Physics of the Earth and Planetary Interiors 270 (2017) 168–175

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Short-period surface-wave phase velocities across the conterminous United States

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ARTICLE INFO

Article history:
Received 7 June 2017
Received in revised form 24 July 2017
Accepted 25 July 2017
Available online 26 July 2017

Keywords:
Surface-wave dispersion
Noise tomography
Earth's crust

ABSTRACT

Surface-wave phase-velocity maps for the full footprint of the USArray Transportable Array (TA) across the conterminous United States are developed and tested. Three-component, long-period continuous seismograms recorded on more than 1800 seismometers, most of which were deployed for 18 months or longer, are processed using a noise cross-correlation technique to derive inter-station Love and Rayleigh dispersion curves at periods between 5 and 40 s. The phase-velocity measurements are quality controlled using an automated algorithm and then used in inversions for Love and Rayleigh phase-velocity models at discrete periods on a 0.25°-by-0.25° pixel grid. The robustness of the results is examined using comparisons of maps derived from subsets of the data. A winter–summer division of the cross-correlation data results in small model differences, indicating relatively minor sensitivity of the results to seasonal variations in the distribution of noise sources. Division of the dispersion data based on inter-station azimuth does not result in geographically coherent model differences, suggesting that azimuthal anisotropy at the regional scale is weak compared with variations in isotropic velocities and does not substantially influence the results for isotropic velocities. The phase-velocity maps and dispersion measurements are documented and made available as data products of the 10-year-long USArray TA deployment.

1. Introduction

In early October, 2013, the final station of the USArray Transportable Array (TA) was installed in eastern Maine, to complete the TA footprint in the conterminous US. Approximately two years later, in late 2015, the stations of the easternmost and final swath of the initial TA deployment were removed. This completed the 10-year-long data-collection phase of the first TA experiment, with the second experiment now underway with station deployments across the state of Alaska.

The TA data set, covering the lower 48 states of the United States on a uniform grid of approximately ~70 km station separation and with nearly two-year-long station deployments, has proved remarkably rich, and has facilitated a wide range of seismological investigations of seismic sources, seismic wave propagation, Earth structure, and additional topics. Elucidating the structure and evolution of the North American continent was the main research focus put forward in the early USArray community-planning documents (Ekström et al., 1998; Levander et al., 1999; Meltzer et al., 1999) and this objective was reiterated and expanded on in the 2010 EarthScope Science Plan (Williams et al., 2010). The number of articles exploiting the USArray TA data set to this end has grown rapidly during the progression of the array across the continent. A 2014 special issue of *Earth and Planetary Science Letters* (Long et al., 2014) provides a good sample of the research sparked by the USArray TA, and many of the studies reported there and other investigations are ongoing.

While a primary seismological goal of USArray is a fully 3-D description of the elastic and anelastic structure of the North American continent, it has been recognized since the early days of planning the project that intermediate research results in the form of well-documented measurements and less-complex models, such as 2-D phase-velocity maps and 1-D local velocity profiles, are of great value (e.g., IRIS, 2005). The importance of these 'data products' is that, while there may be disagreements between researchers about the best way to parameterize and derive a 3-D model of the Earth, agreement may be found around underlying observations and simpler parameterized models derived from well-documented observations. Agreement between data products provides a level of validation of data and methods that is useful for supporting the adoption of large and diverse observations and low-level models in the derivation of more complex 3-D models.

In this paper, I report on the completion of an investigation of short-period Love and Rayleigh wave propagation across the footprint of the TA, and present the corresponding data products,

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http://dx.doi.org/10.1016/j.pepi.2017.07.010
0031-9201/

consisting of dispersion measurements and isotropic phase-velocity maps. The work presented here is an extension of research based on TA data recorded through 2012 described in an earlier study (Ekström, 2014). Preliminary data products were presented in the earlier paper. The analysis and data products presented here include three additional years of TA data, mainly from stations in the easternmost US as well as in southeastern Canada.

The technique used in this paper to derive surface-wave phase-velocity measurements is based on the cross-correlation of continuous seismic noise recorded on a pair of stations. The noise cross-correlation approach, pioneered in seismology by Aki (1957), has been implemented in a number of algorithms by different authors (e.g. Shapiro et al., 2005; Bensen et al., 2007), and has been applied successfully in dozens of papers to subsets of the TA data set (e.g. Lin et al., 2008). The algorithm used in this study has been described previously (Ekström et al., 2009; Ekström, 2014), and its relationship to other implementations is also discussed in these earlier papers.

The focus of the current paper is a new, complete set of Love and Rayleigh phase-velocity maps for the conterminous US derived using the approach described by Ekström (2014). For completeness, the key elements of the methods are summarized in Section 2 of the paper. Section 3 presents the data selection and the results of the inversions for isotropic phase-velocity maps. In Section 4, I present and discuss results from three experiments aimed at exploring the robustness of the phase-velocity maps, and especially the biases that may exist as the result of unaccounted-for complexity of the background noise field and of unmodeled azimuthal anisotropy of the Earth. Section 5 provides a description of the data products resulting from this research, and conclusions.

