Authors & Affiliations
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Presentation title

A novel approach to automated, in-field seismic exploration and monitoring via seismic interferometry with ambient noise

Abstract

High-resolution seismic imaging, i.e., "reflection seismology", is traditionally performed by recording artificial seismic sources (e.g., chemical explosions or vibrating plates/Vibroseis) with a dense set of geophones. While the technique is highly successful, it can be expensive, logistically complex, and invasive and, therefore impractical at times. Passive-source seismic interferometry (SI) is a relatively new technique that seeks to determine Earth's impulse response via cross-correlations of ground-motion data recorded at sets of seismic stations using ambient noise to excite ground motions rather than explicit sources. In a typical SI approach, one station serves as a "virtual source" and the others as receivers and the resulting "virtual source gather" that is obtained from the cross-correlation of signals represents the seismic response ("Green's function") of subsurface structure between the two stations.

Ambient noise techniques can be used to obtain waveforms where acquisition using active sources would not be permitted. They can also be used as a low-cost alternative to active-source imaging to, for example, monitor reservoir production, perform time lapse ("4D") passive seismic imaging, CO_2 sequestration surveillance, or assess seismic hazard in densely populated urban areas.

The most common strategies for ambient noise interferometry allow for its application only after the data have been acquired and fieldwork has been completed. This is a disadvantage because the basic principle of SI is stacking of cross-correlations and autocorrelations over a "long enough" time interval, leading to time series that converge to the inter-station Green's function. The optimal length of the recording period depends on the characteristics of ambient noise at the site, which vary over time and are therefore not known beforehand. Data acquisition parameters, including deployment duration, sample interval, plus instrument configuration, spacing, and gain, among other parameters, cannot be planned in ways that will ensure success while minimizing cost and effort. Experiment durations are typically either too long, which renders them more expensive than necessary, or too short, which risks failure to achieve the experiment's objectives.

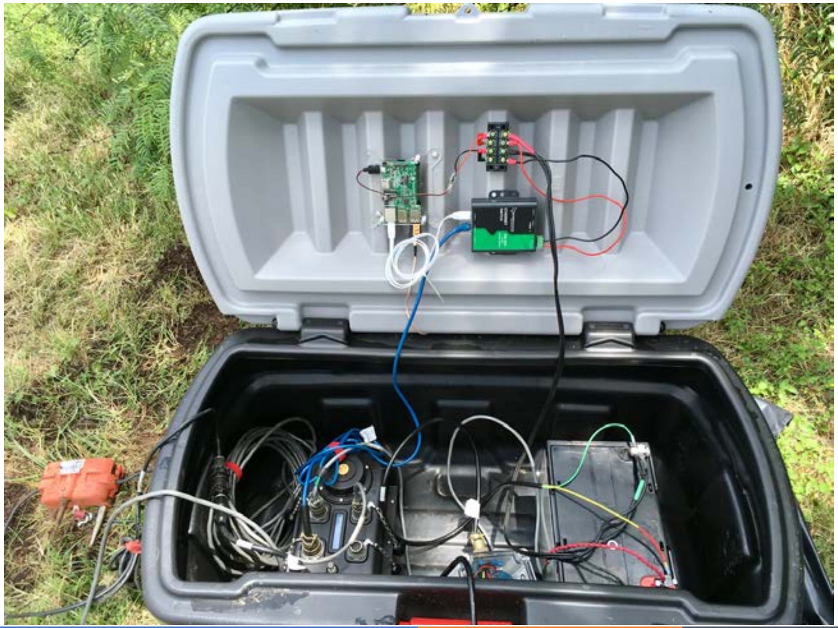
Automated, in-field processing can provide inter-station GF's in near-real-time, allowing for the immediate evaluation of results and enabling operators to alter data acquisition parameters before demobilizing the instruments. In the project entitled "Development of a novel, near-real-time approach to geothermal seismic exploration and monitoring via ambient seismic noise interferometry" our general objectives were to (a) build and test a new-generation seismic system that is capable of acquiring, transmitting, and processing seismic data in near-real-time, (b) apply the new technology in a geothermal field setting to investigate the possibility of extracting supplementary seismic parameter information from ambient seismic noise surveys by exploiting opportunities for adapting survey acquisition parameters provided by near-real-time data processing.

We devised a low-cost approach to automating SI with ambient noise. It relies on existing, widely-available instrumentation and expands that instrumentation's functionality by adding inexpensive micro-processors to perform data handling and processing. Novel features of our solution include: a) Embedding Raspberry Pi processors in a seismic array to perform real-time acquisition and distributed processing, b) creating a mesh Wi-Fi network in the field to transfer data between nodes, c) implementing Apache Cassandra to manage data across the array, and d) using MSNoise, Python-based SI software, to produce "Green's functions" via cross-correlation and stacking. Results are reviewed, progress toward

convergence can be assessed, and messages can be sent that summarize the array's performance, data metrics, and state of health.

In 2016-17 we built a prototype 20-node array and tested it at the Soda Lake Geothermal Field in June 2017. The array successfully performed real-time, in-field processing and produced virtual source gathers after each hour of data acquisition. We are now implementing a few changes to the array design and will build a 150-node array to be tested at a geothermal field in Nevada in 2018. In this presentation we will describe the approach in detail, show results from our field test, and report on the challenges we encountered during the project.

