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EFFECT OF SHARP LATERAL HETEROGENEITY ON THE EARTH'S NORMAL MODES

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Abstract. When inverting normal mode data for global large-scale lateral heterogeneity, possible biases due to small-scale structure are commonly ignored. We conducted two experiments. In the first one, we calculated, with a recently developed first order scattering formalism, the effect of a simplified subduction zone model on the eigenfrequencies of the fundamental spheroidal mode branch. The frequency shifts induced by this single subduction zone appear to be smaller by only a factor of 3 to 4 than shifts observed on long-period seismograms, or than shifts induced by existing models of global upper mantle inhomogeneity. The second experiment involved a model of a hot spot plume on the core mantle boundary. Solving the variational problem with many coupling terms included, we calculated the effect of such a plume on the amplitude of some low angular order modes. The results suggest an effect at least as large as that due to available large scale mantle models. It thus appears, that relatively small-scale, sharp lateral structure in different depth ranges of the Earth may have an important effect on normal mode observations and that these effects may not be ignored in inversions of normal mode data.

Introduction

In the past few years, a number of models of global large-scale heterogeneity in the various parts of the Earth have become available. These models rely on simplified theory concerning the interaction of wave propagation with inhomogeneities and have in common the assumption that the structure is smooth [for the upper mantle: Woodhouse & Dziewonski, 1984, Tanimoto, 1988; for the lower mantle and core: Dziewonski, 1984, Morelli & Dziewonski, 1987].

At least for the upper mantle it is clear, that a significant amount of small-scale structure is present. Recent work by Spakman et al. [1988] and Snieder [1988b] shows that in the upper mantle under Europe lateral heterogeneities exist on a scale of 300 km. Similarly, the results of Olson et al. [1987] suggest that on the core-mantle boundary [CMB] small-scale lateral inhomogeneities may exist as well. Their numerical experiments show that hot spot plumes, measuring only a few hundred kilometers horizontally, may grow from thermal instabilities. This scale is much smaller than the shortest wavelength resolved by the models of Woodhouse & Dziewonski [1984] or Dziewonski [1984].

The effect of small-scale structure on surface waves can, up to a certain extent, be investigated using ray theory [see, e.g., Lay & Kanamori, 1985; Jobert, 1986] but very sharp lateral variations can lead to multipathing and scattering of surface waves [Bungum & Capon, 1974; Levshin & Berteussen, 1979; Snieder, 1988a,b]. The effect of such lateral structures on normal modes is less well understood. Romanowicz & Roult [1986] presented some examples of observations of normal mode frequency shift fluctuations as a function of angular order that could not satisfactorily be fit by existing models of upper mantle inhomogeneity. They suggested an inversion scheme for these observations, that would lead to better constraints on the structure in the vicinity of the great circle, but still under the assumption of smooth structure.

Recently, a formalism has been developed that efficiently describes the effect of small-scale lateral heterogeneities on normal modes [Snieder & Romanowicz, 1988]. In the present paper we use this formalism to calculate the effect of a subduction zone on the eigenfrequencies of normal modes. In a second experiment, we investigate the effect of hot spot plumes on the amplitude of some low angular order modes, using also a newly developed formalism [Lognonné & Romanowicz, 1989]. We use the results of these experiments to discuss the validity of ignoring the effects of small-scale lateral heterogeneities in studies of global structure.

A subduction zone model

In order to calculate the effect of upper mantle laterally heterogeneous structure on the frequency of fundamental normal modes of the Earth, we used first order perturbation theory. The frequency shift was computed using the expression for the location parameter [Jordan, 1978], as given by Woodhouse & Girnius [1982], while the formalism of Snieder & Romanowicz [1988], appropriate for small-scale inhomogeneity, was used for the expressions for source and receiver operators and the interaction matrix. In this example, we ignored terms in the interaction matrix arising from gravitational effects and dispacements of interfaces.

We modeled the subducting slab with a zone of 400 km thickness, extending vertically down to the 670 km discontinuity. The thermodynamical study of a subduction zone by Helffrich et al. [1988] suggests that 400 km is the width of the zone in which the average temperature perturbation is about 400° K, relative to the warmer mantle material. This temperature contrast between the subducting slab and the background model 1066A [Gilbert & Dziewonski, 1975] leads to a velocity contrast of about 2%. The contrasts in the parameters λ, μ and ρ are 5%, 6% and 1%, respectively, assuming an olivine lithosphere.

