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High Resolution Seismic Velocity Structure in the Reno Basin from Ambient Noise Recorded by a Variety of Seismic Instruments

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ABSTRACT

Geothermal prospects may be located in regions characterized by low seismic activity, thus leading to difficulty in estimation of an accurate seismic velocity model. Estimation of velocity models in the upper 5 km of the crust using ambient noise is an inexpensive alternative to active experiments. In the Reno Basin, we are testing a transportable and cost-effective ambient seismic noise processing methodology (when compared to active source experiments) to estimate a high resolution shallow seismic velocity model.

A gap exists for demonstrated extraction of Green's Functions (with Rayleigh waves as the most prominent arrivals) from ambient noise between short and long inter-station distances. In other words, noise-extracted Rayleigh waves are currently sampling less than 0.2 km from the surface, or more than 10 km deep. Also, recent studies demonstrate that ambient noise is effective in exploration seismology for retrieving first-arrival reflections. However, this possibility was not yet demonstrated for inter-station distance larger than several tens on meters. We investigate the possibility of extraction of first arrival reflections and of surface waves from ambient noise Green's Functions (GF's). For this purpose, we use a variety of available instruments in a 60 km x 60 km area in the Reno Basin and innovative adaptations of array and network signal processing techniques.

We investigate recovery of GF's from ambient noise for pairs of different instruments: 1) digital narrow-band seismometer recordings (for instance, S-13 seismometer), 2) analog narrow-band seismometer recordings, digitized after transmission, 3) digital accelerometer recordings; 4) digital broadband instruments, including USArray stations and 5) seismic exploration geophones. Each of these instrument classes presents its own problems for GF recovery and requires appropriate processing. We have developed cross-correlation software to take advantage of all types of instruments in our recording archive and thus enlarge the number of paths for which GF's can be recovered. With a set of traditional inversion programs, we invert the Green's functions for seismic velocity structure in the Reno Basin.

Introduction

One of the criteria for successful identification of Engineered Geothermal System (EGS) prospects is estimation of a seismic velocity model with high enough resolution in the upper 5 km, and with less than 5-10 km lateral resolution. Similar velocity model resolution requirements are in place for urban basin velocity models. For example, a high resolution shear-velocity model in the Reno, NV Basin would result in realistic ground-shaking estimates, in understanding of local faults and of the 3-D basin geometry, and would aid in first-response planning. At an EGS prospect site, similar to parts of the Reno – Carson City Basin, velocity-model estimation with traditional methods such as tomography may be difficult due to low seismicity, or non-uniform earthquake distribution. Even using a fairly good seismic event dataset and very good station coverage, current tomographic studies in the Reno Basin (Preston and von Seggern, 2008) do not allow precise control of basin depth, due to low resolution in the upper 3 km.

As an alternative to expensive active-source experiments to estimate higher resolution shear velocity models, we are investigating a transportable and cost-effective methodology, based on ambient seismic noise processing. We aim to estimate high resolution shear velocity models from 200 m to 5 km depth and we use the Reno Basin as study area. Ambient noise cross-correlation is a relatively new technique (Campillo and Paul, 2003; Lobkis and Weaver, 2001; Larosse et al., 2005; Weaver and Lobkis, 2004). Noise is processed at all frequencies, starting with the high range (MHz), to 7-15 second period microseisms, for inter-station distance respectively from millimeters to hundreds of km. This technique is based on the theoretical result which states that if A and B are two passive sensors (seismic stations), the Green's Function (GF), or the signal that B would receive when A is given an impulsive excitation, can be recovered from the temporal cross-correlation of incoherent noise received at A and B.

Amongst the challenges in developing our non-invasive exploration technique, several are listed below. First, we demonstrate that extraction of Rayleigh waves from the GF's is possible for sub-optimum instruments such as narrow-band seismometers,

