A Fast and Reliable Method for Surface Wave Tomography

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Abstract—We describe a method to invert regional or global scale surface-wave group or phase-velocity measurements to estimate 2-D models of the distribution and strength of isotropic and azimuthally anisotropic velocity variations. Such maps have at least two purposes in monitoring the nuclear Comprehensive Test-Ban Treaty (CTBT): (1) They can be used as data to estimate the shear velocity of the crust and uppermost mantle and topography on internal interfaces which are important in event location, and (2) they can be used to estimate surface-wave travel-time correction surfaces to be used in phase-matched filters designed to extract low signal-to-noise surface-wave packets.

The purpose of this paper is to describe one useful path through the large number of options available in an inversion of surface-wave data. Our method appears to provide robust and reliable dispersion maps on both global and regional scales. The technique we describe has a number of features that have motivated its development and commend its use: (1) It is developed in a spherical geometry; (2) the region of inference is defined by an arbitrary simple closed curve so that the method works equally well on local, regional, or global scales; (3) spatial smoothness and model amplitude constraints can be applied simultaneously; (4) the selection of model regularization and the smoothing parameters is highly flexible which allows for the assessment of the effect of variations in these parameters; (5) the method allows for the simultaneous estimation of spatial resolution and amplitude bias of the images; and (6) the method optionally allows for the estimation of azimuthal anisotropy.

We present examples of the application of this technique to observed surface-wave group and phase velocities globally and regionally across Eurasia and Antarctica.

Key words: Surface waves, group velocity, tomography, seismic anisotropy.

1. Introduction

We present and discuss a method to invert surface-wave dispersion measurements (frequency-dependent group or phase velocity) on regional or global scales to produce two-dimensional (2-D) isotropic and azimuthally anisotropic maps of surface-wave velocities. Such “tomographic” maps represent a local spatial average of the phase or group velocity at each location on the map and summarize large volumes of surface-wave dispersion information in a form that is both useful and easily transportable. Dispersion information in this form can be applied naturally to a number of problems relevant to monitoring the nuclear Comprehensive Test-Ban

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Treaty (CTBT); For example, (1) to create phase-matched filters (e.g., Herrin and Goforth, 1977; Russell et al., 1988; Leach et al., 1998; Levshin and Ritzwoller, 2001, this volume) designed to detect weak surface-wave signals immersed in ambient and signal-generated noise as a basis for spectral amplitude measurements essential to discriminate explosions from earthquakes (e.g., Stevens and Day, 1985; Stevens and McLoughlin, 1997) and (2) in inversions to estimate the shear-velocity structure of the crust and upper mantle (e.g., Villasenor et al., 2001) which is useful to improve regional event locations. The method we discuss here is designed to produce accurate and detailed regional surface-wave maps efficiently and reliably, as well as to provide information about the quality of the maps. The method may be applied, perhaps with a few extensions, to other 2-D inverse problems such as $P_n$ and $S_n$ tomography (e.g., Levshin et al., 2001).

We note, as a preface to further discussion, that the relationship between observed seismic waveforms and an earth model is not linear. Thus, the problem of using surface-wave data to constrain the structure of the crust and upper mantle is nonlinear. In surface-wave inversions, however, the inverse problem is typically divided into two parts: A nearly linear part to estimate 2-D dispersion maps and a nonlinear part in which the dispersion maps are used to infer earth structure. It is the nearly linear part that we call surface-wave tomography and that is the subject of this paper. Some surface-wave inversion methods linearize the relation between the seismic waveforms and an earth model (e.g., Nolet, 1987; Snieder, 1988; Marquering et al., 1996) and iteratively estimate the earth model. Therefore, these methods do not estimate dispersion maps on the way to constructing structural models. We take the path through the dispersion maps for the following reasons.

- Surface-wave dispersion maps, like a seismic model, summarize large volumes of data in a compact form, but remain closer to the data than the models.
- They are less prone to subjective decisions made during inversion and contain fewer assumptions (both hidden and explicit).
- Because of the foregoing, dispersion maps are more likely than models to be consumed and utilized by other researchers.
- Dispersion maps are directly applicable to detect and extract surface waves from potentially noisy records, which is important in discriminating explosions from earthquakes for CTBT monitoring.

On the negative side, dispersion maps contain only part of the information concerning earth structure in the seismogram, are the products of inversions themselves, and contain uncertainties due to both observational and theoretical errors.

There are a number of surface-wave tomographic techniques currently in use by several research groups around the world. These techniques differ in geometry (i.e., Cartesian versus spherical), model parameterization (e.g., global versus local basis functions), certain theoretical assumptions (particularly about wave paths and scattering), the regularization scheme, and whether azimuthal anisotropy can be estimated simultaneously with the isotropic velocities. Because surface-wave tomo-