National Science Foundation

Taking Root

The IRIS-Operated Stations of the Central and Eastern US Network

earthscope IRIS USGS science for a changing world

More information is available at: www.usarray.org/ceusn

ON THE COVER. CEUSN station P57A on Homestead Farm, Martinsburg, West Virginia. *Photo credit: Kenneth Oliver*

Contents

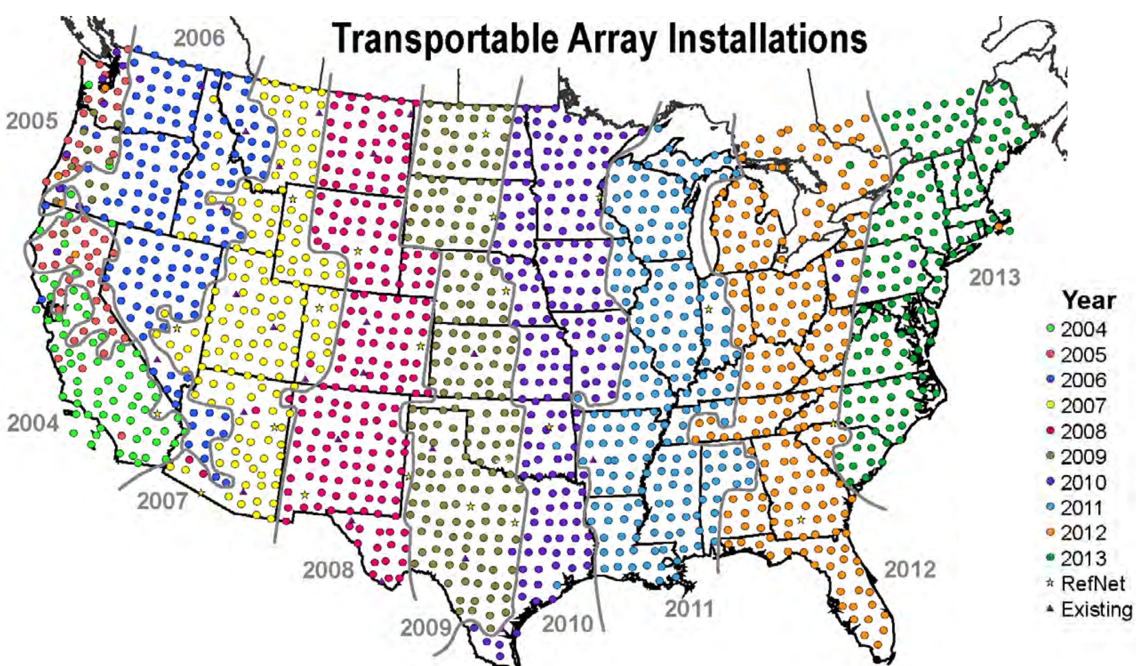
Station technicians Ken Oliver and Dean Lashway hold the vault cover removed from seismic station L49A near Milan, Michigan. The open vault is visible on the right-hand side. *Photo credit: Perle Dorr*

Introduction

The opportunity to improve earthquake monitoring in the central and eastern United States (CEUS) arose through installation of the EarthScope Transportable Array. EarthScope, an ambitious project to study the structure and evolution of the North American continent, was deploying geophysical observatories with funding from the National Science Foundation. The Transportable Array, one of the EarthScope observatories, was already being installed in the CEUS. Operated by the Incorporated Research Institutions for Seismology (IRIS), the Transportable Array was composed of over 400 seismic stations that occupied nearly 1700 sites in a dense 70 km grid across the United States. Each seismic station was installed and remained in place recording ground motion for at least 18 months before being removed and installed further to the east in a moving array. In addition, a wider spaced 300 km grid of stationary seismic stations, the Reference Network (or RefNet), was constructed to serve as a fixed backbone array as the Transportable Array rolled across the country.

The National Science Foundation recognized the unique opportunity afforded by retention of a subset of these temporary Transportable Array seismic stations beyond the standard 18-month deployment. Working with the US Geological Survey, the US Nuclear Regulatory Commission, and the US Department of Energy, the agencies together sought a path forward to keep the Transportable Array stations in place. A new CEUS seismic network was thus created by preserving EarthScope Transportable Array stations that otherwise would have been removed as the Transportable Array continued to roll eastward.

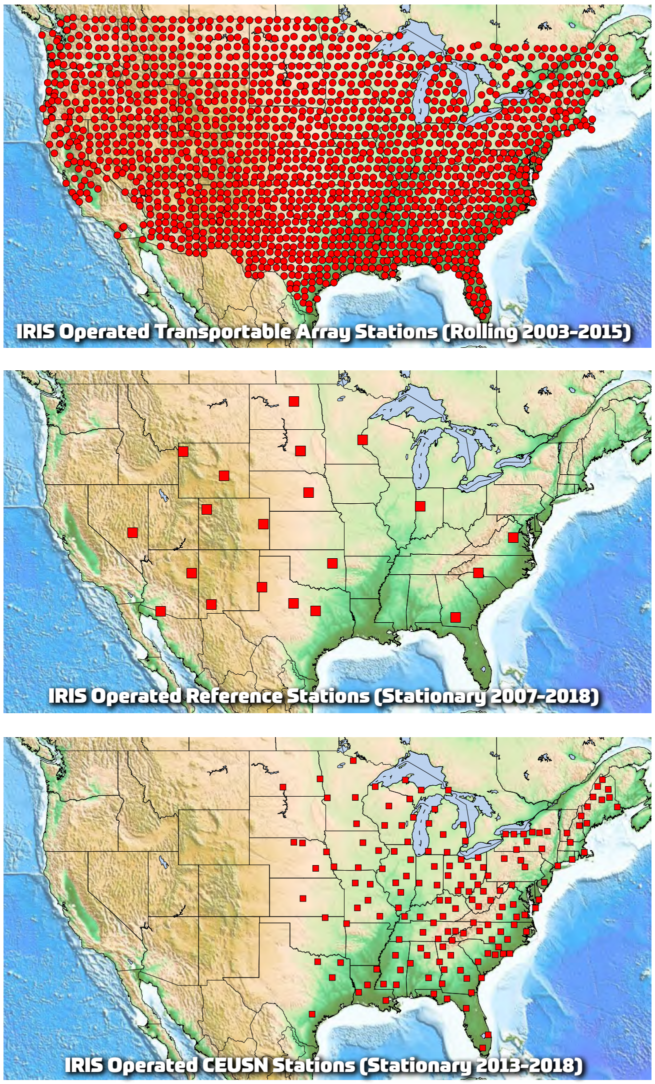
This Central and Eastern US Network (CEUSN) included 159 former IRIS-operated Transportable Array seismic stations that continued to record ground motion data without interruption. The goal of CEUSN was to enable researchers and federal agencies alike to better understand the region's basic geologic framework, background rates of earthquake occurrence and distribution, and seismic hazard potential and associated societal risks. This multi-agency collaboration, an example of "good government," was motivated by the opportunity to use one facility to address multiple missions and needs.