The configuration we used in the experiments is shown in Figure 1. The heterogeneity H extends from 30°N to 30°S on the 0°E meridian, a length comparable to the western Pacific subduction

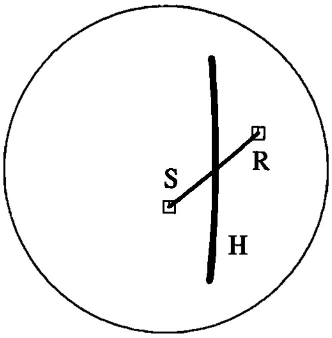

Fig. 1. Configuration used in the experiments with the subduction zone model. H is the heterogeneity; the source S and receiver R lie on a great circle that intersects the heterogeneity at an angle of 45°.

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zone. The source S and the receiver R are placed in such a way, that the great circle intersects the inhomogeneity at an angle of 45°. The heterogeneity lies midway between source and receiver. We consider epicentral distances of 22½°, 45° and 89°. The results are shown in Figure 2, expressed as frequency shifts as a function of angular order, relative to the eigenfrequencies of reference model 1066A. The results show distinct fluctuations of the frequency shifts as a function of angular order, with a periodicity depending on the epicentral distance that is in good agreement with higher order asymptotic theory as developed by Davis & Henson [1986] and Romanowicz & Roult [1986].

The shifts presented in Figure 2 are only a factor of 3 to 4 smaller than observed shifts, as reported by Silver & Jordan [1981], Masters & Gilbert [1983] or Romanowicz et al. [1987]. This difference is rather small, particularly when it is recognized that only a single subduction zone is responsible for the shifts. The periodicity and amplitude of the fluctuations do match the observations reported by Davis & Henson [1986] or Romanowicz & Roult [1986]. The latter authors also calculated frequency shifts due to upper mantle models by Nakanishi & Anderson [1984] and model M84C [Woodhouse & Dziewonski, 1984]. The obtained shifts are of the same overall magnitude as observed shifts, although they do not fit the observations.

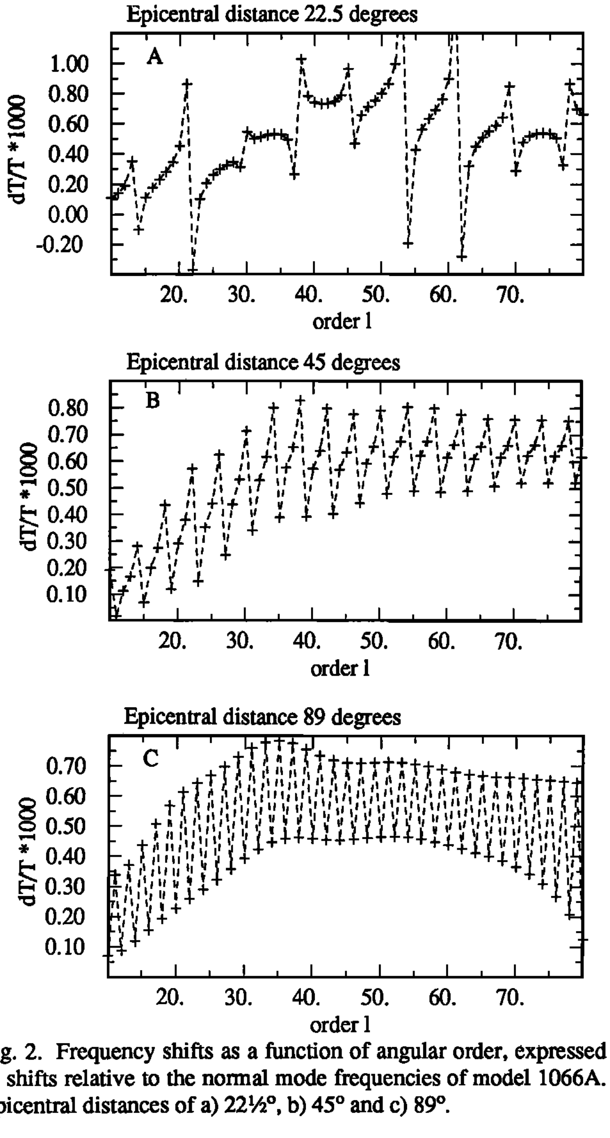
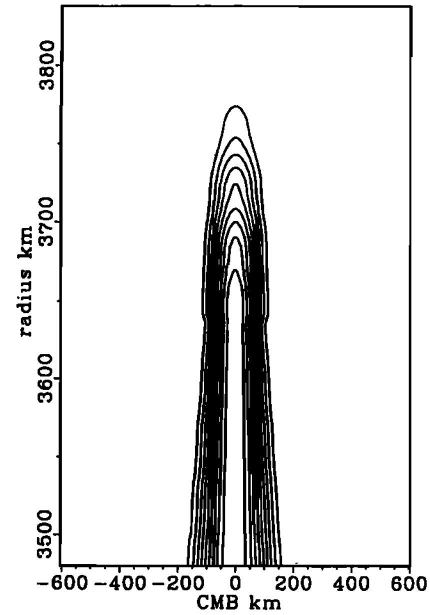


