The Design and Implementation of

EarthScope's USArray Transportable Array

in the Conterminous United States and Southern Canada

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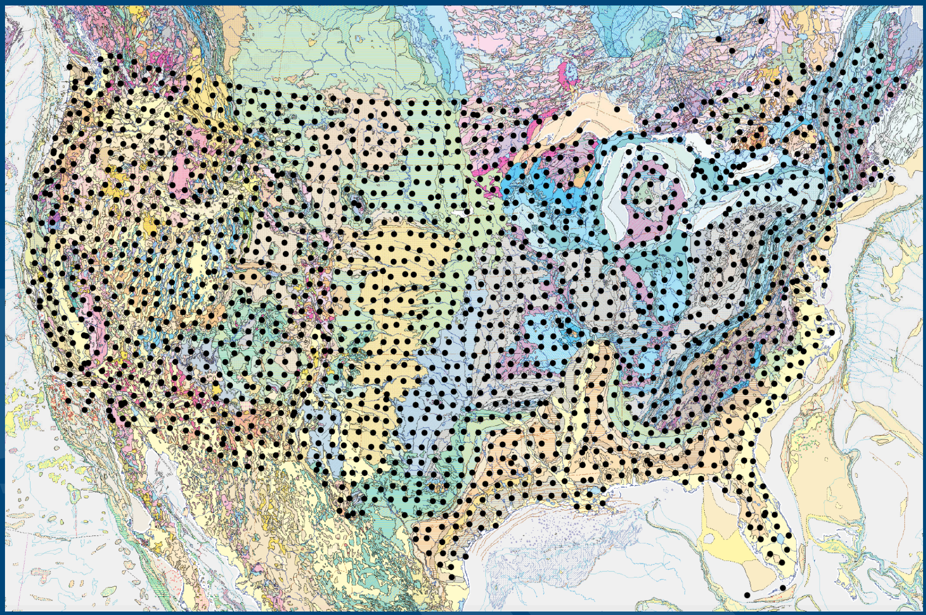
COVER. These images portray the installation of the first Transportable Array (TA) station, TA.109C (Miramar, CA), on May 10, 2004. Its appearance shows numerous small differences when compared to later stations as experience operating the TA resulted in tweaks to the design. This station operated throughout the entire duration of the TA program.



ABOVE. The entire Lower-48 TA, including contributing network stations, is overlain on a map of the bedrock geology of North America (Reed et al., 2005).

A note on the purpose of this document: This report documents the design and implementation details of the complete as-built Transportable Array in the Lower 48 United States and southernmost Canada. The emphasis is on the details that are essential for other network operators and data users to know, including exactly what equipment was used in the TA, how it was installed, and how it was operated. We also explore some of the specific decisions that aided the success of this project.

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1. The Transportable Array

1.1 CONTEXT AND LEGACY

This report reviews key aspects of the design, implementation, and operation of the Transportable Array (TA), a large network of seismometers (Figure 1-1) operated across the conterminous United States (the "Lower 48" or L48) by the Incorporated Research Institutions for Seismology (IRIS). The TA was the largest element of the USArray seismic and magnetotelluric facility, a major component of the National Science Foundation (NSF) sponsored EarthScope program. Begun in 2003, EarthScope supported a suite of community observatories and data collection campaigns to investigate the geologic structure and dynamics of the North American continent. This program included USArray, the Plate Boundary Observatory, the San Andreas Fault Observatory at Depth, and a research grant program for funding PI-led scientific proposals. As a result, EarthScope encompassed several other multidisciplinary observing components, including geodetic, strain, LiDAR, and drill core sampling.

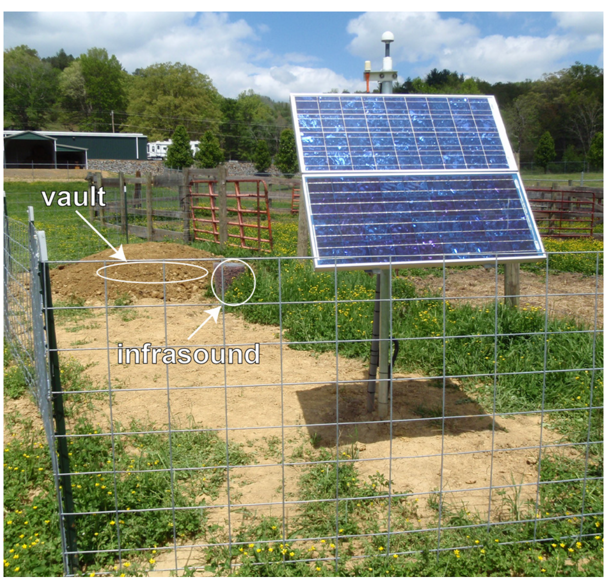


Figure 1-1. TA.W52A (Murphy, NC) represents the finalized design of a TA seismic station, with solar panel assembly adjacent to an infrasound sensor cage and buried seismometer vault.

The L48 TA collected observations of the seismic wavefield at a range of periods and on a continental scale. Stations consisted of observatory-grade broadband seismometers that were deployed on a regular grid at ~400 sites spaced at ~70 km, and each station was scheduled to operate for 18–24 months (Figure 1-2). The initial footprint was established and then "rolled" over the next decade as stations along the western edge of the array were removed and redeployed along the eastern edge at a rate of about 19 per month, maintaining an array with a typical aperture of 2100 km north-south by 850 km east-west. Altogether, 1679 TA stations were operated, and the migrating L48 TA footprint was removed by October 2015 (Figure 1-3).

Specific elements of the TA functioned in longer-term, semi-permanent deployments before, during, and after the passage of the main footprint. The "Reference Network" (RefNet) (2007–2018) included 20 stations that filled out the U.S. Geological Survey (USGS) Advanced National Seismic System (ANSS) backbone network. The TA also operated 27 stations in the Pacific Northwest from 2009 to 2016 as part of the cross-shoreline Cascadia community experiment. Our assessment of the TA includes these stations, but omits a handful that were technically TA but were used for demonstration and testing purposes and did not utilize standard TA design or instrumentation (Appendix A).

In addition, several state agencies and regional network operators adopted 79 TA stations as the array crossed the United States. Some groups absorbed the stations into their networks and altered the configuration, while others hired IRIS to continue to operate stations under the TA network code as part of the Education and Research Network (EARN) program. EARN service peaked at 33 stations. Lastly, IRIS continued to operate and in some cases reinstalled TA stations at 158 sites as part of the Central and Eastern U.S. Network (CEUSN, network identified code N4). The CEUSN originated from a multi-agency partnership

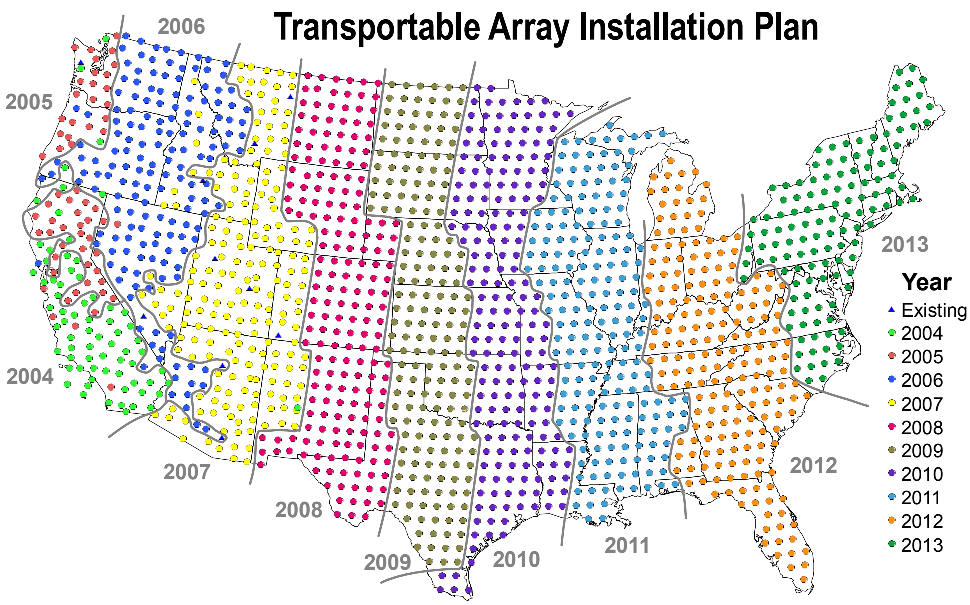


Figure 1-2. Map of the 10-year deployment plan for the TA, showing the nominal grid spacing of 70 km between stations and illustrating the planned year-by-year deployment progress. Note: The westernmost stations reflect the actual deployment locations.

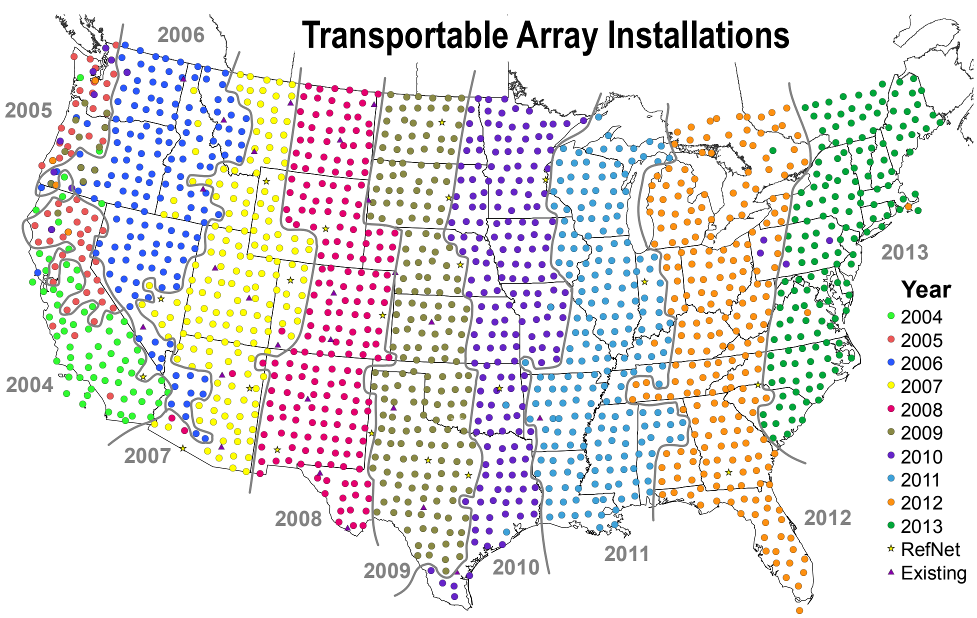


Figure 1-3. Map of the 10-year TA as built. The final station locations achieved the planned grid, year-by-year progress followed the initial plan closely, and additional stations were sited in Canada.

led by NSF and operated until 2018, when the USGS absorbed most of its stations. Regional networks and the USGS similarly adopted most RefNet and Cascadia stations. In these ways, the impact and legacy of the TA discussed in this report has continued beyond its original mission.

1.2 PURPOSE AND SCOPE

The objective of this technical report is to document the design and as-built implementation of the L48 TA. In particular, it highlights:

- Aspects that bear directly on data characteristics or quality—to serve as an archive of information for present or future data users. In particular, this report captures relevant details that are not otherwise provided as part of station metadata.
- Key details about the construction or installation procedures that may be referenced by other station or network operators. We try to emphasize information about operational policies and strategies over transitory technical details (e.g., brands of cellular hardware).

Beyond simply the details of how the TA worked, we hope that readers also appreciate the novelty of how it applied established methods and technology in ways that maximized scientific benefit. Many elements of the TA, including autonomous power, real time communications, and uniform station design were unprecedented for an array of its aperture and density. The site selection and vault design were considerably more involved than typical temporary instrument deployments and resulted in much higher quality data by accounting for best practices of sensor installation honed by permanent networks. Finally, the monitoring of performance created a significantly higher return of quality data than portable array deployments to that point. All of these efforts combined to make the TA successful.

Please also note that this report only covers the operations of the TA in the conterminous United States and southern Canada through July 1, 2017. Beginning in 2014, TA stations were deployed across Alaska and adjacent parts of Canada, with a station spacing of ~85 km. This portion of the TA will operate continuously until at least 2020. Many fundamental aspects of the TA implementation were changed for the deployment in Alaska and Canada, and a similar report for that deployment will be produced.

1.3 INFLUENCE OF EARLIER NETWORKS

The proliferation of digital broadband seismic data collection significantly influenced the design and implementation of the Transportable Array. Beginning in the 1980s, organizations such as IRIS and the International Federation of Digital Seismograph Networks led an international effort to standardize elements of seismic data collection and exchange, from articulated equipment needs to exchangeable data formats and shared operational practices. Developments in seismic array design, such as the construction of the Gräfenberg Array, followed by the joint IRIS-USGS effort to upgrade and modernize the Global Seismographic Network (GSN), led to new technologies and practices for installing and operating stable, autonomous, continuously recording, telemetered broadband stations.

These advances were embraced and further refined by network operators in the United States (e.g., the USGS Advanced National Seismic System, TriNet, Berkeley Digital Seismographic Network) as well as the Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL), the comprehensive IRIS facility for supporting portable seismic data acquisition by PIs. Mature technology and practices were available worldwide through commercial vendors and network operators by the early 2000s, which allowed the TA to leverage a deep knowledge base to create an optimized configuration of station and network design. By virtue of its timing, the TA built upon decades of advancements and development of "best practices" in a variety of settings. Reliance on well-understood hardware and practices at the level of an individual station and small networks allowed the TA to focus on the unprecedented goal of operating a dense seismic network with real time data delivery at the scale of a continent, under a rigorous deployment schedule.

1.4 GOALS AND OBJECTIVES

From a scientific perspective, the Transportable Array was designed to record local, regional, and teleseismic earthquakes to allow significant new insights into the earthquake process, provide 3D resolution of crustal and upper mantle structure on the order of tens of kilometers, and increase the resolution of structures in the deep Earth. In service of these criteria, the proposed size, scope, and operations of the Transportable Array evolved through a lengthy and far-reaching process of input and dialog from a community of scientific stakeholders (e.g., Levander et al., 1999; Meltzer et al., 1999). These discussions began in 1993, a full decade before EarthScope was formally proposed. As scientific and operational priorities were assessed, key elements of the network design were adjusted, including spacing between stations and duration of each station's deployment (Figure 1-4). Community conversations also shifted away from the initial idea of operating TA stations in a model similar to PI-led deployments, settling on a more standardized and actively managed process. The network that was eventually proposed combined the needs of the EarthScope community with the expertise cultivated at IRIS and by other seismic network operators. Throughout the process of devising the TA, a tremendous amount of consideration was applied to both its design and overall implementation.

From a technical standpoint, the TA aimed to deliver data integrity, quality, and quantity while operating across an unprecedented geographic scale and number of stations. At the outset, the philosophy of its deployment and operation set the TA apart from most temporary and permanent networks of the time:

- Use a methodical manufacturing approach, creating uniform and consistently high-quality seismic stations with low maintenance requirements.
- Construct and install stations with a small number of professional field crews that use the same plans and equipment, as much as possible, for every site.
- Review and improve station design based on operational lessons and technological developments.
- Select sites at locations away from potential disturbances, in remote or protected locations separate major activities.
- Create vaults to be resistant to external effects (pressure, temperature, fire, and moisture).
- Use autonomous, low power systems and wireless networks to allow flexibility in site selection and improve reliability by minimizing reliance on outside infrastructure.

Figure 1-4. Example of a notional, time-phased TA network deployment from early community discussions (Meltzer et al., 1999). This particular sequence did not afford year-round operations as a north/south migration does.

- Operate observatory-grade sensors, dataloggers, storage, and communications hardware.
- Design standardized, customized hardware enclosures and fittings to ensure minimal points of failure within the station.
- Assign a downstream data collection center to receive, analyze, and display incoming state-of-health and waveform data streams in near-real time to inform maintenance decisions.
- Completely archive and assess the quality of all data collected by each station at the IRIS Data Management Center (DMC).

The functional requirements for the how the TA was implemented were defined early on included:

- Broadband seismometers providing bandwidth from 500 s to 20 Hz
- Station spacing at 70 km intervals
- Station sites free of cultural noise and episodic noise insofar as it was possible
- Strict adherence to the deployment schedule and budget
- 85% or better data return, with near-real time access to all data
- Production of a catalog of events recorded by the array, serving both as a quality control tool and index into the data (Astiz et al., 2014)

1.5 ROLES AND RESPONSIBILITIES

Deploying the L48 TA required coordinating staff and resources that were distributed across the United States at IRIS offices (Washington, DC, and Seattle, WA), the Array Operations Facility (AOF, New Mexico Institute of Mining and Technology), the Array Network Facility (ANF, University of California, San Diego), and Honeywell Technology Solutions Inc. (Albuquerque, NM), as well as at numerous small awardees. This organization started with the IRIS program management, initially with the Transportable Array Manager in 2004 and growing to include the USArray Director (later retitled Director of Instrumentation Services) and TA Chief of Operations in 2007.

Some staff members were already experienced with the process of collecting seismic data in support of IRIS activities such as the GSN or PASSCAL. For the TA, tasks were demarcated to support a production, manufacturing-style process. Staff adhered to clearly defined procedures, design goals, and technical specifications to become specialists in one or more specific roles of the process. Teams worked year-round to fulfill the principal tasks related to operating a rolling network of stations that for each station were coordinated over a span of years:

- Reconnaissance, siting, and permitting
- Instrument testing, kitting, warehousing, and shipping
- Construction of station civil works
- Installation of station equipment
- Commission, certification, and quality monitoring
- Servicing and maintenance
- Removal of equipment and release of legal liability

These tasks were carried out both in series and in parallel. For a typical station, its reconnaissance, siting, and permitting were conducted up to a year in advance of construction and installation. At any point in time, dozens of TA stations would be in a similar stage of development, and the facility cycled through 200 stations each year in a seasonal process that was repeated over eight years (Figure 1-5). This inherent nature of the production process was used to create and maintain the TA network.

The relationship between the construction, installation, and removal crews was especially critical. In other seismometer deployments, a single group is responsible for all aspects of creating a station. For the TA, the activities of the construction and installation crews were separate and staggered by three to five weeks, allowing their activities to be scheduled independently and specialized.

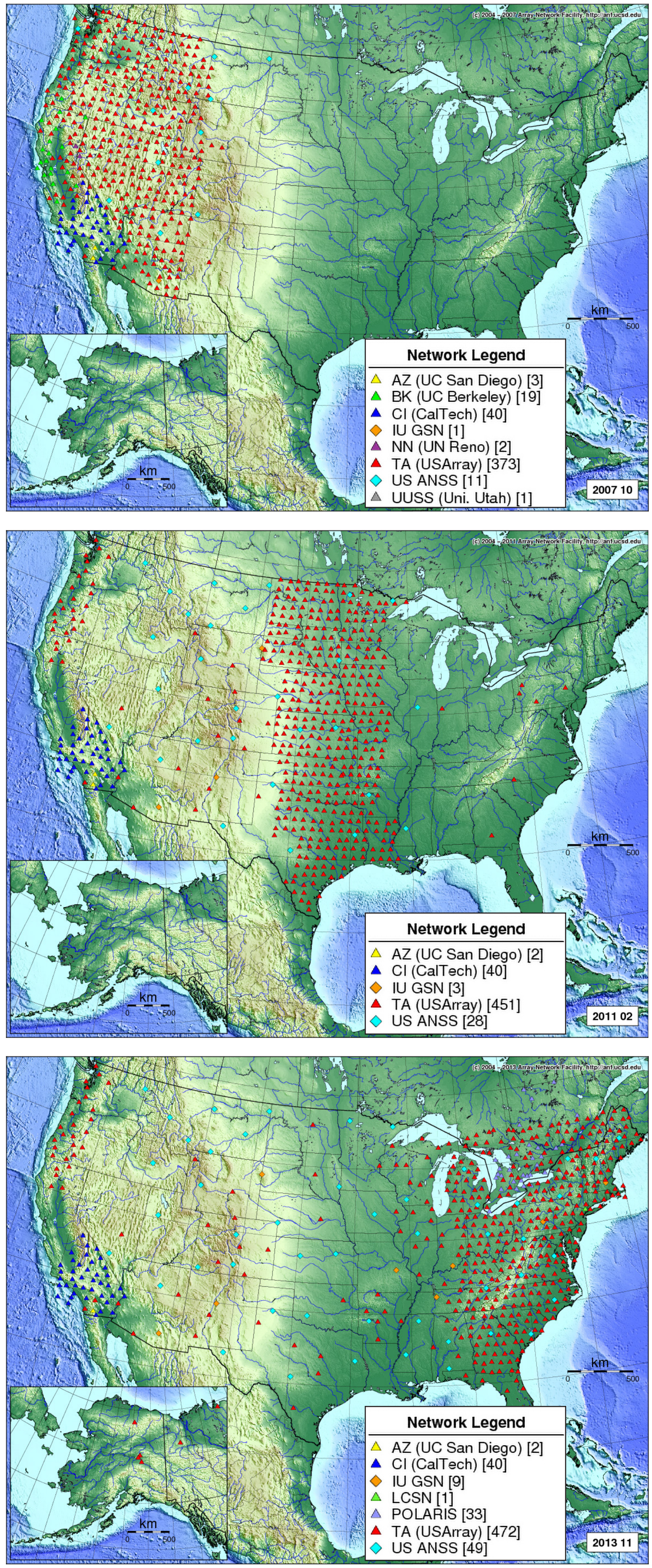


Figure 1-5. A sequence of deployment snapshots generated by the Array Network Facility, showing the TA "rolling" across the mid-continent (http://anf.ucsd.edu/stations/deployment_history.php). The top map shows the array as of October 2007, the middle map is a snapshot from February 2011, and the bottom map shows the array in November 2013, two months after the final stations were deployed.

The overall division of roles and responsibilities across the TA operation created sets of tasks that were both discrete and intertwined and required regular attention and management.

CONSTRUCTION: The construction team consisted of an IRIS supervisor and two to three contractors who were focused on building the civil works at each site as close to uniform and secure as possible. Tasks included excavation, cementing of an underground vault, laying conduit, emplacing a pole to support the solar panels, and erecting livestock fencing as needed. The vault was left sealed but ready for instrumentation.

INSTALLATION: The installation team consisted of two people with expertise in instrumentation to set up the seismometer, datalogger, and communications and power systems. This crew then coordinated with the ANF to initiate data collection and report key information about the installed equipment. The time phasing allowed the construction and installation tasks to proceed independently depending on weather, landowner availability, and other logistical factors. The crews worked at northern latitudes or high elevations during the summer and at southern locations in winter. Thus, the migration of the TA "snaked" across the United States. That activity can be seen here: http://anf.ucsd.edu/cachemovies/maps/monthly_deployment/USArray_deployment_2015_10_qt.rolling.mov.

REMOVAL: A separate removal team swept along the backside of the array to decommission stations that had operated for the planned deployment period. This team made final orientation and other measurements, and disconnected and repackaged station instruments and hardware for use at a new TA station. Prior to removal, instruments were remotely calibrated by the ANF and assessed to ensure they could be immediately redeployed. The removal crew loaded utility trailers with gear and drove them to storage locations near the installation area. The process directly supplied instrumentation to the leading edge of the TA from hundreds of kilometers away. The removal crew also recovered the grounds of each site to the satisfaction of the landowner.

ROLE OF THE ARRAY OPERATIONS FACILITY: The AOF prepared and evaluated new hardware upon receipt from suppliers, and tested instruments reentering service following minor repairs as needed. The AOF also tracked the inventory of TA hardware. A TA Coordinating Office (TACO) within the AOF directed construction contractors, managed the permits, and oversaw engineering design and documentation for all stations. The TA management, as IRIS personnel, actively oversaw and coordinated these activities.

ARRAY NETWORK FACILITY AND SERVICING: The ANF oversaw the certification of each TA station, which entailed coordinating with field crews to initiate data collection, register the equipment installed at the station, and perform several days of comprehensive data and metadata assessment. The ANF received and monitored all incoming data from the TA and furnished station metadata to the IRIS DMC for archiving. It monitored all waveform and state-of-health time series to maintain data integrity at each station and report any outstanding issues to TA management. Service personnel visited stations when required to address issues identified by remote monitoring, and any changes to the configuration of a TA station were sent to and processed by the ANF.

DATA MANAGEMENT CENTER: The IRIS DMC served as the definitive repository for all data and metadata collected by the TA. It validated and archived all data provided by the ANF. The DMC also provided an additional layer of monitoring on all incoming waveform time series, using automated quality control processes and analyst review. These efforts focused on more subtle and time variable aspects of data quality that manifested as waveform anomalies, such as changes to time series spectra, and were intended to characterize less obvious issues across the network.

2. System Overview

2.1 STATION DESIGN PRINCIPLES

The standard TA station was designed for high-quality, broadband, continuous recording of ground velocity, with emphasis on earthquake-generated motions, particularly at longer periods (Figure 2-1). Each station consisted of an enclosure for the sensor and equipment, a nearby mast to provide a mount for solar panels for power, and radio antennas for telemetry and GPS time. A typical station was designed to occupy a relatively small footprint at a site, roughly 6 m x 6 m, in order to maximize permitting opportunities. The station was designed to operate autonomously in as isolated an environment as possible.

The TA station was designed for very low power operation (~4 W) and included the capability to accommodate different modes of telemetry. This design allowed stations to be sited well away from sources of cultural noise—a primary contaminant of seismic data. When a low power telemetry option was not available, communication modules were used that could be separated from the seismic instruments to be near a power source or at a location far enough away that the large photovoltaic (PV) arrays do not become a source of noise from wind. The range of the RF connection is up to 15 km, but often only a kilometer or two across a property to a nearby barn or other structure with commercial power.

The vault enclosures used by the TA were designed to provide a stable thermal environment in many soil/rock conditions for a rigid platform on which the sensor rests. The pre-defined size of the enclosure provided a well-constrained environment for configuring hardware and incorporating any necessary design changes to future sites. The sensor platform was a simple concrete pour, though typically placed at ~2 m depth below grade. The enclosure was meant to be watertight but allow relatively easy access for a straightforward installation. The enclosure could be sized appropriate to the dimension of the local conditions, and the internal mounting of equipment was designed to adjust to varying heights within the enclosure.

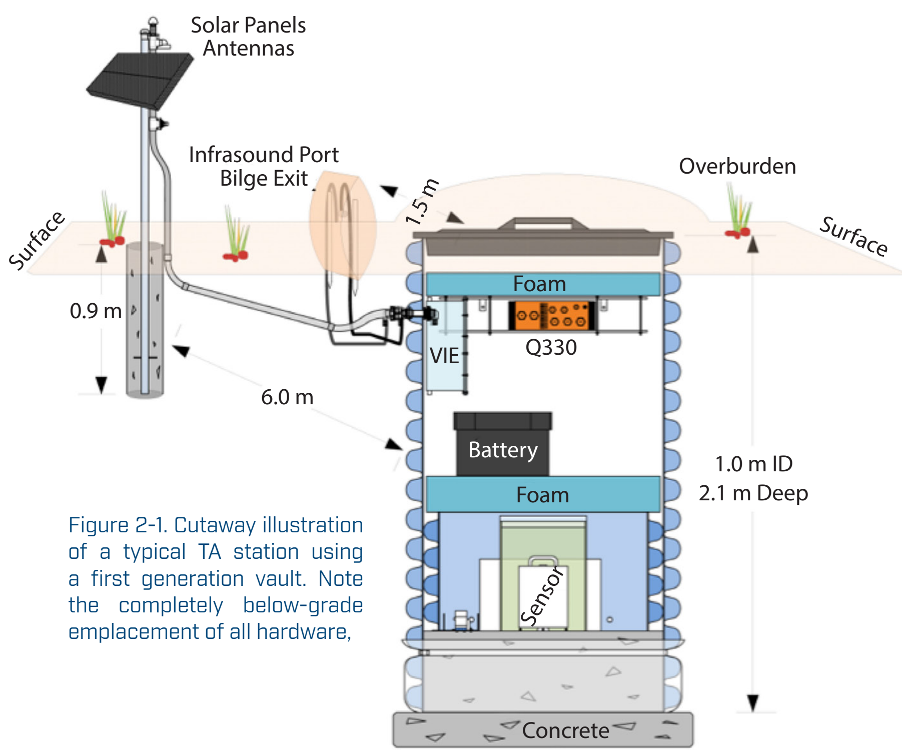


Figure 2-1. Cutaway illustration of a typical TA station using a first generation vault. Note the completely below-grade emplacement of all hardware,

Communication technologies changed rapidly during deployment of the TA. The fundamental goal was IP-based transport with commercially available technologies that did not require special provisioning or long-term, high volume/unit data contracts. The TA preferred digital cellular where available, commercial VSAT, or partnering with schools and colleges for access to existing Internet connections. Consumer broadband services such as DSL, cable modem, and frame relay were occasionally utilized.

