Unraveling overtone interferences in Love-wave phase velocity measurements by radon transform

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SUMMARY
Surface waves contain fundamental mode and higher modes, which could interfere with each other. If different modes are not properly separated, the inverted Earth structures using surface waves could be biased. In this study, we apply linear radon transform (LRT) to synthetic seismograms and real seismograms from the USArray to demonstrate the effectiveness of LRT in separating fundamental-mode Love waves from higher modes. Analysis on synthetic seismograms shows that two-station measurements on reconstructed data obtained after mode separation can completely retrieve the fundamental-mode Love-wave phase velocities. Results on USArray data show that higher mode contamination effects reach up to ∼10 per cent for two-station measurements of Love waves, while two-station measurements on mode-separated data obtained by LRT are very close to the predicted values from a global dispersion model of GDM52, demonstrating that the contamination of overtones on fundamental-mode Love-wave phase velocity measurements is effectively mitigated by the LRT method and accurate fundamental-mode Love-wave phase velocities can be measured.

Key words: Surface waves and free oscillations; Seismic tomography; Computational seismology.

1 INTRODUCTION
Surface waves propagate along the shallow depth of the Earth with energy penetrating into the Earth’s crust and mantle, and are particularly useful for imaging crustal and upper mantle structures. Surface waves at different periods are sensitive to the Earth’s structures at different depths with longer period surface waves sensitive to greater depths, resulting in observed dispersion in surface-wave propagation. Generally, surface waves, including both Rayleigh and Love waves, contain fundamental mode and higher modes, which could interfere with each other. Different modes of surface waves have completely different sensitivities to the Earth’s structures. If they are not properly separated, the inverted Earth structures using surface waves could be biased.

Most surface-wave tomography studies use dispersion curves of fundamental mode in imaging because the fundamental modes of both Rayleigh and Love waves usually have much stronger energy than higher modes and dominate seismograms. One challenge in surface-wave tomography is to accurately measure the fundamental-mode phase velocities and avoid the contamination by overtones. Because energy of fundamental-mode Rayleigh waves often dominates seismograms and their group velocity dispersion curve is completely separated from overtone dispersion curves, fundamental-mode and overtone Rayleigh waves usually tend to be well separated in vertical- and radial-component seismograms in regional and continental scale studies. However, the situation is different for Love waves. The group velocities of fundamental-mode and overtone Love waves are very close to each other (Fig. 1); and fundamental-mode and overtone Love waves severely interfere with each other, especially for waves propagating through ocean basins (e.g. Thatcher & Brune 1969; Forsyth 1975; Nettles & Dziewoński 2011).

Recent studies (e.g. Nettles & Dziewoński 2011; Foster et al. 2014b) have shown that, although predicted errors from overtone interference in single-station fundamental-mode Love-wave phase velocity measurements are less than 1 per cent, errors of contamination are much larger in two-station and array-based measurements: up to ∼10 per cent for two-station measurements and ∼20 per cent for array-based measurements (Foster et al. 2014b). These large errors are induced because two-station and array-based measurements are obtained from differential measurements of individual single-station measurements over short distances and errors caused
by overtone contaminations are expected to be magnified in two-station/array-based phase velocity measurements. The large errors are present in all array-based methods if the fundamental modes are not properly separated from higher modes (Foster et al. 2014b).

In the past two decades, more and more regional arrays are deployed around the world to image high-resolution regional-scale lithosphere structures, and seismologists are measuring fundamental-mode phase velocities from both Rayleigh and Love waves using two-station and array-based methods and combining them to invert for anisotropy of lithosphere. Several methods have been used to reduce the effect of overtone interference (e.g. Cara 1973; Forsyth 1975; Herrin & Goforth 1977, 1979; Okal & Jo 1987; Montagner & Tanimoto 1991; Stutzmann & Montagner 1993; Trampert & Woodhouse 1995, 1996, 2001, 2003; van Heijst & Woodhouse 1997, 1999; Montagner 2002; Yoshizawa & Kennett 2002; Beucler et al. 2003; Lebedev et al. 2005; Beucler & Montagner 2006; Visser et al. 2007, 2008); the concepts of these methods have been well summarized by Foster et al. (2014b). However, to date, few methods are effective in separating fundamental-mode Love waves from higher modes in two-station and array-based measurements due to the overlap of group velocities at intermediate and long periods (~20 to ~100 s).