Fig. 2. Frequency shifts as a function of angular order, expressed as shifts relative to the normal mode frequencies of model 1066A. Epicentral distances of a) 22½°, b) 45° and c) 89°.



Contour interval for ρ : .1 % , for λ and μ : .5 %

Fig. 3. Mantle plume model used in this study. The model has cylindrical symmetry. The contrast between the center of the plume and the reference model is 1% in ρ and 5% in λ and μ.

Our results indicate that sharp lateral heterogeneities in the upper mantle may have a significant effect on the frequencies of fundamental modes. The question we must address is whether, by inverting normal mode data for smooth models, we can recover the low wavelength expression of such localized structures or whether some serious bias is introduced.

Hot spot plume model

In a recent study, Olson et al. [1987] suggested that hot spot plumes may form in the D" layer, as a result of coalescence of thermal instabilities. Associated CMB topography was estimated to have an amplitude of about 5 to 10 km with a wavelength of several hundreds of kilometers. These amplitudes are in agreement with those found by Morelli & Dziewonski [1987], but these authors could not resolve horizontal structures as small as a few hundred kilometers width.

Here we consider a plume model, with the same contrast as the subduction zone of the preceding section, a width of 400 km and a height of 250 km from the CMB (Figure 3), in agreement with the model of Olson et al. [1987]. Ignoring also terms from gravitational and interface effects, the low order hybrid modes ${}_2S_9$ and ${}_4S_4$, were computed for an earth with one CMB plume, taking into account the coupling with the 20 neighboring multiplets. These modes are among the anomalous low order modes observed in recent studies [Ritzwoller et al., 1986; Giardini et al., 1987]. The method used is a variational spectral method, which permits us to compute the interaction terms of such small-scale heterogeneity with reduced effort [Lognonné & Romanowicz, 1989]. The hot spot, which clearly behaves like a scattering point, produces a large change in the amplitude of the modes (Figure 4). In Figure 5 the configuration of the epicentre, the hot spot mantle plume and the GEOSCOPE stations is plotted. This change is of the same order of magnitude as that induced by the present models of the mantle, for example M84C+L02.56 [Woodhouse & Dziewonski, 1984; Dziewonski, 1984]. This may be explained by the effect of low radial order overtone modes interacting with ${}_4S_4$ or ${}_2S_9$,