A novel approach to automated, in-field seismic exploration and monitoring via seismic interferometry with ambient noise



Jay Pulliam, **Diego Quiros**, Frank Sepulveda, Joseph Thangraj, John Queen, Marge Queen, Joe Iovenitti

Seismic Interferometry

- Traditional seismic exploration methods use “controlled seismic sources” (e.g., explosions, Vibroseis, hammer blows) to interrogate the subsurface. This approach can be expensive, intrusive, and damaging to the environment.

- Seismic interferometry (SI) is a relatively new field in seismology – The term interferometry is borrowed from radio astronomy. It can be divided into ambient noise interferometry and controlled source interferometry.

- Ambient Noise Seismic Interferometry - Uses ground motions that occur continuously from non traditional sources (e.g. ocean generated seismic energy, car and railroad seismic energy, wind generated seismic energy, etc)

- The goal of Ambient Noise Interferometry: to extract coherent signal (surface waves and body waves) from ‘noise’ records.

- That is to do subsurface imaging without explicit seismic sources.

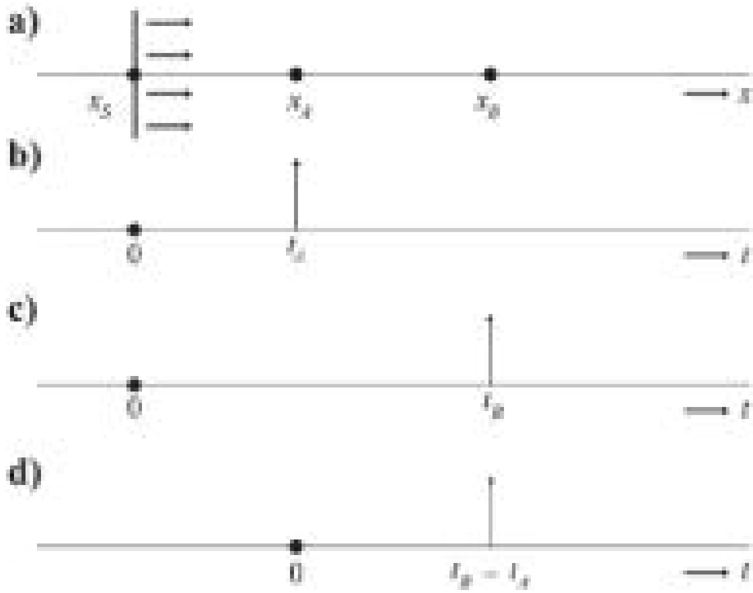
- At the heart of ambient noise interferometry is Cross-correlation of records from different seismic stations, and the sum of the cross-correlations over time.

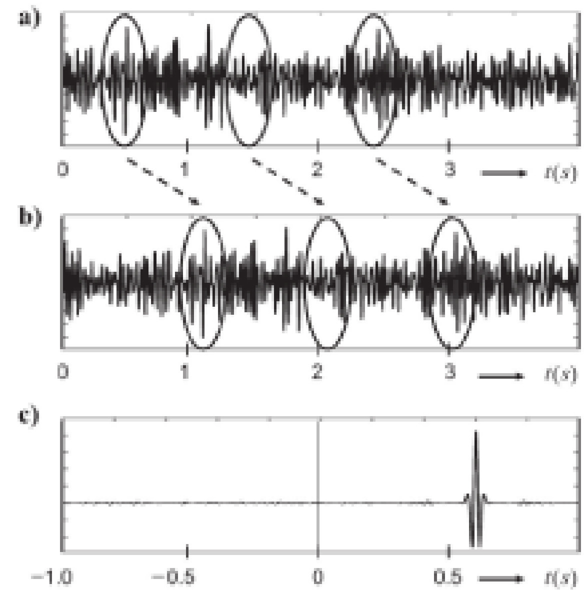
Seismic Interferometry: Basics

The goal: to create a new seismic record from the recorded ambient noise.

How: by cross-correlating the response recorded at seismometer A with that recorded at seismometer B. The source is at an unknown location at Xs

The result is that by cross-correlating we have ‘moved’ the source to XA

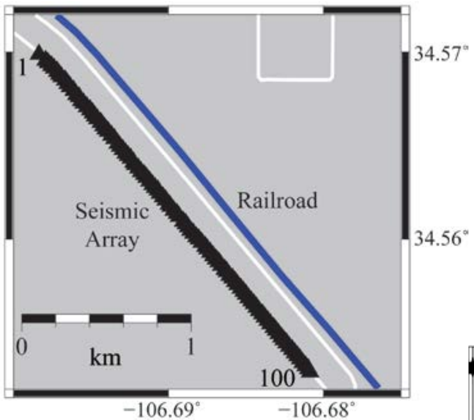


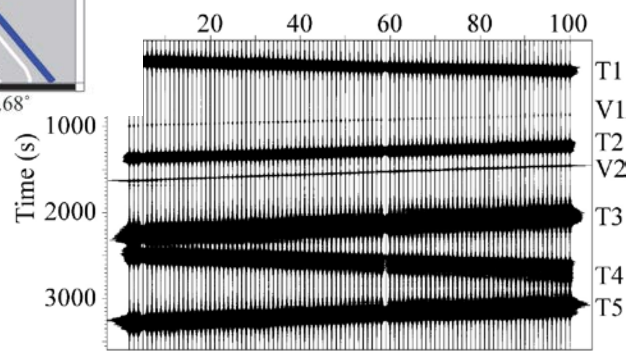


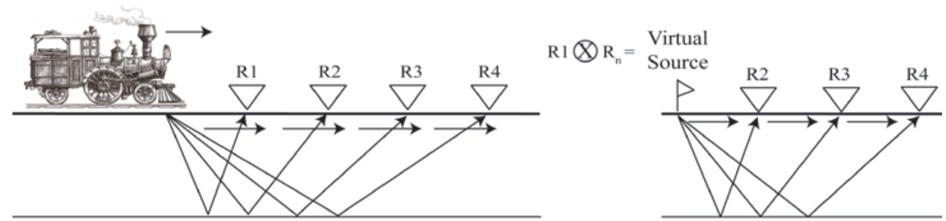
Response observed at XB as if there was an impulsive source at XA