The installation history and station locations for the EarthScope Transportable Array and Reference Network. Stations are colored by the year they were installed as part of a rolling deployment from west to east. Each station remained in the ground for at least 18 months.

Planning, Collaborations, and Oversight

A multi-agency working group of stakeholders was established to identify and prioritize which Transportable Array stations in the eastern half of the United States should continue long-term operations as part of the CEUSN. The Transportable Array Station Selection (TASS) working group applied multiple criteria for site selection to maintain a close-to-uniform distribution while assessing each site's proximity to regions with known seismic hazards, nuclear power plants and other critical facilities, and potential scientific targets. The site selection also de-emphasized regions with significant numbers of existing permanent seismic stations in order to fill in areas that most needed coverage. The IRIS Transportable Array staff worked closely with regional seismic network operators during initial installation of stations, so sites were located, constructed, and operated with input from local contacts. An initial concept for the network was that one in every four stations of the Transportable Array footprint would be retained, which was the basis for the "N4" (one-in-four) network code that was used for the CEUSN.



The seismic stations installed and operated by IRIS as part of EarthScope: (top) Transportable Array of ~400 temporary stations that were installed in a rolling deployment across the United States from west to east from 2003 to 2015. (middle) Reference Network stations that were installed to fill in gaps in the existing seismic coverage to make a 300 km backbone. (bottom) CEUSN stations that were first installed as Transportable Array stations and then operated longer term by IRIS. The Reference Network and CEUSN stations were transitioned to the US Geological Survey and other operators in 2018 and continue to collect observations. Station lists and maps are available at:

> http://ds.iris.edu/gmap/#network=_CEUSN
> http://ds.iris.edu/gmap/#network=_US-REF
> http://ds.iris.edu/gmap/#network=TA

A second working group was formed to review and advise IRIS on the CEUSN as it related to scientific goals and objectives that could be addressed with data recorded by the network. Membership overlapped with the TASS but was intentionally very broad to recognize and incorporate the viewpoints of all CEUSN stakeholders, including university researchers, federal and state governments, and those involved in policy. Because the TASS handled all station location selection, this second working group focused on issues such as the incorporation of the network and the new data into state or regional seismicity assessments for improved hazard characterization.

Both working groups have since been disbanded; however, the valuable feedback that they provided to IRIS was used to improve planning and operations for the duration of the CEUSN.

The National Science Foundation provided the funding for IRIS to retain and operate the CEUSN stations. The US Geological Survey, the federal agency charged with monitoring and reporting earthquakes, assessing earthquake impacts and hazards, and conducting research into the causes and effects of earthquakes, also provided funding and, more recently, assumed operation of the majority of the former Transportable Array stations in the CEUSN. Some of the remaining stations were transitioned to other operators to improve coverage of regional seismic networks or to support educational opportunities with universities by continuing to collect observations of global earthquakes for scientific research.

Station Operations

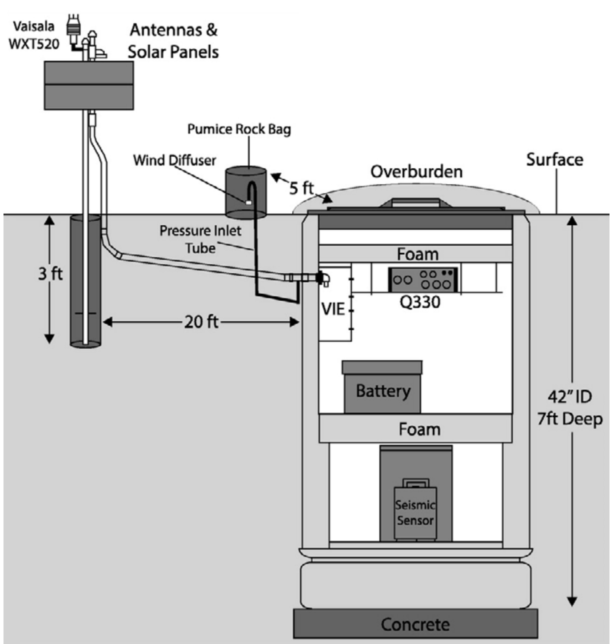
The seismic stations installed and operated by IRIS in the Lower 48 states as part of the EarthScope Transportable Array, the Reference Network, and the CEUSN N4 network were as uniform in design and construction as possible. Each consisted of a refrigerator-sized vault buried in the ground that had a poured concrete base on which the seismometer was placed and a water-tight lid that was covered with soil to help reduce temperature fluctuations inside the vault. The batteries and all electronics for storing and automatically transmitting the data in near-real time were also contained in the underground vault. Solar panels were installed nearby to power the station, and fencing was often erected to protect the vault and panels from damage from humans, farm equipment, and livestock. Additional equipment, including atmospheric pressure, strong motion, infrasound, and weather sensors, were also installed at a subset of stations.

The uniformity of the seismic station configuration was essential for the installation-maintenance-removal process of the EarthScope Transportable Array across the Lower 48 states as well as for recording high-quality data. Station components, such as sensors, batteries, dataloggers, and

IRIS station specialists Mike Couch and Doan Nguyen carefully handle the seismometer during installation of station K57A next to a cornfield in Scipio Center, New York. *Photo credit: Perle Dorr*

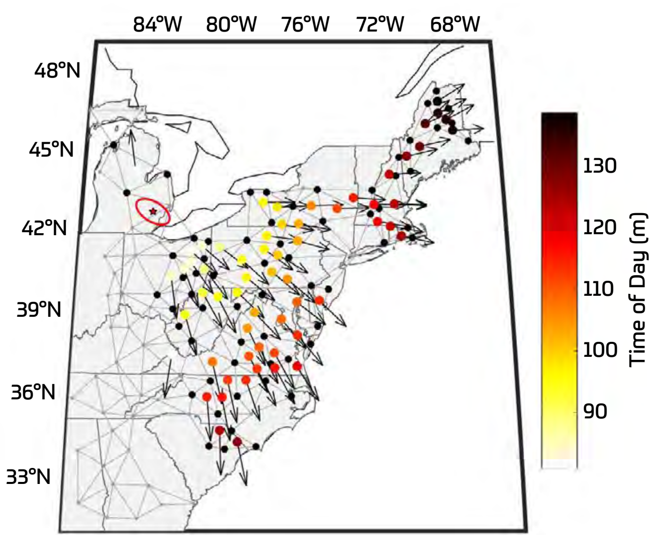
Vault lids were secured with chains and locks before being covered with dirt, like this one at station V51A in Loudon, Tennessee.

