A Community Experiment to Record the Full Seismic Wavefield in Oklahoma

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ABSTRACT

Observing the full seismic wavefield by deploying large numbers of seismometers (also known as large-N deployments) and analyzing the resultant large datasets is now more feasible than ever before as a result of advances in instrumentation, computational power, and data analysis techniques. In 2015, the Incorporated Research Institutions for Seismology (IRIS) proposed a field deployment to provide the research community with experience in new techniques for obtaining full wavefield observations using a range of instrumentation (three-component [3C] nodal-style sensors, broadbands, and infrasound) at multiple spatial and temporal scales. The goals of the experiment were to demonstrate the field use of the nodal sensors, contribute a compelling dataset that could be analyzed through innovative techniques, and evaluate the performance of new array designs and instruments (particularly the 3C nodes). The resulting IRIS Wavefields Demonstration Community Experiment, conducted in north-central Oklahoma during the summer of 2016, collected data that were immediately made open and available at the IRIS Data Management Center (network code YW) and provided a unique and scientifically rich dataset to advance our understanding of the full seismic wavefield. A key finding was that by burying the 3C nodal sensors used in the deployment, substantially lower horizontal noise levels were achieved across a wide range of periods spanning 0.01–100 s.

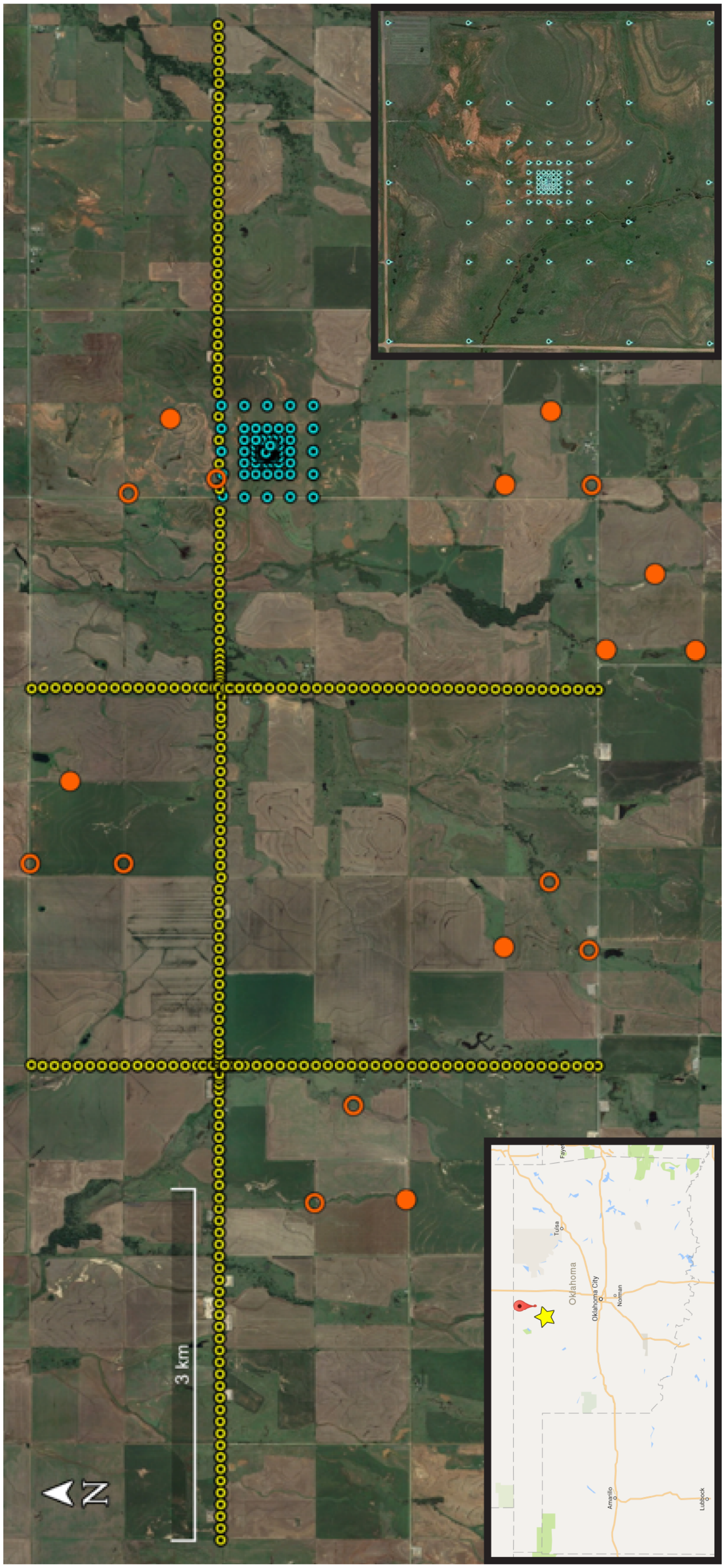
INTRODUCTION

In June 2016, the Incorporated Research Institutions for Seismology (IRIS) led a community experiment to demonstrate the feasibility and usefulness of recording the full seismic wavefield. The experiment location and design were the result of an open competition announced in late 2015. A total of 11 valid concept submissions were received by the deadline in January 2016, and the winning submissions were chosen by a committee made up of nonconflicted community members. The final experiment location and design were a combination of three submissions from (1) Katie Keranen (Cornell) and Xiaowei Chen (Oklahoma); (2) Chuck Langston (University of Memphis); and (3) Heather DeShon (Southern Methodist University [SMU]), M. Beatrice Magnani (SMU), Chris Hayward (SMU), Brian Stump (SMU), Mike Brudzinski (Miami University, Ohio), and Susan Bilek (New Mexico Tech). The experiment was designed to be installed near or above an active seismic lineament with the hope of recording many earthquakes—some at very close range.

This experiment was one of the first academic deployments to field a large number of three-component (3C) nodal-style seismic sensors; others include Brenguier *et al.* (2015), Ward and Lin (2017), and Wu *et al.* (2017). Additional one-component nodal deployments have recently been conducted in Long Beach, California (Lin *et al.*, 2013; Schmandt and Clayton, 2013; Bowden *et al.*, 2015; Nakata *et al.*, 2015), at Mount St. Helens (Hansen and Schmandt, 2015; Hansen *et al.*, 2016; Wang *et al.*, 2017), and also along the San Jacinto fault zone (Hillers *et al.*, 2016; Roux *et al.*, 2016). Seismic nodes are all-in-one seismometer, digitizer, and data logger units enclosed in a small, light, and easy-to-deploy package with onboard Global Positioning System (GPS) timing (Ringler *et al.