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Shallow subsurface velocity estimation using traffic noise at Long Beach, CA

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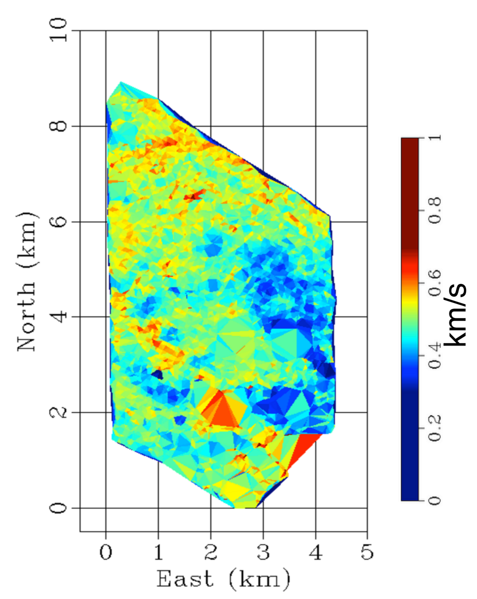
I. Background and motivation

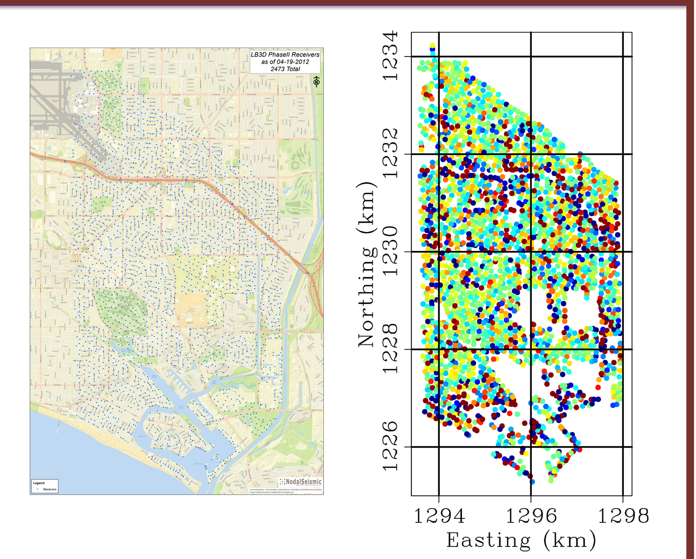
- Identifying shallow subsurface structure is critical to a number of fields:
  - earthquake hazard analysis
  - exploration seismology
- Active-source seismic surveys:
  - expensive to operate
  - not ideal for imaging the near surface
- Advantages of using ambient noise:
  - relatively cheap
  - well-suited for near-surface velocity estimation
- Ambient noise tomography has been most successful in the microseism band
  - *Figure right*: Tomography using ambient noise at 1.25 Hz (Dahlke et al., 2014)



Can we utilize ambient noise at frequencies beyond the microseism band (> 2 Hz) to estimate velocities in the near surface?