A completed seismic station has a small footprint with just a fence surrounding the solar panels and a mound of dirt covering the vault. The vault contains the seismometer, batteries, and electronics. Pictured here is station K50A in Casco, Michigan, where fencing is essential for keeping out the landowner's curious cows.



Schematic of a station showing the seismometer, batteries, and communications equipment inside the underground vault and the above ground solar panels. *Figure from Tytell et al., 2016,* Bulletin of the American Meteorological Society, *https://doi.org/10.1175/BAMS-D-14-00204.1* solar panels, were largely interchangeable, allowing field teams to efficiently troubleshoot a station issue or swap in a spare part. Data quality specialists at the Array Network Facility located at the University of California San Diego, were constantly monitoring stations for unusual recordings and kept in close communication with the field teams. Equipment shipments, inventory, and testing was coordinated with the IRIS PASSCAL Instrument Center (PIC) in Socorro, New Mexico. During the period that IRIS operated the CEUSN N4 stations, three highly experienced station specialists kept the equipment up and running through hurricanes, floods, vandalism, insect infestations, lightning strikes, and snow, and enabled IRIS to transfer a fully operational network to the US Geological Survey for continuing service. The high quality, consistency, and data completeness of the Transportable Array, Reference Network, and CEUSN while operated by IRIS is a testament to this hardworking team in the field, at the IRIS PIC, and at the Array Network Facility. These same attributes extend to the collected data set that has enabled exciting science studies and findings.

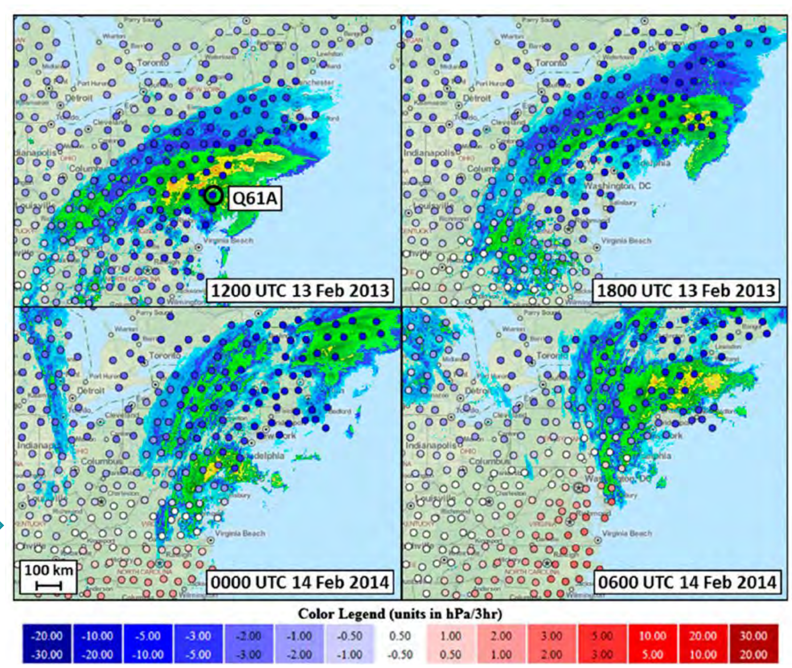
After the US Geological Survey took over operations of the former CEUSN stations, some operation-related characteristics were modified. For example, the US Geological Survey opted to only archive the high sample rate seismic data and only collect strong motion data for events instead of collecting these data continuously. Additional changes to the network, channel, and location codes were also incorporated. For specifics, see a sample station at the IRIS Data Management Center: http://ds.iris.edu/mda/N4/T42B/.



Infrasound recordings at CEUSN stations were used to estimate the timing, location, and the size of a bolide, or large meteor, that exploded and disintegrated in the atmosphere above Michigan on January 17, 2018 (optimal location of the bolide explosion is indicated by the star circled in red). Each grouping of three stations with a coherent detection produced an arrival time displayed in minutes after the start of the explosion event and the direction of the signal is shown by the arrows. *Figure from Hedlin et al., 2018,* Seismological Research Letters, *https://doi.org/10.1785/0220180157*

Observations of Opportunity: Collecting Meteorological and Infrasound Data

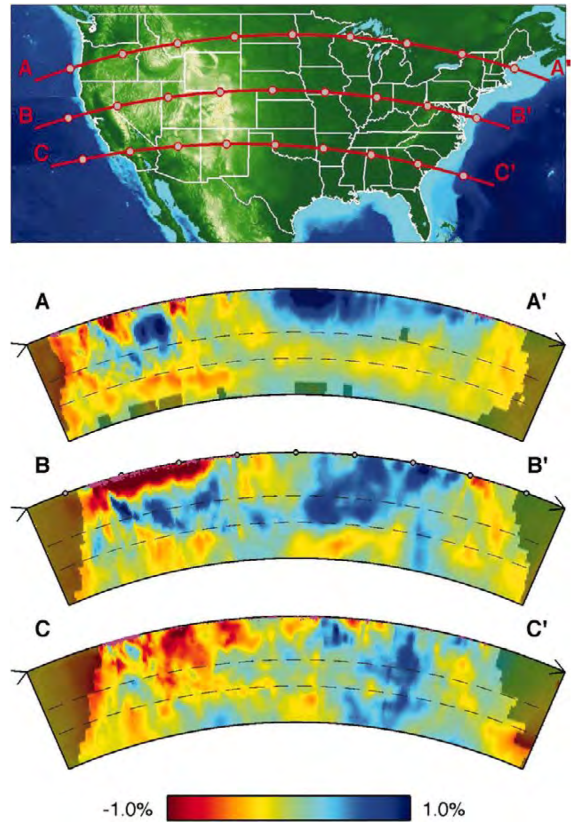
Transportable Array stations in the CEUSN were equipped with barometers and infrasound (this is sound at frequencies below 20 Hz, the nominal lower limit of human hearing) microphones to better understand the signals and noise recorded by the collocated broadband seismometers. More complete meteorological sensors that observed wind and precipitation were field tested on a subset of stations in North Carolina and Virginia, laying the groundwork for collaborations with the National Oceanic and Atmospheric Administration, the National Weather Service, and the MesoWest cooperative project at the University of Utah. These collaborations with meteorological partners were strengthened and expanded as the Transportable Array was built in Alaska, enabling even more science.