*, 2018). Used in the energy industry for years, these types of instruments have only recently begun to see adoption by the academic community. Early-generation nodes (e.g., RefTek 125A "Texans") were not all-in-one instruments (data logger and geophone were separate), were generally single component, lacked onboard GPS, and had limited battery life and disk space. The all-in-one nodes deployed in this experiment were FairfieldNodal ZLand 3C 5 Hz nodes with ~35 days of battery life and sample rates of up to 2000 samples/s. Through lease agreements with the node manufacturer, as well as with community members who owned a small number of identical nodes (Marianne Karplus [University of Texas at El Paso], Fan-Chi Lin [Utah]), IRIS was able to acquire and lead the deployment of 363 3C nodes over a 5×13 km area in north-central Oklahoma (Fig. 1).

The use of 3C nodes enhances our ability to densely sample the seismic wavefield at scales that are not logistically practical with traditional portable passive-source seismic stations. One important goal for this experiment was to demonstrate the field logistics, deployment geometries, and instrument

doi: 10.1785/0220180079



▲ **Figure 1.** Map of Wavefields Experiment in north-central Oklahoma. Nodes are denoted by small circles. Broadband stations are denoted by large circles. Solid large circles indicate the presence of co-located infrasound stations. Inset at the lower right is a zoomed-in view of the gradiometer array, whereas inset at the lower left shows the location of the deployment in Oklahoma (map marker) and Enid (star). The color version of this figure is available only in the electronic edition.

Table 1
Summary of Instrumentation and Deployment Durations

Station Type	Instrument	Number	Installed	Removed	Duration
Node	FairfieldNodal ZLand 3C 5 Hz	363	21–23 June 2016	25–27 July 2016	~30 days
Broadband	Güralp CMG-3T 120 s	18	18–24 June 2016	11–13 November 2016	~5 months
Infrasound	Hyperion IFS3311 microbarometer	9	21–23 June 2016	11–13 November 2016	~5 months

capabilities of these new, small, easy-to-deploy sensors and how the deployment of several hundreds of them could produce a dataset of great scientific interest. IRIS also wanted to see how well the 3C nodes recorded local, regional, and teleseismic arrivals relative to more traditional 3C broadband and infrasound stations, which were also deployed as part of this experiment. With the aging of the current pool of Texan portable instruments, this experiment provided a perfect opportunity to test out a possible replacement instrument with enhanced capabilities.

The original design of the deployment included a controlled-source component to be carried out using a triaxial high-force vibroseis and recorded by the nodal array. The goal of the controlled-source element of the experiment was to contribute the resolution needed for full wavefield imaging at all spatial scales. Unfortunately, permitting issues prevented the seismic source from being deployed, and this component of the wavefield experiment was never recorded.

INSTRUMENT DEPLOYMENT DETAILS

The IRIS Wavefields Demonstration Community Experiment was deployed ~30 km northeast of Enid, Oklahoma, above an active seismic lineament. Prior to installation, all of the node station locations were surveyed to centimeter precision using a real-time kinetic GPS system provided by UNAVCO. The deployment was completed over a period of five days in June 2016, and involved a crew of nearly 50 people, including 30 supported graduate students from more than 20 institutions. Although the deployment could easily have been completed with fewer participants, a goal of the experiment was to provide a hands-on opportunity to work with the new nodal sensors to as many students and community members as funding would allow. After detailed training, the crew was able to deploy a total of 390 stations, including 363 3C nodes, 18 broadband stations, and 9 infrasound stations (Fig. 1; Table 1).