II. Long Beach Seismic Array

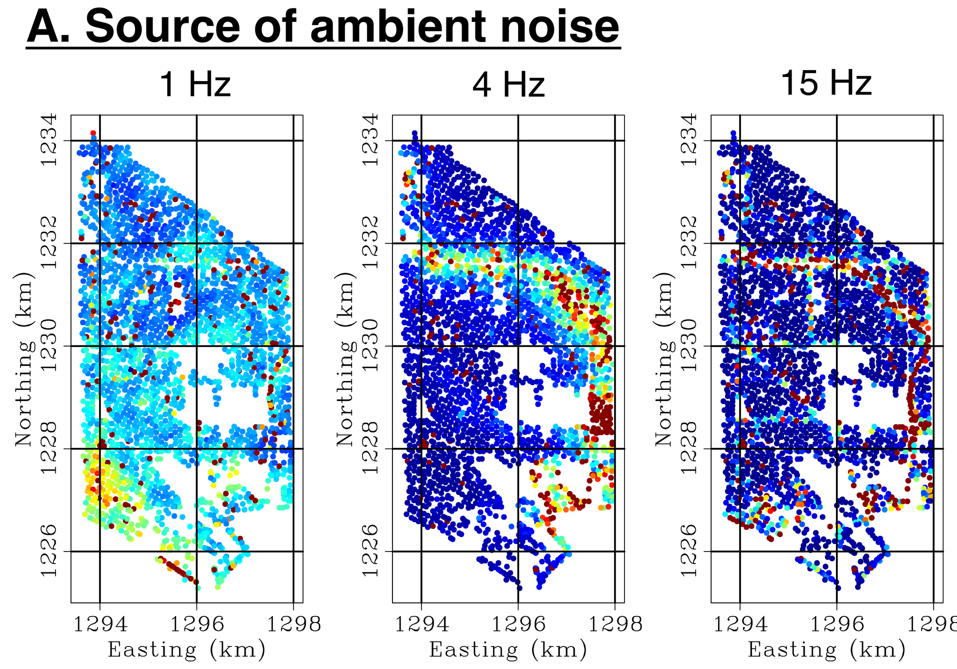
- Deployed in January 2012
- Spatial attributes:
  - 8.5 km x 4.5 km region
  - 2400 vertical geophones
  - 100 m average station spacing
  - *Figure near right*: Layout of array (courtesy of NodalSeismic)
- Temporal attributes:
  - 3 months continuous recording
  - 2 ms sampling rate
  - *Figure far right*: Snapshot of ambient noise data (3-5 Hz)



The size, density, and recording duration of the Long Beach seismic array makes it ideal for passive seismic studies

III. Ambient noise characterization

A. Source of ambient noise

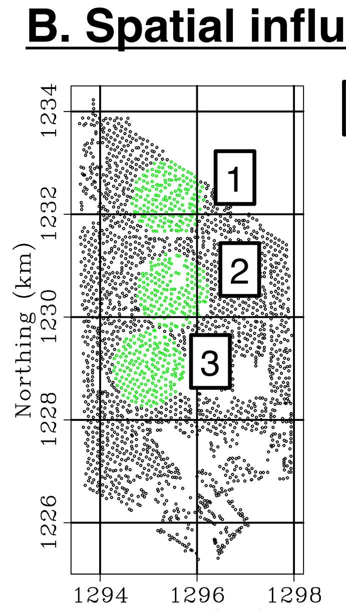


Figures left: Power spectrum plotted at each receiver over different frequencies

Low frequencies: ocean noise

High frequencies: traffic noise

B. Spatial influence of ambient noise at high frequencies



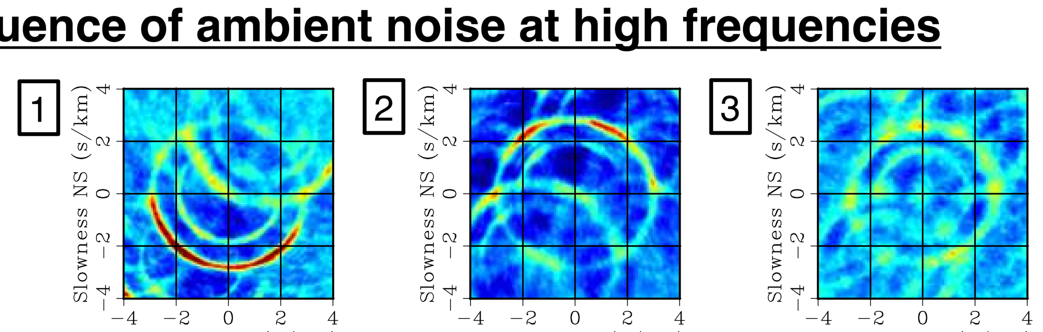


Figure left: Green circles correspond to sub-arrays used for beamforming. Numbers correspond to figures above.

Figures above: Beamforming results on ambient noise (3.5 Hz) for sub-arrays shown in map to the left.