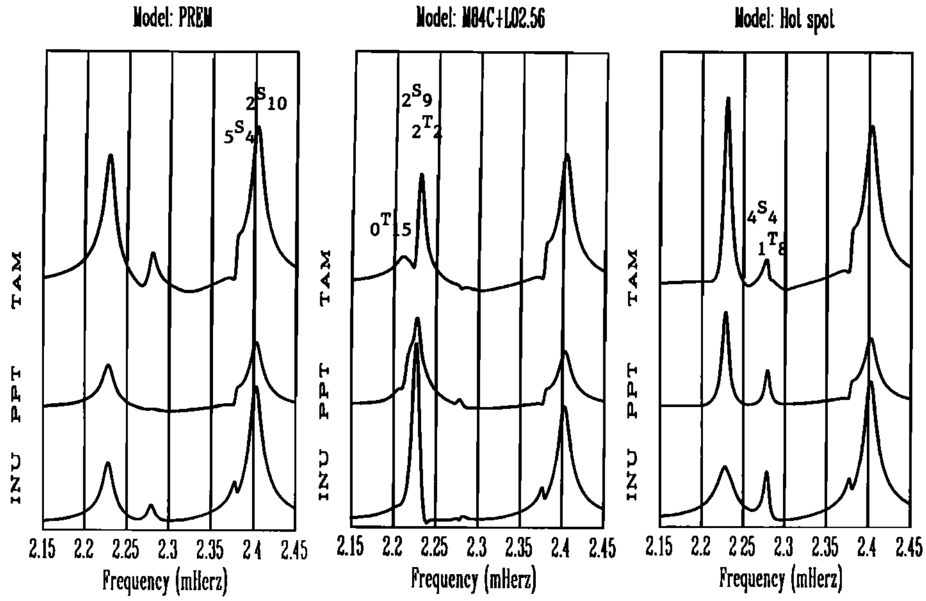


Fig. 4. Synthetic amplitude spectra on the vertical component for the mantle plume model. Modes $_0S_{14}$, $_0S_{15}$ and $_1S_{11}$ have been removed. The calculation corresponds to the case of the Alaskan earthquake of Nov. 30, 1987, 'observed' at 3 different GEOSCOPE stations. The source is characterized by: strike 110°, dip 78° and slip 35°, depth 20 km, moment 0.8×10^{20} Nm. The hot spot is located at the North Pole.

which are more excitable and observable than these anomalous modes. The splitting due to such a small-scale heterogeneity is about 100 times smaller than that induced by the present models of the mantle. Nevertheless, a realistic global distribution of more than 50 mantle plumes [Burke & Wilson, 1976] can be expected to produce a significant splitting of low order lower mantle and CMB sensitive normal modes, in a comparable way as smooth aspherical models [Lognonné & Romanowicz, 1989].

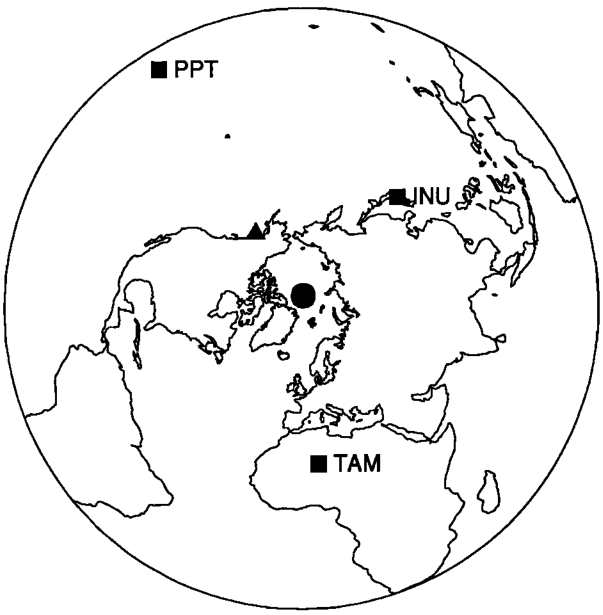


Fig. 5. Configuration used in the hot spot experiment. Squares denote the GEOSCOPE stations INU, PPT and TAM; the hot spot is placed on the North Pole and is indicated by the circle; the triangle gives the epicentre of the earthquake.

This experiment indicates that caution must be taken in the interpretation of low angular order mode observations in terms of smooth heterogeneity, and in particular perhaps, anomalously split modes, which, until now have been interpreted under the assumption of isolated multiplets [Ritzwoller et al., 1986; Giardini et al., 1987].

Conclusions

The results presented in this paper indicate that normal mode frequencies can be influenced considerably by sharp lateral heterogeneities, in various parts of the earth. The frequency shifts induced by a simple subduction zone model are smaller by only a factor of 3 or 4 than observed frequency shifts on long-period seismograms. This implies that such small-scale heterogeneities may not be plainly ignored in inversions of normal mode data. Further research on the bias introduced on the frequency and amplitude of normal modes is necessary.

The effect on the amplitude of anomalous modes induced by the hot spot plume model is also worth attention. Here again we may not ignore the theoretical complications due to coupling of modes induced by small-scale heterogeneity.

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