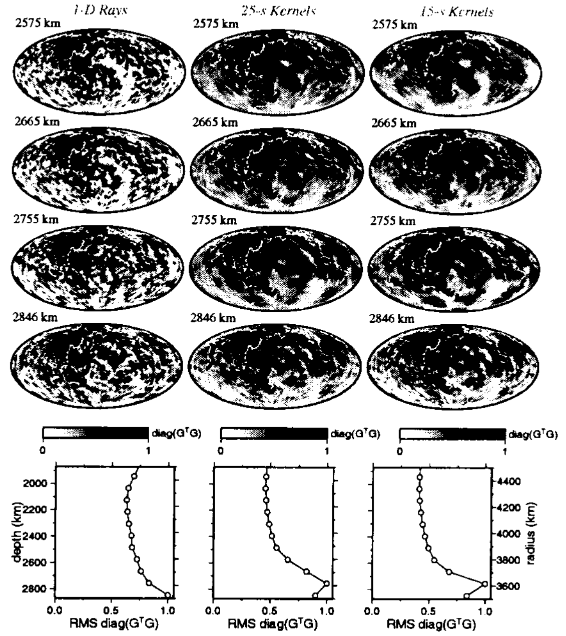

Fig. 3. Comparison of relative sampling density of differential S_d–SKS and ScS–S traveltime residuals associated with the sensitivity of infinite-frequency, 25-s, and 15-s waves, respectively. The values of $diag(G^TG)$ are plotted on geographic map views, and the root-mean-square of those values of each layer below 1850 km is also shown on the bottom of the diagram. G is *Gram* matrix corresponding to path lengths passing through each block in ray tomography and to volumetric kernels (Kd^3x) in finite-frequency diffraction tomography.

In Fig. 4, the model is instead parameterized in terms of multiresolution representation using spherical Harr wavelets. Clearly, those short-wavelength features observed in previous simple-block inversions are poorly-resolved due to lack of data sampling. The degree 2 variation is still robust and the magnitude or spectrum of shear velocity perturbations are better recoverd in the multiresolution formulation.

Summary

1. Given similar variance reductions, the 3-D kernel inversion yields smoother models with much larger velocity perturbations than those ray-based models.

2. The smoothing may arise from the off-path sensitivity of actual finite-frequency traveltimes as revealed from the 3-D kernel. The whole mantle heterogeneity inferred from all the contemporary 3D earth models is probably underestimated because wavefront healing is completely neglected in the ray approach.

3. Multiscale inversions suggest that the current Sd-SKS and ScS-S residuals only resolve the robust features in long-wavelength, degree 2 variations.

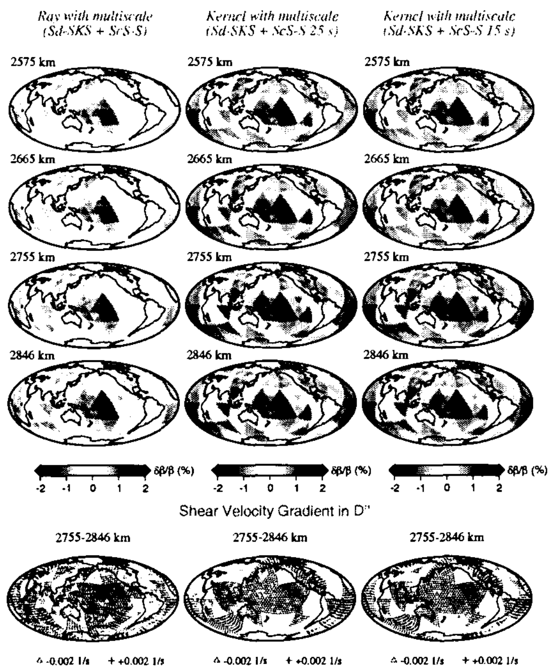

Fig. 4. Comparison of shear velocity perturbations near CMB from multi-scale tomography. The data kernel is constructed in the same way as that in spherical block inversion, while the model is alternatively parameterized in terms of multiresolution representation that invokes spherical Harr wavelets and yields the solution with the resolving power compatible with the actual nonuniform data sampling.

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