Interstate 405 influential near the interstate; local roads influential away from the interstate (better distributed)

IV. Virtual source method

A. Ambient noise cross-correlation

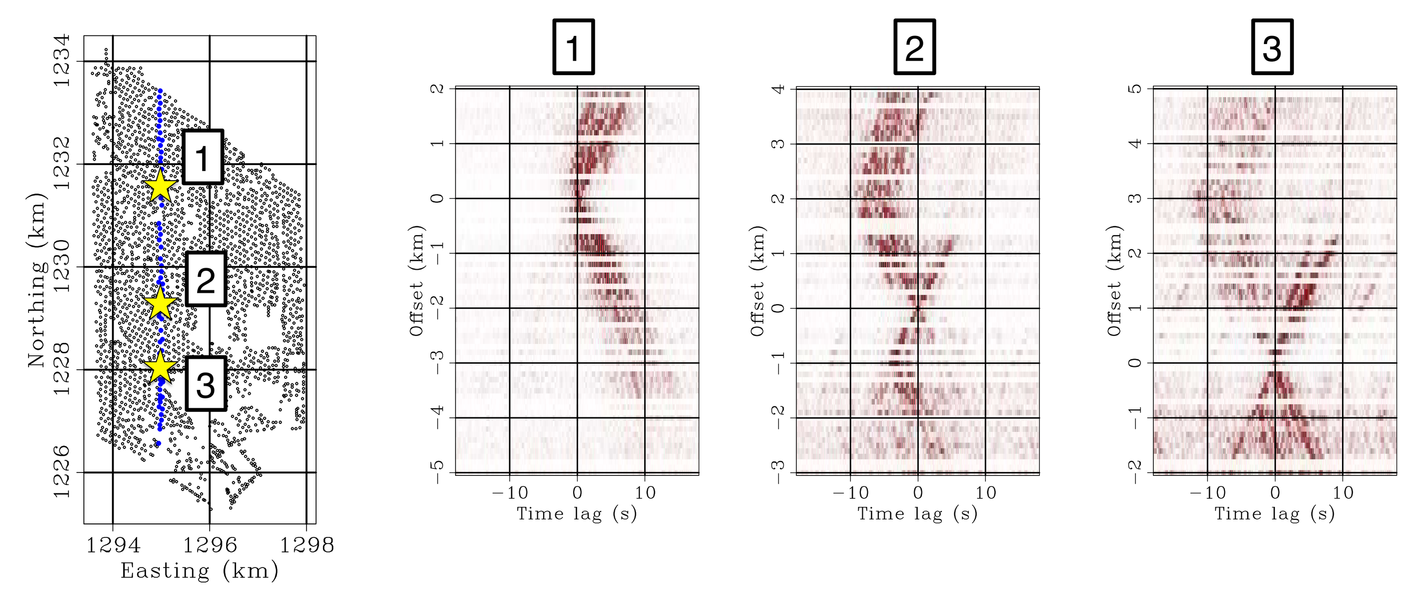
- Compute the averaged whitened coherency (Weemstra et al., 2014)
  - *Equation 1* below
  - Performed on 32 days of continuous data, divided into non-overlapping two-hour time windows

$$[G(x_B,x_A,\omega)+G^*(x_B,x_A,\omega)] \approx \left\langle \left(\frac{U(x_B,\omega)}{\{|U(x_B,\omega)|\}}\right)\left(\frac{U^*(x_A,\omega)}{\{|U(x_A,\omega)|\}}\right)\right\rangle \quad (1)$$

G : Green's function; x : receiver location; ω : frequency; U : spectrum of recorded noise; $*$: complex conjugate; $|\cdot|$: magnitude of spectrum; $\langle\cdot\rangle$: time-averaged ensemble; $\{\cdot\}$: running window average

Cross-correlation of ambient noise simultaneously recorded at two receivers yields an estimate of the Green's function between them

B. Virtual source gathers



Interstate 405 and local roads generate the Rayleigh waves observed in the correlations

Figures above: Virtual source gathers at three different locations (☆) along a receiver line. Correlations are bandpassed for frequencies between 3 and 5 Hz.

