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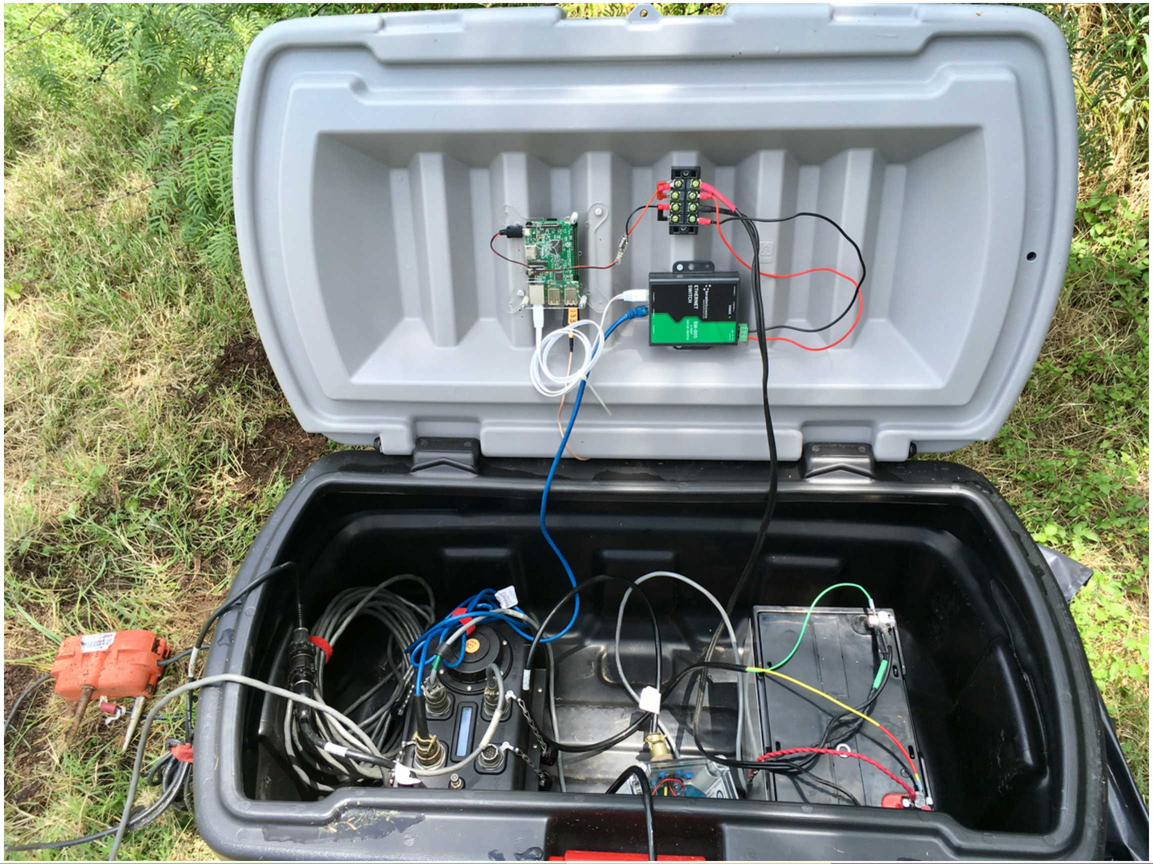

Development of a Novel, Near Real Time Approach to Geothermal Seismic Exploration and Monitoring Via Ambient Seismic Noise Interferometry

Project Officer: Holly Thomas

Total Project Funding: $980,907

November 13, 2017

Principal Investigator:
Jay Pulliam
Baylor University

SubTER award EE0007699

Relevance to Industry Needs and GTO Objectives

- 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.
- “Ambient noise”—ground motions that occur continuously—can be used with an approach called “seismic interferometry” (SI) to perform subsurface imaging without explicit seismic sources.
- Instead, one records ground motion continuously for periods of time and identifies waves that traverse the array via cross-correlations between time series recorded at different locations.

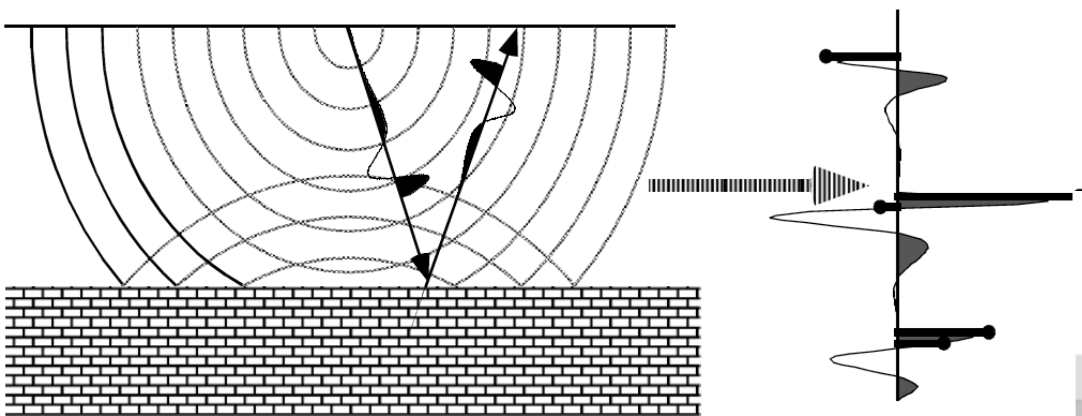

Figure from Margrave (2006). Methods of Seismic Data Processing, CREWES, U of Calgary, 410 pp.

