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Can we estimate local Love wave dispersion properties from collocated amplitude measurements of translations and rotations?

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[1] We investigate the possibility of determining local dispersion characteristics of Love waves using seismograms of transverse acceleration and rotation rate around a vertical axis recorded at the same site. Assuming plane-wave propagation, phase velocity information is contained in the frequency-dependent amplitude ratio of the two different types of ground motion. We perform tests of this method using real measurements from a ring laser system and a broadband seismometer at the geodetic observatory Wettzell in southeast Germany as well as synthetic seismograms computed by normal mode summation. While general dispersion characteristics can be recovered, we show that the contribution of overtones impedes the use of this method for structural inversion. To extract the structural information contained in collocated measurements of rotations and translations, a full waveform inversion is necessary. **Citation:** Kurrle, D., H. Igel, A. M. G. Ferreira, J. Wassermann, and U. Schreiber (2010), Can we estimate local Love wave dispersion properties from collocated amplitude measurements of translations and rotations?, *Geophys. Res. Lett.*, *37*, L04307, doi:10.1029/2009GL042215.

1. Introduction

[2] During the past decade, interest in the measurement and analysis of seismic rotations has steadily increased [e.g., *Lee et al.*, 2009]. While it was long known that for a comprehensive understanding of ground motions it is necessary to measure – besides three components of translation and six components of strain – three components of rotation, a lack of suitable instruments with sufficient sensitivity prevented their investigation. Only the development of large, high-sensitivity ring lasers made it possible to measure rotational ground motions induced by teleseismic earthquakes [*Stedman et al.*, 1995; *McLeod et al.*, 1998; *Pancha et al.*, 2000; *Schreiber et al.*, 2006, 2009]. With such instruments it is now possible to observe rotational ground motions induced by seismic events stronger than magnitude 6 over a wide range of epicentral distances.

[3] One possible application of rotation measurements is structural inversion based on collocated recordings from seismometers and rotation sensors [*Fichtner and Igel*, 2009; *Bernauer et al.*, 2009]. As has been shown in several previous studies [*Igel et al.*, 2005; *Cochard et al.*, 2006; *Igel et al.*, 2007], waveforms of rotation rate around a vertical axis and transverse horizontal acceleration recorded at the same site show a high similarity in the Love wave part. This is expected theoretically for plane horizontal shear waves in a homogeneous medium, and the observed similarity suggests that the assumption of plane waves is acceptable. For such a plane horizontal shear wave, the rotation rate ω_z around a vertical axis is proportional to transverse acceleration a_T with their ratio being twice the horizontal phase velocity [e.g., *Pancha et al.*, 2000; *Igel et al.*, 2005]: $a_T/\omega_z = 2c$. Using normal mode theory, *Ferreira and Igel* [2009] could show that this relation also holds for fundamental mode Love waves in smooth, laterally heterogeneous media.

[4] Hereafter, we call the amplitude ratio $a_T/2\omega_z$ the apparent phase velocity c_{app}. According to *Fichtner and Igel* [2009], the sensitivity of such apparent phase velocities to Earth structure is concentrated near the receiver. Using full ray theory simulations, *Ferreira and Igel* [2009] showed that rotation amplitudes are strongly influenced by the local structure near the receiver. These findings suggest that it might be possible to use collocated rotation and translation measurements to determine a local Love wave dispersion curve, i.e., the frequency-dependent phase velocity of fundamental mode Love waves, and to compile a local ground model.

[5] It has already been shown that amplitude ratios of transverse acceleration and rotation rate, determined for different parts of Love wave trains using sliding time windows, yield apparent phase velocities between 3 and 6 km/s, as expected for fundamental mode Love waves [*Igel et al.*, 2005; *Cochard et al.*, 2006; *Igel et al.*, 2007]. In addition, a slight decrease of the apparent phase velocities with time, corresponding to the dispersive behavior of these waves, could be observed.

