Deep Earth rotational seismology

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Motivation

Rotational seismology is an emerging field and it promises to bring new information about the interior of the Earth. Assuming plane wave propagation, we can compute the ratio between the transverse acceleration a_T and the vertical rotation rate $\dot{\Omega}_z$ to find that

$$\frac{a_T}{\dot{\Omega}_z} = \frac{a_T}{\nabla \times v_T} = 2c, \tag{1}$$

where $\nabla\times$ is the curl operator, v_T is the horizontal velocity and $c = \omega/k$ is the phase velocity.

This means that transverse acceleration and vertical rotation rate are in phase with a difference in amplitude given by $2c$. The velocity c is defined by [3] as the apparent velocity and it is currently being used in exploration seismology studies [7, 11, 10]. Up to today, it is unclear whether rotational records may contain more (or different) information than the conventional translational records. Here we show that rotational records can be used for studying the Earth's lowermost mantle.

Data and data processing

We use information from one rotational and one translational seismometer installed in the Wettzell Observatorium, Germany (latitude 49.14° and longitude 12.88°). The proximity of both instruments allow us to make direct comparison between the records.

To study the Earth's lowermost mantle, we analyze clear S, ScS and some SdS waves in both translational and rotational records. A total of 33 events are found with a good signal to noise ratio. Data processing was performed using Obspy [5] and included bad-pass filtering between 3–25s and rotation to radial (R) and transverse components (T) for the translational records.

We show in Fig. 1 (a-b) the clear presence of S and ScS waves in both translational and rotational records for the event 2010-06-12, lat 7.8506°, long 91.9546°, Mw 7.5 and also SdS waves for the event 2013-10-01, lat 53.1368°, long 152.8959°, Mw 6.7.