In this study, we present a method which applies high-resolution linear radon transform (LRT) to telesismic surface waves to separate fundamental-mode Love waves from higher modes. We analyse both synthetic seismograms and observed seismograms from the USArray to demonstrate the effectiveness of our method in mitigating overtone interferences in two-station measurements.

2 METHOD

Due to overlapped group velocities of fundamental-mode and overtone Love waves, one cannot directly inspect and separate the fundamental mode from overtones in time domain. However, we can recognize and pick different modes in its period–phase-velocity (p–v) domain because the fundamental mode and overtones of Love waves have separated phase velocity dispersion branches (Fig. 1a). It is possible to reduce overtone contamination if we can transform seismograms in time domain to the p–v domain and then isolate different modes in the p–v domain and re-transform them back to the time domain.

Luo et al. (2008, 2009) has developed a method to image Rayleigh-wave dispersive energy and separate multimode Rayleigh waves from a multichannel record by high-resolution LRT in near-surface applications. In this study, we apply the LRT to intermediate- and long-period Love waves that are used to constrain lithospheric structures.

The forward LRT maps the radon panel $\mathbf{m}$ (in the frequency–slowness (f–s) domain) into the data space $\mathbf{d}$ (seismograms in the frequency–epicentral distance (f–x) domain) under the action of the operator $L = e^{i2\pi/p\cdot\mathbf{x}}$,

$$\mathbf{d} = L\mathbf{m}$$

(1)

in which $p$ is the slowness ($p_{\text{min}}$ and $p_{\text{max}}$ being the range of slowness values investigated), and $x$ is the epicentral distance between source and station ($x_{\text{min}}$ and $x_{\text{max}}$ being the epicentral distance range). Casting the radon transform as an inversion problem, $\mathbf{m}$ can be obtained by choosing an L1 norm for the model and an L2 norm for the data misfit. So $\mathbf{m}$ can be defined by solving the system of equation (Trad et al. 2002, 2003):

$$\left(\mathbf{W}_m^T L^T \mathbf{W}_d \mathbf{W}_d^T \mathbf{W}_m^T + \lambda I\right) \mathbf{W}_m \mathbf{m} = \mathbf{W}_m^T L^T \mathbf{W}_d \mathbf{d}$$

(2)

where $I$ denotes the identity matrix, $\mathbf{W}_d$ is a matrix of data weights, $\mathbf{W}_m$ is a matrix of model weights, and $\lambda$ is the trade-off parameter that controls balance between data misfit and model constraints. Small $\lambda$ will allow minimum data misfit $\left\| \mathbf{W}_d (\mathbf{d} - L \mathbf{W}_m^T \mathbf{W}_m \mathbf{m}) \right\|^2$, and large one will allow smoothness model $\left\| \mathbf{W}_m \mathbf{m} \right\|^2$. Eq. (2) can be solved very efficiently by conjugate gradient (CG) algorithm (e.g. Sacchi & Porsani 1999; Trad et al. 2002, 2003). Although LRT has been widely applied to high-frequency industry seismic data, Wilson & Guittin (2007) have demonstrated that this method can also be applied to teleseismic data and there are no fundamental differences between low-frequency and high-frequency applications.

The processing flow of LRT includes the following two steps. First, we image dispersive energy by high-resolution LRT. We select seismograms from a common earthquake and recorded by a number of stations with their propagating great-circle paths all falling in a small (3° in this study) azimuthal bin. According to eq. (1), we transform the seismograms in time domain to the frequency domain and set the slowness $p$ ranging from 0.2 to 0.4 s km$^{-1}$ (equivalent phase velocity from 2.5 to 5 km s$^{-1}$). LRT is performed for each
frequency slice using a weighted preconditioned CG algorithm following eq. (2). After that, we obtain the radon panel in the $f-s$ domain. Linear interpolation is used to transform the radon panel from the $f-s$ domain to the $p-v$ domain. At least six stations are required in imaging dispersive energy by LRT (Dal Moro et al. 2003; Luo et al. 2008). Second, we perform mode separation. The energy of fundamental mode is selected manually and the rest energy is muted in the $p-v$ domain, leaving the radon panel only containing the fundamental mode of surface waves. Then, we apply the forward radon operator to the radon panel that only contains the fundamental-mode surface waves and finally obtain seismograms only containing fundamental-mode surface waves.

3 APPLICATION TO SYNTHETIC DATA

To demonstrate the effectiveness of LRT in separating fundamental-mode Love waves from higher modes, we first apply this method to synthetic Love waves at 20–150 s periods in which period band Love waves are most sensitive to crustal and upper mantle structures and have the severest interferences between the fundamental mode and higher modes.