Stations were designed to be as close to identical as possible, using a manufacturing approach. They were constructed by the same crews, which used the same design and commonly available construction materials. The initial design was field tested before being extended to the TA. Notable changes to the design of stations (e.g., vault material, vault interface enclosure [VIE], auxiliary instrumentation) during the life of the TA were the result of closely monitoring network performance, and they were implemented carefully and made only if they did not diminish the existing data quality and function. The mode of communications and model of broadband seismometer were the most common elements of a station that may have varied from site to site.

Table 2-1. General criteria used for selecting TA sites.
15 km area of flexibility around an initial point
Telemetry (cell or AC VSAT) is feasible, including sufficient power requirements
Landowner is agreeable
Site is sufficiently removed from sources of vibration • Roads: >300 m from minor roads and >1.5 km from major roads • Railroads: >3 km or >10 km in a basin • Pipelines: >2 km • Oil and gas production: >3 km from wells and injection facilities • Irrigation: >2 km from large agricultural and water storage pumps • Rivers: >3 km from dams and weirs, >1 km for whitewater, n/a for slow moving water • Wind: ridgetops w/hard rock may be considered, but constant high winds should be avoided • Construction and mining: >2 km from large projects • Sedimentary basins: avoid when possible in favor of competent rock to mitigate multipathing effects

The equipment used in a TA station was designed to provide a sustainable, uniform, flexible, redundant system that evolved as needed over a 10-year period. Coupled with real time telemetry, the collection of environmental, state-of-health, and later atmospheric time series provided comprehensive observations of station conditions and allowed its function to be remotely adjusted as needed. Permanent onsite archive of all recordings provided a backup to the telemetered data.

Many of the topics explored in this section are also thoroughly documented in an interactive website designed during operation of the TA (Digital Appendix).

2.2 SITE SELECTION

The site for each TA station was selected using a rigorous but flexible protocol that entailed office reconnaissance, field scouting, a written reconnaissance report and technical review, and a verification visit prior to permitting (Tables 2-1 and 2-2). Initial prospective locations were identified using the idealized 70 km spacing of planned TA stations. Each nominal target was surrounded by a 15 km radius (~20% of station spacing) "watch circle," with only minimal preference placed on proximity to its center. The objective was to find a seismically quiet site with a manageable permit within 10 km of the target. If none were available within 15 km, a review of the location would result in potential adjustment of neighboring sites.

Office reconnaissance relied on maps, aerial photos, and GIS analysis, including regular use of Google Earth, Topo6, and GeoPDF products. The GeoPDF maps (Digital Appendix) were produced by TACO and provided a color-coded geographical ranking to guide individual TA site selection within the watch circle. This analysis was followed by calls to obtain local assistance as needed and to set up visits. Potential for cellular

Table 2-2. Guidelines during specific site selection and permitting process.
Site meets several basic conditions: • Away from low-lying areas prone to flooding • Secure from vandalism (i.e., generally out of view) • Subject to the landowner's preferences-often at the margins of fields or near outcrops they do not plow • Suitable for vehicle access by service teams • Avoid complex permit requirements where possible

coverage was also investigated during this phase. This research was followed by field scouting under a student siting program (for more information on this program, see section 4.2) that entailed evaluating potential locations, assessing local conditions, verifying cell coverage or VSAT capability with specific protocols, and talking to potential hosts and other local residents. In all cases of landowner interaction, the goal was to determine the agency or landowner, introduce the project, gauge interest, establish an appropriate office contact, and obtain a sample permit if the landowner had an existing form (e.g., timber companies). Observations from these actions were combined into a standard reconnaissance report form.

Several potential sites were evaluated if they appeared free of noise sources from both infrastructure and geology. Choices were narrowed down by ease of permitting with landowners. We favored landowners where both negotiations and the land-use agreement to access the property and install the station were simple. Students visited sites to identify a preferred potential location. They then compiled a reconnaissance report for each potential site that outlined the proposed configuration of the station, including power and communications. TA staff visited selected potential locations to confirm details acquired by students such as cell reception and landowner willingness, resulting in a recommendation for a candidate site. TA management reviewed every candidate site and, if approved, an attempt was made to get a use permit for the candidate site. Should the candidate site permit be rejected, another potential site identified earlier in the process was elevated to be the candidate site.

Deployment began in southern California, in part to leverage a large selection of existing stations from regional networks (CI, BK, NN), allowing us to establish an initial footprint and exercise data flow processes at the earliest opportunity. The contributing stations were chosen to satisfy the network design criteria for station spacing and in some cases were upgraded to meet the TA standard for seismic sensor, datalogger, and telemetry capacity (Figure 2-2). Contributing stations were a major part of RefNet as well as the footprint of the TA in southern Canada. Additionally, in California, Nevada, and New Mexico, the TA cooperated with regional network operators to obtain siting permits, primarily with public land agencies.

The station code assigned to each station (which conforms to SEED format; SEED stands for Standard for the Exchange of Earthquake Data) consists of three characters representing geographic location (Figure 2-3). The first alphanumeric character indicates the row of TA stations, translating to latitude from north to south. The second and third characters are numeric and represent column or longitude from west to east. The fourth character identifies the sequence of stations installed at a given grid point with "A" being the first, "B" the second, and so on. Normally, only one station would lie at a grid point, but if a station must be relocated more than 25 m

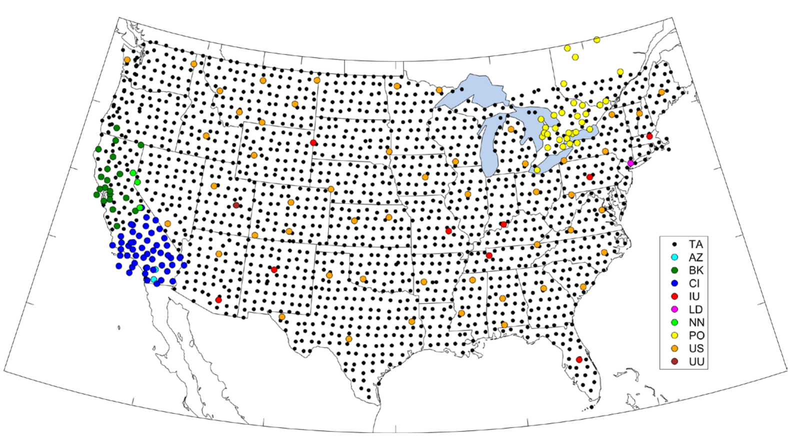


Figure 2-2. TA deployment with contributing stations from other networks. These stations played a vital role in the TA network, but are not standard TA station design and thus not included in this report.

[A-Z,1-9,0][1-66][A-Z]

[row-latitude][column-longitude][site iteration]

Examples:
H12A (Stanley, ID)
P39B (Salisbury, MO)
062Z (Marathon, FL)

Figure 2-3. Definition of a TA station code, with examples.

or if there was a significant change in emplacement of the broadband sensor, the scheme was designed to support this possibility. A fifth character is possible for SEED station codes; however, this character was not used in the final TA station naming. A handful of TA stations, mostly in RefNet, did not conform to this schema; their names conform to the ANSS Backbone naming convention, where the first two letters reflect the place name followed by the two letter state code, for example, KMSC (King's Mountain, South Carolina). Stations in California and Nevada that had been flagged for potential adoption by regional network operators during the siting process were also given place name-related station codes, for example, BEK, BNLO, HELL.

The station codes were included in the subject line of all e-mail communications, further streamlining communication and facilitating accurate searches of e-mail. Even during the siting process, grid points were referred to by their station code, with the addition of a sequential suffix for various potential sites. The mathematical center of grid point location had a sequence number of zero and each potential site incremented by one. On installation, that location used only the station code and dropped the trailing sequence numbers.

Station locations were measured to an accuracy of five decimal places in latitude and longitude, or meter-scale resolution. These high-accuracy locations were available via the standard data access tools at the IRIS DMC, but various public-facing displays of stations were reduced to two decimal degree accuracy to discourage intrusion at stations.

2.3 VAULTS AND CONSTRUCTION

Vaults in the TA were designed to provide a dry, thermally stable, secure, structured environment for data acquisition. The type of vault deployed evolved over two generations based on improvements that were identified after prolonged operation across a variety of sites. In both cases, the vault consisted of a vertical enclosure buried so that the lip was 20 cm above grade, depending on the exact site conditions, with concrete anchoring its base. The vault itself was emplaced into a void dug by a backhoe, and the surrounding earth would be backfilled up to grade. The vault was secured at the top with a tight-fitting lid and a locking chain covered with up to 30 cm of overburden, and insulated within with foam disks.

The standard first generation vault for USArray consisted of an ADS 107 cm (42 in) diameter HDPE plastic corrugated sewer pipe (commercially available) cut to 2.13 m (7 ft) length and buried vertically 1.83 m (6 ft) into the ground (Figure 2-4). In special circumstances where complete burial was not practical, the pipe could be cut onsite to shorten its vertical height. The pipe had an impermeable membrane (45 mil Firestone EPDM geomembrane) strapped across the bottom that was pushed into a pond 1.14 m^3 (1.5 yd^3) of concrete poured into the bottom of the hole. An additional 1.14 m^3 of concrete was then poured inside the tank to a depth of 20 cm, trapping the membrane between layers of concrete. The hole was backfilled. In cases where the hole had been excavated through relatively

Figure 2-4. Construction of TA.BNLO (3/7/05) using a first generation vault.

Figure 2-5. Reconstruction of TA.H17A (9/19/11), Yellowstone National Park. The original vault was replaced with a second generation vault to mitigate leaks and achieve better performance.

impermeable material, an impermeable apron was placed around the tank mound to shed water away from the disturbed area.

In 2011, the second generation vault was introduced (Figures 2-5 and 2-6). Freeman Engineered Products produced this custom vault in response to a request for proposals from IRIS as a modification to an existing cistern product, and it resulted in improved vertical compression strength relative to the first generation vault. It was produced in two variants, 2.2 m (87 in) and 1.4 m (55 in) tall. Approximately two dozen stations used the shorter version at places where site and access considerations necessitated a shallower than normal vault. The tank is still commercially available to other interested groups. It was constructed from roto-molded plastic as a single unit with an integral floor. The floor was convex downward to avoid accumulation of air pockets in the liquid concrete beneath the tank. The integrated floor eliminated the need for the rubber membrane and greatly reduced water leakage into the tank. Other features of this tank included:

- Molded in flat bulkhead for the cable pass-throughs—eliminating compound curvature surface on the corrugated tank that often was the source of leaks
- Welded-in shelf, near the top of the tank, to hold the data logger
- Flats to provide attachment points for the VIE, discussed in a subsequent section of this report
- Double lip seal for vault lid, with integral rubber tie-downs, for a secure and more water tight lid attachment
- Interior lips to hold the foam disks that divided the tank into multiple chambers

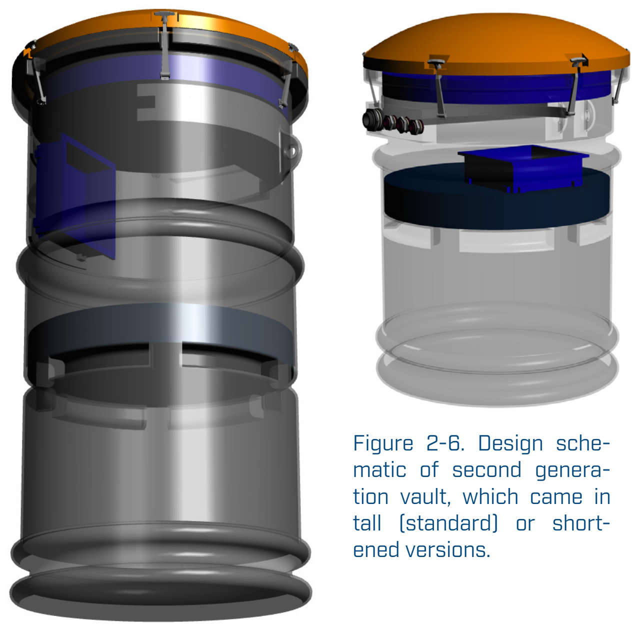


Figure 2-6. Design schematic of second generation vault, which came in tall (standard) or shortened versions.

The first generation vault performed well at many sites, but did not have sufficiently high compressive strength along the axis of the pipe. It was prone to being deformed vertically due to the weight of overburden, which sometimes became saturated with water. The compression or compromise of the membrane sometimes resulted in water entering the TA vaults. Bilge pumps were always included in the design, mounted on the floors of vaults to mitigate small leaks and in many cases this worked well. At a few stations, a combination of conditions caused regular water intrusion or a failure of the pump or tubing, leading to flooded vaults. The second generation vault addressed this issue in the vast majority of cases.

In both cases, the vault lid was typically completely covered with a mound of soil, making it fairly unobtrusive. Field crews tried to keep stations out of the wind and out from under trees, often selecting hillsides or ridge saddles. The mound of soil provided a measure of fire protection, keeping the plastic tank away from contact with flame, and it deterred animals and potential vandals. A drawback was that wintertime visits could encounter frozen mounds that made vault entry and reburial difficult and occasionally impossible.

The decision to bury the vault nearly to grade, add a layer of overburden, and include internal layers of insulation was designed to improve thermal stability. Modern broadband seismometers use a leaf-spring seismometer design, which is extraordinarily sensitive to thermal variations (Wielandt and Streckseisen, 1982). Even temperature variations that are a fraction of a degree Celsius can dramatically raise the level of long-period noise at TA stations. These choices, coupled with an insulated sensor emplacement, imparted considerably more thermal stability when compared to shallow vaults.

A mast for one or more solar panels, GPS antenna, and telemetry was erected at a minimum of 4.5 m (15 ft) from the tank and preferably 6.7 m (22 ft) (further away resulted in lower signal from wind induced vibration of mast). Longer distances were possible with special cabling terminations, particularly of the cellular or freewave radio. A 3.8 cm (1.5 in) PVC conduit was buried in a 0.3 m (1 ft) deep trench between the mast and vault. At stations installed with atmospheric sensors, a hollow tube with diffuser port was installed in a small cage filled with cinders to muffle wind noise and was located one to two meters from the station. The tube led to the sensors underground in the tank and was occasionally a source of water entry.

Detailed manuals on the construction and parts reference for both generations of vaults are available as part of this report (Digital Appendix).

2.4 INSTALLATION

The installation team traveled to a TA site approximately one to three weeks after construction to conduct the installation. Tasks included emplacing, orienting, and testing the sensor, datalogger, baler, VIE, and other station hardware elements. The sensor and batteries sat in the bottom portion of the tank, the VIE was mounted along the inside of the vault near the top, and the data logger sat on a shelf nearest the lid. In shorter vaults, the VIE, datalogger, and an additional battery were placed on the top level (Figure 2-7). Layers of foam were used to divide the tank into three chambers to stabilize the temperature and the vault was capped with a manufactured plastic lid. Extensive notes were taken and photo documentation collected at each station to record site conditions, exact instrument serial numbers, and any items of note.

The installation procedure began with making accurate, precise, and permanent orientation reference mark for the seismometer, emplacing it and any secondary sensors, connecting the power supply elements, interconnecting the station components via the VIE, configuring station information, and establishing the telemetry capability. Cellular modems were the standard design for installation. VSAT and/

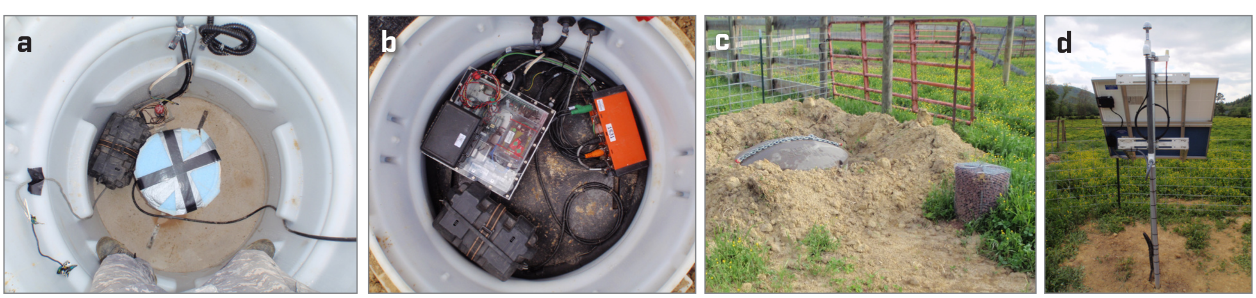


Figure 2-7. TA.W52A (Murphy, NC), featuring (a) completed lower chamber, with seismometer wrapped in blue foam insulation and battery to its left, (b) completed upper chamber, (c) buried vault with infrasound enclosure, and (d) solar/gps/communications mast. Note that this is a shorter version of the second generation vault, with the VIE resting horizontally.

or radio setup required one to two additional days on site to build and configure the necessary hardware and infrastructure. For AC VSAT the dish, RF link, and hardware were placed on a mast near the power source. For solar (DC) VSAT this included a separate solar panel array placed at a significant distance (20–30 m) from the station.

In parallel, the installation team assembled the mast-supported PV array and radio antennas and erected fencing. Time to install a station average about 10 hours on site. Once the station was online, communication back to the ANF was verified. Site metadata were recorded and transmitted to the ANF via an email report, with full details of the installation due within a week of installation. In subsequent sections, we highlight some of the more relevant details of station design.

2.5 VAULT INTERFACE ENCLOSURE

The VIE unit is a protective housing used for electronics and auxiliary equipment, connecting and adjacent to the Quanterra Q330 datalogger (Figure 2-8). In 2009, it replaced a panel utilizing exposed DIN rail interconnections deployed during the first few years of TA operations. The VIE houses all electrical interconnects for the station and contains electronic and sensor units that are part of a TA station. In the final L48 configuration, the VIE contained:

- Power regulation circuit board with numerous LED indicators
- Quanterra Packet Baler 44, including USB media for data storage
- Connector interface circuit board
- PV Charge controller
- Modems, radio, or satellite terminal equipment
- Quanterra Environmental Processor (QEP) with temperature and pressure sensor
- Precision pressure transducer (Setra 278 barometer) ported to the outside
- Infrasound sensor (Hyperion 4321) ported to the outside

The VIEs are commercially produced by Solarcraft and Kinemetrics and factory assembled in large batches. This allows the configuration and testing of the enclosure and cables as part of the manufacturing process. A VIE unit measures 17 × 17 × 8 in, with a 0.5 in thick Lexan clear acrylic bulletproof front panel and an IP68 rated seal (fit enough to withstand dust, dirt, and sand, and resistant to submersion up to a maximum depth of 1.5 m underwater for up to 30 minutes). The rigid, protected, modular housing allows for better flexibility and increased reliability, encouraging economical packaging choices for small ancillary devices and protecting the commercial modems, charge controllers, and circuit boards. It can serve as a field replaceable unit to simplify troubleshooting at a station.

Cabling within the VIE uses industry-standard hardware connections, with external MS style connectors and molded termination. It converts Q330 interfaces

Figure 2-8. Close-up of the vault interface enclosure, or VIE: (a) internal components with lid removed, (b) as installed in a typical vertical configuration (TA.L62A), and (c) the connections on the side of each unit (TA.D60A).

internally to IDC flat ribbon and RJ45 connectors that can easily be reconfigured to connect to associated devices internal to the VIE. A custom, high-efficiency power regulation circuit supplies the sensor and filters power for the Q330 and Baler. There is a load shedding/mode switch that allows fault-free switchover to a reserve power system that also provides a coordinated duty cycle to the communication device and baler operation. The reserve power can be an alkaline battery pack, an air-cell or other primary battery type, or a rechargeable battery with a separate isolation circuit for charging current. The VIE also integrated several station functions, such as coordinating the daily power reset for communications equipment, remotely controlling the power interrupt for the sensor, and monitoring and signaling operation of the vault bilge pump.

2.6 POWER

All TA stations were powered by a solar-rechargeable AGM battery system to mitigate noise from utility wires and the potential for damage from power surges. A typical TA station draws 4–6 W during operation and is sufficiently powered to be able to operate year-round (Figure 2-9). TA stations were equipped with one to three 90 W solar panels on a side-of-pole mount to a 3 m (10 ft) mast (Figure 2-10). The number of panels depended on the latitude of operation and available skyview. The panels were generally low to the ground but above grass and snow levels, usually one to two meters. Panels were typically oriented from horizontal by the local latitude plus 15° (e.g., the solar panel at a station at 40°N latitude would be set to 55° from horizontal).

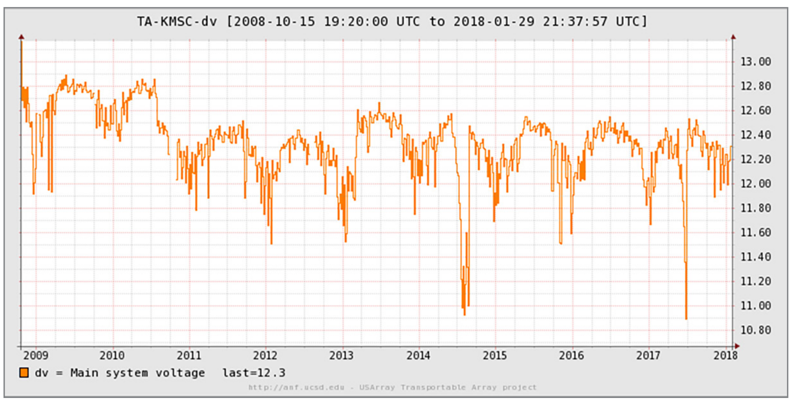


Figure 2-9. Voltage levels at TA.KMSC (a RefNet station that did not use grid-based naming scheme) show seasonal variations in power levels based on constant discharge and variable input voltage from its solar panel.

Figure 2-10. TA.KMSC had excellent skyview, and with cellular telemetry it only required a single solar panel to operate.

External communications modules (i.e., those physically distinct from the station) were nearly always powered by host AC (Figure 2-11). The power consumption of the AC-hosted equipment (whether VSAT or cable modem or DSL modem) was about 25 W, and amounted to ~225 KWH per year. Although the energy consumption is relatively low compared to energy consumption by a typical household, we reimbursed landowners at a standard rate, if they requested it. The connection between the external communications module and the station used wireless ethernet bridge radios.

External communication modules without AC power, such as VSAT terminals, were powered by PV solar arrays sized for the expected amount of sun (Figure 2-12). Four configurations were used, consisting of four, six, eight, or ten panels. For the northern latitudes, the solar panel installations included heaters, and for the southern latitudes, they included exhaust blowers. The system is mounted on a single 4- to 6-inch pole, with top-of-pole mounts for panels and a side-of-pole mount for the electronics/battery enclosure. These systems required two persons and about a day to install.

The station PV arrays were mounted on a 2-inch schedule 40 galvanized steel pole 10 feet long and installed 22 feet from the tank and connected via cabling run in 1.5-inch conduit. The mounts allowed for one to three panels that are wired in parallel. The PV cables were connected to a Morningstar PS15M charge controller and to one to three Concorde PVX-1040T AGM 100 AH batteries. These batteries are designed for solar charging (i.e., low charge currents, low power loads, and a resiliency to deep discharge; they are not typically available at auto supply stores). The station load is routed through a 15 A thermal breaker and distributed to communication, sensor, and datalogger equipment.

A Morningstar P15M solar charge controller managed the input from the solar panels, the charge regulation of batteries, and the output to station loads including low voltage disconnect. A station regulator further managed the load to the sensor, datalogger, and communication devices within the station. Remote commands to the Q330 could cycle power to the sensor for 11 seconds to reset the seismometer electronics and occasionally distinguish between signal anomalies arising from the sensor or arising in the datalogger electronics. Epochs of half amplitude signals could, very rarely, spontaneously occur and were often corrected via remote manipulation.

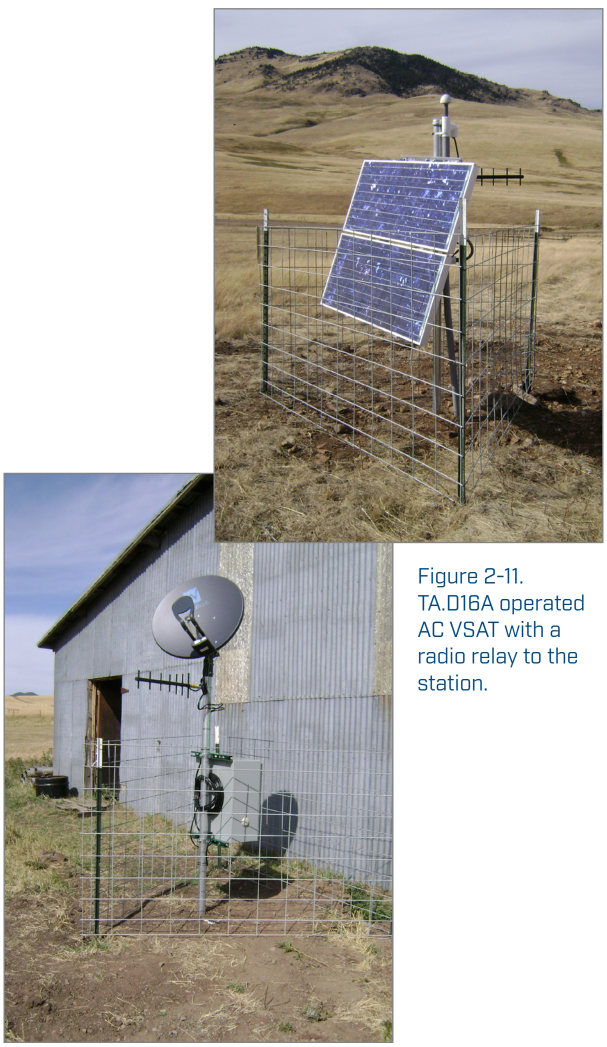


Figure 2-11. TA.D16A operated AC VSAT with a radio relay to the station.

Figure 2-12. TA.N02C operated DC (solar) VSAT with a large bank of solar panels to provide additional power to the communications system

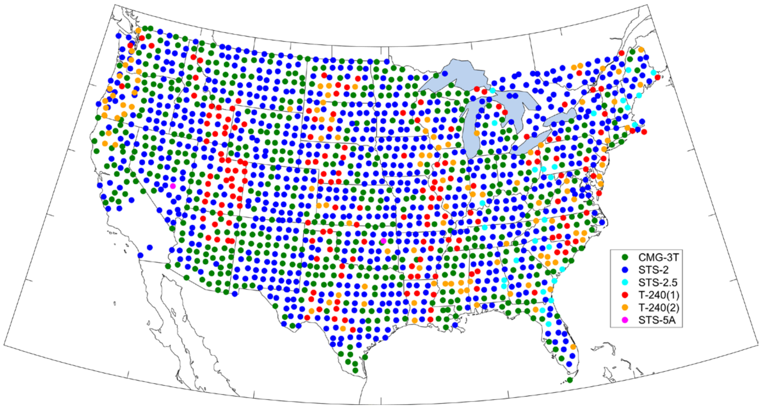


Figure 2-13. Distribution of seismometer types operated across the TA network, based on the initial broadband seismometer installed at each station.

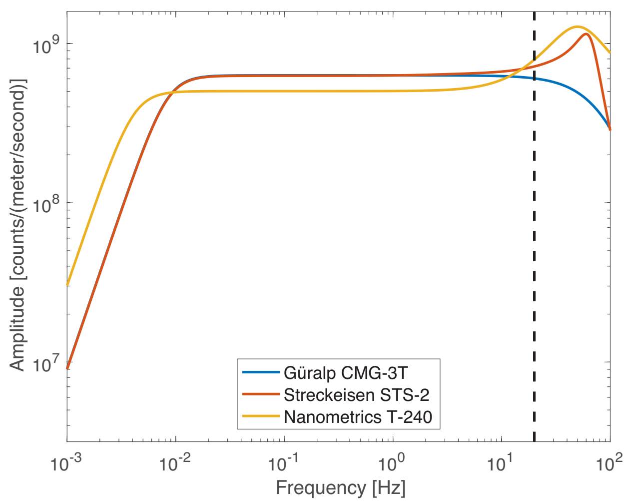


Figure 2-14. Individual responses of the main three broadband seismometers operated by the TA. Dashed line indicates the Nyquist frequency.

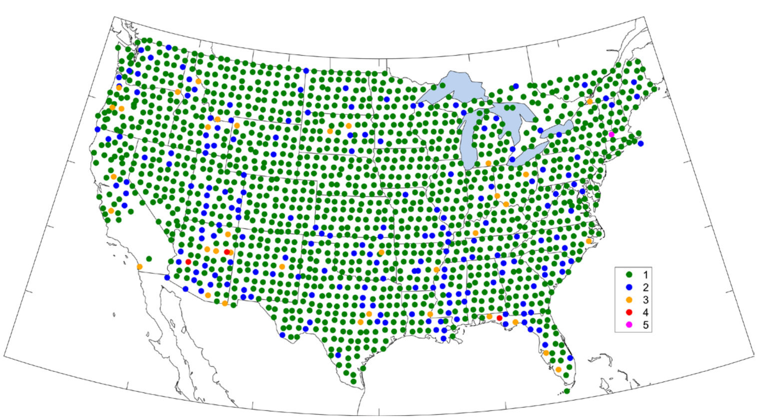


Figure 2-15. Count of broadband seismometers installed at each TA station.