2. Summary of methods

The processing and analysis occurs in four steps. In the first step, continuous long-period seismograms from the USArray TA and additional stations are cross-correlated in 4-h-long time segments to form normalized cross-correlation spectra $\rho_{ijk}(\omega)$, where i and j are station indices and k is a time-segment index. The normalized cross-correlation spectra are summed to form stacked spectra,

$$\rho^S_{ij}(\omega) = \sum_{k=1}^{N_{ij}} \rho_{ijk}(\omega), \tag{1}$$

where N_{ij} is the total number of 4-h-long records available for a station pair (typically around 3000), and $\rho^S_{ij}(\omega)$ is the stack.

The second and third steps of the analysis build on the spectral approach of Aki (1957). In his formulation, the observed cross-correlation spectra are compared with the theoretical expression for the cross correlation of data from two stations in an isotropic surface-wave noise field,

$$\bar{\rho}(r, \omega_0) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right), \tag{2}$$

where $\bar{\rho}(r, \omega_0)$ is the cross correlation, r is the receiver separation, J_0 is the Bessel function of the first kind and zeroth order, and $c(\omega_0)$ is the phase velocity between the receivers at frequency ω_0. In the second step, the zero crossings of the real part of the stacked cross-correlation spectra are identified using a simple algorithm. In the third step, the observed zero crossings are associated with specific zeros of the Bessel function, leading to corresponding phase-velocity estimates,

$$c(\omega^Z_n) = \frac{\omega^Z_n r}{z_m}, \tag{3}$$

where z_m is the mth zero of the Bessel function, and ω^Z_n is the frequency of the nth observed zero of the cross-correlation function. Most of the complexity of the algorithm is related to making correct associations of observed zeros with zeros of the Bessel function and eliminating unreliable observations. Once a sequence of zeros has been associated, the discrete $c(\omega^Z_n)$ are joined to define a dispersion curve.

In a small modification to the approach of Ekström (2014), in which Eq. (2) was used for determining phase velocities associated with zero crossings not only for the vertical component but also for the transverse component, I here instead use the corresponding expression derived for Love and Rayleigh wave motion recorded on horizontal components (Aki, 1957; Haney et al., 2012),

$$\bar{\rho}_H(r, \omega_0) = \frac{1}{2} J_0\left(\frac{\omega_0}{c(\omega_0)} r\right) - \frac{1}{2} J_2\left(\frac{\omega_0}{c(\omega_0)} r\right), \tag{4}$$

where $\bar{\rho}_H$ denotes a horizontal-component cross-correlation function, and J_2 is the Bessel function of the first kind and second order. As $-J_2$ asymptotically approaches J_0 for large values of the argument, this modification is not expected to have a large effect on the results. As discussed below, maps obtained using Eqs. (2) and (4) are, indeed, nearly indistinguishable.

In the fourth step of the analysis, the dispersion curve is interpolated at discrete periods and the phase velocity is rewritten as an observed travel time, $\tau_{ij} = \frac{X_{ij}}{c_{ij}}$, where X_{ij} is the distance between stations i and j, c_{ij} is the measured phase velocity, and τ_{ij} is the corresponding travel time. The travel times are then used to map the geographic variations of isotropic phase slowness across the footprint of USArray using a parameterization in terms of N latitude–longitude pixels. The model travel times τ^P_{ij} are constructed as

$$\tau^P_{ij} = \sum_n^N X^n_{ij} p_n, \tag{5}$$

where the slowness in each pixel n is p_n, and the fractional path length in each pixel is X^n_{ij}. The data fit is calculated as

$$\chi^2 = \sum_{ij}^K \left(\frac{\tau_{ij} - \tau^P_{ij}}{\sigma_{ij}}\right)^2, \tag{6}$$

where the summation is over the K station pairs ij for which an observation is included at a particular period, and σ_{ij} is an estimate of the observational uncertainty. The best-fitting slowness model is determined by solving the damped least-squares problem

$$\min(\chi^2 + \nu R^2), \tag{7}$$

where R^2 is the roughness of the slowness variations and ν is a smoothing coefficient.

3. Data and results

Data recorded on the TA stations for the period January 2006 through December 2015 were collected and processed. The set of TA stations was augmented by stations of the US National Seismic Network (US), the Caltech Regional Seismic Network (CI), the Berkeley Digital Seismograph Network (BK), the ANZA Regional Network (AZ), the Leo Brady Network (LB), the Western Great Basin/Eastern Sierra Nevada Network (NN), the Lamont-Doherty Cooperative Seismographic Network (LD), and the Global Seismographic Network (IU and II). Data from 33 stations of the Canadian Polaris Network (PO) operating in southeastern Canada were also included. Cross-correlation stacks were calculated for vertical, transverse, and radial components of all station pairs separated by less than 600 km. Dispersion curves were determined and sampled for inter-station travel times at 5, 6, 8, 10, 12, 15, 20, 25, 30,