[6] In this study, we try to estimate Love wave dispersion curves using the simple relationship given above. The procedure is described in detail in section 2. To assess the suitability of this method, it is applied to real data recorded at the geodetic observatory Wettzell (WET) in southeast Germany as well as synthetic seismograms based on the summation of normal modes.

2. Determination of Apparent Phase Velocity

[7] To determine the apparent phase velocity of fundamental mode Love waves, we analyze seismograms of

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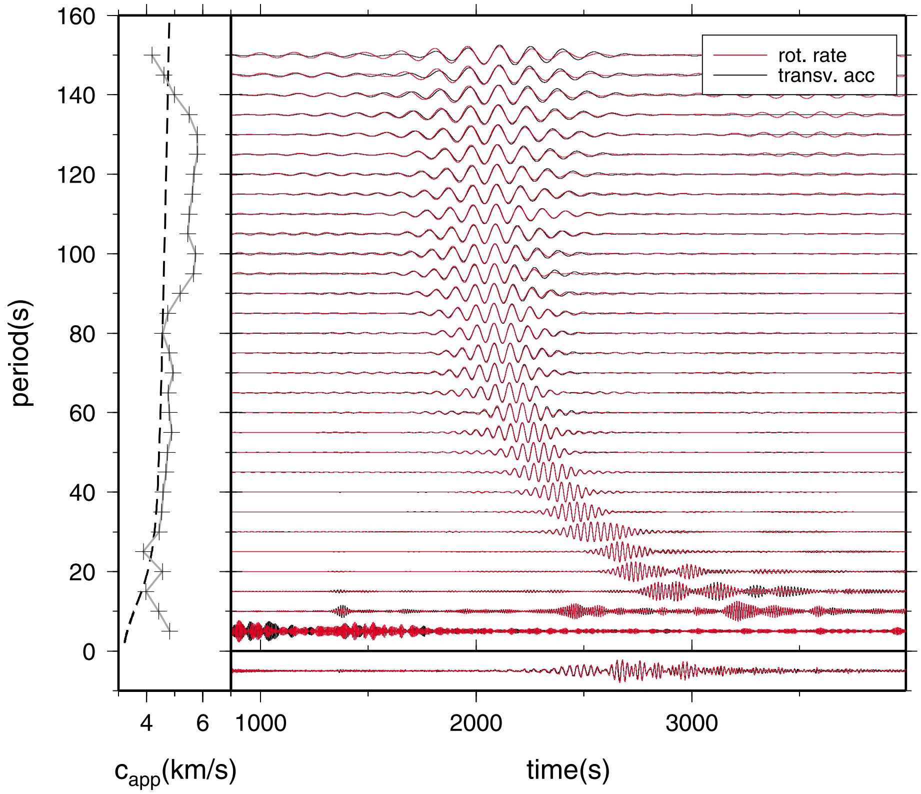

Figure 1. (right) Estimation of apparent Love wave phase velocity using band-pass-filtered seismograms recorded at Wettzell after the $M_W = 7.4$ Kuriles earthquake on Jan 15, 2009. Transverse acceleration (black) is scaled such to fit vertical rotation rate (red). The lowermost traces are the unfiltered broadband seismograms. (left) The apparent phase velocity, i.e., half of the scaling factor, is plotted (crosses), together with a dispersion curve for PREM (dashed line).

rotation rate ω_z and transverse acceleration a_T, recorded after strong earthquakes with the ring laser and a Streckeisen STS-2 broadband seismometer at the station WET. The seismometer records which are proportional to ground velocity for $T < 120$ s are first differentiated and corrected for the seismometer response to obtain ground acceleration. The horizontal components are rotated into a radial and a transverse component. The ring laser records only have to be divided by a frequency-independent gain factor to get the vertical rotation rate. As a next step, a sequence of narrow band-pass filters with center periods T_c is applied to the data (see Figure 1). To determine ratios between the band-pass-filtered Love wave amplitudes, a time window Δt around the arrival of the fundamental Love wave train is selected according to Love wave group velocity $v_g(T_c)$ as predicted by the Preliminary Reference Earth Model (PREM) [*Dziewonski and Anderson*, 1981]. In this time window, we pick the maximum of the transverse acceleration record. For a time window of length $4T_c$ around this maximum, the amplitude ratio a_T/ω_z between acceleration and rotation is determined by a least-squares fit. Then, half of this ratio is the apparent phase velocity at period T_c:

$$c_{app}(T_c) = \int_{t_{\max}-2T_c}^{t_{\max}+2T_c} a_T(t)\,\omega_z(t)\,dt \Bigg/ 2\int_{t_{\max}-2T_c}^{t_{\max}+2T_c} \omega_z^2(t)\,dt$$

We assess the reliability of each value by cross correlation and visual inspection of the band-pass-filtered traces. Only those periods are considered for which the waveforms are clearly dominated by fundamental mode Love waves and the correlation coefficient between rotation rate and transverse acceleration exceeds a threshold of 0.75.

[8] Figure 1 illustrates this for the $M_W = 7.4$ earthquake on Jan 15, 2009 East of the Kurile Islands. The seismograms were filtered at periods from 5 to 150 s. The match between rotation rates (given in red) and transverse accelerations (black) is almost perfect. The relative scaling factor between rotation and acceleration is equal to $2c_{app}$, whereas the absolute scaling is such that all traces have the same maximum. The apparent phase velocity $c_{app}(T_c)$ is given in Figure 1 (left).

[9] Albeit we are interested in the frequency-dependent phase velocity, we perform the estimation in the time domain, because this enables us to quickly assess data quality and a possible contamination through phases other than Love waves. This is only possible in the time domain, and we found no disadvantages compared to a determination of the ratios in the spectral domain.

3. Measurement Results

[10] The apparent phase velocities for the Kuriles event in Figure 1 lie all between 4 and 6 km/s, and a general trend of an increasing c_{app} with increasing period can be observed. However, it is not clear how accurate these estimates are and

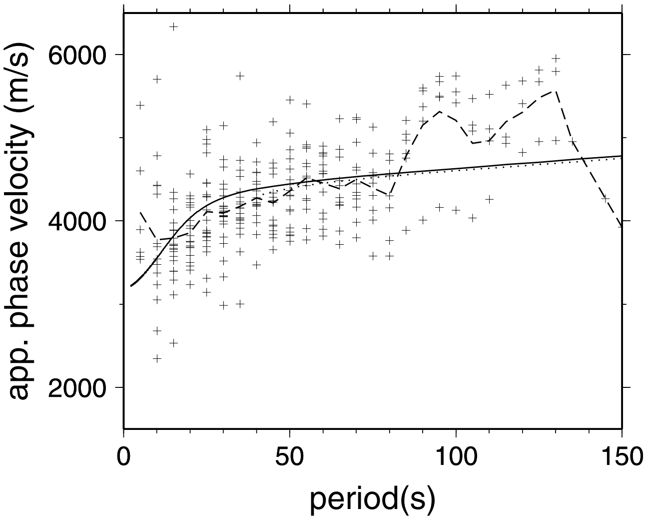

Figure 2. Apparent Love wave phase velocities from 28 earthquakes recorded at the station WET (crosses). Also shown are the average (dashed line) and dispersion curves determined from PREM (solid line) and the 3D models CRUST2.0 and S20RTS (dotted line).

if they can be used to obtain new information about Earth structure.

[11] Figure 2 contains apparent phase velocities from 28 earthquakes recorded at the Wettzell observatory (see Table S1 of the auxiliary material).[1] The magnitudes range from 5.4 to 9.0 and the distances from about 1200 to 17000 km. All of them are shallow events with a depth smaller than 70 km. While most events could be used to estimate amplitude ratios at periods from 10 to 80 s, at longer periods only few of them fulfilled the condition of a correlation coefficient higher than 0.75 between rotation rate and transverse acceleration. For both the ring laser and the seismometer data, the signal-to-noise ratio decreases at lower frequencies. Thus, the deviations of the average apparent phase velocity from the value expected from PREM increase with increasing period. Between 10 and 80 s, however, the maximum difference between the average and the curves determined from PREM and the combination of CRUST2.0 [*Bassin et al.*, 2000] with S20RTS [*Ritsema et al.*, 2004] is only 6%, and it seems possible that these differences might be further reduced for a larger number of events.