2.7 SENSORS

Broadband Seismometers

The seismic wavefield at each TA station was recorded by a three-component broadband seismometer. We used modern, force-feedback, vault-style instruments produced by well-established manufacturers. In order of usage, these models were the Streckeisen STS-2 (49.1% of initial installs), Guralp CMG-3T (32.3%), and Nanometrics T-240 (16.9%). The STS-2 and CMG-3T seismometers formed the initial set of instruments and were deployed from 2004 to 2006. By late 2007, new T-240s were being added into the deployment. This resulted in a mostly random distribution of sensors at the scale of the entire footprint, but with regions where T-240s are more prevalent (Figure 2-13). A handful (1.7%) of stations used STS-2.5 and STS-5A posthole broadband seismometers when needed. They were mostly installed near the end of the L48 deployment in preparation and testing for the future TA deployment in Alaska. All these sensors have typical broadband response curves with a flat response from ~120 seconds to ~50 Hz (Figure 2-14). The TA used two versions of the T-240, both of which have a longer period response that is flat to 240 seconds and a less linear response at 5–10 Hz when compared to the CMG-3T and STS-2.

These instruments performed well, especially given the rigorous cycling of emplacement and removal, with 86% of TA stations operating for the entire duration of deployment with the originally installed sensor (Figure 2-15). Approximately 11.6% of the TA (195 stations) needed a single replacement sensor. Another 36 stations required a second, and only four required a third or fourth replacement sensor at some point. Nearly half of those replaced (48.6%, or 16.3% more than the inventory population) were CMG-3Ts. In contrast, only 22.9% of replacements were for STS-2s (26.2% less than the inventory population), while 27.1% were T-240s (10.2% more than the inventory population) (Figure 2-13). We concluded that CMG-3Ts were most likely to fail under the demands of this operation, and we relied upon these instruments less as the deployment progressed.

Strong Motion Sensors

The TA operated strong motion sensors at key sites as test installations and as part of the Reference Network or Cascadia Initiative, or in preparation for their adoption into the CEUSN (Figure 2-16). These instruments have a frequency response that is flat to acceleration (Figure 2-17). The Kinemetrics Episensor was prone to a "zinc whisker" defect (e.g., Anderson et al., 2015), which introduced small steps in the acceleration record of a single component (Figure 2-18). These steps are visible in the ambient noise spectra of an affected station as an elevated, straight line level higher than the microseism peak. The defect creates poor results when integrating the time series record to displacement. The manufacturer repaired several units.

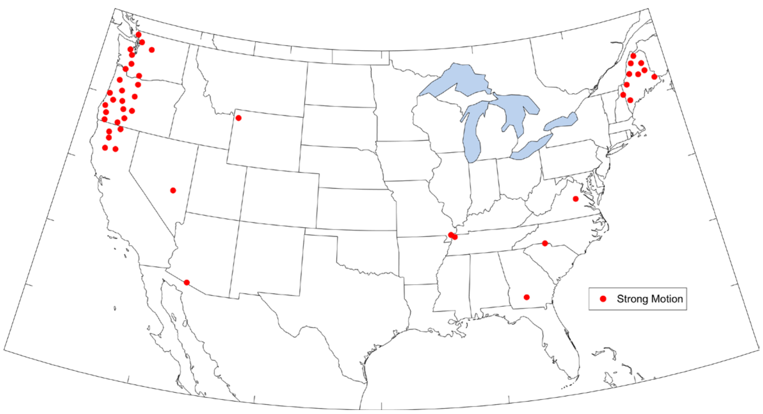


Figure 2-16. TA stations that operated strong motion instruments.

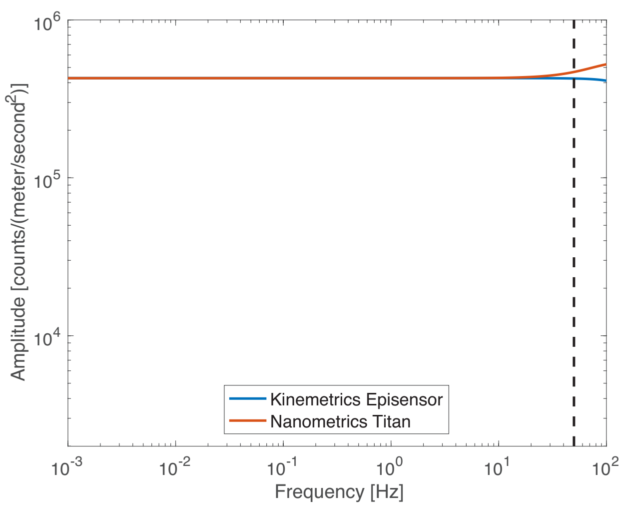


Figure 2-17. Individual responses of the two strong motion accelerometers operated by the TA. Dashed line indicates the Nyquist frequency.

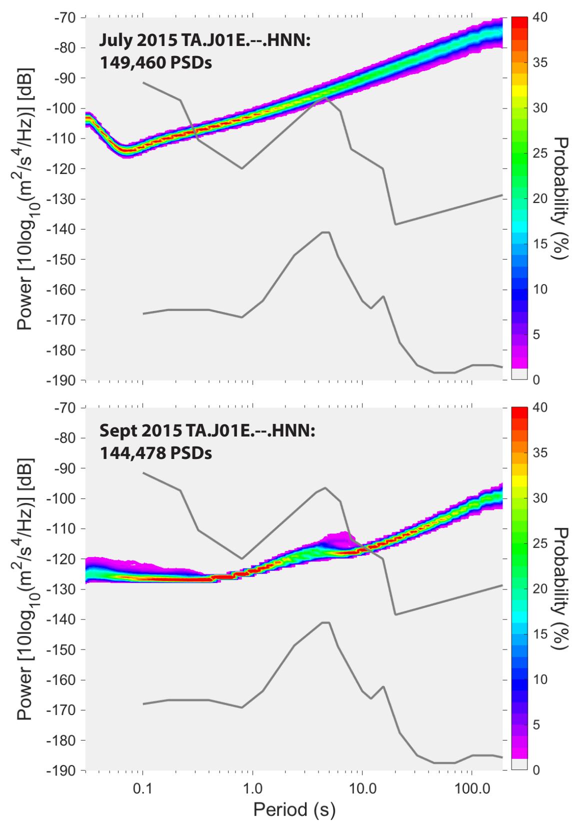


Figure 2-18. Example of the effect of "zinc whiskers" in monthly power spectral density estimates, before and after replacement of the sensor.

Auxiliary Sensors

The TA began to add environmental and atmospheric observations to stations midway through the L48 deployment (Figure 2-19). In late 2009, the QEP was added to the VIE system. The QEP serves as a subsidiary component to the Q330, providing an additional three input channels under the SEED location code EP. It includes a micro-electro-mechanical (MEMS) barometer, and temperature and relative humidity sensors. The response of the MEMS is not precisely known, but it is not considered sensitive at periods less than 100 seconds.

In 2011, the University of California, San Diego (UCSD), was awarded an NSF Major Research Infrastructure (MRI) grant to support further addition of atmospheric instruments to all remaining TA stations. A Setra 278 barometer and Hyperion Infrasound microphone were routed through the QEP as part of standard station installations (Figure 2-20). Both the QEP and atmospheric sensors were deployed at pilot installations where reference instrumentation operated (e.g., Piñon Flat Observatory and the International Monitoring System [IMS] infrasound array) before being included at all new stations. The response of the Setra 278 uses an offset and range, and so SEED blockette 62 was used to define the response as a first-order polynomial (see equation below). Most sites have a 5 V output range corresponding to 800–1100 mbar recording range, but 10 of the high-altitude Setra 278 models were used in appropriate locations (e.g., TA.H17A at 2400 m elevation in Yellowstone National Park) that have a 5 V output range from 600 mbar to 1100 mbar:

$$P = 800 + 1.5 \times 10^{-4} C \quad \text{or} \quad P = 600 + 1.5 \times 10^{-4} C$$

where P is pressure in mbar and C is counts.

In 2015, 10 Hyperion sensors were returned to their manufacturer for calibration tests. These instruments were deployed multiple times during a four-year period and show about a 2.5% shift in their sensitivity during that period. One sensor showed obvious corrosion from exposure to water, and although it still functioned, the response had drifted by 17%. As such, effort should be made to keep these sensors in dry enclosures whenever possible.

Finally, Vaisala WXT520, and later WXT536, meteorological packages were operated at a small number of TA stations, including a grid of stations in the Southeast (Tytell et al., 2016) as part of a UCSD project collocated with a dense grid of National Weather Service stations. The Vaisala sensor connected to the serial port of the QEP. Similarly, from 2008 to 2010, several TA stations in central Colorado operated Paroscientific microbarometers and Validyne and Chaparral acoustic gauges as part of a small PI experiment on seismic-acoustic coupling (Rogers et al., 2008).

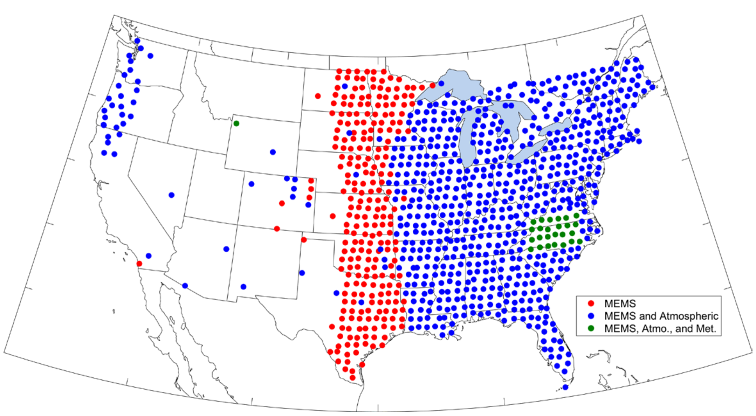


Figure 2-19. Distribution of auxiliary atmospheric and meteorological sensors across the TA: red = MEMS only, blue = MEMS/barometer/infrasound, green = MEMS/barometer/infrasound/meteorological packages.

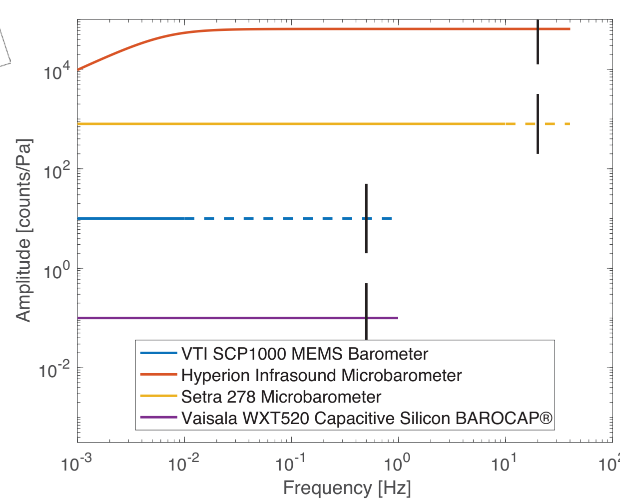


Figure 2-20. Responses of the various pressure sensors used at TA stations. Dashes show where instrument responses are not calibrated. The plotted responses terminate at the sampling rate of each instrument, and the black bars show the Nyquist frequency for each instrument.

Seismometer Emplacement and Orientation

Precise, accurate orientation and secure, well-insulated positioning of the broadband sensor was key to sensor emplacement at each station. The TA design goal was to orient the sensor within 2° of true north. Initially, this entailed measuring a magnetic compass bearing at ground level and projecting these vectors to the base of the vault. While this traditional method of orienting was successful in some settings, it became clear from teleseismic earthquake surface wave polarization analysis (Ekström and Busby, 2008; Ekström and Nettles, 2018) that many stations had orientation errors well outside of the design goal limits. It is a difficult procedure to accomplish accurately and routinely.

In late 2007, we began to use an IXSEA Octans IV interferometric fiber-optic gyroscope to ensure accurate orientations at TA stations (Figure 2-21). The Octans uses the effect of Earth's rotation on laser interferometric paths, a phenomena known as the Sagnac Effect (Post, 1967), to determine orientation with 0.2° accuracy. Measurement at a station usually required 10 minutes for the Octans to settle into a stable measurement following power up. These instruments were delicate and expensive, requiring careful transport and storage. All subsequent TA stations had orientations measured by an Octans during the installation and removal of the sensor. In the eastern half of the array, the TA also utilized the MultiWave Azimuthal Pointing System (APS), which uses differential GPS measurements with laser line projection to estimate orientation at the base of the vault. This method requires GPS skyview, and is accurate to ~0.5°. Neither the Octans nor differential GPS are susceptible to interference from magnetic fields, ensuring accurate measurements. Reference alignment jigs were established at warehouse locations to test the repeatability of the devices over the field seasons.

The orientation and insulation of the sensor may take up to an hour on site. Orientation measurements were used to create a permanent reference mark(s) on the tank bottom (Figure 2-21). A metal ruler was fastened

Figure 2-21. Example of orienting an STS-2 seismometer using the Octans at TA.N15A. Notice the shock watch stickers that might indicate an Octans had suffered a crippling impact. Once oriented, the sensor is then packaged and insulated.

to the concrete base to allow the sensor, and any subsequent replacements, to be oriented exactly on a physical reference; the legs of the sensor, which are oriented with respect to the sensor's sensing elements, are located using a metal jig against the ruler. The installation crew then placed the sensor within a protective bag, surrounded it with a 38 cm (15 in) diameter tube that was anchored to the tank floor with plastic anchor screws, covered the sensor in sand, and capped it with foam insulation. The insulating materials helped to secure the sensor against inadvertent jarring, such as during servicing or from a large nearby earthquake, to which it may not be able to recenter. In addition, the sand and thermal insulation dampen sources of noise from temperature variation, leading to lower and more stable ambient noise levels recorded at long periods on both the vertical and horizontal channels.

Surface wave polarization measurements were extended to other permanent stations within the TA footprint (stations from the GSN, ANSS, and other regional networks) that contributed to its dataflow (Figure 2-22). These results demonstrated that many stations within these networks were also not consistently oriented accurately. A summary of these results (Ekström and Nettles, 2018) demonstrates some of the more extreme examples (Figure 2-23). These observations were shared with the relevant network operators as they were discovered, and the operators have in turn undertaken reassessments of station orientation based on the experience and practices of the TA. Octans and APS are now commonly used in the installation of permanent seismometers.

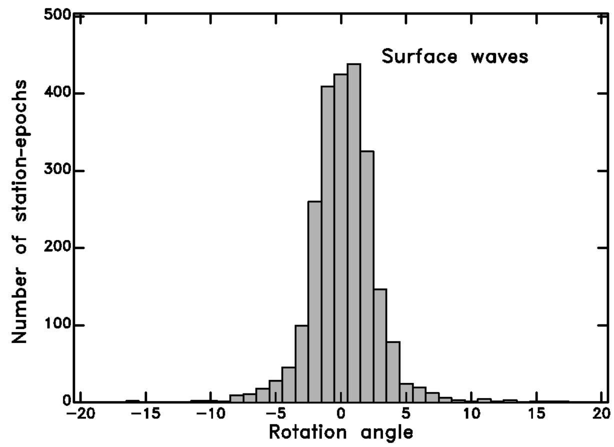


Figure 2-22. Histogram showing the distribution of robust median rotation angles for 2365 station-response epochs based on analysis of orientation using teleseismic surface-wave (Ekström and Nettles, 2018).

LONY–US	LH1–00	0.0	2011.125	2015.365	58	−16
LONY–US	LHN	0.0	2006.015	2011.121	58	−16
GMR–CI	LHN	0.0	2006.318	2007.308	36	−11
HEC–CI	LHN	0.0	2011.056	2013.158	79	−11
HEC–CI	LHN	0.0	2006.002	2011.052	144	−10
OGNE–US	LH1–00	0.0	2015.068	2015.365	12	−10
CWC–CI	LHN	0.0	2006.002	2011.052	32	−9
GMR–CI	LHN	0.0	2007.314	2015.365	404	−8
ISA–CI	LHN	344.0	2006.002	2007.232	11	−8
ISA–CI	LHN	344.0	2010.025	2013.031	42	−8
TUQ–CI	LHN	0.0	2006.002	2007.308	22	−8
TUQ–CI	LHN	0.0	2010.191	2013.281	56	−8
C03A–TA	LHN	356.3	2007.194	2008.045	30	−8
D03A–TA	LHN	358.6	2007.043	2008.043	32	−8
H23A–TA	LHN	0.7	2008.293	2009.260	17	−8
Y22C–TA	LHN	354.9	2006.028	2006.358	23	−8
IRM–CI	LHN	0.0	2011.065	2015.365	133	8
E06A–TA	LHN	11.2	2006.248	2008.134	61	8
V42A–TA	LHN	3.3	2011.134	2013.046	30	8
X41A–TA	LHN	358.6	2011.156	2013.047	35	8
DGMT–US	LHN–HR	0.0	2006.034	2011.130	98	8
OGNE–US	LH1–00	18.0	2011.125	2015.066	45	8
IRM–CI	LHN	0.0	2009.326	2011.060	32	9
BW06–US	LH1–00	0.0	2014.257	2015.365	25	9
OGNE–US	LHN	18.0	2008.169	2011.121	25	9
V45A–TA	LHN	8.8	2011.135	2013.072	41	10
FMP–CI	LHN	0.0	2006.002	2009.075	68	11
FMP–CI	LHN	0.0	2009.078	2010.222	35	11
FMP–CI	LHN	0.0	2010.223	2015.365	168	11
AAM–US	LHN	0.0	2009.230	2011.121	22	11
AAM–US	LHN	0.0	2006.002	2009.170	40	12
LGU–CI	LHN	0.0	2006.002	2006.242	12	13
AAM–US	LH1–00	0.0	2011.125	2015.365	92	13
ACSO–US	LHN	0.0	2006.002	2006.291	11	13
LGU–CI	LHN	0.0	2006.258	2008.218	41	15
LGU–CI	LHN	0.0	2010.191	2014.105	85	16
LGU–CI	LHN	0.0	2008.226	2010.189	42	17
SCI2–CI	LHN	0.0	2007.235	2015.365	57	21
BASO–PO	HHN	0.0	2012.001	2013.317	33	85

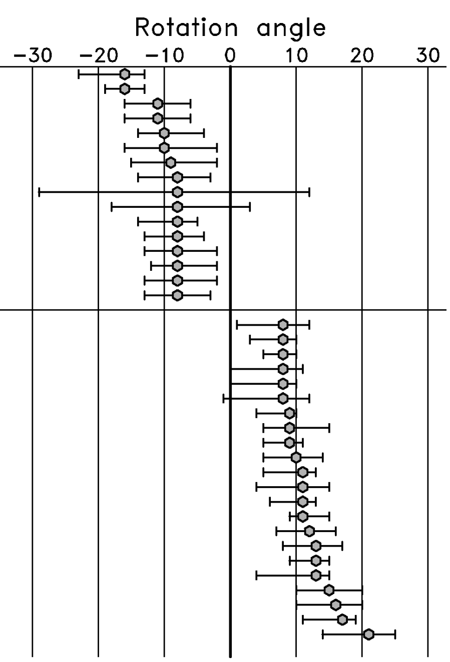


Figure 2-23. Estimated rotation angles for stations and epochs that deviate >7° from the reported orientation (Ekström and Nettles, 2018). Station, channel, reported sensor orientation, epoch start time, epoch end time, number of observations used in the calculation of the median, and the median deviation are listed for each estimate. The deviation for BASO-PO (bottom row) is 85°. The TA operated stations represent a very small fraction of outlier stations and none greater than 10°.

2.8 DATA ACQUISITION SYSTEMS

The TA used exclusively the Quanterra Q330, a commercially available observatory-grade datalogger, as the core component of its data acquisition system (Figure 2-24). The Q330 digitizes three to six channels with 24-bit resolution and uses a Quanterra Packet Baler to permanently store time series data on site. The vast majority of stations operated in a standard three-channel input mode with the broadband sensor. Additionally, 52 TA stations (10 flagged to be in the CEUSN, 9 Reference Network, and 33 Cascadia Initiative stations) operated in six-channel mode to support a co-located strong motion sensor. During the first several years of the TA, a spinning-disk Baler14F was used for onsite storage. This was replaced beginning in 2009 with the Baler 44CT, which was integrated into the VIE, holding up to 2 x 64 Gb of removable USB drive storage. The file structure and means of accessing the data are different between the two models, but they served the same function as local data storage and wrote miniSEED records according to the same prescription. At stations in 10 seismically quiet locations (Appendix B), a Q330HR was used to provide higher sensitivity and dynamic range (three channels digitized at 26 bits, the other at 24 bit) for small signals. These were limited to the Reference Network, and required special consideration because the Q330HR version consumed three times as much power and had unique metadata.

The Q330 uses a Delta Sigma modulated digitizing process and a cascade of finite impulse response (FIR) filters to provide seven choices of time series data at different sample rates. In this practice, the analog voltage signal from a seismometer is digitized with a very high initial sample rate, then progressively low-pass filtered and decimated to 200 samples per second (sps) to 40 sps and down to as low as 1 sps. In the L48 TA configuration, the 40 sps, 1 sps, 0.1 sps, and 0.01 sps rate channels were recorded—the rates 0.1 sps and 0.01 sps were decimated in downstream clients and not by the Q330. The length of digital filters and the sampling sequence were arranged to time align the output sample with UTC, providing synchronous sampling across the array. The response description used for SEED was approximated by a single composite FIR filter for each sample rate. In addition, the UH and VH channels had more than one FIR stage. The Q330 allowed the choice of linear phase (acausal) filters or minimum phase (causal) filters, depending on the application. The TA used all linear phase filters except for high sample rate strong motion channels. The manifestation of the FIR filter in the overall instrument response was a <5% ripple in amplitude near the Nyquist frequency.

Figure 2-24. Typical Q330 installation at TA.D56A.

Just more than half of all TA stations were equipped with a Quanterra Environmental Processor (QEP), which acts as an external digitizing module for weather, pressure, and infrasound signals and includes additional state-of-health information such as humidity and input voltage. The QEP was housed inside the VIE and uses a two-way serial connection to the Q330 to maintain timing synchronization with the Q330 main digitizer. The QEP has an optional one- or three-channel analog input. In the TA, we used the three-channel option but digitized only two additional signals. The proximity of the digitizer input to the infrasound sensor allowed power savings and reduced protection circuitry in the infrasound sensor. The implementation of QEP in the TA began in December 2008 and continued for every station thereafter. SEED channels originating within the QEP have location codes EP.

At a typical TA station, research-grade seismic and atmospheric data are sampled at 40 sps and delivered in real time (i.e., typically less than two seconds latency; see Steim and Reimiller, 2014). Lower sample rate data (1 sps) from the sensors were also provided that can aid processing of long time segments. Finally, state-of-health channels from the Q330, QEP, and sensors were also transmitted in real time, and some were selected for archiving at 1, 0.1, and/or 0.01 sps in miniSEED.

The Q330 uses a GPS engine optimized for timekeeping to synchronize an internal sampling clock, accurate to within a few microseconds. The Q330 produces time-stamped data packets every second for transmission to one or more receivers and includes the timing quality and any differences between the internal and external time. It is also automatically adjusted to leap-second corrections for UTC synchronization to variations in the length of day, which occurred on December 31, 2005, December 31, 2008, June 30, 2012, and June 30, 2015. As a general rule, researchers utilizing time series across these transitions should be aware of the potential for their software to mishandle the leap-second and introduce apparent one-second anomalies. Many other aspects of the Q330 functions are documented in technical publications and documents produced by Quanterra and Kinemetrics at http://www.q330.com or https://kinemetrics.com.

2.9 DATA COLLECTION

Communications

The goal of the TA was to establish real time IP-based communications at every installed station. The preferred order for data service providers was cellular, radio to AC VSAT, radio to land-based Internet, and radio to DC VSAT. As a result, we used cellular and AC VSAT at nearly all TA stations (Table 2-3, Figure 2-25). Sierra Wireless Raven X cell modems were most commonly used. Cellular communications encompassed

Type	% of Stations	Total Additional Time to Set Up (hours)	Time to Set Up (hours) by Component
Internal Cellular	84	0	n/a
Ext. VSAT w/AC	9	10	4 AC enclosure + 4 VSAT + 2 Radios
Ext. VSAT DC	6	15	9 DC + 4 VSAT + 2 Radios
Ext. Radio to Internet	1	8	2 Radios + 2 Cabling + 4 Mount Enclosure

Table 2-3. Stations using non-cellular communication required extra time to build and configure.

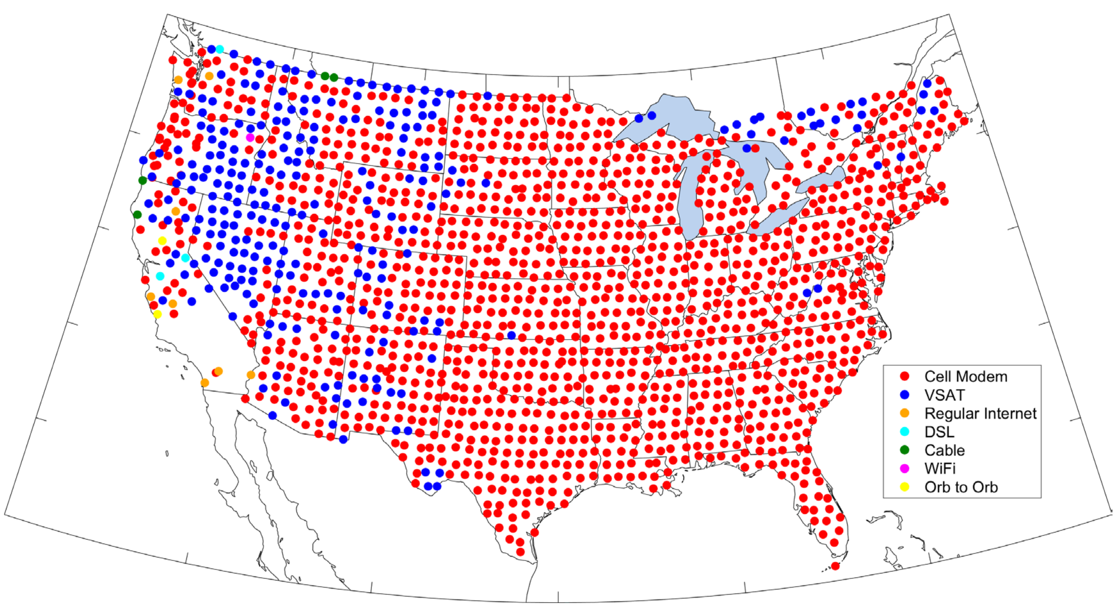


Figure 2-25. Final telemetry configuration for TA stations, through 7/20/17.

nearly all stations, including those in rural areas across the central and eastern United States where mobile coverage was well established. In remote parts of the western United States and southern Canada, VSAT communications were regularly used and even constituted a majority of stations in Oregon, Nevada, and Idaho. A small number of stations in the westernmost TA footprint used land-based Internet options (e.g., DSL, cable). For line-connected modems and VSAT communication systems, a radio link connected the station to its communication hardware to provide electrical isolation—an air gap between station equipment and these devices. This approach allowed more flexibility between the communication site requirements and the station siting criteria. Although the radios have a range of up to 50 km line-of-sight, usage cases for the TA were usually within a few hundred meters between station and receiver. Commercial VSAT (e.g., Viasat Wild Blue) and cell service providers were selected based on availability and performance, with Verizon being used more than AT&T. Sites with inconsistent communications performance were switched from VSAT to cellular or vice versa.

The communications configuration required some refinement during initial TA rollout. The DC power module was designed for a 30 W load, but in general this option was more difficult to install and operate in all conditions. The system often required a duty cycle of the power to the terminal in a ratio of one hour on to four hours off, which introduced latency to the data flow and indeterminacy for command and control processes. Additionally, for some cellular service providers (particularly in the early years, 2005–2008), the TA was required to periodically interrupt cellular connection. This was accomplished by having Antelope deregister (log out) from the Q330. The connection was then reestablished on a set time interval or by receiving a point-of-contact (POC) packet from the Q330 with a programed delay of five minutes. To ensure reliable modem operation, a routine daily power cycle for the modem was part of the initial VIE design.