To generate synthetic Love waves, we choose a model for a typical oceanic plate, similar to the one used by Nettles & Dziewoński (2011), because the fundamental-mode and higher mode Love waves propagating across a oceanic plate have overlapped group velocities as shown in Fig. 1. The oceanic-plate model is designed as one having a type A0 crust (Mooney et al. 1998; Bassin et al. 2000) underlain by a mantle of the Preliminary Reference Earth Model (PREM; Dziewoński & Anderson 1981). The calculated Love-wave phase and group velocity dispersion curves for this model are shown in Fig. 1. In 25–80 s period range, the fundamental-mode and higher mode group velocities overlap with each other, leading to strong-mode interference between fundamental-mode and higher mode Love waves.

We compute synthetic seismograms by normal-mode summation (Gilbert & Dziewoński 1975) for surface waves which are emitted by a shallow strike-slip earthquake and propagate through the oceanic-plate model. A Love-wave seismogram can be represented as a sum of $N$ dispersed surface-wave mode branches ($n = 0, 1, 2, \ldots, N$). Synthetic seismograms are computed using the program of Modal Summation from the package of Computer Programs in Seismology (Herrmann & Ammon 2004). The selected receivers, from which synthetic seismograms are obtained, are located along a great-circle path and have the corresponding epicentral distances ranging from 20° to 150° and a 0.5° interval in the direction of maximum Love-wave radiation. Two Love-wave synthetic data sets are computed: one with only the fundamental mode and the other including fundamental and the first four higher modes, with the amplitude ratio of 1:0.6:0.3:0.3:0.3 between those five modes. Two examples of synthetic seismograms are plotted in Fig. 2(b), and a record section of all synthesized data is plotted in Fig. 2(c). Clear interference between those five modes can be noted from the differences of waveforms for these two data sets (Fig. 2(b)).

We apply the LRT to those synthetic seismograms containing both fundamental mode and four overtones to obtain dispersive energy in the $p-v$ domain, which is plotted in Fig. 2(a). Clear energy of fundamental mode and four overtones are seen in the $p-v$ domain with the phase velocity dispersion curves well separated from each other. To isolate the fundamental mode, we manually select the fundamental-mode dispersive energy in a corridor outlined by the red dashed lines in Fig. 2(a) and mute the rest energy (Fig. 2a), leaving the radon panel only containing the fundamental-mode Love waves. We then apply the forward LRT (eq. 1) to the radon panel to reconstruct the fundamental-mode Love waves. Two examples of the reconstructed seismograms after model separation are plotted against the synthetic seismograms of fundamental Love waves for comparison in Fig. 2(b). Apparently, the reconstructed seismograms are almost exactly the same as those fundamental-mode synthetic seismograms, indicating that the LRT works perfectly in separating the fundamental mode from higher modes for synthetic data.

Furthermore, we use a two-station method (e.g. Yao et al. 2006) to measure the interstation phase velocities between a pair of stations. For the two-station method to work, we ensure the earthquake and the station pairs are approximately aligned in a same great-circle path (less than 3° in azimuth) to cancel the effects of both the source and structures outside the station pairs on the traveltime difference. The interstation phase velocity is obtained by calculating $C(T) = \Delta D/\Delta t(T)$, where $C(T)$ is the phase velocity at period $T$, $\Delta D$ is interstation distance and $\Delta t(T)$ is the interstation phase traveltime difference that is estimated from cross-correlation of narrow bandpass filtered waveforms at a central period $T$. Fig. 2(d) shows the results of the two-station phase velocity measurements for the two synthetic data sets and the reconstructed seismograms obtained after mode separation at 75 s period, plotted as deviations from the theoretical fundamental-mode Love-wave phase velocities (black line in Fig. 1a) as a function of the epicentral distance of the two-station midpoint. The two-station measurements on the synthetic fundamental-mode-only seismograms show very small deviations (<0.02 per cent) from the theoretical value. The interference from higher modes could either delay or advance the apparent phase velocity of the fundamental mode, thus introducing oscillating pattern of phase velocity deviations (Boore 1969). The two-station measurements on the synthetic seismograms that have both fundamental mode and four higher modes show oscillating deviations. The deviations vary from −16.3 per cent to 15.2 per cent for 75 s Love waves, reflecting severe overtone interference in measuring fundamental-mode Love-wave phase velocities. The two-station measurements on the reconstructed seismograms after model separation are very close to the theoretical fundamental-mode phase velocities, indicating that overtone interference on fundamental-mode Love waves can be perfectly mitigated after mode separation by high-resolution LRT.