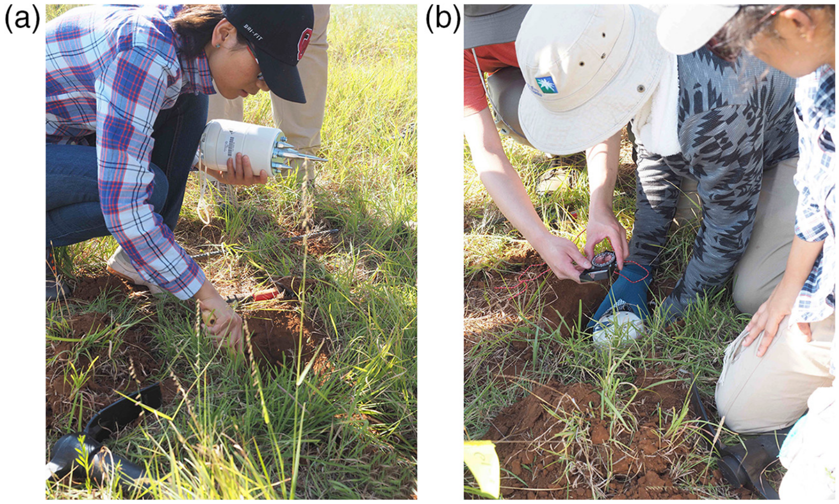
The nodal sensors were deployed in two different array configurations. About 112 nodes were deployed in a seven-layer nested gradiometer measuring 800×800 m on the outer ring and 13×13 m on the inner ring. Each ring was composed of 16 nodes. This gradiometer array configuration was chosen because it has the dual ability to measure the seismic wavefield using standard frequency–wavenumber techniques and spatial wave gradients. The gradiometer was broadband in that seismic wavelengths of local *P*, *S*, and surface waves from 150 to 10 km can be measured. The arrangement of 16 seismometers per ring also allowed analysis of the problems of spatial gradient computations that naturally rely on relative amplitude variations between array elements. The gradiometer design was part of Chuck Langston's original proposal and was incorporated into the final experiment design.

The remaining ~250 nodes were deployed in three seismic lines along local farming roads and over one or more preidentified seismogenic faults. One line ran east–west approximately 13 km, spanning the width of the entire deployment. The remaining two lines were north–south lines, each 4.8 km in length, located approximately 3 km apart and intersecting the east–west line. Nodes were placed every 100 m along the three seismic lines, except within 250 m of the two intersection points, where nodes were placed as close as 33 m apart (creating two cross-shaped subarrays). Placing the lines over an active sequence provided a rich dataset, which allowed the community to study the evolution of faulting and stress, design innovative detection and location capabilities, calculate detailed source parameters (stress drops, *b*-values, mechanisms, ground motions, etc.), and improve subsurface velocity and attenuation imaging. The lines also provided an opportunity for piggy-backed active source experiments and high-density acoustic-to-seismic conversions, though unfortunately the active source component of this experiment was not able to be carried out. The three lines operate as an ~6—km high-density regional array, providing substantial array gain for regional signals as well as ray parameters for teleseismic signals.

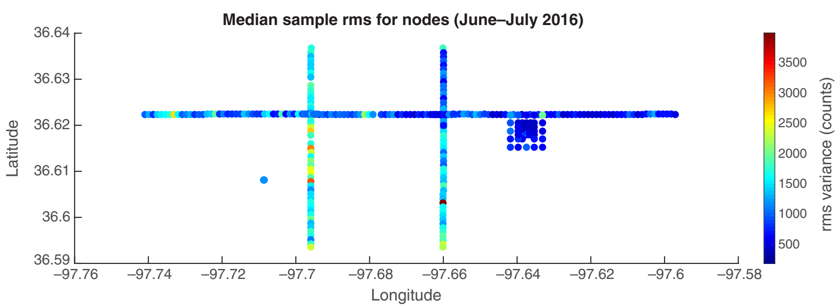
All nodes in our deployment recorded at 250 samples/s with a gain of 12 dB and were buried such that the top of each node was ~3–5 cm below the surface (Fig. 2). A gain of 12 dB was chosen because when combined with the nodal bit weight and geophone sensitivity it produces a result closest to what Principal Investigators (PIs) would get with a typical Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) broadband sensor connected to a Q330 or RT-130 data logger with a gain setting of 1. A sample rate of 250 samples/s was chosen to ensure we could record high-frequency energy (up to at least 100 Hz) from expected local seismicity beneath the array.

The broadband stations were deployed in six miniarrays of three stations each. This Golay array configuration (also proposed by Langston) was deployed around the center of the nodal arrays (seismic lines and gradiometer) with the intention of recording the lower-frequency portion (< 5 Hz) of the seismic wavefield. Like the gradiometer, the Golay array is also a self-similar array that produces a uniformly sampled coarray.