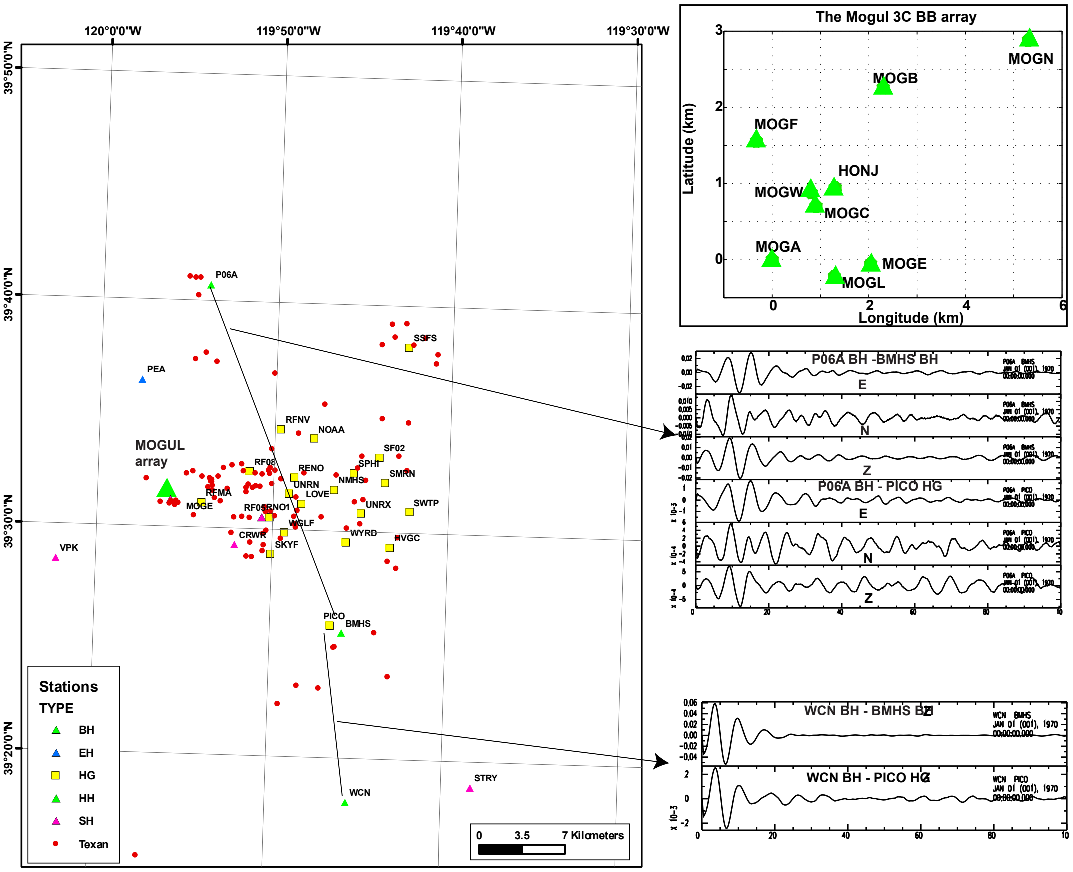


Figure 1. The left plot shows a local map of permanent stations (BH broadband, EH digital short-period, HG accelerometer, HH high sample rate broadband, SH short-period analog); of 2008 temporary "Texan" stations (red dots) and a map of the RAMP deployment (green triangle in the left plot and right upper plot) in the Reno Basin area. The right plots show GF's retrieved from 2 years of ambient noise crosscorrrelations for the paths in the left plot. Stations BMHS (BH) and PICO (HG) are ~ 1 km apart. The right plots show that we retrieve similar Green's functions for the vertical (Z) or all three components, E, N, Z, when BMHS and PICO are paired with two broadband instruments (WCN and P06A, BH).

analog-transmission seismometers and accelerometers available in the Reno Basin (Figure 1). Second, we develop appropriate filtering and signal-processing methods to extract information for stations at distances for from hundreds of meters to tens of km. The "rule of thumb" is that the inter-station distance should be at least three times to several tens of times larger than the maximum wavelength of the seismic phases of interest. Also, the depth probed is usually 1/3 of the Rayleigh seismic wavelength. Thus, for example, with group velocity ~3 km/s, three-second period Rayleigh waves sample best 3 km below the surface, and may be observed at stations farther than 27 km apart. Third, we investigate whether autocorrelations of seismic noise can provide structural information beneath the respective station. Finally, we attempt to extract the GF first-arrival reflection component between pairs of seismic exploration geophones (Figure 1, red dots) of a temporary deployment in Reno.

With a set of traditional inversion programs, we further invert the Green's functions for shear-velocity structure in the Reno Basin.