[12] Although we find no direct dependence of the apparent phase velocity on parameters like source location, orientation or magnitude, the distribution of earthquakes used should be as uniform as possible. There are several potential reasons for the discrepancies between the model curves and the measurements. As already mentioned, one of the major problems is noise, especially at longer periods [e.g., *Widmer-Schnidrig and Zürn*, 2009]. Although recent technical improvements led to a significant reduction of the noise level in the ring laser data, it is still several times higher than the noise in the horizontal components of the seismometer data at periods above 100 s.

[13] Another more basic source of uncertainty comes from the fact that the phase velocity estimation in this study is based on the assumption that the seismograms that we use contain isolated, plane fundamental Love waves only. However, both the ring laser data and the transverse seismic data might contain contributions of Rayleigh waves due to tilting of the ring laser, Love-Rayleigh coupling or off-great-circle propagation. In addition, non-planar wavefronts, site effects or the presence of higher modes can affect the amplitude ratios considerably. In principle, it should be possible to reduce the effects of non-planar wavefronts or Rayleigh wave contributions on the apparent phase velocities by requiring a high similarity between vertical rotation rate and transverse acceleration. Since it is not possible to exclude the influence of higher modes by this means, we study this effect in more detail in the next section.

4. Effects of Higher Modes

[14] To quantify the influence of higher mode Love waves on the apparent phase velocity, we computed synthetic seismograms by summing normal modes [*Gilbert*, 1971]. The normal mode approach allows us to easily analyze the effects of particular mode branches on the resulting amplitudes and their ratios.

[15] Figure 3a shows synthetic seismograms for the Kuriles event at the station WET. We calculated single branch seismograms for the fundamental mode and the first three overtones as well as a 'full' seismogram composed of the toroidal modes up to the order $n = 19$. The eigenfunctions were computed using PREM. We directly compare rotation rate with transverse acceleration, the latter scaled such to get equal amplitude maxima. The fit between rotation rate and transverse acceleration is excellent.

[16] Figure 3b displays the respective power spectral densities of rotation rate. Since the event is relatively shallow (36 km depth), the fundamental mode has by far the highest amplitude. However, the first overtones are also present and must not be neglected. This can be seen from the full seismogram at the bottom and, more prominently, from the power spectral density.

[17] For each case, we calculated amplitude ratios to obtain apparent phase velocities, using the method described in section 2. In Figure 3c, the dispersion curves determined from these amplitude ratios are compared with theoretical ones expected for PREM. If only a single mode branch is included, the respective dispersion curve can be reproduced well. However, if modes of more than one branch are summed, the power spectral densities and thus the amplitude ratios become more complex. Since the fundamental mode predominates, the dispersion curve for the full seismogram is still close to that for the fundamental mode, but the contribution of overtones causes significant fluctuations which depend on the location and the orientation of the source. Thus, to determine Love wave dispersion curves in this way, it would be necessary to exclude any contribution of overtones to the seismograms. Since overtones are always present, even for very shallow earthquakes, and separating them from the fundamental mode is very difficult [e.g., *van Heijst and Woodhouse*, 1997; *Beucler et al.*, 2003; *Visser et al.*, 2007], it seems rather unfeasible to use dispersion curves determined from amplitude ratios as reported here for

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[1] Auxiliary materials are available in the HTML. doi:10:1029/2009GL042215.