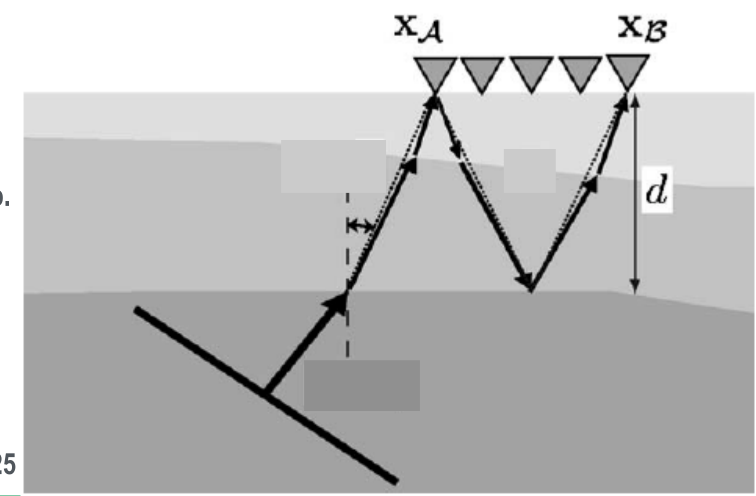

Figure from Ruigrok, E., X. Campmanb, K. Wapenaar (2011). Comptes Rendus Geoscience, 512-525

Relevance to Industry Needs and GTO Objectives

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- By eliminating the need to provide a seismic source, the costs, logistical efforts, and environmental consequences of seismic surveys can be reduced substantially.
- Cross-correlations for different time periods can be stacked improve signal-to-noise ratios and to construct “virtual source gathers”, much like in controlled-source reflection seismology.
- Since it depends on stacking, SI can make good use of intermittent data, data that is recorded at irregular intervals, differing durations, etc., whereas traditional methods depend on all geophones operating optimally during infrequent, critical source events.