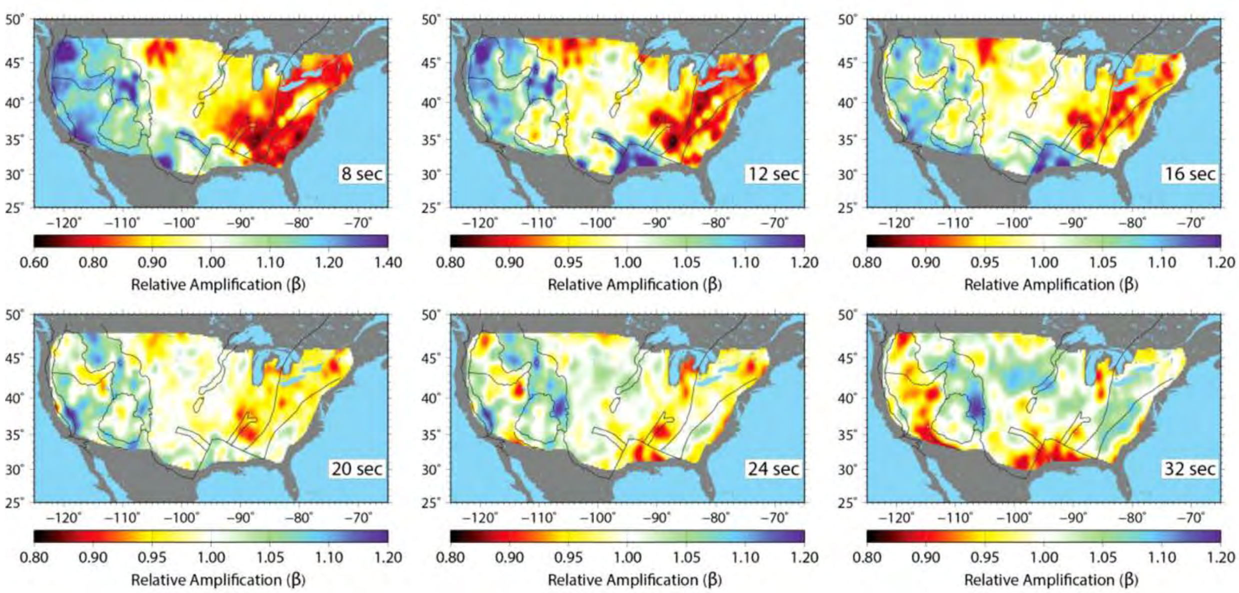
Pressure as recorded by Transportable Array stations (circles) (some to be incorporated into the CEUSN) in New England. Red colors indicate higher pressure tendencies and blue colors indicate lower pressure tendencies. Overlaying the stations is radar reflectivity imagery depicting a snowstorm that moved northward over the course of two days in 2014. *Figure from Jacques et al., 2015,* Monthly Weather Review, *https://doi.org/10.1175/MWR-D-14-00274.1*

Imaging the North American Continent

The primary goal of the EarthScope Transportable Array was to map Earth's structure beneath the North American continent by collecting high-quality recordings of earthquakes using broadband seismometers installed on a dense grid. Researchers have used a number of methods, both well established and revolutionary, to achieve this goal and continue to analyze the collected data set to improve their models. Interesting Earth features observed using Transportable Array data have also prompted follow-on denser deployments of sensors to enhance the resolution.



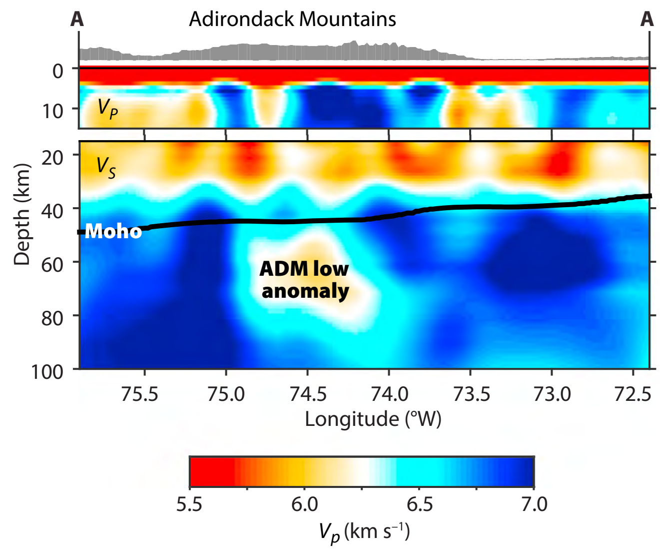
The fastest and first-arriving seismic waves from earthquakes occurring around the world recorded by the Transportable Array stations were used to generate images of Earth beneath North America. Similar to a CT scan or CAT scan, these cross sections of the mantle down to 1000 km depth show variations in the speed that seismic P waves travel through Earth. Blue colors indicate faster P-wave speeds, and red colors indicate slower speeds. The dashed lines show depths of 410 km and 660 km, which corresponds to the depths within Earth where materials change properties. *Figure from Burdick et al., 2017,* Seismological Research Letters, *https://doi.org/10.1785/0220160186*



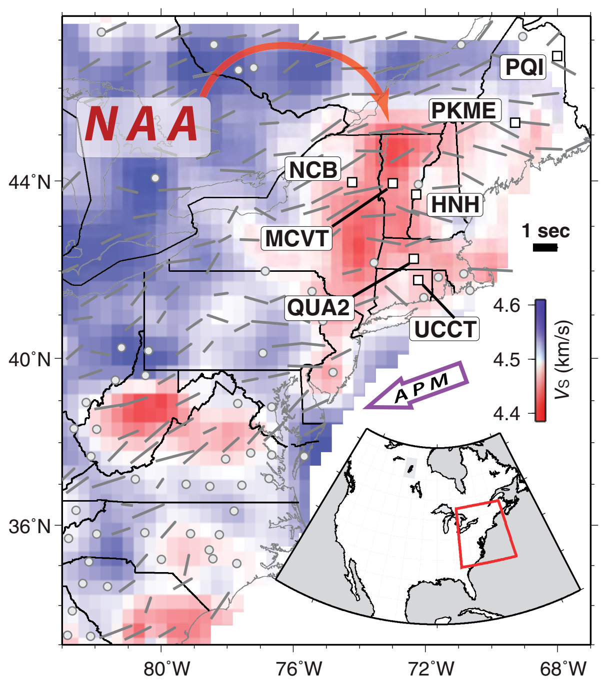
A new technique was developed to use the background noise recorded by Transportable Array stations instead of the earthquake signals to image Earth's structure beneath North America. These maps show the surface-wave amplification measurements using the ambient noise cross-correlation technique. Each map is referenced to an average, with higher amplification in blue and lower amplification in red. The top row of higher frequencies outlines tectonic features in the upper 10 km of the crust, while the maps in the bottom row are at lower frequencies that reach deeper into Earth—down to the upper mantle. *Figure from Bowden et al., 2017,* Journal of Geophysical Research: Solid Earth, *https://doi.org/10.1002/2017JB014804*