The broadband stations each used Güralp CMG-3T sensors and RT-130 data loggers and were sampled at 100 samples/s. Each broadband station was installed ~1 m



▲ **Figure 2.** (a) A student prepares a hole for installation of a node. (b) Students orienting a three-component (3C) 5Hz node during installation at one of the gradiometer sites. The color version of this figure is available only in the electronic edition.



▲ **Figure 3.** Node median sample_rms metric over the period 20 June to 20 July 2016. Note the elevated values seen on the western north–south line and southern portion of the eastern north–south line. The color version of this figure is available only in the electronic edition.

below the surface inside a plastic vault with a poured concrete base. Infrasound stations were co-located with nine of the broadband stations; each used Hyperion microbarometers with RT-130 data loggers and were sampled at 100 samples/s. The microbarometers record atmospheric perturbations and the inlets of each sensor were connected to several microporous soaker hoses laid out on the ground surface to reduce wind-generated noise. Chris Hayward (SMU) contributed and managed the installation of the infrasound stations.

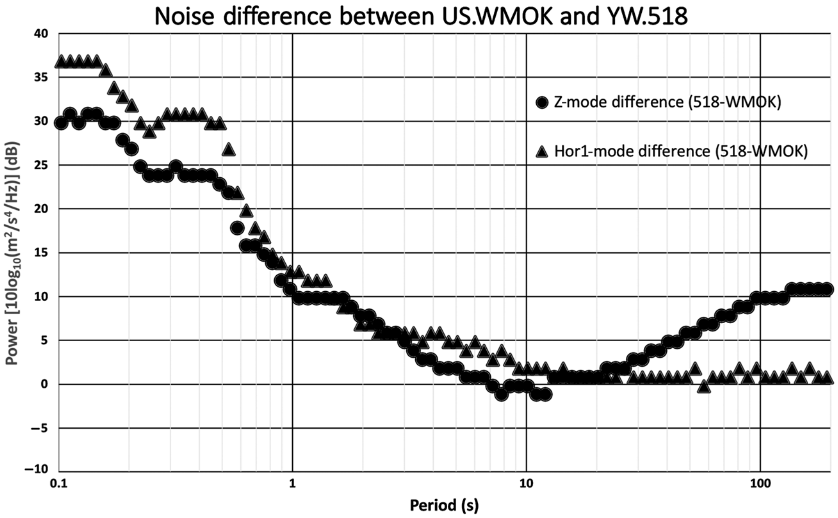
The nodal sensors were deployed for approximately 30 days from 20 June to 20 July. The broadband and infrasound stations were deployed for approximately five months from 20 June to 10 November. The broadband stations had been scheduled for removal in September 2016, but the deployment was extended due to the M_L 5.8 Pawnee, Oklahoma, earthquake on 3 September 2016. SMU, with support from the U.S. Geological Survey, sponsored real-time telemetry for the broadband stations following the Pawnee earthquake.

OVERALL DATA QUALITY AND AVAILABILITY

The entire Oklahoma Wavefields dataset has been archived at the IRIS Data Management Center (DMC) under the network code YW and is freely open and available for use. The data for the experiment in miniSEED format are 931 GB and are accessible using all standard DMC access mechanisms. Using tools provided by IRIS PASSCAL (Hess *et al.*, 2017), the primary copy of data is stored in a PH5 archive. Researchers can use the DMC's PH5-based webservices (see Data and Resources) to extract data with the same tools used to access other data at the DMC, with the added benefit of selecting data gathers based on shot information. Data return for the nodes was 98% during the period 20 June to 20 July 2016. Out of 363 nodes deployed only 5 returned no data. Two such nodes were damaged by shovels during demobilization and one node was destroyed by a road grader. Data return rates for the 18 broadband stations in the network averaged 98% during the period 20 June to 15 November 2016. Only three broadband stations had data problems, including 502 (stopped recording on 10 October 2016), 505 (gappy data from late July through late September), and 510 (offline from 15 September to 10 October 2016).

An analysis of data quality has been conducted and is summarized here. We examined the sample_rms metric computed by the IRIS data quality metrics webservice MUSTANG (Modular Utility for STAtistical kNowledge Gathering; see Data and Resources) to determine average noise levels across the network. The sample_rms metric displays the root mean square (rms) variance of trace amplitudes within a 24-hr window. For our analysis, we calculated median sample_rms values over the period 20 June to 20 July 2016 for the three channels at each node. The resulting medians were then averaged to yield a single sample_rms for each node. Monthly median sample_rms values were fairly consistent across the network, though we did observe elevated values for some nodes deployed on the north–south lines (Fig. 3). We suspect the higher rms values may be due to the installation method or degree of coupling with the near-surface soil.