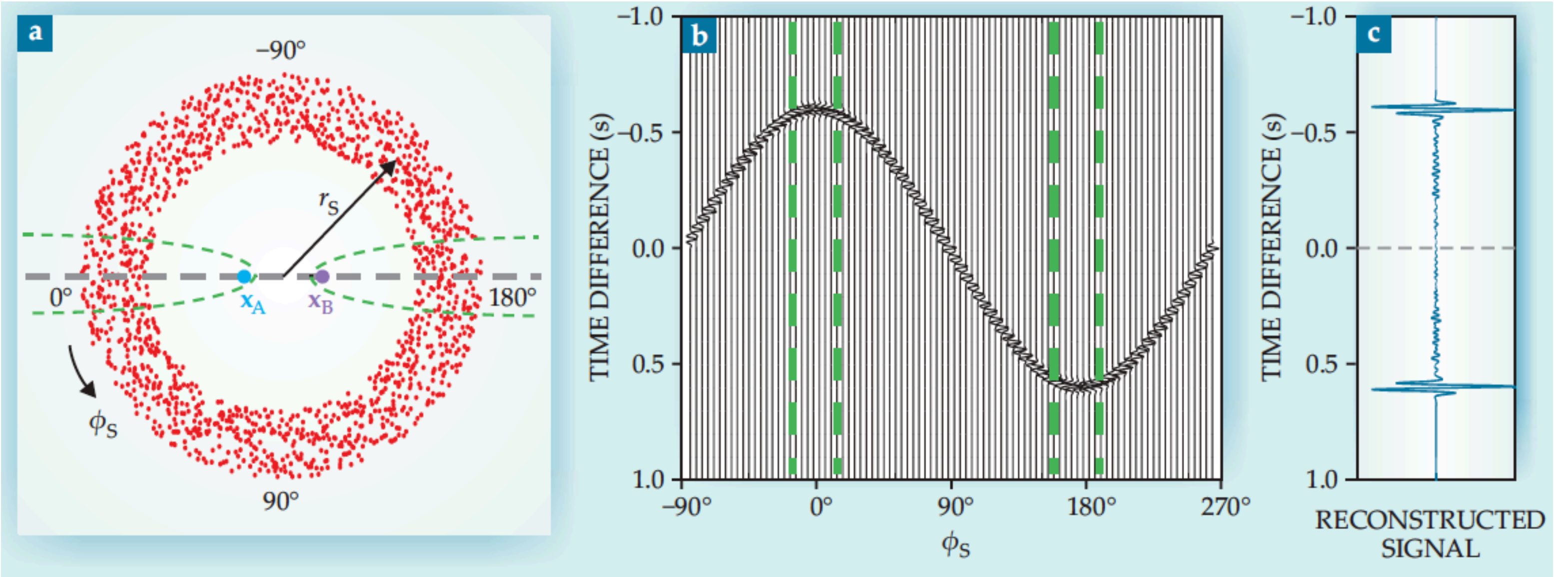


Figure from Snieder, R., & K. Wapenaar (2010). Physics Today, 44-49

Relevance to Industry Needs and GTO Objectives

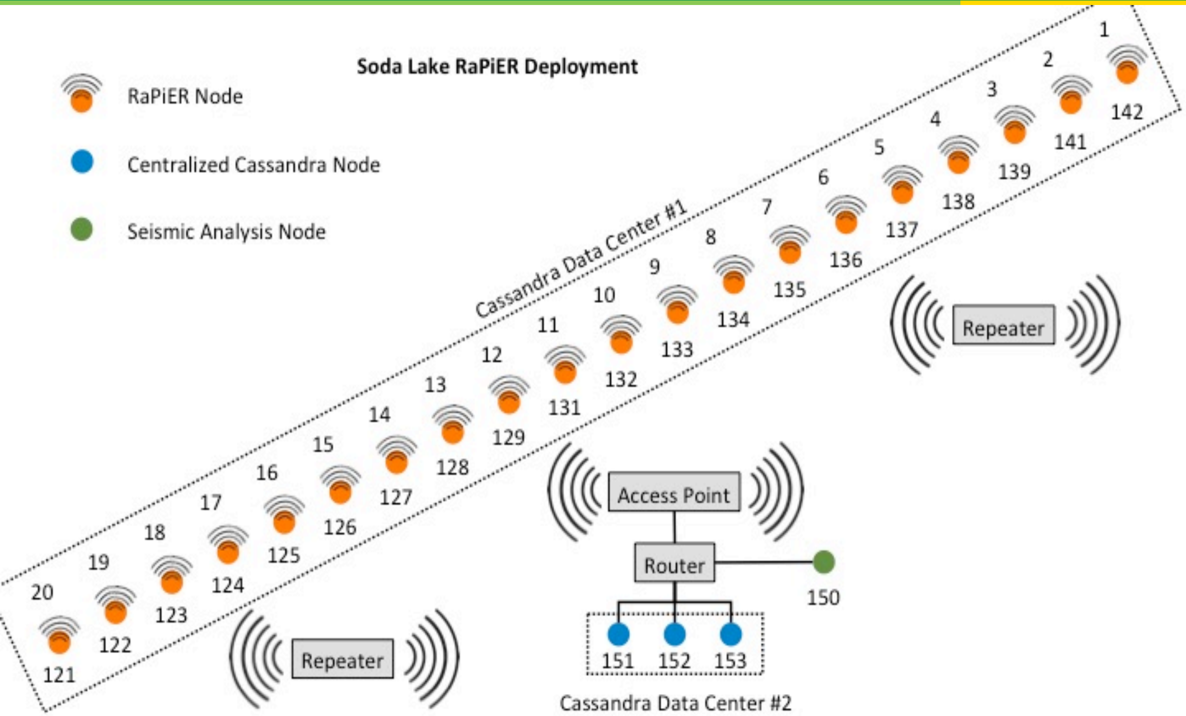
(1) Build and test a new-generation seismic system that is capable of acquiring, transmitting, and processing seismic data in near-real-time→"**R**aspberry **Pi** **E**nhanced **R**EFTEK" (RaPiER).

(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.

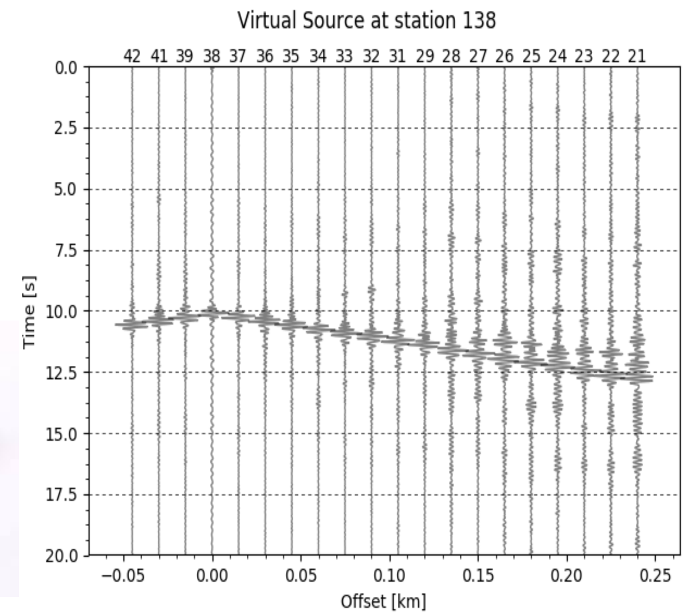
(3) The project has two Budget Periods; in Budget Period 1 we designed, built, and tested a 20-node array, in Budget Period 2 we will scale up to ~150 nodes and longer aperture.