Network Design and Function

The overarching network of the TA is a distributed set of hosts linked via Internet Protocol (IP) to a central set of virtual machines (Figure 2-26). The station's Q330 datalogger acts as a data server and must be contacted by a client. Data flow begins after an authentication process and session negotiation. Typically, the datalogger sits behind gateway devices, including cell modems, satellite terminals, and DSL routers, and this arrangement adds some complexity to access from an external client. The datalogger implements a POC packet outbound to a list of recipients in order to convey the IP address, serial number, and other information to a host computer at the ANF, which allows it to discover a dynamically assigned IP address. In the case of the TA, data flow is managed using UDP protocol that is enhanced by a proprietary transport protocol designed to tolerate field communication conditions. Window sizes, acknowledged time-outs, and retransmission intervals are adjustable to types of communication such as radio links, cellular, or VSAT. On either end of the communication process are object ring buffers (orbs), which are circular buffers of packetized data that allow clients to add or process packets independently of transit irregularities.

The requirement for network communications to utilize Internet Protocol (IP) was based on a need for secure but transparent interface with TA stations, in contrast to serial connections via modems, for example. This enabled flexibility in network function that had several major benefits throughout operation of the TA. IP access allowed communications to evolve (rapidly) with telemetry device improvements and security policies to meet individual station needs and needs across the TA as it matured. It facilitated access from various authorized partners who operated the TA, ranging from the distributed IRIS management staff, the AOC, ANF, and DMC, as well as the designers and manufacturers of key TA components. This allowed a wide audience to monitor, analyze, and improve system performance. It also allowed stations to be reconfigured remotely, new firmware to be installed over the air, and encouraged the development of various state-of-health tools.

Transmitted data are of two types: (1) those within a packet representing one or more channel time-series segments with the attendant descriptive channel header information, and (2) the requested status that travels along with a packet. On an uncongested link, the Q330 sends all channel data each second in

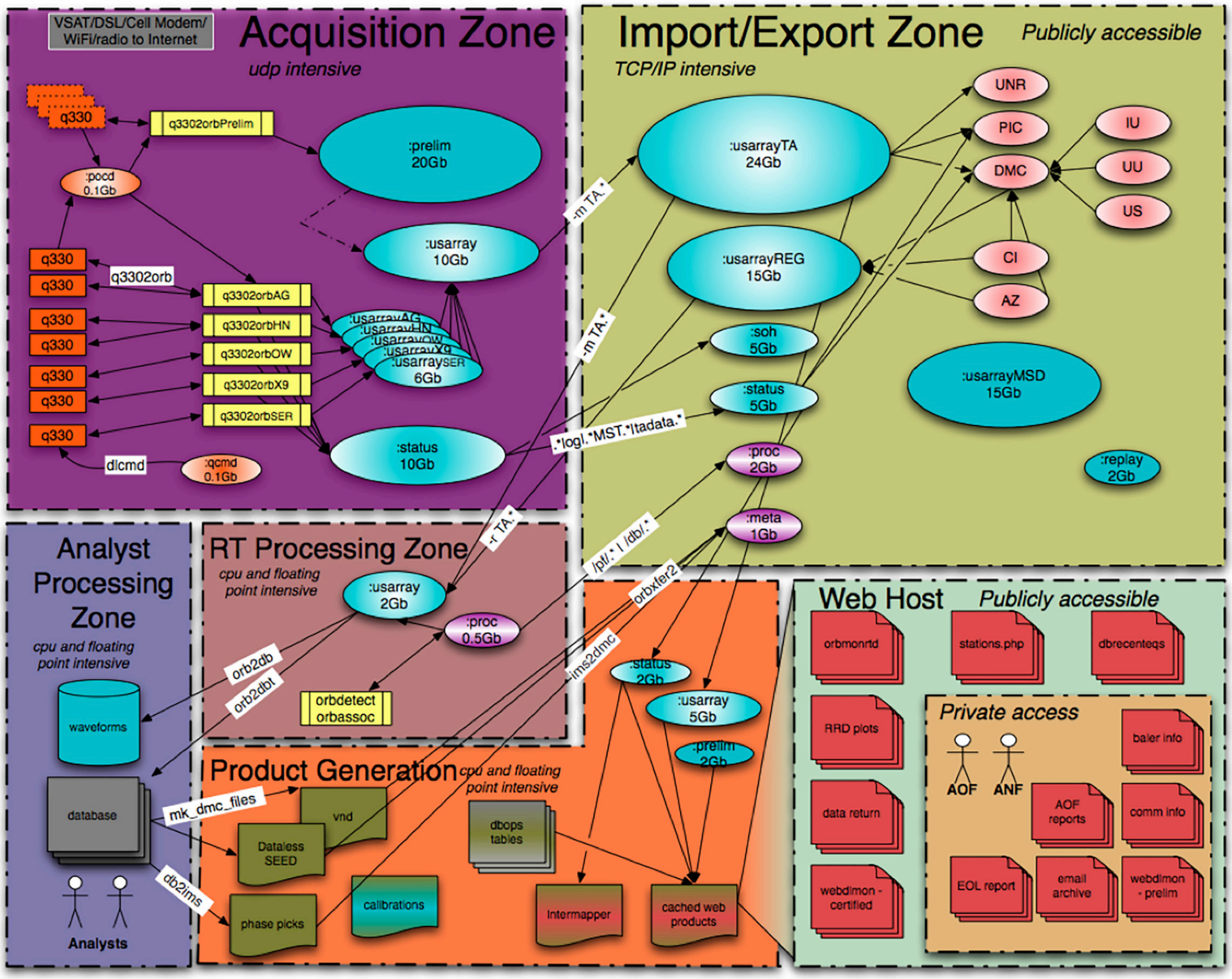


Figure 2-26. Visualization of TA network dataflow through various virtual machines at the ANF. Data are managed through various stages using object ring buffers, or orbs. For data acquisition, orbs separated the processing of freshly installed stations from groups of stations with certified metadata. Data were also split between orbs for seismic, auxiliary sensor data, and status information, which helped to enable state-of-health monitoring. For import/export, different orbs imported contributing network data from the DMC, managed external user collection of TA data, transferred metadata and unreviewed solutions, arrivals, and other information, and shipped out data recovered from balers. The real time/analyst and processing/product generation virtual machines (later combined into one) ran event detection, review, and database/waveform writing to disk. Dataless SEED were generated here and moved to the export process. Monitoring tools were also run on dataflow and process continuity. For web hosting, virtual machines handled public and private display of documentation and generated products.

536-byte packets using a data record sequence number to reorder retransmitted packets. When a connection is broken, data are queued in memory and transmission is resumed upon reconnection. The telemetry buffer for TA stations can span about 18 hours, depending on several different configuration options and the number of channels in use. If there is a gap in telemetry, generally all SEED channels are affected, though the duration of the gap may appear longer or shorter depending on the sample rate.

The Array Network Facility, located at UCSD, operated the network computing systems. They began as Sun Solaris architecture, migrated through an Apple server phase to eventually run on a set of Linux virtual machines. The main acquisition software used was the Antelope System from Boulder Real Time Technology. This software used a combination of object ring buffers and interconnected clients to pass information between different instances of the program, including to other seismic network operators and the IRIS DMC, or to clients performing distinct tasks such as writing data to disk (in 4096 byte SEED packets) or clients that processed event associations into a database. It also had command ring buffers to issue commands and control to the remote stations. A number of clients parsed status information that was displayed, analyzed for alarms, or compiled into databases for historical review. The ANF created an extensive database environment and JavaScript Object Notation tables to inform many diagnostic displays. Networked devices were also monitored through IT management software Intermapper and SNMP polls. The system of informative interactive displays was key to real time diagnosis of station conditions and contributed to high data return from the TA stations.

Data Handling

The process of reviewing and archiving TA data involved cooperation of both the ANF and IRIS DMC, and encompassed (1) regularized quality assessment and routine weekly reports of issues with signal quality or station performance and (2) iterating on data completeness for archived metadata and data from volumes telemetered in real time and those collected from station local archives. Quality control measures spanned three categories: data accuracy, data integrity, and signal quality. Data accuracy screening ensured that the metadata properly describe the channel, examining whether the amplitude and polarity of waveforms were consistent with expected location, orientation, and response of the seismometer. Data integrity was related to continuity of the time series as it was transmitted and reassembled in different volumes. This was often tabulated by packet management utilities that detected and reported gaps in a time series per day, gaps in the last hour or 24 hours, and percent of data return for a day. Signal quality was often the most difficult to quantitatively characterize, ranging from flat-lined channels (a time series with no signal at all), to half-amplitude signals, to signals corrupted by invalid boom positions or noisy sensor elements. Automatic detection of quality issues began at the onsite datalogger, which performed an amplitude calibration and issued a calibration error, if found out of range, to indicate that the amplitude may be inaccurate. Similarly, the datalogger reported when time labels were known to be inaccurate.

For more synoptic assessments of data quality, full-time seismic analysts at the ANF reviewed the incoming data and confirmed automated picks on event detections. Poor quality signals or timing errors were reported to a common email thread. A comprehensive "reactor panel" display of all stations contained visual highlights of bad conditions such as anomalous mass positions, degraded timing quality, and high telemetry link cycles or gaps, and the display automatically sorted the several hundred stations into a priority order. The application allowed clicking on a status value displayed to view the history for the past day, week, month, year, or lifetime. In addition, data specialists at the IRIS DMC reviewed all data at 1 sps in large panels of stations and each week prepared an internal report (http://crunch.iris.washington.edu/reports/_US-TA/) that highlighted station signal quality problems and provided a positive annotation that every station was reviewed. The DMC also used a suite of automated metrics to comprehensively characterize incoming time series data. These were open to the public and regularly examined by the DMC data specialist, as well as TA management, to explore specific data quality issues. Each issue that affected the quality of archived time series was documented for external users in Data Problem Reports (DPRs), which are searchable here: http://ds.iris.edu/ds/nodes/dmc/data/dpr.

On a weekly basis, a senior TA engineer reviewed diagnostic panels and prepared a highlighted list of station issues. Generally, these were sorted by a station being OUT (no data recorded), DOWN (station working but no telemetry), or OTHER (miscellaneous hardware issues). This was combined with the signal quality report from the DMC for review by TA management. This was used to form a prioritized plan for mitigating problems that was subsequently discussed in weekly conference calls with all TA staff. The important steps in the quality control process were comprehensive screening for new problems, tracking of existing problems, and guidance by management as to what to address next. Finally, as batches of stations were completed, the ANF and DMC worked closely and carefully to reconcile the onsite and telemetered time series data sets to ensure that the archived record from each station was maximized in the DMC archive.

3. Data, Metadata, and Quality Measures

3.1 BASIC CHARACTERISTICS

Data for the TA are written in SEED, the digital data format introduced for seismology applications in the late 1980s (see Ringler and Evans, 2015, for an introduction to the format). The SEED scheme provides a comprehensive representation of data and their accompanying metadata. It uses shorthand nomenclature to identify time series with a set of abbreviations, usually letters, to represent the location where the data were recorded and some characteristics of the instrument and sample rate. The data form consists of two parts: a concatenation of digital, compressed time series packets (data as miniSEED) and a set of response descriptions that describe an epoch of the packetized data (metadata as dataless SEED). For the purposes here, an individual time series is referred to as a channel. A station often has a collection of channels with various sample rates, and it generally means that all of those channels share the same physical locale. The station code is up to five characters long and must be unique within the two-letter network code. For instance, TA_H17A is the station code H17A within the TA network code. Conventions used for station codes were covered in section 2.2. Tables 3-1 to 3-4 display an extensive a set of TA channel definitions. At times, there are very similar instruments recording at a station and the channel code is then further distinguished by a two-character location code. Historically, many operators were slow to adopt explicit location codes except when needed, and therefore the default code is "blank blank," which may be challenging to recognize in text for filename construction or when forming a data request. The blank location code is prevalent in TA SEED data. In practice, requests to the IRIS DMC must include two dashes "--" to access data from a blank location code. Filenames extracted from SEED typically represent files in a NET.STA.LOC.CHA scheme, for example, TA.R58A..BHZ, where the blank location is represented with no characters in between periods.

Channel	Instrument	Parameter (unit)	sps
ACE	Q330	log of significant changes to clock status	n/a
LOG	Q330	log of Q330 and operator actions (text)	n/a
OCF	Q330	daily snapshot of configuration (binary)	n/a
LCQ	Q330	clock quality (%)	1
LCE	Q330	clock phase error from UTC (sec)	1
VCO	Q330	voltage control oscillator value (range 0–4095, median = 2048, no units)	0.1
VEA	Q330	GPS antenna current (A)	0.1
VEC	Q330	system input current (A), not including Baler, sensors, etc., that share power connection via Q330 connector	0.1
VEP	Q330	input power supply voltage (V)	0.1
VKI	Q330	internal temperature (°C)	0.1
VPB	Q330	percentage of telemetry packet queue in use for current Data Port (%)	0.1
VM[1-6]	Q330	boom position channels (V)	0.1

Table 3-1. Channels associated with the Q330, location code "__". sps = samples per second.

In addition, there are a handful of rarely used or "dummy" channels that are archived for one or more TA stations. These channels are either not intended for use or indicate a temporary configuration from one or more test instruments and thus may not provide the same utility as standardized TA data. They include microbarometers and infrasound microphones operated at several TA stations in 2008–2010 and testing of an infrasound sensor at two TA stations (Appendix C). QEP and VM0 are more commonly found dummy channels that were not intended for use. One station reported seismometer boom voltages at VMU/VMV/VMW, which are associated with the STS-2 seismometer.

3.2 METADATA

Metadata for seismic stations represent the vital parameters for understanding the disposition site and account for the station's instrumentation. For the TA, metadata encompass the station's geographical parameters (site name, location, elevation), as well as the type and serial numbers of key hardware and the orientation of the seismometer. Metadata include the start and end date of the station, and show multiple epochs of operation if changes to the configuration of the station had been manifested in updates to the metadata. Metadata can be represented in various forms, but are archived as dataless SEED, which for a station contains a list of all locations, channels, and specific instrument responses. For the TA, and all IRIS networks, this information can be parsed through utilities such as the metadata aggregator (mda), which allows drill-down into the metadata associated with each recorded channel (Figure 3-1). As noted earlier, information regarding latitude and longitude underwent special handling when

Channel	Instrument	Parameter (unit)	sps
LDM	QEP	MEMS absolute barometric pressure (Pa)	1
LKM	QEP	internal temperature inside VIE (°C)	1
LIM	QEP	internal humidity inside VIE (%)	1
LEP	QEP	supply voltage (V)	1
LCE	QEP	clock phase error w.r.t. UTC (sec)	1
LCO	QEP	oscillator control value (V)	1

Table 3-2. Channels associated with the Quanterra Environmental Processor (QEP), location code EP. sps = samples per second.

Channel	Instrument	Parameter (unit)	sps
HH[E,N,Z]	broadband seismometer	ground velocity (m/s)	100
BH[E,N,Z]	broadband seismometer	ground velocity (m/s)	40
LH[E,N,Z]	broadband seismometer	ground velocity (m/s)	1
VH[E,N,Z]	broadband seismometer	ground velocity (m/s)	0.1
UH[E,N,Z]	broadband seismometer	ground velocity (m/s)	0.01
HN[E,N,Z]	strong motion seismometer	ground acceleration (m/s^2)	200, 100
LN[E,N,Z]	strong motion seismometer	ground acceleration (m/s^2)	1

Table 3-3. Channels associated with broadband and strong motion seismometers, location code "__". Two broadband seismometers at the same station were distinguished by setting "01" as the location code of the second sensor. sps = samples per second.

Channel	Instrument	Parameter (unit)	sps
BDF	Hyperion NCPA	infrasound, relative barometric pressure (Pa)	40
LDF	Hyperion NCPA	infrasound, relative barometric pressure (Pa)	1
BDO	Setra 278	absolute barometric pressure (Pa), with offset	40
LDO	Setra 278	absolute barometric pressure (Pa), with offset	1
LWD	Vaisala WXT520	wind direction (° clockwise from N)	1
LWS	Vaisala WXT520	wind speed (m/s)	1
LDV	Vaisala WXT520	exterior pressure (Pa)	1
LKO	Vaisala WXT520	exterior temperature (°C)	1
LIO	Vaisala WXT520	exterior humidity (%)	1
LRO	Vaisala WXT520	rain intensity (0.1 mm/hour)	1
LRH	Vaisala WXT520	hail intensity (hits/cm^2/hour)	1
LKH	Vaisala WXT520	heater temperature (°C)	1
LEH	Vaisala WXT520	heater voltage (V)	1
LEW	Vaisala WXT520	supply voltage (V)	1
LER	Vaisala WXT520	reference voltage (V)	1

Table 3-4. Channels associated with atmospheric and meteorological instruments, location code EP. sps = samples per second.

Network	TA :: USArray Transportable Array (NSF EarthScope Project) :: TA Network Map :: DOI
Station	R58B :: Mineral, VA, USA :: USArray Transportable Array :: R58B Station Map :: RESP :: SAC PZs :: XML
Latitude	37.963600
Longitude	-77.878700
Elevation	116
Start	2012/08/02 (215) 00:00:00
End	2015/04/28 (118) 23:59:59
Epoch	**2015/01/20 (020) 18:00:00 - 2015/04/28 (118) 14:18:52**
Instrument	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co
Channels (Hz)	Location --: HHE (100), HHN (100), HHZ (100)
Epoch	**2012/08/02 (215) 00:00:00 - 2015/04/28 (118) 14:18:52**
Instrument	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co
Channels (Hz)	Location --: BHE (40), BHN (40), BHZ (40), LHE (1), LHN (1), LHZ (1), UHE (0.01), UHN (0.01), UHZ (0.01), VHE (0.1), VHN (0.1), VHZ (0.1)
Instrument	Setra 278 microbarometer/Q330 w/Environmental Proc
Channels (Hz)	Location EP: BDO (40), LDO (1)
Instrument	Quanterra 330 Linear Phase Composite
Channels (Hz)	Location --: ACE (0), LCE (1), LCQ (1), LOG (0), OCF (0), VCO (0.1), VEA (0.1), VEC (0.1), VEP (0.1), VKI (0.1), VM0 (0.1), VM1 (0.1), VM2 (0.1), VM3 (0.1), VM4 (0.1), VM5 (0.1), VM6 (0.1), VPB (0.1)
Instrument	Q330 w/Environmental Processor, fixed State of Hea
Channels (Hz)	Location EP: LCE (1), LCO (1), LDM (1), LEP (1), LIM (1), LKM (1)
Instrument	Hyperion microbarometer/Q330 w/Environmental Proce
Channels (Hz)	Location EP: BDF (40), LDF (1)
Instrument	Episensor 200 Hz 10 Volt per g/Quanterra 330 Linea
Channels (Hz)	Location --: HNE (100), HNN (100), HNZ (100), LNE (1), LNN (1), LNZ (1)
MetaData Load	2016/03/04 (064) 21:20:03

Figure 3-1. View of metadata for TA.R58B on the IRIS DMC metadata aggregator (http://ds.iris.edu/mda/TA/R58B). Hyperlinks allow for drilldown of information on specific channels as well as access to the response information.

displayed publicly. These quantities were precise to five decimal places in the dataless SEED, but were truncated to two places when displayed on both the mda and ANF station pages. This policy was later relaxed for the mda pages following the removal of the migrating TA footprint in 2015.

3.3 DATA QUALITY MEASURES

Characterizing the key facets of data quality was a major effort throughout the operation of the TA. Broadly speaking, these efforts centered on measuring data integrity, data return, and the overall noisiness of TA stations relative to each other and global benchmarks. These assessments were used routinely by TA management to prioritize servicing and often resulted in significant improvements to the stations as they operated. Here we summarize these aspects of the TA's data quality, demonstrating how elements of data quality varied across as the TA over time.

Integrity – Uptime and Completeness

Data integrity encompasses measures of overall uptime, the overall percentage of data received vs. expected, and completeness or the number of gaps within an ideally continuous time series. These parameters were examined by channel, station, and network. As a network, the TA had a performance metric to operate at >85% uptime and a goal to avoid any gaps in data return. Automated reports on the fifth of each month showed the percentage of expected data available from TA stations for one month and three months arrears. This information was used to gauge the near-term and longer-term archival status of the network, both for TA stations and contributing networks such as the USGS ANSS and other regional network stations. During the first several years, the data return of the TA rose from ~96% to 99%, then over 99%, as the network became more efficient and improved both its station uptime as well as real time telemetry performance (Figure 3-2).

For this report, we more closely examined TA data availability. We incorporated metrics for "percent_availability" and "dead_channel" from the IRIS MUSTANG quality control metric database. By factoring in whether one or more channels from a station were "dead" or flat-lined, usually due to sensor failure, periods when scientifically useless data were delivered and archived could be discarded. Because TA stations

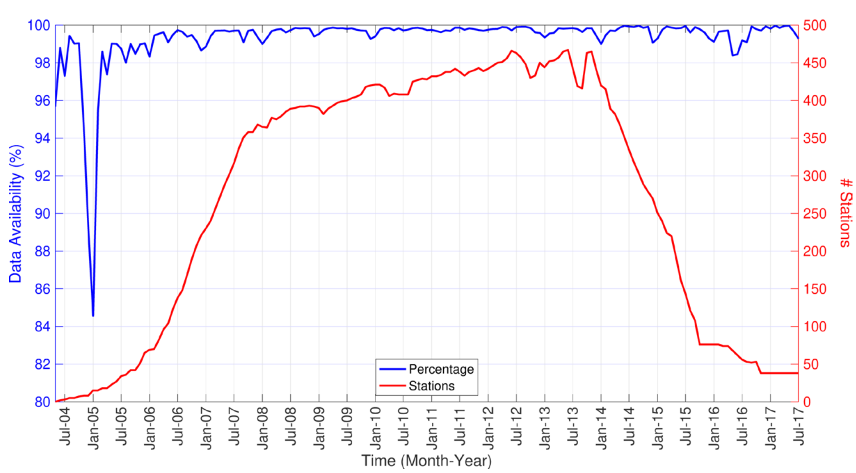


Figure 3-2. Comparison of average data availability and number of deployed stations for the TA per month.

were closely monitored, this data purge was not a common occurrence and does not significantly lower the measurement of data availability. Only four TA stations (E50A, G10A, J03A, L32A) experienced data availability of less than 95% through their deployment (Figure 3-3). The mean uptime of all TA stations was 99.7%. This figure exceeds the raw availability, not accounting for dead channels, of networks such as the ANSS, which had an uptime of 94.6% among stations that contributed to the TA network during the same time span. Overall, 98.9% of TA station-days had 100% data availability (Figure 3-4).

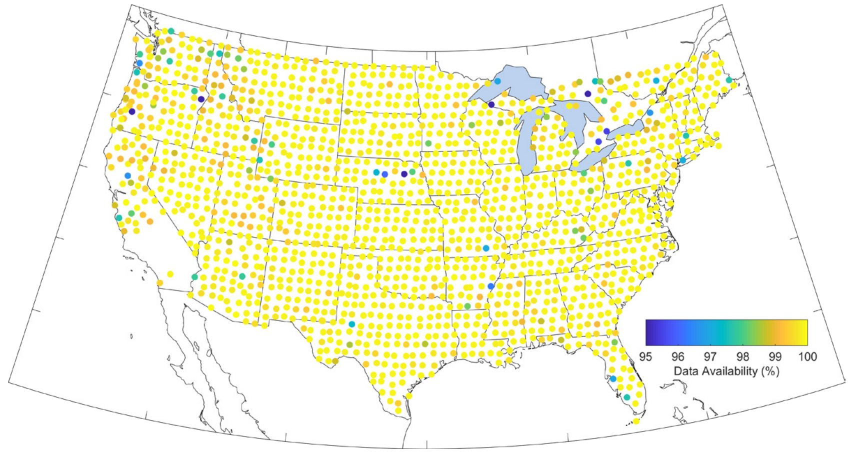


Figure 3-3. Data availability for the TA.

Another element of data integrity concerns data continuity. Gaps in archived time series fragment the seismic record at a station and reduce its overall utility. Interruptions in telemetry or a more serious issue with one or more hardware components usually caused these gaps. The former was an issue during the early years of the TA, when the limitations of various telemetry options were still being discovered at specific stations. In our final assessment, only 13,248 out of 1,299,560 station-days contained one or more gaps (Figure 3-4). In addition, another 8,137 station-days had no data. Overall, 122 TA stations experienced no gaps in recording throughout their entire deployment and the monthly number of gaps by the TA decreased as the full array moved eastward (Figure 3-5). Most TA stations operated for considerable durations before experiencing a gap in the archived time series (Figure 3-6). The length of longest continuous segment of data at a single station ranges from 50.9 to 1827.6 days (~5 years), with the median being 416.8 days, or more than half the length of a typical deployment (Figure 3-7). In particular, firmware updates to the Q330 caused by changing the configuration of the station required a reboot to the data acquisition system. Each time this occurred, it caused a time tear in the data stream from that station. This pattern

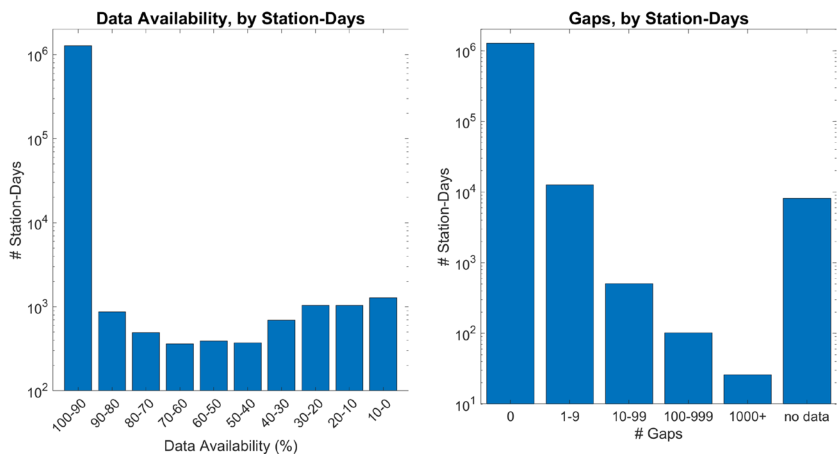


Figure 3-4. Histograms of data availability (left) and gaps (right) by station-day.

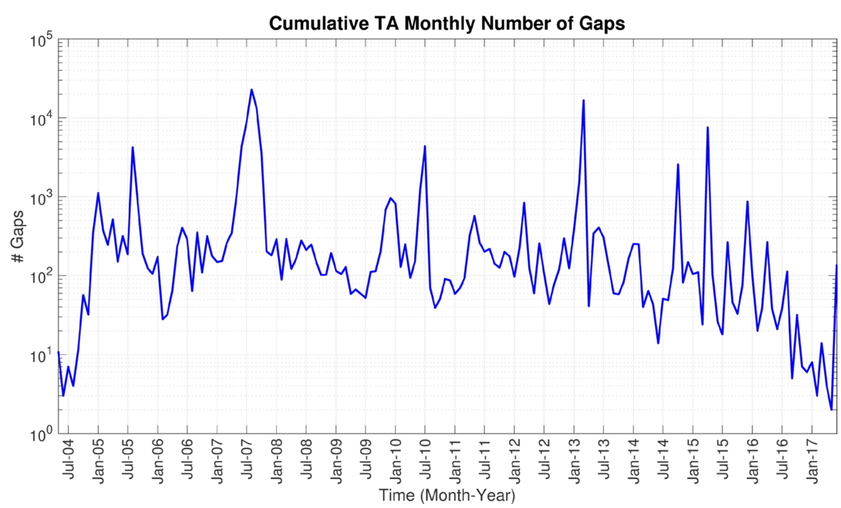


Figure 3-5. Cumulative gaps per month for the entire TA network.

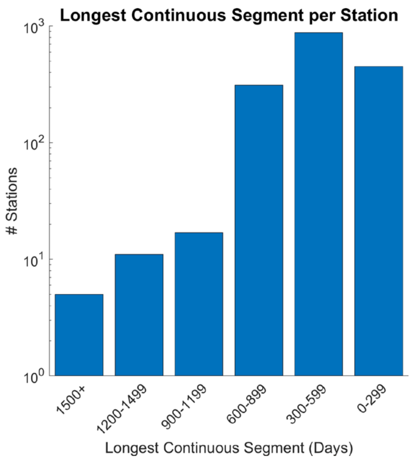


Figure 3-6. Histogram of longest continuous segment of data per station.

