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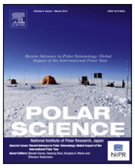

Search for latitudinal variation of spectral peak frequencies of low-frequency eigenmodes excited by great earthquakes

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Abstract

Continuous waveform records of STS-1 seismometers of the Incorporated Research Institutions for Seismology (IRIS) and superconducting gravimeters of the Global Geodynamics Project (GGP) obtained during the 2004 Sumatra-Andaman, the 2010 Chile, and the 2011 off the Pacific coast of Tohoku earthquakes are examined to search for latitudinal variations of the spectral peak frequencies of ${}_0S_0$, ${}_1S_0$, and ${}_0S_2$. No latitudinal variation is determined. The observed spectral peak frequencies are identical to those of the Preliminary Reference Earth Model (PREM).

Keywords: Free oscillation; D″ layer; Eigenfrequency; Latitudinal variation; Degree-two heterogeneity

1. Introduction

The Earth's free oscillations excited by great earthquakes provide a powerful tool for investigating the structure of the Earth's deep interior. The oscillation of the Earth with a finite size can be expressed as the sum of the eigenmodes of spheroidal oscillations (${}_nS_l^m$) and torsional oscillations (${}_nT_l^m$), where n, l and m respectively denote the radial, angular and azimuthal orders (see Dahlen and Tromp (1998) for details). Their eigenfrequencies reflect the velocity structure of the Earth's interior. The spherically symmetric Earth causes degeneration by which singlets ($m = -l,l$) sharing the same l and n have the same frequency. The Earth's rotation and the spherical asymmetry of its deep structure results in a breakdown of the degeneracy and the spectral peak of a multiplet splits into $2l + 1$ closely–spaced peaks.

The core–mantle boundary (CMB) Stoneley modes have an oscillation energy concentrated around the CMB. Inner core modes account for much of the oscillation energy in the inner core. CMB Stoneley modes and inner core modes are generally designated as core modes. Master and Gilbert (1981) first reported that the splitting of spectral peaks of multiplets of core modes is significantly wider than that predicted for the rotation of the spherically symmetric Earth. Spectral splitting of this kind was designated as anomalous splitting.

Anomalous splitting has attracted the attention of seismologists. Various deep asymmetrical structure models have been proposed as a cause of the anomalous splitting. Woodhouse et al. (1986) concluded that the

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cause of the anomalous splitting was seismic anisotropy in the inner core. Li et al. (1991) pointed out that seismic anisotropy in the inner core failed to explain the anomalous splitting of ${}_3S_2$ (1.106 mHz, a core mode) and some other core modes. Widmer et al. (1992) claimed that the cause of the anomalous splitting should be in the outer core. Romanowicz and Bréger (2000) proposed a polar cap model in which the heterogeneity concentrates around the rotation axis in the outer core. To explain the anomalous splitting of ${}_3S_2$, Tsuboi and Saito (2002) considered a soft-core splitting model which had a thin layer with small rigidity at the base of the outer core. Stevenson (1987) reported that no lateral perturbation of density larger than 10^{-5} in the outer core should be maintained because of hydrostatic considerations.

The anomalous splitting of all associated modes, including ${}_3S_2$, has not yet been modeled and its cause remains an open question.

2. Non−standard approach for anomalous splitting

It seems worthwhile to attempt to introduce a minimum variation to the standard theory if one cannot determine the cause of the anomalous splitting within the framework of the standard theory of free oscillations. In the D″ layer, the ultra-low velocity zone (ULVZ) is distributed above the CMB beneath the central Pacific (e.g. Mori and Helmberger, 1995). Garnero and Jeanloz (2000) pointed out that a perturbation of the density correlates negatively with a perturbation of the velocity in the ULVZ. Elastic constants are the products of the density and the weighted sum of the squares of V_P and V_S. The equations of motion of an elastic body include only the perturbation of the density if the perturbations of elastic constants are zero as a result of the negative correlation. From this perspective, Kawasaki (2011) proposed a non-standard approach for eigenfrequencies with no perturbation of the elastic constants to introduce latitude-dependent frequencies of eigenmodes, which are designated herein as pseudo-eigenfrequencies. The Appendix presents an outline of the theoretical approach of Kawasaki (2011).

Referring to Mori and Helmberger (1995) and Garnero and Jeanloz (2000) who derived the C02 type heterogeneity in the D″ layer, Kawasaki (2011) proposed a "degree-two heterogeneity" in the D″ layer. The reference model is the Preliminary Reference Earth Model (PREM) of Dziewonski and Anderson (1981). The "degree-two heterogeneity" has no perturbations of the density, V_P, or V_S above a depth of 300 km above the CMB and in the core. Perturbations of 10%, −5%, and −5% of the density, V_P and V_S, respectively, are given at the CMB, the bottom of the D″ layer. For the D″ layer, a linear gradient of the perturbation is assumed between the top and the bottom of the D″ layer. All perturbations have a latitudinal dependence of a $\cos 2\theta$-type. In the case of "degree-two heterogeneity", pseudo-eigenfrequencies of a multiplet vary with $\cos 2\theta$ (θ is the latitude) of an amplitude of a few percent (Kawasaki, 2011). This variation might yield a scattering of the pseudo-eigenfrequencies leading to the observation of apparently wider splitting of core modes. This has motivated us to seek a latitudinal variation of the pseudo-eigenfrequencies using low-frequency eigenmodes obtained from recent great earthquakes. Furthermore, the development of broadband seismic/geodetic observation networks in high latitude areas, including the polar region, enables us to examine latitudinal variations with accuracy.

To search for a $\cos 2\theta$-type latitudinal variation, we specifically examine radial modes of ${}_0S_0$ (eigenfrequency of 0.816 mHz and eigenperiod of 1228 s by PREM), ${}_1S_0$ (1.631 mHz and 613 s by PREM) and lowest-frequency eigenmodes of ${}_0S_2$ (0.309 mHz and 3233 s by PREM). The radial modes of ${}_0S_0$ and ${}_1S_0$ have no splitting and are significant in the spectra at many stations for low attenuation (Q of around 5000). Therefore we expect that a latitudinal variation can be found if it exists. Because ${}_0S_2$ is isolated from nearby eigenmodes, these do not contaminate its spectral peaks of singlets.

We do not examine Stoneley-type normal modes (e.g. ${}_1S_7$−${}_1S_{15}$) in this study. One of the reasons is that they have many singlets within a single multiplet and the frequency shifts are difficult to recognize. The other is that their oscillation energy is concentrated below the CMB rather than in the D″ layer.

3. Data and methods

We analyze 37-day-long continuous records of the vertical component of STS-1 seismometers at the Incorporated Research Institutions for Seismology (IRIS) stations and superconducting gravimeters at the Global Geodynamics Project (GGP) stations, as obtained from three recent great earthquakes: the 2004 Sumatra-Andaman earthquake (Mw 9.1) of 26 December, 2004; the 2010 Chile earthquake (Mw 8.8) of 27 February, 2010; and the 2011 off the Pacific coast of Tohoku earthquake (hereinafter, the Tohoku earthquake) (Mw 9.0) of 11 March, 2011 (Fig. 1). The