(4) 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



Raspberry Pi 3

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

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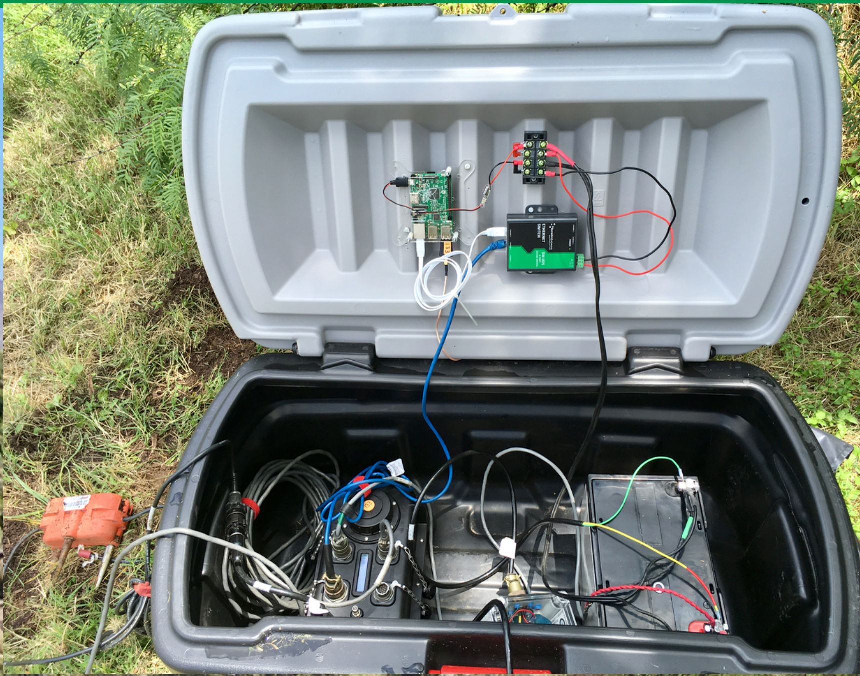

Methods/Approach -- Challenges

- 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 processor;
  - 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, which meant it was (a) inexpensive and (b) all had limited options for configuration, and (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.
- Body waves, as opposed to surface waves, dominate ambient noise, but imaging is best performed with body waves (whereas surfaces waves are best for estimating a velocity model);

Technical Accomplishments and Progress: Soda Lake (NV) Field Test

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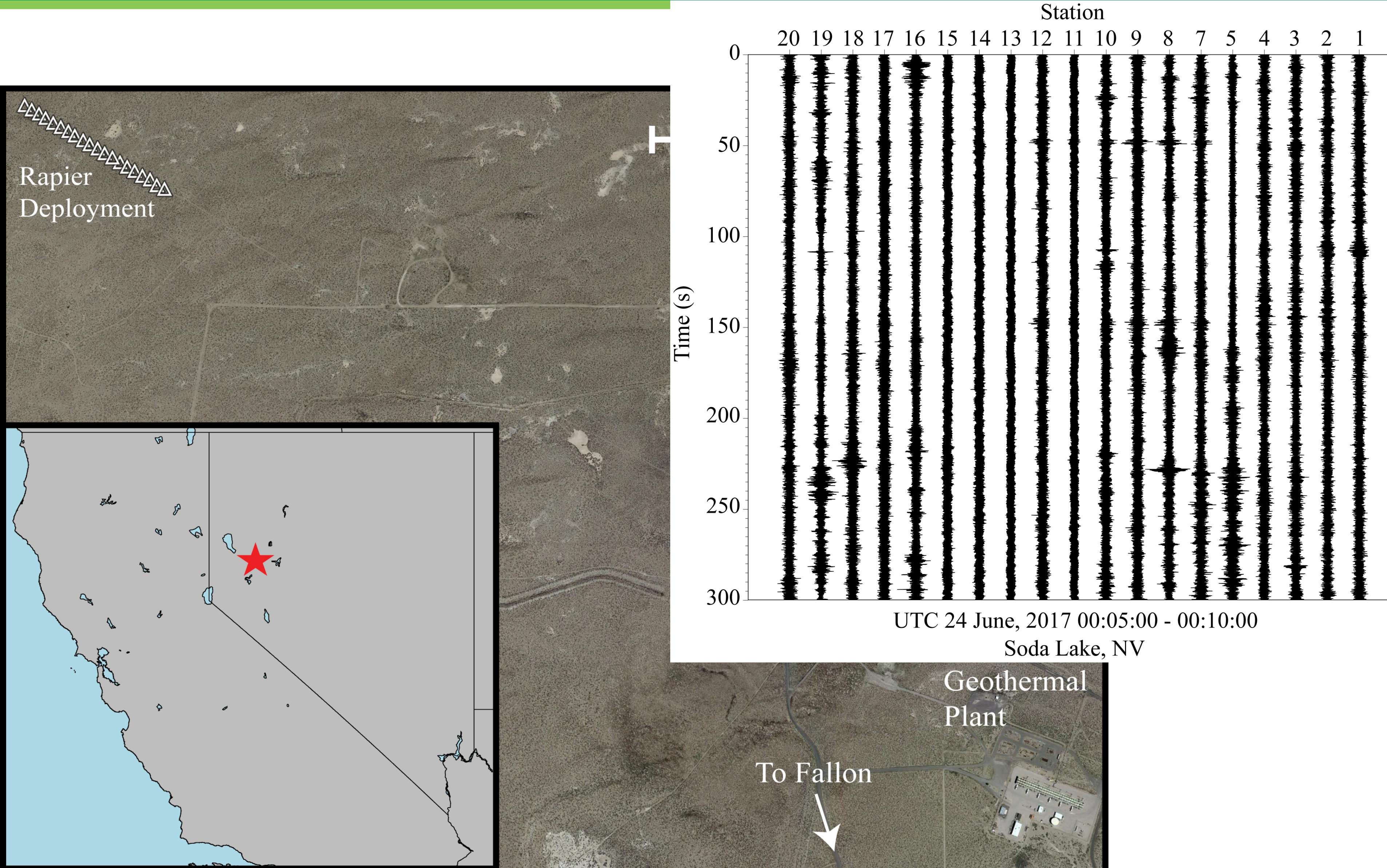

