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A new approach for surface wave tomography I: theory

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Most studies of regional surface wave tomography have been based on two-stage inversion processes (e.g., partitioned waveform inversion). The first stage of such an approach is to invert waveforms for path-average 1-D models, although such 1-D models tend to suffer from the non-uniqueness; i.e., several different models can give comparable levels of waveform fit. However, even if the 1-D models differ, the multi-mode phase speeds estimated from such different 1-D models are quite similar as long as the waveforms are fitted well. This is mainly due to the fact that the phase speeds are represented through a depth integral. Working with such robust information of multi-mode phase speeds as a function of frequency rather than with 1-D models themselves, we propose an alternative multi-stage approach for reconstructing 3-D images of the upper mantle from surface wave inversion based on three separate inversion processes.

In the first stage, multi-mode phase speeds of surface waves are measured from waveform fitting or using any other convenient estimator of surface wave dispersion for each path; e.g., direct dispersion measurements for the fundamental mode and the mode stripping technique for the higher modes.

In the second stage, multi-mode phase dispersion maps are obtained by the iterative use of linear inversions for dispersion maps. First, the multi-mode dispersion maps are obtained from the conventional ray theory with the great-circle approximation. Then, they are updated iteratively incorporating with finite-frequency effects of surface wave propagation including the deviation of surface wave paths from the great-circle. The influence zone associated with finite frequency surface waves can be obtained using Fresnel-area ray tracing. With careful consideration of the stationary-phase field around a path, we have defined the influence zone for surface wave paths as 1/3 of the width of the first Fresnel zone, in which surface waves are coherent in phase; i.e., we can not distinguish phases between different paths within the zone. Therefore we can regard an observed phase speed as an average speed within this influence zone. We can thus efficiently treat the effects of finite frequency of surface waves for each mode in the phase speed models. Azimuthal anisotropy for each mode as a function of frequency can also be extracted from the measured phase speed at this stage.

In the third stage, employing a set of local 1-D inversions for the local shear wavespeed structure and anisotropy, 3-D shear wavespeed structure can finally be recovered from the local dispersion curves assembled from the multi-mode phase speed maps.

The advantage of this three-stage approach is that different styles of information can be brought together in the same framework. Thus multi-mode dispersion, finite-frequency effects and polarisation anomalies of surface waves can be incorporated simultaneously and efficiently to constrain the 3-D Earth model, by working with multi-mode phase speed maps as a function of frequency. The new approach can be applied to both regional- and global-scale inversions and allows the extension of surface wave tomography to regions where wavespeed contrasts are large.