Final Technical Report

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Title: Applying Ambient Noise Cross-Correlations to Improve Seismic Event Location Capabilities in the Western and Central United States

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Abstract

The purpose of the work is to exploit the legacy of the EarthScope USArray Transportable Array to improve the ability to locate and characterize small earthquakes across the US. In particular, the aim is to apply information from short period surface waves (7-15 s period), which have traditionally not been used to determine seismic locations. The reason for their non-use is that propagation effects on surface waves are large and historically have not been modeled well. Consequently, predictions of arrival times for surface waves have not been accurate enough for surface waves to be useful to constrain locations in the context of regional body waves. This situation has changed with the development of ambient noise tomography, which provides unprecedented information about short period surface wave propagation – notably, group and phase arrival time information for Rayleigh and Love waves from 6 to 40 s period. The specific purposes of the work of this grant were to investigate the application of this emerging information to improve the location capability for small earthquakes in the US, to develop the methods to apply this information, and to advance toward capabilities so that these methods can be introduced into an operational environment at USGS.

The work carried out for this project was broken into three tasks: **Task 1:** re-computation of the ambient cross-correlation data base for the EarthScope Transportable Array and ANSS stations west of -95° longitude in the central and western US; **Task 2**: optimization and documentation of the location method and code based on ambient noise; and **Task 3**: re-locating earthquakes in the central and western US that are part of the North American Moment Tensor project. There are several concrete products delivered to NEIC.

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Task 1. Re-computation of the cross-correlation database

Cross-correlations have been computed between pairs of TA stations, pairs of USArray Backbone stations, and every TA-Backbone pair. Daily cross-correlations are computed for data observed between Apr 1 2005 and Dec 31 2011. There are1298 participating stations that have been operative since Apr 1 2005 to July 1 2011. This number includes 1133 TA stations and 165 Backbone stations. These sets of stations are shown in Figure 1. The cross-correlation data base containing 485,318 cross-correlations, the list of cross-correlations and participating stations, as well as the format description for cross-correlations are in the delivered package. The technique for obtaining cross-correlations is described in detail by Bensen et al. (2007). A user's manual describing the structure of the data base and the means for extracting cross-correlations from it is attached to this report.

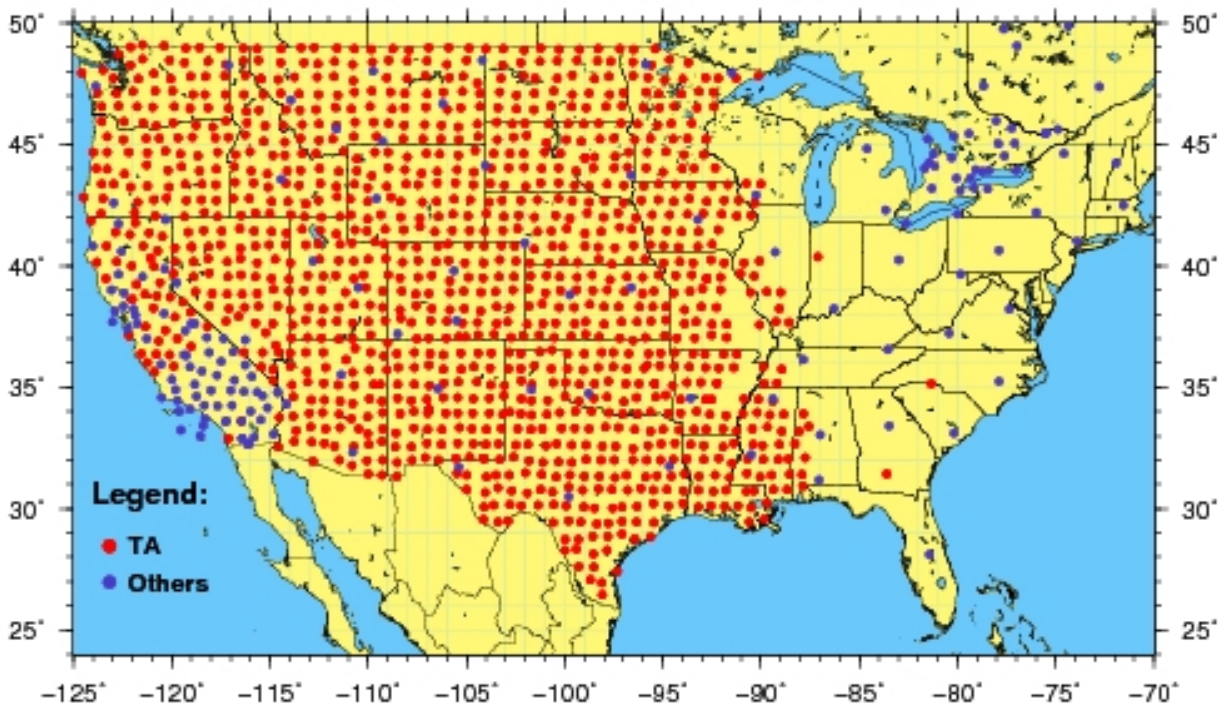

Fig. 1. Locations of ~1300 participating stations.