Virtual Source Gather for "Source" 121

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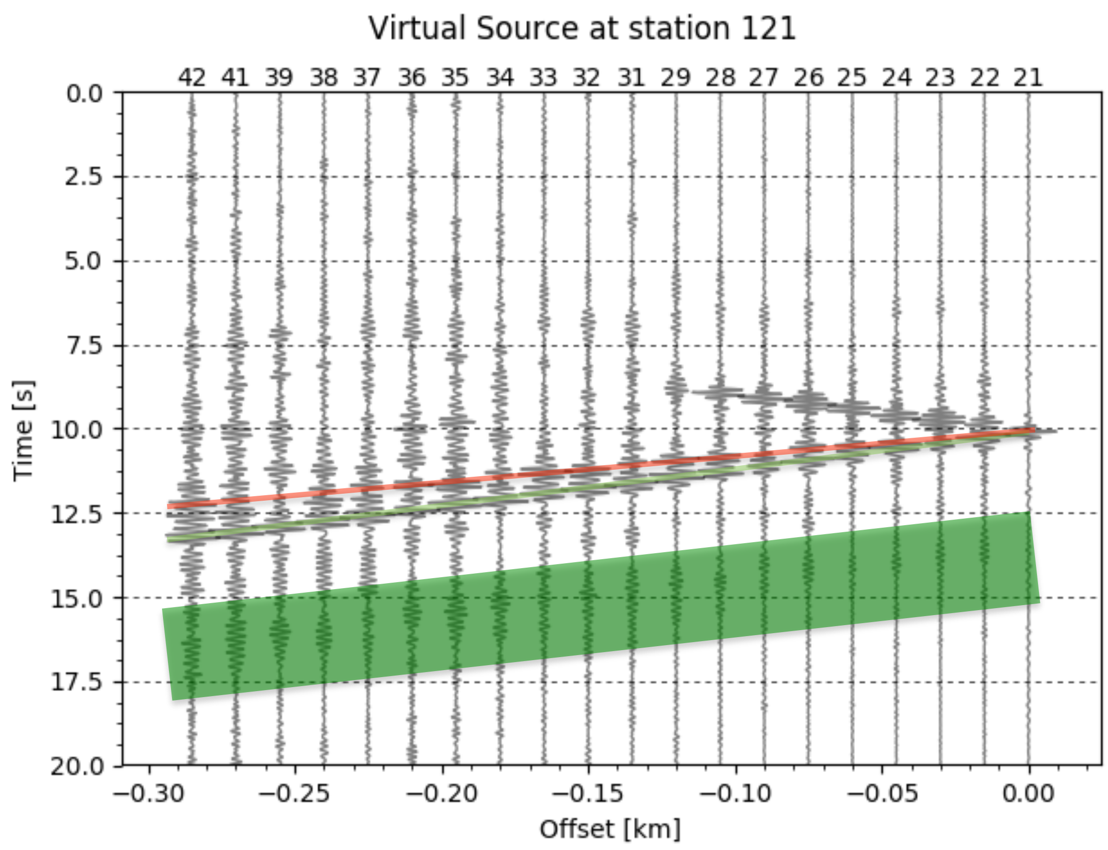