Uplift in the Adirondacks

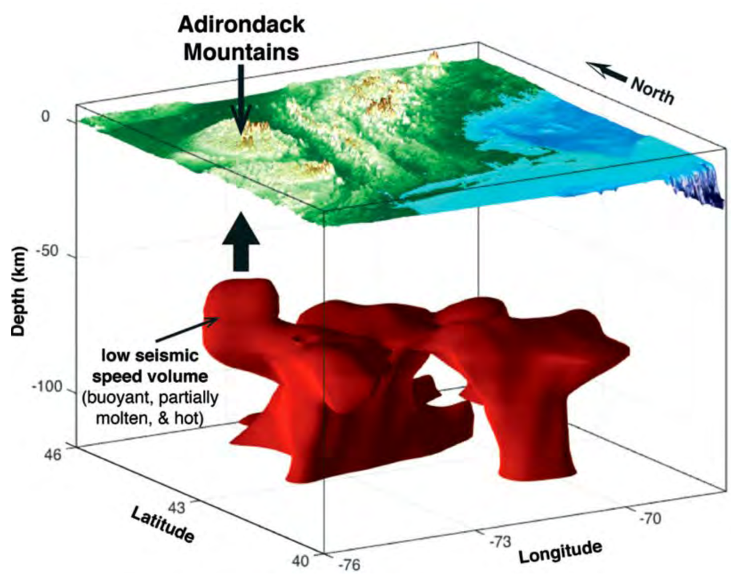
The formation of the Adirondack Mountains in northeastern New York has puzzled scientists for decades. Now, advanced seismic imaging techniques allow scientists to view the lithosphere beneath the mountains to determine what is causing them to rise. Using data from over 175 broadband seismometers, including instruments in the EarthScope Transportable Array and CEUSN, researchers have been able to detect an area beneath the Adirondacks that slows down seismic waves. This low velocity anomaly, likely due to high temperature, is located at a depth of 50–85 km and has a diameter of ~70–100 km. Data also show that this small region may be connected to a larger and deeper zone of low seismic wave speed that runs beneath southern New England and eastern New York. Some researchers speculate that these features are the result of mantle upwelling when New England passed over the Great Meteor hotspot, eventually uplifting the Adirondack Mountains.



An area beneath the Adirondack Mountains (ADM) that slows down seismic waves may be related to uplift of this region. These cross sections each show two models of seismic wave speeds recorded by seismic stations at the surface: the top uses the first-arriving P waves for the top 15 km of Earth and the bottom uses later-arriving S waves to image from 15 km to 100 km depths. The boundary between Earth's crust and mantle—the Moho—is shown as the thick black line. *Figure from Yang and Gao, 2018,* Geophysical Research Letters, *https://doi.org/10.1029/2018GL078438*



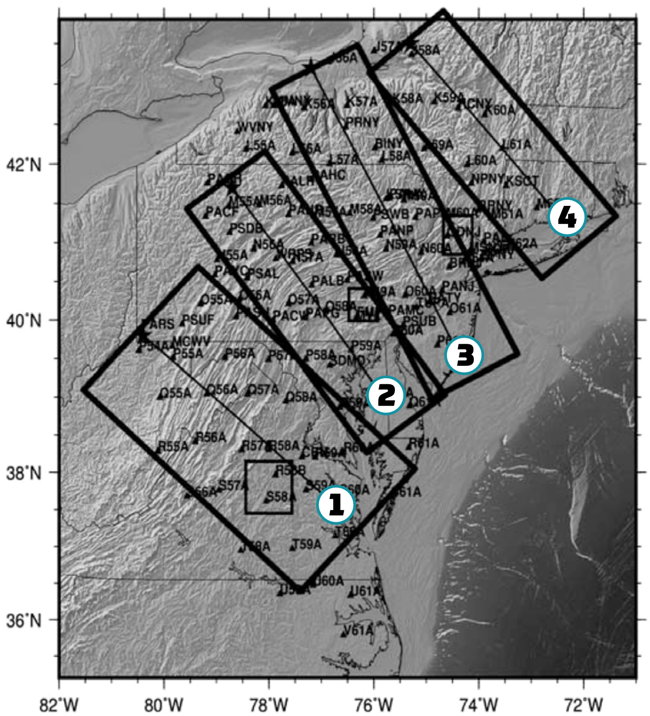
Using a different modeling technique, the same area beneath the Appalachian region (labeled "NAA") appears to be deformed more recently. The average shear wave splitting measurements (gray bars) show the alignment of the fast polarization direction, which is related to how the material deformed. Circles are stations without any detected alignment. *Figure from Levin et al., 2017* Geology, *https://doi.org/10.1130/G39641.1*