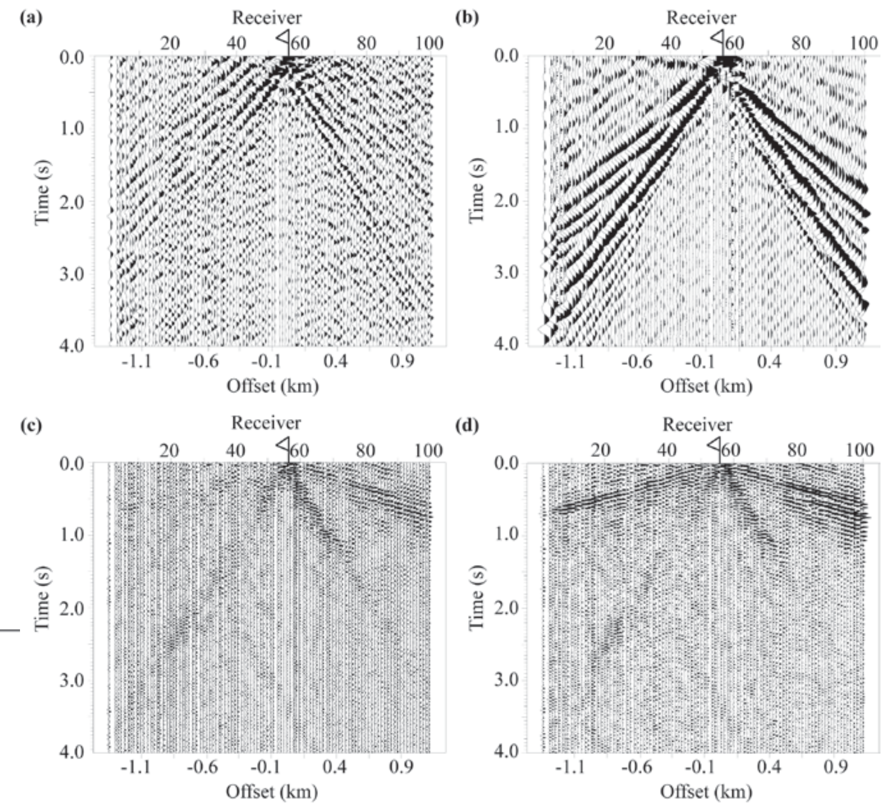
Response observed at XB as if there was a noise source at XA

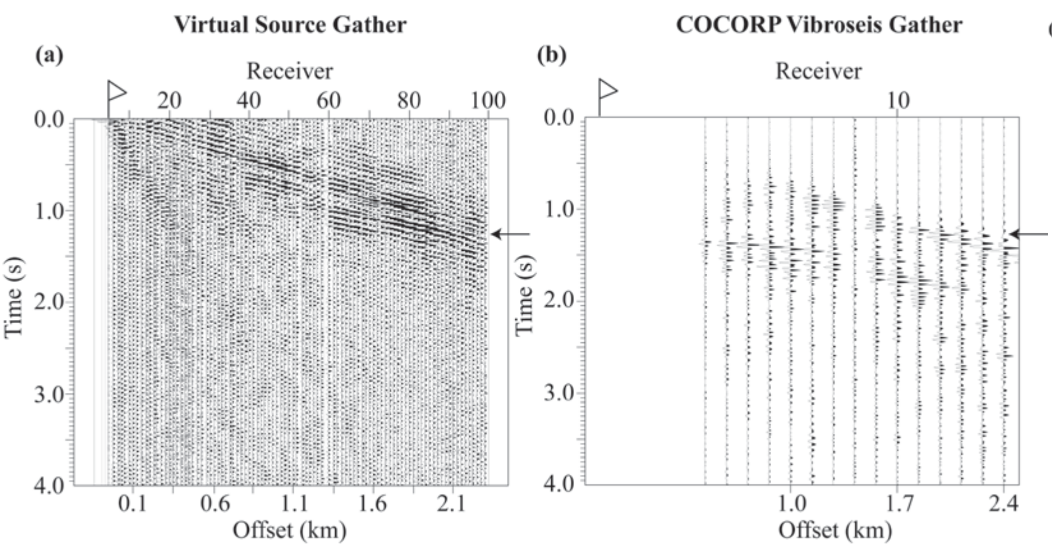
Seismic Interferometry: Example Rio Grande Rift











Figures from Quiros et al (2016). Geophys J. Int.

Goals of the project:

(1) Build and test a new-generation seismic system that is capable of acquiring, transmitting, and processing seismic data in near-real-time→"**R**aspberry **Pi** **E**nhanced **R**EFTEK" (RaPiER).

(2) Apply the new technology in a geothermal field setting to investigate the possibility of extracting supplementary seismic parameter information from ambient seismic noise surveys by exploiting opportunities for adapting survey acquisition parameters provided by near-real-time data processing.