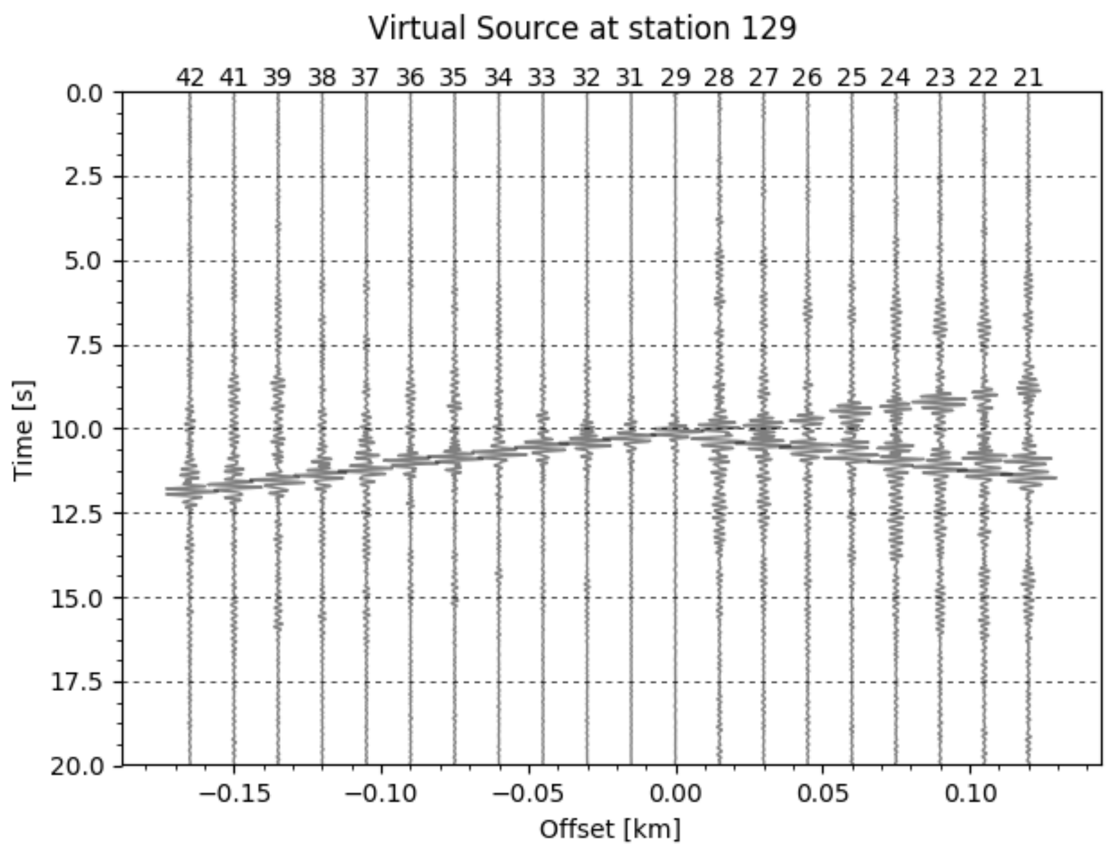
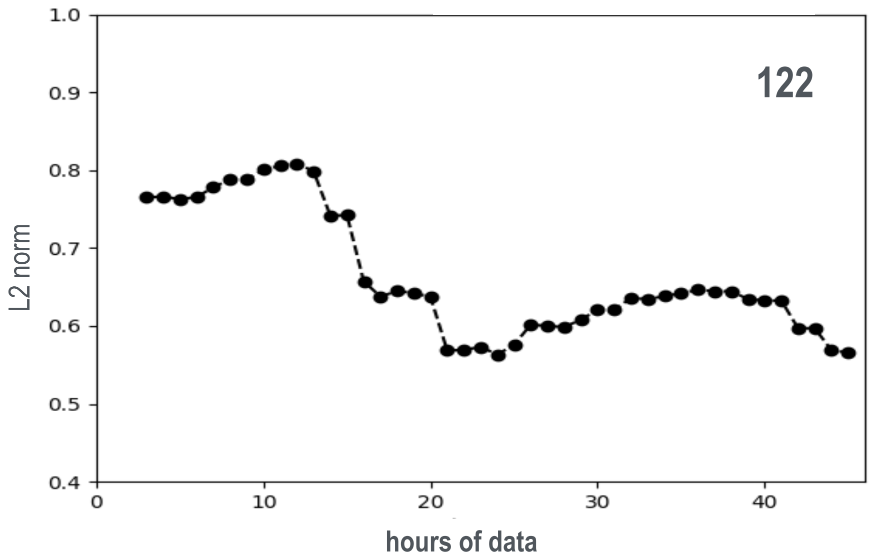
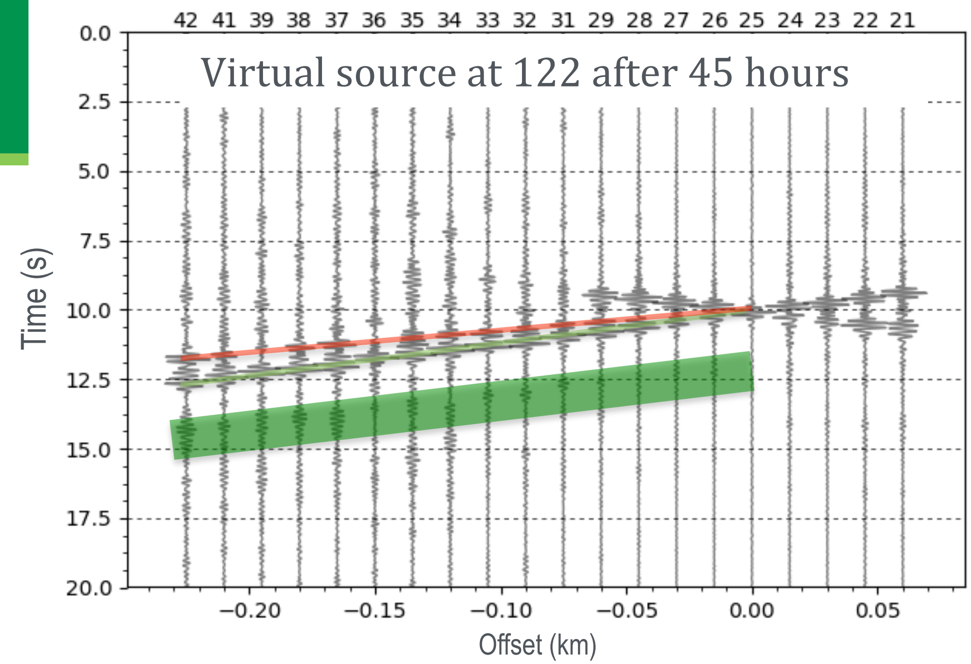


