The importance of mantle azimuthal anisotropy for the coupling of Earth's normal modes

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Aim

To show how large the effect of realistic mantle azimuthal anisotropy is on normal-mode data and assess whether normal modes are well-suited to infer from them the Earth's azimuthally anisotropic structure.

Normal modes

Earthquakes of magnitude ≥ 7.5 make the entire Earth oscillate at distinct eigenfrequencies, depending on the Earth's internal structure. The corresponding patterns of displacement, the eigenfunctions, are the Earth's normal modes (**Fig. 1**). They are divided into **spheroidal modes** ${}_nS_l$ (P-SV motion) and **toroidal modes** ${}_nT_l$ (SH motion).

The resonance between normal modes due to Earth's 3-D structure (and it's rotation and ellipticity) is called **normal mode cross-coupling**. Coupled modes exchange energy, meaning that for a coupled spheroidal and toroidal mode, the toroidal mode can be observed on vertical-component seismograms and the spheroidal mode on horizontal-component seismograms.

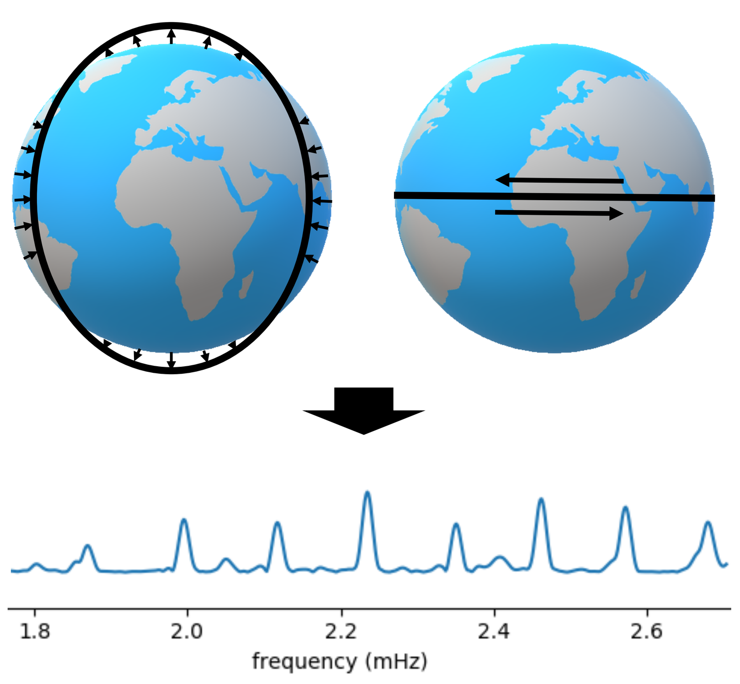

Figure 1: Earth's free oscillations after a large earthquake are divided into spheroidal and toroidal normal modes, which appear as distinct peaks on the frequency spectrum.

Modelling azimuthal anisotropy

In addition to normal-mode coupling through isotropic 3-D structure, modes also exchange energy as a result of anisotropic structure (**Fig. 2**).

YB1314ani

We implement existing surface-wave models of azimuthal anisotropy from Yuan & Beghein (2013, 2014) in the upper mantle and the transition zone in the forward calculations of synthetic normal-mode seismograms. The anisotropy model, YB1314ani, contains values for 4 out of 16 elastic parameters describing azimuthal anisotropy (Gc, Gs, Ec and Es) in spherical harmonics at each 100 km depth.