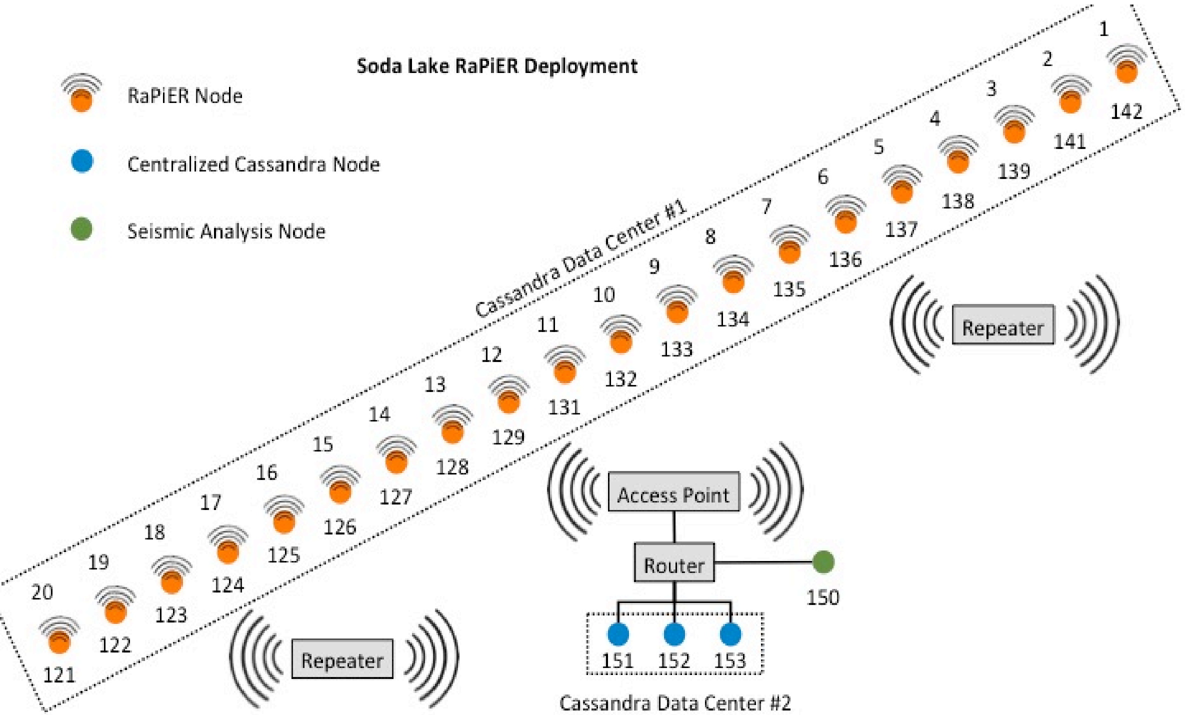
(3) The project is divided into 2 phases

Phase 1: we designed, built, and tested a 20-node linear array,

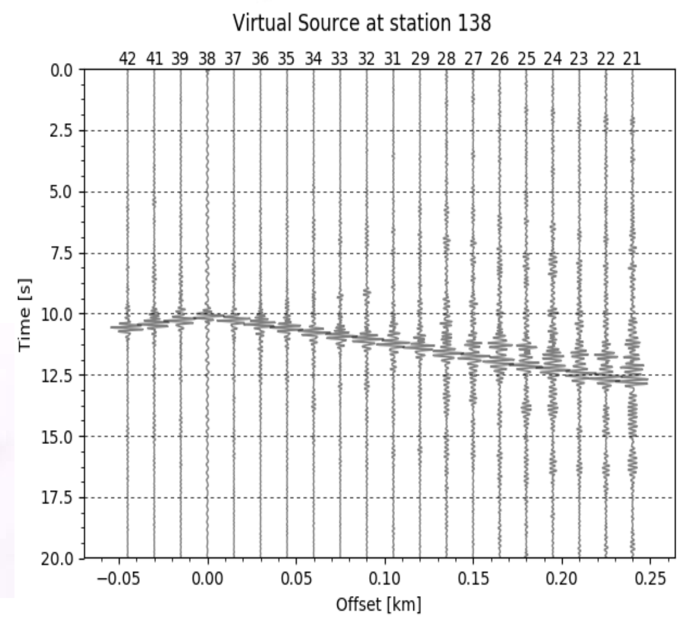
Phase 2: we will scale up to ~150 nodes and longer aperture.

I will be reporting Phase 1 results today: System Design and Integration, Processing strategy and software, Results of Field Tests.

Methods/Approach -- RaPiER Overview



Trimble REF TEK 130S-01 Broadband Seismic Recorder



Automated, in-field processing may be able to produce Green's functions in near-real-time, allowing for the immediate evaluation of results and enabling operators to alter data acquisition parameters before demobilizing instruments.

Methods/Approach -- RaPiER Overview

MSNoise

A Python Package for Monitoring (Seismic Velocity Changes) using Ambient Seismic Noise

The Apache Cassandra database is the right choice when you need scalability and high availability without compromising performance. Linear scalability and proven fault-tolerance on commodity hardware or cloud infrastructure make it the perfect platform for mission-critical data.Cassandra's support for replicating across multiple datacenters is best-in-class, providing lower latency for your users and the peace of mind of knowing that you can survive regional outages.

Apache CASSANDRA

PROVEN

Cassandra is in use at Constant Contact, CERN, Comcast, eBay, GitHub, GoDaddy, Hulu, Instagram, Intuit, Netflix, Reddit, The Weather Channel, and over 1500 more companies that have large, active data sets.