We also investigated the data quality from the broadband stations. Using MUSTANG to compute noise spectra, we find that from June through November 2016 average broadband spectra are comparable to the closest U.S. reference network station (US.WMOK, 230 km southwest) for periods greater than 10 s, but are 10–35 dB noisier at periods less than 10 s (Fig. 4). We suggest these elevated noise levels (including



▲ **Figure 4.** Differential spectral amplitudes (dB) between Wavefields broadband station 518 and U.S. reference network station WMOK, 230 km southwest of our array. Note that below 10 s period, noise levels at the YW array are increasingly higher than seen at WMOK, sometimes as much as 35 dB higher at 0.1 s/10 Hz.

an odd spectral bump between periods of about 0.3 and 0.5 s) may be related to noise from nearby wind turbines.

In addition to seismic data, the infrasound data collected from the nine stations that were part of this deployment have been archived at the DMC.

INITIAL OBSERVATIONS

The array successfully recorded many local earthquakes, including an M_L 2.7 local event located a few kilometers away (Fig. 5), which clearly shows moveout of the seismic energy across the entire array. Even more exciting was the recording of an M_L 6.3 teleseismic event (Fig. 6), which demonstrated the ability of the nodes to register teleseismic arrivals in spite of their 5 Hz corner frequency.

During the experiment, we installed two nodes directly on the surface adjacent to one of the broadband stations and installed two nodes in the standard manner (buried with the top of the node about 3–5 cm below the surface). A comparison of the spectra from the surface nodes, the buried nodes, and the co-located broadband station showed a dramatic difference in horizontal noise. Spectra for the surface-node horizontals were as much as 15 dB higher than for the buried nodes across a wide range of periods from 0.01 to 100 s (Fig. 7). It is our hope that these results will encourage PIs to take the additional time (~5 min /station) to bury their nodes in the service of collecting quieter data.

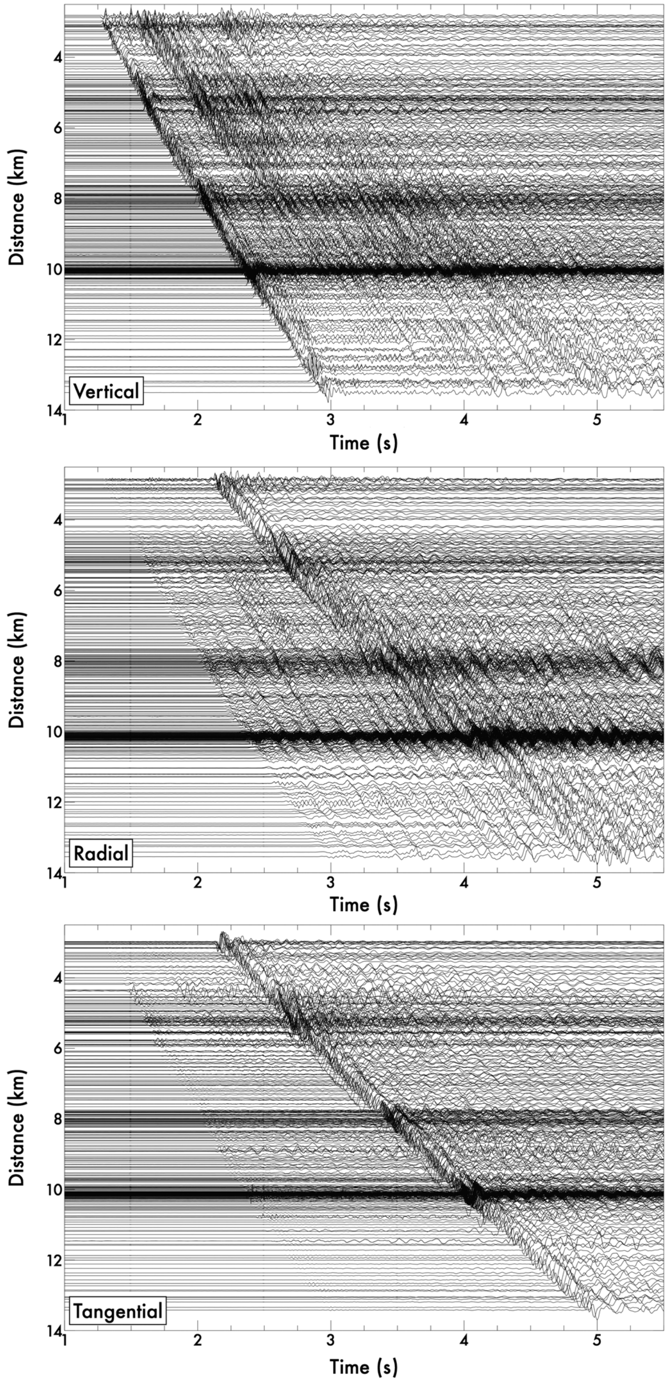
In August 2017, IRIS hosted a student short course focused on data processing and analysis of the Oklahoma Wavefields dataset. Among other topics, students were introduced to high performance computing and parallel processing, ambient noise cross correlation, and visualization concepts. IRIS also used this course to test the performance of a prototype data brick—a large but portable network-attached storage device paired with a small dedicated server. With the server running a local version of the International Federation of Digital Seismograph Networks standardized data access webservice, participants evaluated rapid local distribution of a relatively large dataset; a concept that could be employed in local research groups. Although the size of the Oklahoma Wavefields dataset was not exceedingly large, it did provide a convenient-size test for future large-N datasets and the strategies that will be required to store and share them.