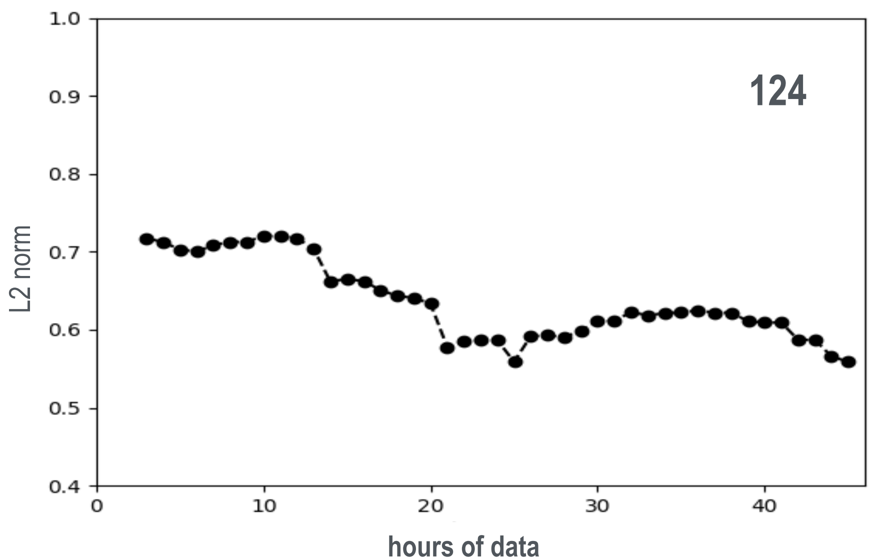
Virtual Source Gather for "Source" 129

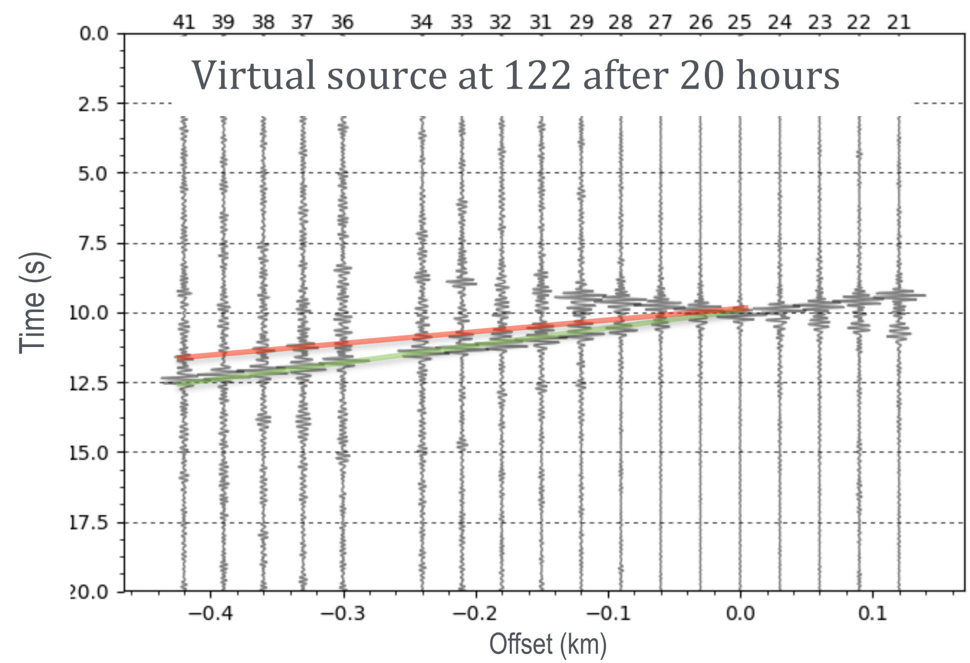


Green's function convergence









Technical Accomplishments and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Milestone 1.1: Revisions to Project Management, Technology Maturation, and Data Management Plans as needed.	No revisions have been needed	Sept 2017
Milestone 1.2: Meetings held by the end of Q1	Meetings were held in Nov & Dec 2016	Dec 2016
Milestone 1.3: Documentation of instrument request. (Q1)	Instrument request was made in December 2016; documentation was provided with Q1 report	Jan 2017
Milestone 2.1: 22 functioning RaPiERs have been constructed and are operating. (Q2)	Functioning RaPiERs were all constructed by April 30, 2017	April 2017
Milestones 2.2 – 2.6: 20-node array performs data transfer and computations in timely manner. (Q2)	The 20-node array was functional in mid-May 2017	May 2017
Milestone 3.1: Permit to perform field test at Soda Lakes Geothermal Field obtained. (Q1)	Permit obtained by the end of Q2	March 2017
Milestones 3.2 – 3.7: Build and interpret a dataset of virtual shot gathers, assess the potential to produce an in-field initial P and S velocity model. (Q3)	We conducted the field test at SLGF in June 2017 and submitted a Phase 1 report in July 2017	July 2017
Milestone 5.1: Site is selected for the second (Phase 2) field test by the end of M2.	Reviewed the available geophysical information at a eight sites, ruled out several, and are continuing to evaluate the remaining candidates.	Anticipated Jan 2018
Milestone 5.2: The permit and NEPA documentation will be completed by the end of M5.	Pending the final decision on a site for the BP2 field test.	Anticipated May 2018
Go/No-go Decision -- A presentation will be made at the end of Task 3.	The Go/No-go presentation was made on 30 Aug 2017.	August 2017

Research Collaboration and Technology Transfer

- We are an academic/industry collaboration ourselves. We do not anticipate adding new partners until we have field-tested the larger-scale array.
- The technology we used is all open to the public and all of our systems integration and parameter tuning are documented and available to interested parties.
  - Presentation scheduled at Fall meeting of the American Geophysical Union
  - Article for peer-reviewed journal in preparation.
  - Anyone who wants to reproduce what we have done will find a complete roadmap.
  - However, we anticipate making a few changes as we scale up to a 150-node array in BP 2, so we do not anticipate making additional efforts to publicize the technique until after the second field test.

Future Directions -- Plans for Phase 2

- Hardware: Finalize solutions to
  - Wi-Fi network compartmentalization → Better equipment has been identified