FAULT TOLERANT

Data is automatically replicated to multiple nodes for fault-tolerance. Replication across multiple data centers is supported. Failed nodes can be replaced with no downtime.

PERFORMANT

Cassandra consistently outperforms popular NoSQL alternatives in benchmarks and real applications, primarily because of fundamental architectural choices.

DECENTRALIZED

There are no single points of failure. There are no network bottlenecks. Every node in the cluster is identical.

SCALABLE

Some of the largest production deployments include Apple's, with over 75,000 nodes storing over 10 PB of data, Netflix (2,500 nodes, 420 TB, over 1 trillion requests per day), Chinese search engine Easou (270 nodes, 300 TB, over 800 million requests per day), and eBay (over 100 nodes, 250 TB).

DURABLE

Cassandra is suitable for applications that can't afford to lose data, even when an entire data center goes down.

YOU'RE IN CONTROL

Choose between synchronous or asynchronous replication for each update. Highly available asynchronous operations are optimized with features like Hinted Handoff and Read Repair.

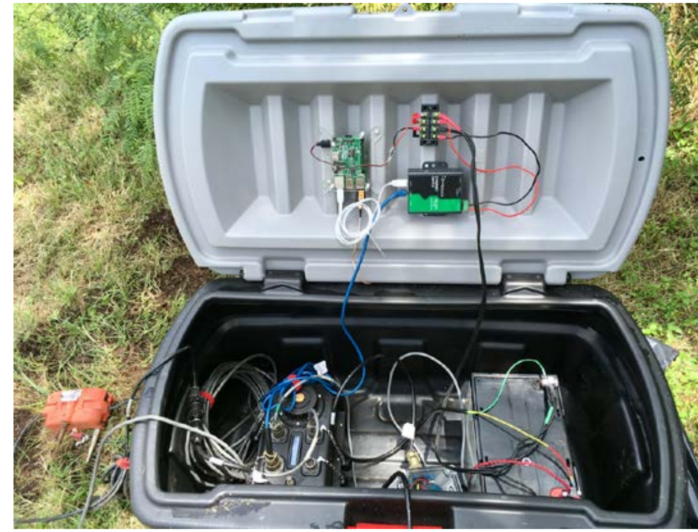
ELASTIC

Read and write throughput both increase linearly as new machines are added, with no downtime or interruption to applications.

PROFESSIONALLY SUPPORTED

Cassandra support contracts and services are available from third parties.