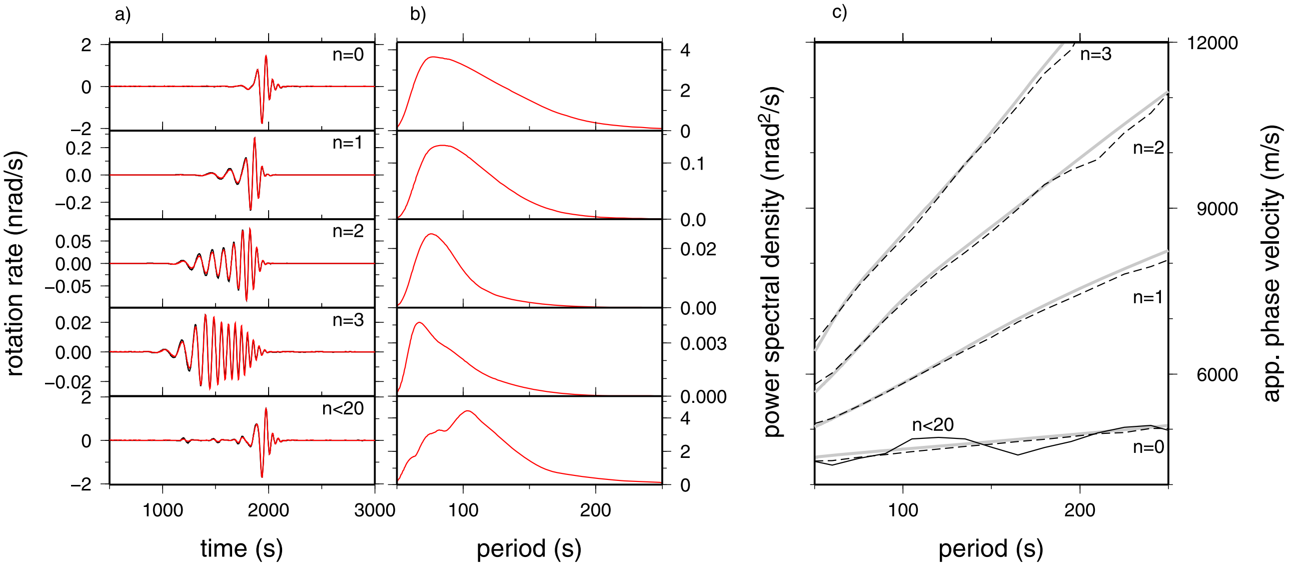

Figure 3. Effect of higher modes on estimated Love wave dispersion curves. (a) Synthetic seismograms computed by summation of toroidal modes. Shown are transverse acceleration (black) and vertical rotation rate (red) for single mode branches ($0 \leq n \leq 3$) and for all modes with $n < 20$. All seismograms are computed for the $M_W = 7.4$ Kurile Islands event on Jan 15, 2009, recorded at the station WET. (b) Power spectral density of rotation rate shown in Figure 3a. (c) Dispersion curves determined from amplitude ratios of transverse acceleration and rotation rate. For $n = 0$, $n = 1$, $n = 2$ and $n = 3$, the dispersion curves (dashed) are close to the theoretical ones (gray), for the full seismogram (black solid line), significant fluctuations are observed.

structural inversion. Instead, an inversion based on the full waveforms as proposed by *Bernauer et al.* [2009] might be a promising alternative.

5. Conclusions

[18] We examined the possibility of estimating Love wave dispersion curves using amplitude ratios between transverse acceleration and vertical rotation rate. Measurements at the geodetic observatory Wettzell show that this is possible in principle, given seismograms with a high signal-to-noise ratio. However, as for all applications using measurements of surface wave amplitudes, the accuracy is rather poor. Based on synthetic seismograms computed by normal mode summation, we showed that even in the ideal case of noise-free seismograms the results deviate significantly from the underlying 1D reference Earth model PREM. These differences are due to the superposition of fundamental and higher mode surface waves and are sufficient to make the results unsuitable for a subsequent structural inversion. Thus, for a joint inversion of rotation and translation measurements, it is necessary to take the full waveforms into account.

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