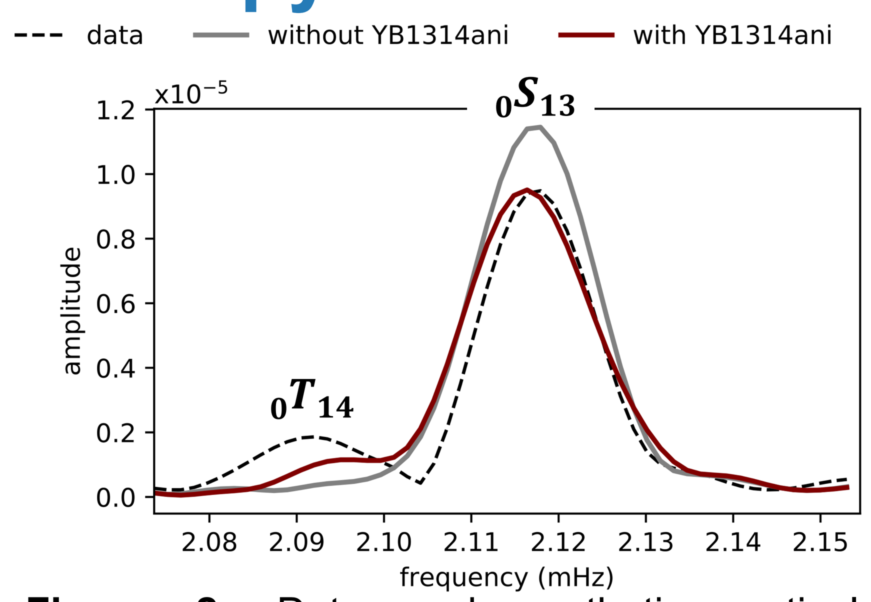

Figure 2: Data and synthetic vertical-component spectra at station LVZ for the 28 March 2005 Sumatra earthquake. Synthetics were computed for S20RTS (Ritsema et al. 1999) with and without azimuthal anisotropy model YB1314ani. The anisotropy coupling between the modes is shown by a decrease in the spheroidal mode's amplitude and an increase in the amplitude of the toroidal mode.

Results

We find that

- Azimuthal anisotropy model YB1314ani has a notable effect on normal-mode frequency spectra (**Fig. 3**) and structure coefficients c_s^t (**Fig. 4**), implying that (1) normal modes can be used to constrain azimuthal anisotropy inside the Earth and (2) azimuthal anisotropy needs to be considered when inferring Earth structure from normal-mode data;
- The effect of azimuthal anisotropy on normal-mode data is comparable to and often larger than the effect of mantle density variations;
- The proximity in frequency of CMB Stoneley modes (modes that have strong sensitivity in the CMB region) to the fundamental modes ${}_0S_l$ and ${}_0T_l$, which are strongly affected by YB1314ani, means that the measurements of Stoneley modes may be affected by azimuthal anisotropy in the upper mantle and the transition zone.