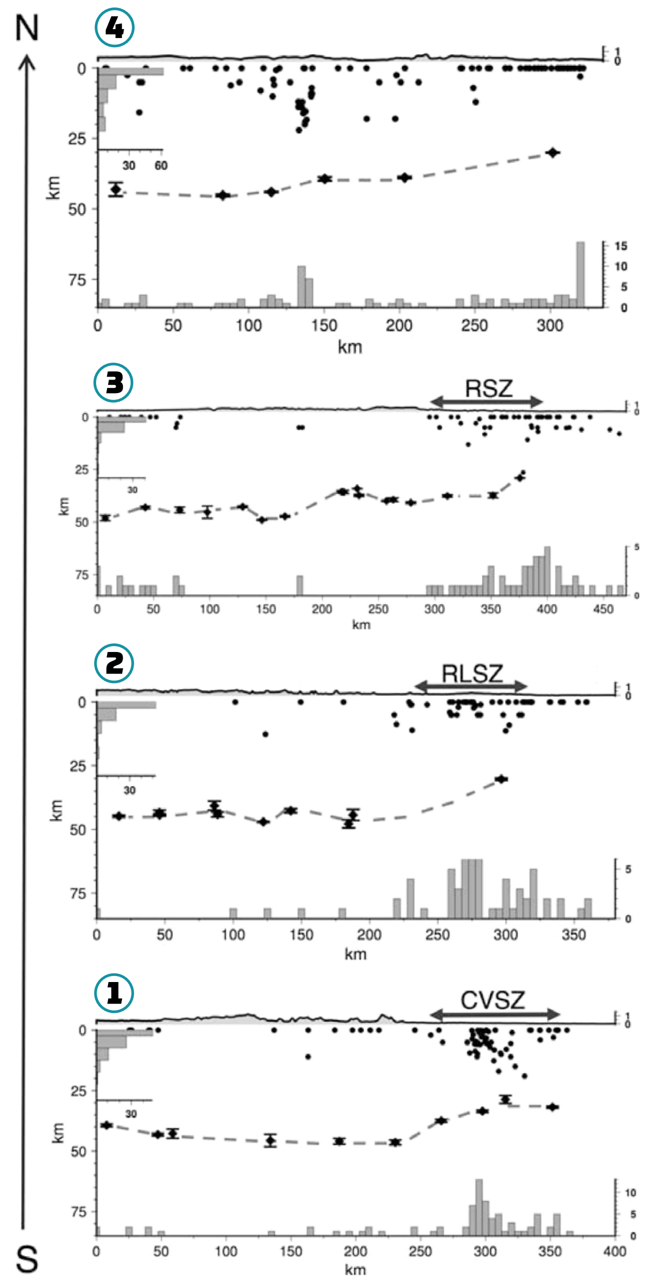


A three-dimensional view of the area of low seismic speeds. *Figure from Yang and Gao, 2018,* Geophysical Research Letters, *https://doi.org/10.1029/2018GL078438.*

Earthquake hazard maps are created primarily by using the history of earthquake occurrence to determine where future earthquakes might occur, how big those earthquakes might be, and how often they are likely to occur. This information is then combined with knowledge of how local and regional ground conditions and geology are likely to impact what is felt during an earthquake and how shaking could affect local population centers and infrastructure.

In areas like the central and eastern United States, seismic hazard assessment is difficult because the earthquake record is relatively short, seismic networks have historically been sparse, and the driving mechanisms for seismicity are not well constrained. However, the increase in seismic station density as a result of the EarthScope Transportable Array and other state and regional networks has provided researchers with an unprecedented view into the seismicity patterns of this region. Using earthquake catalogs from 1568 to 2016, including data from 26 permanent EarthScope Reference Network stations and 76 Transportable Array stations, researchers found that changes in crustal thickness associated with the Appalachian Mountains coincide with earthquakes clusters. It is speculated that the thicker crust acts as a buttressing force that serves to concentrate stress and seismicity just where crustal thickness changes, which could help identify and understand seismic hazards in these areas.

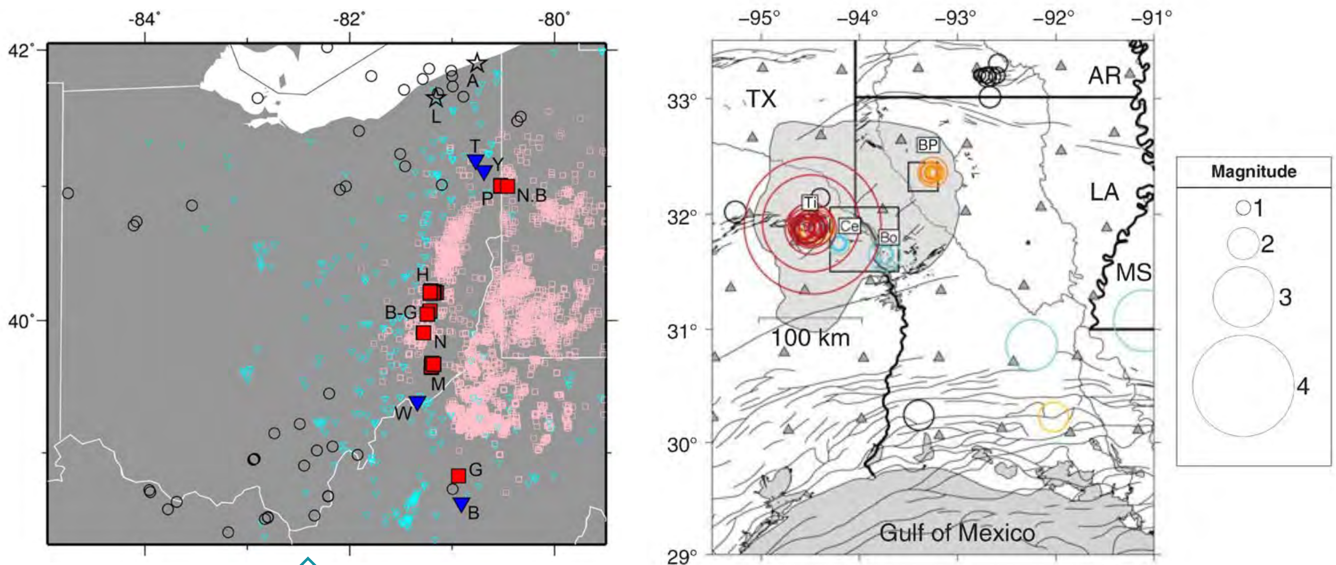




Map showing the seismic stations used to calculate the thickness of Earth's crust beneath the Mid-Atlantic states, with cross sections on the right showing both the top of the crust (diamonds connected by a dashed line) as well as earthquakes (black circles). CVSZ = Central Virginia seismic zone. RLSZ = Reading-Lancaster seismic zone. RSZ = Ramapo seismic zone. *Figure modified from Soto-Codero et al., 2018,* Seismological Research Letters, *https://doi.org/10.1785/0220170084*

Monitoring for Natural and Human-Induced Earthquakes

There is significant interest in induced seismicity, especially in the central and eastern United States. While seismic networks have been installed in some areas, most of this region has not been adequately monitored for seismicity. A catalog that lists all low-magnitude earthquakes that occurred in these areas is important for establishing the background levels of seismicity prior to any hydraulic fracturing activities or wastewater injection. It is also important to be able to detect smaller ground motions that may be induced or triggered by human activities. Denser spacing of high-quality, continuously recording stations can address both of these issues. When the Transportable Array stations were installed in this region, the sampling rate for the seismic records was increased from 40 samples per second to 100 samples per second, which improved the ability of this network to detect and record very small events.