V. Group travel time selection

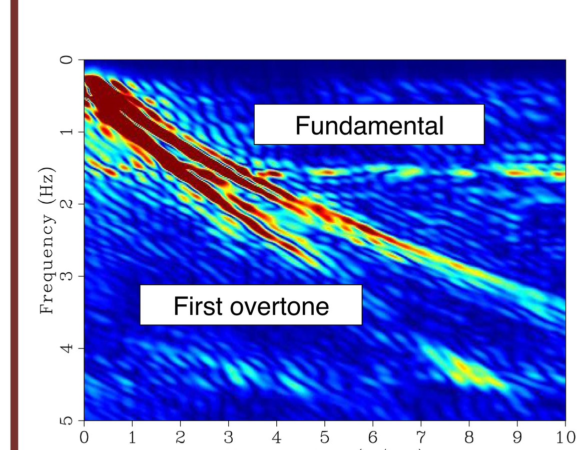
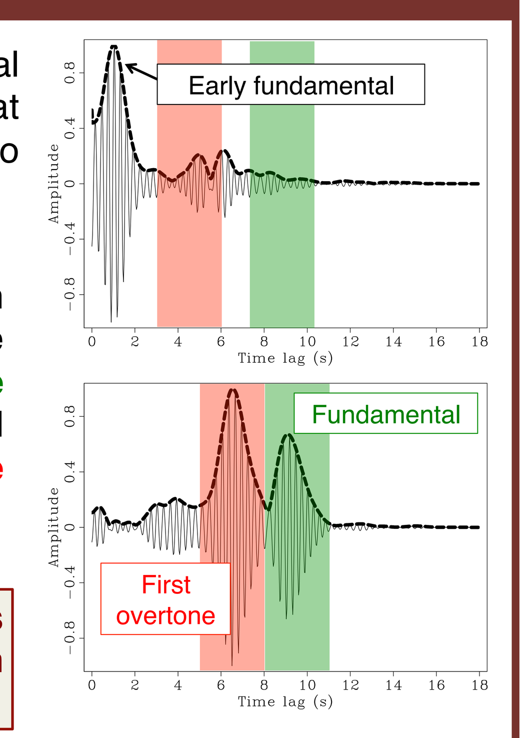
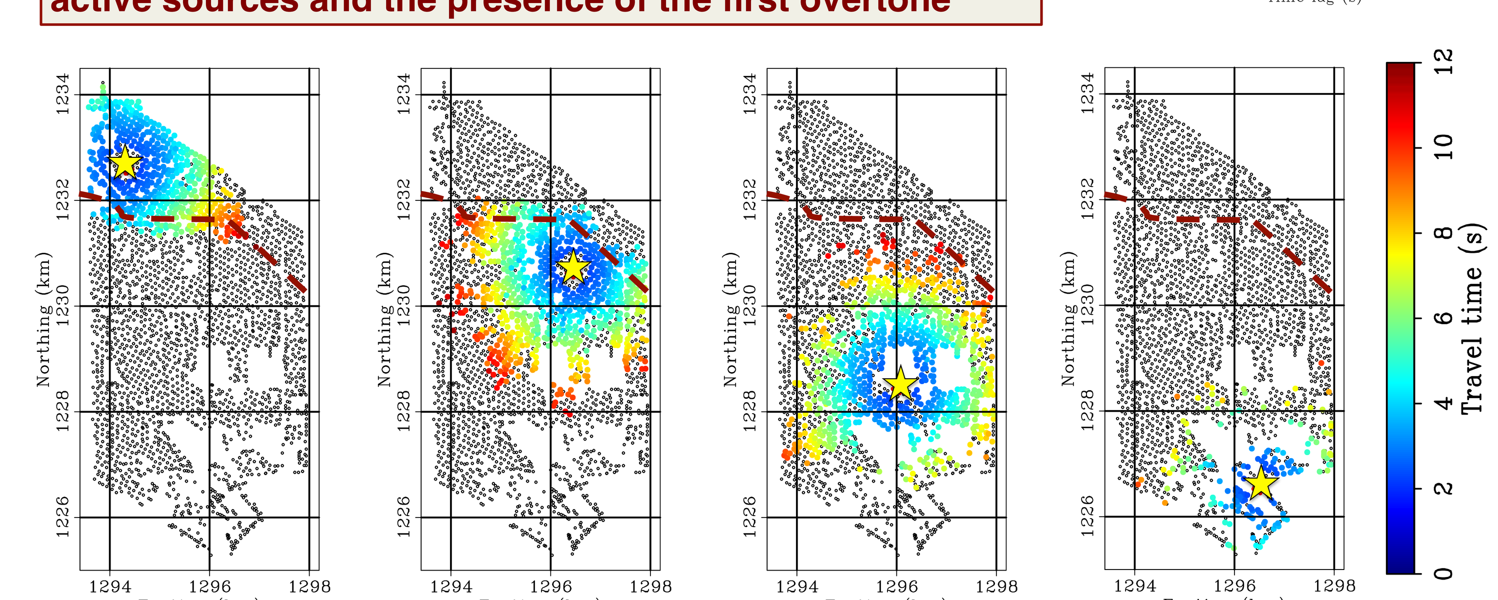