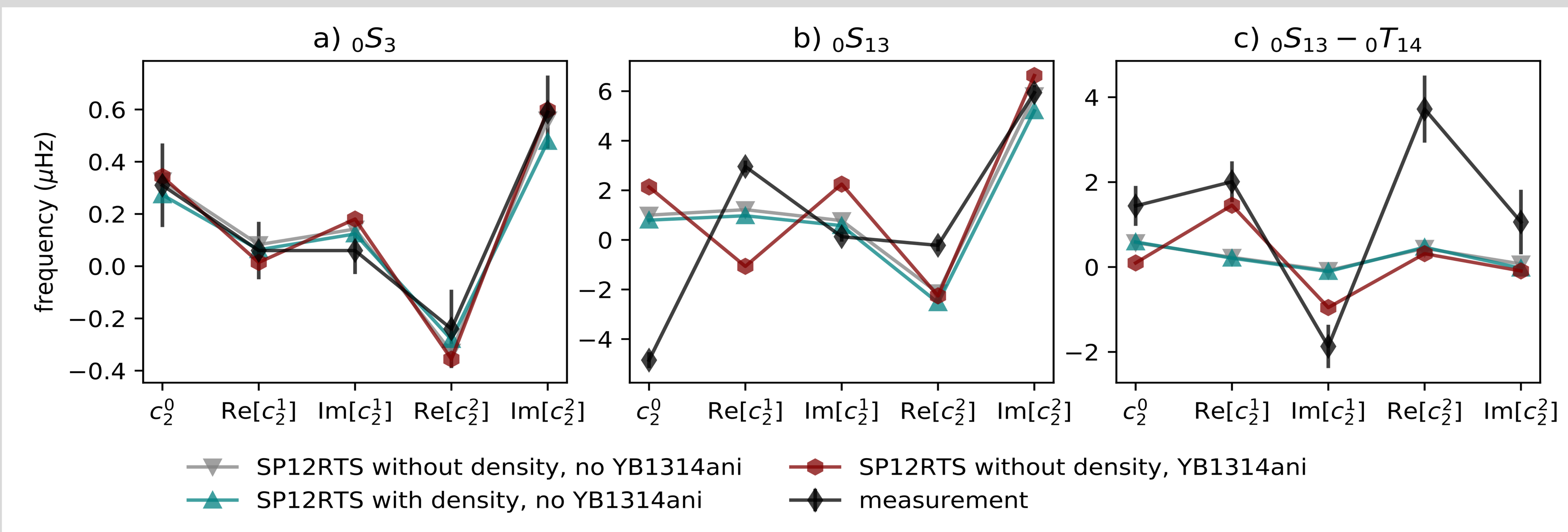

Figure 4: Measured and predicted degree-two structure coefficients c_s^t for self-coupled modes ${}_0S_3$ (a) and ${}_0S_{13}$ (b) and cross-coupled modes ${}_0S_{13} - {}_0T_{14}$ (c). The ${}_0S_3$ measurements are from Deuss et al. (2013); the ${}_0S_{13}$ and ${}_0S_{13} - {}_0T_{14}$ measurements are from Resovsky & Ritzwoller (1998). Predictions as indicated in the legend show the effect of adding either mantle density variations or azimuthal anisotropy (YB1314ani) to calculations for mantle velocity model SP12RTS. The c_s^t coefficients define how a mode's frequency is affected by Earth structure of degree s and order t. Measured c_s^t coefficients are generally used to infer Earth structure from normal-mode data.