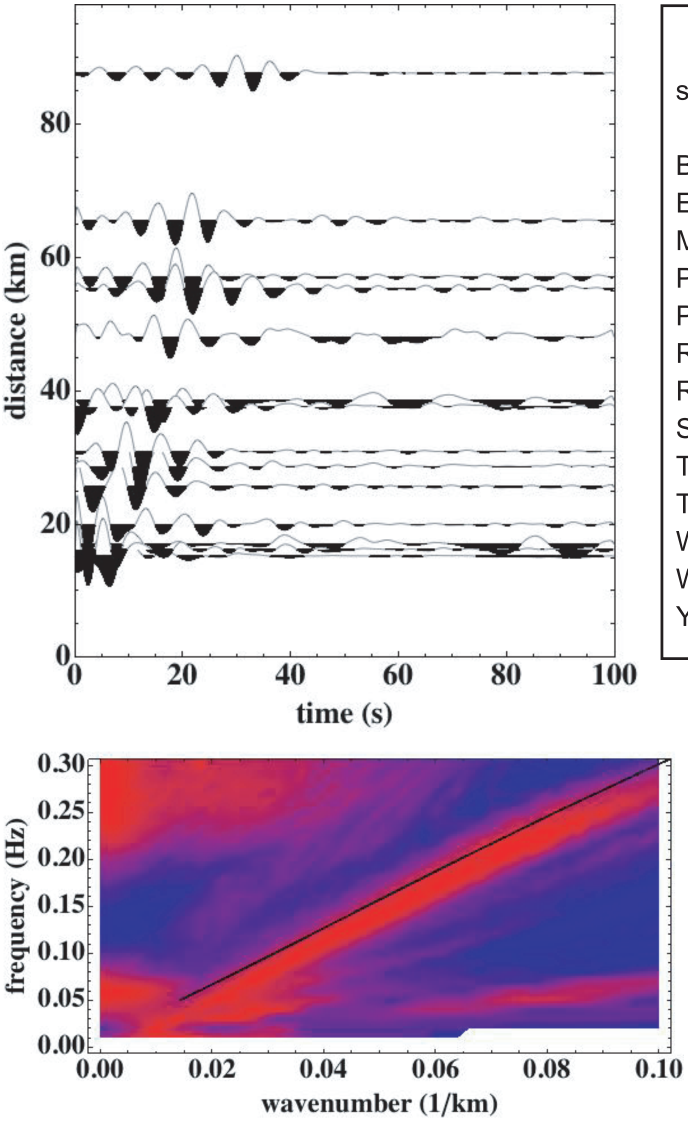
Database

Ambient seismic noise recorded from 2007 to 2009 is processed at permanent and temporary seismic stations in the Reno Basin, including a 10-km aperture accelerometer (HG channels) ANSS array, several digital short period (SP) sensors, several analog – transmission short period sensors (we name "analog") and three broadband (BB) sensors (Figure 1). We also use an array of portable stations (Anderson et al., 2008) installed in Mogul, West Reno to record an earthquake swarm in 2008. The array (~ 2.5 km aperture) included initially four (within 1 km), and ultimately, nine IRIS (Institutions for Research in Seismology) RAMP broadband, three-component stations (Figure 1, right upper inset) These six-component stations included broadband Trillium seismometers and force-balance accelerometers (Episensors). The Mogul stations (Figure 1, upper right inset) recorded continuous waveforms for approximately two months. We also use a "Texan" deployment in Reno (red dots in Figure 1). As described by Dhar et al., 2008, from May 15 to July 15, 2008, ninety Flexible Array single-channel RefTek RT-125A recorders were deployed in Reno and Sparks to record the same Mogul sequence. Five deployments (106 locations) consisted of groups of vertical 4.5-Hz, leveled geophones continuously recording for a four-day period.

Results

Extraction of GF's using different instrument pairs. Narrow-band analog recordings typically have a very narrow usable passband, with little accurate measurement of true ground motion at low frequencies (f < 0.2 Hz) and have records often plagued by spikes and dropouts. On narrow-band digital recordings, the combination of the inherent seismometer roll-off at < 1 Hz and of too few counts per volt of seismometer output leads to inadequate measurement of true ground motion at less than 1 Hz. The records are affected by datalogger noise and transmission noise. Yet, in Figure 2 we show that GF's can be recovered on narrow-band records at least in the microseismic frequency band. Using long periods of time (two-three years) and a transformation of the waveforms with a broadband, 0.1 Hz corner-frequency instrument transfer function, we retrieve GF's at distances as short as 15 km.