Figure left: FK plot of a virtual source gather centered at Interstate 405 used to estimate apparent velocities.

Figures right: Traces from correlations. Picks are made inside fundamental mode windows. SNR is calculated by ignoring first overtone windows.



Fundamental-mode travel time picks of correlations account for both early arrival times associated with active sources and the presence of the first overtone



Figures above: Travel time maps at four different virtual source locations (☆). Only travel times associated with SNR greater than 5 are shown. Interstate 405 is highlighted in red.

VI. Straight-ray tomography

- Minimize objective function, J, in *Equation 2* in a weighted least-squares sense
  - Employ a conjugate gradient approach
  - Regularization strength, ϵ, determined though an L-curve analysis
  - Weights, $\mathbf{W}$, based on the standard deviation of daily correlation picks

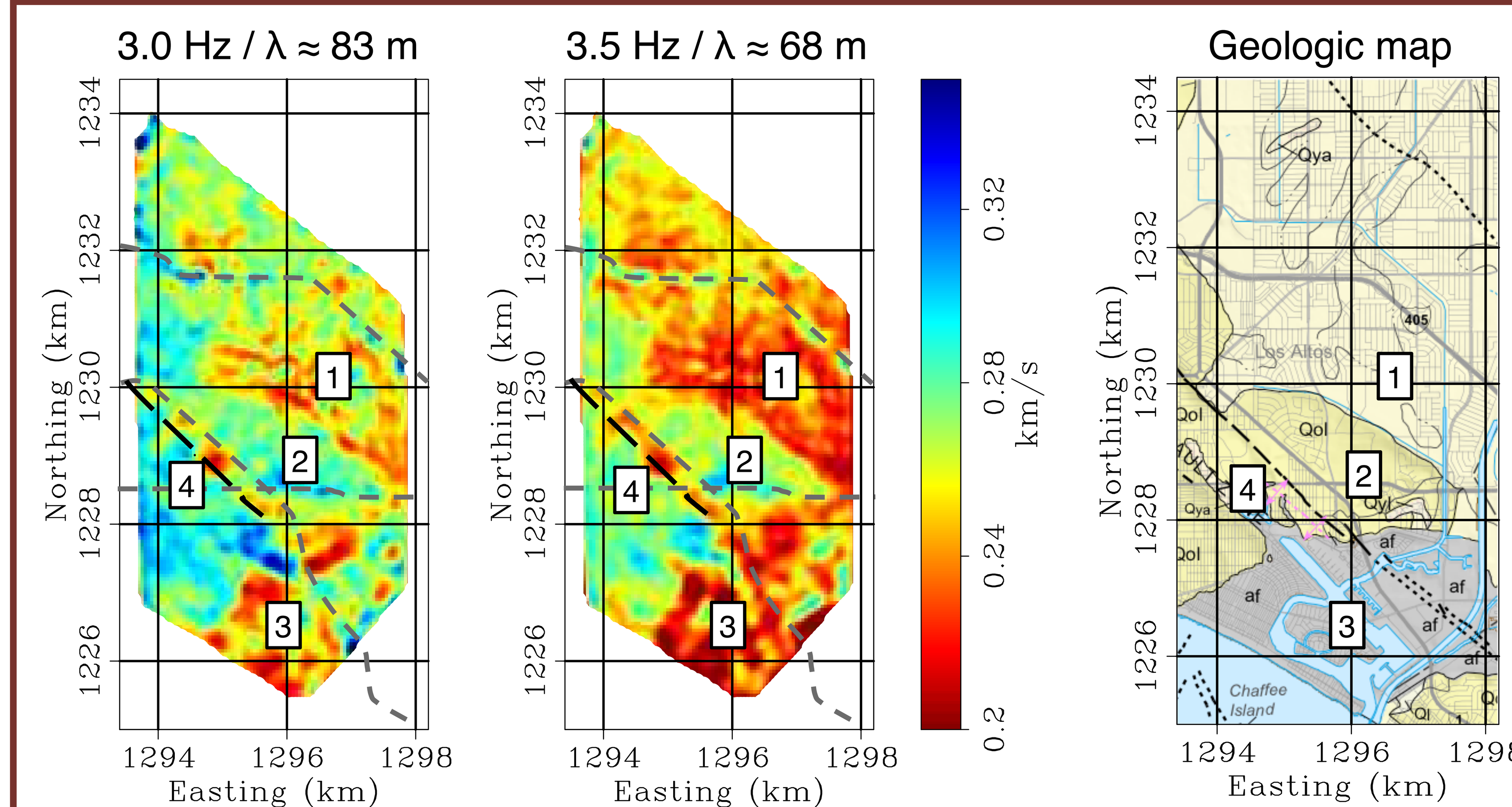
Frequency	3.00 Hz	3.50 Hz
Min. SNR	5	5
Offset range	0.5–1.7 km	0.4–1.5 km
Traces kept (out of 2,890,143)	530,876 (18%)	403,523 (13%)

$$J(\Delta \mathbf{m},\epsilon)=||\mathbf{W}(\mathbf{F}\Delta \mathbf{m}-\Delta \mathbf{t})||_2^2+\epsilon||\nabla^2\Delta \mathbf{m}||_2^2 \quad (2)$$

$\Delta \mathbf{m}$: slowness perturbation; $\mathbf{F}$: straight-ray tomography operator; $\Delta \mathbf{t}$: travel time perturbation; ∇^2 : Laplacian roughening operator

Group velocities tend to show more variation with structure at depth than phase velocities

VII. Group velocity maps



Figures above: Group velocity maps at two frequencies (average wavelengths are also listed). Geologic map of the region is provided for comparison (California Department of Conservation, 2012). Major roads are outlined in grey. The trace of the Newport Inglewood fault is outlined in **black**. Numbers correspond to observations below.

Observations:
(1) Low-velocity zone ←→ Holocene to late Pleistocene alluvial fan deposits (unconsolidated)
(2) High-velocity zone ←→ Late to middle Pleistocene lacustrine deposits (slightly consolidated)
(3) Low-velocity zone ←→ Artificial fill in Alamitos Bay
(4) Low-velocity linear trend ←→ Newport-Inglewood Fault zone

VIII. Conclusions

- Ambient seismic noise field at high frequencies is heavily influenced by traffic noise
- Cross-correlation techniques produce virtual source gathers dominated by traffic-induced Rayleigh waves
- Group velocity maps correlate well with structures outlined in a geologic map of the survey region
- Results suggest that ambient noise tomography can be effective in areas with dense infrastructure
- The demonstrated methodology is both low cost and ideal for continuous monitoring of the near surface

Acknowledgments

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