  - Need for more robust embedded systems for aggregator & Cassandra nodes
  - Connecting aggregator nodes to the centralized Cassandra nodes
  - Need for more reliable connections with DC-to-DC converter

  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

Future Directions

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Milestone or Go/No-Go	Status & Expected Completion Date
Milestone 4.1: The 130 RaPiER units are built by the end of Q6.	We expect to complete the construction of the units by the end of Q7 (June 2018)
Milestones 4.2 – 4.6: All nodes are communicating via a mesh network; seismic processing is functional; 130-node configuration performs data transfer and computations in a timely manner by the end of Q6.	We expect to have the entire array functioning reliably by the end of Q8 (September 2018)
Milestone 5.1: Select site for the second (Phase 2) field test.	January 2018
Milestone 5.2: The permit and NEPA documentation will be completed by the end of M5.	May 2018
Milestones 5.3-5.6: Perform field test of 150-node array. Build and interpret a dataset of virtual shot gathers, assess the potential to produce an in-field initial P and S velocity model, as well as a set of seismic parameters providing additional, useful seismic information. Finalize seismic data processing and interpretation.	We expect to conduct this field test in September 2018 (postponed due to the difficulty of working in high temperatures in Nevada in the summer). We will complete the remainder of the tasks by the end of October 2018.
Milestone 6.2: Monthly meetings have been held at the end of each month.	End of project
Milestone 6.3: Quarterly Reports have been submitted at the end of each Project Quarterly.	End of each quarter
Milestone 6.4: A Final Scientific Report has been submitted by the end of Q8.	End of project (March 2019)
Milestone 6.5: Publications have been submitted to industry and peer-reviewed journals by the end of calendar year 2018.	March 2019

Mandatory 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.
  - Wi-Fi bandwidth in the field depends on peculiar (indeterminate) factors but our implementation of ambient noise processing handles interruptions gracefully.
- A strategy that expands the functionality of existing, industry-standard instrumentation has been developed and field-tested.
  - Apache Cassandra will run successfully on Raspberry Pi 3 processors but it consumes nearly all available RAM (1GB).
  - Many other applications of embedded micro-processors in seismic arrays (e.g., seismic site characterization, aftershock monitoring and location, surface wave modeling, etc.
  - This approach could be an important component of “Big Data” handling.
- Whether this same strategy is feasible for larger arrays with greater aperture will be determined in Phase 2.