We have also encouraging results using short-period digital recordings, even though they are predominantly narrow-band



Instruments Used in the Recovery of GF's

station	km from VPK	description
BAB	15.20	NSL analog narrow-band seismometer
EUR	65.53	NSL analog narrow-band seismometer
MPK	19.91	NSL analog narrow-band seismometer
PO6A	25.60	Earthscope broadband seismometer
PNT	57.12	NSL analog narrow-band seismometer
RNO1	17.08	NSL digital narrow-band accelerometer
RUB	48.09	NSL digital narrow-band seismometer
STR Y	38.59	NSL digital narrow-band seismometer
TAH	37.69	NSL analog narrow-band seismometer
TNK	28.67	NSL analog narrow-band seismometer
WCN	30.88	NSL broadband seismometer
WV A	55.34	NSL digital narrow-band seismometer
YER	87.63	NSL digital narrow-band seismometer

Figure 2. Record section (left) of recovered GF's for an analog seismometer (VPK) and the instruments shown in the right inset. Note inter-station distance from 15 to 87 km. The lower plot shows the frequency-wavenumber estimate for the waveforms in the upper right plot. Note good correspondence with the reference dispersion curve (black line) from Priestley and Brune (1988).

(corner frequency >= 1 Hz) with response rapidly decreasing at frequencies lower than 1 Hz.

Investigations using accelerometer recordings (HG channels) have to overcome several obstacles: 1) a very large diurnal drift due to ambient temperature changes; 2) the instrument response discriminates against faithful recording of low-frequency ground motion; 3) removing the instrument response to obtain displacement is not a trivial exercise; 4) accelerometers usually operate in trigger mode; 5) spurious noise. "Good" noise is usually Earth seismic noise, cultural noise and atmospherically induced noise. Unlike BB recordings, the accelerometer recordings are affected by internally generated self-noise (sensor noise). Accelerometer noise might make impossible the recovery of GF's from continuous data without further signal processing. However, in Figure 1, right plots, we show almost identical GF's retrieved for an accelerometer (PICO) paired with two different BB instruments (P06A and WCN), when compared to GF's retrieved from a close (within 1 km) BB instrument (BMHS) paired with P06A and WCN.

The surface wave dispersion curves retrieved from GF's are inverted with a set of traditional inversion programs for shear velocity structure in the Reno Basin.

Ambient noise autocorrelations for P reflection Green's function estimation beneath each station. Continuous waveform autocorrelation may be used to image the individual station substructure. Claerbout (1968) showed that, for a horizontally layered medium, the autocorrelation of the transmission response of a seismic noise source in the subsurface yields the reflection response. Preliminary results using vertical components at temporary BB stations in Mogul, shown in Figure 3, overleaf, indicate that the technique has promise, and, if successfully used here it will provide additional structural information to aid in the analysis and interpretation of other geophysical and geological data.

P reflection Green's function estimation between pairs of seismic stations. Not only the surface-wave portion of the GF can be retrieved from inter-station ambient noise cross-correlation, but also body-wave reflections (primaries as well as multiples) from layer interfaces (Draganov et al., 2007). To retrieve the earth's reflection response from cross-correlations of seismic noise recordings we perform an analysis closely following the study by Draganov et al., 2007. These authors retrieve surface waves by inter-station ambient noise cross-correlation, and extract body-wave reflections (primaries as well as multiples) from layer interfaces. During their experiment, cross-correlation of ten hours of seismic background noise acquired in a quiet desert area resulted in several coherent events (interpreted as reflections), which aligned very well with reflections obtained from an active survey at the same location. In our future investigations we will assess whether an experiment with different instrument