SUMMARY

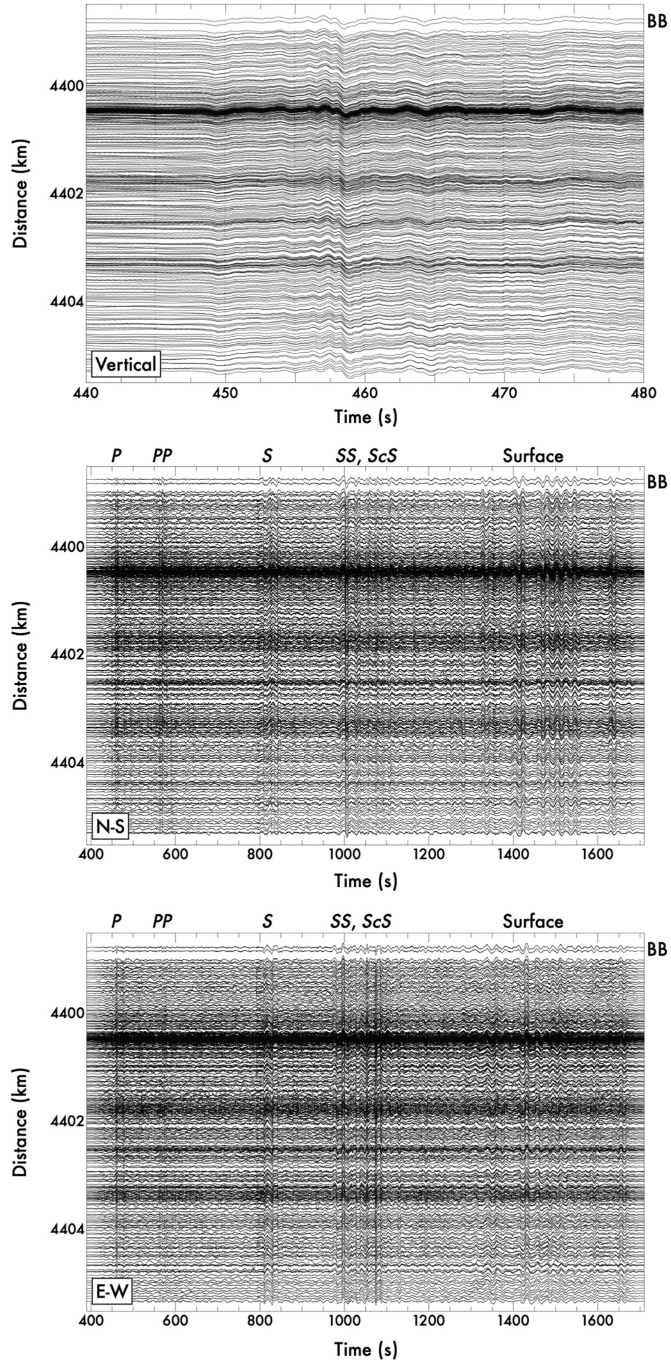
The IRIS Wavefields Demonstration Community Experiment succeeded in fielding and deploying cutting-edge technology to record the full seismic wavefield in a seismically active area of high interest to the community. The experiment yielded one of the first openly available 3C nodal datasets during a time of increasing community interest in these kinds of sensors and employed several array geometries, at least two of which had never been deployed before. Experience gained in the deployment and recovery of new instrumentation has informed best practices that IRIS and the PASSCAL Instrument Center have implemented and shared with the community. Additionally, scientific investigations are exploring the capabilities of the nodal sensors, including receiver function analyses by Ward and Lin (2017). Proximity of the deployment to active seismic lineaments makes it likely that the dataset includes many earthquakes recorded in high fidelity and at close range across a wide spectrum of frequencies. It is our hope that this open dataset will be extensively mined by the community to yield new insights into full wavefield analysis techniques as well as instrumentation capabilities for expanding the range of science PIs can accomplish during field deployments.