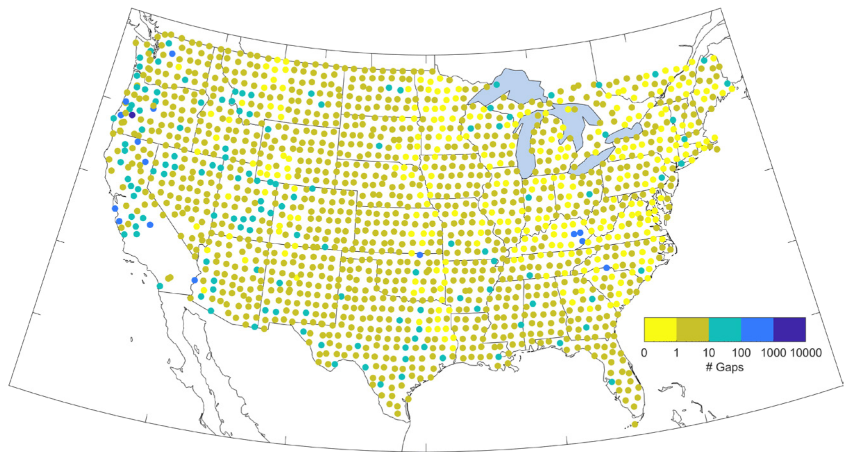


Figure 3-7. Longest continuous segment of data per station.

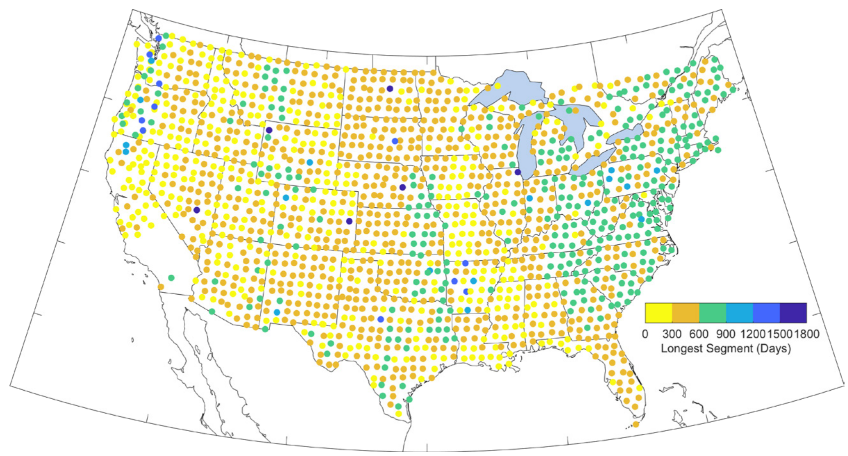


Figure 3-8. Cumulative gaps per station.

manifests in a north-south "banding" appearance in the length of longest segments within the Great Plains, first with the addition of the QEP and later with the inclusion of microbarometers and infrasound. Once the station design was finalized, the frequency of gaps decreased as the network moved into the eastern United States (Figure 3-8), which manifests in the related increase in longest continuous segment at a regional scale.

Signal Quality – Noise Performance

Observing of the signal power recorded at a seismic station in between earthquakes allows operators to characterize its capability to record events cleanly. As such, the TA actively monitored the noise levels across the network to assess its general performance as well as spot specific data issues that often manifested in the station spectra. The siting constraints of the TA sought to reduce spurious noise, which would obscure not only the seismograms of small earthquakes but also other environmental phenomena, as well as degrade the effectiveness of various methods for imaging Earth structure. Each day, the ambient power spectra for each component at each station were computed using the methods of McNamara and Buland (2004). These spectra are now complete for the entire operation of the TA and can be downloaded or perused through MUSTANG.

These spectra demonstrate how the noise levels of the array compare to global reference new high- and low-noise models (NLNM, NHNM) (Peterson, 1993). We produce representative statistics from the probability density function (PDF) of all power spectral density (PSD) measurements for the entire network (Figure 3-9) and by station (Figure 3-10). The average (mean, median, and mode) noise performance of the TA network is consistently well below the high-noise model for both vertical and horizontal components at all periods. This outperforms previous temporary deployments of seismometers and is a direct result of how the TA was intentionally designed, with siting that avoided common sources of noise and a rigid and thoroughly insulated subsurface vault to house the seismometers. There is also no indication that the different broadband seismometers or change in vault design used in the TA manifested in the spectra of TA stations and thus consider all observations a faithful record of the local ambient noise state throughout the footprint.

The noise level of the TA at certain periods had a strong seasonal effect (Figure 3-11). As has been observed in seismic noise spectra in North America for decades, the ambient noise level of the oceanic microseismic signal increases considerably during winter. The background noise level of higher frequencies also vary over time, as a function of the array's geographic distribution. Performance of individual TA stations varies the most at high frequencies and on the horizontal components at long periods, which are generally the hardest channels to achieve very low noise performance due to the tilt signal from pressure and temperature variations. Regional trends related to both cultural and environmental sources of noise in some cases correlate with various geologic structures (Figures 3-12 to 3-15). The coasts, regions of thick sediment deposits such as the Mississippi Embayment, and regions closer to large urban areas have consistently higher noise levels than more remote, interior continental environments.

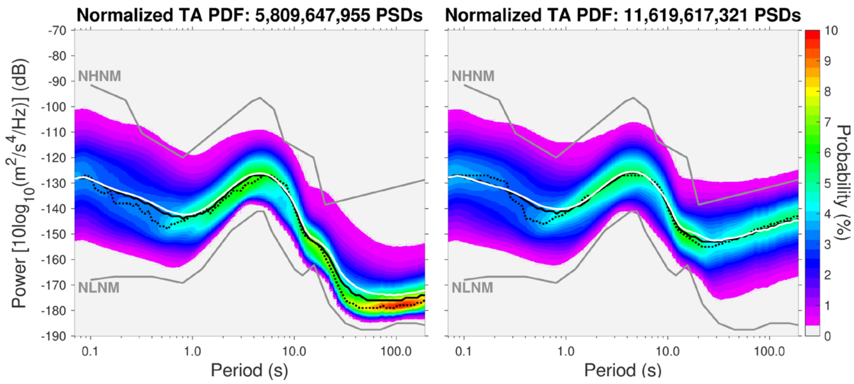


Figure 3-9. Composite probability density function of all power spectral density measurements from the TA network for vertical (left) and combined horizontal components (right). The mean (white), median (black), and mode (dotted black) of all spectra are displayed along with the NLNM and NHNM. The y-axis (power, dB) has logarithmic units; therefore, increments relate to an increase or decrease in power by a factor of 10.

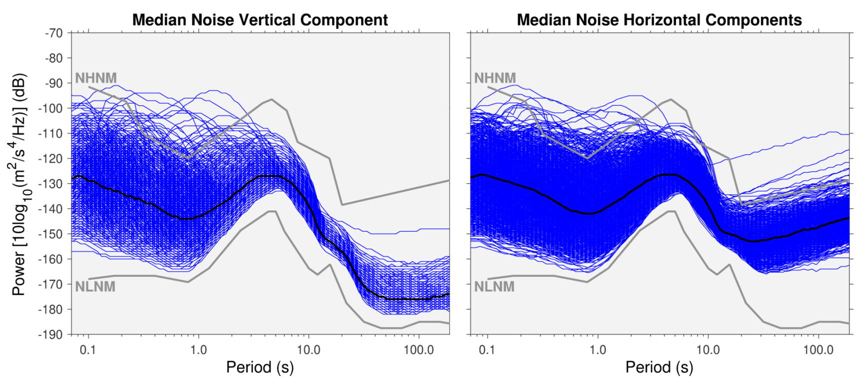


Figure 3-10. The median spectra (blue) of the vertical (left) and averaged horizontal (right) components for each TA station, with the median (black) of all stations and the NHNM/NLNM (gray).

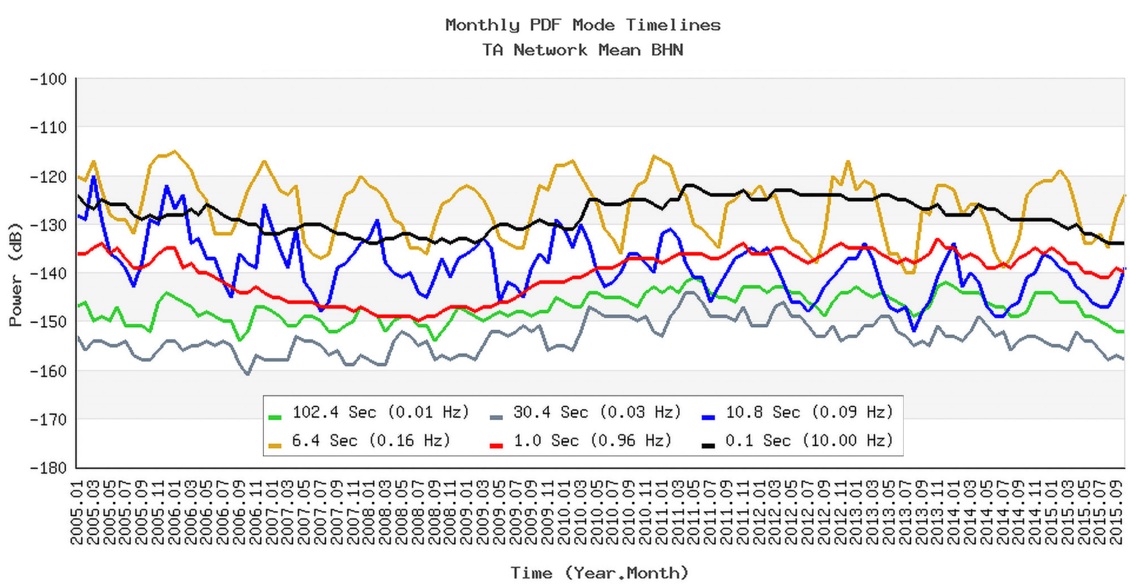
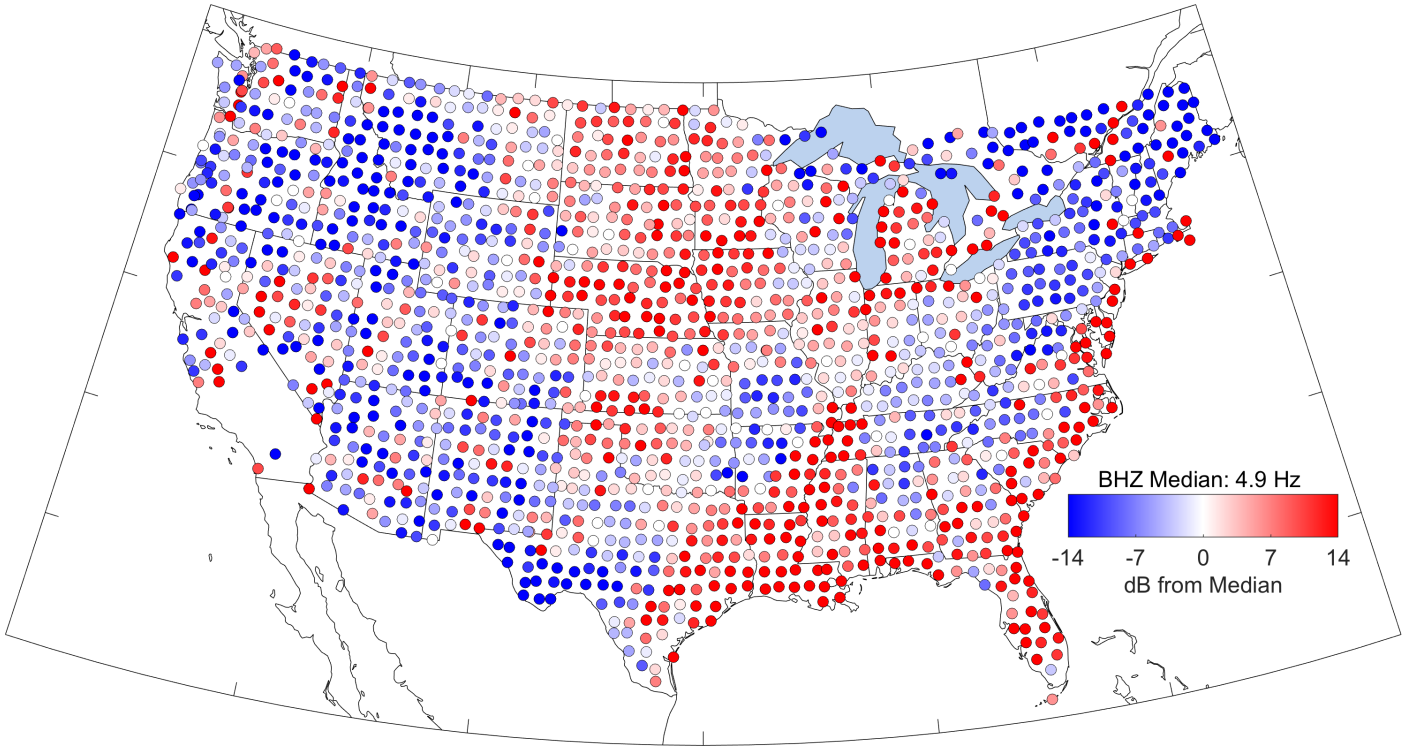


Figure 3-11. Mode of the cumulative spectral power of the entire TA for six different periods of interest. This analysis was automated and produced regularly by the DMC for each station-channel to monitor network performance.



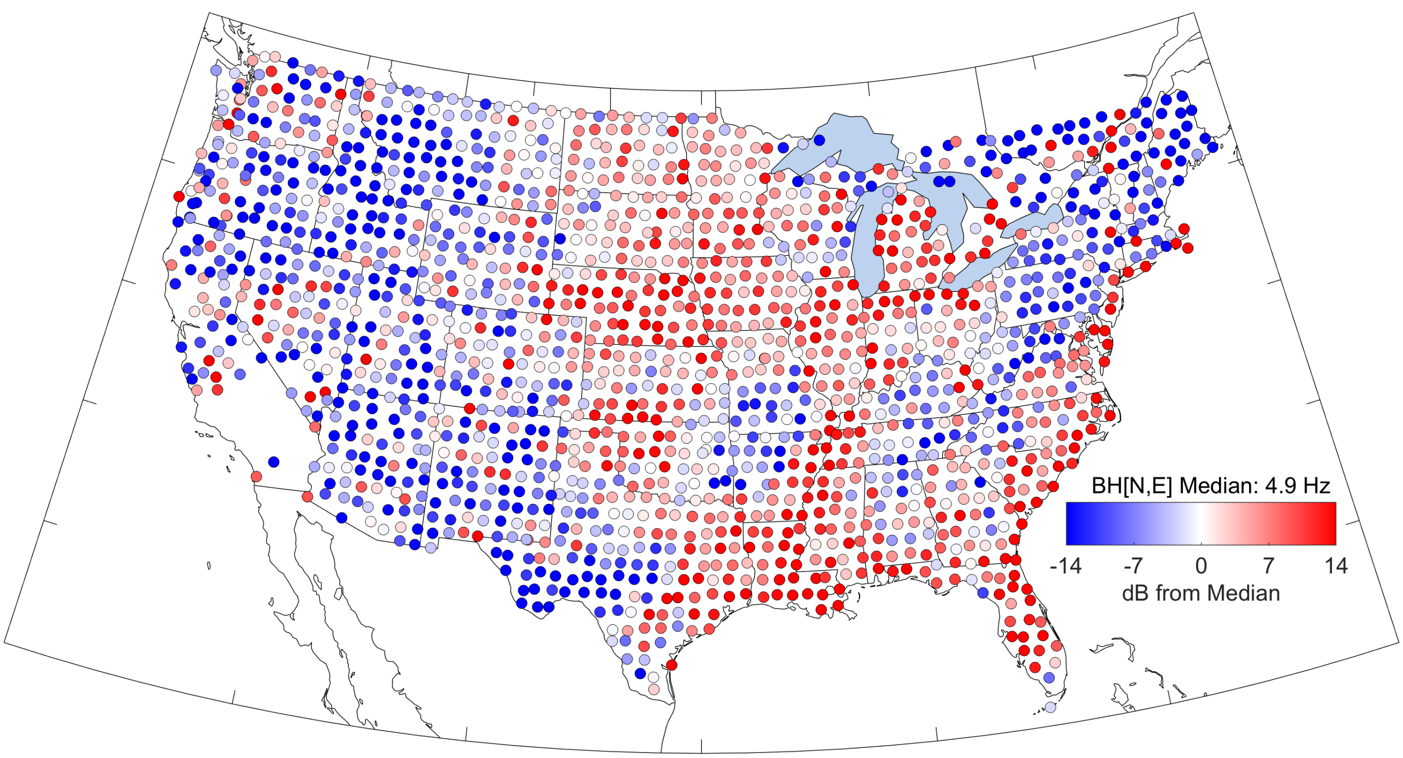
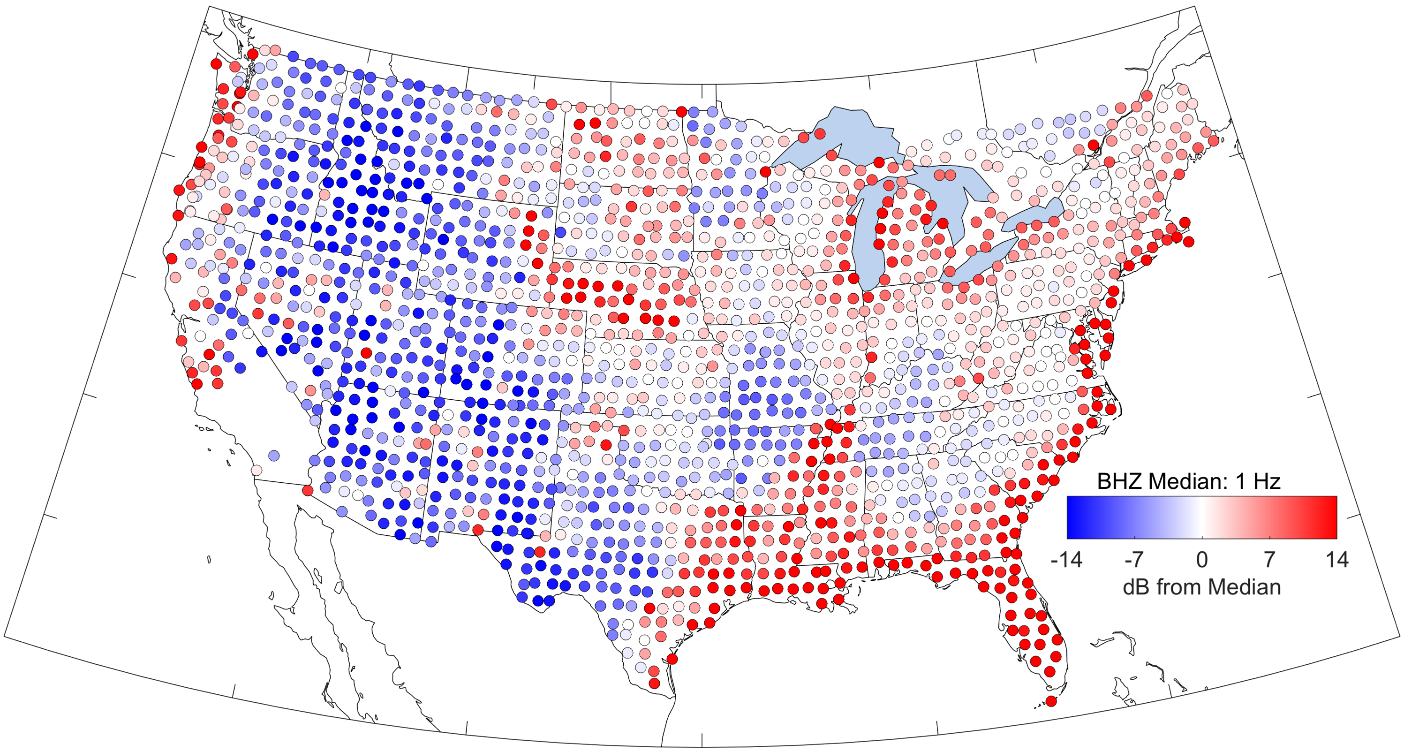


Figure 3-12. Deviation from the cumulative median for the network of the median noise spectra at ~4.9 Hz for the vertical and averaged horizontal components. Color scale limits are based on the approximate 10th and 90th percentile distribution of measurements.



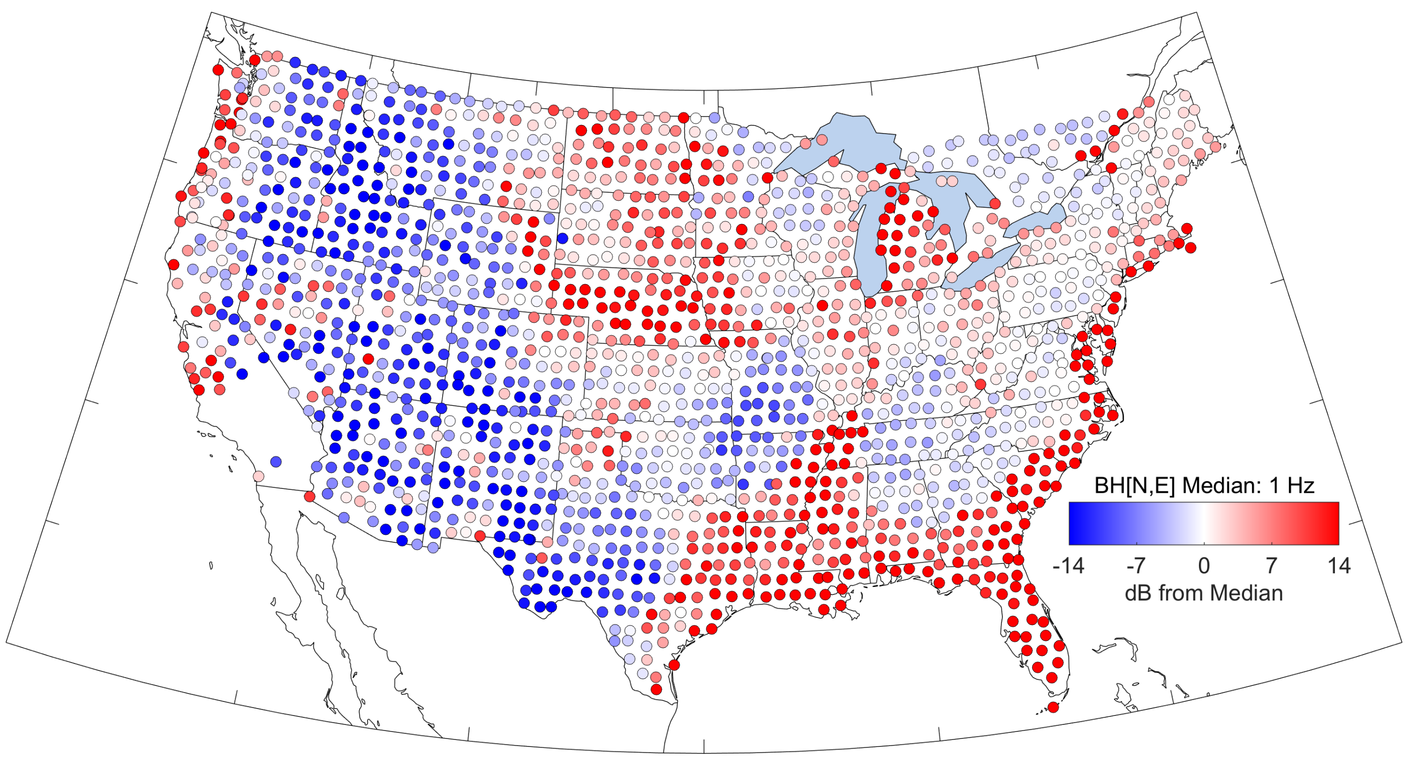
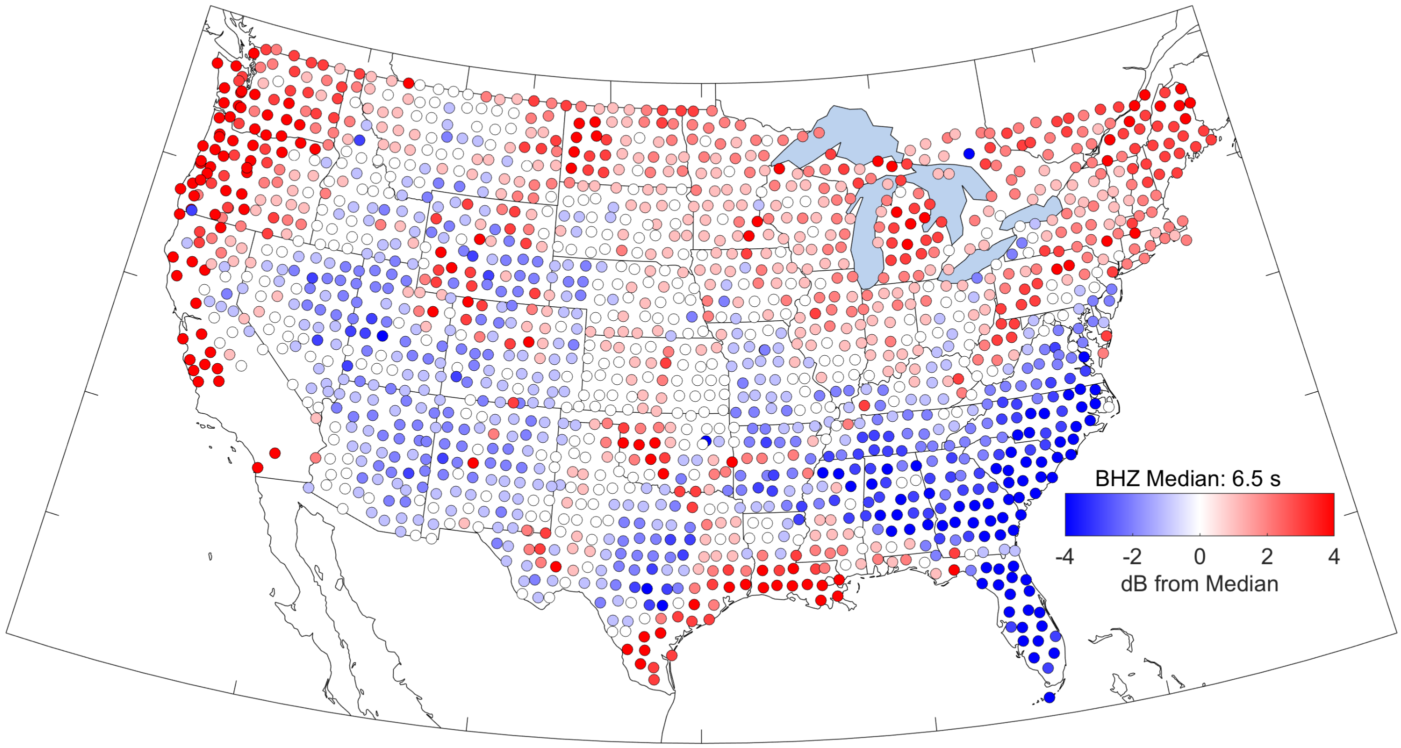


Figure 3-13. Deviation from the median of the median noise spectra at ~1 Hz/1 sec.