(left) Earthquakes (2010–2017) detected using Transportable Array stations (not drawn) in Ohio and neighboring states, some of which are now operated by the Ohio Geological Survey. The dark blue triangles are earthquake sequences induced by wastewater injection and the red squares are earthquake sequences induced by hydraulic fracturing. Letters label the earthquake sequence names: A: Ashtabula, B: Braxton, B-G: Belmont–Guernsey, G: Gilmer, H: Harrison, L: Lake, M: Monroe, N: Noble, N.B: North Beaver, P: Poland, T: Trumbull, W: Washington, and Y: Youngstown. Smaller cyan triangles show wastewater disposal wells, and horizontal drilling wells are shown in pink squares. Circles are earthquakes that likely occurred naturally. Stars are earthquakes that may have been induced in the 1980s. *Figure from Brudzinski and Kozlowska, 2019,* Acta Geophysica, *https://doi.org/10.1007/s11600-019-00249-7* (right) Earthquakes detected using Transportable Array stations (gray triangles) in Texas and Louisiana from early 2010 to mid-2012. *Figure from Walter et al., 2016,* Seismological Research Letters, *https://doi.org/10.1785/0220150193*

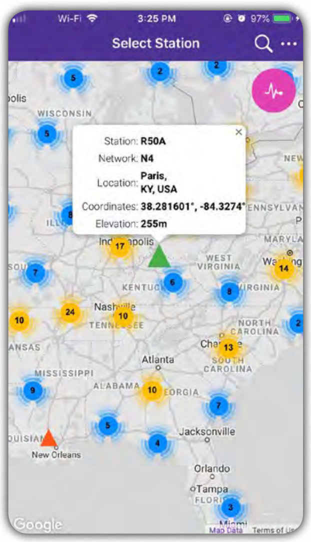
While the Transportable Array was in the central and eastern United States, 64%–83% of the seismic events detected were located only by EarthScope stations.

– L. Astiz, Array Network Facility, University of California San Diego

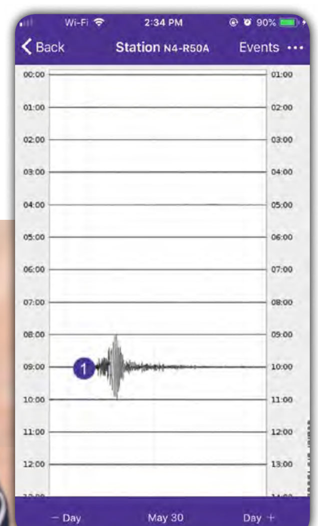
Station Monitor

The successful deployment of EarthScope Transportable Array seismic stations across the contiguous United States was attributed in part to the generosity of more than 1000 private landowners who hosted a majority of the nearly 1700 stations on their property. While typically solar panels and a mound of dirt were the only visible components of these stations, the landowners could easily view the real-time ground motions being recorded by the seismometers at "their station" with an easy-to-use web-based application. The original version of Station Monitor enabled the landowner to enter their station's unique identifier to view today's or yesterday's recording of all ground motion at their site. The landowner could also select a recent earthquake from a list and see what that event looked like as recorded at their station. Anyone with an Internet-connected computer could also use the Station Monitor application by entering a zip code to view the recording from the nearest station.

The IRIS Station Monitor has been re-designed as a free app for mobile devices and is available from the Google Play and Apple stores as well online as an upgraded web-based application. With a new look and enhanced features, the user can now view recordings from CEUSN stations as well as thousands of seismic stations reporting data in real time from around the world. These recordings show ground motion generated by earthquakes, volcanic eruptions, and other seismic sources such as storms, trains, and quarry blasts. Basic information about seismic recordings, introductory videos, and links to earthquake-related resources are also available in the improved and easy-to-use IRIS Station Monitor. The app has been useful for public outreach and for monitoring any broadband seismic stations with real-time data archived at the IRIS Data Management Center.



Download the free IRIS Station Monitor app from the Google Play and Apple stores or use online at www.iris.edu/app/station_monitor.



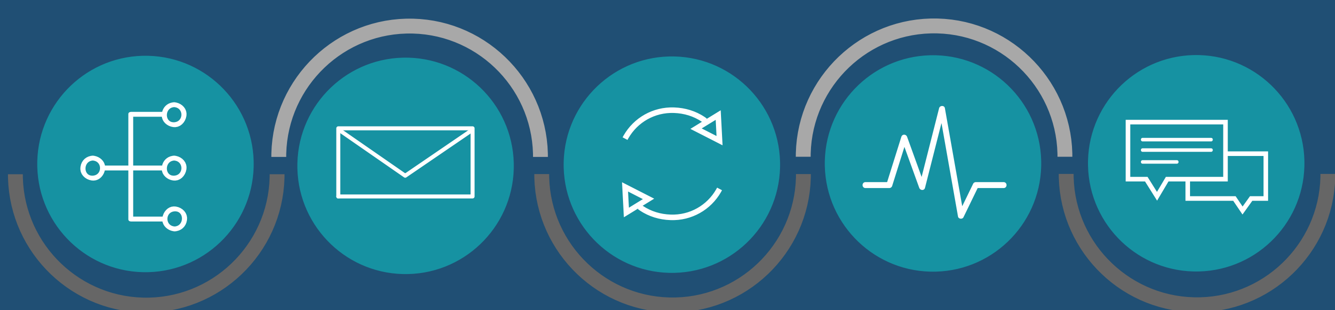
Transitioning Stations to Other Operators

Throughout deployment of the EarthScope Transportable Array, IRIS encouraged the transitioning of stations to longer-term operation by other groups. Because station equipment was uniform and the network was already operating on efficiency of scale, IRIS offered a subscription service to universities and regional network operators to assist them in keeping a station in the ground and recording data. In these cases, IRIS would continue to be responsible for ongoing permits, station maintenance, and data delivery. In other cases, a new operator would work with IRIS to obtain their own permits with the landowners hosting stations, then purchase the equipment and take over maintenance responsibilities and data delivery.

In 2018, along with the transfer of the 143 CEUSN N4 and Reference Network stations to the US Geological Survey, IRIS transferred an additional 11 stations to other operators and removed the 24 remaining stations to conclude the Lower 48 portion of the EarthScope Transportable Array, Reference Network, and CEUSN.

The process of transferring a currently operating seismic station from one operator to another may seem simple at first, but there were many potential complications and delays along the way. All station transfers required obtaining a new permit with the landowner or agency, transitioning communications accounts and billing, validating inventory and requesting equipment ownership changes, setting up metadata and servers, carefully coordinating the switchover of real-time data acquisition and archiving at the IRIS Data Management Center, and transferring station servicing and maintenance history. The complexity of station transfers was compounded when there were differences between new operators—different contacts, regulations, requirements, needs, and experience. The end result of all that work was to keep a functional seismic station in the ground to record and archive high-quality data for the seismological community that ultimately will advance discovery, research, and education in seismology, and improve our understanding of seismic hazards.

Steps for transitioning a seismic station to a new operator



Coordinate with new operator for timeline, responsibilities, contacts, and expectations.

Re-permit the site with landowner or agency for new operator and obtain release of current permit.

Confirm telemetry accounts and metadata are set up on receiving end with new operator.

Test telemetry transfer then proceed with full transfer. Confirm data acquisition at the IRIS Data Management Center.