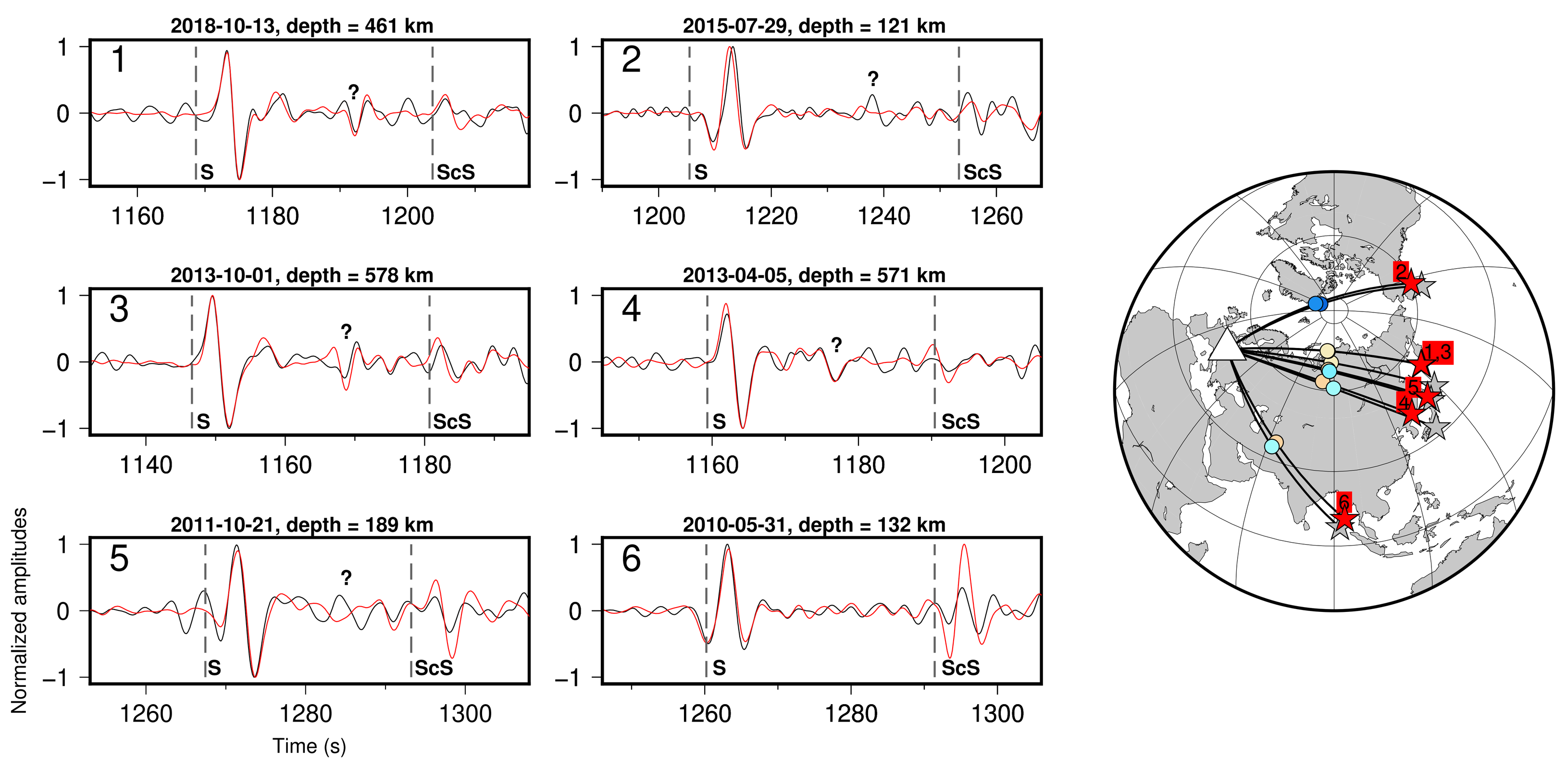

Figure 1: Left: Accelerograms (red curves) and rotational rates (black curves) corresponding to six selected earthquakes. Seismic traces have been normalized. Dashed lines correspond to S and ScS arrival times predicted in PREM [2] using Obspy-TauP [5]. Right: Map of the station location (white triangle), event locations (red stars) and great-circle-paths (black lines).

Methodology

We present a methodology for imaging the Earth's lowermost mantle combining rotational and translational recordings at the surface. When a wave is propagating in a layered medium, the application of Snell's law yields the definition of the ray parameter p which is constant along the ray and provides an estimate of the horizontal velocity

$$p = \frac{\sin i}{v} = s \sin i, \tag{2}$$

where i is the incidence angle, s is the slowness ($s = 1/v$) and v the velocity of the medium. The ray parameter p represents the apparent slowness of the wavefront in the horizontal direction (horizontal slowness, [8]). The ray parameter p can be related to the velocity of the medium at three different locations: the source, the receiver and the turning point [9]

$$p = \frac{\sin i_s}{v_s} = \frac{\sin i_0}{v_0} = \frac{\sin i_d}{v_d}, \tag{3}$$

where the subscripts $(s, 0, d)$ refer to the source, receiver and turning (or deepest) point of the ray, respectively. If the wave does not reflect at an interface, then the deepest point of the ray will travel horizontally ($i_d = 90°$), therefore the velocity of the medium at the deepest point of the ray is equal to the inverse of the slowness. Using the definition given by eq. (3) and amplitude information from S and ScS waves we can obtain local values of the velocity at the turning and the reflection points, respectively, of the travel paths as follows

$$\left(\frac{\delta v}{v}\right)^{S} = -\frac{1}{2}\left(\frac{a_T}{\dot{\Omega}_z}\right)^{S}(p)^{S}_{\text{PREM}} - 1, \qquad \left(\frac{\delta v}{v}\right)^{ScS} = -\frac{1}{2\chi}\left(\frac{a_T}{\dot{\Omega}_z}\right)^{ScS}(p)^{ScS}_{\text{PREM}} - 1,$$
$$\left(\frac{\delta v}{v}\right)^{\text{LM}} = \chi\frac{(a_T)^S}{(a_T)^{ScS}}\frac{\left(\dot{\Omega}_z\right)^{ScS}}{\left(\dot{\Omega}_z\right)^{S}}\frac{(p)^S_{\text{PREM}}}{(p)^{ScS}_{\text{PREM}}} - 1, \qquad \chi = \frac{(\sin i_d)^{ScS}_{\text{PREM}}}{(\sin i_d)^{ScS}_{\text{obs}}}, \tag{4}$$

where we have normalized by PREM [2], the symbol $(\sin i_d)^{ScS}$ is the sine of the reflection angle of the ScS wave at the CMB (angle between the tangent to the ScS ray at the CMB and the normal to it). Assuming that we are able to obtain the ratio of transverse acceleration a_T and vertical rotation rate $\dot{\Omega}_z$ from seismological observations, we are left to compute the angle of incidence of the ScS wave (i_d^{ScS}) in eqs. (4). To relax this requirement we assume $\chi = 1$.