Task 2. Refining and documenting the location method

We updated and revised the location method and software described in our Proposal and documented the resulting code. Support for the revision of the methodology came from a contract with DoE. A detailed description of the revised algorithm is given in the published paper by Levshin et al. (2012), attached to this report as **Deliverable 3.**

The revised algorithm includes the simultaneous analysis of Rayleigh and Love wave data and by this means provides a smaller bias in location in comparison with use of Rayleigh waves alone. Numerous examples of relocation of events in the western and central US are given in the papers by Levshin et al. (2012) and Ritzwoller et al. (2012). These events occurred in California, Utah, Nevada and Montana. These papers present a more stable algorithm based on comparing the measured group velocity curves from each event and the ambient noise cross-correlation records and extend the method to include Love waves, which we found to be much less liable to yield-biased locations than are Rayleigh waves. Love waves, however, typically are lower SNR observations than Rayleigh waves, and epicentral locations based on Love waves display higher variance than those based on Rayleigh waves. The epicentral locations for shallow crustal events, based on jointly interpreting Rayleigh and Love waves, are preferable to locations based on Rayleigh or Love waves alone. This is because the joint estimator balances the need for low bias and low variance in the location estimate.

The effect of inclusion of Love wave data in the location algorithm can be seen in Table 1 extracted from this paper. The algorithm and corresponding documentation were transferred to Dr. Morgan Moschetti (NEIC),

The further development of location technique using ambient noise information is on the way. It is based on the use of three-dimensional model of the Earth lithosphere obtained by two-dimensional surface wave tomography (see the next section).

Table 1. Locations using Rayleigh(R) waves, Love waves (L), and both waves (RL)

Event	Ref-R (km)	Ref-L (km)	Ref-RL (km)	*Misfit (s)*			*Ellipse (km)*		
				R	*L*	*RL*	*R*	*L*	*RL*
Earthquake, CA	0.7	1.9	0.7	1.2	1.4	1.5	2.6	3.9	2.7
Mine collapse, UT	0.4	0.7	0.7	1.4	1.6	1.4	1.4	1.7	1.2
Earthquake, UT	1.3	0.0	0.4	0.9	1.3	1.3	1.7	3.1	1.7
Wells Event, NV	0.6	1.1	0.6	0.7	1.0	0.9	1.1	1.7	1.1
aftershock#1	0.7	0.7	0.4	0.7	0.9	0.8	1.1	1.4	0.9
aftershock#2	0.4	0.6	0.4	1.0	1.1	1.0	1.8	2.4	1.4
aftershock#3	1.1	0.7	0.7	0.7	0.8	0.7	1.0	1.3	0.8
aftershock#4	0.0	1.0	0.7	0.9	0.8	0.9	1.4	1.4	1.0
aftershock#5	1.2	1.4	1.2	0.8	0.8	0.8	1.4	1.5	1.0
aftershock#6	0.4	1.2	0.7	0.6	0.8	0.8	1.1	1.7	1.1

Here "Ref-R" is the distance between the reference location and the Rayleigh wave location. "Ref-L" is the same but for Love waves. "Ref-RL" is the same but using both types of waves. "Misfit" is the minimum value (sec) of the misfit functionals F_R, F_L, and F_{RL}. "Ellipse" is the length (km) of the semi-major axis of the 95% confidence ellipse. Epicentral grid spacing is 500m for earthquakes and 200m for the Utah mine collapse.

Task 3. Relocating events in the western and central US

Numerous examples of event locations in the western and central US were presented in the papers mentioned above. The procedure presented in these papers may also be performed by comparing theoretical group velocity curves (computed, e.g. from existing group velocity maps or a 3-D model) with the group or phase velocity measurements obtained from the event records. We believe that the current method is preferable because it compares measurements (obtained on ambient noise cross-correlation) with measurements (obtained on event records). However, using curves from existing group (or phase) velocity maps computed from ambient noise tomography (e.g., Moschetti et al., 2007; Yang et al., 2007; Lin et al., 2008; or many others) or from curves predicted from a 3-D model that originated by inverting ambient noise dispersion maps (e.g., Yang et al., 2008; Moschetti et al. 2010ab; Shen et al., 2013ab) would make the algorithm more flexible and provide less biased locations than are Rayleigh waves. We show here an example of

location obtained with use the preliminary version of this algorithm with 1D-regional model (Fig.2) and a 3D-model obtained by the ambient noise tomography (Fig. 3)..