DATA AND RESOURCES

Data described and analyzed in this report were collected as part of the Incorporated Research Institutions for Seismology (IRIS) Wavefields Demonstration Community Experiment using Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) and rented instruments. These data have been archived at IRIS Data Management Center (DMC) under network code YW and can be accessed at ds.iris.edu/mda/YW?timewindow=2016-2016. Data products used in this report were produced by MUSTANG, the IRIS data quality metrics service, and can be accessed at service.iris.edu/mustang. The Oklahoma Wavefields dataset has been assigned the following doi: 10.7914/SN/YW_2016. Additional information about the experiment, including photos of the deployment, can be found at www.iris.edu/wavefields. Information about the process used to archive Oklahoma Wavefields dataset

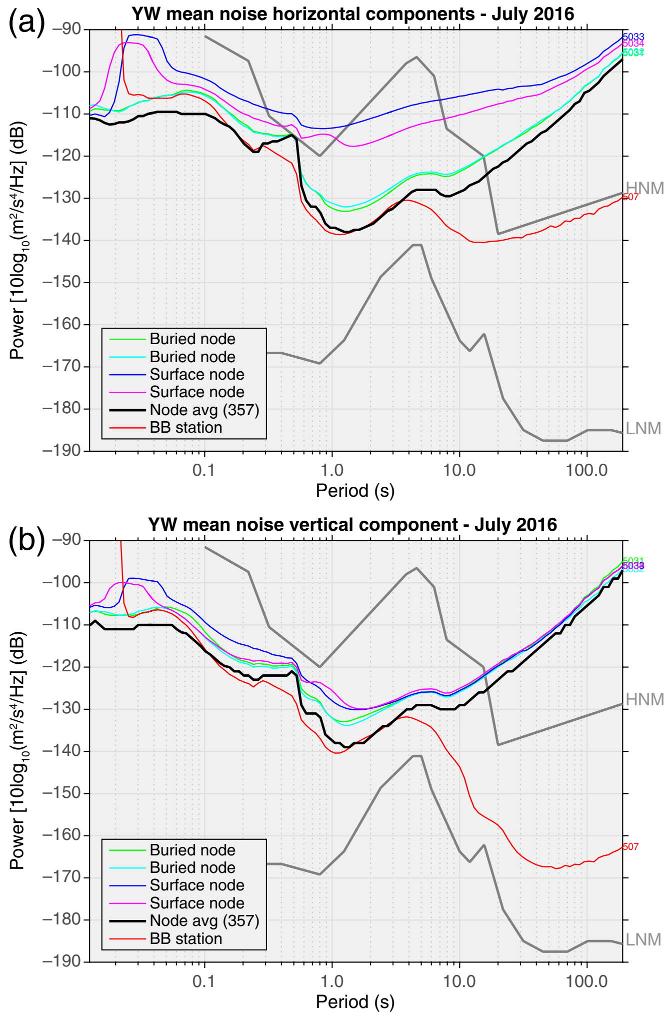


▲ **Figure 5.** Record sections for an M_L 2.7 earthquake on 8 July 2016 that occurred within a few kilometers of the array. This plot includes all 363 nodes and the 18 broadband stations. The data have been rotated to show the radial and tangential signal components and are otherwise unaltered.



▲ **Figure 6.** Record sections for an M_L 6.3 earthquake in Ecuador, which occurred on 11 July 2016. Here, we show traces in velocity, corrected for instrument response, and filtered between 0.05 and 2.00 Hz (below the 5 Hz corner of the nodal instruments) to highlight the consistency of 3C teleseismic arrivals across the array. We focus on 40 s around the *P*-wave arrival on the vertical component, and on a considerably longer time span on the horizontal components to show a variety of body-wave arrivals. The top two traces in each plot are from broadband (BB) stations, providing a clear example of broadband data quality within the array.

in PH5 at the DMC can be found at www.passcal.nmt.edu/content/data-archiving/documentation/active-source. IRIS has created a page of resources for node owners and users, which includes the names and contact information of some community members who own nodes. Principal Investigators (PIs) interested in using nodes and/or collaborating with



▲ **Figure 7.** Averaged median power spectral density (PSD) plot for (a) averaged horizontal components and (b) vertical component of co-located buried nodes, surface nodes, and one broadband station during the period 1–20 July 2016. An averaged median PSD for all 363 nodes in the network (black line) is also plotted. Note the much higher power seen for the two surface nodes across a wide range of periods, especially on the averaged horizontal components. Also of interest are two anomalous bumps in the spectra—one between 0.3 and 0.5 s (likely due to noise from nearby wind turbines), and another between 0.02 and 0.05 s (source unknown). The color version of this figure is available only in the electronic edition.

current-node owners are encouraged to visit www.iris.edu/hq/noderesources. All websites were last accessed on January 2018.

ACKNOWLEDGMENTS

Funding for the Incorporated Research Institutions for Seismology (IRIS) Wavefields Demonstration Community Experiment was provided by the National Science Foundation through the Seismological Facilities for the Advancement of Geosciences and EarthScope (SAGE) award (EAR-1261681). Approximately 100 nodes were leased to this project from the University of Texas at El Paso (Marianne Karplus) and the University of Utah (Fan Chi Lin). A special thanks to Marianne Karplus for her expertise and training on node deployment, as well as assisting with node data offload. Broadband station installations were led by personnel from the IRIS Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center, New Mexico Tech. Southern Methodist University provided telemetry support for the broadband stations (Heather DeShon and M. Beatrice Magnani) as well as installation and service of infrasound stations (Chris Hayward). Infrasound instrumentation was provided in part from the project funded by the U.S. Army Engineering Research and Development Center (ERDC), under W912Hz-11-C-0065, Studies of Broadband Seismo-acoustic and Infrasound Datasets Using Various Sensing Platforms. The Oklahoma Geological Survey provided excellent field support during the installation and demobilization of the equipment. Road access was approved and granted by the Garfield County Commission. Permits for the installation of individual broadband stations and the node gradiometer were granted by seven different and welcoming landowners. Andy Frassetto assisted with the creation of Figures 5 and 6. Most important was the hard work of 30+ graduate students from 20 different institutions who braved the Oklahoma heat to help install these arrays.