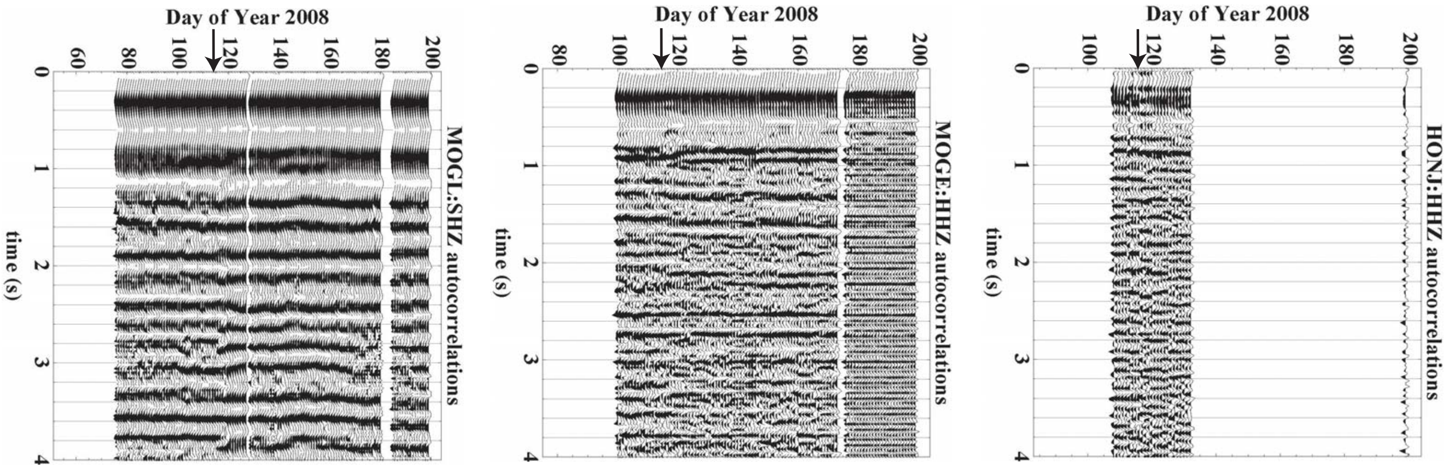


Figure 3. Filtered (one second high pass, zero phase Butterworth) autocorrelation beam displays for three temporary, three- component broadband RAMP stations (MOGE, HONJ and MOGL) near Reno, Nevada, are interpreted as reflections in the crust. The temporary stations were installed ~ 1 km from the Mogul earthquake swarm of 2008. Autocorrelations are estimated in one hour intervals with a method similar to one developed by Bensen et al., 2008. Each vertical trace shows the average autocorrelation for one day. A layer ~2 km thick, present for MOGE and MOGL stations, with ~4 km/s P velocity, is considered responsible for the reflection at one-second time lag. The existence of this layer is also suggested by independent measurements. Note that changes in the auto correlation (not yet understood) occur during the 5.0 Mw main shock of the sequence, on day 117 (black arrows). We interpret the strong reflection patterns as a result of a great amount of seismic energy released during the earthquake swarm.

geometry (inter-station separation of the order of km versus tens of meters in the Draganov et al., 2007) and different analysis time span (several days of continuous Texan recordings as opposed to ten hours in the same study) will produce the same successful outcome. Retrieved seismic reflection data sets will be processed with John Louie's open-source JRG system for seismic research (www.seismo.unr.edu/jrg).

Conclusions and Future Investigations

We have encouraging results in testing a transportable and cost-effective ambient seismic noise processing methodology to estimate a high resolution shallow (< 5 km deep) seismic velocity model. We have demonstrated extraction of surface waves from ambient noise GF's and extraction of P-reflection GF beneath each station. The next stage of our investigations will be related to extraction of P reflection Green's function estimation between pairs of seismic stations, using the Texan deployment in the Reno Basin.

References

Anderson, J. G., I. Tibuleac, R. Anooshehpoor, G. Biasi and K. Smith (2008), Ground Motions Recorded During the 26 April, 2008, MW=5.0 Earthquake in Mogul, Nevada, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract S53C-04.

Bensen, G.D., M.H. Ritzwoller, M.P. Barmin, A.L. Levshin, F. Lin, M.P. Moschetti, N.M. Shapiro, and Y. Yang, Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, Geophys. J. Int., 169, 1239-1260, 2007.

Campillo, M. and A. Paul, 2003. Long-Range correlations in the diffuse seismic coda, Science, 229, 547-549.

Dhar, M, S., Thompson M., Kell-Hills A., Louie J. N., Smith K. D., Tirabassi J., Tom S. and Irwin T (2008), Educating a Community Impacted by an Earthquake Swarm: 106 Volunteers Host Earthscope Flexible Array Recorders During the Mogul, Nevada sequence, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract PA13B-1342 1340h

Draganov, D., K. Wapenaar, W. Mulder, J. Singer and A. Verdel, 2007. Retrieval of reflections from seismic background noise measurements, Geophys. Res.Lett. **34,** L04305, doi:10.1029/2005GL028735.

Larose, E., A. Derode, D. Clorennec, L. Margerin, and Michel Campillo, 2005. Passive retrieval of Rayleigh waves in disordered elastic media, Phys. Rev. E 72, DOI:10.1103/PhysRevE.72.046607.

Lobkis, O. I. and R. L., Weaver, 2001. On the emergence of the Green's function in the correlations of a diffusive field, J. Acoust. Soc. Am., 110, 3011-3017.

Preston, L., and D. von Seggern, Joint Seismic Tomography/Location Inversion in the Reno/Carson City Area, Final Report to the National Earthquake Hazard Reduction Program, U. S. Geological Survey Award Number 07HQGR0022, 2008.

Weaver, R. L. and O. I., Lobkis, 2004. Diffuse fields in open systems and the emergence of the Green's function. J. Acoust. Soc. Am., 116, 2731-2734