4 APPLICATION TO USARRAY DATA

Having applied LRT to synthetic data, in this section, we further demonstrate the effectiveness of this method in separating fundamental-mode Love waves from higher modes by applying this method to real Love waves recorded by USArray.

For demonstration, we select three teleseismic events (Fig. 3a) with surface-wave magnitudes larger than 5.0 and epicentral distances from 35° to 65° relative to the stations we select from USArray. We collect the two horizontal components of seismograms recorded by USArray and then rotate them to the transverse and radial components. We isolate Love-wave seismograms from the transverse components using a time window of Love waves defined by group velocities of 3–6 km s$^{-1}$. At last, the mean, trend, and instrument responses are removed from the seismograms. We use the same two-station method as used for the synthetic data to measure interstation phase velocities. Because the two-station method is based on the principle that the two stations and the event must align nearly along a common great-circle path, we only select those
station pairs with the differences of their azimuth angles smaller than 3° and their interstation distances ranging from 350 to 750 km.

To investigate the overtone interference, we compare two-station phase velocity measurements, including two sets of measurements obtained from Love waves before and after LRT mode separation, respectively, with those phase velocities calculated from the Global Dispersion Model GDM52 (Ekström 2011). The GDM52 is a model of global dispersion maps for fundamental-mode Rayleigh and Love waves in a period range of 25 to 250 s. The data used in constructing this model are collected from globally distributed seismic stations and earthquakes. As demonstrated by Foster et al. (2014b), overtone contaminations on the single-station measurements of fundamental-mode Love waves are typically oscillating in the range of ±1 percent and are averaged out in tomography with measurements from various paths with different epicentral distances, that is, the global Love-wave dispersion maps of the GDM52 model are almost free of overtone contaminations. Thus, if the fundamental-mode dispersion curves of Love waves measured from USArray data are accurate, these measurements should be close to the reference values from GDM52.

We apply the LRT to the transverse components of seismograms to separate the fundamental-mode Love waves as we do for the synthetic seismograms and then measure the interstation phase velocities using the two-station method. To visualize the effectiveness of LRT in separating fundamental-mode Love waves from higher modes, as an example, we plot the dispersive energy in the $p$–$v$ domain in Fig. 3(e) for Event C as we do for the synthetic data in Fig. 2(a). Clear energy of fundamental mode and overtones is seen in the $p$–$v$ domain (Fig. 3(e)) with their phase velocity dispersion curves separated from each other. Love-wave seismograms before and after mode separation are plotted together in Fig. 3(f) for comparison for two examples from stations TA-F12A and TA-B11A. Large differences of waveform between original waveform and fundamental-mode Love waves are observed, indicating strong interferences of fundamental mode and higher modes.

Figs 3(b)–(d) show the two-station phase velocity measurements for all selected station pairs with and without the mode separation, plotted as deviations from the reference values from GDM52. We only plot the deviations at certain periods (34 s for Event A, Fig. 3b; 30 s for Event B, Fig. 3c; 70 s for Event C, Fig. 3d) where
Figure 3. Two-station phase velocity measurements of original (black cross) and mode-separated (blue diamond) Love waves for three selected teleseismic events. The selected stations of USArray for two-station measurements are colour coded for the three events and plotted in (a). The two-station measurements for event A, B and C are plotted as a function of the epicentral distances of two-station midpoints in (b), (c) and (d), respectively. The measurements are plotted as deviations relative to the interstation phase velocities predicted from GDM52. The interstation distances of these two-station measurements range from 350 to 750 km. (e) Dispersive energy of Event C in the $p$–$\nu$ domain. The dispersive energy is constructed by high-resolution LRT for Love waves recorded by the TA stations shown as blue in (a). The two red dashed lines outline the energy range of the selected fundamental mode. (f) Comparison of seismograms (filtered in the period band from 25 to 80 s) between original waveforms (in black) and reconstructed fundamental-mode waveforms (in red) for two examples recorded at stations TA-F12A and TA-B11A.
the fundamental-mode Love waves are most severely contaminated by higher modes. Two-station phase velocity measurements from the original Love waves without mode separation scatter around the reference values roughly within ±10 per cent range. The ranges of deviations are similar to those two-station measurements shown by Foster et al. (2014b), which is believed to be caused by contamination of higher modes.