Methods/Approach -- Overview

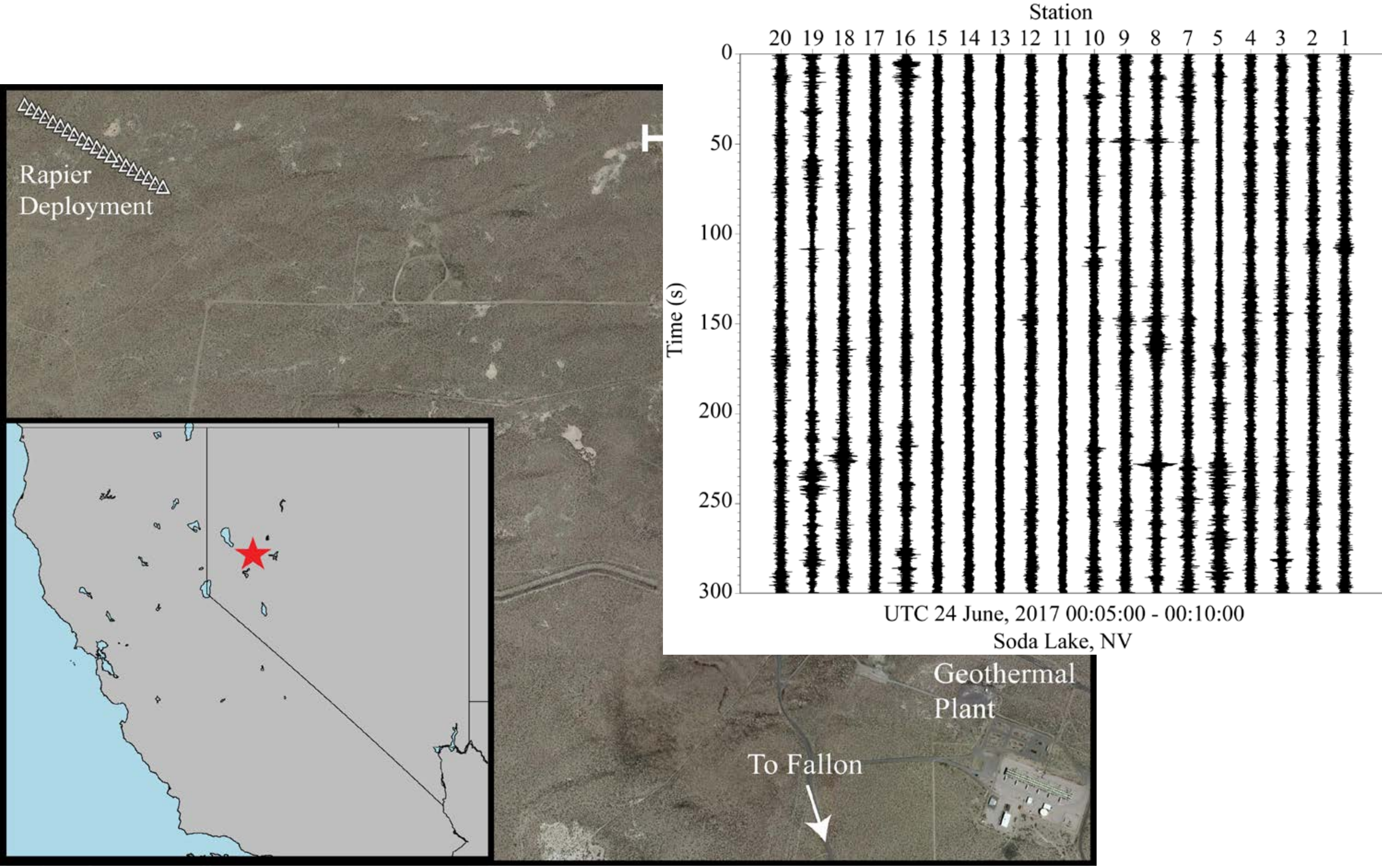


Methods/Approach -- Challenges

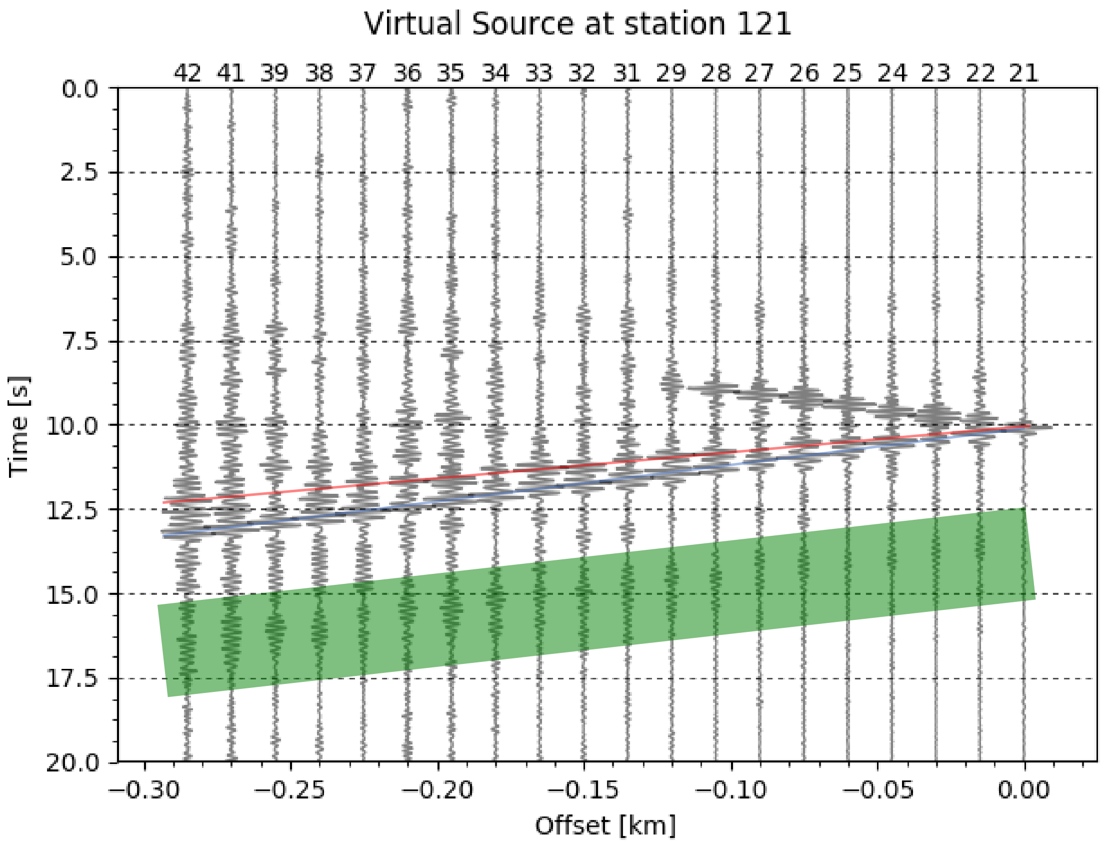
- To our knowledge,
  - a Raspberry Pi had never been integrated with a REF TEK 130 digitizer;
  - Apache Cassandra & MSNoise had never been implemented on a Raspberry Pi
  - No one seems to have resolved the problem of objectively determining GF convergence in an automated process
- The equipment we used, aside from the REF TEK 130, was largely consumer-oriented
  (a) Inexpensive
  (b) all had limited options for configuration
  (c) not robust (poor quality connectors, fragile housing, etc.).

- A Wi-Fi network in the field over uneven terrain is challenging to set up and maintain with high bandwidth.