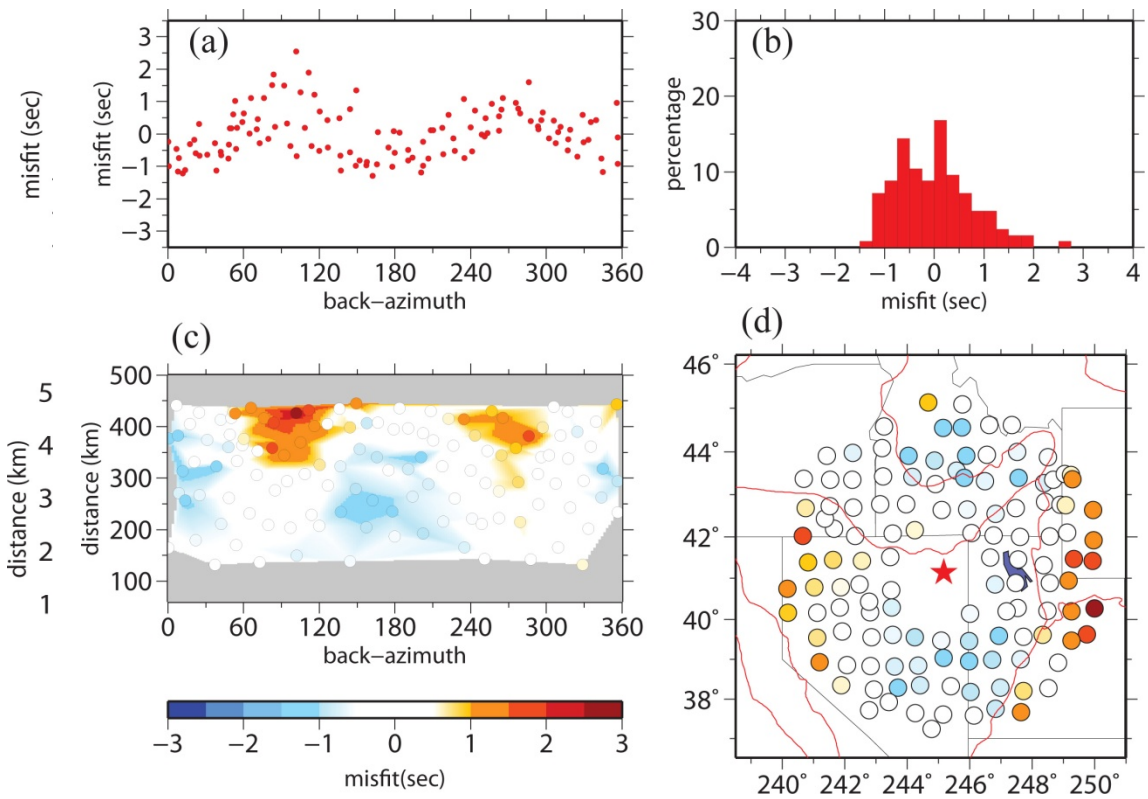

Figure 2. Summary of misfit to observations of phase travel time at 12 sec period observed after the Wells aftershock #4 (Feb 28 2008, M=3.9) using an average 1-D model for the region after correcting for the source mechanism. (a) Misfit at individual stations plotted as a function of azimuth (N=0°, E=90°, etc.). (b) Histogram of misfit (RMS misfit = 0.92 s). (c) Color-coded misfit plotted as a function of back-azimuth and distance. (d) Color-coded misfit plotted at the station locations.

In contrast with Figure 2, an accurate 3-D model allows phase travel times to be fit much more accurately, as Figure 3 illustrates. This will allow better epicentral location estimates based on phase travel times as well as provide better estimates of focal mechanism.