Provide site history, equipment maintenance, and additional guidance on operations.

Legacy of the Transportable Array in the Lower 48

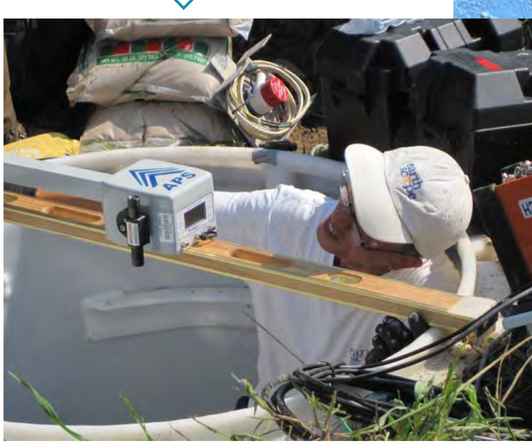
Execution of the EarthScope Transportable Array depended on deployment of seismic stations at a scale that had not been previously attempted in the United States. With such a vast geographic area to cover and the extremely large number of components, seismic station construction strategies necessitated consistent procedures. At the same time, operation of such a large-scale network provided many new opportunities, such as the development of state-of-health display tools. The core tenets of station uniformity, independently operating field crews, and continuous review of data quality were maintained by a highly coordinated team distributed across the United States.

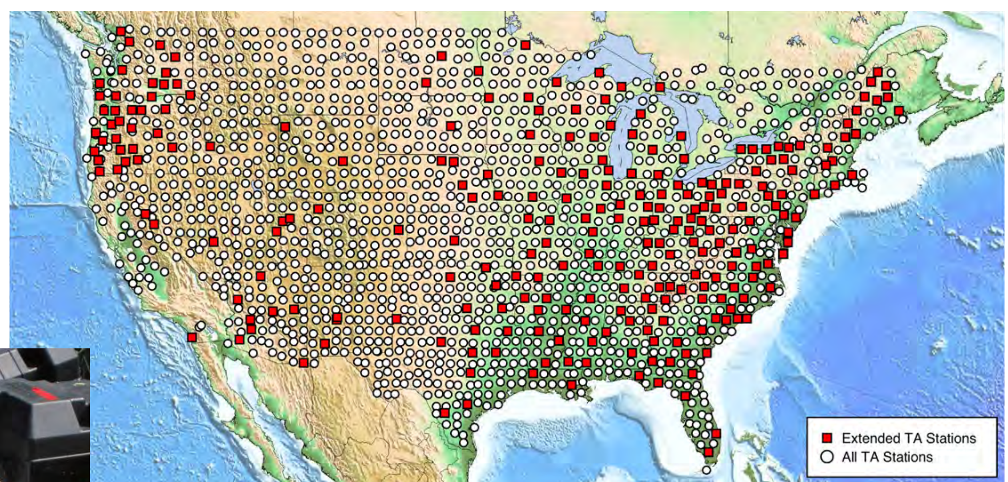
Primarily using private landowners to host the stations rather than state and federal agency landowners resulted in a faster permitting process and contributed directly to the project's public outreach component. Additional strategies, including the incorporation of collocated sensors such as pressure and meteorological sensors, have built new collaborations outside of the field of seismology and strengthened existing partnerships.

Procedures were frequently evaluated and modified as necessary to hone the strategy, incorporate newly available technologies, and respond to operational mode changes from planning to installation and construction, and from maintenance to closure or transfer. These stages often overlapped, and changes would be made to meet the needed expertise and staffing requirements. Throughout the whole process, a strong team culture was encouraged through weekly team calls and an annual in-person team meeting. These intentional activities brought the domain expertise of each team member to the table, encouraging discussion and understanding of the roles each person played. An invited researcher would also present results at the team meetings, which motivated the team to take individual pride in the scientific accomplishments of the Transportable Array project.

The Transportable Array has provided a model for all aspects of seismic network operation, in addition to creating a legacy of stations that continue to collect data in the footprint left by the Transportable Array. Techniques for deploying and operating the Transportable Array have already been utilized by other programs throughout the world such as ChinArray or proposed for Subduction Zone 4D and Canada's EON-Rose. The established procedure for transitioning stations to other operators, developed during deployment of the Transportable Array, Reference Network, and CEUSN in the Lower 48 states, is now being followed during the final segment of the EarthScope Transportable Array in Alaska.

IRIS station specialist Doan Nguyen confirms the orientation of a sensor at station K57A near Scipio Center, New York. *Photo credit: Perle Dorr*





A map showing all sites occupied by EarthScope Transportable Array and Reference Network (white circles). The Transportable Array provided ~70 km spacing and dense coverage of the entire Lower 48 states and parts of southern Ontario and Quebec, Canada. All Transportable Array stations were installed and operated by IRIS for at least 18 months. The red squares indicate stations that later transitioned to longer-term operation by a university, state, or federal agency—the large majority as part of the CEUSN.

Acknowledgments

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- IRIS Program Manager Robert Busby, who has managed the execution of the EarthScope Transportable Array from the initial vision through implementation and operations, and, finally, through transition into the CEUSN legacy.
- TASS Working Group Members: Gregory Anderson, Harley Benz, Robert Busby, Matt Fouch, Art Frankel, Mike Hansen, Robert Herrman, Annie Kammerer, Won-Young Kim, Tim Leftwich, Stephen McDuffie, Anne Meltzer, Jeffrey Munsey, Andrew Murphy, David Spears, Brian Stump, Mitch Withers, and Robert Woodward.
- CEUSN Working Group Members: Rasool Anooshehpoor, Gail Atkinson, Grant Bromhal, Mike Brudzinski, Won-Young Kim, Chuck Langston, Jim Lewkowicz, Tom Owens, Tom Pratt, and David Spears.
- EarthScope Transportable Array construction, installation, service, and removal teams included many individuals, but Mike Couch, Doan Nguyen, and Howard Peavey were especially involved in the CEUSN. For insight into their world, read a few of their stories written by Maia ten Brink at http://www.usarray.org/field_stories.
- All landowners, state and federal agencies, and universities who supported science by hosting CEUSN and Transportable Array equipment on their property.
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The Transportable Array staff and collaborators at the 2013 annual Transportable Array Team Meeting held in Woods Hole, MA.

Station specialists Mike Couch and Doan Nguyen get ready to install the vault interface enclosure for station K57A, which contains the electronics equipment that controls the station's power, data collection, and communications. *Photo credit: Perle Dorr*

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CEUSN station L44A on Ryerson Woods Lake County Forest Preserve in Illinois, now operated by Northwestern University. *Photo credit: Dean Lashway*

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