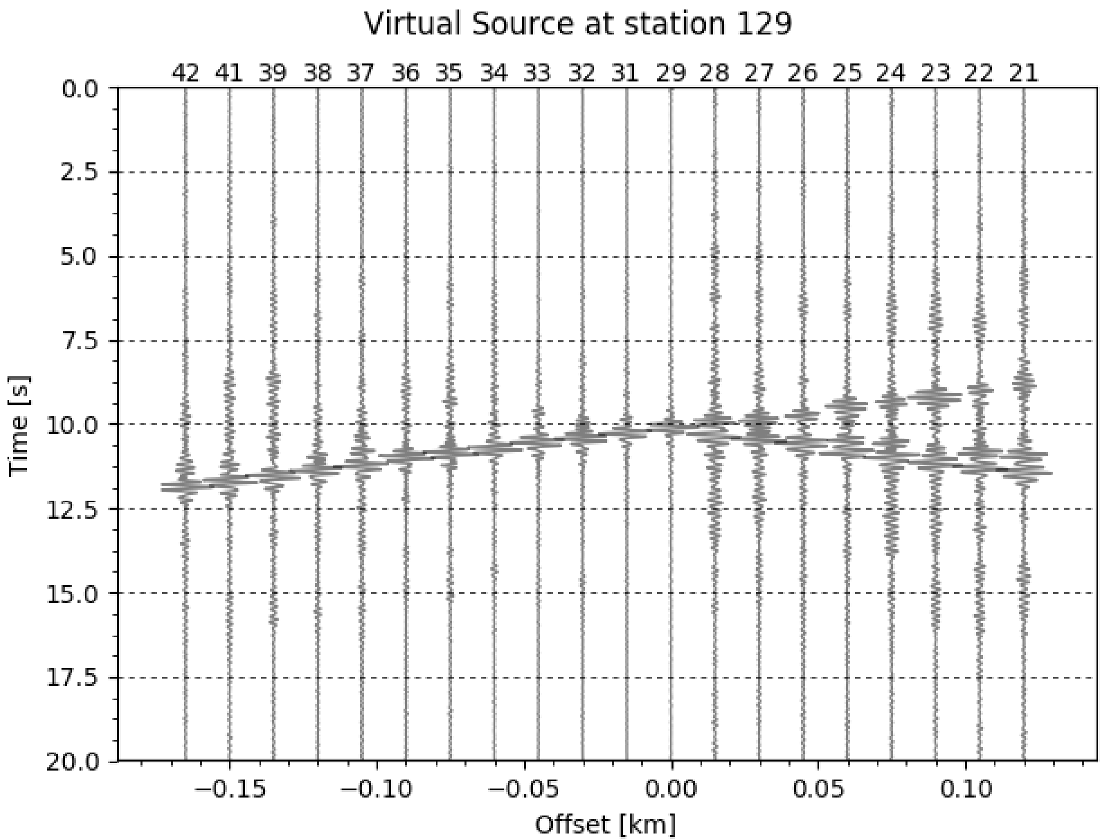
Soda Lake (NV) Field Test



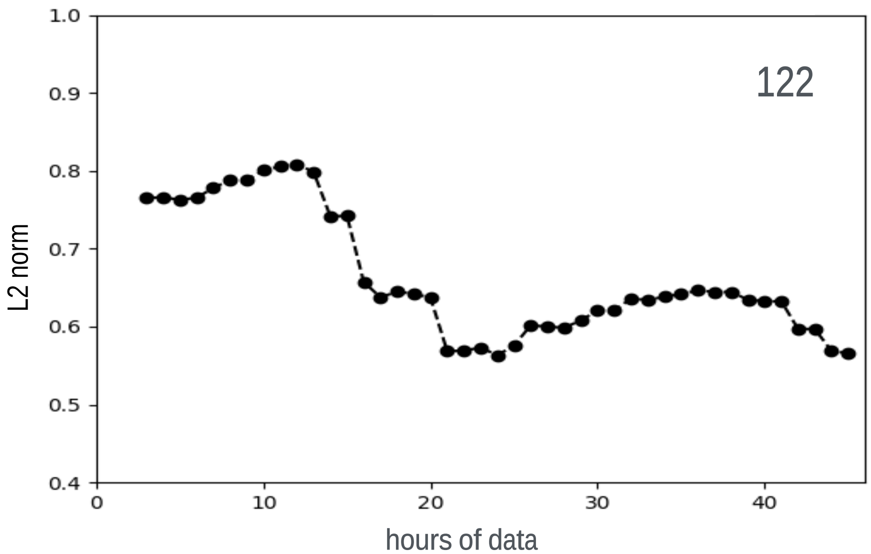
Virtual Source Gather for “Source” 121

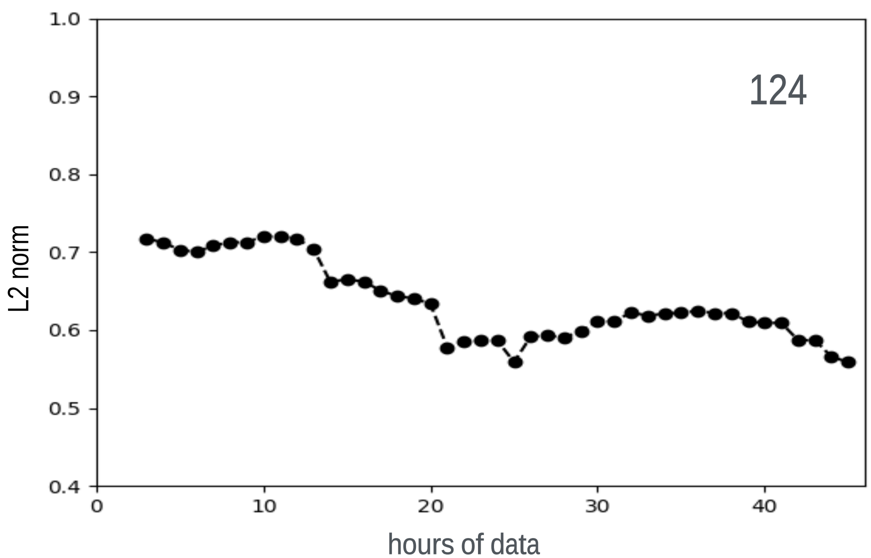


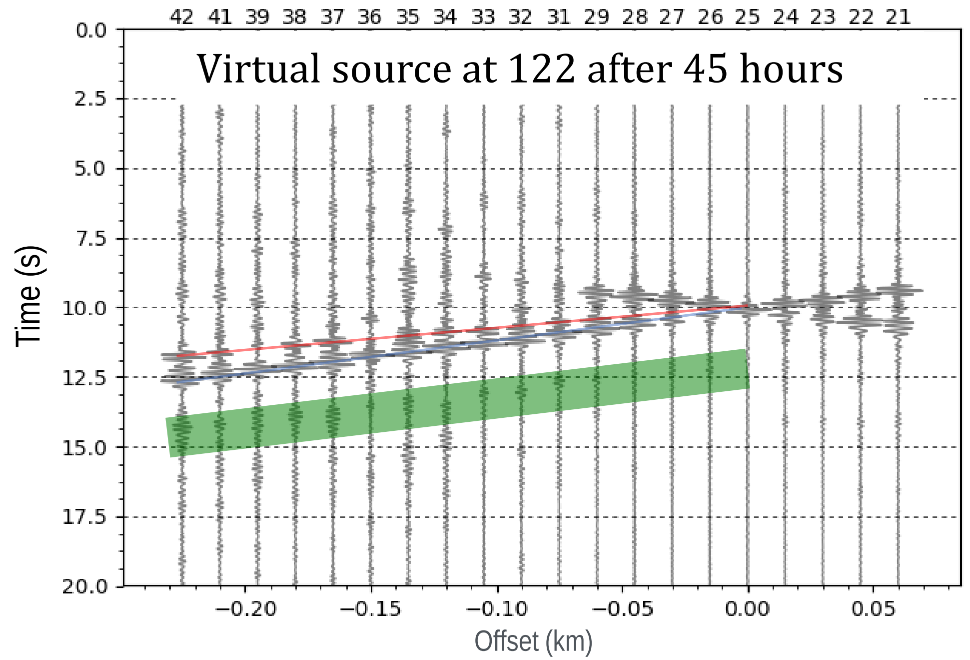
Virtual Source Gather for “Source” 129

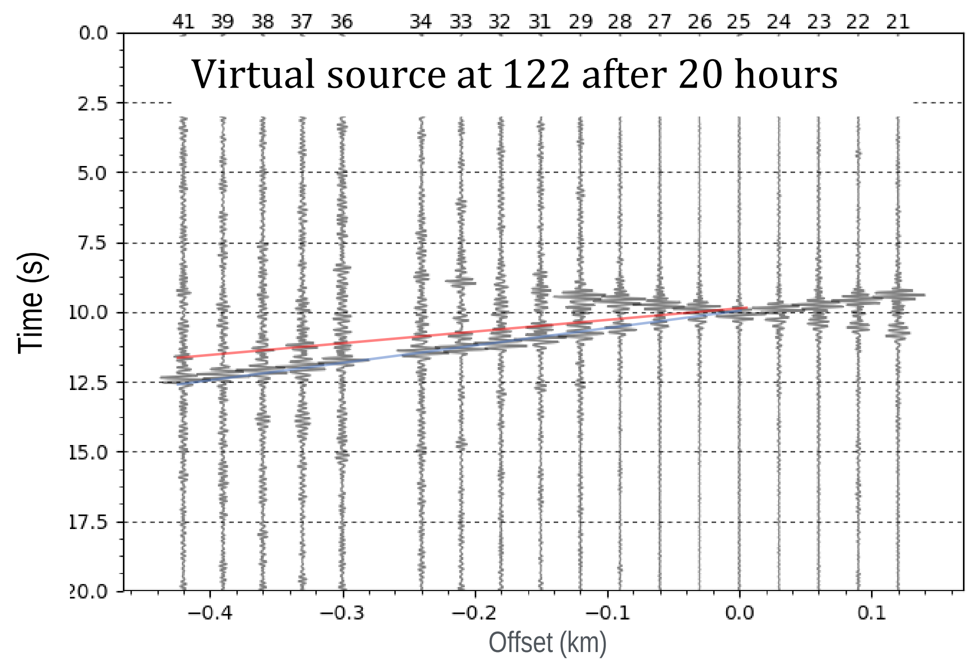


Green’s function convergence









Future Directions -- Plans for Phase 2

- Hardware: Finalize solutions to
  - Wi-Fi network compartmentalization → Better equipment has been identified

  Once those issues are settled we will build 130 additional RaPiER nodes
- Modeling
  - Compute surface (Rayleigh) wave group velocity dispersion
  - Model dispersion curves to find 1D Vs beneath Soda Lake array
- Software
  - Determine viability of real-time computation of surface (Rayleigh) wave group velocity dispersion
  - Implement on RaPiER nodes if it is deemed viable
- Field test prep
  - Settle on site for the large-scale field test
  - Obtain permits to perform field test
- Perform field test with 150-node array
  - Interpret and write up results

Summary Slide

- Automated, real-time, in-field seismic interferometry with ambient noise is feasible for small arrays.
  - Benefits include flexibility in data acquisition, which should lead to greater success rates and lower costs.

- A strategy that expands the functionality of existing, industry-standard instrumentation has been developed and field-tested.
  - Many other applications of embedded micro-processors in seismic arrays (e.g., seismic site characterization, aftershock monitoring and location, surface wave modeling, etc.
- Whether this same strategy is feasible for larger arrays with greater aperture will be determined in Phase 2.