REFERENCES

Bowden, D. C., V. C. Tsai, and F.-C. Lin (2015). Site amplification, attenuation and scattering from noise correlation amplitudes across a dense array in Long Beach, *Geophys. Res. Lett.* **42,** 1360–1367, doi: 10.1002/2014GL062662.

Brenguier, F., P. Kowalski, N. Ackerley, N. Nakata, P. Boué, M. Campillo, E. Larose, S. Rambaud, C. Pequegnat, T. Lecocq, *et al.* (2015). Toward 4D noise-based seismic probing of volcanoes: Perspectives from a large-N experiment on Piton de la Fournaise Volcano, *Seismol. Res. Lett.* **87,** no. 1, 15–25, doi: 10.1785/0220150173.

Hansen, S., and B. Schmandt (2015). Automated detection and location of microseismicity at Mount St. Helens with a large-*N* geophone array, *Geophys. Res. Lett.* **42,** no. 18, 7390–7397, doi: 10.1002/2015GL064848.

Hansen, S. M., B. Schmandt, A. Levander, E. Kiser, J. E. Vidale, G. A. Abers, and K. C. Creager (2016). Seismic evidence for a cold serpentinized mantle wedge beneath Mount St Helens, *Nature Comm.* **7,** Article Number 13242.

Hess, D., S. Azevedo, N. Falco, and B. C. Beaudoin (2017). HDF5 based format for integrating and archiving seismic data, presented at the *2017 Fall Meeting, AGU*, New Orleans, Louisiana, 11–15 December, Abstract IN42B-03.

Hillers, G., P. Roux, M. Campillo, and Y. Ben-Zion (2016). Focal spot imaging based on zero lag cross-correlation amplitude fields: Application to dense array data at the San Jacinto fault zone, *J. Geophys. Res.* **121,** no. 11, 8048–8067, doi: 10.1002/2016JB013014.

Lin, F.-C., D. Li, R. W. Clayton, and D. Hollis (2013). High-resolution 3D shallow crustal structure in Long Beach, California: Application of ambient noise tomography on a dense seismic array, *Geophysics* **78,** no. 4, Q45–Q56, doi: 10.1190/geo2012-0453.1.

Nakata, N., J. P. Chang, J. F. Lawrence, and P. Boué (2015). Body-wave extraction and tomography at Long Beach, California, with ambient-noise interferometry, *J. Geophys. Res.* **120,** 1159–1173.

Ringler, A. T., R. E. Anthony, M. S. Karplus, A. A. Holland, and D. C. Wilson (2018). Laboratory tests of three Z-land fairfield nodal 5-Hz, three-component sensors, *Seismol. Res. Lett.* doi: 10.1785/0220170236.

Roux, P., L. Moreau, A. Lecointre, G. Hillers, M. Campillo, Y. Ben-Zion, D. Zigone, and F. Vernon (2016). A methodological approach towards high-resolution surface wave imaging of the San Jacinto Fault Zone using ambient-noise recordings at a spatially dense array, *Geophys. J. Int.* **206,** no. 2, 980–992, doi: 10.1093/gji/ggw193.

Schmandt, B., and R. W. Clayton (2013). Analysis of teleseismic *P*-waves with a 5200-station array in Long Beach, California: Evidence for an abrupt boundary to Inner Borderland rifting, *J. Geophys. Res.* **118,** no. 10, 5320–5338, doi: 10.1002/jgrb.50370.

Wang, Y., F.-C. Lin, B. Schmandt, and J. Farrell (2017). Ambient noise tomography across Mount St. Helens using a dense seismic array, *J. Geophys. Res.* **122,** no. 6, 4492–4508, doi: 10.1002/2016JB013769.

Ward, K. M., and F. C. Lin (2017). On the viability of using autonomous three-component nodal geophones to calculate teleseismic *Ps* receiver functions with an application to Old Faithful, Yellowstone, *Seismol. Res. Lett.* **88,** no. 5, 1268–1278, doi: 10.1785/0220170051.

Wu, S.-M., K. M. Ward, J. Farrell, F.-C. Lin, M. Karplus, and R. B. Smith (2017). Anatomy of Old Faithful from subsurface seismic imaging of the Yellowstone Upper Geyser basin, *Geophys. Res. Lett.* **44,** no. 20, 10,240–10,247, doi: 10.1002/2017GL075255.

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Published Online 11 July 2018