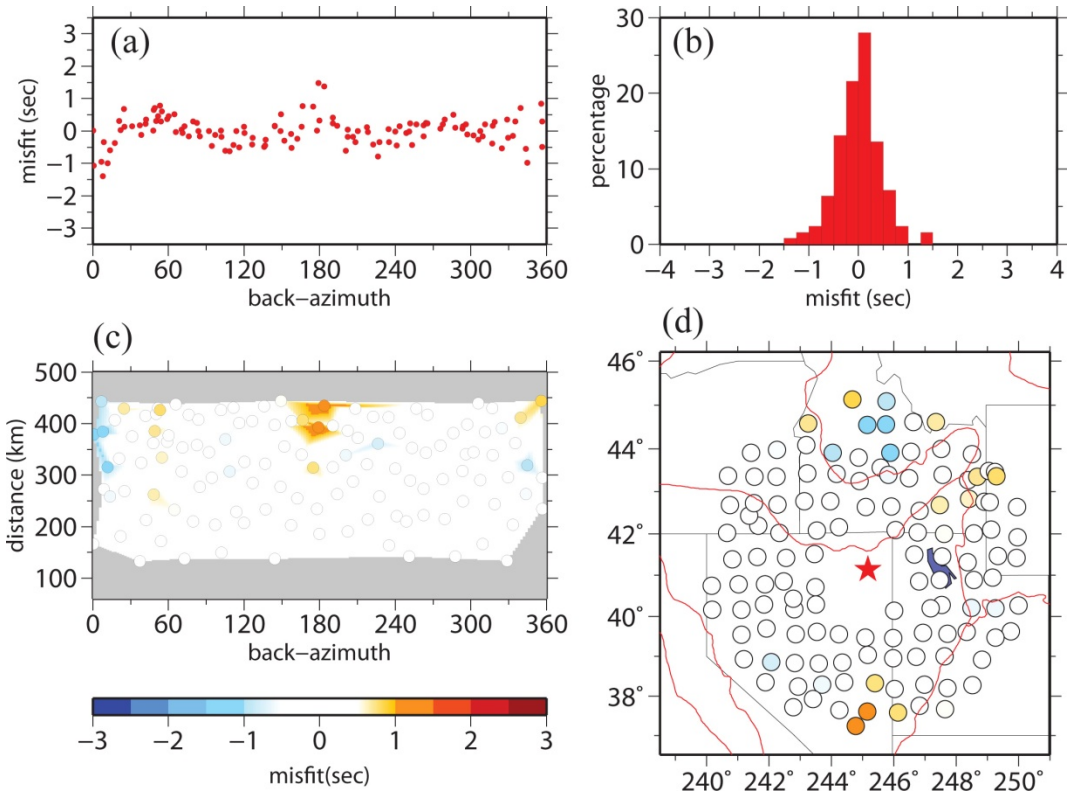

Figure 3. The same as Fig.2, but computed from the 3-D isotropic model of Shen et al. (2012) with the azimuthal anisotropy from Lin et al. (2011). RMS misfit = 0.44s.

This figure demonstrates that the use of a detailed 3D-model obtained from the ambient noise tomography may be successfully used for location of small events within the US covered by USArray.

We are continuing to develop this algorithm of location in combination with the estimation of the source parameters. Due to the revision of the location algorithm, which was approved by Dr. Moschetti, we have changed the sequence of actions, and postponed the test of our revised approach for 140 events mentioned in the work statement.

Conclusions

The described work provides the means to improve the accuracy of location for small events within the US covered by the USArray. As shown by Levshin et al. (2012), the joint use of Rayleigh and Love wave data decreases the bias in location caused by effects of unknown source mechanism and depth. Further development of the location algorithm based on recently developing 3D-models of lithospheric structure obtained from ambient noise tomography (with other data such as receiver functions) by, for example, Shen et al. (2013a,b) with simultaneous determination of source mechanism and depth is in progress and is exceptionally promising.

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Deliverables

We produced three concrete deliverables that have been delivered to NEIC via Dr. Morgan Moschetti, who acts as deliverable coordinator.

Deliverable 1. Cross-correlation database. Deliverable product AMCC_Z_2005-2011-1.0 contains directory COR_2005.4_2011.12 as an ambient noise cross-correlation database and files:

(1) COR_2005.4_2011.12.site: contains site descriptor table.
(2) COR_2005.4_2011.12.ccwfdis: contains cross-correlation descriptor table.
(3) CCManual.pdf: includes format description for database and descriptor tables.
(4) README.

Deliverable 2. Location code with associated documentation. The location code is delivered with full documentation. Note: the current version of the location code, which is based on matching the envelope functions of ambient noise empirical Green's functions to event waveforms, is already running at NEIC in Golden.

Deliverable 3. Re-location catalog and report of re-location test. The paper by Levshin et al., 2012, describing the new algorithm and results of tests for several events at the USA, which has been published in Geophysical Journal International, is considered as our Deliverable 3. This revision in the final deliverable was discussed and approved by Dr. Morgan Moschetti.