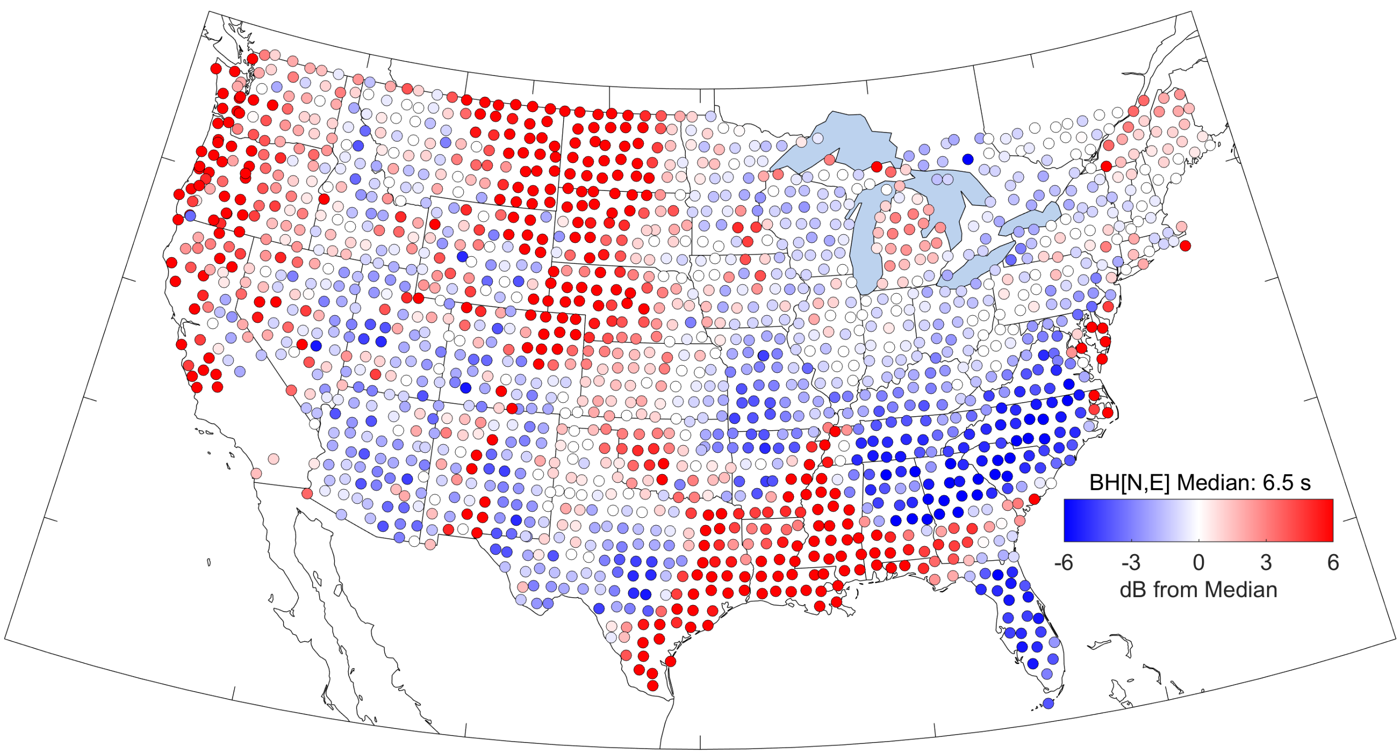
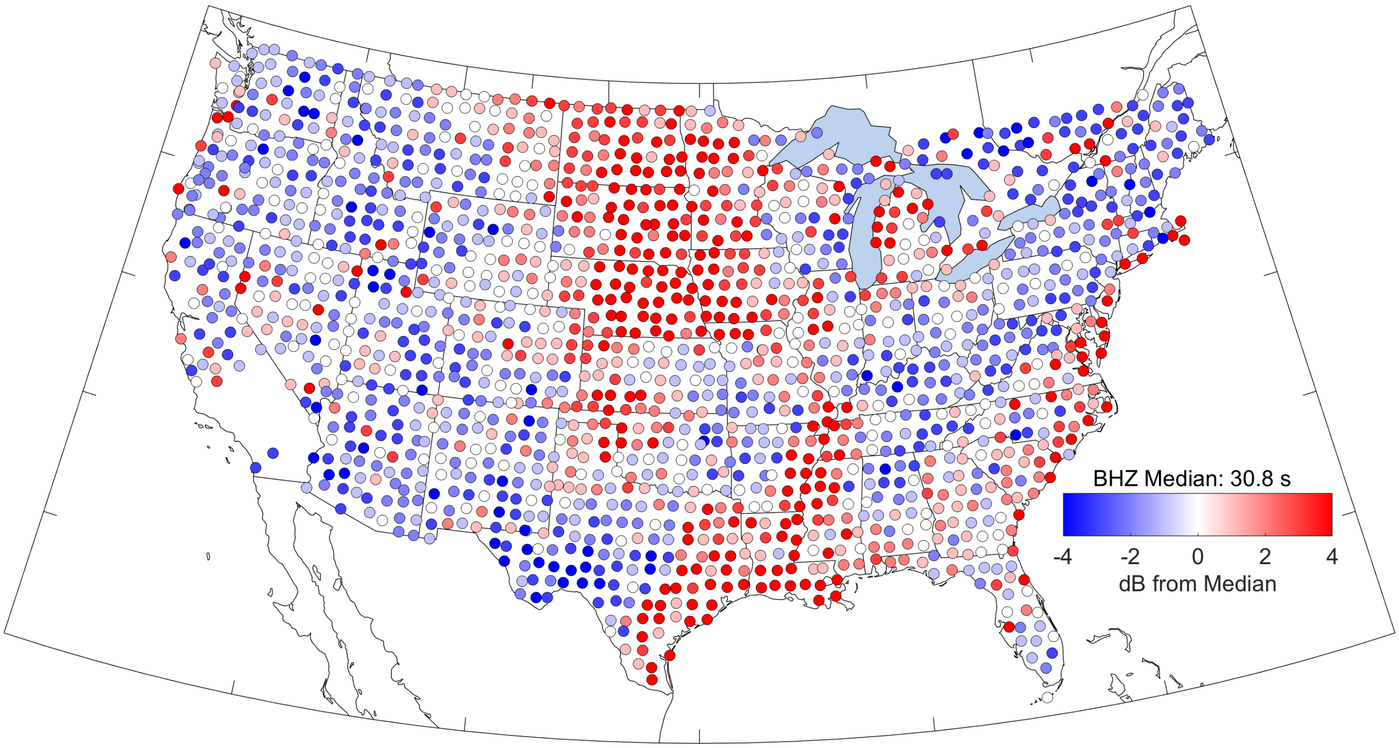


Figure 3-14. Deviation from the median of the median noise spectra at 6.5 sec.



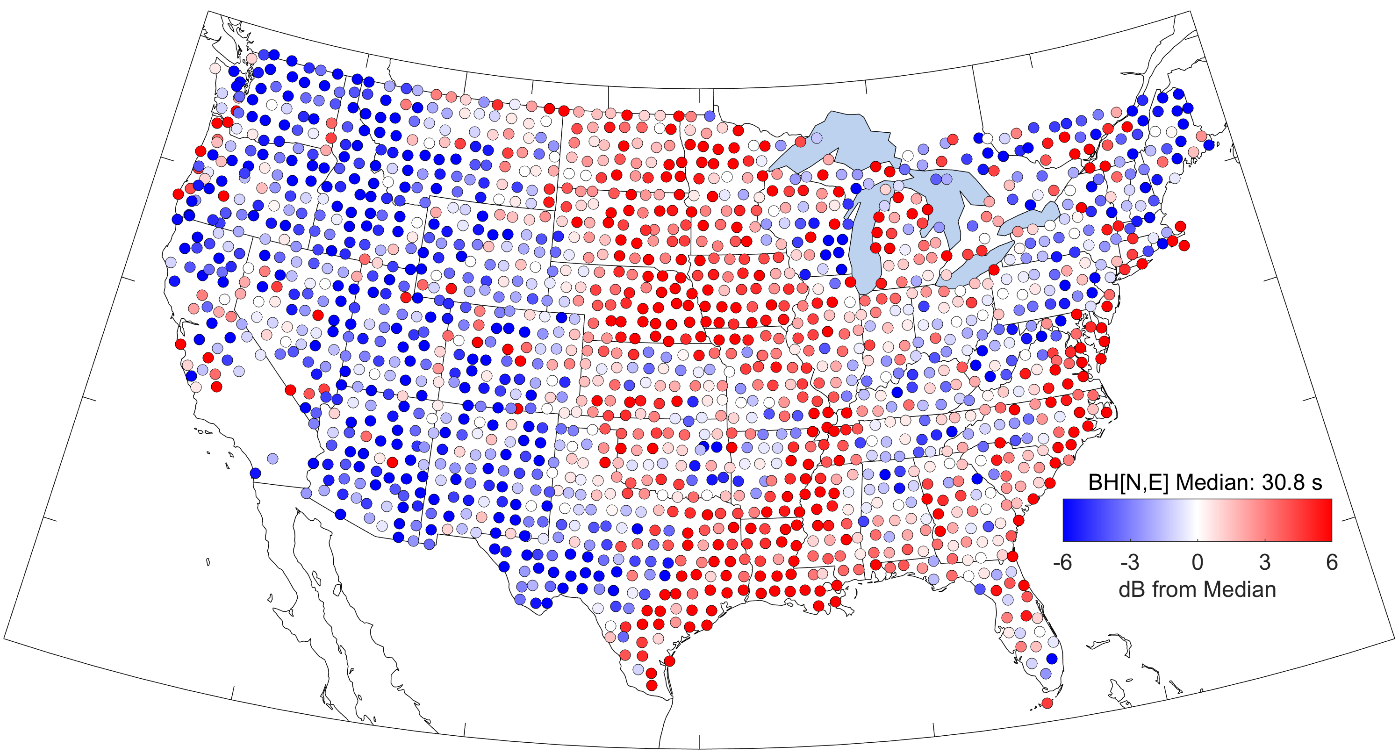


Figure 3-15. Deviation from the median of the median noise spectra at 30.8 sec.

3.4 CALIBRATION

The Array Network Facility utilized an automated process to command, capture, and analyze calibration signals applied to TA stations in situ via Antelope. The calibration analyses were used to verify amplitude and phase response while sensors were operating in the field. Stations were calibrated at the start and end of deployment, and the results were archived as a data product at the IRIS DMC. The calibration itself consisted of a white noise signal, generated by the Q330 and recorded during both input and output. The amplitude of the calibration signal is kept consistent for each sensor type. Variations in the amplitude sensitivity (gnom) reflect variations in the calibration circuit, rather than the sensor output. Calibration signals were 1.5–4 hours in length and were effective at frequencies of 0.001–20 Hz.

In September 2009, the TA underwent a network-wide calibration experiment (Figure 3-16). By this point, the network had operated as a fully deployed array for over two years and had since migrated into the Rocky Mountains and westernmost Great Plains. The experiment iteratively worked through 10% of TA stations at a time in random subsets so as to not to impede the function of the entire network during this process. It worked on each station

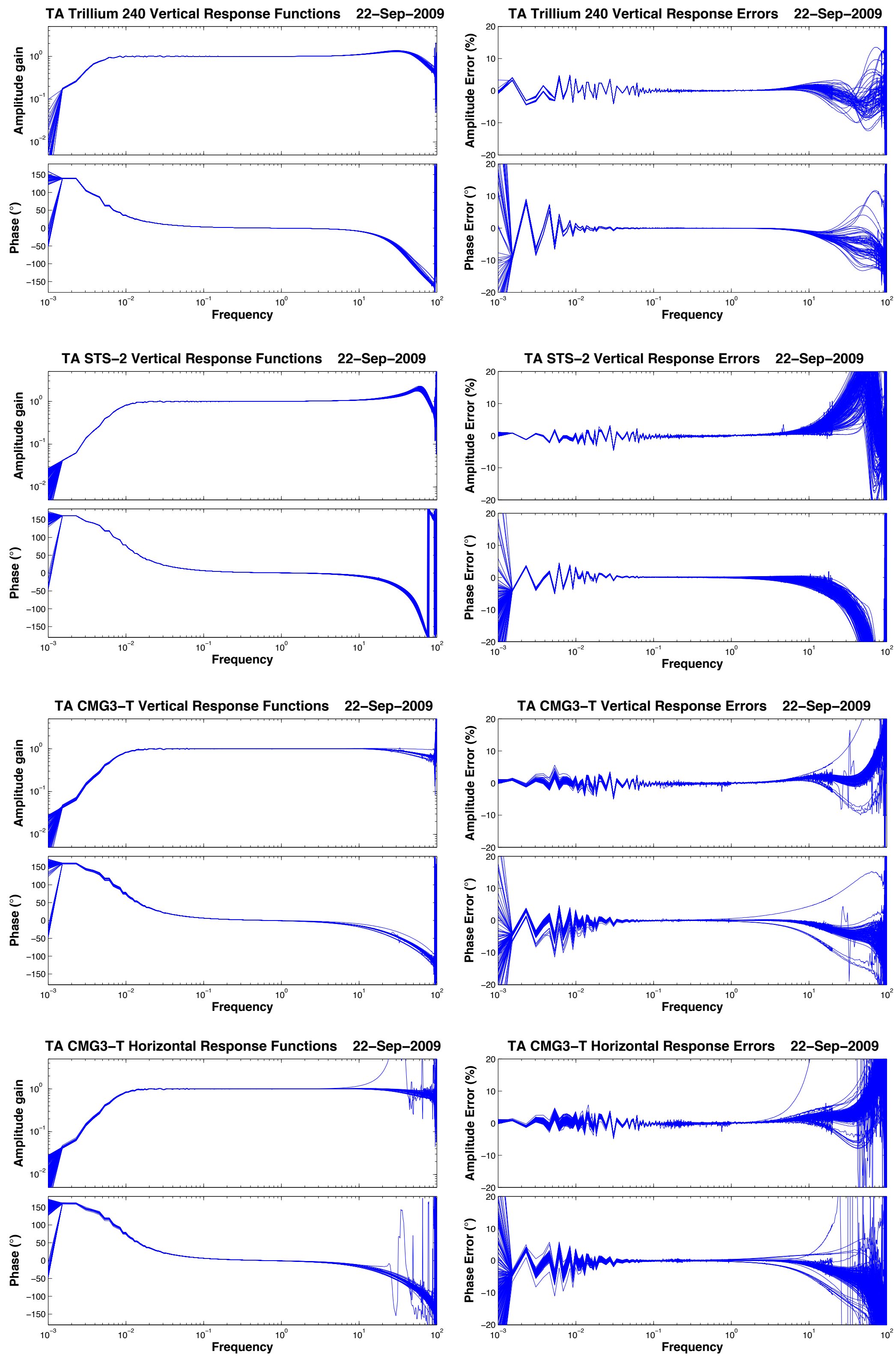


Figure 3-16. Amplitude and phase response functions for each type of TA seismometer (left) and errors in percentage relative to the nominal response (right). Both the raw measurements as well as calculated error for amplitude and phase reflect that most TA seismometers operated consistently with a nominal response function.

in two four-hour windows and lasted a total of six days. During the calibrations, the recorded sample rate was increased to 200 sps, with the calibration signal input via Antelope, and then the network-wide output was used to render an empirical response for the frequency band of 0.001–100 Hz. Each subset of stations took hours for the full calibration to run, before moving to the next subset of stations. The calibration used 198 STS-2, 121 CMG-3T, and 60 T-240 seismometers. The vast majority of seismometers, across all models, were in the range of nominal response when analyzed. A handful of clearly anomalous stations were identified, and subsequent assessment showed that most problems appeared to be in the sensor calibration circuits (Figure 3-17). Overall, the main three broadband sensors maintained consistent responses throughout the duration of the TA, such that the nominal response was used in all cases.

3.5 PROMINENT AND DOCUMENTED ISSUES

A variety of cryptic or nuisance-level issues cropped up during operation of the TA, some of which are thoroughly documented but still unresolved. These issues constitute the "known knowns" that may impact the quality of TA data. Some issues, such as magnetic sensitivity and recentering, are endemic to operating broadband seismometers and are included here to promote general awareness. Others, like SNOFLU and channel amplitudes, may result from specific hardware configurations used with the TA. Identifiable occurrences of these issues were logged in Data Problem Reports. When a signal was absent or clearly flat-lined, no report was produced. In cases where boom positions were offscale for extended periods or half amplitudes were displayed on a channel, these oddities were mostly noted. Occasionally, some were missed. There were and currently still are no mechanisms in place within IRIS Data Services for feedback from scientific users to report suspected anomalies to operators or to a collective reporting scheme, other than the DPR.

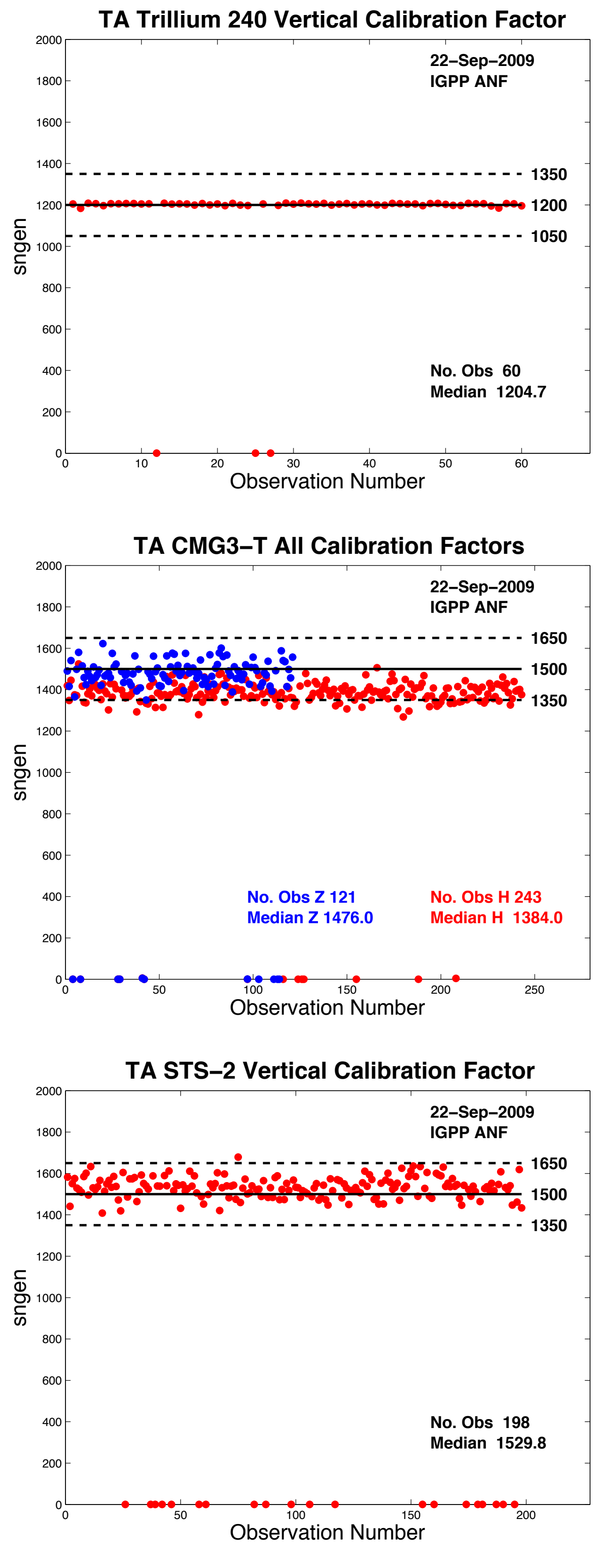


Figure 3-17. Calibration factor (sngen) plots for various instruments and components show the spread of results within reasonable bounds.

Magnetic Response of Broadband Sensors

Broadband seismometers use force feedback systems, which contain ferromagnetic metal and thus are susceptible to magnetic fields. This appears as a "compass needle" effect (e.g., Forbriger, 2007) when the mass spring is torqued by changes in the field intensity and direction. In addition, seismometer actuator coils may be sensitive to magnetic flux resulting from geomagnetically induced currents (GICs). Corresponding voltages associated with GICs may explain the observed frequency dependence in magnetic field response (Kozlovskaya and Kozlovsky, 2012). The amount of magnetic noise observed on a seismometer relates to the type of sensor, local site effects and infrastructure, use of permalloy shielding, and geomagnetic latitude. Both STS-2 and T-240 sensors have shown sensitivity at long periods to the vertical component of the magnetic field (Forbriger, 2007; Forbriger et al., 2010; Kozlovskaya and Kozlovsky, 2012) in empirical studies of deployed sensors during space weather events. These effects become more pronounced at high latitudes and during strong geomagnetic activity.

The TA collaborated with Albuquerque Seismological Laboratory to measure the magnetic sensitivity of STS-2, CMG-3T, and T-240 seismometers using a Helmholtz coil, providing a consistent, site-independent measure of magnetic sensitivity at periods of 1 to 10 seconds. In these tests, variation of a vertical magnetic field from ±0.00065 T manifests as signal that can be used to calculate the sensitivity of each component (Forbriger, 2007) (Table 3-5). Overall, the STS-2 shows approximately one-third the magnetic response of the CMG-3T and T-240. The components of the CMG-3T are more uniformly susceptible to vertical field variation, while the T-240 response is dominated by its vertical component, an equal sum of internal Galperin elements.

Siting criteria for the TA were generally successful in minimizing magnetic noise on seismometers from many recognizable sources. However, by ~2007 we had noticed that the current draw from the spinning disk of the Baler14 produced noise onset at intervals of minutes to hours whenever data were being written to the drive. This issue was initially addressed by extending the distance between the seismometer and Baler within the TA vault, which generally resolved the problem. However, as soon as the solid state Baler44 was introduced, the TA began installing these units instead of the older Baler14, thus obviating this issue. Careful placement of battery cables relative to sensor location and generally avoiding step changes in DC current are recommended mitigation measures.

Mass Positions and Recentering

The Q330 at each TA station also reports the mass position voltages of its broadband seismometer to the ANF, and these data were tracked as part of state-of-health monitoring (Figure 3-18). Due to the sheer quantity of stations to monitor, it was determined early in the deployment that automating the process of sending mass recenters would be critical. Mass recentering commands were issued by an automatic network-centered quality control process managed by the ANF that

Sensor	s_Z	s_N	s_E	$\lvert S \rvert$
CMG-3T	0.260	0.366	0.312	0.547
STS-2	0.153	0.073	0.082	0.188
T-240	0.495	0.040	0.043	0.499

Table 3-5. Emprically measured magnetic sensitivity ($m{*}s^{-2}/T$) of each component and the overall sensor response.

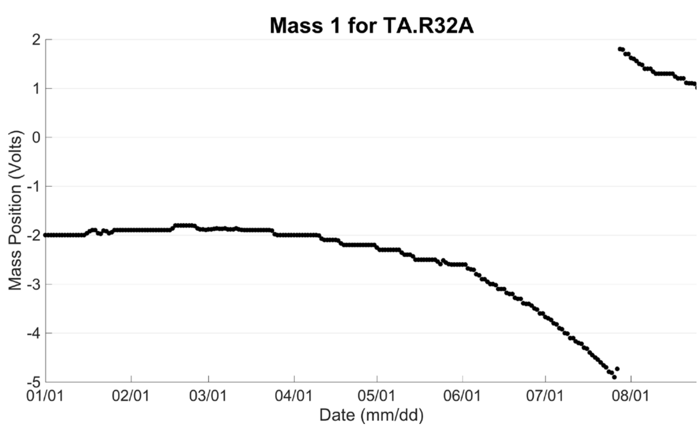


Figure 3-18. An episode of mass position drift and recentering for TA.R32A, which operated an STS-2 with limits of ±12 V.

accounted for different voltage thresholds depending on the model of seismometer. The automated process was suspended at the discretion of the ANF analysts for about a week following great earthquakes (e.g., M > 7.8) so as to reduce perturbations in long-period records. This process was also used occasionally for prominent regional earthquakes. As the masses of a sensor drift out of alignment, a recentering command is used to realign the instrument. Recenters can be clearly witnessed in both the average daily voltage measurements available through the IRIS DMC MUSTANG quality metrics as well as in raw time series (Figure 3-19), and take several minutes to settle back to normal levels. The average number of recenters across the array was 12.8 per station. Out of 1679 stations, only 176 required recentering more than 25 times. The most recenters required by a station was 291 (H32A), while 51 stations required none (Figures 3-20 and 3-21).

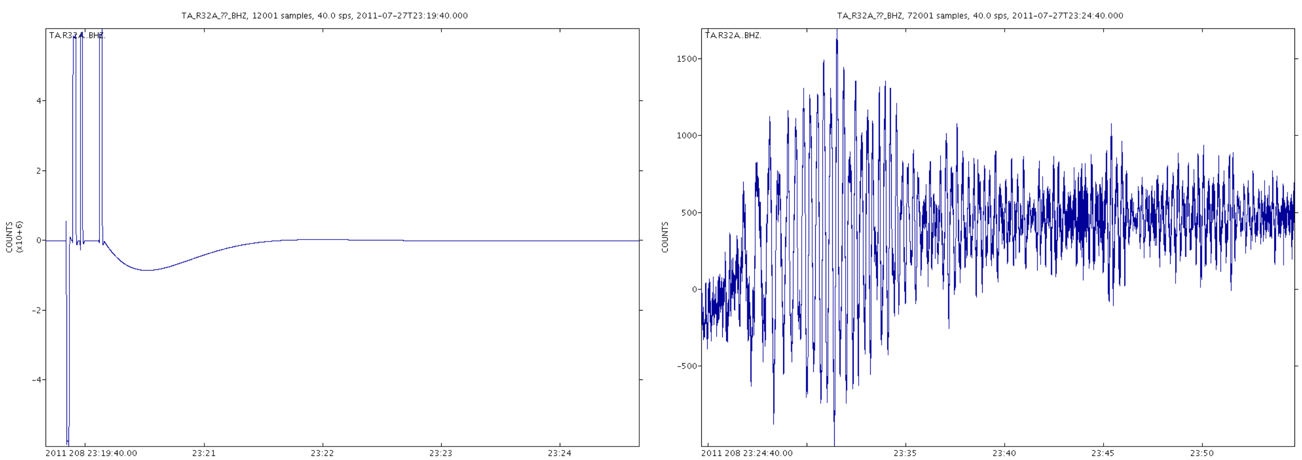


Figure 3-19. The effect of the recentering is shown on the time series for TA.R32A..BHZ. The recentering and subsequent settling of the instrument is displayed for five minutes and then an additional 30 minutes at different vertical scales.

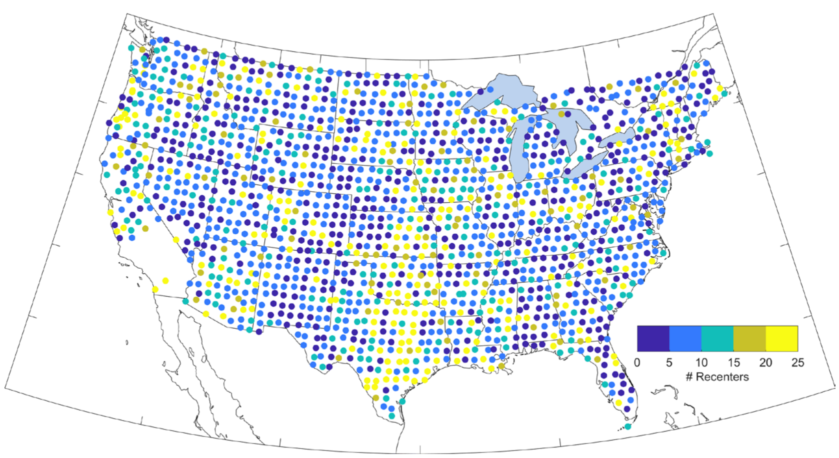


Figure 3-20. Mass recenters at each TA station through 7/20/17. Color scale saturates at 25.

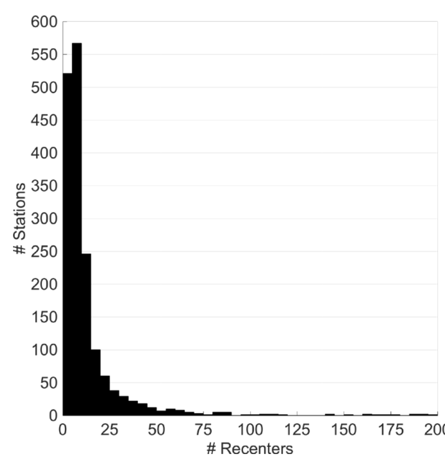


Figure 3-21. Histogram of recenters for all TA stations.

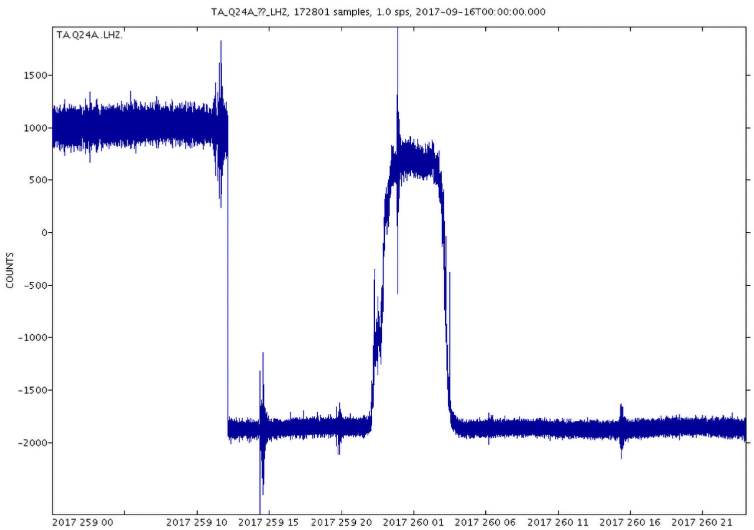


Figure 3-22. "Half amplitude" behavior observed for TA.Q24A..LHZ. The time series shows the characteristic sudden amplitude reduction and large offsets which cannot be linked to ground motion.

Channel Amplitudes

Thirty-three stations experienced a sudden decrease in amplitude of one or more analog channels reflected in all associated SEED channels, for example, BHZ, LHZ, and VHZ. These spells of "half-amplitude" recordings lasted on the order of days to weeks and occasionally months (e.g., Figure 3-22). The behavior sometimes resolved spontaneously or after a calibration but also recurred in some instances. The issue was permanently resolved by replacing one or more components, including the Q330, cabling, and sensor. Subsequent investigation revealed that the cause stemmed from differential signal inputs used in the analog sensor-to-digitizer connections. The analog signal was of equal and opposite amplitude on the two conductors to reduce noise contamination. When one conductor becomes disconnected, the observed amplitude is roughly halved. The disconnection can occur within the sensor, in the connectors, in the cables, or within the digitizer and can occasionally be reset, even remotely, by exercise of control functions or a power cycle of the device. In data records, this appears as a sudden change in amplitude by half, which may correct days or weeks later. We documented those instances with Data Problem Reports.