Love-wave phase velocity deviations could be also caused by other factors, including off-great-circle propagation (Alsina et al. 1993; Foster et al. 2014a) and finite-frequency propagation effects (e.g. de Vos et al. 2013). Foster et al. (2014a) have found that, for those events we choose in this study, the errors of phase velocities at 15–100 s periods caused by the deviations from the off-great-circle propagation fall in the range ±1 per cent, which is consistent with the results of Alsina et al. (1993) for surface waves traveling through oceanic paths into European continents. Regarding finite-frequency effects, De Vos et al. (2013) have indicated that, for two-station phase velocity measurements, although sensitivity along the interstation path is dominant, there is still considerable sensitivity far outside the interstation path. Furthermore, they suggest that, in order for the two-station method to work, one needs to only choose those station pairs for which there are no strong anomalies at the regions located outside the interstation paths but close to the station with shorter epicentral distance. In this study, three chosen oceanic events first pass through oceanic plates and then propagate into the US continent where phase velocity anomalies at our interested periods (34 s for Event A; 30 s for Event B; 70 s for Event C) are small, about only 5 per cent according to Jin & Gaherty (2015). Thus, we consider that the finite-frequency effect outside the interstation path on the phase velocity measurements should be much smaller than the observed 10 per cent deviations. Thus, we consider that the large deviations are mainly caused by contamination by higher modes, which is expected for Love waves propagating through oceanic plates and testified by the dramatic reduction of deviations after mode separation.

After LRT is applied to separating the fundamental mode from overtones, the two-station phase velocity measurements from the reconstructed seismograms are very close to the reference values. The deviations mostly vary in the ±1 per cent ranges (Fig. 3). The means of deviations are only 0.60 per cent, 0.74 per cent and 0.72 per cent with standard deviations of 0.26 per cent, 0.43 per cent and 0.32 per cent for the three chosen events, respectively. These small differences are reasonable and could be caused by the presence of small-scale phase velocity heterogeneities which are not well mapped in the GDM52 model based on globally distributed stations and earthquakes, or the off-great-circle path propagation and finite-frequency effect which are not taken into account in our calculation.

Overall, the strong reduction of deviations of these two-station measurements relative to GDM52 after mode separation again demonstrates the effectiveness of LRT in separating fundamental-mode Love waves from higher modes.

5 DISCUSSION AND CONCLUSIONS

Love-wave seismograms often contain both fundamental mode and higher modes. Measurements of fundamental-mode Love-wave phase velocities are affected by the presence of overtones. In these cases, seismograms need to be inspected prior to the analysis and desired mode of surface waves need to be separated before measuring phase velocities. Because group velocities of fundamental-mode Love waves and overtones overlap at certain period ranges, it is impossible to separate them in time domain. This study has demonstrated that by converting time domain seismograms to the p–v domain using radon transformation, we can recognize and pick different modes because phase velocity dispersion curves of different modes are separated from each other (Fig. 1a). Furthermore, we can isolate the fundamental mode out and then accurately measure fundamental-mode Love-wave phase velocities, mitigating the overtone interference in Love-wave tomography.

It should also be mentioned that properly constructing and separating fundamental-mode surface waves in the radon panel of the p–v domain is the key step in performing mode separation. In constructing the p–v domain, seismograms collected from a number of stations for each event must have similar propagation characteristics. This requirement is apparently satisfied for a group of stations located in a small region and recording teleseismic events. However, in some circumstances where there are very strong horizontal and/or vertical velocity variations, phase velocities of different surface-wave modes could overlap and interfere with each other in the p–v domain so that it is difficult to separate fundamental-mode surface waves from seismograms by high-resolution LRT. Even though these cases are rare in regional surface-wave tomography using teleseismic events, great efforts should be taken to examine dispersion curves of different modes and S-wave velocity structures to properly carry out mode separation.

In this paper, although we only demonstrate the effectiveness of LRT in separating fundamental-mode Love waves using two-station method, LRT can also be applied to array-based measurements. The principle of applying LRT to a seismic array is similar to the application to the two-station measurements. For example, for a large seismic array like USArray, we can first divide the large array to a series of mini arrays with several hundred kilometre aperture, and then apply LRT to surface waves recorded at each mini array to separate the fundamental mode because teleseismic surface waves recorded in a mini array have similar propagation paths and meet the requirement for LRT.

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REFERENCES