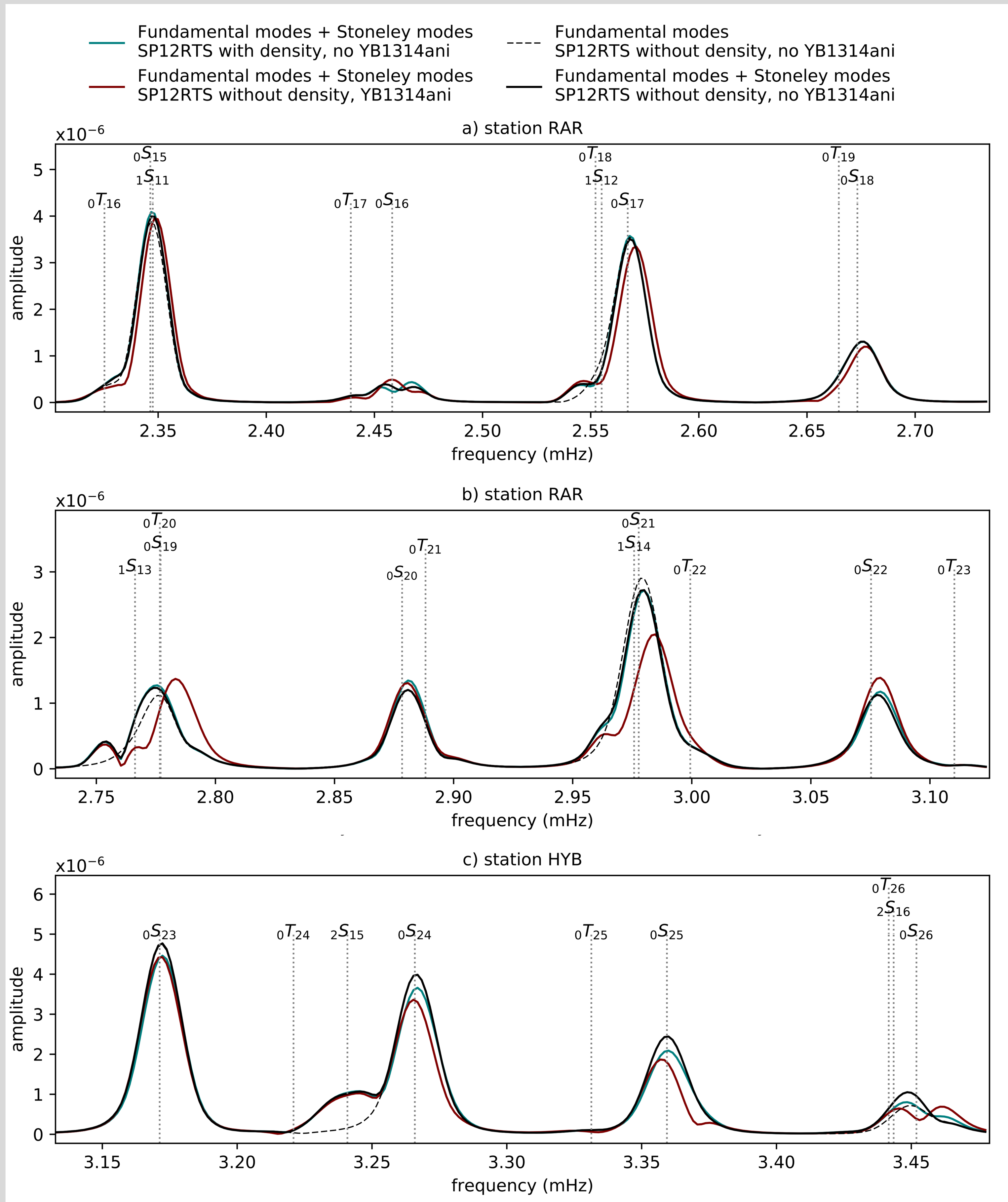

Figure 3: Synthetic vertical-component spectra for the 9 June 1994 Bolivia earthquake. The spectra as indicated in the legend show the effect of adding either mantle density variations or azimuthal anisotropy (YB1314ani) to calculations for mantle velocity model SP12RTS (Koelemeijer et al. 2015).

Discussion

Koelemeijer et al. (2017) used measurements of Stoneley modes (Koelemeijer et al. 2013) to infer the density of the large low shear velocity provinces (LLSVPs) in the lowermost mantle under Africa and the Pacific, finding light LLSVPs as opposed to earlier studies (e.g., Ishii & Tromp 1999).

We have shown that azimuthal anisotropy considerably affects the normal-mode frequency spectrum in general, and in particular near the Stoneley-mode peaks. Accounting for azimuthal anisotropy would therefore result in more reliable models of the Earth's 3-D density structure.

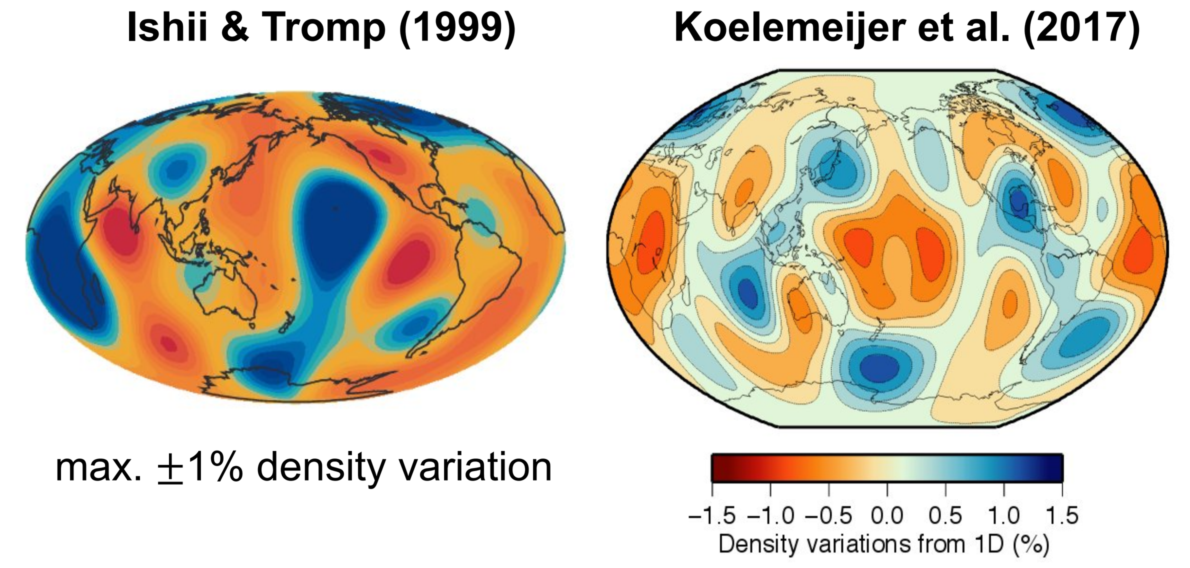

Figure 5: Normal-mode density models at 2850 km depth, showing that normal-mode data have been used to find both dense (Ishii & Tromp 1999) and light LLSVPs (Koelemeijer et al. 2017).

Outlook

How can we obtain mantle azimuthal anisotropy from normal-mode data?

References

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