Results

To test whether eqs. (4) can help to resolve lower mantle heterogeneity, we perform synthetic tests using the TauP toolkit [1] and implemented in Obspy [5]. We assume a PREM model with a shear velocity anomaly of height $H = 2300$ km and $\delta v/v = -2.2\%$. Predictions at the S wave turning point are shown in Fig. 2-a. Similarly, assuming a PREM model with a shear velocity anomaly of height $H = 365$ km and $\delta v/v = -3\%$. Predictions at the ScS reflection point (assuming $\chi = 1$) are presented in Fig. 2-b.

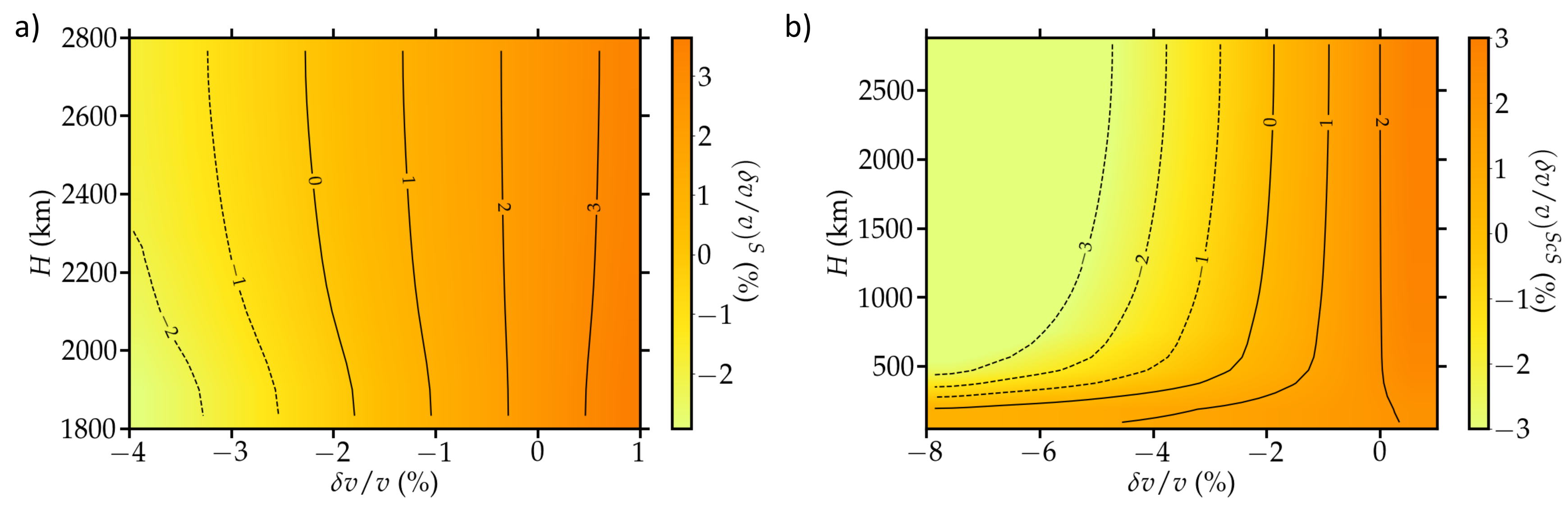

Figure 2: Ray theory predictions of eqs. (4).

Using information of 12 different events we show what will be the shear wave velocity perturbation predicted by our methodology and compare the results against different tomographic models S40RTS [6] and SEMUCB [4] (see Fig. 3).