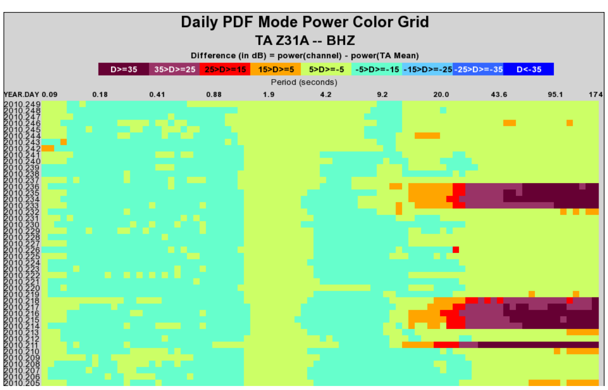


Figure 3-23. SNOFLU seen on the noise spectra for TA.Z31A.--.BHZ. Each row represents an individual station-day, and the statistical mode of the power of the time series spectra is plotted from short (left) to long (right) periods. The power for the average spectra of the entire TA network is subtracted out, and the plot is colored to emphasize days where the mode for any given period is above or below this average. SNOFLU distinctly appears at periods longer than 10 seconds in three distinct episodes, when the mode power becomes tens of dB higher than average.

Sudden Noise Onset Fixed by Lock/Unlock (SNOFLU)

Stations running Guralp CMG-3Ts occasionally exhibited a sudden increase in noise levels at periods longer than ~25 seconds (Figure 3-23). This increased noise would last for days to weeks without intervention and was only resolved by remotely issuing a lock/unlock command. This issue was managed by vigilant monitoring of stations operating these instruments. Various hypotheses have been advanced, with the most convincing that dust or debris accumulates within the sensor plate gap or magnet assembly and the lock/unlock process wipes this clear. It is also known that the leveling motors used inside the CMT-3T sensor can jam during lock/unlock, rendering one or more channels dead. About 30% of the CMG-3T population performed for many years quite well, but sorting through the problematic instruments was a discouraging and costly exercise.

Noise Induced by Thermal Fluctuations

Some stations with T240s and, to a much lesser extent STS-2s, exhibited weeks long episodes of high levels of noise on horizontal channels (Figure 3-24). These noisy intervals generally coincided with periods when temperatures in the vault exceeded 27°C. No firm conclusion was made whether these noise levels were sensor related or induced by other power system electronics—electrically or magnetically.

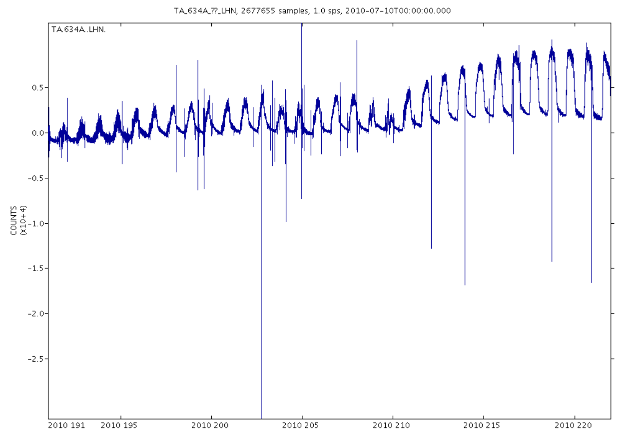


Figure 3-24. Continuous time series from 7/10/2010 to 8/10/2010 (31 days) at TA.634A..LHN. The diurnal signal relates to varying temperature of the vault throughout the day. The variations in amplitude on the time series relate to the magnitude of the temperature change experienced inside the vault.

4. Operational Characteristics

4.1 PHILOSOPHY

Key aspects of how the TA was operated are unprecedented when compared to the established practices for running networks of temporary or permanent stations at the time. These choices were strategic and motivated by the need to collect the highest quality data while adhering to a budget and schedule. These operations served the manufacturing process at the core of the TA deployment and touched all aspects of the project. The characteristics highlighted here are novel approaches to common activities that served as a mechanism for improving STEM student engagement, public outreach, various aspects of network and station quality, and overall record keeping. The continuous assessment of the operations and drive for improvement within the TA operation also led these practices to evolve as needed.

4.2 SITING AND PERMITTING

Initial reconnaissance of potential station sites was performed in most cases by teams of trained undergraduates that worked during the summer (Figure 4-1). IRIS made subawards to universities in the region where new TA sites were to be acquired. A faculty member at a local university recruited two to six students for a 10-week session in the summer. At the beginning of the summer, the students received training/orientation via a multi-day USArray Siting Workshop that generally involved up to five university groups and 24 students. The students then worked in teams of two, and typically used university vehicles to travel to their allotment of target sites.

There were major advantages to employing students from local universities in this part of the operation. First, the universities provided a local credibility and familiarity that was more relatable to the average landowner, and students were received more openly than someone directly associated with the federal government. It is impossible to gauge, but it is likely that far more sites were permitted on the first try with this model. In addition, this project presented a unique opportunity for students to serve as representatives of a nationwide scientific effort. Potential sites were narrowed down based on a stringent set of criteria, noted earlier. Student teams were expected to submit reconnaissance reports for each site visited at an increased pace throughout the summer as they became more efficient and familiar with the reconnaissance process. In all instances they were expected to maintain clear, thorough, and thoughtful communication with any prospective landowners. Additionally, students were reminded to use basic safety and navigation practices during their reconnaissance trips. Finally, many students came to recognize that the experience of working as a professional with clear deliverables due, in a science project and advocating for a science objectives in dialogs with members of the public, was a career enabling exercise. It takes courage to approach a doorstep, explain yourself and your scientific intentions to an unsuspecting landowner and, for the most part,

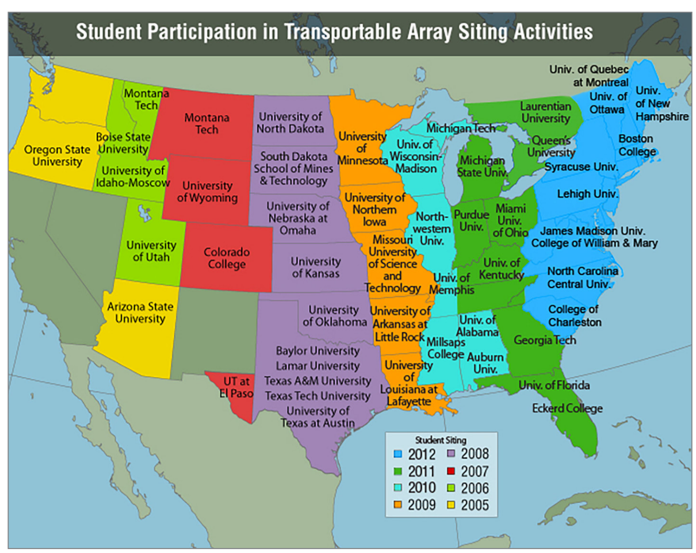
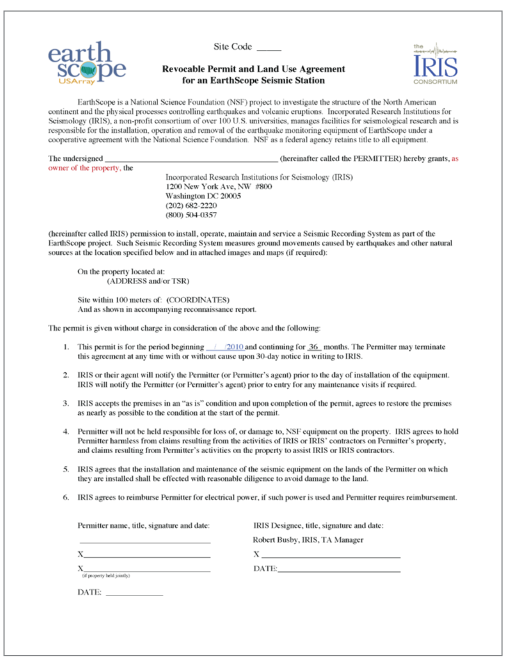


Figure 4-1. Universities with students participating in TA siting, by year and region. TA stations in California, Nevada, and New Mexico were selected using a similar process, but with the assistance of regional network operators.

enjoy a civil and interesting discourse. We think that has proved educational for aspiring scientists in how to convey science clearly and effectively to the public.

Where possible, it is desirable to choose sites that will require minimal effort to obtain a permit. In terms of the ease of obtaining a permit, the preferred land ownership went in the order from private-individual, private-corporate, state/provincial (parks, reserve, university), federal agency/crown land. U.S. federal agencies included the U.S. Fish and Wildlife Service, BLM/USGS, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and National Park Service. No attempt was made to permit in federal or state wilderness areas. Corporate landowners included timber companies, water management agencies, airports, utilities, and cities/counties. Individual-owned lands included ranches/farms, homesteads, and vacant lots. In interactions with federal agencies and corporate landowners, the role of the student was to determine the agency responsible, introduce the project, establish an office contact, and obtain a sample permit, where applicable. With individuals, the orientation process included gauging initial interest, explaining the project to provide proper context, and documenting the exact location of the station at each site.

Each reconnaissance report underwent a technical review with TA staff to make a site selection. Following this review, TA staff conducted a verification visit within a few weeks to finalize the location and confirm with the landowner basic understanding of project commitments, and verify the method of data communication to be used at the site. Permits were requested for durations of 24–36 months, and request packets were sent to landowners within a few months of verification. The packet included copies of the permit (Figure 4-2), the reconnaissance report, and TA project description (Figure 4-3). Accepted permits were typically received back at IRIS within weeks to months following signature by the landowner. All the permit correspondence, siting database, and status maps were managed from the Array Operations Facility in Socorro by the Siting Coordinator and Permit Coordinator under the guidance of the IRIS Chief of Operations and TA Manager.



Site Code _____

Revocable Permit and Land Use Agreement
for an EarthScope Seismic Station

EarthScope is a National Science Foundation (NSF) project to investigate the structure of the North American continent and the physical processes controlling earthquakes and volcanic eruptions. Incorporated Research Institutions for Seismology (IRIS), a non-profit consortium of over 100 U.S. universities, manages facilities for seismological research and is responsible for the installation, operation and removal of the earthquake monitoring equipment of EarthScope under a cooperative agreement with the National Science Foundation. NSF as a federal agency retains title to all equipment.

The undersigned ______________________ (hereinafter called the PERMITTER) hereby grants, as owner of the property, the

Incorporated Research Institutions for Seismology (IRIS)
1200 New York Ave, NW #800
Washington DC 20005
(202) 682-2220
(800) 504-0357

(hereinafter called IRIS) permission to install, operate, maintain and service a Seismic Recording System as part of the EarthScope project. Such Seismic Recording System measures ground movements caused by earthquakes and other natural sources at the location specified below and in attached images and maps (if required):

On the property located at:
(ADDRESS and/or TSR)

Site within 100 meters of: (COORDINATES)
And as shown in accompanying reconnaissance report.

The permit is given without charge in consideration of the above and the following:

1. This permit is for the period beginning __/__/2010 and continuing for 36 months. The Permitter may terminate this agreement at any time with or without cause upon 30-day notice in writing to IRIS.
2. IRIS or their agent will notify the Permitter (or Permitter's agent) prior to the day of installation of the equipment. IRIS will notify the Permitter (or Permitter's agent) prior to entry for any maintenance visits if required.
3. IRIS accepts the premises in an "as is" condition and upon completion of the permit, agrees to restore the premises as nearly as possible to the condition at the start of the permit.
4. Permitter will not be held responsible for loss of, or damage to, NSF equipment on the property. IRIS agrees to hold Permitter harmless from claims resulting from the activities of IRIS or IRIS' contractors on Permitter's property, and claims resulting from Permitter's activities on the property to assist IRIS or IRIS contractors.
5. IRIS agrees that the installation and maintenance of the seismic equipment on the lands of the Permitter on which they are installed shall be effected with reasonable diligence to avoid damage to the land.
6. IRIS agrees to reimburse Permitter for electrical power, if such power is used and Permitter requires reimbursement.

Permitter name, title, signature and date:
____
X______________________
X______________________
(if property held jointly)
DATE: __________

IRIS Designee, title, signature and date:
Robert Busby, IRIS, TA Manager
X ______________________
DATE:______________________

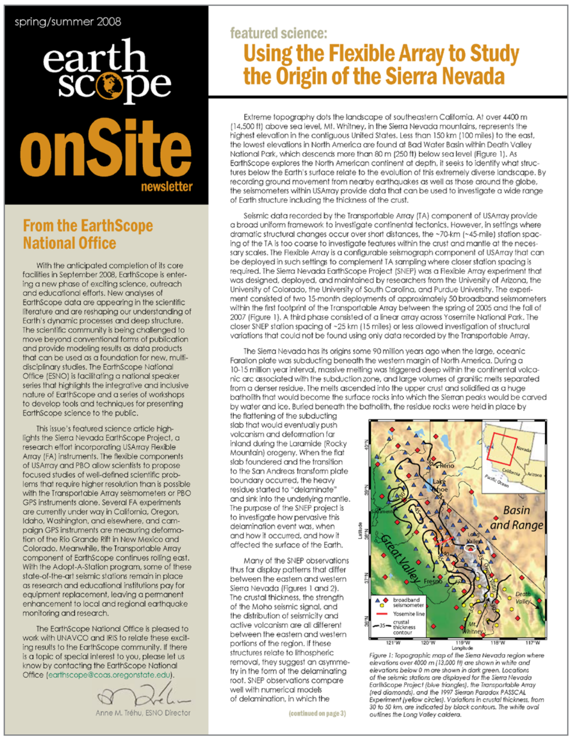
Figure 4-2. Example of the standard permit and land use agreement for a TA station.

Figure 4-3. Information pamphlet provided to prospective station hosts.

4.3 STATION HOST ENGAGEMENT

During operation of the TA, multiple avenues were employed to engage landowners and other station hosts. During the permitting process, a one-page information sheet was provided to prospective station hosts that provided a description of EarthScope and the requirements of hosting a station (Figure 4-3).

After installation, IRIS provided a periodic *onSite* newsletter (Figure 4-4) and documentation on the USArray Station Monitor, which provided web-based views of the daily ground motion in helicorder form at each station (Figures 4-5 and 4-6). These web pages fostered a sense of participation and a facilitated dialog with landowners who became invested in the success of the TA deployment. A later web version of USArray Station Monitor replaced the original and continues as: https://www.iris.edu/app/station_monitor. The new version uses web services and may eventually be configured to generate views of historical L48 station webicorders. In addition, landowners were contacted and apprised of any developments relative to their station well in advance, and were provided with a point of contact with TA staff should the need arise.


spring/summer 2008

earth scope

onSite

newsletter

featured science:

Using the Flexible Array to Study the Origin of the Sierra Nevada

From the EarthScope National Office

Figure 4-4. Example of the *onSite* newsletter, which was periodically mailed to all landowners hosting TA stations.

Figure 4-5. USArray Station Monitor splash page.

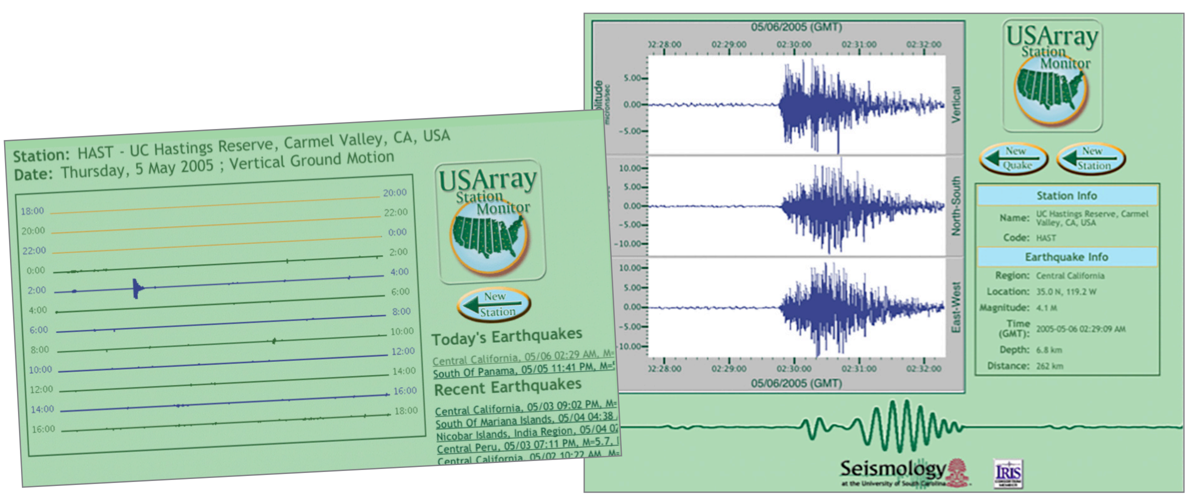


Figure 4-6. Original views of the station monitor, showing 24-hour helicorder and event specific seismograms.

4.4 FIELD ACCEPTANCE CRITERIA AND CERTIFICATION

The acceptance criteria for TA installations relied on visual inspection of the constructed site and installed hardware, completion of checklists of onsite measurements or procedures, and a formal certification by the ANF of the hardware functionality and data/metadata quality. The durability and overall quality of the installation was unable to be immediately and thoroughly assessed, but over time, performance often correlated with the quality. The acceptance of stations was linked to performance incentives for the contractors responsible for station construction and installation. These incentives provided a level of control at the management level that encouraged quick production of stations but verified that the stations had been properly constructed and installed to specification.

When certifying a newly installed TA station, all data were embargoed at the ANF and not delivered to the IRIS DMC. Certification involved assessment of metadata, waveforms, and state-of-health information at each station, as well as cross-verification between the field engineers and ANF analysts. Through this process, station data/metadata were evaluated for accurate seismometer model and response, and station location, sensor orientation, channel order, signal amplitudes and polarity, and time labeling were confirmed. Validation required observing a few well-resolved earthquakes and comparing the waveforms recorded by the station with its neighbors in the TA. The ANF also tested a random binary pulse calibration and sensor remote control functions. Once certified, all metadata and data from the outset of installation were forwarded to the IRIS DMC, allowing the site to be visible to external users. If information could not be reconciled, or the station did not perform to specification (e.g., impaired communications, poor mass positions) and could not be certified, then installation crews returned to the station to rectify the issue(s) that resulted in a failed certification.

4.5 QUALITY CONTROL AND MONITORING

Large seismic networks require active and detailed monitoring. Rendering of widely encompassing, digestible, actionable, state-of-health, and data quality information was paramount to efficient operation of the TA. A large number of automated analyses and quality control procedures were developed to provide actionable information on every aspect of a TA station throughout its deployment. Both email alerts and web-based views were used to highlight potential state-of-health issues that would need attention from staff at the ANF or the field crews. Routine monitoring and quality assessment were performed both by the ANF and the IRIS DMC.

At the ANF, automated email alerts were configured to warn of pump activity, out-of-range mass positions, GPS lock failure, and anomalous system voltages or datalogger reboots. These alerts would also report daily data return and information on gaps in data for individual stations. In addition, the ANF automated the periodic download of data packets from each station as a status query for the Q330 and Baler. Due to the scale of the network and individual variation in sensors deployed, it became obvious early on in the deployment that automating a response to problems involving mass positions was necessary. Twice per day, a check of the mass positions at each station was done to see if the threshold for a mass recenter on that instrument was surpassed and if so, that a recentering command was issued. In addition, calibrations were automatically issued when a change in equipment at a station was registered. A database at the ANF captured each mass recenter and calibration that was sent, which was then monitored to infer equipment failure if a station did not respond or was requiring too many interactions.

A graphical, web-based approach was used display and sort various state-of-health information for the TA network. One GUI was the Data Logger Monitor (DLMon), which displayed status information relevant to various systems (power, communications, GPS, seismometer mass positions) at each station (Figure 4-7). Station-specific hardware was also displayed to discriminate any differences in configuration across the network. Each tile on the DLMon board was clickable, allowing a user to examine past performance for clues on current behavior. During the initial years, the TA also used SeisNetWatch, an open-source network monitoring software package produced by ISTI to monitor and control data acquisition through a GUI (Figure 4-8). SeisNetWatch allowed for the monitoring of stations using pre-configured performance thresholds, usually related to signal quality or data integrity. SeisNetWatch had been previously developed for and used by Caltech/USGS TriNet, which contributed many stations to the initial TA footprint. The TA usage continued to evaluate/develop its performance with a large number of stations.

The IRIS DMC produced and stored a suite of metrics to characterize the quality of TA data. For example, PQLX was used to calculate the ambient noise spectra for TA stations. A basic noise PDF for each component could be browsed down to the scale of a day in the Quality Analysis Control Kit (QUACK) web page hosted by the DMC. QUACK also included daily measurements of signal RMS, mean, percent availability, number of gaps/overlaps, largest gap and overlap, and STA/LTA plots all similarly browseable. In addition, the more internally facing crunch.iris.washington.edu website provided more detailed presentations of noise performance, including timelines of the mode noise level at specific periods, color grid plots showing over or below average spectral performance over time, and maps of noise performance at selected periods for the entire TA (Figure 4-9). A profile of each TA station was maintained on the crunch page and updated throughout its operation. This included reports related to each site visit, covering construction, installation, servicing, and removal as well as a list of metadata changes and a short station history.

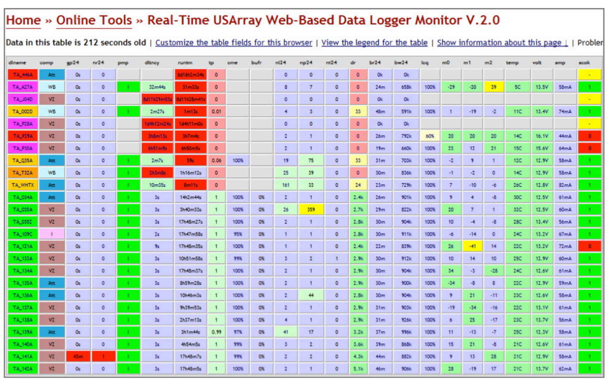


Figure 4-7. Example view of the DLMon for L48 TA stations.

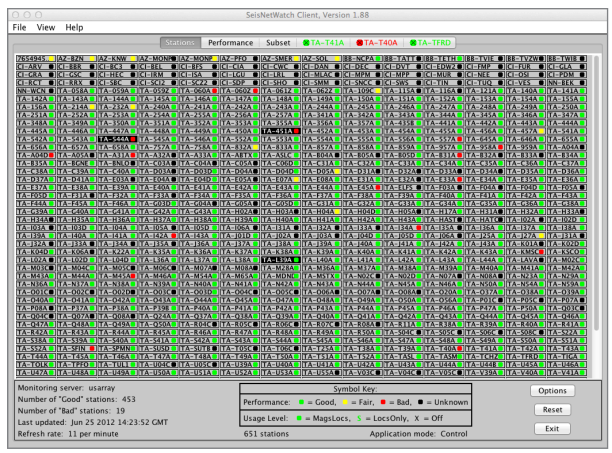


Figure 4-8. Reactor control panel view in SeisNetWatch.

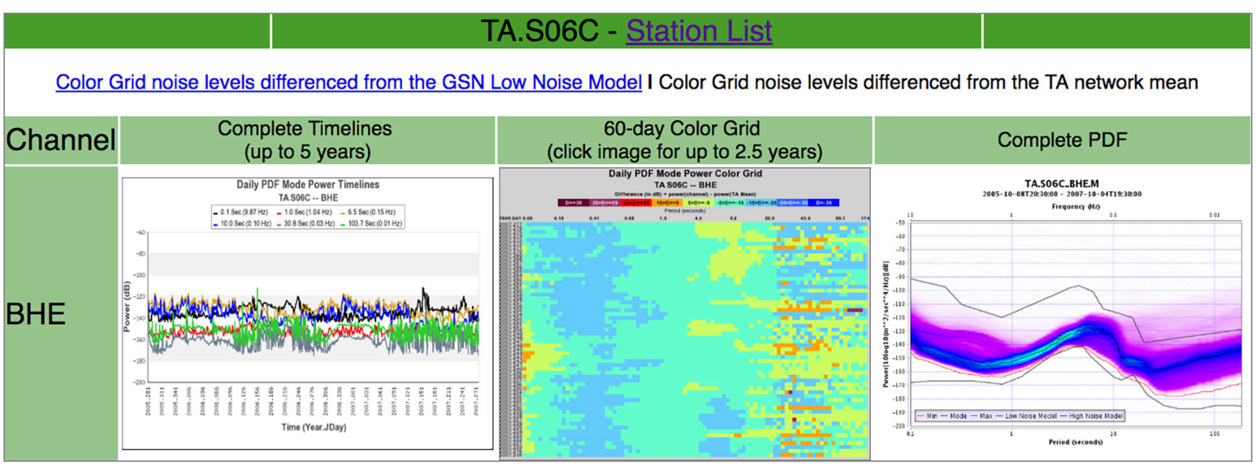


Figure 4-9. Example of detailed noise performance views mode power, color coded spectra, and cumulative PDF) for TA.S06C.--.BHE taken from its crunch page.

4.6 SERVICING

A few roving field engineers performed routine maintenance on the TA, informed by active station monitoring by the ANF and DMC. The diverse set of information collected and visualized by these groups provided actionable intelligence to TA management, allowing for appropriate, prioritized deployment of servicing teams and materials. Nearly all of this information was accessible through the ANF public website, enabling field engineers and managers to consult various metrics while diagnosing and prioritizing station repairs.

Service visits were scheduled to honor the terms of how a station was permitted, such as seasonal unavailability and the need to provide advance notification to landowners. Work was completed and a standard email-based report identified activities performed, condition of the station, and any equipment that was changed, especially that which affected metadata. Occasionally, TA management would determine that a station required a more serious intervention, such as relocating the installation. Service reports were sent via email with the subject line formatted to serve as a simple identifier for each visit, and scripts automatically processed emails into database entries.

4.7 MANAGING METADATA AND MERGING DATA

Because of both the scale and usually daily changes to the TA, station metadata were updated regularly, much more frequently than any comparable network. Metadata were updated and distributed from the ANF as needed, typically twice per week. Metadata updates were needed for newly installed stations, equipment swaps, removals, or when errors were discovered with orientation, listed equipment, or instrument response for a set of equipment. The goal was to get accurate metadata to the IRIS DMC within one to three days of arrival at the ANF of the email announcing a change.

Tracking the equipment history at each site was accomplished using the batch file processing functionality of the Antelope software program dbbuild. These batch files included information that was collected from the installation, service, or removal reports sent to the ANF by the field crews. Those loosely formatted text files would track the equipment installed at a station for a particular time period and reference externally available response files. The response files were collated within Antelope based on the specifications provided by the equipment manufacturers. No sensor specific sensitivity values were used. Based on the results of calibration tests, all sensors were within 90% of the nominal value, so using the generic response for a sensor type was considered acceptable. The dbbuild program rendered a database with location and response information for all stations. From here, dataless SEED files of the metadata for individual stations were generated and automatically passed along to the IRIS DMC and made available for pickup from the ANF (Figure 4-10).

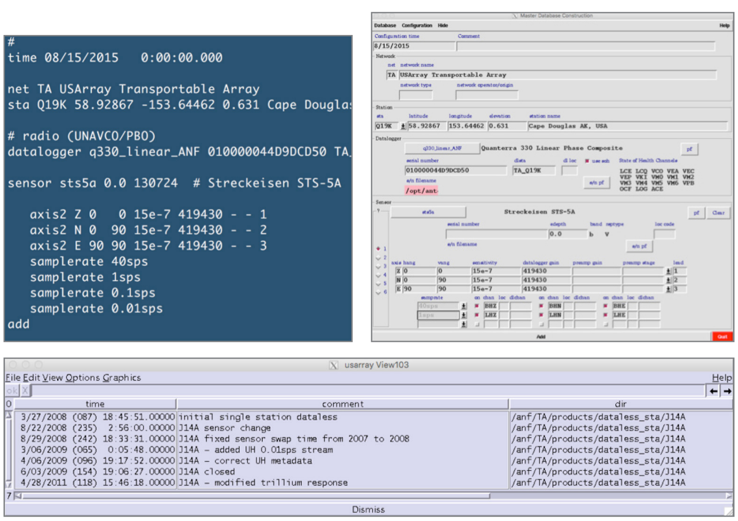
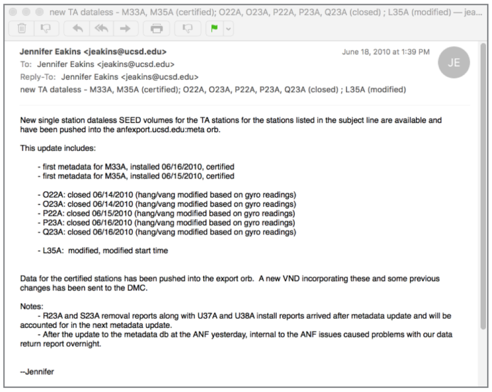


Figure 4-10. Example from batch file input for dbbuild metadata generation (top left), GUI interface to dbbuild (top right), and view of database table that tracked metadata updates (bottom).