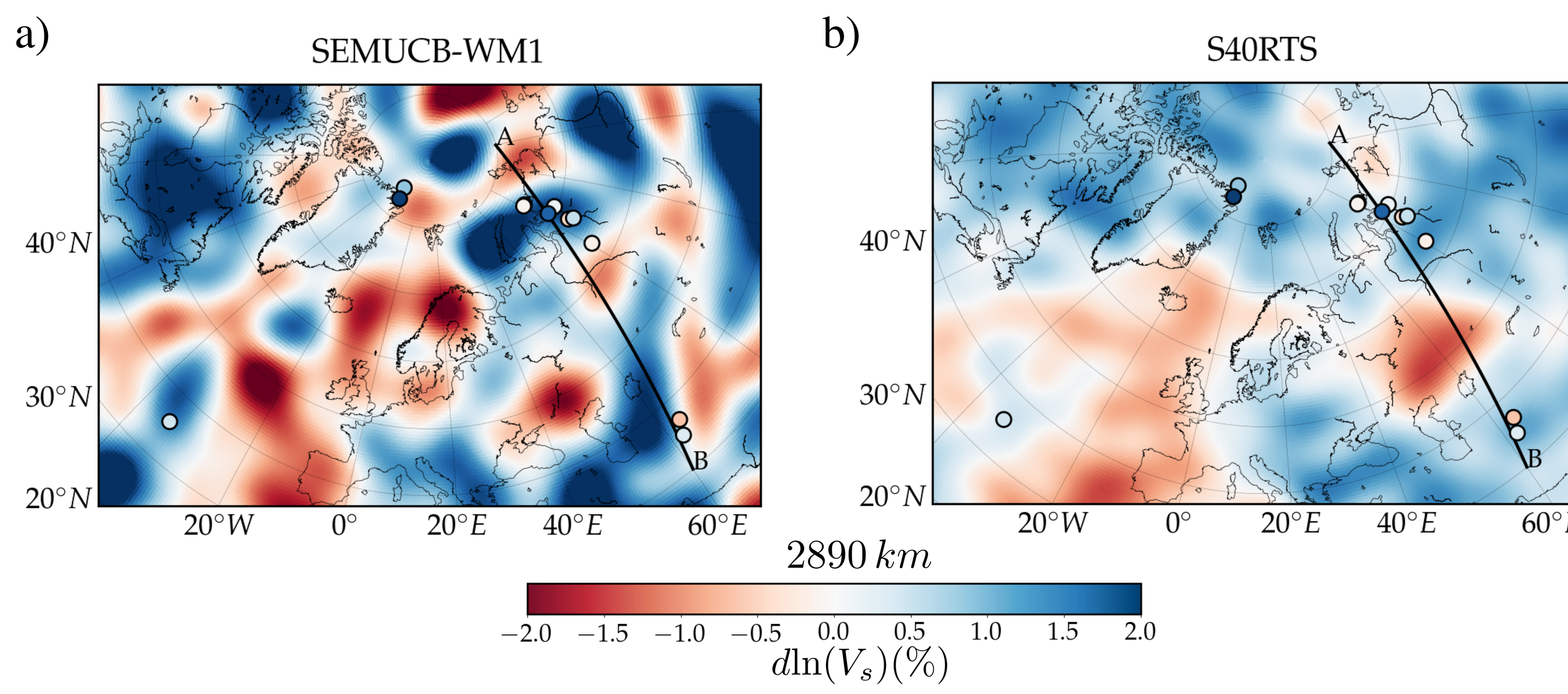

Figure 3: a) and b) Comparison between our calculated velocity perturbations using ScS and S waves displayed over the shear velocity perturbations of the lowermost mantle predicted by the tomographic models SEMUCB-WM1 and S40RTS. Our results for velocity perturbation is color coded with the same scale as the velocity model and displayed by the colored circles.

Take home message

We have used rotational and translational seismic data and show that teleseismic waves sampling the deep Earth can be detected in rotational data. Applying the approach to rotational and translational records from the Wettzell observatory with co-located translational and rotational sensors we are able to resolve core-mantle boundary velocity variations using an example dataset.

The methodology presented in this work has the potential to provide means to refine, better constrain and perhaps to find consensus among different regional Earth models and therefore decipher the nature of major structures such as the large low velocity provinces (LLVPs) beneath the Pacific and Africa, ultra low velocity zones (ULVZs), and the D″ layer by providing sharper images of the Earth's lower mantle.

References

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