Metadata used a simple naming convention that included both the SEED network and station codes and a date/time for when the file was generated. This scheme allowed for potentially missing or lost-in-transfer metadata to be easily noticed. Additionally, sending both an inward facing email to just IRIS DMC and ANF staff along with a more broadly distributed


new TA dataless - M33A, M35A (certified); O22A, O23A, P22A, P23A, Q23A (closed) ; L35A (modified) — jea...

Jennifer Eakins <jeakins@ucsd.edu> June 18, 2010 at 1:39 PM
To: Jennifer Eakins <jeakins@ucsd.edu>
Reply-To: Jennifer Eakins <jeakins@ucsd.edu>
new TA dataless - M33A, M35A (certified); O22A, O23A, P22A, P23A, Q23A (closed) ; L35A (modified)

New single station dataless SEED volumes for the TA stations for the stations listed in the subject line are available and have been pushed into the anfexport.ucsd.edu:meta orb.

This update includes:

- first metadata for M33A, installed 06/16/2010, certified
- first metadata for M35A, installed 06/15/2010, certified

- O22A: closed 06/14/2010 (hang/vang modified based on gyro readings)
- O23A: closed 06/14/2010 (hang/vang modified based on gyro readings)
- P22A: closed 06/15/2010 (hang/vang modified based on gyro readings)
- P23A: closed 06/16/2010 (hang/vang modified based on gyro readings)
- Q23A: closed 06/16/2010 (hang/vang modified based on gyro readings)

- L35A: modified, modified start time

Data for the certified stations has been pushed into the export orb. A new VND incorporating these and some previous changes has been sent to the DMC.

Notes:
- R23A and S23A removal reports along with U37A and U38A install reports arrived after metadata update and will be accounted for in the next metadata update.
- After the update to the metadata db at the ANF yesterday, internal to the ANF issues caused problems with our data return report overnight.

--Jennifer

Figure 4-11. Example email documenting "what changed" in the latest metadata update.

email summarizing what changes had been released helped end-users be aware that changes had been made (Figure 4-11). Because of the rapidly changing footprint and systematic updates of metadata, end users had to adapt their previous practices and download metadata often.

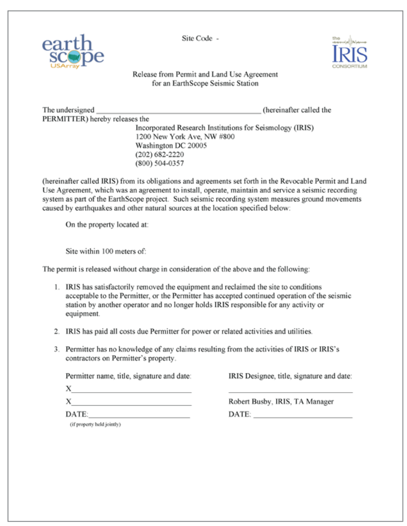
The ANF was also responsible for finalizing the archiving of data from each removed station. For each station this entailed comparing the telemetered data with the onsite archive from its baler, which was rotated in from the field. The onsite data were amended with any telemetered data that filled gaps resulting from equipment failure, and the entire record was replaced at the IRIS DMC, representing a transition from R to Q in the miniSEED data type flag. The local records contain additional annotations in the miniSEED fixed header (e.g., inaccurate time tag), which are subsequently scanned by the DMC's MUSTANG data quality system and placed in an attribute database. The effort of merging the two data archives was intensive but had a measurable impact on the completeness of the TA data set, increasing the total TA data return by about 1%.

4.8 CONFIGURATION CONTROL

Design updates to the instrumentation and hardware at TA stations were most often rolled out at newly installed stations. These updates occasionally had to be revised for deployed stations as part of service trips. Changes included AirLink (later Sierra Wireless) cell modems (three versions), implementation of the VIE and later the QEP and associated atmospheric sensors, use of Octans and APS for measuring orientation, and alteration of the vault construction materials. Each change was made carefully and resulted from a process that involved extensive discussion beforehand, professional design, review and refinement, and close monitoring. Changes were only implemented when their downstream impacts to the entire TA operation were fully assessed. The configuration of each station was logged in detail with site visit reports and documented in an extensive photo gallery, which was available to all TA team members. This gallery was updated for each station visit, allowing subsequent verification of its change history.

4.9 DECOMMISSIONING

After approximately 18 to 24 months of operation, a crew of two field engineers with a small excavator came to "decommission" a station in a manner to meet the permit holder's requirements. The process of contacting the landowners would begin approximately six months before the scheduled removal month. This timeframe ensured that the landowner was aware of the pending visit, and the field crew could coordinate removal dates and what was needed for the remediation process. Many private landowners were happy to keep the vaults in place after the seismic equipment was removed. However, many federal, state, county, and municipally owned sites required complete removal of the vault and concrete pad and reseeding of the site with native grasses or vegetation. Each landowner was asked to sign a release form after the decommissioning indicating that IRIS was no longer liable for any issues related to the existence of the station (Figure 4-12).


Site Code -

Release from Permit and Land Use Agreement
for an EarthScope Seismic Station

The undersigned ______________________________ (hereinafter called the PERMITTER) hereby releases the
Incorporated Research Institutions for Seismology (IRIS)
1200 New York Ave, NW #800
Washington DC 20005
(202) 682-2220
(800) 504-0357

(hereinafter called IRIS) from its obligations and agreements set forth in the Revocable Permit and Land Use Agreement, which was an agreement to install, operate, maintain and service a seismic recording system as part of the EarthScope project. Such seismic recording system measures ground movements caused by earthquakes and other natural sources at the location specified below:

On the property located at:

Site within 100 meters of:

The permit is released without charge in consideration of the above and the following:

1. IRIS has satisfactorily removed the equipment and reclaimed the site to conditions acceptable to the Permitter, or the Permitter has accepted continued operation of the seismic station by another operator and no longer holds IRIS responsible for any activity or equipment.
2. IRIS has paid all costs due Permitter for power or related activities and utilities.
3. Permitter has no knowledge of any claims resulting from the activities of IRIS or IRIS's contractors on Permitter's property.

Permitter name, title, signature and date:
X______________________
X______________________
DATE:__________________
(if property held jointly)

IRIS Designee, title, signature and date:
____
Robert Busby, IRIS, TA Manager
DATE: __________________

Figure 4-12. The station release form used for the TA.

Shutting down the data acquisition and "closing" the station followed a predetermined procedure. Approximately two weeks before equipment removal final step and random binary calibrations were performed and reviewed to prevent defective equipment from being transferred to a new station that was being installed further to the east. Upon arrival at the station, the removal crew would make a series of measurements to verify the metadata for the station, including latitude/longitude, distance from vault lip to concrete floor, serial numbers of equipment, and sensor orientation measurements using an Octans or APS. Measurements were made along the sensor's alignment markings, and the orientation of the ruler placed in the north direction on the concrete pad was determined.

All station hardware was then removed and the site remediated in accordance with the permit and per the wishes of the site owner. The removal crew would then repackage the seismic equipment, batteries, solar panels, and appropriate communications equipment required for the installation crew to use at another station the following month. Most equipment went directly to an installation storage area near the next work area. In some cases, the AOF would need to ship supplementary equipment to the installation crew that was not directly sent from the removal crew.

The information collected by the removal crew was included in a report that was used to officially shut down the station, including logging the final data recording date/time. For many stations, in addition to supplying a closure date in the metadata, there was a second measure of sensor orientation. This occasionally resulted in reassessment of the reported azimuth of the recorded sensor channels, sometimes going back to when the station was deployed. The balers, and later flash drives, with all of the data recorded during the station deployment, were shipped to the AOF, where the data were downloaded from the physical media and the files then uploaded to the ANF. The baler data were used to replace the telemetered data already archived at the IRIS DMC.

After the station decommissioning was completed, each landowner/permit holder would receive a "station digest," which summarized the key parameters related to the stations deployment and its recording history over the course of the deployment time period (Figure 4-13). These digests also typically included state-of-health and quality characteristics that would be of interest to data users. The station digests may be accessed here: http://ds.iris.edu/ds/products/stationdigest. The station digests we also used to partially satisfy the requirement by some state and federal land management agencies to submit annual reports. Private landowners also received EarthScope paraphernalia such as t-shirts, hats, and coffee mugs in appreciation of their participation in the project.

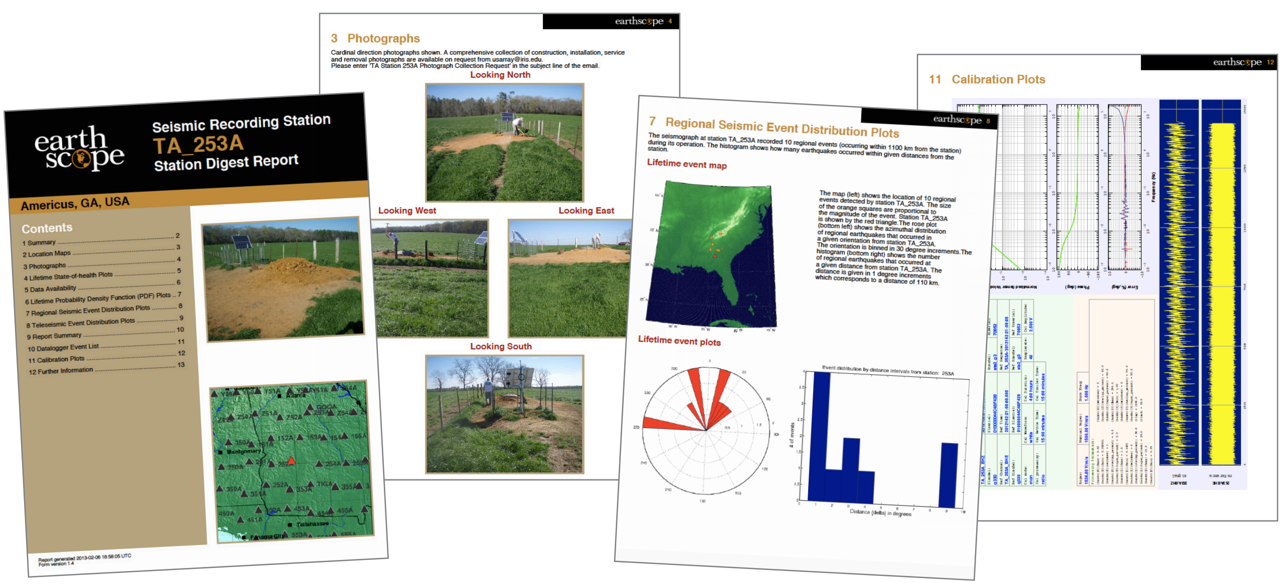


Figure 4-13. Pages from the station digest produced following the completion of TA.253A.

5. Reflections

5.1 SUMMARY

This document highlights many aspects of the disciplined approach that yielded the Transportable Array. The TA was different. It operated on a vast scale, leveraging established technology, hardware, and techniques and pushing them in new directions to meet ambitious goals. It took on, and solved, numerous problems of how to efficiently operate a network of seismometers at the scale of a continent, making high-quality data available in real time for immediate science returns.

The acknowledged success of this project was the result of careful planning and execution at every stage of its evolution. The network was operated using uniform design and operational principles. The TA viewed each station as part of that network from the start, instead of a collection of ad hoc, individual stations. This vision meant that the TA operated more like an assembly line than most previous approaches to collecting seismological data, with dedicated staff roles and consistent station designs. Because the fundamental design elements of TA stations were based on mature technology, and assembled systems were carefully tested, significant risk was avoided in large-scale production.

The TA demonstrated that massively scaled projects can be successful, provided that they are thoughtfully planned, properly funded, and carefully executed. Our hope is that similar scales of geophysical observing will happen again. In such cases, we strongly advise those undertaking such efforts to consider all operational aspects early in project development and be flexible to change. The TA required years to evolve from its initial concept to its first station in the ground. Moreover, that first station took many months to evolve from a notional grid point to a functional scientific installation. Scientists, engineers, and managers must consider a staged approached with repeatable, validated methods that have been tested and refined. That conceptual framework enables approaching similar projects and completing tasks in an organized fashion.

5.2 WHAT WORKED WELL

A handful elements in the implementation and operation of the TA had especially broad ramifications in the success of the project and the quality of the data that made it to the seismological community.

- Engaging local universities in the EarthScope project and student reconnaissance, despite direct advice from an external review panel and subsequent recommendation not to do so, on the grounds it would lead to risky delays.
- Having specialized crews separately handle construction and installation, while a different group concentrated on operating stations. Most seismic networks today continue to mistakenly task station support staff to build new stations. It is complex task with a transient, intense effort. The production of similarly designed stations allows dedicated construction and installation crews to become experts in that aspect of the operation.
- Announcing completed tasks via timely, structured emails encouraged the organization to engage as a team.
- Advanced diagnostic displays aided the management of nascent issues and occasionally raised the alarm on widespread problems, for instance, when a cell modem firmware update would “brick” the modem after 5–15 days and that update had already been distributed to about a hundred modems.
- Annual team meetings were instrumental in building trust and familiarity between individuals with a wide range of backgrounds. During the year, these individuals often worked alone or in small teams but relied on others to perform enabling and associated functions with short notice and high reliability. Shipping equipment to hotels, reconfiguring a VSAT router, and updating a datalogger entry were support functions provided to the field crews on short notice to keep the TA rolling.

5.3 LESSONS LEARNED

The lessons gleaned from operating the TA came in many forms. These examples highlight both specific problems that had to be solved and wisdom gained from experience. They also demonstrate how design and process often interrelate.

QEP Disconnect

The initial QEP implementation contained a bug such that if station suffered from power brownout, its QEP would become disconnected from the system and cease reporting data. Switching the power source for the QEP to one with a low voltage disconnect to the QEP after 2010 solved this problem.

Merging Onsite Baler and Real Time Telemetered Data

This process is difficult to perform routinely and involves sending large quantities of data into an already populated archive. This can result in complex indexing of different versions of the same data. More modern approaches would consider very deep local buffers of the telemetry data and simply patch the gaps in the telemetry record directly. Early on it was quite difficult to determine what data were, in fact, in the DMC archive as compared to local storage, and it was less difficult to simply build as complete a data volume as possible and resend it. Now the DMC can more reliably report what it has, but delivery of very large volumes of data may require separately verifying their completeness.

Mass Position Offscale

For the TA, a recentering does not necessarily mean the seismometer was offscale and the data were unusable. Recentering was performed proactively to prevent that from occurring. The recorded velocity outputs would be affected only if the boom position reached the maximum value (so-called offscale). We preferred a network-driven command, so as to suspend recentering in times following important events. Unfortunately, there is still no clear understanding of which velocity channels are affected when a mass position channel is offscale. For example, any single mass position channel offscale for STS-2 and T-240 sensors results in corruption of all three velocity outputs, whereas only a single channel of a CMG-3T is affected.

Orientation Confirmation

Estimates of sensor orientation produced by the Waveform Quality Group at the Lamont-Doherty Earth Observatory (Ekström and Busby, 2008; Ekström and Nettles, 2018) are invaluable cross checks on field procedures, which sometimes revealed improperly operating devices or, more commonly, a field procedure deviation due to some onsite deficiency (e.g., bad cable, dead computer).

Use of Vaults – Flooding and Future Considerations

Use of TA vaults in long-term installations (>2 years) has provided some experience for the long-term use of this vault design. Because vaults are emplaced below grade, they are susceptible to flooding. Vertically oriented corrugated pipe is susceptible to compression from the heavy load of overburden piled on the lid. Filling the rings with structural (boat) foam or grout would likely remedy this situation. In general, settling of the soil and insects degrading the sealing gasket materials can create leaks at various points in the assembly. At dry locations leaks are easily remedied by putting a drainage pump within the vaults. In wet environments, leaks can lead to persistent station maintenance and damaged hardware, resulting in minor station downtime, although the network uptime for longer term TA and CEUSN stations remains >98%. The newer custom molded tanks were far superior but occasional leaks still occurred. There were several instances of vaults operating without issue even though they were completely submerged in transitory flooding.

With the wide availability of reliable posthole broadband seismometers, and an efficient means to create a hole for emplacement, we generally prefer future installations to utilize above-grade enclosures for the electronics and batteries with a downhole sensor emplacement, including a second hole for a strong motion sensor. Such designs have been utilized extensively in Alaska and in the upgrade of L48 TA stations. A seismometer emplaced in a shallow borehole far out-performs a shallow pit vault, even one placed on bedrock, and is much easier to maintain.

Concluding Remarks

For the TA, the geographic scale, number of instruments, and quality of data were fundamental to the science of the experiment. Operationally, the facility concept was extraordinarily simple: 400 stations on a 70 km grid, cover the country in 10 years. The implementation, as proposed and funded, was impossible. It only gradually became less so.

At the outset, I described TA implementation as being much closer to manufacturing than research. It was to be a community facility in which the data led to research, following these general steps:

- Develop a plan
- Establish a process
- Always look to improve the process
- Avoid unnecessary change as much as possible

In our case, the very large number of complex instruments deployed over a vast geographic area meant it was essential not to mass-produce mistakes.

In the summer of 2013 and again in 2015, the TA Team, and especially its field crews, put in an enormous effort to meet the goal of reaching the entire continental United States with 1687 stations fully installed on schedule and removed on schedule. This was more than originally planned and on budget—a fantastic achievement.

That dedication was part of a culture that came about because of pride in workmanship, encouraging and supportive feedback from scientists and team members themselves, and a sense of purpose. Monitoring of large projects establishes whether the motivation and execution are working, but it hardly encourages those key factors.

Today, a new iteration of the Transportable Array is operating in Alaska, which requires even greater attention to the design fundamentals and utmost care in implementation. It is, in many technical aspects, a whole new ballgame. Fortunately, we have a new team meeting the challenges every day.

— Bob Busby, TA Manager

Acknowledgments

TRANSPORTABLE ARRAY TEAM

The success of the Transportable Array resulted directly from the dedication and commitment of its staff and management. To complete such a project on time and on budget with outstanding data return required cooperation, respect, and reliance on each other to perform at high levels despite the difficult field conditions, distributed team and management framework, and massive scale of the operations. The roster for the entire TA team highlights the 76 staff members who were employed on the project from 2003 to 2015 in the Lower 48, Some members of the TA Team participated for more than a decade, while others joined for a just few intense years. Thank you, all.

Management

Robert Busby
Perle Dorr
Doug Ford
Andy Frassetto
Katrin Hafner
Robin Morris
Bob Woodward
Rob Woolley
David Simpson
Rick Stout

TA Coordination Office

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Cyndie Dever
Denise Elvrum
Cheryl Etsitty
Shanon Helbock
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Allan Sauter
Steve Welch

Reconnaissance

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Larry Jaksha
Don Lippert
Jean Miller
Graylan Vincent

Construction

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Steve Christman
Mike Flanagan
Tony Gonzales
Ronald Grubb
Mack Hardy
Trent Hooten
Trey Hooten
Ron Kessenich
Mack Maclauchlan
Reggie Pearl
Daniel Stewart

Installation

Kenneth Oliver
Jerry Hollinan
Elgin Hinson
Charlie Lurton
Bob Pierce

Service

Dan Knip
Doan Nguyen
Howard Peavey

Removal

Anthony Kim
Dean Lashway
Tom Mazon
Mark Miller

AOF

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Bruce Beaudoin
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Vladislav Martynov
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Tami Mulder
Rob Newman
Juan Reyes
Jon Tytell
Frank Vernon
Malcolm White

DMC

Tim Ahern
Peggy Johnson
Gillian Sharer
Chad Trabant

TRANSPORTABLE ARRAY GOVERNANCE

The TA received invaluable advice from proponents and partners in the geoscience community. This group includes dozens of scientific advisors who served on governance committees that advised and oversaw the project. We sincerely appreciate the contribution of time and expertise from these individuals.

USArray Advisory Committee (2005-2013)

Harley Benz
Michael Bostock
Larry Brown
Doug Christensen
Adam Dziewonski*
Göran Ekström
Matthew Fouch*
Michael Gurnis
Roger Hansen
Karl Karlstrom
Rainer Kind
James Knapp
Charles Langston
Thorne Lay
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Vadim Levin
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In particular, there were several proponents of the TA during its visioning stage, 1997–2003, who helped to catalyze the momentum necessary in the scientific community to even propose such a project. Thank you Alan Levander, Anne Meltzer, Paul Silver, and a host of others for your dedication and foresight.

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The technical integration of many commercially available components into a functioning and reliable system required the commitment to detailed and sustained interaction of between staff of the TA and groups that designed and manufactured the equipment. Available products were originally not designed for the specific purpose of the TA, and we had to adapt the product or our approach to reconcile. That was a struggle, but it ended well and was aided by the tenacity and commitment of these project partners. In particular, Joe Steim (Quanterra Inc.), Danny Harvey (Boulder Real Time Technologies), Rob Collins (Solarcraft Inc.), and Frank Vernon (University of California, San Diego) all made enormous contributions to the technical design and implementation of the TA.

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References

Anderson, D., J. Anderson, D. Ford, L. Gee, G. Gyure, C.R. Hutt, E. Kromer, L. Li, B. Marshall, K. Persefield, A. Ringler, M. Sharratt, T. Storm, D. Wilson, D. Yang, and Z. Zheng, 2015, Upgrade of the new China digital seismograph network, *Seismological Research Letters*, doi: https://doi.org/10.1785/0220140182

Astiz, L, J.A. Eakins, V.G. Martynov, T.A. Cox, J. Tytell, J.C. Reyes, R.L. Newman, G.H. Karasu, T. Mulder, M. White, G.A. Davis, R.W. Busby, K. Hafner, J.C. Meyer, and F.L. Vernon, 2014, The Array Network Facility Seismic Bulletin: Products and an unbiased view of United States seismicity, *Seismological Research Letters*, doi: https://doi.org/10.1785/0220130141

Ekström, G., and M. Nettles, 2018, Observations of seismometer calibration and orientation at USArray stations, 2006–2015, *Bulletin of the Seismological Society of America*, doi: https://doi.org/10.1785/0120170380

Ekström, G., and R.W. Busby, 2008, Measurements of seismometer orientation at USArray Transportable Array and Backbone stations, *Seismological Research Letters*, doi: https://doi.org/10.1785/gssrl.79.4.554

Forbriger, T., 2007, Reducing magnetic field induced noise in broadband seismic recordings, *Geophysical Journal International*, doi: https://doi.org/10.1111/j.1365-246X.2006.03295.x

Forbriger, T., R. Widmer-Schnidrig, E. Wielandt, M. Hayman, and N. Ackerley, 2010, Magnetic field background variations can limit the resolution of seismic broad-band sensors, *Geophysical Journal International*, doi: https://doi.org/10.1111/j.1365-246X.2010.04719.x

Kozlovskaya, E., and A. Kozlovsky, 2012, Influence of high-latitude geomagnetic pulsations on recordings of broadband force-balanced seismic sensors, *Geoscientific Instrumentation, Methods, and Data Systems*, 1, 85–101, doi: https://doi.org/10.5194/gi-1-85-2012

Levander, A., E.D. Humphreys, G. Ekström, A.S. Meltzer, and P.M. Shearer, 1999, Proposed project would give unprecedented look under North America, *EOS*, 80, 245, 250–251, https://doi.org/10.1029/99EO00181

McNamara, D.E., and R.P. Buland, 2004, Ambient noise levels in the continental United States. *Bulletin of the Seismological Society of America*, doi: https://doi.org/10.1785/012003001

Meltzer, A., R. Rudnick, P. Zeitler, A. Levander, G. Humphreys, K. Karlstrom, G. Ekström, R. Carlson, T. Dixon, M. Gurnis, P. Shearer, and R. van der Hilst, 1999, USArray Initiative, 9, *GSA Today*, 8–10.

Metlzer, A., R. Carlson, T. Dixon, G. Ekström, M. Gurnis, G. Humphreys, K. Karlstrom, A. Levander, R. Rudnick, P. Shearer, P. Silver, R. van der Hilst, and P. Zeitler, 1999, *USArray – A Synoptic Investigation of the Structure, Dynamics, and Evolution of the North American Continent* [White Paper]

Peterson, J., 1993, Observations and modeling of seismic background noise, U.S. Geological Survey Open File Report, 93-322.

Peterson, J., and C.R. Hutt, 1989, *IRIS/USGS plans for upgrading the Global Seismographic Network*, U.S. Geological Survey Open File Report, 89-471, https://doi.org/10.3133/ofr89471

Post, E.J., 1967, Sagnac Effect, *Reviews of Modern Physics*, 32, https://doi.org/10.1103/RevModPhys.39.475

Reed, J.C., Jr., J.O. Wheeler, and J.E. Tucholke, comps., 2005a, Geologic Map of North America: Boulder, Colo., Geological Society of America, Decade of North American Geology Continental Scale Map 001, scale 1:5,000,000, http://rock.geosociety.org/Store/detail.aspx?id=DNAGCSMS1

Ringler, A.T., and J.R. Evans, 2015, A quick SEED tutorial, *Seismological Research Letters*, doi: https://doi.org/10.1785/0220150043

Rogers, R.M., A. Sauter, R.W. Busby, T. Kim, C. Hayward, and B.W. Stump, 2008, Infrasound observations at USArray sites – A preliminary investigation of the utility of seismo-acoustic observations on a regional scale, *Eos Transactions*, American Geophysical Union, 89(53), Fall Meeting Supplement, Abstract S33B-1944

Steim, J.M., and R.D. Reimiller, 2014, Timeliness of Data Delivery from Q330 Systems, *Seismological Research Letters*, https://doi.org/10.1785/0220120170

Tytell, J., F. Vernon, M. Hedlin, C. de Groot Hedlin, J. Reyes, B. Busby, K. Hafner, and J. Eakins, 2016, The USArray Transportable Array as a platform for weather observation and research, *Bulletin of the American Meteorological Society*, https://doi.org/10.1175/BAMS-D-14-00204.1

Wielandt, E., and G. Streckeisen, 1982, The Leaf-Spring Seismometer: Design and performance, *Bulletin of the Seismological Society of America*, 72, 2349–2367

Appendix A. Omitted Stations

The stations listed below were excluded from the report because of their atypical characteristics. In many cases however, they have good quality seismic data and can be used for scientific purposes.

Station	Site
TASL	Snake Pit, Albuquerque Seismic Lab, NM
TASM	ASL Pad, Albuquerque Seismic Lab, NM
TASN	ASL Pad, Albuquerque Seismic Lab, NM
TASO	ASL Pad, Albuquerque Seismic Lab, NM
TASP	ASL Pad, Albuquerque Seismic Lab, NM
TFRD	Ford Ranch, Anza, CA
TVZX	IRIS PASSCAL Warehouse, Socorro, NM
Y22C	IRIS PASSCAL Instrument Center, Socorro, NM
Y22D	IRIS PASSCAL Instrument Center, Socorro, NM
Y22E	IRIS PASSCAL Instrument Center, Socorro, NM

Appendix B. Stations Operating Q330HR

Station	Site
214A	Organ Pipe National Monument, Ajo, AZ
BGNE	Belgrade, NE
BRSD	Miller, SD
KMSC	Kings Mountain, Blacksburg, SC
KSCO	Kaye Shedlock's, Cheyenne Wells, CO
MDND	Maddock, ND
R11A/R11B	Troy Canyon, Currant, NV
SFIN	Lafayette, IN
SPMN	Marine on St. Croix, MN
TUL1/TUL3	Leonard, OK

Appendix C. Non-Standard Channel Configurations

Channel	Sensor	Stations
[B,L,U,V]DE	Chaparral 2.5 microphone	N24A, N25A, O25A, P25A, Y22D
VDI	Paroscientific 600 microbarometer	N24A, N25A, O25A, P25A, P26A, Y22D
VD[O,0]	Paroscientific 600 microbarometer	Y22D
[U,V]DF	Validyne DP250 & DP350 microphone	N24A, N25A, O25A, P25A, Y22D
[B,L]DG	NCPA/Hyperion microbarometer	Y22D, TPFO

Digital Appendix

Several additional documents detail aspects of the TA that are beyond the scope of this report. These include a reference documentation website created during the operation of the TA, examples of GIS siting reports, and detailed construction procedures for a site. These documents are located at http://www.usarray.org/researchers/obs/transportable/l48_ta_report.

BACK COVER PHOTO. On September 30, 2013, the Transportable Array project staff gathered for a science symposium held at Woods Hole Oceanographic Institution to commemorate the completion of Lower 48 TA installations.

earthscope

USArray Transportable Array

http://www.usarray.org

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